TECHNOLOGICAL INNOVATION CHALLENGE: R&D STRATEGIES FOR CREATING DISRUPTIVE TECHNOLOGY AND THE CHOICE BETWEEN CREATION AND ADAPTATION

YU DAN

(B.Eng, Zhejiang University in China)

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SUMMARY

The *Disruptive Innovation* Theory has created a significant impact on management practices and aroused plenty of rich debates within academia. Copious as the studies are, the scattered and conflicting nature of the literature on disruptive innovation in the last decade may pose a state of ambiguity for future research, thus necessitating a comprehensive review at this juncture. In the 1st essay (Chapter 2), the basic concept and potential misinterpretations of the theory have been clarified first. Believing in the predictive value of the theory on firm performance, I then summarize and critique the research on how to enable potential disruptive innovation from internal, external, marketing, and technology perspectives. The different perspectives have inspired me to identify a number of key research directions within the disruptive innovation domain. Future research by integrating disruptive innovation with other research domains have also been briefly discussed, for example, Open Innovation. Finally, practical contributions are also made by outlining a series of potential inhibitors and enablers of disruptive innovation as managerial "take-aways".

One major finding of the reflective review is that the technology perspective has not been sufficiently addressed in the literature. In Chapter 3, the exploratory case study of disruptive technology — Sony transistor radio has revealed that technology could indeed play a key role in technological disruptive innovations; hence it is worthwhile for further research. This motivated the second essay (Chapter 4), in which I have studied

empirically how potential disruptive technologies could be created purposefully as options for potential disruptive innovations. Based on the intensive studies of seven cases of technological disruptive innovations, four R&D strategies have been proposed, namely miniaturization, simplification, augmentation and exploitation for another application. These four R&D strategies have been further verified by means of the Delphi method with a panel of 25 experts who agreed to assess if these strategies were likely to be used in another 30 disruptive examples. The frequencies of their utilization were also compiled and the implications discussed**.** This study has taken the initial step for research on deliberate and systematic strategies to create disruptive technology candidates that would in turn help firms to become serial disruptors.

The four R&D strategies provide guidance to firms that are active to be creators of innovations. However, as entrant firms are always smaller and weaker, many of them choose to adapt to new product innovations or change of design rules, rather than innovating by themselves. The third essay (Chapter 5) is devoted to empirically compare which contributes more to the success of entrepreneurial firms, creation of or adaptation to design rules. Applying Cox regression model on the data of the de-novo startups that were established in the fast growing period of the industry, I find its implications to the entrepreneurship research. While the entrepreneurship literature pays much more attention to discovery than creation, there is no significant result that discovery of entrepreneurial opportunities contributes more to longevity. In addition, the literature so far only uses either creation or discovery to explain the entrepreneurial action, it is found that the longevity of firms that doing both is significantly longer than firms only discover or create. It is really about the degree of discovery vs. creation or the balance between the two. Punctuated equilibrium and ambidexterity could be the possible mechanism to balance the two.

Overall, the thesis has advanced the knowledge in the front end (i.e. the technological perspective) of disruptive innovation, and the discussion between creation and adaptation has enlightened the balanced view of creation and discovery of entrepreneurial opportunities.

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Chapter 1

Introduction

1.1 Research background

The literature on management of technological innovation is full of anecdotes that show over and over again how profitable and stable products, processes and services were replaced by new ones and the new entrants replaced the well-managed incumbent firms as the industry leaders of the new generation. Research scholars are consistently making every endeavor to improve our understanding on the inquiry that why well-managed incumbent firms could be dethroned by new entrants in technological innovations. There are several milestone contributions that addressed the inquiry from various angles ever since the seminal work of “Creative Destruction” by Schumpeter (1942). They include “Structured Routines” by Nelson and Winter (1982) from knowledge management perspective, “S-Curve” by Foster (1986) via the lens of innovation lifecycle, “Competence-enhancing vs. Competence-destroying” by Tushman and Anderson (1986) focusing on competence perspective, “Architectural Innovation” by Henderson and Clark (1990) creating a new product architecture perspective and “Disruptive Innovation” by Christensen (1997, 2003) adding customer perspective.

It is rare that a scholarly work by Christensen on disruptive innovation has drawn so much attention from both academia and industry. In industry, Christensen was elevated by the business press to the status of “guru” (Scherreik, 2000). The two books entitled “The Innovator’s Dilemma” and “The Innovator’s Solution” have been best sellers for many years. Furthermore, the Disruptive Innovation Theory has been found to apply widely to electronics industry (personal computers, wireless communications, digital camera and internet appliances), steel industry (minimills), mechanical excavator industry (disruptive hydraulics technology), electric utility industry (distributed power generation enabled by gas turbines, micro-turbines, fuel cells), biomedical devices (micro/nano technology) and service industry (financial services, hospitals, retails, e-learning).

In academia, Christensen’s paper has been widely cited (e.g. Citation in Strategic Management Journal over 300 times). However, it has also aroused a growing body of rich debates and studies within academia [1], including debates on the fundamental definition, predictive value of the theory and studies on how to enable a successful disruptive innovation from many perspectives. Copious as the studies are, the scattered and conflicting nature of the literature on disruptive innovation in the last decade poses a state of ambiguity for future research, thus necessitating a comprehensive and reflective review at this juncture.

[1] The details of the debate could be obtained from two special issues: IEEE Transactions on Engineering Management, 2002 and Journal of Product Innovation Management, 2006.

1.2 Research objectives

Therefore, the first essay of this thesis aims to critique and integrate current studies in this domain, and to raise questions to initiate future research. Since definition is the foundation for all future research and the basic definition of disruptive innovation is under hot debate, the first objective is to clarify the concept of disruptive innovation and some common misinterpretations. The second objective is to evaluate the theoretical and empirical developments of disruptive innovation theory in order to identify the future research agenda. The literature is organized in two groups, i.e. within the disruptive innovation domain and its integration with other research domains. Furthermore, I intend to discuss the literature within the disruptive innovation domain according to the nature of topics and perspectives, such as internal vs. external, marketing vs. technology. The final objective is to propose a series of potential inhibitors and enablers of disruptive innovations from the empirical studies as practical contributions.

The reflective review shows several promising future research directions, and I specifically choose one for further study, which becomes the research question that leads to Chapter 3 and Chapter 4 (the 2nd essay) in this thesis. Compared with other perspectives such as internal, external and marketing, the technology perspective has received very limited coverage to date. This may lead to the perception that it is sufficient to be vigilant and quick to spot the opportunity as soon as a disruptive technology occurs at some time in the future.

In Chapter 3, an exploratory case study has been conducted with the objective to understand whether or not the technology perspective is important, which will imply whether further attention is needed. The findings of the case study on Sony's transistor radio clearly show that the creation of certain disruptive technologies could indeed be extremely challenging, especially if it is based on a new scientific discovery. Hence, it is reasonable to argue that in some cases, technology could indeed play a key role in technological disruptive innovations. This is consistent with the arguments on the distinctiveness and challenging nature of creating technology candidates for disruptive innovations (Kostoff et al., 2004; Schmidt & Druehl, 2008; Walsh, 2004). Therefore, it is timely to conduct research on the enabling roles of technology in disruptive innovation.

Due to importance of technology, the objective of Chapter 4 (my second essay) is to study empirically how potential disruptive technologies could be created purposefully as technology options for potential disruptive innovations. As this stream of research is still in a nascent stage, I decide to use multiple case studies to derive suitable R&D strategies that could guide corporate R&D to create technology options for potential disruptive innovations. In order to increase the reliability and generality of the strategies, I want to identify all the known cases of technological disruptive innovations in the literature that (1) conform to the definition; (2) come from various industries, countries, and time periods, and (3) have sufficient data support. In addition, by using Delphi method, I planned to invite an expert panel that consists of relative experts from industry and the R&D community to assess the applicability of my strategies. The R&D strategies would take the initial step in creating a more deliberate and systematic strategy framework to create disruptive technologies. With more disruptive technologies appear and documented in the future, both success and failure, more robust strategies would be developed to help firms become serial disruptors.

The R&D strategies explain how to become creators of innovations; yet not every firm is willing to or capable to be creators of a whole product innovation, or even changes of components or design rules. Firms can choose adaptation to design rules as an alternative of creation. Therefore, the 3rd essay shifted the focus from the discussion on strategies for creators to the comparison between creation and adaptation. The hard disk drive industry was the study context since it was full of changes of design rules and entrepreneurial opportunities from late 1970s to 1999.

Technological innovations forced changes of design rules, and new design rules further led to entrepreneurial opportunities for startup firms. De-novo startup firms could be divided into those that created entrepreneurial opportunities and those that discovered them. The first objective is to empirically compare the relative contribution of creation vs. discovery of entrepreneurial opportunities to startup firms' longevity, following conceptual differentiation between the two alternatives by Alvarez and Barney (2005). Especially noteworthy, the literature so far only uses a single-side theory to explain the entrepreneurial action, yet it is found firms that did both creation and discovery were the most successful firms. Hence, the second objective is to compare the relative contribution of "both creation and discovery" versus "only creation or discovery" to startup firms' longevity and discuss the reasons and implications. However, as I design the study within the hard disk drive industry, the findings and subsequent conclusions would be valid in my study context and needs further caution to generalize to other contexts.

1.3 Organization of the thesis

The thesis is divided into six chapters. A brief description of the structure of each chapter is provided as follows:

Chapter 2 (Essay 1) – A comprehensive and reflective review of disruptive innovation theory: This chapter covers the overall literature review in disruptive innovation domain. Section 2.1 is the introduction and preview. The evolution, description, and clarification of the concept of disruptive innovation in Section 2.2 and 2.3, would serve as a major foundation for further research in this area. In Section 2.4, i.e. "Predictive use of the disruptive innovation theory", the main conclusion that disruptive innovation theory can be applied to anticipate the future of firms supports the efforts made to study how to enable a disruptive innovation in Section 2.5. In "Enabling potential disruptive innovation", 4 perspectives have been summarized and critiqued, namely internal perspective, external perspective, marketing perspective and technology perspective. In particular, since there is a substantial body of literature that can be classified under internal perspective, it is further broken down into 4 aspects, which are human resources, organizational culture, resource allocation and organizational structure. Thereafter, the new research agenda has been proposed in Section 2.6, including directions within and outside disruptive innovation domain. Many inhibitors and enablers of disruptive innovation have also been discussed in Section 2.6. Section 2.7 summarizes the literature review and highlights its contributions to both theory and practice.

Chapter 3—An exploratory case study on the technological dimension of disruptive innovation: This chapter zooms in on the technology perspective of disruptive innovation, with the purpose to reveal the importance of technology in technological disruptive innovations. Section 3.1 is a transition from Chapter 2. Section 3.2 explains the rationale for choosing case study method and the reasons for selecting transistor radio for my study. Transistor is justified as a disruptive technology in Section 3.3. The challenging nature of Sony transistor radio's development is elaborated in Section 3.4. Section 3.5 discusses the roles played by key members of the team. Insights from the exploratory case study are discussed in Section 3.6. In the last Section 3.7, the conclusion is drawn that technologies in disruptive innovations are sometimes indeed challenging and worthwhile for purposeful creation in advance. The conclusion paves the way for designing R&D strategies to create candidate technologies for potential disruptive innovation in the next chapter.

Chapter 4 (Essay 2) –R&D strategies for creating candidate technologies for potential disruptive innovation: Section 4.1 starts to explain the link between this chapter and chapter 2 and chapter 3. It is followed by relative theoretical background such as the extant research on creating candidate technologies for potential disruptive innovations. Section 4.3 introduces the research design of this essay, the reasons of using multiple case studies to identify the strategies and the reasons of using the Delphi technique to verify the wide application. In Section 4.4, 4 R&D strategies are formulated, and each of them is drawn from 2 cases. Assessment of general application of the 4 strategies by Delphi method follows in Section 4.5, and relative implications are also discussed in Section 4.5. Section 4.6 summarizes the key findings, points out the contributions and discusses the limitations.

Chapter 5 (Essay 3) – Creation vs. discovery of entrepreneurial opportunities in hard disk drive industry: Section 5.1 explains the transition from Chapter 4, shifting the research focus from only creation to the comparison between creation and discovery/adaptation. The relevant literature streams in entrepreneurship and modular design are discussed in Section 5.2. Section 5.3 explains the research design in detail. Section 5.4 presents the findings on entrepreneurial firms' entry strategy choices between creation vs. discovery and how the entry strategies influenced longevity of firms. Section 5.5 discusses the implications on entrepreneurship literature in two layers. They are comparison between creation and discovery and comparison between performing both and performing only one. The chapter ends by summarizing the contribution and limitation of the essay.

Chapter 6 – Summary of contributions: This last chapter summarizes the thesis by showing the overall contribution of the thesis in Section 6.1 and the contributions of the three essays separately in Section 6.2 to Section 6.4.

Chapter 2

A Reflective Review of Disruptive Innovation Theory

2.1 Introduction

One type of technological innovation emerging as strategically important in practice is "*Disruptive Innovation*", popularized by Christensen (1997). Disruptive innovation is a powerful means for broadening and developing new markets and providing new functionality, which, in turn, may disrupt existing market linkages (Adner 2006; Charitou & Markides 2003; Christensen 1997; Christensen & Bower 1996; Christensen & Raynor 2003; Danneels 2004; Gillbert 2003; Govindarajan & Kopalle 2006). The theory has created a significant impact on management practices and aroused plenty of rich debate within academia. Two prominent journals in technology management research, namely the *IEEE Transactions on Engineering Management*[2] and the *Journal of Product Innovation Management*[3], have organized special issues for topics associated with disruptive innovation. The substantial literature currently is conflicting and ambiguous for future research, which motivated me to conduct a comprehensive review.

This chapter aims to (1) clarify the concept of disruptive innovation and some common misinterpretations; (2) evaluate the theoretical and empirical developments of

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2 Special issue of Disruptive Innovation in IEEE TEM, Vol. 49, No.4, Nov. 2002. There were 8 papers from Page 319 to Page 397.

3 Special issue of Disruptive Innovation in JPIM, Vol. 23, Iss. 1, 2006. There were 7 papers from Page 2 to Page 55.

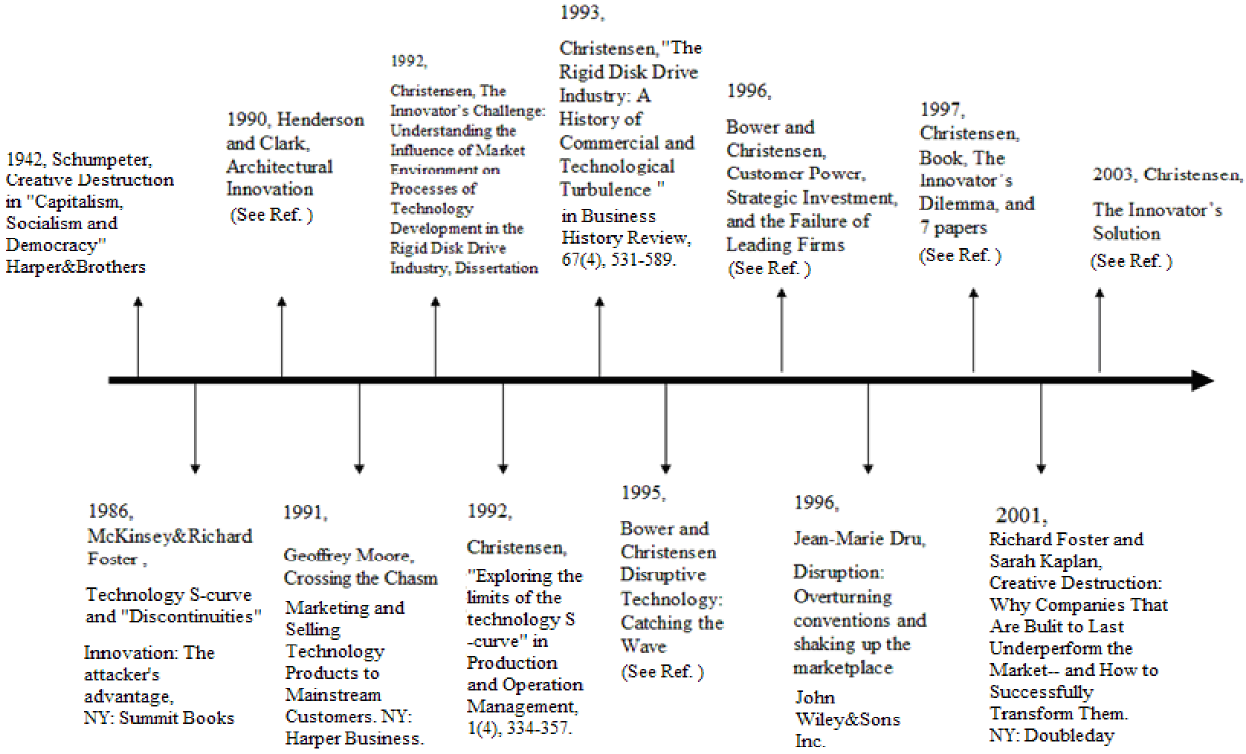
disruptive innovation theory in order to identify the research gaps to be addressed in the future; (3) propose a series of potential inhibitors and subsequent enablers of disruptive innovations as managerial "take-aways".

The review of Disruptive Innovation Theory is structured by three major themes in this chapter. The first theme is the research on "what is disruptive innovation", including the evolution and description of the theory and the actual definition of disruptive innovation. The second theme discusses the predictive value of the theory. The last theme summarizes the contributions on how to enable a disruptive innovation from various angles such as internal versus external, and marketing versus technology. A series of potential inhibitors and enablers of creating a disruptive innovation are identified based on the discussion of the last theme.

2.2 Evolution and description of disruptive innovation

Disruptive Innovation Theory, advanced by Christensen (1996, 1997, 2003, 2006), was built up based on a series of previous technological innovation studies (Figure 2.1). In 1997, Christensen published his influential book entitled "*The Innovator's Dilemma*". The book articulated the basic theory of disruptive technology in a comprehensive and detailed manner.

FIGURE 2. 1[4] Timeline of evolution of disruptive innovation theory

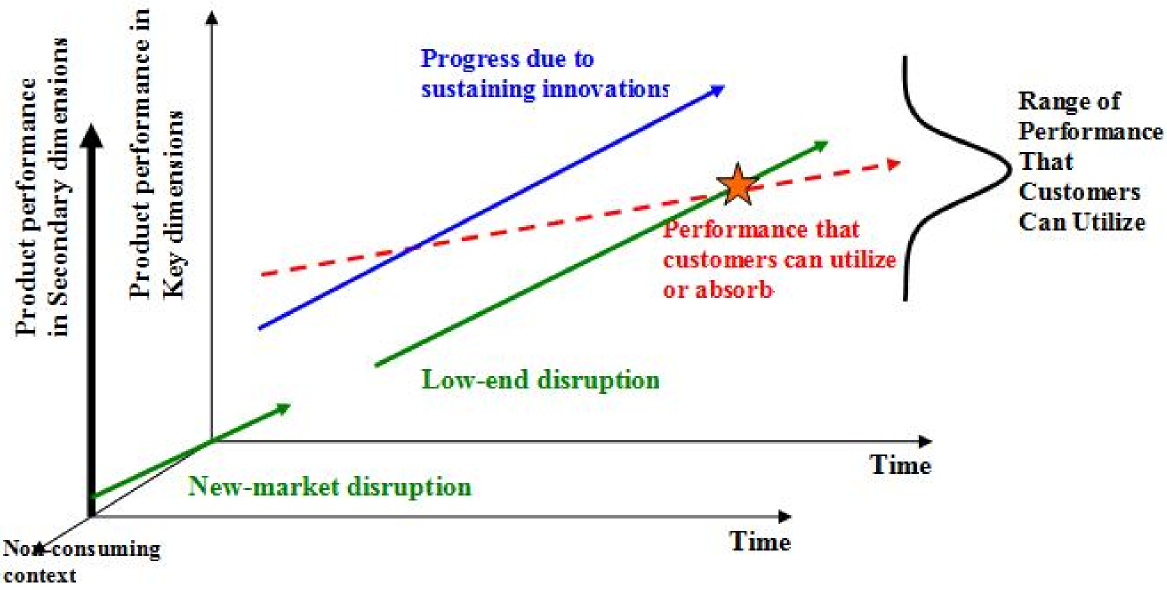


Disruptive innovation happens in a process. According to Christensen, disruptive technologies are technologies that provide different values from mainstream technologies and are initially inferior to mainstream technologies along the dimensions of performance that are most important to mainstream customers. He introduces the important aspects of changing performance with time, plots the trajectories of product performance provided by firms and demanded by customers for different technologies and market segments, and shows that technology disruptions occur when these

4 This figure was summarized based on the early literature of technology discontinuity as well as papers and books of Christensen.

trajectories intersect (Figure 2.2). In its early development stage, each product based on certain disruptive technology could only serve niche segments that value its nonstandard performance attributes. Subsequently, further development could raise the disruptive technology's performance on the focal mainstream attributes to a level sufficient to satisfy mainstream customers. While improved, the performance of the disruptive technology remains inferior compared to the performance offered by the established mainstream technology, which itself is improving as well. In fact, the performance of the mainstream technology could have exceeded the demand of mainstream customers, resulting in "performance overshoot" with over-served customers. The market disruption occurs when, despite its inferior performance on focal attributes valued by existing customers, the new product displaces the mainstream product in the mainstream market. There are two preconditions for such a market disruption to occur: performance overshoot on the focal mainstream attributes of the existing product and asymmetric incentives between existing healthy business and potential disruptive business. Christensen documented these technology and market dynamics in numerous contexts such as hard disk drives, earthmoving equipment, and motor controls.

FIGURE 2. 2 The disruptive innovation model



In order to resolve the innovator's dilemma over how well-managed incumbent firms can avoid dethronement by developing disruptive technologies from their sustaining competitive paradigms, Christensen (2003) published another book entitled "The Innovator's Solution". In this book, he replaced disruptive technology with the term "disruptive innovation" because he widened the application of the theory to include not only technological products, but also services and business models innovation such as discount department stores, low-price, point-to-point airlines, and online businesses education. Markides (2006) further argued that technological innovations were fundamentally different from business model innovations, and he called for a finer categorization within disruptive innovation. I also believe disruptive innovation is a more appropriate term than disruptive technology to describe the entire phenomenon, as business model innovations are heavily involved. Moreover, Christensen refined his theory and emphasized that disruptive innovations could be broadly classified into low-end and new-market disruptive innovations (Christensen & Raynor 2003). While low-end disruptions are those that attack the least-profitable and most overserved customers at the low end of the original value network, new-market disruptions create a new value network, where it is the nonconsumption, not the incumbent, which must be overcome (Christensen & Raynor, 2003).

Owing to the evolving knowledge in innovation management and potentially pervasive applications, scholars from various disciplines of management research have generated more and more critiques, doubts, and challenges concerning the disruptive innovation theory, particularly on the fundamental question of what the disruptive technology actually is.

2.3 Definition and misinterpretations of disruptive innovation

Mainstream studies divide technological innovations into two types, but use different terminologies for different stages in history. There are two general classes of technologies: (1) revolutionary, discontinuous, breakthrough, radical, emergent, or step-function technologies; (2) evolutionary, continuous, incremental, or “nuts and bolts” technologies (Florida & Kenney, 1990; Morone, 1993; Utterback, 1994). Each categorization serves to explain certain phenomena but suffers from anomalies of its own.

For example, the famous classification using competency-enhancing innovations versus competency-destroying innovations was established from the company perspective, which could explain the success of incumbent firms in the face of breakthrough innovation, thus contradicting the widely accepted statement that established companies tend to do well only in incremental innovation but falter in the face of breakthrough innovation (Tushman & Anderson, 1986). The subsequent notable work of modular versus architectural innovation (Henderson & Clark, 1990) could further explain why great firms fail in the core technological innovations, as companies with strong competences in component technologies might ignore the competitive implications of the architecture changes. Hence, the architectural innovation theory explained an anomaly that competency-enhancing or destroying theory could not adequately account for. In the same vein, it was the anomaly of the hard disk drive industry in recent decades which could not be adequately explained by previous research that motivated Christensen to develop the disruptive innovation theory and to classify innovations as sustaining versus disruptive.

In terms of the definition and scope of disruptive technology, a very heated discussion has been triggered (e.g. Adner, 2002; Benner & Tushman, 2003; Bower & Christensen, 1995; Chesbrough, 2001; Christensen & Raynor, 2003; Danneels, 2004; Gillbert, 2003; Govindarajan & Kopalle 2004, 2006; Henderson, 2006; Husig *et al.* 2005; Markides, 1998, 2006; Paap & Katz 2004; Tellis, 2006). Some researchers were supporters of Christensen, in general, but proposed their own slightly different views.

For example, Adner (2002) identified that a critical reason for the switch of consumer choices from sustaining to disruptive innovation was the decreasing marginal utility from the performance improvements in major dimensions, in addition to new value propositions and affordable prices discussed by Christensen. Meanwhile, others criticized the vagueness of the concept of disruptive innovation. Danneels (2004) suggested that several authors seemed to think that Christensen did not provide a precise and consistent definition of the term disruptive technology. Tellis (2006) challenged it would be very difficult to differentiate underperforming technologies from a technology with inferior performance but finally ending up being disruptive.

Especially noteworthy is Govindarajan and Kopalle's contribution that introduces an innovation measure to include high-end as well as low-end disruptions, provides a more general view of disruptiveness of innovations, and explore beyond the case of low price/low performance (Govindarajan & Kopalle, 2006). Disruptive innovation (having inferior performance in traditional attributes) with a high price, which Govindarjan and Kopalle referred to as high-end, is indeed a white space that Christensen's theory (inferior performance and low unit cost) has not set foot in (Fig.3, right-lower quadrant). Cellular phones exemplify such a disruptive innovation with an initially higher price. The cellular phone was first accepted by corporate executives who appreciated its convenience and portability despite its relatively high price. When it was introduced, the mainstream market still preferred land-line phones because of their reliability, cost, and coverage. However, over time, further developments in cellular technology allowed it to offer reliable coverage at a price point that satisfied the needs of mainstream consumers, which caused the disruption. Christensen (2006) expressed his appreciation of their efforts to define the phenomenon even more precisely. A complementary framework recently refined new-market disruption into two types, fringe-market low-end encroachment and detached-market low-end encroachment, with the cell phone as the representative of detached-market low-end encroachment (Schmidt & Druehl 2008).

Govindarajan and Kopalle (2006) performed a series of analyses to establish the reliability and validity of the disruptiveness scale. The reliability measures, exploratory factor analysis, confirmatory factor analysis, and statistical tests strongly support their measure. According to their measure, a disruptive innovation should (1) be inferior on the attributes that mainstream customers value; (2) offer new value propositions to attract a new customer segment or the more price sensitive mainstream market; (3) be sold at a lower price; and (4) penetrate the market from niche to mainstream.

What constitutes a real disruptive innovation deserves examination from different lenses and it is crucial to discuss the definition in any further research on disruptive innovation. So do the clarifications of some potential misunderstandings. Three of them are highlighted and discussed here. First, disruption is a relative phenomenon. Dell Computers began by selling computers over the telephone or by mail. For Dell, the initiative to begin selling over the Internet was a sustaining innovation compared with its previous business model. For Compaq, HP, and IBM, marketing directly to customers was decidedly disruptive because of its impact on their retail channel partners

(Christensen & Raynor, 2003). In another situation, online stock brokerage was a sustaining innovation (financially attractive) relative to the business models of discount brokers, such as Schwab and Ameritrade, because it helped them discount even better. The same innovation was disruptive (financially unattractive) relative to the business model of Merrill Lynch (Christensen, 2006).

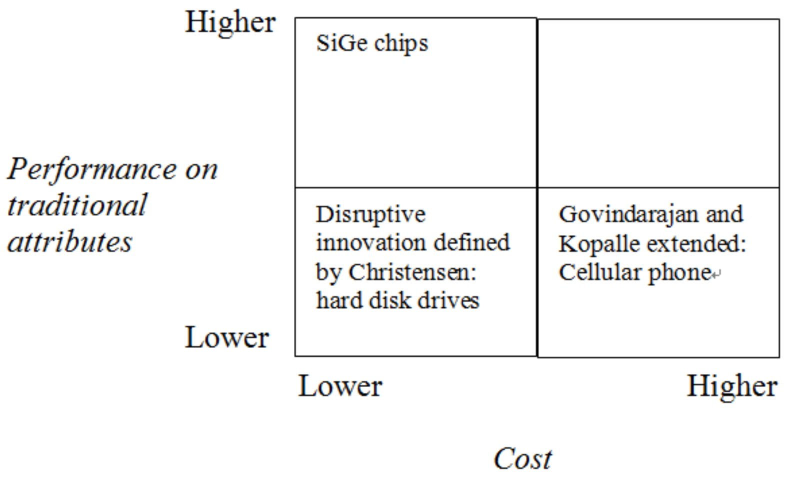
Second, disruptive innovation does not always imply that entrants or emerging business will replace the incumbents or traditional business; it does not imply that disruptors are necessarily startups. In fact, an incumbent business with existing high-end technologies still can survive by concentrating on how to satisfy its most demanding but least price-sensitive customers. Although digital cameras have been widely appreciated because of their light weights, small sizes, multiple functions, and affordable prices, professional photographers would still prefer the analog camera in extremely high resolution needs, unique surveillance needs, for example. Indeed, an incumbent business could still maintain a profitable niche market at the very high end without total displacement by digital imaging. Hence, a disruptive innovation ultimately could have a major impact on an existing market without totally displacing it (Schmidt & Druehl, 2008). In some cases, incumbent firms played the roles of smart disruptors. They include IBM's success in personal PCs, Control Data's success in 5.25-inch hard disks, Sony's success in Walkmans, HP's success in inkjet printers, Kodak's and Fuji's success in digital imaging, and Intel's success in Centrino chip-sets, to name a few well-known cases. Incumbents could survive the disruptive wave or even take the role of disruptors after they have accumulated transformational experience[5] (experience related to previous market entry) from the past (King & Tucci, 2002).

Third, disruptive innovation is not equal to destructive innovation. A technological innovation that has superior performance in key dimensions with a relatively low-cost structure would directly invade the mainstream market and cause more serious destructive effects than a normal disruptive innovation that focuses on low cost but initially lower performance. IBM's new generation of communication chips using SiGe is a good example. SiGe based chips can increase switching speeds by 4 times and greatly reduce power requirements; furthermore, were they manufactured using existing semiconductor fabrication plants, it would save great time and reduce costs by saving billions in new capital investments. Due to the superior performance and much reduced costs, the severe destructive impacts on its competitors (Lucent, Motorola, Infineon, etc) forced them to quickly become followers. SiGe has become a mainstream technology for the wireless communication industry since then. Hence, SiGe-chip, as shown in the left-upper quadrant of the matrix in Fig 2.3, caused serious destructive effects on incumbents, but definitely was not a disruptive innovation. In this school of thought, Utterback and Acee provided a more comprehensive view of technological innovations by adding the

5 King and Tucci (2002) differentiated two types of experience in their paper, static experience and transformational experience. Static experience is gained from further elaboration of existing structures, positions, and strategies. Their example is market positioning. The more a firm gains experience producing and selling products to its existing customers, the less likely it would be to enter new markets (This is consistent with Christensen's argument on over attention to existing customers). However, transformational experience is gained from changing these attributes. The more a firm gains experience reorganizing or redirecting its effort to new markets, the more likely it would be to continue to do so.

third dimension—ancillary performance, and what Christensen defined as disruptive innovation was one of the eight possibilities (Utterback & Acee 2005). Van Orden et al. (2008) further proposed a comprehensive framework including 3 high-end and 3 low-end encroachment patterns, and emphasized that the 3 high-end encroachment patterns (with destructive effects) are not disruptive.

FIGURE 2. 3
A Matrix of technological innovations based on cost and key performance dimensions



As Christensen (2006) has pointed out, he should have perhaps followed Intel in calling the phenomenon "Christensen's effect" to avoid the possible misinterpretation of disruptive innovation as radical or destructive innovation. Smith (2005) has commented in his book review that the new product development professionals would be served well to adopt the definitions of sustaining and disruptive innovations and to avoid the mistake of calling all radical innovations disruptive.

In this section, different categorizations of technological innovations have been discussed and it has been observed that each seems able to explain the anomalies of other categorizations, but suffers from anomalies of its own. That is the reason why a new theory and terminology of disruptive innovation have come into existence, and by no means is it a simple replication or extension of previous terminologies. In addition, the heated debate over the precise definition and refinement of disruptive innovation has been discussed and 3 potential misinterpretations have been outlined.

2.4 Predictive use of the disruptive innovation theory

Many research scholars have challenged the predictive use of Disruptive Innovation Theory. Barney argued that "it may simply be the case that some firms are lucky in their technology choices". Those firms with lucky choices were subsequently scrutinized and a retrospective rationale for their success was formed (Barney, 1997). Ex ante predictions involve predicting what performance the market will demand along various dimensions and what performance levels technologies will be able to supply. It is not entirely clear what methods exist for such predictions (Danneels, 2004). If one must wait until the disruption has occurred, then what predictive value is there in the concept (Tellis, 2006)?

Christensen (2006) has refuted the assertion of Danneels and Tellis that disruptiveness was defined post hoc. The model was derived from histories, but the definition of disruptiveness exists independent of the outcomes. The dethronement of incumbents is frequently observed but this is not necessarily always the outcome of disruptive innovation, as disruptive innovation does not always imply that the entrant business will completely replace the incumbent business and the winners will take all.

Aside from the criticism, some researchers, on the other hand, have made efforts to better address the predictive value of the theory. Schmidt (2004) proposed a model which may give firms some tools to use in assessing whether a market is ripe for disruption. His main idea is that if the part-worth curves for traditional attributes show somewhat of an overshoot and are correspondingly underserved in secondary attributes, then a new lower-cost product might conceivably be successful by emphasizing the secondary attributes while sacrificing performance on the traditional set. If the new product's performance could be improved over time with regard to traditional attributes, eventually the new product could be expected to move up market, reflecting low end encroachment (Schmidt, 2004). Paap and Katz (2004) pointed out general guidance to predict future disruption, such as "do not ignore your customers, both current and potential". The issue is to identify the drivers of the future, those that emerge when old drivers reach their leverage limit, and those that emerge when your customers' environment changes. Danneels (2004) has suggested tailoring extant technology forecasting methods to forecast potential disruptive technology. Govindarajan and Kopalle (2006) believe that the disruptive innovation framework indeed could help us make ex ante predictions about the type of firms likely to develop disruptive innovations. For example, since Firm A's *willingness to cannibalize* is higher than that of Firm B, Firm A would appear more likely than Firm B to develop disruptive innovations (Govindarajan & Kopalle, 2006; Druehl & Schmidt, 2008). It is believe that, based on the causes of incumbent firms' success or failure and subsequent solutions, we may be in a better position to tell the fate of a firm in a new wave of disruptive innovation. The argument that disruptive innovation theory can be applied to anticipate the future of firms supports the efforts made in the next section to study how to enable a disruptive innovation.

2.5 Enabling potential disruptive innovation

Empirical literature has generally found that discontinuous innovations are developed and commercialized by new entrants (Anderson & Tushman, 1990; Christensen & Bower, 1996; Foster, 1986; Henderson & Clark 1990; Tushman & Anderson, 1986). The research on disruptive innovation may reinforce the view that entrant firms have a better chance of success in discontinuous innovation compared to incumbent firms because of their smaller sizes, shorter (path-dependent) histories, and more limited commitments to value networks and current technological paradigms (Macher & Richman, 2004; Walsh et al. 2002).

Interestingly, a small number of large incumbent firms managed to identify and exploit a potentially disruptive technology before being disrupted by others (Ahuja & Lampert, 2001; Christensen & Bower, 1996; Paap & Katz, 2004; Rothaermel, 2001; Hill & Rothaermel, 2003). Hence, the findings have raised pertinent questions on why most large incumbents failed but some survived. What essentially would decide or contribute to firms' success in disruptive innovation?

The review in this section attempts to answer this by analyzing the literature from different perspectives: A) Internal perspective, the business models and organizational challenges of incumbent firms; B) External perspective, the context and environment; C) Marketing perspective, customer orientation under disruptive change; and D) Technology perspective, technological strategies for disruptive innovation. These 4 perspectives emerged from the attempt of the previous literature to answer two valuable questions, namely why a well-managed incumbent firm could fail in technology innovations, and how a seemingly inferior technology could grab the market shares and even replace the dominant technology. This also explains a subsequent observation that the studies turned out to be quite unbalanced in favor of perspectives A and C. For the first question on why most incumbents would fail but some succeed, most of the problems lie more in the incumbent itself than in environment and context. Hence, the internal perspective carries more weight than the external perspective. For the second question on why inferior technology could win, the entrants with initially inferior technology generally win because of innovative business models or a deep understanding of non-consumption. The use of technology that is initially inferior might also convey the misinterpretation of simplicity, which further leads to fewer studies on the enabling roles of technology.

2.5.1 Business models and organizational challenges of incumbent firms

A substantial body of literature has elaborated on enabling disruptive innovation from the organization itself. The explanations are sorted in 4 aspects: (1) Human Resources; (2) Organizational Culture; (3) Resource Allocation; and (4) Organizational Structure.

2.5.1.1 Human resources

There are two sub-aspects within the scope of human resources, managers and employees. The manager sub-aspect attributes an organization's failure in meeting the challenge of disruptive innovations to the competence of its managers. Firstly, senior managers may not understand the promise of disruptive innovation because their views of the world are deeply entrenched and largely shaped by their current experiences (Henderson, 2006). Most of them were trained in conventional business programs to manage organizations that served established markets with well-defined product lines. Therefore, an additional team at the corporate level is required to be particularly responsible for collecting disruptive innovation ideas and putting them into implementation (Christensen & Raynor, 2003). Moreover, long-term-oriented, subjective-based incentive plans should be adopted instead of short-term-oriented, formula-based incentive plans for key executives (Govindarajan & Kopalle, 2006) so that the senior managers will not be confined by the rigid incentives and avoid the risks of disruptive innovation. Secondly, middle managers also matter since most strategic proposals take their fundamental shape at the lower levels of hierarchical organizations. As middle managers usually have the most to lose in any basic change, they are likely to allocate their resources to sustaining innovations that bolster their current fiefdom and careers (Christensen & Raynor, 2003; Denning, 2005). Thirdly, there may be different performances between founders and professional managers in disruptive innovations. Founders have an advantage in tackling disruption because they not only wield the requisite political clout but also have the self-confidence to override established processes (Christensen & Raynor, 2003). The manager aspect discusses the key roles of both senior and middle managers as well as the different performances between founders and professional managers, explaining why incompetence of managers could be a main obstacle to a promising disruptive innovation.

Research has also been done to explain the success or failure of disruptive innovations from the employees' perspective. For example, the team research on a successful disruptive project, I-mode in NTT DoCoMo, found that the team members were composed of carefully selected risk-takers and that the firm also recruited outside expertise (Murase, 2003). In terms of decision making, Christensen argued that capturing ideas for new growth businesses from people in direct contact with markets and technologies can be far more productive than relying on analyst-laden corporate strategy or business development departments—as long as the troops have the intuition to do the first-level screening and shaping themselves. In the following process of implementation for the disruptive idea, instead of accepting one-size-fits-all policies, executives should spend time ensuring that capable people work in organizations with processes and values that match the task. Another interesting observation is that disruptors are usually founded by frustrated engineering teams from established firms (Christensen & Bower, 1996). Hence, the incumbent firms should take measures to prevent disruption from outside due to brain drain of talents and disruptive ideas. One solution would be establishing spin-offs as discussed in the sub-aspect of "organizational structure".

2.5.1.2 Organizational culture

A firm's culture is a critical component of its success. Culture is an effective way of controlling and coordinating people without elaborate and rigid formal control systems (Tushman & O'Reilly, 2002). However, culture is a double-edge sword that sometimes results in the failure of innovation. When great changes such as disruptive innovation occur, cases studies have shown that the organizational culture generates cultural inertia which is so difficult to overcome directly that it is a key reason why managers often fail to introduce timely and substantial change even when they know that it is needed (Christensen & Raynor, 2003; Henderson, 2006; Tushman & O'Reilly, 2002). Hence, it is important for incumbents to prepare for and institute organizational change and unlearn[6] deeply entrenched values[7] at the advent of potential disruptive

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6 Unlearning is defined as the process by which people and firms eliminate old logic and substitute it with something fundamentally new (Baker & Sinkula, 2005).

7 An organization's values are the standards by which employees make prioritization decisions, those by which they judge whether an order is attractive or unattractive, whether a particular customer is more

innovation. Nevertheless, some integral elements of culture such as entrepreneurship, risk taking, flexibility, and creativity should be preserved and valued in order to develop disruptive innovations (Murase, 2003; Govindarajan & Kopalle, 2006).

2.5.1.3 Resource allocation

Failure in disruptive innovation can also be caused by the resource allocation process. The primary inhibitor is the structured routines[8] (Nelson & Winter, 1982) such as the key evaluation factor of financial returns (Christensen, 2006) and the traditional market research reports. These structured routines constrain the actions of incumbent firms and evaluate emerging disruptive projects by the same criteria applied to existing businesses. Once established, structured routines were difficult to change. Another arch criminal is resource dependence[9], which means firms are locked into businesses in which they have accumulated resources (Christensen, 2006) and tend to investment more on the businesses where firms have enough resources. As a result, firms generally respond to the emergence of competitively threatening technologies by intensifying their

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important or less important than another, and whether an idea for a new product is attractive or marginal. Values often represent constraints; they define what the organization cannot do (Christensen & Raynor, 2003).

8 Nelson and Winter asserted that firms built competitive advantage by developing better routines that other firms and that superior routines were developed only through the faithful replication of effective behaviors.

9 Resource dependence means organizations are dependent on critical resources, those resources that necessary for the survival of the organization. Or formulated differently, resource dependence controls whether and to what extent various resources should be allocated to innovative activities (Pfeffer & Salancik, 1978).

investments to improve the conventional technologies used by their current customers (Christensen & Bower, 1996), thus missing the opportunity for new disruptive innovations. In summary, the structured routines (deep-rooted methods to evaluate projects) particularly financial measurements, and resource dependence (investment based on the profile of existing resources) hinder the development of potential disruptive innovation.

Some scholars have conducted empirical research to solve the resource allocation difficulties. One solution is to use strategic buckets to independently manage sustaining vs. disruptive projects (Chao & Kavadias, 2007; Hogan, 2005). Another is summarized based the case study of Good Manufacturing Practice (GMP)[10], which have projects in all the different pipeline phases and manage each phase as a mini-project (Hogan, 2005).

2.5.1.4 Organizational structure

The aspect of organizational structure covers the discussion on the sizes of firm and business units, the debate on spin-offs versus ambidextrous organization, and the proposal on collaboration between incumbent firms and startups.

The first sub-aspect is the relationship between the number and size of business units and the success of disruptive innovation. Innovation research has largely focused

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10 Good Manufacturing Practice or GMP is an organization developing and commercializing novel pharmaceutical, medical device and diagnostic technologies. The firm’s website http://www.gmpcompanies.com/

on firm or business unit size as a key determinant of R&D effectiveness (Cohen & Klepper, 1996; Tsai & Wang, 2005) and the recent trend argues that R&D investments are more productive for small than for large firms when introducing new products (Lee & Chen, 2009; Lejarraga & Martinez-Ros, 2008). In the research particularly on disruptive innovations, both case studies and surveys in high-tech industries have also shown that the size of the firm is negatively correlated to the success of disruptive innovation (Christensen & Raynor, 2003; DeTienne & Koberg, 2002; Tushman & O'Reilly, 2002). The implication is that a large corporation should keep its flexibility by having smaller business units so that it can continue to keep its decision makers excited and take emerging opportunities seriously. Nevertheless, a counter-argument argues that redundant overhead expenses can be eliminated when business units are consolidated into much larger entities (Christensen & Raynor, 2003). Another counter-view claims that organizations must also cope with the demands of architectural interdependences which often require larger, more integrated organizations.

One of the main proposals by Christensen to solve the innovator's dilemma is to set up an *autonomous organization* to develop and commercialize the venture. The key dimensions of autonomy relate to processes and values (unique cost structure) rather than geographical separation or ownership structure (Christensen & Raynor, 2003). He further argues that autonomous organizations are essential because, of incumbent leaders that succeeded at disruption (Chesbrough, 2001; King & Tucci, 2002), almost all of them had maintained their industry-leading positions by setting up an autonomous business unit or skunk works and giving it unfettered freedom to forge a very different business model appropriate to the situation (Christensen, 2006).

Without an isolated autonomous organization, can the parent organization equip itself with dual resources, processes, and values to manage both sustaining and disruptive innovations? Tushman and O'Reilly (2002) proposed the concept of *ambidextrous organizations* as a solution to manage discontinuous innovations. From the many successful examples cited, such as HP, J&J, and ABB, Tushman and O'Reilly (2002) tried to promote the ability to simultaneously pursue both incremental and radical innovation which would significantly improve the technical performance and satisfy the existing customers. However, disruptive innovation, due to the initial inferior performance, could not attract the same attention from senior managers and existing customers. Hence, their potentially valuable contributions may not be applicable in the case of disruptive innovation.

Some other researchers found that the open innovation theory may be applied to manage disruptive innovation (Chesbrough & Crowther, 2006; Paap & Katz, 2004). New startups always have innovative and potential disruptive technology strengths, but they lack the complementary assets that belong to the incumbent leaders (Rothaermel, 2001). Some researchers have empirically found that spin-offs, alliances, market transactions, and acquisitions are comparatively optimal for corresponding points in different stages of disruptive innovation (Claude-Gaudillat & Quelin, 2006). The empirical multiple case studies by Macher and Richman (2004) found that IBM, Kodak, and HP have adopted either form or a combination of different forms of collaborations to create disruptive innovations. Apart from research on different forms of open innovation, collaborator attractiveness has also been studied. A survey by Rothaermel (2002) found that a startup's new product development, economies of scope, public ownership, and geographic location in a regional technology cluster are positively associated with the startup's attractiveness as an alliance partner to create potentially disruptive innovation.

2.5.2 Context and environment

Looking beyond the firm level analysis, some scholars have searched for reasons of being disrupted from the context and environment of the firm because organizations are often locked into commitments reflected in the expectations of investors and analysts, public promises and goals, and existing relationships with resource providers and suppliers (Denning, 2005). For example, individual technologies cannot become commercialized unless other related technologies have been developed prior to or together with its introduction; thus, the relationship with technological suppliers and partners are of great significance for disruptive products commercialization (Myers, 2002).

In addition, early research has found that effective organizations in environments with substantial technological, legal, or social uncertainty tend to undertake reorientations or quantum innovations that include disruptive innovation (Tushman & Anderson, 1986).

Finally, it is interesting to compare how different contextual factors may influence the disruption process. Chesbrough's (1999) empirical research has shown that the disruption of hard disk drives in the US did not happen in Japan, mainly because the regulations and culture of Japan did not encourage entrepreneurship and the financing system was inefficient to support the development of disruptive ideas. There is an insightful case study on the Personal Handphone System (PHS) which shows that the PHS failed in Japan, yet later became a very successful disruptive innovation in China[11]. The economic conditions and entrepreneurial culture explained the distinctive results. These studies indicate that the success of disruptive innovation also depends on the variation of some contextual factors such as regulation, entrepreneurship culture, and economic conditions of different countries.

2.5.3 Customer-orientation under disruptive changes

Another major stream of literature has elaborated on the customer orientation under disruptive changes, which attempted to seek solutions from the customer's perspective. Danneels (2002) proposed that a second-order marketing competence is the ability to add new customers to address new markets. In the case where established companies are not really blind-sided by the development of new technological capabilities, it is likely that they may fail to link the development of such technological

11 The case study was conducted by the Center for Management Research, Indian Council for International Amity, particularly on UTStarcom, case code BSTR184, 2005.

advances to changes in the marketplace, changes in consumer needs, or market conditions. The key to avoiding the negative effects of disruptive technologies is to focus on what is happening with customer and operational needs. Govindarajan and Kopalle have found that the higher an SBU's emerging customer orientation, the more disruptive the innovations it developed would be (Govindarajan & Kopalle, 2004).

Other scholars argued that mainstream customer orientation and emerging customer orientation are not two options at opposite ends of a continuum, but that they are independent of each other – suggesting that firms can develop both orientations simultaneously (Narver, et al. 2004; Slater & Mohr, 2006; Baker & Sinkula, 2005). A customer-oriented firm can serve current customers and also remain vigilant of non-consumption in emerging markets (Chandy & Tellis, 1998; Day, 1999; Slater & Mohr, 2006).

Henderson (2006) articulated that incumbent firms failed to respond to disruptive innovations because responding appropriately required building competencies they were ill-equipped to acquire, not because they focused too much on existing customers and high-margin opportunities. It could be true that, in some cases, incumbent firms did identify the needs of the low-end or emerging customers but lacked the market-related competencies to quickly respond to disruptive innovation.

As suggested by the above studies from the literature, it could not be emphasized more the importance of carefully finding the emerging market and deeply understanding the customers' latent needs, because a firm's disabilities in finding new markets for new technologies may be its most serious innovation handicap (Christensen & Bower, 1996). Next, the question becomes: how does a firm find the emerging market and understand the potential customers' needs?

Some scholars have provided several techniques to understand how customers behave rather than simply how they say they would behave. Some popular methods include customer visit programs, empathic designs, lead-user processes, research on customer's customers, targeting developing markets, etc (Mohr et al., 2004; Slater & Mohr, 2006). However, no detailed studies have elaborated on the processes of using each popular method to identify the latent needs.

2.5.4 Technology perspective of disruptive innovation

Compared with other dimensions such as business models, organizational challenges, customer orientations, and environment influences in disruptive innovation, the technological dimension has received very limited coverage to date. This might lead to the perception that it is sufficient to be vigilant and quick to spot the opportunity when such a disruptive technology may occur at some time in the future. However, in some cases, the creation of certain disruptive technologies could indeed be extremely challenging, especially if it is based on a new scientific discovery (Yu & Hang, 2008; elaboration in Chapter 3).

There are very few publications on the purposeful creation of technologies for disruptive innovation in the front end, with Kostoff et al. (2004) and Walsh (2004) as two exceptions. In the first study, Kostoff et al. have highlighted the necessity to propose a systematic approach to identify or create potential disruptive technologies that was not addressed in the extant literature. However, they interpreted disruptive innovation as innovations that could provide dramatic improvements and were more efficient with higher unit performance. This failed to observe the essence of disruptive technologies which are initially inferior to the existing technologies in traditional attributes. Furthermore, while they made great efforts to develop a clear-cut roadmap, they did not realize that an over-detailed roadmap might be counter-productive because disruptive innovation is discontinuous in nature and the research has focused on the fuzzy front end. In the second study, Walsh (2004) modified the emerging technology roadmapping tool to guide the development and commercialization of disruptive technologies for the microsystems and nanotechnology industry. Nevertheless, the cases in point of MEMS and nanotechnology are very debatable as disruptive technologies. These approaches aimed to address discontinuous innovations that are different from continuous/incremental types of sustaining innovation. Unfortunately, their findings did not really address the "initially inferior" disruptive technology creation. The explicit identification of R&D strategies specific to the creation of disruptive technology or products on purpose has remained a research gap. These R&D strategies would provide practical guidance to R&D managers, as well as to further enhance the predictive value of the theory.

Apart from technology roadmapping that would purposefully create technology or product candidates for disruptive innovations, an alternative strategy may be to scan the technological landscape for new application or development of existing technology, products, and some modules of products. It remains an unexplored question whether there is any systematic way to identify new disruptive opportunities for applying existing technology or products. There are some examples such as the application of TRIZ, a systematic invention approach[12] or patent analysis (e.g. Young, Jong & Sang, 2008; Yoon & Lee, 2008).

2.6 Discussion and directions for future research

It is clear from the previous sections that the *Disruptive Innovation Theory* has been extensively studied in the extant literature. The extant literature pertaining to disruptive innovation has been organized into the 3 major themes with a clear logic link in this essay. The evolution, description, and clarification of the concept of disruptive innovation at the beginning would serve as a major foundation for further research in this area. In "Predictive use of the disruptive innovation theory", the main conclusion that

12 For more information on TRIZ as a technology forecasting tool, please refer to papers in the TRIZ journal. http://www.triz-journal.com/

disruptive innovation theory can be applied to anticipate the future of firms supports the efforts made to study how to enable a disruptive innovation. In “Enabling potential disruptive innovation”, various perspectives have been studied. Many inhibitors and corresponding enablers of disruptive innovation have been discussed and they are summarized in Table 2.1.

TABLE 2. 1 Potential inhibitors and enablers of disruptive innovation

Perspectives	***Aspects***	***Sub- aspects***	***Inhibitors/ Problems***	***Enablers/ Solutions***
Internal	Human Resources	Managers	(1) Senior managers are limited by their current experiences. (2) Senior managers were trained to manage well-defined product lines. (3) Middle managers have the most to lose in disruptive change. (4)Professional managers follow routines to manage established business.	(1) Create a core team to collect disruptive ideas and put them into implementation. (2) Design long-term-oriented, subjective-based incentive plans instead of short-term-oriented formula-based incentive plans for key executives. (3) Founders are better positioned to tackle disruption.
		Employees	(1) Knowledge lack and risk-averse attitude of employees. (2) Reply on analyst-laden corporate strategy to collect or create disruptive ideas. (3) Disruption from outside due to brain drain of talents and disruptive ideas.	(1) Team members are composed of carefully selected risk-takers and they also recruit outside expertise. (2) Capturing disruptive ideas from people in direct contact with markets and technologies. (3) Spin-offs as one possible solution to prevent brain drain and protect disruptive ideas.
	Organizational Culture		(1) The cumulative culture becomes cultural inertia which is so difficult to attack directly.	(1) Prepare for and instituting organizational change and unlearn its deeply entrenched values. (2) Some integral parts of culture should be preserved and valued such as entrepreneurship, risk taking, flexibility and creativity.

Resource Allocation		(1) Structured routines are used to evaluate both emerging disruptive projects and existing businesses. (2) Financial results are a particularly bad tool to manage disruption. (3) Resource dependence locked firms into existing business and push firms to invest more on conventional business when threatened from low end.	(1) Less formal, allow managers to proceed intuitively rather than having to be backed up by careful research and analysis. (2) Strategic buckets to separately manage sustaining and disruptive projects. (3) Manage a large project as the sum of several sequential mini-projects.
Organizational Structure	Organizational Size	(1) The size of the firm and business units will be negatively related to disruptive innovation.	(1) Large corporations keep the flexibility to have small business units within them, so they can continue to have decision makers who can become excited about emerging opportunities.
	Spin-offs or Ambidextrous organization	(1) Autonomous organization means geographical separation and ownership change. (2) Spin-offs could be tricks to get the disruption off the managers' agenda.	(1) Typical form of autonomous business units is spin-offs or skunk works, but essentially is a different set of processes and values.

		Collaboration between incumbent firms and startups	(1) An innovative idea with disruptive potential but in lack of complementary assets.	(1) Collaboration between incumbents and startups in various forms such as licensing IP, alliances, market transaction and acquisition at different stages of disruptive projects. (2) As a startup, increase own attractiveness for potential collaboration by improving new product development performance, economies of scope, public ownership and geographic location to a technology cluster.
External			(1) Organizations locked into the relationship with resource providers and suppliers which prevent them from developing disruptive projects. (2) Complementary technologies have to be developed prior to or together with introduction of potential disruptive products. (3) Poor financing systems, lack of entrepreneurs.	
Marketing			(1) Fail to link the development of technological advances to changes in the market. (2) Focus too much on existing customers and high-margin opportunities.	(1) Focus on what is happening with customer and operational needs. (2) Emerging customer orientation (3) Mainstream and emerging customer orientation can co-exist. (4) Develop techniques to understand needs of new customers.
Technology			(1) An over detailed roadmap might be	(1) Strategies for purposeful creation of

	disastrous as disruptive innovation is discontinuous in nature and the research has focused on the fuzzy front end.	technologies as options for potential disruptive innovation. (2) Find new application of existing technology, product or key modules of product.

Nevertheless, a number of interesting research directions deserve further examination within the disruptive innovation domain. Although some of them might be valuable to all discontinuous innovation in a wider scope, as disruptive innovations are discontinuous in nature, I shall limit my discussion to the theory development of disruptive innovations. Seven of them are briefly discussed as follows. To begin with, there are many enablers listed in Table 2.1. One suggestion for a more complete analysis of disruption is a larger empirical study that tries to compare precisely which combinations of the enablers are most important. Secondly, the middle managers are reasonable in voting against disruption because they have to defend their current turf and avoid taking responsibility for risky projects. Is there a mechanism that could encourage middle managers to support potential disruptive projects while securing their positions and careers in the company? In addition, company founders have been observed to perform better than professional managers in disruptive innovations, but there are no empirical tests yet to prove this argument. A subsequent question would be how to improve the management education programs to equip professional managers with the capabilities to initiate disruptive changes? Thirdly, the literature has shown that keeping the size of business units reasonably small would contribute to the development of disruptive innovation, but this also causes cost increases and difficulties in architectural interdependence. How to optimize the number and the size of business units in a large organization could be an important topic for future research. Fourthly, this aspect of organizational culture has shown that organizational cultural inertia is indeed detrimental to the promotion of disruptive innovation. When should the unlearning efforts be initiated? If some elements of culture such as entrepreneurship and risk taking should be preserved, then what elements should be eradicated?

A longitudinal study of firms on their mechanisms to overcome cultural inertia and update the major elements in organizational culture would offer more practical insights. Fifthly, it has been advised in the manager sub-aspect that a special core team should be created at the corporate level to be responsible for collecting disruptive innovation ideas and putting them into implementation (Christensen & Raynor, 2003: 281). It is also suggested that front-line employees are a very good source of disruptive ideas since they are in direct contact with markets and technologies (Christensen & Raynor, 2003: 282). Therefore, future research could compare the roles played by front line employees and the core team to find whether they are contradictory or complementary. Is the importance contingent on different conditions such as project stage and business nature? Another future research direction is dealing with the problem of disruption from outside due to brain drain. Spin-offs are an effective method and it could be investigated whether there are any other methods more effective than spin-offs. Sixthly, potential disruptive technologies could not be commercialized unless complementary technologies are ready or partners (e.g. suppliers) do share the similar view of the disruptive potential. More research is needed to study the interorganizational linkage behind the collective efforts for disruptive innovation (Denning, 2005). Finally, studies on different context in different countries could also be useful in understanding how to make a potential disruptive innovation successful taking into account contextual factors such as regulation and entrepreneurship culture.

In addition, four new areas of research could be initiated by integrating the literature of disruptive innovation and that of other related research domains. First, an implication from the literature of *Open Innovation* may be that disruptive innovations could benefit by collaboration between incumbents and startup firms; however, the existing literature has not clearly discussed the fundamental motivations of collaboration. Is it because of complementary assets or appropriability? What are the factors that incumbents and startups should balance separately when making decisions to collaborate? Will these factors be significantly different from those of the collaborations for sustaining innovations? Furthermore, regarding the specific forms of collaborations, apart from stake ventures, joint ventures, and even acquisitions, how about other forms such as sharing and IP licensing? What are the potential challenges in the collaboration for disruptive projects using the form of IP licensing?

Second, the review on marketing perspective has suggested that the behavior of only gathering information on mainstream customers' needs and responding to such needs was detrimental to disruptive innovations, whereas an orientation toward small but emerging customer segments might aid in the development of disruptive innovations. How to find emerging markets and understand the needs of new customers is still a question of tremendous interest. Fortunately, the techniques of understanding customer needs such as focus groups and customer visit programs in the marketing literature may provide potentially effective tools to find emerging markets and understand the latent needs of customers. What are the weaknesses of these existing techniques in understanding latent customer needs? Are they helpful to new customer identification? Future research could tailor the existing techniques of marketing literature to address the emerging customer orientation for disruptive products and services.

Third, among the 4 perspectives of enabling potential disruptive innovation, the technology perspective has received the least coverage and needs to be investigated since the enabling role of technologies is also critical to the success of disruptive innovation. This perspective may be addressed by integrating the literature in technology forecasting. For example, one research direction is the purposeful creation of technology candidates for potential disruptive innovation. Another direction is to identify possible new applications of existing technologies. Both directions might be realized by developing methods using techniques in technology forecasting, such as technology roadmapping, TRIZ, patent analysis, and data mining. Future research could strive to apply existing techniques to create a potential disruptive technology or find new application for existing technology and product.

Fourth, cases have been observed where the success of disruptive innovation may be influenced by one contextual factor—economic conditions in the context and environment subsection. It implies another convergence of literature between disruptive innovation and the *Bottom of the Pyramid* (Prahalad, 2004). The Pyramid, or the Economic Pyramid in full, refers to the categorization of the world population according to their purchasing power parity. The majority of the world population resides at the bottom of the pyramid, while a very small amount of the population sits on the top. At individual level, the purchasing power parity at the top is over 13 times more than that at the bottom. However, by multiplying the population at group level, the potential market revenue at the bottom is over 3 times more than that at the top. Therefore, the poor represent latent market segments for firms' new growth. In fact, the bottom of the pyramid could be an ideal target market for disruptive technologies because the low-end model appeals to the most price-sensitive customers who usually live in the bottom of the pyramid. In addition, disruptive innovators have to initially compete against nonconsumption which firms may easily find at or near the bottom rather than at the top of the pyramid. Firms such as Honda, Toyota, and General Motors were studied to support the idea of possible disruption from the bottom (Hart & Christensen, 2002). Future research could study how to use the disruptive innovation as one approach to tap the business potential of the majority at the bottom.

In addition to the potential research within the disruptive innovation domain and integration with other domains, the research so far has mostly been based on the inquiry of why incumbent firms fail and how to prevent dethronements. Research on the entrant firms has only focused on the attractiveness of startups as collaborators. Since the incumbents have been guided to take actions against startups, how should startups respond when incumbents fight back instead of fleeing away to the high-end? More research is needed to guide the startups, as they are generally weaker and smaller.

The final discussion on future research directions is on methodology. Most of the studies were case-based and qualitative in nature, and very few papers were written based on quantitative methods such as modeling (Adner, 2002; Schmidt & Druehl, 2008) and survey (Govindarajan & Kopalle, 2006; Rothaermel, 2002). In addition, the theoretical implications from many case-based studies would need further empirical evidence. The development of a scale to measure the disruptiveness of innovation by Govindarajan and Kopalle (2006) has paved the way for more empirical testing of existing implications using quantitative methods, such as method triangulation, to increase the robustness or correct wrong conclusions. All the above potential research directions are summarized in Table 2.2.

TABLE 2. 2 Future research topics of disruptive innovation

Perspectives	***Aspects***	***Sub-Aspects***	***Question***
Internal	Human Resources	Managers	(1) What mechanism could encourage middle managers to support potential disruptive projects while securing their positions and careers in the company? (2) Call for empirical tests to show significant performance differences between founders and professional managers. (3) How to improve management education programs to equip professional managers with the capabilities to initiate changes?
		Employees	(1) Which is the better source of disruptive idea generation, a special team at corporate level or front-line employees? Are they contradictory or complementary? (2) How to prevent external disruption due to brain drain of talents or disruptive ideas?
	Organizational Culture		(1) When should the unlearning efforts be initiated? (2) What elements of the culture should be eradicated at the advent of disruptive innovation?

	Resource Allocation		(1) What are the other inhibitors in existing resource allocation process apart from structured routines and resource dependence? What are the subsequent solutions for other inhibitors?
	Organizational Structure	Organizational Size	(1) How to optimize the number and the size of business units in a large organization to provide favorable conditions for both architectural interdependences and opportunities of disruptive innovation?
		Spin-off or Ambidextrous Organization	(1) Any case to show sustaining and disruptive innovation can be developed in the same business unit? (2) If sustaining and disruptive innovation can be developed in the same business unit, how to manage the co-existence?
		Collaboration between incumbents and startups (Integration with research on Open Innovation)	(1) What are the factors incumbents and startups should balance separately when making decisions to collaborate with each other to develop potential disruptive innovations? (2) Collaborations can be formed for either sustaining innovations or disruptive innovations. Would the factors considered to make collaboration decision be significantly different?
External	Context and Environment		(1) What are the environmental determinants of disruptive innovations? (2) Why disruptive innovation of certain technology can happen in Country A rather than Country B?

Marketing	Customer-Orientation under Disruptive Changes (Integration with research on techniques of understanding customers in marketing research)	(1) How to identify the emerging market and understand the needs of new customers?
Technology	Technological strategies for Disruptive innovation (Integration with research on technology forecasting)	(1) How to create candidate technologies for potential disruptive innovation by technology roadmapping? (2) How to find new application and development of existing technology, product and key modules of product by TRIZ or patent analysis?
Additional Research Directions		
Bottom of the Pyramid		(1) How to use disruptive innovation theory as an approach for tapping the large business potential at the bottom of the Pyramid?
Startup firms		(1) How should startups respond, if not being acquired, when incumbents fight back instead of fleeing away to the high-end?
Method		(1) Empirical testing of existing implications by quantitative research methods.

2.7 Conclusion

In this chapter, a reflective review of the extant literature on disruptive innovation theory has been presented. The definition and 3 potential misinterpretations of the concepts have been discussed to clarify the basic understanding of disruptive innovation. Believing in the predictive value of the theory on firm performance, I have subsequently summarized and critiqued the research on how to enable potential disruptive innovation from internal, external, marketing, and technology perspectives. Although the research to date has substantially studied this topic, there is still room for future improvement in different aspects, which is natural for almost all theory building processes. Seven potential future research directions have been identified within the disruptive innovation research domain. In addition, I have briefly discussed potential integrations with other research domains such as Open Innovation and others, further research on startup firms and research methodology. Finally, in addition to theory building, managerial implications are pointed out by extracting the inhibitors and enablers of disruptive innovations from the pool of literature. My hope is to make the widely scattered literature on disruptive innovation more systematic and tractable to scholars and to stimulate future research along these proposals.

Chapter 3

An Exploratory Case Study on the Technological Perspective of Disruptive Innovation

3.1 Introduction

As reviewed in Chapter 2, there is little study in the literature on the technology perspective of disruptive innovation compared with the other 3 perspectives. The Disruptive Innovation Theory has clearly explained how seemingly inferior technologies could eventually topple a large incumbent firm. However, this "initially inferior" characteristic has also given rise to the misperception that it is not technologically challenging. Furthermore, products of disruptive innovation are always simple and easy to use, which further leads to underestimation of the role played by technology in disruptive innovation. This chapter is devoted to understand more deeply how a disruptive innovation, the shirt-portable transistor radio, was created by Sony with great determination to overcome overwhelming technological challenges. This revelatory case study is conducted with two purposes: first, to prove that in some cases, the creation of certain disruptive technologies could indeed be extremely challenging, especially if it is based on a new scientific discovery; second, to stimulate insights on how a company may create technologies for disruptive innovation by purpose rather than by chance.

3.2 Research design

The case study method allows investigators to retain the holistic and meaningful characteristics of real-life events (Yin, 2003; Eisenhardt, 2007). It contributes to the understanding of causation more than correlation. Also given the lack of prior research, qualitative case study is appropriate in this nascent stage (Edmondson & McManus, 2004).

The case of Sony transistor radio is selected for the following reasons: first, it exactly fits Disruptive Innovation definition and it is a new disruption compared to vacuum-tube based radios; second, it is a technological DI with high technology involvement, instead of pure business model DI; third, Sony has been the only firm that becomes a serial disruptor so far (Christensen, 2003); fourth, a substantial amount of archive was freely available in public websites as well as company publications. Well documented over 50 years, they were objective and provided the details of the story from various angles, thus forming archival data that serve as the primary data that are complemented by interviews; fifth, it would be a surprising but convincing case to study whether its development was technologically challenging; finally, the rich content helped me to generate several insights on purposeful creation of DI.

3.3 Transistor as a disruptive technology

Nowadays, for most purposes, the vacuum tube has been replaced by the much smaller, less power-hungry, and less expensive transistor in many applications. However, in what way or ways did it constitute a disruptive technology? This section will demonstrate the disruption by the theoretical framework of Disruptive Innovation in terms of trajectory diagram, key constructs comparison and value networks.

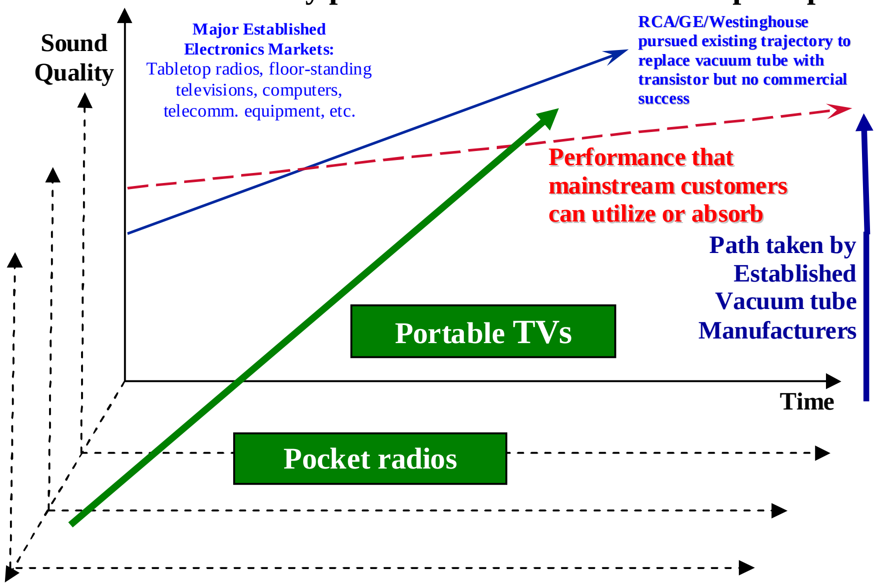
According to the dominant metrics of radio performance in the mainstream market, these early transistor radios were really bad, offering far lower fidelity and much more static than the vacuum tube-based tabletop radios that were the dominant design of the time (Christensen, 1997: 201). These transistors could not handle the power required to be used in the mainstream market such as applications in tabletop radios and big floor-standing televisions. But if these deficiencies could be overcome, the transistors could be the successors to vacuum tubes which had the problem of being bulky, creating lots of heat and so on.

During the 50s, most of the leading electronics companies such as RCA, GE, and Westinghouse regarded transistor as a potentially new radical technology which would help them to sustain their mainstream electronics business. They focused their R&D on improving the sound quality and fidelity of transistors to match those of the vacuum tubes. They invested as a group, in today's US dollars, between 1 and 2 billion trying to make the transistor good enough to be used in the mainstream market but did not achieve any influential commercial success after 10 years of intensive R&D effort.

Sony, being a small company then, did not have any substantial resource to pursue a similar radical technology development. But it intuitively identified a new market composed of teenagers that valued the attributes of the pocketability of transistor radio based on much smaller transistors compared with vacuum tubes. It enabled teenagers to do something that they could not do before—listen to rock'n'roll music out of their parents' earshot, though the music quality could not compete with tabletop vacuum tube radios[13] (Morita, Reingold & Shimomura, 1987). Hence the inferior transistor radio sales that the mainstream customers disliked found customers who were non-consumers in the past. The typical trajectories pursued by both large incumbents and Sony on how to improve and apply the transistor technology are illustrated in Figure 3.1. The accumulative profit from transistor radio provided strong financial support to further improve technical performance of transistors. Sony later introduced its first portable television in 1960 thus making another successful disruption.

[13] "Sony Corporation", Retrieved 15/03/08, WWW, http://brands-history.info/?page_id=4

FIGURE 3. 1 Sony pursued the new-market disruptive path[14]



The success of portable radios caused no pain to the leading electronics incumbents because they did not lose any of their existing customers. As can be seen from the feedback of leaders of incumbent firms, they still aimed to improve transistors until it could substitute vacuum tubes in established applications which they considered as breakthrough achievements. Even after the initial success of Sony's transistor based radios, they despised the miniaturization of Japanese radios as fad. In the late 1950s, an optimistic Westinghouse executive, C.J. Urban put it like this: "*We can meet foreign competition with innovation and creativity*." Benjamin Abrams, Emerson's founder and president, was even more upbeat, predicting in mid-1959 that "*the Japanese import will kill itself off and disappear—within the next 12 months we will see a material decline in Japanese imports*." They ignored the potential threat from Japanese miniaturized portables and continued their current effort to improve transistor with premium

[14] The first new market application of the transistor was in hearing aids around 1952, which happened to value the very low power consumption and less than one-tenth the cost of the tube models of hearing aids, but the hearing aids market was NOT the target of Sony.

sound quality targeted largely at the mainstream home applications (Schiffer, 1991). However, in 1965, the transistors became good enough in terms of sound quality and power requirement in bigger machines, such that within the next 3 years many customers got sucked out of the vacuum tube plane into the transistor plane[15]. These large incumbents just vaporized overnight. The key constructs in the disruption process can be summarized in Table 3.1.

The value network comparison is shown in Figure 3.2. The black and grey curves represent the S-curves of vacuum tube based and transistor based radios separately. The market was experiencing a shift in value networks from sound quality and fidelity to pocketability and low price. Transistor radios emerged and progressed on uniquely defined trajectories in the value network of price and pocketability (the grey curve in Figure 3.2b) until they could satisfy the performance demanded in the value network of sound quality and fidelity (the grey curve in Figure 3.2a), although performance was still inferior to vacuum tube based radios (the black curve in Figure 3.2a). At this point, they would begin to penetrate the established value network (Figure 3.2a) and displace vacuum tube based radios.

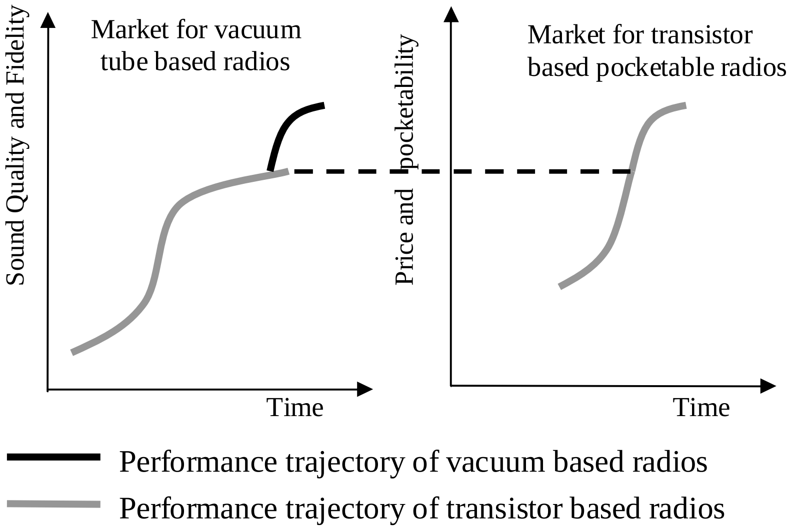
TABLE 3. 1 Key constructs comparison between disruptee and disruptor

COMPANIES	Disruptee: RCA/GE/Westinghouse	Disruptor: Sony
TECHNOLOGIES	Existing technology: Vacuum tube based radio	Emerging technology: Transistor based pocketable radio
ADVANTAGES IN TECHNICAL ATTRIBUTES (when transistor was introduced in 1950s)	Primary/key attributes that mainstream historically valued: sound quality; fidelity	Secondary/new attributes that mainstream ignored: miniaturized; low-cost; less power hungry.
MARKET	Existing market: Customers of Tabletop radios, floor-standing televisions etc, adults	New market: Teenagers who like to listen to rock 'n' roll music
TIME OF DISRUPTION	1965—1968	

[15] C. M. Christensen, "Capturing the Upside", *IT conversation, Retrieved 30/07/07*, WWW, http://www.itconversations. com/ transcripts/135/transcript-print135-1.html

FIGURE 3. 2 Comparison of value networks

FIGURE 3.2a Value network of sound quality and fidelity **FIGURE 3.2b Value network of price and pocketability**



3.4 Technology Development Challenges

In this case study, it has been found that Sony had to overcome tremendous technical challenges to create transistor radios ahead of potential competitors. They are summarized in this section under 4 sub-headings.

3.4.1 Transistor technology not available in the US

In early 1952, Ibuka, the founder of Sony, convinced Bell Labs (jointly owned by Western Electric and AT&T) to license the transistor patent to his Japanese company. While most American companies were researching the transistor for high-end military applications, Ibuka envisioned applying it to commercial communications. When he went to the Ministry of

International Trade and Industry[16] (MITI) of Japan to obtain a license for manufacturing the transistor, MITI gave a point-blank refusal: "*Transistor cannot be produced so easily*" and they questioned how a small factory could produce such a complex thing as the transistor (Morita, 1987). Furthermore, in the harsh economy after World War II when Japan was just beginning to accelerate its recovery from the war, foreign currency was so scarce in Japan that MITI was not eager to grant permission[17] . Ibuka was eloquent on the possible uses of this little-known device, and it took him six months to convince the bureaucrats. Finally in August 1953, Morita, the co-founder of Sony, visited Western Electric and signed a provisional agreement contingent upon MITI's approval. This Totsuko[18]-WE agreement did not cover technology, but only the rights to manufacture the transistor[19]. According to Morita, "*I must make it clear that the transistor … was not something that we could license and produce and use right off the shelf", "This solid-state device was something completely new to our experience*", *"developing the transistor for our use would be a job that would challenge the skills of all the engineers in our company*" (Morita et al., 1987). Not only MITI, even Ibuka's old friend questioned him: "*Even in the U.S. transistors are used only for defense purposes where money is not object. Even if you come out with a consumer product using transistors, who can afford to buy a machine with such expensive devices?*"[20].

[16] In post war Japan, the real power resides in two government agencies: The Ministry of Finance and the Ministry of International Trade and Industry (MITI). MITI decides which industries will be targeted for future growth, which companies will have access to foreign currency and technology, and which goods will be protected by tariffs' and red tape from imports

[17] Interview with Dr Y. Kaneda, who was a former Executive Deputy President and Representative Director of Sony, 18/04/2007.

[18] Totsuko was the precursor of Sony before 1958.

[19] Genryu, *Sony Challenges 1940-1968*, Sony Corporation, 1988.

[20] "Rest Assured We Can Make it", Sony Corporation, Retrieved 10/03/08, WWW, http://www.sony.net/Fun/SH/1-4/h6.html

At that time, the transistor was not available to be applied in any market except hearing aids and Sony did not have the technological know-how in transistors. Unperturbed by the skeptical eyes of MITI and the warning from friends, Ibuka set a firm R&D goal to pursue the project of developing an affordable and pocketable transistor radio.

3.4.2 Material science challenge

The early transistor invented in Bell Labs used a slab of germanium, the negative part, to which indium, the positive part, was alloyed on each side. After a period of intensive analysis, the Sony team reasoned that since negative electrons moved faster than positive ones, they could achieve higher frequency by reversing the polarity. That meant replacing the positive-negative-positive configuration to negative-positive-negative, but they could not find the right material. As Indium had too low a melting point for their purpose, they began to experiment using gallium and antimony, but it didn't work well either. At one point, everyone seemed stumped and they thought of using phosphorus to replace antimony. Unfortunately, they found that Bell labs had already tried this approach and failed. As Morita said, "*It was very complicated work, and our project team went through a long period of painstaking trial and error, using new, or at least different, materials to get the increased frequency we needed.*" They even had to rebuild and virtually reinvented the transistor. Nevertheless, one team kept trying what was called phosphorus doping method, using more and more phosphorus in the process and finally succeeded at the end that greatly shocked the Bell labs scientists.

3.4.3 Miniaturization challenge

In order to fit the transistor and other electronics components into their small radio, they needed to miniaturize almost everything such as the capacitor, the loudspeaker, the inductor, the transformer, and even the battery. At that time, most of the components were produced by subcontractors. Sony could not purchase the components readily from the market because most Japanese manufacturers produced radio components that copied both the design and size of those made in US. Finding or designing other parts small enough to fit together was not easy at all. Ibuka went around to every individual component manufacturer and persuaded them to start to miniaturize every component from scratch and that was the major driver for a prosperous electronics industry in Japan in due course – this effort was so significant and impactful that the French daily paper, Le Figaro described Mr. Ibuka as the father of the Japanese post war industrialization. Meanwhile, Sony engineers designed and made the Printed Circuit Board (PCB) by themselves and eventually it became Sony Chemicals Corporation that is very profitable subsequently[17].

In pursuit of miniaturization and compactness, the world's first real shirt-potable transistor radio was introduced by Sony in March 1957, by the model name of TR-63. It was made with an all new imaginative design with many purpose-built miniature components (e.g. its microscopic solid dielectric variable capacitor).

3.4.4 Cost reduction challenge

In the nascent stage, commercial transistors were very expensive, with an average price in late 1953 of around US$ 8 each, whereas an ordinary vacuum tube for radios was less than US$ 1 (Schiffer, 1991). Hence, how would one develop the capability to mass-produce transistors to make it low-cost with better production yield was a very tough challenge to address. Sony employed cheap labor instead of high-tech manufacturing operations. Luckily, the Japanese labor costs in the late fifties were about one-seventh of those in the United States. Hence, the portable transistor radios of Sony could be cheaper than their counterparts of US competitors. However, the postwar Japanese could not afford the transistor radios produced by Sony even after Sony tried its best to reduce the cost. They hence strategically set the American market as their first target, because the success in selling a high-tech consumer product to people in the world's mightiest industrial nation would be a significant coup[17]. The purchasing power and the scale of the niche market laid a solid foundation for further penetration of transistor radios. The international market perspective was a key enabling factor for Sony's success.

3.5 Key roles played by core team members

A glance at the key members of the transistor development project would also help us to identify the key managerial characteristics which underpinned their ability to create disruptive technologies.

(1) Dr. Leo Esaki was the chief scientist in Sony. The process using more phosphorus (for high-frequency application) was sentenced to death by Bell Labs before their intensive experiments at Sony. As the head of Sony research laboratories, Makoto Kikuchi recalled in those days the level of research and engineering in the US was so high that "*the voice of Bell Labs was like the voice of God* " (Morita et al., 1987). Esaki dared to challenge the authority and tried to think out of the box. He and other team members successfully developed the high-frequency transistors, paving the way for the subsequent invention of portable transistor radios. The outstanding ability of Dr. Esaki was also evidenced by his discovery of the diode tunneling

effect during his research at Sony, for which he was later awarded a Nobel Prize in Physics in 1973 (Morita, et al., 1987).

(2) Akio Morita, with a deep technical background, could understand and support the technical R&D needed to improve the transistor. He played a critical role in financing the project. Although he agreed with Ibuka to go into this unknown field, SONY as a small company did not have sufficient credit finance[16]. He spent a very hard time selling and marketing the new product. He was the marketing champion in Sony's serial disruptive innovations from transistor radio to Walkman.

(3) Masaru Ibuka nicknamed "genius inventor", was instrumental in securing the licensing of transistor patent to Sony from Bell labs in the 1950s, thus making Sony one of the first companies to use transistor in non-military areas. Morita told the public, "*I always trusted him (Ibuka) absolutely—even when there was little more than a dream to build on. He has a great genius for innovation*"[18]. Without explicit market demands, without methods of manufacturing transistor radios, without support from MITI or friends, Ibuka had the courage and intuition to set a visionary R&D goal for Sony to aim for low cost while maintaining adequate performance at the very early stage of a science/engineering breakthrough.

(4) Kazuo Iwama volunteered to head the transistor team. At that time, Western Electric (owns the Bell Labs together with AT&T) did not provide specifications for the manufacturing equipments. He learnt everything from the plant tours. Based on his prodigious reports and transistor technology, the team managed to start making transistors and just in half a year, they had begun to build a transistor radio prototype[18]. Iwama was a scientist who knew the scientific mind; so he encouraged the research team to add more phosphorus to see further results. The

phosphorus method eventually worked, expanding on which Sony developed the high-frequency device they needed.

(5) Much of the credit of the TR-55 must go to the sterling efforts of Junichi Yasuda, the electric engineer and his circuit designers. The early transistors' yield still left much room for improvement, and their characteristics remained uneven. This was where Yasuda's team came into play. At that time radio circuits were of the superheterodyne type. The team made as many as 12 different varieties of these local oscillator coils in an attempt to reduce the spread of characteristics. Apart from the circuits, TR-55 was ahead of its time in that it used a Printed Circuit Board (PCB). Although today we take PCB for granted, a large amount of research and improvement went into its design in those early days. Yasuda's pioneering team had to do everything on its own.

Led by these capable men, Sony did manage to bring shirt-portable radios into huge success, a record of less than 10 years after the invention of a basic device (which was a Nobel Prize level of breakthrough) and 3 years after Sony started from scratch. The contributions of key persons are summarized in Table 3.2.

TABLE 3. 2 Contributions of key persons to invent portable transistor radios

NAME	POSITION	CONTRIBUTION	IMPLICATION
Leo Esaki	Physicist	Developed the high-frequency transistors, paving the way for subsequent invention of portable transistor radios	Technical talent, has the risk-taking courage to challenge authority and think out of box
Akio Morita	Co-Founder	Financed the project, marketing champion	Companies are in urgent needs of marketing champions such as Morita who has the tacit wisdom on how to create disruptive technologies in advance.
Masaru Ibuka	President	Obtained the license, set up the mission	Set counter-intuitive R&D goal to aim for low cost while maintaining adequate performance at the very early stage of a science/engineering breakthrough, and lead the team with shared vision
Kazuo Iwama	Project leader	Responsible for R&D of this project, sent prodigious reports and principles of transistor technology back to Sony	Inter-disciplinary talent, experienced manager who knew the scientific mind.
Junichi Yasuda	Electric engineer	Designed twelve different varieties of local oscillator coils. Designed PCB all by them.	Technical talent, very creative and innovative.

3.6 Discussion

The revisit of the transistor radio R&D has provided important insights into how disruptive technologies were created in Sony in the past. Several important lessons could be learnt and are discussed as follows:

The low cost was obviously the critical factor in Sony's conquest of transistor based portable radios. Ibuka once said to Morita "*Let's make transistors for a radio which anyone can afford to buy*"[18]. From the beginning, they already set the affordable price target in consideration of price-sensitive customers. This consideration contributed to not only Sony's disruption against incumbents of vacuum tube based radios, but also success in the competition with US producers of transistor radios[21]. Another impressive finding is that Sony was very smart to make R&D efforts in technologies which can provide new values to compete against nonconsumption. Ibuka clearly stated the vision of the new company: "*We shall maintain our business operations small, advance technologically and grow in areas where large enterprises cannot enter due to their size*"[22]. From mainstream customers' perspective, *Consumer Reports* remarked on the early transistor radios' poor tone quality, unpleasant distortion at high volume, low power output, and excessive background noise[18]. If Sony attempted to improve their radios in these performance aspects, it would have no difference from other U.S. producers. By competing against nonconsumption, Sony set a more practical technical hurdle for itself: the product just had to be good enough in order to find delighted emerging customers who appreciated new values but with low purchasing power. It has been tested that emerging customer orientation would favor the disruptiveness of innovation (Govindarajan & Kopalle, 2004). The focal case has further verified this hypothesis. Further research argued that the mainstream customer orientation and the emerging customer orientation are not mutually exclusive but are independent of each other, suggesting that firms can develop both orientations simultaneously (Narver, Slate & MacLachlan, 2004; Slater & Mohr, 2006). In fact, Sony was much engaged to satisfy their existing customers of tape recorders while targeting at emerging opportunities in teenagers' pocket. The business of transistor radio was not growing at the expense of its recorder business. This leads to the first proposition.

[21] The leading companies in U.S. such as Zenith mounted an aggressive all-American campaign, targeting two shirt-pocket models at teenagers in 1960s; however, their prices were still uncompetitive and by the end of 1963, no all-American sets survived.
[22] Y. Hara, "Sony, electronics ordered 'to go'", EETIMES online, Retrieved 15/03/08, WWW, http://www.eetimes.com/pecial/special_issues/millennium/companies/sony.html

Proposition 1: Diversified customer orientation is viable and positively related to creating technologies for disruptive innovation.

I have also found that a consistent and compelling vision, incessantly communicated by a company's senior team, is crucial in developing disruptive innovation of this nature. In fact, on October 18, 1954, the Regency TR-1, the world's first transistor radio was put on the market. At that time, Sony was close to manufacturing its first radios when it heard that an American company had beaten them to the punch. But they kept up the hard work and eventually produced a radio they named TR-55. However, TR-1 and earliest models of Sony such as TR-55 and TR-72 had failed to create considerable success. Buried in meditation for some time, Sony decided to speed up the miniaturization process and their work finally paid off with the world's first pocket transistor radio TR-63 1 year later. They consistently pursued their vision and never gave up, even when they were behind their US competitors, when they failed in the commercialization of the first few products, when there were doubts from MITI and Ibuka's friend whose view was dominant in his profession, and when they had to make many trials and errors in material challenges. This leads to the second proposition.

Proposition 2: A consistent and compelling vision to inspire emotional commitment provides major foundation for creating technologies for disruptive innovation.

It could not overemphasize that disruptive technological innovation may require an international perspective. Sony, as a Japanese brand locating their battlefront of shirt-portable transistor radios in U.S. has its own wisdom. Even they have tried their best to minimize the cost, the price was still expensive in the eyes of post-war Japanese. However, compared with US equivalents, the Japanese transistor radios were very competitive in terms of price, which enabled their success in the niche market of American teenagers. One recent paper has carefully studied how the international context was actually present in the process of disruptive innovation development and indicated that both the degree and international scope matter. Combined with the focal case, it leads to Proposition 3.

Proposition 3: International market perspective at the beginning increases the likelihood of firm's success in niche market, thus contributing to creating technologies for disruptive innovations.

As can be seen in Table 3.2, the leading team was composed of risk-takers with diversified capabilities in technology, management and marketing. They were creative and determined on a coherent vision. A doctoral study on I-mode disruptive innovation in NTT DoCoMo has found similar characteristics of team members in the creation of disruptive technology (Murase, 2003). This leads to the next proposition.

Proposition 4: A development team with characteristics such as shared vision, risk-taking courage, diversified capabilities, creativity, and determination increase the likelihood of creating technologies for disruptive innovation.

The case study in this chapter has given strong evidence that the R&D needed for creating disruptive technology might not be as simple as incremental; they were indeed discontinuous.

Generally speaking, the R&D leading to the creation of disruptive technologies could indeed be extremely challenging and suitable as agenda for use-inspired upstream research in companies as well as universities, especially if they are based on new scientific discoveries. Companies are therefore advised to pay attention to the significant technological challenges in disruptive innovation, in addition to the perspective of business model and marketing.

Starting with transistor radio, Sony has established the unique competencies in transistor-related technologies and miniaturization. In the following years, they produced a steady miniaturization of today's typical range of consumer electronic products: transistor TV, walkman, videotape recorder, home-use video cassette recorder, 3.5-inch floppy disk, CD player, 8-mm video, Mavica, MiniDisk, digital VCR and flat-screen TV. By creating disruptive technologies ahead of competitors, the company could command a substantial lead to sustain competitive advantages.

3.7 Conclusion

As a whole, the focal case study has indicated that creating candidate technology for potential disruptive innovation is a worthwhile research direction, not only to fill the gap in theory, but also to satisfy the industrial needs to create new growth and to sustain competitive advantages. Sony has unconsciously pursued the disruptive path; with appropriate creations of new technologies for disruptive innovation, Sony made a series of successful disruptions and became one of the world's largest electronics conglomerates.

Four propositions have been proposed on how to deliberately create technologies for disruptive innovation. It is noted that they cannot be generalized at this stage with a single case of detailed study.

However, it is clear that miniaturization was a core R&D strategy used in the creation of the disruptive technology for the Sony pocket radio. Whether this R&D strategy was more widely used, and what were other R&D strategies which were employed in other disruptive products would need further study, as attempted in the next chapter.

Chapter 4
R&D Strategies for Creating Technology Candidates for Potential Disruptive Innovation

4.1 Introduction

The literature review in chapter 2 has shown that creating potential disruptive innovation has been increasingly regarded as a promising strategy to fend off potential disruptors or to simply achieve successive growth of companies. The focus of creating DI has been on business model, and the business model perspective of technological DI. It has largely ignored the technological perspective, assuming that the needed technology would emerge from the R&D Labs once in a while.

It is understandable that the extant literature as well as the practice in industry have paid due attention to the significant roles of business models in disruptive innovation, since sustaining and disruptive innovations vary in business models such as Dell's direct marketing model and online remote education. However, concerning market-driven R&D, the R&D of disruptive innovation is fundamentally different from the R&D of sustaining innovation[23]. Pursuit of excellent performance in major dimensions to address explicit needs of mainstream customers is normal R&D for sustaining innovation. In contrast, downgrading the performance for low-end opportunities or just maintaining satisfactory performance in major dimensions and exploring latent needs in other dimensions for non-consumption is disruptive R&D for disruptive innovation. Therefore, I believe that research on sustaining R&D could not be directly used for disruptive R&D, and it is timely to conduct research on the enabling roles of technology in disruptive innovation.

[23] If it is pure science driven R&D without any downstream connection with products, we may not need to differentiate sustaining and disruptive R&D.

For a start in Chapter 3, it is found that technologies indeed played very important roles in technological DI such as transistor radios. More examples can be given such as inkjet printers (Hang, Yu & Chai, 2007). In this chapter, I first reviewed papers in the literature on the purposeful creation of DI from the technology perspective. Unfortunately, the findings failed to observe the initially “inferior performance” of DI; thus the explicit identification of R&D strategies specific to the creation of disruptive technologies and product candidates has remained as a research gap.

My research aims to address this gap. By formulating R&D strategies, I would extend the research on the technology aspect of disruptive innovation, complementing the existing literature on DI. It is also hoped that the findings of this research will be helpful to R&D managers in pursuing the strategic intent of creating disruptive technology candidates to enhance the technology options of the company (Boer, 2002; Rouse & Boff, 2004).

4.2 Theoretical background

Regarding the definition of disruptive innovation, as discussed in Section 2.3, Govindarajan & Kopalle (2006) have defined disruptive innovation to be (1) inferior on the attributes that mainstream customers value; (2) offer new value propositions to attract a new customer segment or the more price sensitive mainstream market (3) sold at a lower price and (4) the market penetration goes from niche to mainstream. I would use this definition including the 4 criteria as the foundation for case nomination and subsequent discussion. Based on the fundamental definition, a finer categorization of disruptive innovations has been discussed in the literature. A disruptive technological innovation differs from disruptive business model innovation (Markides, 2006). My research would discuss within the scope of technological disruptive innovation, and excludes pure business model disruptive innovations such as discount department stores and online educations.

Generally speaking, both technologies and business models play important roles in product innovations. However, the comprehensive and reflective review of the extant literature in disruptive innovation has shown that most scholars in this field have largely focused on the management and business model challenges in disruptive innovation, assuming the suitable technology or product is readily available (Yu & Hang, 2009). This implies disruptive innovation in essence seems to be the innovation in business models. Furthermore, technological uncertainty was not considered as a major issue in disruptive innovation literature, unlike most literature on radical innovation (Leifer, McDermott, O'Connor, Perters & Rice, 2000; O'Connor & Ayers, 2005) that extensively study technology uncertainty.

Besides the academic community, it is more likely that companies, both incumbents and new start-ups would invest their R&D of new scientific/engineering discoveries targeting at a sustaining innovation as they readily appreciate the eventual market potential of higher performing products. Even if these discoveries are better developed as disruptive technologies, many companies do not have the process or discipline to be proactive to grasp the opportunity (Christensen & Raynor, 2003). In addition, the initial performance of disruptive technology is indeed inferior when compared to existing technology which sustains the mainstream market. All these may lead to the perception that it is sufficient to be vigilant and be quick to spot the opportunity when a disruptive technology first emerges some time in the future.

Even firms proactively create emerging technologies which may be disruptive to the core business, a new problem will arise in bootstrapping a whole business (e.g. launch marketing campaign and establish new distribution channel) with considerable investment on the new disruptive technology. As noted by Tennenhouse[24], "*The new business will only increase heterogeneity out of the system, knocking diversity out **of** the gene pool. Ultimately, that was not healthy for us*." (Maccormack & Herman, 2005). Hence, developing disruptive technologies or products from scratch as a new area to be added to the existing business portfolio may be either too ambitious or a difficult choice. This will in turn reinforce the pattern that disruptive technology only occurs by chance or occasionally.

However, I believe it is high time to conduct research on the enabling roles of technology as regarding market driven R&D, disruptive R&D is fundamentally different from sustaining R&D. For example, there are certain technologies that inherently have weaknesses in the conventional application domain, and such technologies could create disruptive opportunities in new application domains if purposefully explored. Fuzzy logic is such a case. When fuzzy logic was first introduced in 1965, both the academic and industry communities ignored it as it was obviously inferior to precision logic in all the mainstream control applications (Abramovitch & Bushnell, 1999). However, fuzzy logic was superior to precision logic in the sense that it enabled software developers to program computers that could handle vagueness and uncertainty in many human reasoning and thought processes. In spite of this new capability, fuzzy logic (and fuzzy control) was largely ignored as a serious way to develop control technology until Hitachi engineers in Japan applied it successfully to provide smooth acceleration/deceleration control of subway trains in 1988. Progressively, fuzzy logic/control has become a pervasive and basic technology to create new feedback control applications (Abramovitch & Bushnell, 1999), since there are many consumer and industrial automation applications which do not require extreme precisions. This case shows that fuzzy logic is a disruptive innovation compared to precision

[24] David Tennenhouse was the R&D Director of Intel Research in 2004. The quotation is cited from the Harvard Business Case "Intel Research: Exploring the Future", No. 9-605-051, written by Maccormack and Herman, 2005.

logic. The case also reveals that it is the basic characteristics of the technology that determines the disruptive nature of the innovation, suggesting that technologies play more important roles than business models in some cases. Digital cameras versus their analog counterparts is a similar case (Henry & Goh, 2009).

The importance of technology is also demonstrated in my case study on transistor radio in Chapter 3, which shows that the creation of certain disruptive products could indeed be extremely challenging, especially if it is based on a new scientific discovery. Schmidt & Druehl (2008) also found that some opportunities of new market disruption (which named as detached market low-end encroachment) were often very risky and technologically challenging.

Although important and challenging, creation of disruptive technologies or product candidates from purposeful R&D to provide additional technology options was rare and needs to be promoted. There were two recent attempts in the literature to propose a systematic approach to identify disruptive technologies (Kostoff et al., 2004; Walsh, 2004). Unfortunately, they did not really develop methods for creation of disruptive technologies with initially inferior performance. In the first study, Kostoff et al. (2004) proposed a systematic approach to identify disruptive technologies through the first stage of literature text-mining to create suitable ideas, followed by the second stage of special workshops and roadmapping exercise. They interpreted disruptive innovation as innovations that could provide dramatic improvements and were more efficient with higher unit performance. This failed to observe the essence of disruptive technologies which are initially inferior relative to the existing technologies in traditional attributes. Furthermore, while they made great efforts to develop a clear-cut roadmap, they did not realize an over-detailed roadmap might be counter-productive (Augsdorfer, 2008) for two reasons—first, disruptive innovation is discontinuous in nature, and hence dynamic changes could occur unexpectedly; second, the front-end R&D is often fuzzy. In the second study, Walsh (2004) modified the emerging technology roadmapping tool to guide the development and commercialization of disruptive technologies for the microsystems and nanotechnology industry. However, the cases in point of MEMS and Nanotechnology were very debatable as disruptive technologies. These approaches aimed to address discontinuous innovations which are different from continuous/incremental type of sustaining innovation. Unfortunately, their findings did not really address the "initially inferior" disruptive technology creation. The explicit identification of R&D strategies specific to the creation of disruptive technology or products on purpose has remained as a research gap.

4.3 Research design

The qualitative method using multiple case studies is the most appropriate method because qualitative methods are more appropriate for nascent theory, as I am not dealing with theory testing where quantitative methods may be appropriate (Edmondson & McManus, 2004). Furthermore, case studies are rich, empirical descriptions that allow investigators to retain the holistic and meaningful characteristics of real-life events, and multiple case studies are generally considered more robust than single case study (Yin, 2003; Eisenhardt & Graebner, 2007).

A sequential research design is applied with four steps, as shown in Table 4.1.

TABLE 4.1 Research design for R&D strategies development

	Step 1	Step 2	Step 3	Step 4
Key actions	Select qualified cases	Study specific technology, function and performance of products in all 37 cases in order to understand the technological changes and the R&D strategies applied to enable such change	Detailed study on 7 cases	(1) Use Delphi method to increase validity and reliability; (2) Design questionnaire for at least 2 rounds of investigations; (3) Summarize results from investigations
Data sources (archival data)	Books, journal articles on disruptive innovation	Company websites, journal articles and books	Company websites, journal articles and books	No
Data sources (interview data)	No	No	Interview 13 professionals, some from disruptor companies (Table 4.2)	Use questionnaire to seek advices of 25 experts from 5 technological fields
Results	37 disruptive cases have been selected for further study	(1) 4 R&D strategies identified; (2) Reference manual including all cases introduction prepared for the Delphi method		(1) Application of 4 R&D strategies on 30 cases accepted by expert panel; (2) Application frequency summarized and implication analyzed

TABLE 4.2 Data Sources from Interviews

Case	Name	Firm	Position	Date	Place
Transistor Radio	YK	Sony	Former Executive Deputy President & Representative Director	April, 2007	Tokyo, Japan
	MT		SVP, Corporate Executive, Technology Policy& Relations		
2.5 inch Hard Disk Drive	MK	Seagate	Ex-Head of Seagate Research	Nov-Dec, 2007	Email
	SKT		VP Engineering and R&D Director Singapore	Dec, 2007	Singapore
	DC		Executive Director, Singapore	Jan, 2008	
	BCS	National University of Singapore	Professor specialized in Magnetic Recording; Ex-Senior Technical Staff Member, IBM	May, 2008	
Simplified Tank Gauging machine	FY	Gilbarco Veeder-Root Asia	Managing Director	March, 2008	Singapore
	TKK		Technical Director	Feb, 2008	
Centrino	LH	Nanyang Technological University	Research Fellow specialized in IC designs	Jan, 2009	Singapore
	NBB	Intel	Ex-R&D Engineer	Dec, 2008	
War Games	ECMK	ST Electronics, Training and Simulation Systems Pte ltd.	Senior Vice President	Aug, 2008	Singapore
	IO		CTO		
	LEK		Vice President, Defense & Security Business		

In Step 1, I began my case studies by collecting successful technological disruptive innovations across a wide range of industries and the unit of analysis is the technology/product. Collectively, as a pool of raw data, these cases were carefully filtered by Govindarajan & Kopalle's definition (Govindarajan & Kopalle, 2006). Since the disruptive innovation theory only became popular and being widely studied for one decade, there are not many examples being studied and documented. Furthermore, some disruptive innovation cases among these examples were business model rather than technological innovations (e.g. discounted airlines (Christensen, 2003:63)), and they are outside my research scope. In addition, some technological innovations were claimed to be disruptive but in fact did not observe the definition of Christensen (1997) or Govindarajan & Kopalle (2006) (e.g. High Voltage electrical system (Vojak & Chambers, 2004)). Nevertheless, 37 cases were finally found and they are really technological disruptive innovation in nature and also with sufficient data support[25]. My examples pool therefore covers most of the qualified cases in the extant literature.

In Step 2, for all the 37 cases, the case study protocol is as follows: First, I studied the specific technologies, functions and performances of each case with particular focus on what technological changes had taken place between disruptor and disruptee products. Second, R&D strategies that could be used to achieve such technological changes were analyzed. However, as many cases were historical cases and interviews with the original designers and successors were not feasible, I decided to select some cases for very detailed study and finally I managed to focus on 7 of them (Table 4.3). For case sampling, the research aim is to provide normative recommendations to create disruptive technologies, i.e. the inquiry of knowing "how" rather than testing "how" or "why". As Failure cases did not observe the insights-oriented sampling criteria (Eisenhardt & Graebner, 2007), they were not selected as in similar situations in Keupp et

[25] The data supports of these cases are either from literature or our empirical studies.

al.(2009) and Probert et al.(2003). Table 4.3 justified the 7 cases as disruptive technologies by the 4 criteria in Govindarajan & Kopalle (2006).

These 7 cases have been selected for detailed studies in Step 3, as they represent disruptive innovations from various industries, regions and in different periods. Some cases such as Wii Games Console and Tank Gauging Machine are more recent examples studied by myself. By studying these 7 cases extensively, I have identified 4 preliminary strategies.

A preliminary study of the remaining 30 cases has revealed that the identified R&D strategies were generally applicable to these cases and no new strategies could be found at this macro level. Instead of doing a further verification study by myself, I decided to invite an expert panel to participate in evaluating my findings by the Delphi method (Grisham, 2009) in Step 4. This method was chosen because this type of strategy development does not lend itself to precise analytical techniques but can benefit from subjective judgments on a collective basis. Another reason is that the heterogeneity of the participants can be preserved to assure validity of the results (i.e. avoidance of domination by influential individuals). It was sufficient to conduct two rounds of investigation because on one hand, the answers from the 2nd round were significantly convergent (detailed explanation in Section 5), and on the other hand, all experts told me they would not change their answers if more rounds were conducted.

The expert panel is selected according to the following steps: I first divided the 30 remaining cases into 5 technological categories, namely “Industrial/Commercial Computer Hardware and Software”, “Consumer Electronics”, “Communications/Networking”, “Healthcare and Medical Equipment”, and “Process and Mechanical Engineering”. All experts are very experienced professionals invited from relevant technological areas such as computer engineering, electrical and electronics engineering, communication, and biomedical engineering

(Appendix 1). Among the 25 experts, 16 are university professors very active in research and technology creation; 4 are directors in charge of national research institutes[26]; 2 are CEOs of high-tech firms; 1 is CTO; 1 is technical director; and 1 is a senior advisor of a high-tech firm. On average, they have 23 years of working experience in specific technological areas.

[26] In Singapore, Agency for Science, Technology and Research (ASTAR) is the dominant mission-oriented R&D organization, charting the course for Singapore's Science and Technology. It comprises a number of research institutes, and directors from 4 of the research institutes were invited to join our expert panel.

TABLE 4.3 Justification of nominated cases as disruptive innovations

Conditions of Disruptive technological innovation	**Transistor Radio**	**2.5 inch Hard Disk Drive**	**Automatic External Defibrillators**	**Simplified Tank Gauging machine**	**Wii**	**Centrino**	**War games**
Low end or new market disruption	new market	new market	new market	low end	new market	new market	low end
Disruptee	floor-standing TVs and radios	3.5 inch Hard Disk Drive	Manual External Defibrillators	Traditional Tank Gauging machine	PS3 and Xbox360	Pentium series	Military training devices
Niche market	American teenagers who likes rock 'n' roll	Laptop application	public and home application	China, for non professional operation	Females & seniors	Portable PC	Recruiting of soldier
Mainstream market	Adult customers of home audio equipments	Enterprise solution and desktop application	hospitals non-acute care and non-treatment areas, and emergency service	U S and EU, for professional operation	18-49 male	Desktop PC or scientific calculation	Various military training programs
Key performance	Sound quality and Reliability	Capacity, data transfer rate	VF detection capability, time required for energy shock, variety of therapies offered	Tank Gauging capability; In-tank leak testing; Automated calibration of tank chart	Processing speed, high-definition graphics and sound for realism	Processing speed	Network playability, local scenario storage and graphic quality
New value proposition	pocketability, power consumption	small size, light weight	ease of usage, increase survival rate, significant cost reduction	input and Display, small size	user-friendly interface	battery life and wireless application	Significant cost reduction
Unit cost comparison	lower	lower	lower	lower	lower	lower	lower

In the questionnaire (Appendix 2), the disruptive innovation theory was firstly introduced followed by an example. In the second step, the 4 strategies were introduced with one example for each strategy. After ensuring that these were experts who had basic knowledge of disruptive technologies and the proposed strategies, they were requested to go through 30 disruptive cases and decide what strategy (strategies) were used for each case. In the mean time, a reference manual including 1 to 1.5 pages of explanations for each case is provided. It was helpful when some experts wanted to evaluate cases in the category where they had knowledge but the technological category did not exactly fit their research areas/working responsibilities.

4.4 Identification of the four R&D strategies

The detailed study of 7 cases yielded 4 R&D strategies, as summarized in Table 4.4. Wii Game Consoles has applied two of these strategies. This result suggests that these strategies are not mutually exclusive and could be combined as input for the strategy-crafting efforts of firms. They are presented in a strategy framework as shown in Figure 4.1. I shall further illustrate details of these identified strategies using 2 different cases as follows. Each strategy is firstly defined, and the two detailed case examples were used to explain how the strategy was applied.

FIGURE 4.1 Framework for R&D Strategies to create potential disruptive products

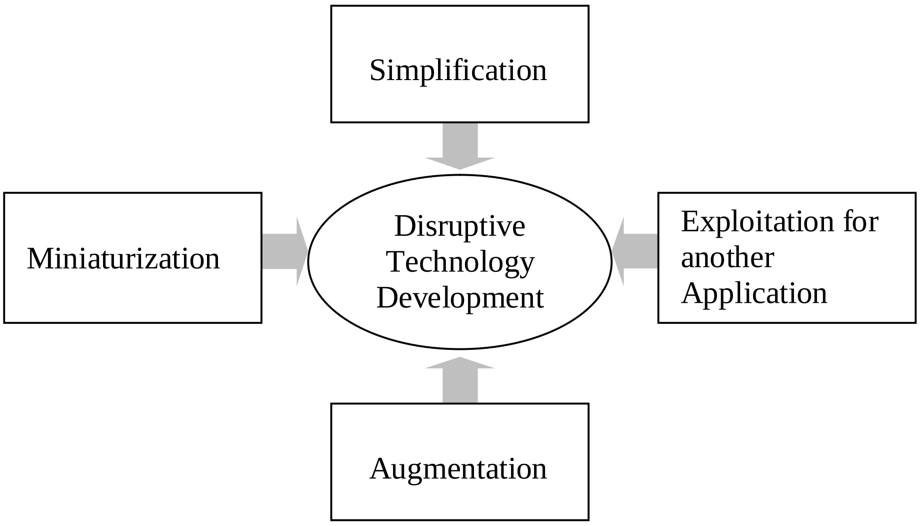


TABLE 4.4 R&D strategies proposals

Cases	R&D Strategies			
	Miniaturization	Simplification	Augmentation	Exploitation for another application
Transistor Radio	√			
2.5 inch Hard Disk Drive	√			
Wii Games Console			√	√
Intel Centrino			√	
Simplified Tank Gauging Machine		√		
War Games				√
Auto. Ext. Defibrillators		√		

4.4.1 Strategy 1 Miniaturization

In the past few decades, consumers have accepted products enabled by disruptive technologies. Many of them have been smaller and lighter (Kostoff et al., 2004). Miniaturization Strategy is defined as the strategy to design or construct products on a smaller scale to increase the benefits of portability and convenience. It is important to point out at this juncture that there are two possible routes to achieve miniaturization. One is by heavy investment of time and resources to achieve a much superior product with significant reduction in size but without degradation in key performance — this type of breakthrough R&D is adopted in creation of radical innovation (Leifer et al., 2000). The other one is modest investment of time and resources to achieve a smaller but good enough product to facilitate disruptive innovation. I am referring to the second route in this study. Two cases which used the miniaturization strategy are transistor radio and hard disk drive.

Transistor radio

Nowadays, for most purposes, the vacuum tube has been replaced by the much smaller, less power-hungry, and less expensive transistor in many applications. But back in 1950s, according to the dominant metrics of radio performance in the mainstream market, these early transistor radios were really bad in performance, offering far lower fidelity and much more static than the vacuum tube-based tabletop radios that was the dominant design of the time (Lynn, 1998). Nevertheless, Sony, a small company, discovered a new market composed of teenagers that valued the attributes of the pocketability and cheap price of transistor-based radios. It enabled teenagers to do something that they could not do before—listen to rock'n'roll out of their parents' earshot, though the music quality could not compete with tabletop vacuum tube (Morita, 2006). Gradually, with the advancement in technical performance of transistors, transistor-based radios gradually displaced vacuum-based radios in late 1960s. The performances and cost comparison of vacuum-tube based radios and transistor radios in late 1950s are shown in Table 4.5.

TABLE 4.5 Comparison of performances and cost between vacuum tube based radios and transistor based radios

When the first real shirt-potable transistor radio was introduced in March 1957.	**Vacuum Tube based floor-standing Radios (VTR)**	**Transistor based portable Radios (TR)**	**Comparison**
Sound Distortion	Highly linear without negative feedback, especially small-signal types; Operation was usually in Class A or Class AB, minimizing crossover notch distortion.	Considerable negative feedback caused high Distortion. Class B totem-pole circuits were common, which caused severe crossover distortion.	TR inferior
Music	Smooth clipping was widely considered more musical.	Sharp clipping, in a manner widely considered non-musical.	TR inferior
Reliability	Characteristics highly independent of temperature, greatly simplifying biasing.	Device parameters varied considerably with temperature, complicating biasing and increasing likelihood of thermal runaway, hotspots and irreproducible behavior.	TR inferior
Speaker protection	Output transformer in power amplifier protected speaker from DC voltage due to malfunction and protected tubes from shorts and blunts spikes from speaker.	Nearly all transistor power amplifiers had directly-coupled outputs that could damage speakers, even with active protection.	TR inferior
Variation of Device capacitances	Device capacitances varied only slightly with signal voltages	Device capacitances tended to vary wildly with applied voltages Miller effect).	TR inferior
Power Consumption (one vacuum tube vs. one transistor)	$\frac{200MW}{2\times10^{9}}$	$\frac{20W}{2\times10^{9}}$	TR superior
Size per radio	330 x 235 x 110mm	112 x 71 x 32mm	TR superior
Cost per radio	At least £100 (over US $100 in late 1950s)	US$20~US $30	TR was over 4 or 5 times cheaper than VTR.

Source: Vacuum Tubes and Transistors Compared, *Adapted from IEEE & Eric Barbour,* http://milbert.com/articles/tube_transistor_feature_comparison, http://www.thevalvepage.com/radios/rad1955.htm , http://www.robertopiecollection.com/Application/Products/Bush-radios/bush-radios-1GB.asp and the interviews.

In order to fit the transistor and other electronics components into their small radio, Sony engineers needed to miniaturize almost everything such as the capacitor, the loudspeaker, the transformer, and even the batteries. At that time, most of the components were produced by subcontractors. Sony could not purchase the components readily from the market because most Japanese manufacturers produced radio components that copied both the design and size of those made in US. Finding or designing other parts small enough to fit together was not easy at all. Ibuka, one of the two company founders, went around to every individual component manufacturer and persuaded them to start to miniaturize every component from scratch and that seeded the growth of a prosperous electronics industry in Japan since then.

With a clear vision to pursue miniaturization and compactness, Sony overcame all technological hurdles within 3 years to introduce the world's first real shirt-potable transistor radio TR-63 in March 1957. It was made with an all new imaginative design with many purpose-built miniature components (e.g. its microscopic solid dielectric variable capacitor). Starting with transistor radio, Sony has established the unique core competence in product miniaturization. In the following years, this core competence enabled Sony to develop a range of consumer electronics products. Miniaturization Strategy has enabled Sony to create a series of twelve disruptive new-growth businesses between 1950 and 1982.

2.5 inch Hard Disk Drives

A more recent example of successful Miniaturization strategy is in the 2.5 inch hard disk drives. It has enabled the hard disk drive companies such as Seagate to create a new market disruption in the mobile computing applications. It is also beginning to encroach the 3.5 inch hard disk drives in enterprise solution. Table 4.6 presets the performances and cost comparison between 3.5 inch and 2.5 inch hard disk drives (HDD). Although 3.5 inch HDD outperformed 2.5 inch HDD in major dimensions such as overall capacity and data transfer rate, the smaller size, lighter weight and lower price of the 2.5 inch drives have enabled a niche market of mobile/laptop applications (Table 4.6).

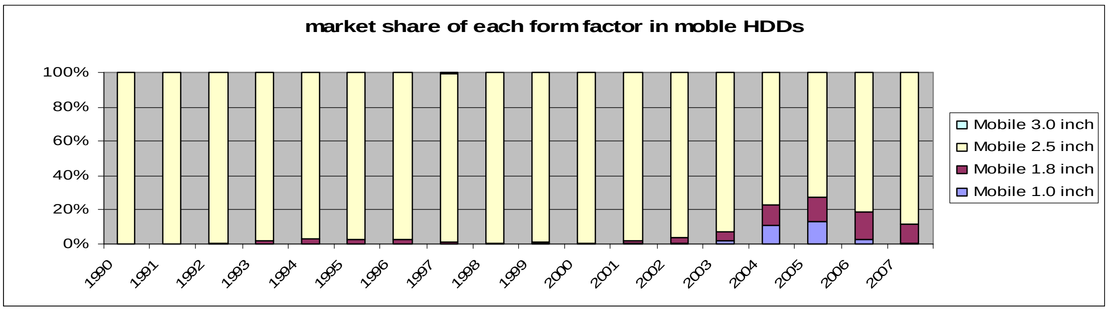
TABLE 4.6 Comparison of performances and cost between 3.5 inch and 2.5 inch hard disk drives

When the first 2.5 inch HDD was introduced in 1988.	**3.5 inch Hard Disk Drives**	**2.5 inch Hard Disk Drives**	**Comparison**
Capacity	20~300MB	20MB	2.5” inferior
Average positioning time (msec)	20	28	2.5” inferior
Average rotational delay (msec)	8.3	8.9	2.5” inferior
Average access time (msec)	28.3~73.3	36.9	2.5” inferior
Data transfer rate (Kbytes/sec)	625~937.5	625	2.5” inferior
Size	101.6 mm x 25.4 mm x 146 mm	69.85 mm x 9.5–15mm mm x 100 mm	2.5” superior
Cost	US$230~3460	US$230.8	2.5” superior

Sources: Trend Focus Report, 1988 and http://en.wikipedia.org/wiki/Hard_drive

It was the flourish of hand-held digital mobile devices in 1990s that marked the boom of 2.5 inch hard disk drives demand, and it became a major high-growth business even without the disruption of the 3.5 inch drives. However, the 2.5 inch HDD has the potential to eventually disrupt the 3.5 inch drive in mainstream applications such as desktop computers. As shown in Figure 4.2 and Figure 4.3, 2.5 inch HDDs dominate the application of mobile HDDs since early 1990s and have started to compete for market share of 3.5 inch HDDs in enterprise solution since 2005.

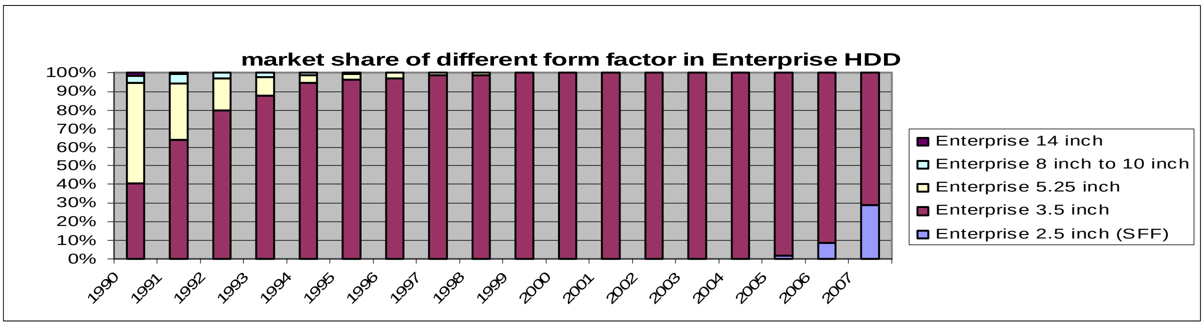
FIGURE 4.2 2.5 inch HDD dominates the market application of mobile HDD



Source: Disk/Trend Reports from 1990 to 1999;
Trend Focus Reports from 2000 to 2007

FIGURE 4.3

2.5 inch HDD started to disrupt 3.5 inch HDD in enterprise application since 2005



Source: Disk/Trend Reports from 1990 to 1999;
Trend Focus Reports from 2000 to 2007

My study has revealed that there were longitudinal changes of the Miniaturization pattern in hard disk drive industry from Winchester 14 inch drive to 8 inch, 5.25 inch, 3.5 inch, 2.5 inch, and to 1.8 inch. The pattern repeated in Computer industry, from the mighty corporate mainframe computers to minicomputers, personal computers, laptop computers, and to personal digital assistants. In a broader industry setting, miniaturization pattern could be tracked and their trend predicted. Design and construct to a smaller scale may hence be feasible to create the next generation of disruptive products in some industry sectors although the accurate timing of their occurrence may still be rather difficult. Furthermore, the literature on modular design and vertical disintegration (Langlois, 1992; Baldwin & Clark, 2000) has indicated that miniaturization of established products involves miniaturization of most if not all modules, which can demand substantial efforts from not only the firms that attempt to create disruptive innovations, but also the component suppliers of these firms.

4.4.2 Strategy 2 Simplification

The Simplification Strategy is used to create potential disruptive products based on the current products of overly-high complexity and excess functionality, so that the population that historically lacked the skills to use current products can become new customers. Simplification is not only to reduce redundant features or the degree of performance in certain feature(s) but also to focus on the new value proposition that is most delightful to its targeted customers. This strategy has been identified from two cases:

a Simplified Tank Gauging machine in the China market and an Automated External Defibrillator (AED).

Tank Gauging machine TSL-2

Inventory control is a basic need of the Oil and Gas Industry. The main reason is to ensure that the amount of the fuels added in and taken out of the refinery, terminal or petrol station are accounted for correctly and completely. Tank Gauging machines are developed to measure the oil flow which performs the function of inventory control in petrol stations. Traditional Tank Gauging machines widely adopted in US and European markets around year 2000 have highly automated functions and a large capacity up to 12 tanks with a premium price around US 10,000.

In 2000, a large number of firms in the Tank Gauging business went to China with their new models of tank gauging machines, and the most successful model was TLS2, released by Company A after several trials and errors. Table 4.7 lists the performances and cost comparison between TLS350R, the representative of traditional tank gauging machines in US and Europe and TLS2, the new model in China. Compared with the traditional machines, TLS2 is inferior in most dimensions, but is good enough to apply in China market. The new value proposition of "Graphic touch screen display" (Most operators in China petrol stations do not understand English around 2000) and significant lower cost made TLS2 a very successful disruption to traditional models in Chinese market. According to my field study in Company A, with technical improvements in the simplified TLS2, it has started to draw attention from the US market, and their high-end models based on TLS350R may suffer from the destiny of cannibalization[27].

TABLE 4.7 Comparison of performances and cost between traditional tank gauging machine and simplified tank gauging machine

When the simplified Tank Gauging machine TSL2 was introduced in 2000.	**TLS350R, representative of traditional tank gauging machine**	**TLS2, simplified tank gauging machine**	**Comparison**
Automated calibration of tank chart	Yes	No	TLS2 inferior
Automated Inventory Reconciliation	Yes	No	TLS2 inferior
Tank Gauging capability	Maximum of 12 tanks	Maximum of 6 tanks	TLS2 inferior
Expandable	Yes, by adding on expansion cards	No. Features were fixed	TLS2 inferior
In-tank leak testing	Standard feature (Capable of detecting leak of 0.1 gph)	Optional feature (Capable of detecting leak of 0.2 gph)	TLS2 inferior
Input/Output relay (to control external devices)	Flexible to add multiple relays	One relay provided	TLS2 inferior
Input and Display	Input via 24-buttons keypad. Single line display (Text Only)	Graphic touch screen display, more user-friendly for people who did not understand English.	TLS2 superior
Price (assuming standard configuration)	US$10k	US$5k	TLS2 superior, at least 2 times cheaper.

Sources: http://www.A.com/page/TLS-350R for TLS350R; http://www.A.com/page/TLS-2 for TLS2; http://www.A.com/page/MonitoringConsoles

To be concise, the entry behaviors of leading firms at product level can be boiled down to 5 strategies: (1) Advocate the successful models used in USA/Europe; (2) Sell successful models but with high-level features turned-off; (3) Make a new automatic tank gauging machine with different level sensing methods (Capacitive/Servo); (4) Sell probe to local system integrator (BOS/probe approach); and (5) Create a new product with low-

[27] Interview with the Technical Director and Managing Director of Company A on September 27th, 2007. They have been working in Company A since 1990s.

end existing features and most valuable new features for the Chinese market. Only Company A adopted the last entry strategy. Before 2000, the Chinese market was dominated by 2 domestic firms with over 90% market share. In 2001, when a large number of foreign firms participated in the competition, Company A has occupied 52% of the Chinese market with its simplified Tank Gauging machine. Particularly noteworthy from this case, simplification does not exactly equal to high-level features cut-off, presented in the second entry strategy. It is a new product, not only with reduced redundant features or the degree of performance in certain feature(s) but also with a new value proposition that is most delightful to its targeted customers.

The success of Company A on its TLS2 was not a smooth march without any hitch. Table 4.8 presents how A experienced 4 trials and errors, and finally applied the simplification strategy to command huge success based on their disruptive product.

TABLE 4.8 An iterative process of product entry strategy of Company A

	1st time	2nd time	3rd time	4th time
Strategy	**Offered high-end models only to major oil companies during initial move**	**Created TLS-50 in 1998 as a low-price basic model**	**Offered probe only but with software produced by Company A**	**Created TLS-2**
Success or Failure	Failure	Failure	Failure	Success
Reasons	Management noted existing models not suitable for local oil companies, thus abandoned.	Very limited functionality was not accepted; Abandoned when management realized this was the incorrect solution	Not successful by allowing access through a converter box; Use to negate local suppliers using same approach	Had just enough features to match requirements; Provided touch-screen as a way to address language issue; affordable price.

Automatic External Defibrillator

Sudden Cardiac Arrest (SCA) has been one of the leading causes of death that can strike people at any time and any place, and the leading cause of SCA is ventricular fibrillation (VF). Defibrillator is an apparatus used to apply an electric current to the heart to restore its normal rhythm. Early defibrillation is very critical to reviving patients in SCA. Manual External Defibrillators (MED) dominated the defibrillation market until the introduction of the Automated External Defibrillator (AED). MED are full function defibrillators that support multifunctional operations making it only suitable for highly-skilled medical personnel who have received training in advanced cardiac life support and rhythm recognitions. While AED is a portable defibrillator designed for minimally-trained or untrained non-medical personnel. When compared in traditional performance measures, AED are all inferior to MED (Table 4.9). However, its mobility and ease of usage are great attributes well suited for saving lives as the likelihood for successful resuscitation would decrease by approximately 7 to 10% with each minute following the SCA. In addition, the cost of AED is 5 to 6 times cheaper than hospital MED, promoting AED from public consumers who are highly price sensitive to Pre-Hospital service, even to traditional hospital segment (Table 4.9).

TABLE 4.9 Comparison of performance and cost between MED and AED

When AED emerged in 1999.	**Manual External Defibrillators (MED)**	**Automatic External Defibrillators (AED)**	**Comparison**
VF Detection Capability	Professional interpretation always had no error.	VF Detection Capability (1) Accuracy between 76% and 96% (2) Specificity was almost 100%	AED inferior
Time Required to Charge for Energy Shock	Up to 200 Joules in 5 seconds	Up to 150 Joules (Inclusive of VF detection) in 15 to 30 seconds	AED inferior
Therapies offered	Shock delivery at variable energy levels of 1-10, 15, 20, 30, 50, 70, 100, 120, 150, 170, up to a maximum of 200 Joules	Shock delivery at a preset of 150 Joules of non-escalating energy level for adults and 50 Joules for children	AED inferior
Time to Defibrillate – in a Hospital area	Ability to monitor and provide shock in 5 seconds.	Only able to treat VF, Taking 15 to 30 seconds between shocks	AED inferior
Time to Defibrillate – in a Public area	12 minutes	4 minutes	AED Superior -Increased survival rate by 49%
Cost of a single MED or AED	US $4000 to $23000	US$ 2000 to $3000	AED was 5 to 6 times cheaper than MED.

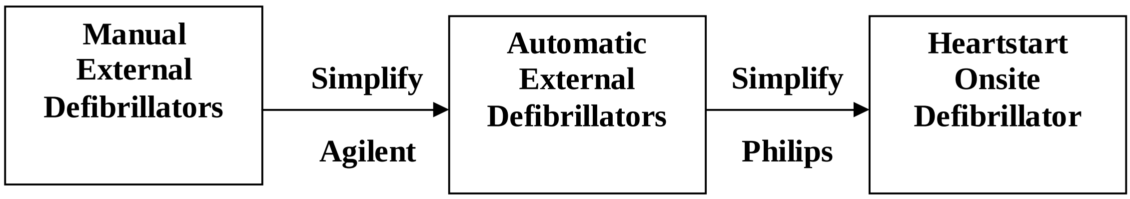
Philips Medical Systems (PMS) entered the AED market by acquiring Agilent Technologies' Healthcare segment in 2000[28]. AED product was not new as it was simplified from the mature and established technology of the existing MED. Recognizing a non-consumption group of 121 million homes in US, Philips Medical Systems further simplified the portable AEDs to introduce the first commercial Heartstart OnSite

[28] Frost & Sullivan's news: Philips' Advances in AED Markets at: http://www.frost.com/prod/servlet/press-release.pag?docid=40301975, accessed in June, 2008.

Defibrillator through over-the-counter sales without prescriptions in 2005, successfully extending AED applications to homes, communities, schools and businesses. A very easy-to-use user interface empowers even ordinary users to save lives.

FIGURE 4.4

Simplification strategy used twice in automatic external defibrillators



Christensen (2003) has advocated the application of the 80/20 rule to simplify a high-end sustaining technology to be disruptive as most of their sophisticated features might not be usable at the low-end or a new niche market. By such a simplification, and coupling with simple automation and new design to make them easy to use and yet affordable, a suitable disruptive product could be created.

4.4.3 Strategy 3 Augmentation

Augmentation Strategy suggests that firms can augment the existing sustaining product with a disruptive feature. This means that the traditional primary performances that mainstream customers historically valued could still be maintained at a satisfactory level of performance, while the R&D could focus on adding creative disruptive features.

This Strategy was applied in two cases, Nintendo Wii Game Console and Intel Centrino Microprocessor.

Wii

In 2006, Nintendo launched its new home video game console Wii to compete with Sony's PlayStation 3 and Microsoft's Xbox360 as the seventh generation product in the video game history. The mainstream competitive dimension in video game market was led by Sony and Microsoft's high-end technological trivia such as the synergistic processing elements for higher processing speeds and the superior graphics for resolution and realism. Wii did not want to engage in the same battle for higher performance demanded by traditional customers who are young males. Instead, it tried to disrupt this market by its new product strategy, which focused on winning "fringe" customers through the new games interface. The performance and cost comparison between Wii and its competing products is shown in Table 4.10.

TABLE 4.10 Comparison of performance between Wii, PlayStation 3 and Xbox360

When Wii was fisrt introduced in Nov, 2006.	**PlayStation 3**	**Xbox360**	**Wii**	**Comparison**
CPU processing speed	Cell processor, power PC-based core @3.2GHz*1	Xbox360 processor, power PC-based core @3.2GHz*3	Broadway processor, power PC-based core @729 MHz	Wii inferior
Memory	256MB GDDR3 VRAM @700MHz, 256MB XDR Main RAM @3.2GHz	512MB of 700MHz GDDR3 RAM,10 MB of embedded DRAM	88 MB main memory, 3 MB embedded GPU texture memory and framebuffer	Wii inferior
Graphic Processing Units	550MHz NVIDIA	500MHz Ati	243MHz Ati	Wii inferior
Storage	Detachable 2.5" HDD slot x 1	Removable HDD 20G, 12x dual-layer DVD-ROM	512 MB built-in NAND flash memory	Wii inferior
Video	HDTV resolutions from 480i up to 1080p	Supported at 16:9, 720p and 1080i, anti-aliasing. Standard-definition and high-definition video output supported	480p (PAL/NTSC), 480i (NTSC) or 576i (PAL/SECAM), standard 4:3 and 16:9 anamorphic widescreen	Wii inferior
Online capabilities	free online games, online service for purchasing downloadable games, chatting with friends in the network and browsing web with PS3	access to voice chatting and text message, got challenge with other gamers online	not available, but could purchase games, get news and weather updates and browse the internet with the Wii on Nintendo U.S. website	Wii inferior
Controller	Wireless Controller	Wireless Controller support (up to 4)	sensing wireless controller	Wii Superior
Cost	US$806 (20G)	US$525	US$160	Wii Superior

Sources:http://en.wikipedia.org/wiki/Wii_launch#Release_dates_and_pricing ;
http://en.wikipedia.org/wiki/Wii;
http://en.wikipedia.org/wiki/PlayStation_3 ;
http://en.wikipedia.org/wiki/Xbox_360;
http://money.cnn.com/magazines/fortune/storysupplement/wiiremote/index.htm

However, based on the sustaining product, the affordable Wii includes a motion-sensitive wireless Wii Remote Controller, which utilizes a commercially available MEMS acceleration sensor to enable such actions like racing-game steering and a tennis swing to be done through natural movements of your hands rather than just your thumbs.

Wii Sports, packaged with the Wii console, introduces players to these and other experiences. It has thus been able to realize its CEO's vision to bring games to non-conventional customers by attracting females and older folks to become a new and large category of game players. Although Wii is an incremental improvement in the sustaining trajectory compared with its predecessor, the disruptive feature of sensing controller has brought a huge market success for Nintendo.

Centrino

Intel Centrino chipsets, developed by Intel R&D Centre in Haifa, Israel, was a huge commercial success. Instead of developing higher-performance microprocessors which was the R&D goal of Intel Headquarters in the US, Intel Israel R&D management set a completely different goal of transforming laptops into mobile offices as a potential new-market disruption. The R&D engineers then concentrated on adding new features to its existing low-end microprocessors – features which were not yet appreciated in the mainstream market at that time. The result was a hugely successful Centrino chipsets product (Kanellos, 2003), which includes an energy-efficient Pentium-M processor (with different architectural features to combine routine instructions and tasks to save time and energy) and a wireless Local Area Network chipset to facilitate mobile internet access and other wireless applications. The market has demonstrated that eventually the strategy of augmenting existing microprocessors with new features of battery life extension and wireless connectivity enabled Intel to command premium prices. Table 4.11 presents the performance and cost comparison between Pentium 4 and Centrino. The low-end energy-efficient Pentium-M processor is also listed to illustrate how Centrino was developed based on existing Pentium M and disruptive feature of wireless connection.

TABLE 4.11 Comparison of performance and cost between Pentium 4 and Centrino

In 2003, when Centrino was first introduced	**Pentium 4 (Mobile Pentium 4 M)**	**Pentium M (Banias)**	**1st Generation Centrino (Montara)**	**Performance comparison**
Clock Speed	1.3 GHz to 3.8 GHz	900MHz to 1.7 GHz	1.3GHz to 1.6GHz	Centrino inferior
Hyper Threading Technology	Yes	No	No	Centrino inferior
Front Side Bus Speed	up to 1066 MT/s	200MT/s	800MT/s	Centrino inferior
Integrated Wireless Communication	N/A	N/A	an Intel Pro/Wireless LAN adapter.	Centrino superior
Battery life	2 to 3 hours	4 to 5 hours on a 48 W-h battery	4 to 5 hours on a 48 W-h battery	Centrino superior
Cost (USD)	900 and above	423	800	Centrino superior

Sources: http://www.pctechguide.com/71CPUTech_Centrino.htm
http://en.wikipedia.org/wiki/Centrino; http://en.wikipedia.org/wiki/Pentium_M
http://www.intel.com/products/notebook/chipsets/855gm/855gm-overview.htm
http://computers.pricegrabber.com/processors-unboxed-oem/m/377221/
http://www.nationmaster.com/encyclopedia/Pentium_M
http://reviews.zdnet.co.uk/hardware/components/0,1000001694,10003237,00.htm?r=6

The existing literature has argued that the mainstream customer orientation and the emerging customer orientation are not mutually exclusive, suggesting that firms can develop both orientations simultaneously (Narver et al., 2004; Slater & Mohr, 2006). Maintaining the key performances in mainstream market to satisfy current customers while augmenting a sustaining product with new disruptive features to attract potential new customers is one effective way to develop both orientations in parallel, and to create technology candidates for potential disruptive innovation.

4.4.4 Strategy 4—Exploitation for another Application

When attacked by disruptive entrants, incumbents could also think of new applications to reposition their existing products in addition to the option to fight back. On the other hand, entrepreneurial firms could take the initiative to leverage on progress of certain sustaining technology which has already created affordable, high-tech products or components to create potential disruptive innovations in another targeted application. The strategy of Exploitation for another application covers two perspectives: repositioning existing technology and borrowing existing technologies for targeted applications. The two cases in point are war game products in military training industry and MEMS enabled controller in Wii Game console.

Game products in military training

Owing to keen competition in sustaining innovation, the product performance would continue to improve substantially with time. But soon the increased performance demanded by the customers may also cost much more and this could limit further business growth. The military training simulator market is a good example here. The mainstream simulator product has been revolutionized since the introduction of sophisticated computer technologies. They improved rapidly with time but the cost has also gone up as the demanding high-end customers could afford it. But recently, PC-based games which were developed for the entertainment market were found to be "good enough" as training tools for less demanding customers especially those who were severely financially constrained (Roger, 2007). They are also good enough to be used as a recruiting tool for new soldiers. The military simulation is being transformed by PC games. A serial of virtual training devices has been developed particularly for military training, from SIMNET to Close Combat Tactical Trainer (CCTT), to OneSAF. With significant performance improvements in gaming consoles such as network playability, local scenario storage and graphic quality, games of Spearhead, America's Army and On-Line Virtual Environment (OLIVE) gradually emerged in military training applications.

As the games consoles like the PlayStation and Xbox further improve their capabilities, moving some of the training simulators to these consoles could represent further cost reduction. As discussed by Roger, several potential disruptions have started to take place in the low-end of the military training industry by exploiting products from the games industry (Roger, 2007).

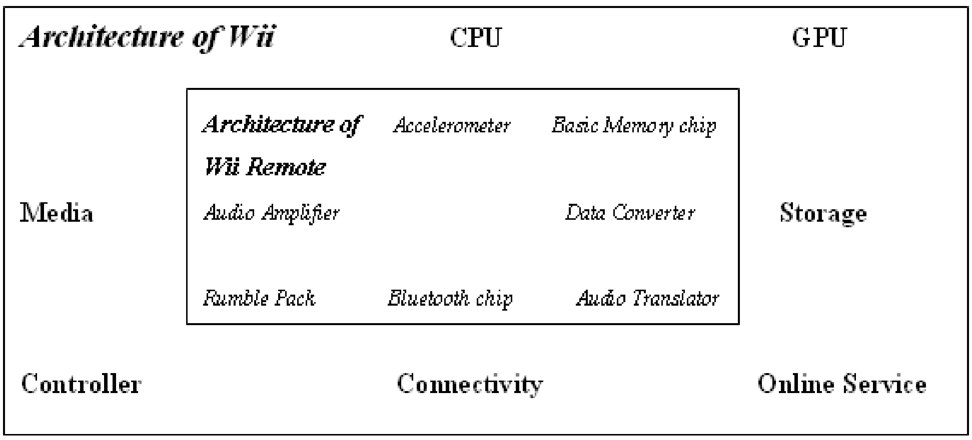
MEMS in Wii

The successful disruptive innovation of Nintendo Wii used Strategy 3—Augmentation. Nintendo Wii also used Strategy 4—Exploitation for another application. The only module that superior to Xbox360 and PS3 is Wii controller, also called Wii Remote, a wireless and motion-sensitive controller. The ergonomic design links player's movement and direction pointed at in space directly to the display and change on screen, acting as warrior's sword, artist's paintbrush or a golf club, rather than the common combination of buttons and joysticks. As the most multifaceted gaming device ever, Wii

Remote plays into the conventional motions you make everyday, offering an intuitive, natural way to play games. Because of Wii Remote, Nintendo Wii has successfully leapfrogged the Microsoft Xbox360 even though Microsoft launched it a year ahead and outsold Sony PlayStation 3 which is featured with its new Blue-ray technology.

Wii Remote, as the highlight module of Wii console, is also a system consists of several components (Figure 4.5), and the component of accelerometer is the magic driver to enable the wireless sensing of 3D movement. The MEMS accelerometer found its new applications beyond the original purpose in automobile crash-sensing. In Wii Remote, a MEMS acceleration sensor is used to enable such actions like racing-game steering and tennis swing to be done through natural movements of your hands rather than just your thumbs. Wii Sports, packaged with the Wii console, introduce players to these and other experiences. Hence, the new application of MEMS sensors in game consoles significantly contributed to Wii's successful disruption.

FIGURE 4.5 System Architecture of Wii



4.5 Verification of the wide application of the identified R&D strategies

As shown earlier in Table 4.4, 7 cases are analyzed in detail, with the attempt to explain the 4 R&D strategies. In order to further improve the validity and general applicability of the identified R&D strategies, and also to look for possible strategies which may have been missed, 25 experts were invited to participate in the assessment of the application of the 4 R&D strategies. The results from 1st and 2nd round Delphi method are summarized in Tables 4.12 to 4.16. “A” and “B” indicate the level of confidence of specific answer. I requested experts to put down “A” if they are professionals in the technology category and they are very sure of their answer. On the other hand, “B” implies the experts make the answer based on their knowledge in the technological category, combined with the case reference manual.

TABLE 4. 12
Delphi result for Category 1- Industrial / commercial computer hardware and software

Examples		**Answers from the experts panel in 1st round**				**Answers from the expert panel in 2nd round**			
Disruptive Product	**Mainstream Product**	**Miniaturization**	**Simplification**	**Augmentation**	**Exploitation for another application**	**Miniaturization**	**Simplification**	**Augmentatio n**	**Exploitation for another application**
3.5 inch hard disk drive	5.25 inch hard disk drive	8A,12B		A,B	2B	10A,12B	B		B
Minicomputer	Mainframe	5A,5B	8A,7B	A	3B	5A,7B	13A,8B		B
Microcomputer	Minicomputer	10A,6B	8A,3B	A,B	A,2B	13A,7B	5A,5B		B
Palm pilot, RIM blackberry	Notebook computer	8A, 6B	7A,4B	A,B	A,4B	11A,4B	6A,4B		3B
Microprocessor	Complex logic circuits based on PWB	9A,4B	3A, 7B	2A,B	2A,6B	12A,7B	5A,5B	2B	3B
RISC microprocessors	Normal Microprocessors	3A,2B	5A,8B	A,4B	A,B		8A,9B		
Small business accounting software QuickBooks	Mainstream accounting software	2B	A,16B	A,B	2B	B	4A,17B		B
Google search engine	Yellow pages	A,	3A,3B	3A,4B	5A,4B		2B	5A,8B	7A,4B
Oracle's relational database software run on minicomputer	Incumbents' relational database software run on mainframe		A,10B	A,B		B	4A,9B		

TABLE 4.12 Delphi result for Category 1- (continued)

Examples		**Answers from the experts panel in 1st round**				**Answers from the expert panel in 2nd round**			
Disruptive Product	**Mainstream Product**	**Miniaturization**	**Simplification**	**Augmentation**	**Exploitation for another application**	**Miniaturization**	**Simplification**	**Augmentatio n**	**Exploitation for another application**
SQL database software	Oracle database software	B	8B	A,B	2B		2A,10B	B	2B
Email	Postal Service		2A,4B	3A,5B	4A,4B		A,2B	7A,6B	6A,2B
Linux	UNIX	B	A,8B	2A,3B	2A,B	B	2A,10B	4A,2B	
Digital animation	Full-length animated movie		3A,5B	4B	2A,2B		5A,8B	4B	5A,2B

TABLE 4. 13 Delphi result for Category 2 - Consumer electronics

Examples		**Answers from the experts panel in 1st round**				**Answers from the expert panel in 2nd round**			
Disruptive Product	**Mainstream Product**	**Miniaturization**	**Simplification**	**Augmentation**	**Exploitation for another application**	**Miniaturization**	**Simplification**	**Augmentation**	**Exploitation for another application**
Canon photocopiers	High-speed Xerox machine	4A,7B	A,11B	B		9A,5B	2A,11B	B	
Point and shoot Brownie camera	Expensive complicated photography	2A,6B	A,14B	A	2B	3A,7B	6A,15B		B
Raku-Raku phones for silver-hair people	Multifunctional mobile phone		4A,11B	A,B	3B		9A,14B		2B
Walkman	Traditional music player	7A,8B	2B	3B	4A,2B	11A,8B		2B	5A,5B
Small-sized microwave oven	Normal-sized microwave oven	3A,12B	A,6B	A,2B	2B	6A,15B	2A,5B		2B

TABLE 4. 14 Delphi result for Category 3 - Communications/networking

Examples		Answers from the experts panel in 1st round				Answers from the expert panel in 2nd round			
Disruptive Product	**Mainstream Product**	**Miniaturization**	**Simplification**	**Augmentation**	**Exploitation for another application**	**Miniaturization**	**Simplification**	**Augmentation**	**Exploitation for another application**
Wireless telephony	Wireline phones	5A,3B	B	5A,7B	2A,2B	5A,3B		10A,7B	3B
802.11	Local-area wireline network	4A	A,B	4A,5B	2A,B			8A,10B	B
Routers based on packet-switching technology (enable VOIP)	Routers based on traditional circuit-switching equipment	A	A	4A,8B	5A,2B			6A,12B	6A,7B

TABLE 4. 15 Delphi result for Category 4 - Healthcare and medical equipment

Examples		Answers from the experts panel in 1st round				Answers from the expert panel in 2nd round			
Disruptive Product	**Mainstream Product**	**Miniaturization**	**Simplification**	**Augmentation**	**Exploitation for another application**	**Miniaturization**	**Simplification**	**Augmentation**	**Exploitation for another application**
Endoscopic surgical equipments	Complicated heart procedures	2A,8B	5B	3B	3B	5A,11B		2B	2B
Portable diabetes blood glucose meters	Large blood glucose testing machines	2A,12B	A,11B		2B	5A,14B	3A,11B		2B
Sonosite	Professional ultrasound device	2A,9B	A,7B		2B	4A,13B	5A,8B		

TABLE 4. 16 Delphi result for Category 5 - Process and mechanical engineering

Examples		Answers from the experts panel in 1st round				Answers from the expert panel in 2nd round			
Disruptive Product	**Mainstream Product**	**Miniaturization**	**Simplification**	**Augmentation**	**Exploitation for another application**	**Miniaturization**	**Simplification**	**Augmentation**	**Exploitation for another application**
Minimill	Integrated mill	7B	7B	B	3B	10B	20B		2B
Blended plastics	Engineering plastics		2B	8B	B		B	17B	
Plastic-encased tools with universal motors	Handheld electric tools before 1960	2B	A,7B	A,B		2B	4A,11B	2B	
50cc Supercub	Traditional motorcycle	5B	10B	B	5B	B	3A,18B		2B
Hydraulically actuated excavator	Cable-actuated excavator		5B	A,4B	4B		A,9B	A,11B	2B
Digital watches	Mechanical watches	3B	4B	A,4B	A,6B			5A,9B	5A,4B

The answers from the first round show that there more Bs than As, suggesting experts are conservative to give As in order to secure the accuracy. In addition, the majority of examples have at least one answer for all 4 strategies, suggesting a bit scattering nature of the answers. All experts are free to interact with us if they do not understand the disruptive innovation concept, the 4 strategies or the contents of the 30 cases. Some experts called me for a comprehensive interview (e.g. Prof SB), and some experts wrote down in their 2nd round answer such as "*Have understood Oracle better after speaking to friends that have good understanding of the software*."(Prof TA)

The second round answer shows significant consensus compared with the first round answers, as cells in the table are either full of As and Bs, or are empty or mostly with 1 or 2 Bs. In addition, 269 As are observed compared with 199 As previously, suggesting experts are more confident in the accuracy of the answers since they understand the examples better by (1) consulting their friends who are experts in specific case; (2) discussing with me about their confusion and (3) searching more information by themselves. Finally, I highlighted the convergent answers in gray, and all As are included in the convergent answers, further enhancing the degree of consensus. I consider the gray-cell answers as the final answers (i.e. which example use which strategy), and summarized the frequency of strategy application both for each technology category, and for the 30 cases as a whole (Table 4.17).

TABLE 4. 17 Application frequencies of the 4 R&D strategies

Technological Areas	Miniaturization	Simplification	Augmentation	Exploitation for another application
Industrial/Commercial Computer Hardware and Software	5	10	3	3
Consumer Electronics	4	4	0	1
Communications/Networking	1	0	3	1
Healthcare and Medical Equipment	3	2	0	0
Process and Mechanical Engineering	1	4	3	1
Overall frequency	14	20	9	6
Relative frequency among all 4 R&D strategies	28.6%	40.8%	18.4%	12.2%

In Table 4.17, the differences in the application frequencies are indeed very substantial. For example, "Miniaturization" and "Simplification" strategies are significantly used more frequent than the rest, which reflects the lifestyle trend towards convenience and agility. On the other hand, little utilization of "Augmentation" and "Exploitation for another application" strategies imply plentiful untapped disruptive opportunities. The potential opportunities will be discussed in detail. It is noticed that the application frequencies and further analysis are dependent on the cases chosen. However, as stated in "Research Design" section, I tried to find all available cases in the literature; hence the application frequencies represent the status quo.

4.5.1 Implication for miniaturization strategy

Miniaturization is the second most frequently used strategy among the 4 strategies, with a percentage of 28.6%. Furthermore, it is the most frequently used strategy in "Consumer Electronics" category and "Healthcare and Medical Equipment" category. This implies that with technology advances in areas such as microelectronics, nanotechnologies, and optimization of architecture designs, firms are recommended to miniaturize their products into compact and portable disruptive products to tap the potential growth opportunities, particularly in Consumer electronics and Healthcare industry.

4.5.2 Implication for simplification strategy

As there exist many high-end sustaining technologies, both incumbents and entrants could proactively simplify them to create potentially disruptive technologies. This strategy was the most frequently used among the 30 cases, widely applied in categories such as "Computer Hardware and Software", "Consumer Electronics" and "Process and Mechanical Engineering". It is anticipated that companies will find this strategy to be in line with the trend of open innovation (Chesbrough, 2003) as the high-end technology (before simplify) could be sourced externally from universities or other organizations. On the other hand, universities and research institutes have found a lot of difficulties in directly transferring their high-end technologies to small and medium enterprises (SMEs) (Campo, 1999). Simplification strategy provides a possible channel to high-end technology or product transfer to industry if the universities/research institutes proactively simply their high-end technologies, in consultation with the SMEs to better appreciate the "job-to-be-done" market needs, to create appropriate disruptive products for the SMEs which will in turn use them in introducing disruptive innovation.

4.5.3 Implication for augmentation strategy

In sustaining innovation, the goal of R&D is to enhance known product features appreciated by mainstream customers. A goal to enhance other features which may be disruptive but with market uncertainty is often difficult to justify initially. The successful case of Nintendo demonstrated that it was possible to set and realize such a R&D goal.

It is noted that this R&D strategy should be more acceptable to incumbent companies as it does not entail the classical disruptive innovation route of abandoning or challenging a sustaining technology. Yet Table 4.17 shows that it was not frequently used. It is thus recommended that successful examples like Intel and Nintendo be given much more publicity as they could spur more awareness of the potential of this strategy and hopefully more applications in the near future.

4.5.4 Implication for exploitation for another application strategy

Finally, there is a possibility of leveraging on sustaining progress of certain established products which has already created affordable, high-tech components. The use of the light weight, good quality and yet low-cost head phones in the Walkman (Nayak & Ketteringham, 1994) was one classical example. The literature on text-mining (Yoon, Phaal & Probert, 2008) and patent mapping[29] could be applied

[29] Guide book for practical use of "Patent map for each technology field", Asia Pacific Industrial property center, Japanese patent office, 2000.

here to help search for appropriate product candidates to be borrowed or exploited for potential disruptive products.

From Table 4.17, it is also observed that this approach has been under-utilized. This needs not be the case if the R&D managers are encouraged to leverage on technologies from other fields or other applications to create suitable candidates of disruptive products. It is also anticipated that the trend of Open Innovation would spur more interest in this R&D strategy for disruptive product creation.

4.6 Conclusion

In this chapter, I have discussed the strategic intent of developing disruptive technologies as technology candidates or options to create potential DI. 4 R&D strategies have been identified which could be used individually or in combination to purposefully create disruptive technology candidates. They are miniaturization, simplification, augmentation, and exploitation for another application (Figure 4.1). Adopting such a systematic and explicit R&D strategy framework would hopefully help more companies to become disruptors. However, the R&D strategies are not intended to be prescriptive and no "one" or "best" strategy exists. Rather, managers might use them as input for their own strategy-crafting efforts or as tools to benchmark their own efforts.

The R&D strategies developed are specific for disruptive technologies. In order not to confuse with R&D for radical technologies, it is important for the R&D managers to keep 3 points in mind when applying them: (1) the disruptive technology must be affordable with good enough performance; (2) it should create new features valued by the current non-consumers; (3) the time and resources required are not as moderate – much less demanding than those for radical R&D.

Especially noteworthy, R&D strategies for purposefully creating disruptive technologies are valuable tools to tap two growing mass-markets. The first is the emerging economies with a rapidly growing middle class (Christensen et al., 2004; Brown and Hagel III, 2005). Some multinational companies have already started to establish R&D centers in these high-growth local markets at the "Bottom of Pyramid" (Prahalad, 2004; Immelt, et al., 2009). They would need to achieve both an order-of-magnitude improvement in price-performance and relative affordability which are indeed in line with the objectives of purposeful R&D for creating disruptive technologies. The second is the "Silver hair market" which is fast emerging in both developed and developing countries (Irie et al., 2005). It offers another golden opportunity for companies to conduct purposeful R&D for creating appropriate disruptive technologies to address such high-growth but price-sensitive markets which simultaneously demand adequate performance.

The 4 R&D strategies have been identified based on intensive case studies of well-known applications. Constructive and inspiring as they are, ideally, they are better to be collectively exhaustive. My 4 R&D strategies are proven strategies to develop technology options for potential disruptive innovation based on the cases available. With new disruptive innovations emerging especially in the two new mass-markets outlined above, new strategies may be developed in future research.

Chapter 5

Creation versus Discovery of Entrepreneurial Opportunities: The case of Hard Disk Drive industry

5.1 Introduction

The 4 R&D strategies identified in Chapter 4 can be used to help firms become creators of disruptive innovation. The strategies have been found to be widely applicable in the general electronics industry. Firms can enter an industry by creating a whole product innovation, or a specific design rule, and the literature has shown successful examples of design rules creators such as IBM and Apple that survived very long in the industry (Baldwin & Clark, 2000). However, there are also firms that entered the industry by adapting to design rules designed by others. For example, it was found that more firms entered the broadcasting industry by adapting to design rules (Funk, 2007). So far no research has been conducted to compare creation of versus adaptation to design rules, to answer how the choice of creation versus adaptation is associated with the success of firms. This chapter elaborates the role of adaptation as an alternative to creation, and empirically compares the relative contribution of creation of versus adaptation to design rules to entrepreneurial firms' success.

Creation and adaptation to design rules are concepts in the modular design literature. In this stream of literature, all products can be represented as multiple levels of subsystems that are organized in a hierarchical fashion (Simon, 1962, 1996;

Tushman & Murmann, 1998) where design rules define how these sub-systems or independent modules interact (Baldwin & Clark, 2000). Systemic innovations often lead to new architectures that may define new design rules or even completely new subsystems where these new architectures often lead to the entry of new firms (Langlois & Robertson, 1992; Baldwin & Clark, 2000; Brusoni & Prencipe, 2001; Langlois, 2003; Chesbrough, 2003; Jacobides, 2005). Entrepreneurial firms can either create or adapt to design rules when entering the industry or making new products.

Analogous to creation of versus adaptation to design rules in modular design literature, there are also comparative theories in entrepreneurship literature to describe entrepreneurial actions. Scholars typically differentiate between two types of entrepreneurial action. Shane's (2003) "individual-opportunity nexus" approach argues that entrepreneurial opportunities are created by exogenous shocks to the industry or market and entrepreneurs play a passive and reactive role to discover and adapt to them (Shane, 2003). Venkataraman's (2003) creation theory of entrepreneurship argues that entrepreneurial opportunities are created endogenously by the actions of individuals exploring ways to produce new products and services. Others (Baker & Nelson, 2005; Gartner, 1985) have extended the creation theory of entrepreneurship by describing the process that entrepreneurs use to proactively create a new venture. Alvarez & Barney (2006) conceptually contrast these two theories by articulating their fundamental assumptions and predictive values in creating new products, services and ventures.

By analogy, a link has been established between the modular design literature and the entrepreneurial literature. For each change of design rules, if new firms entered the industry during certain change in design rules, this change can be considered as one providing an entrepreneurial opportunity. Cases in which firms created new design rules are classified under the creation of an entrepreneurial opportunity. Cases in which firms adapted to design rules are classified as the discovery of an entrepreneurial opportunity.

Therefore, apart from an empirical study to compare creation versus adaptation to design rules, this chapter (the 3rd essay) is also an empirical study to contrast the success of de-novo startup firms that created versus those that discovered entrepreneurial opportunities. The research setting is the hard disk drive (HDD) industry between 1978 and 1999. The context of the HDD industry and the study period were selected for 3 reasons. First, there were a number of systemic innovations that required a change in the design rules during this period. These changes of design rules brought forward plenty of entrepreneurial opportunities. For example, 8 inch, 5.25 inch, 3.9 inch, 3.5 inch, 2.5 inch, 1.8 inch and 1 inch disk drives were developed during this time period and each of them required new architectures and design rules. Second, a larger number of firms entered the industry during these two decades than other periods[30]. Third, there is a large amount of data available in industrial reports and I have obtained access to these reports.

Based on an analysis of the industry between 1978 and 1999, 21 changes of design rules were identified. For each de-novo startup firm, their actions of creating or adapting to new design rules (i.e. creation or discovery of entrepreneurial

[30] Before the two decades, i.e. from 1950s to 1970s, HDD industry was almost dominated by several large incumbent firms and IBM was the pioneer and the largest leading player. Not many startup firms

opportunities) can be traced. Combined with data on their survival years (i.e. success of startup firms), two questions can be answered: first, whether creation contributes to the success of startup firms; second, whether discovery contributes to the success of startup firms; third, which is more important or contribute more to firm success.

5.2 Theoretical background

Shane (2003) proposed the "individual-opportunity nexus" approach or what some call the "Discovery Theory of Entrepreneurship." This theory argues that entrepreneurs play a passive role in the creation of entrepreneurial opportunities. Opportunities are created by exogenous shocks to the market and not by entrepreneurs themselves. Entrepreneurs only become active when they begin to exploit an opportunity by bringing "agency to opportunity" (Shane, 2003). Furthermore, opportunities in the Discovery theory are assumed to exist independently of whether or not the entrepreneurs are seeking to exploit them. In this sense, opportunities in Discovery theory are like lost luggage at a train station that is waiting to be claimed. The entrepreneur's task is to become aware that this luggage exists and then claim it (Alvarez & Barney, 2006). Since opportunities are created by exogenous shocks, in principle, everyone can try to exploit them if they are sufficiently skilled. When such a large number of people can potentially exploit an opportunity, it would be difficult for anyone to generate surplus profits (Barney, 1986; Schumpeter, 1939).

An alternative to Discovery Theory is the "Creation Theory." Rather than being passive with respect to the creation of new opportunities, Creation Theory argues that

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were able to enter. After 2000, industry consolidation reshaped the competitive landscape and only several large incumbents are still alive today.

an entrepreneur's actions are the essential source of these opportunities. As opposed to waiting for exogenous shocks to create opportunities before they act, entrepreneurs proactively create the opportunities (Bhide, 1999). Creation Theory suggests that entrepreneurship is not about "climbing mountains" of opportunities, but rather, about "building mountains" of opportunities that are recognized, only after they have been exploited (Alvarez & Barney, 2006).

There are several challenges to creating entrepreneurial opportunities. Market feedback from efforts to create an opportunity may be difficult to understand, may be misleading and can even give individuals incorrect clues as to the direction in which entrepreneurs should further proceed (Alvarez & Barney, 2006; Choi, 1993). The creation process is also path dependent in that small differences in initial decisions can lead to large differences among entrepreneurs over time (Arthur, 1989). Very few firms could successfully manage the creation process.

Existing literature mainly focuses on discovery of entrepreneurial opportunities, and there are very few discussions on comparison between the two alternatives. Alvarez and Barney started to conceptually compare creation versus discovery but there is no paper on whether creation or discovery theory is more valuable or contribute more to startup firms' success. My study is devoted to empirically compare discovery versus creation and the research question is: Which contributes more to success of de-novo startup firms, creation of entrepreneurial opportunities or discovery of entrepreneurial opportunities?

I can empirically examine the contributions of creation versus discovery of entrepreneurial opportunities to success by drawing from the literature on modular design. Beginning with Nobel Prize Winner Herb Simon's research, many scholars have noted the hierarchical nature of systems. Simon and other scholars have noted that all products, including basic materials such as glass and chemicals can be represented as multiple levels of subsystems that are organized in a hierarchical fashion (Simon, 1962, 1996; Tushman & Murmann, 1998). A parallel hierarchy of firms can also be defined where the differences between the hierarchies of subsystems and firms will depend on the degree of vertical integration in firms (Tushman & Murmann, 1998; Christensen & Rosenbloom, 1995).

Two key concepts for analyzing vertical disintegration are modular design (Ulrich, 1995; Sanchez & Mahoney 1996; Brusoni & Prencipe, 2001; Christensen *et al*, 2002) and design rules (Baldwin & Clark, 2000; Langlois, 2003). Modular designs are those in which the interfaces that determine how the functional components or "modules" in a product, process, or organization design will interact are specified to enable the substitution of component variations within the design (Sanchez & Mahoney 1996). "Design rules" constrain the ways interfaces can be specified between different modules within a product or stages in a value chain (Jacobides, 2005) to ensure compatibility between them (Baldwin & Clark, 2000; Langlois, 2003). The greater the extent to which design rules are open, the greater the extent to which new startups may emerge to provide modules and thus to occupy new positions in vertically disintegrated layers of the industry (Langlois & Robertson, 1992; Baldwin & Clark, 2000; Christensen et al, 2002; Langlois, 2003).

For example, a transistor radio, as a system, is composed of subsystems such as a printed circuit board, capacitor, loudspeaker, transformer, and batteries. Looking at these modules in more detail, batteries are composed of a top cap, heat sealed case, several voltaic cells, and other modules. The size of the battery is one example of a design rule in that it determines how batteries are plugged into transistor radios. The existence of standard sized batteries such as Double A and Triple A batteries reflects the emergence of these design rules.

Another example is personal computers. A PC system consists of subsystems such as a central processing unit, random access memory, read-only memory, disk drives, operating system, and other peripherals. Various design rules define how these different sub-systems interact. Looking at the personal computer in more detail, a disk drive also consists of various subsystems in which design rules define how these subsystems interact; and this is the focus of my research.

The literature on modular design differentiates between firms that create the design rules and those that adapt to them. A company can compete as an architect, creating design rules, for a product made up of modules. Or it can compete as a designer of modules that conform to the architecture, interfaces, and test protocols of others (Baldwin & Clark, 1997). Creating the design rules enables firms to control the architecture and thus the direction and pace of innovation. Research has found that such firms are able to make above-average profits (Baldwin and Clark, 2001). On the other hand adapting to design rules is much easier and can be done much faster than creating the design rules (Baldwin & Clark, 1997).

For example, IBM defines and controls the design rules for the personal computer. Nintendo defines the subsystems in a typical video game console as well as the design rules among these subsystems. Apple created the design rules that define how the i-Pod, i-Tunes, and other sub-systems in the system interact. On the other hand, it can be said that other firms have *discovered* these design rules and subsequently provided sub-assemblies, parts, and software that conform to these design rules.

New design rules are needed when there is a change in architecture, or sometimes called a technological discontinuity (Tushman & Anderson, 1986; Anderson & Tushman, 1990), changes in architecture require new design rules (Langlois & Robertson, 1992; Baldwin & Clark, 2000; Brusoni & Prencipe, 2001; Langlois, 2003; Chesbrough, 2003; Jacobides, 2005). Both the new architecture and the new design rules provide entry opportunities for de-novo startups. Interestingly, few papers in the entrepreneurial literature have analyzed how these new architectures and new design rules for them provide opportunities for de-novo startups. An exception is Funk's paper on vertical disintegration and entrepreneurship in the broadcasting industry, which demonstrated that new architecture and new design rules indeed provided entry opportunities for de-novo firms. For those de-novo startup firms, they entered industry either by discovering or creating new design rules. It was also found mostly firms entered by discovering those architecture and design rules (Funk, 2007).

Analogous to Alvarez & Barney's work, entrepreneurial firms can either create or discover design rules. Opportunities that emerge from firms creating new design rules are regarded as a "creation of an entrepreneurial opportunity." Opportunities that emerge from firms adapting to design rules are regarded as a "discovery of an entrepreneurial opportunity." Especially noteworthy, I do not assume technological innovation equals to changes of design rules, or they both equal to entrepreneurial opportunities. Firstly, although most of technological innovations lead to changes of design rules, but some technological innovations inside subsystems may not lead to changes of design rules between this subsystem and other subsystems. Secondly, although changes of design rules reduce entry barriers and bring forward entrepreneurial opportunities for de-novo startup firms, if no startup firms successfully enter the industry during a change of very complex design rule that initiated by incumbent firms, the design rule change exists but entrepreneurial opportunity does not since no startup firms entered.

5.3 Research Design

There are 5 steps to analyze de-novo startups' creation and discovery of entrepreneurial opportunities. I use disk/trend, some classic books in HDD industry as major sources of data and data triangulation is performed by interviewing industrial professionals to achieve results of each step (Table 5.1).

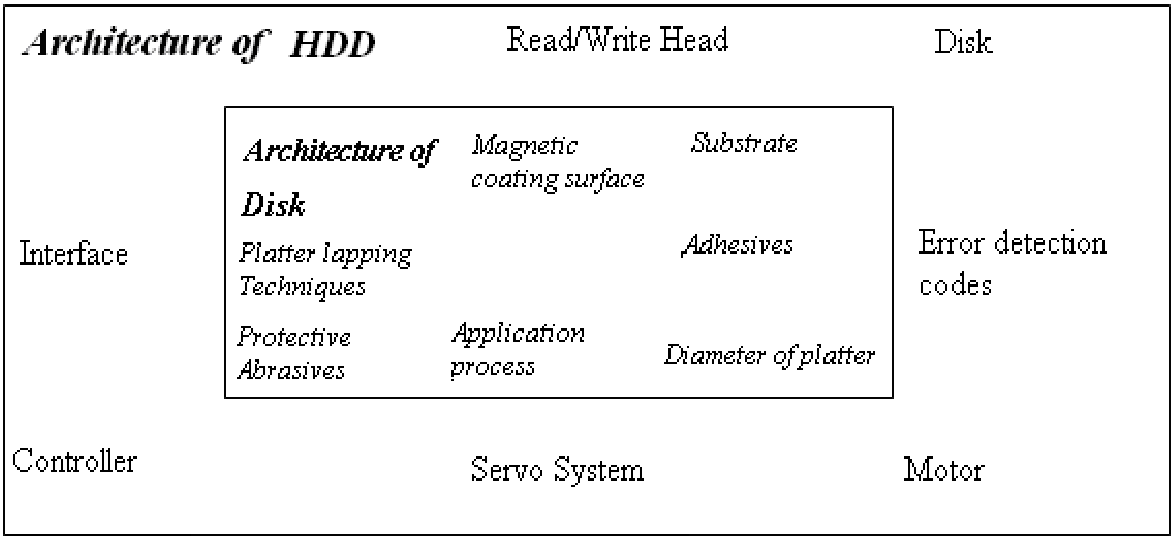
TABLE 5. 1 Research procedures, data sources and results

	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6
Key concepts for study	Hierarchal system of HDD	Technological innovations from 1978 to 1999	Changes of design rules	De-novo startup firms as creators or adaptors for each change of design rules	Profiles of all de-novo startups, including establishing year, creation and adaptation of design rules and longevity	Statistical analysis on data
Data sources (Archival data)	(1)Book: "Magnetic recording -The First 100 years"; (2)PhD thesis of Clay Christensen; (3) Book: "From Silicon Valley to Singapore"	Disk/Trend-"Technical review" chapter	Disk/Trend-"Technical review" chapter	Disk/ trend-"manufacturer profiles"; Disk/ trend -"product models released during the year"	Integration of previous steps	Table 5.6-5.9
Data sources (Interviews)	(1) Dr. Edward Grochowski, Computer Storage consultant,AOL; (2) Dr. Shigeo Nakamura, Senior researcher, Hitachi	(1) Prof. Bhatia Singh, ECE, NUS (worked in HDD industry over 30 years); (2) Lim Pun Seong, Executive Director, IDEMA[31] Singapore	(1) Prof. Bhatia Singh, ECE, NUS (2) Lim Pun Seong, Executive Director, IDEMA Singapore	Prof. Bhatia Singh, ECE, NUS (worked in HDD industry over 30 years)	No	Mr. C.S. Chang, Director of test center, Qualcomm (worked in Seagate for many years)
Results	Fig. 5.1	Fig. 5.4; Table 5.2	Fig. 5.4; Table 5.2; Table 5.4	Table 5.5	Table 5.6-5.9	Table 5.10; Fig.5.5-5.8

5.3.1 Hierarchal system of hard disk drive

I started with the hierarchical system of HDDs. As shown in Figure 5.1, a hard disk drive consists of several major subsystems such as read-write head, disk, motor, servo system, interface, controller, and error detection codes in the first layer. Each of these subsystems can be further broken down into sub-subsystems. For example, as shown in Figure 5.1, the disk[32] consists of substrate, magnetic coating, adhesive, and other sub-subsystems.

FIGURE 5. 1 Hard disk drive as a nested hierarchy of sub-systems



Source: Adapted from (Christensen, 1997, Figure 2.1)

I examine changes of design rules in the subsystems where the subsystems have been independently provided by HDD firms; thus each change of design rules has provided entry opportunities for de-novo startups. It is found that every subsystem in the first layer and 3 subsystems in the second layer of disk namely magnetic coating surface, substrate and form factor (Diameter of platter) have been independently produced by HDD firms.

5.3.2 Technological innovations from 1978 to 1999

[31] IDEMA stands for "The International Disk Drive Equipment and Materials Association"
[32] The recording disk normally has several platters. For each platter, the outside layer is magnetic coating surface and the inside layer is substrate.

For each subsystem in the first layer and 3 subsystems of disk in the second layer, the second step is to investigate the significant technological innovations for that subsystem from 1978 to 1999 mainly by the Disk/Trend Report, which is considered very reliable in the industry. In particular, a special chapter called "Technology review" covered the major innovations in the industry each year. These chapters summarized the historical evolution, state of the art, and the prediction of future development for most of the key subsystems in a hard disk drive, such as Read/Write heads, recording disk including form factor (the size of platters), substrate (the inside layer of a platter) and magnetic coating surface (the outside layer of a platter), interface and controller, servo system, encoding and error correction codes and so on. To avoid missing any significant technological innovation, I also discussed my findings with two very experienced industrial professionals.

5.3.3 Changes of design rules

In the third step, I studied the Disk/trend reports again and discussed with these two experts to identify the specific changes in design rules that derived from these technological innovations. After extensive consultation with the industrial professionals, it was found that only 21 of the 24 technological innovations led to changes of design rules. Among these 21, I was not able to obtain sufficient data on two of them (Digital Servo System and Embedded Controller). Therefore, 19 innovations were studied. These 19 innovations led to 19 changes in design rules. I looked at whether the de-novo startups created or adapted to these 19 design rules.

5.3.4 Definition and measurement

De-novo startups were identified using the *Disk/Trend* reports. De-novo firms are defined as those firms that were newly established with the purpose to enter the hard disk industry as opposed to de-alio firms, which are established firms that enter from another industry. If a de-novo startup merged with another de-novo startup, it continued to be defined as a de-novo startup. Firms that were spun off from incumbents or that were the result of a merger between multiple de-alio firms are not considered de-novo startups. For example, the joint venture between Hitachi and Fujitsu, which is called Nippon Peripherals, is not considered a de-novo startup. Similarly, Lexicon, a spinoff from Olivetti, is also not considered a de novo startup.

I considered the entry actions of de novo startups with respect to design rules only during their early years of existence when they were truly startups instead of incumbents. I considered their actions until they were five years old. Both conditions had to be met before it was considered to create or adapt to design rules. As shown in Figure 5.2, firms in the left-upper quadrant were the firms in my research scope.

FIGURE 5. 2 Research scope of de-novo startup firms

	Less than 5 years	More than 5 years
De-novo (initially enter HDD industry)	De-novo start-up firms	
De-alio (enter HDD industry from other industries)		

Defined in this way, factors such as organizational size, age, startup firm's resources are controlled as the de-novo startup firms studied are under similar conditions for these variables.

Finally, I used longevity to measure success of de-novo startup firms because the popular measurements of firm success such as financial incomes and market shares would be more appropriate to evaluate incumbent performances. Alternatively, the success of de novo startups should be measured by their survival years (Khessina & Carroll, 2008; Ganco & Agarwal, 2009).

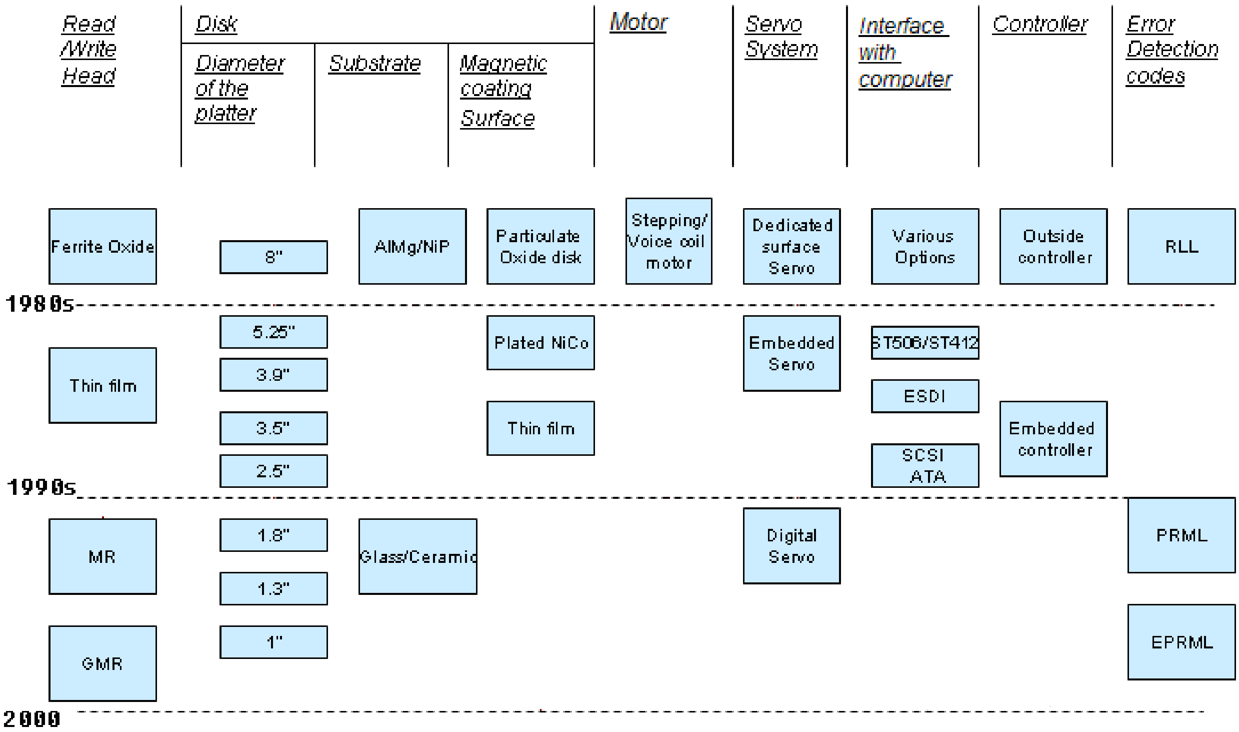
Step 1 to step 3 focus on methodology, such as design of research context and definitions of key concepts, whereas step 4 to step 6 focus on findings that will be discussed in the next section.

5.4 Findings

Figure 5.3 and Table 5.2 (Column 1) summarize the technological innovations in the HDD industry that are covered in the "Technology review" chapter of Disk/Trend report. These technological innovations are organized by subsystems (Table 5.2, Column 2). As shown in Table 5.2, there are a total of 24 technological innovations that had a significant impact on hard disk drives. For example, there were 3 significant technological innovations in one subsystem called read/write head from 1978 to 1999, namely the first change from ferrite oxide head to thin film head in 1979, the second change from thin film head to magneto-resistive head in 1991 and the third change from magneto-resistive head to giant magneto-resistive head in 1998.

Another set of examples is technological innovations in form factor (i.e., change in disk diameter). The disk form factor changed 7 times from 8 inch in the late 1970s to 5.25 inch in 1981, 3.9 inch in 1982, 3.5 inch in 1983, 2.5 inch in 1988, 1.8 inch in 1991, 1.3 inch in 1992, and 1 inch in 1999. The abbreviations of all technical terms are summarized in Table 5.3.

FIGURE 5. 3 24 Technological innovations in hard disk drives from 1978 to 1999



Source: Disk/Trend, chapters of "Technology review", from 1979 to 1999;
Notes: The recording disk normally has several platters. For each platter, the outside layer is magnetic coating surface and the inside layer is substrate.

TABLE 5. 2 Summary of technological innovations and their modules

Technological innovation	Disruptive innovation	Subsystem	Changes of design rules	Data availability	Introduction year
Thin Film Head	No	Read/Write Head	Yes	Yes	1979
Magneto-Resistive Head	No		Yes	Yes	1991
Giant Magneto-Resistive Head	No		Yes	Yes	1998
5.25 inch Form Factor	Yes	Disk, the Diameter of the platter	Yes	Yes	1981
3.5 inch Form Factor	Yes		Yes	Yes	1983
1. 8 inch Form Factor	Yes		Yes	Yes	1991
2.5 inch Form Factor	Yes		Yes	Yes	1988
3.9 inch Form Factor	Yes		Yes	Yes	1982
1.3 inch Form Factor	Yes		Yes	Yes	1992
1 inch Form Factor	Yes		Yes	Yes	1999
Glass or Ceramic substrate	No	Disk, substrate	No	Not applicable	1989
Plated NiCo coating	No	Magnetic coating surface	No	Not applicable	1981
Thin Film coating	No		No	Not applicable	1983
Embedded Servo System	No	Servo System	Yes	Yes	1970s
Digital Servo System	No		Yes	No	1990
ST506 Interface	No	Interface with computer	Yes	Yes	1980
ST412 Interface	No		Yes	Yes	1985
Enhanced Small Disk Interface	No		Yes	Yes	1983
Small Computer System Interface	No		Yes	Yes	1986
Parallel AT Attachment Interface	No		Yes	Yes	1986
Embedded Controller	No	Controller	Yes	No	1988
Run Length Limited Error Detection Codes	No	Error Detection Codes	Yes	Yes	1979
Partial Response Maximum Likelihood Detection Codes	No		Yes	Yes	1990
Extended Partial Response Maximum Likelihood Detection Codes	No		Yes	Yes	1997

Source: Calculation based on raw data from Trend/Disk reports from 1979 to 1999. Whether technological innovations changed the design rules are documented based on interviews.

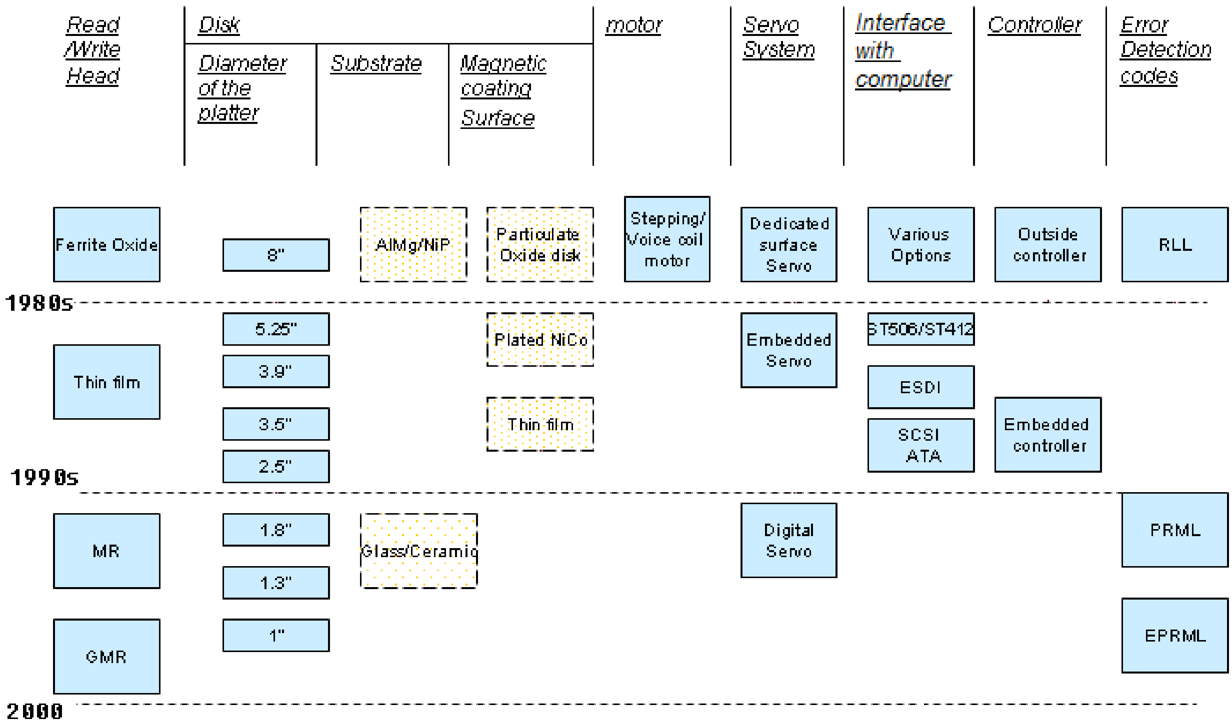
TABLE 5. 3 Definitions of acronyms

Abbreviation	Full Name	Module	Notes
"	5.25" means 5.25 inch	Form Factor	
EIDE	Enhanced IDE(Integrated Drive Electronics)	Interface with computer	
EPRML	Extended Probable Response Maximum Likelihood	Error detection codes	
ESDI	Enhanced Small Disk Interface	Interface with computer	
ESS	Embedded Servo System	Servo System	
FOH	Ferrite Oxide Head	Read/Write Head	
GMRH	Giant Magneto Resistive Head	Read/Write Head	
HDD	Hard Disk Drive		
IDE/ATA/PATA	Integrated Drive Electronics/AT attachment/Parallel ATA	Interface with computer	IDE, ATA, or PATA refer to the same interface
MRH	Magneto Resistive Head	Read/Write Head	
PC/AT	Personal Computer / Advanced Technology	Interface with computer	IBM 2 generation PC
PMRH	Perpendicular Magnetic Recording Head	Read/Write Head	
PRML	Probable Response Maximum Likelihood	Error detection codes	
RLL	Run Length Limited	Error detection codes	
SAS	Serial Attached SCSI (Small Associates System Interface)	Interface with computer	
SASI	Shugart Associates System Interface	Interface with computer	
SATA	Serial Advanced Technology Attachment	Interface with computer	
SCSI	Small Computer System Interface	Interface with computer	
ST506		Interface with computer	The interface of Seagate's first 5.25 inch hard disk drive
TFH	Thin Film Head	Read/Write Head	

Most of these technological innovations led to changes in design rules while a few did not. One example of design rule change is the change of Read/write heads from Thin Film Head (TFH) to Magneto Resistive Head (MRH) because they not only restructured the head internally; they also changed the interaction between the recording heads and the magnetic coating surface of disk (the outside layer of platter). This is because MRH allows the use of weaker written signals and thus enables the bits to be spaced closer together on the disk without interfering with each other. In addition, it also reduces floating heights of heads over the disk. On the other hand, an example of technological innovation with no change of design rules is the change in substrate since they did not impact on the interaction between the recording head and the media. Based on the interviews, it was found that 21 of the 24 technological innovations led to changes in design rules. Three technological innovations that involved the changes in disk substrate material did not lead to changes in the design rules. These are highlighted in Figure 5.4 with dotted lines. They were the change from AlMg/NiP to Glass/Ceramic, the change in magnetic coating from Particulate Oxide to Plated NiCo, and the change from plated NiCo to thin film.

Table 5.4 lists the 21 technological innovations (Table 5.4, Column 1) that led to changes in the design rules, the adjacent modules that being impacted (Table 5.4, Column 3) and how these technological innovations changed the design rules (Table 5.4, Column 4).

FIGURE 5. 4 21 Technological innovations that changed the design rules



Dotted lines designate the technological innovations that did not lead to changes of design rules.
Source: Disk/Trend, chapters of "Technology Review", from 1979 to 1999

TABLE 5. 4 Technological innovations that changed the design rules

Technological innovation	**Subsystem A that have new innovation**	**Subsystem B that affected by innovation of A**	**Examples of how design rules were changed between subsystem A and subsystem B**
Thin Film Head	Read/Write Head	Disk	1. Improve the way digital bits are stored on disk; 2. Reduce flying height from head to disk; 3. Reduce numbers of heads and platters
Magneto-Resistive Head			
Giant Magneto-Resistive Head			
Run Length Limited Error Detection Codes	Error detection codes	Interface and disk	1.Different interfaces match different error detection codes; 2.Improve data storage and linear bit density on recording disk
Partial Response Maximum Likelihood Detection Codes			
Extended Partial Response Maximum Likelihood Detection Codes			
5.25 inch Form Factor	Diameter of the platter, form factor	motor, head and disk	1.Reduce the distance and time that head motors move heads in order to perform random seek; 2. Increase numbers of platters and heads to maintain capacity
3.5 inch Form Factor			
1. 8 inch Form Factor			
2.5 inch Form Factor			
3.9 inch Form Factor			
1.3 inch Form Factor			
1 inch Form Factor			
Embedded Servo System	Servo system	Disk and motor	1. Change from traditional status that one platter surface contains nothing but servo information and the others nothing but data to new status that data and servo information together on each platter
Digital Servo System			1.Add quartz crystal controlled microprocessor 2.Connect and control motors with significant higher frequencies
Embedded Controller	Controller	Interface	1.Stimulate the improvement in advanced interfaces
ST506 Interface	Interface with computer	Controller and Error detection codes	1.Advanced interfaces moved controller from outside to inside; 2.Different interfaces matched different Error detection codes
ST412 Interface			
Enhanced Small Disk Interface			
Small Computer System Interface			
Parallel AT Attachment Interface			

For each change in the design rule, I looked at whether the de-novo startups created or adapted to the design rule. For example, Table 5.5 shows the number of firms that created the design rules and the number that adapted to (i.e., discovered) new design rules for the technological innovation called 5.25 inch disk drives. Compared with the previous generation of 8 inch disk drives, the new 5.25 inch drives were much smaller with lighter weight, lower power consumption and lower unit cost. The smaller form factor changed the design rules in hard disk drives in 3 ways. First, the smaller form factor (the size of the platter) works with higher-speed spindles and other high-performance hardware to enhance rigidity. Second, the smaller size reduces the distance that the head actuator must move the heads side-to-side to perform random seeks. Third, 5.25 inch drives use more platters and read/write heads to compensate for the capacity.

As shown in Table 5.5, Disk drives with a 5.25 inch form factor were first released in 1981 by Seagate. Seagate pioneered new applications for their products by reconfiguring conventional Winchester technology into a package size that can compete with 5.25” floppy disk. The timing for the introduction of a 5.25” was perfect, catching the wave of desktop computers. Seagate enabled this application by trial and errors, selling drives to whoever would buy them (Christensen, 1997). There were also the other 4 de-novo start-up firms established by industrial veterans to create 5.25 inch and design rules in 1980, such as Irwin International Industries, MiniScribe, Rotating Memory Systems, and Rodime. They released their own 5.25 inch models in 1981. On the other hand, 2 firms, namely Shugart Associates and Tandon, quickly realized the potential of 5.25 inch format originated by Seagate

Technology, and supplied evaluation units of their own and shipped them by end of 1981. Therefore, I recorded 5 creators and 2 adaptors in 1981 in the first row of Table 5. Rather than completely adapting to the new design rules created by Seagate and other firms in 1981, Applied Information memories, Maxtor and Microscience International released their 5.25 inch drives with several innovative design features intended to improve reliability in 1983. They were recorded as creators in 1983. There were no creators from then on, and all de novo small startup firms that adapted to the 5.25 inch and its design rules are documented as adaptors. By 1984, 56% of all firms in the hard disk drive industry have released 5.25 inch disk drives, which imply 5.25 inch Form Factor was not a new change thus was not an entrepreneurial opportunity any more. Hence, I looked at whether the de-novo startups created or adapted to the design rule until 1984.

TABLE 5. 5 Creators and adaptors of design rules for 5.25 inch form factor between 1981 and 1984

Year	Number of de-novo startups that "adapted to 5.25 inch design	Names of Adaptors	Number of de-novo startups that created 5.25 inch design	Names of Creators
1981	2	Shugart Associates, Tandon	5	Irwin International Industries, Seagate, MiniScribe, Rotating Memory Systems, Rodime
1982	3	Atasi, Evotek, Priam,		
1983	4	Athenaeum Technology, Cogito, Tulin, Vertex	3	Applied Information Memories, Maxtor, Microscience International
1984	2	Advanced storage technology, Josephine county Technology		

Source: Analysis based on Trend Focus and Disk/Trend reports

For the 19 changes of design rules, tables are designed similarly to Table 5.5 in order to trace the number and profiles of de novo firms that created or adapted to (i.e., discovered) each new design rule. Collectively, 47 de-novo small startups entered the industry between 1978 and 1999, and they are summarized in Tables 5.6 to Table 5.9 according to establishment date. Columns 3-6 summarizes the module or subsystem that the firm produced and whether the firm created or established the design rule. Column 7 lists the number of years of survival for each firm. For example, consider the first de-novo start-up Dastek, which was established in 1978 (Table 5.6). It created a new generation of disk head—thin film heads and the design rules that defined the interaction between disk heads and adjacent modules such as disks and actuators. Therefore, I list "TFH Dastek created 1 new design rule" upon entry and in fact it only created 1 design rule in its 4 years survival period, and it did not adapt to any emerging design rule created by others. It was forced to close down after 4 years due to patent litigation by IBM.

TABLE 5. 6
De-novo startups that were established between 1978 to 1981

Establish Year	Firm name	Design Rules Created		Design Rules adapted to		Years of Survival
		Module	No.	Module	No.	
1978	Dastek	TFH	1			4
1979	Priam			5.25(1982)	1	11
1980	Tandon	5.25	1	ST506	1	8
1981	Atasi	5.25	1	ST506	1	3
1981	Evotek			5.25	1	2
1981	Irwin International Industries	5.25	1	Embedded servo	1	2
1981	Miniscribe	5.25	1	ST506	1	9
1981	Rodime	5.25; 3.5(1983)*	2			10
1981	Rotating Memory Systems	5.25	1			1
1981	Seagate	5.25; ST506; ST412 (1985)	3	TFH	1	28+**
1981	Amcodyne			RLL; Embedded servo	2	4

Source: Data analysis based on Disk/Trend reports from 1979 to 1981 and other information from websites

Notes: 3.5(1983)* means Rodime created new design rules for 3.5 inch hard disk drives in 1983, 2 year after entry when Rodime was still a small de-novo startup firm. Otherwise, default means the year of entry.

27+** indicates Seagate is the only de-novo firm that still survives today with over 27 years history.

TABLE 5. 7
De-novo startups that were established between 1982 to 1984

Establish Year	Firm name	Design Rules Created		Design Rules adapted to		Years of Survival
		Module	No.	Module	No.	
1982	Applied Peripheral systems			TFH;RLL	2	3
1982	Ibis			TFH(1986)	1	8
1982	Syquest Technology	3.9	1	Embedded servo	1	16
1982	Applied Information memories	5.25	1			3
1982	Athenaeum Technology			5.25	1	2
1982	Cogito	5.25	1			6
1982	DMA systems			5.25; Embedded servo	2	3
1982	Maxtor	5.25; ESDI	2	TFH(1986)	1	25
1982	Microscience International	5.25	1	5.25; Embedded servo	2	10
1982	Vertex Peripherals			5.25	1	3
1982	Microcomputer Memories	3.5	1			5
1983	Tulin			5.25; Embedded servo	2	4
1983	Lapine Technology			3.5	1	4
1984	Advanced Storage Technology			TFH; 5.25; RLL(1985)	3	1
1984	Josephine county Technology			5.25	1	4

Source: Data analysis based on Disk/Trend reports from 1982 to 1984

TABLE 5. 8
De-novo startups that were established between 1985 to 1989

Establish Year	Firm name	Design Rules Created		Design Rules adapted to		Years of Survival
		Module	No.	Module	No.	
1985	Peripheral Technology			ST412; Embedded servo;3.5; RLL(1986)	4	2
1985	Plus Development			3.5;RLL	2	6
1986	Brand Technologies			RLL; 3.5(1988)	2	6
1986	PrairieTek	2.5	1	Embedded servo; RLL	2	5
1986	Conner Peripherals			Embedded servo; RLL;3.5; TFH(1989)	4	10
1987	Cardiff Peripherals			TFH; RLL	2	4
1987	Comport			3.5; RLL	2	3
1987	Kalok			3.5; Embedded servo(1992)	2	7
1987	Data Tech Memories			Embedded servo; RLL;3.5; TFH(1989)	4	1
1988	Areal Technology			3.5;TFH; Embedded servo; 2.5(1988)	4	7
1988	Magtron			Embedded Servo(1991); TFH	2	4

Source: Data analysis based on Disk/Trend reports from 1985 to 1989

TABLE 5. 9
De-novo startups that were established between 1990 to 1996

Establish Year	Firm name	Design Rules Created		Design Rules adapted to		Years of Survival
		Module	No.	Module	No.	
1990	ORCA Technology			TFH	1	2
1991	ECOL.2			TFH; Embedded servo	2	1
1991	Integral peripherals	1.8	1	TFH; Embedded servo; PRML(1994)	3	7
1991	Calluna Technology			TFH; 1.8; Embedded servo	3	10
1992	Minister Peripherals			TFH;1.8; 2.5(1994)	3	6
1992	NOMA I			MRH; PRML	2	6
1996	JT Storage			MRH; PRML(1997)	3	3
1996	Momentum Peripherals			1.8	1	2
1996	Tottori Sanyo			2.5; PRML	2	2
1996	Castlewood Systems			MRH;PRML	2	5

Source: Data analysis based on Disk/Trend reports from 1990 to 1999

The data shown in Tables 5.6-5.9 were used to calculate the number of opportunities that can be defined as discovery versus creation. As stated in “Research Design” section, I use c*reating new design rules* to present c*reating entrepreneurial opportunities*, and a*dapting to emerging design rules* to present d*iscovering entrepreneurial opportunities*. Hence, we can use the data of creation of versus adaptation to design rules to study the relative contribution of creation versus discovery of entrepreneurial opportunities to startup firms’ long-term success.

As shown in Table 5.10 and Figure 5.5, 6 out of the 47 de novo startup firms entered the industry by only creating new components and their related new design rules, for a percentage of 13%. 31 of the 47 firms entered the industry by only adapting to new components and their new design rules, which were created by other firms, for a percentage of 66%. 10 of the 47 firms entered the industry by both creating and adapting to new design rules, for a percentage of 21%. In other words, almost five times as many de-novo startup firms did “only discover” as did “only create.”

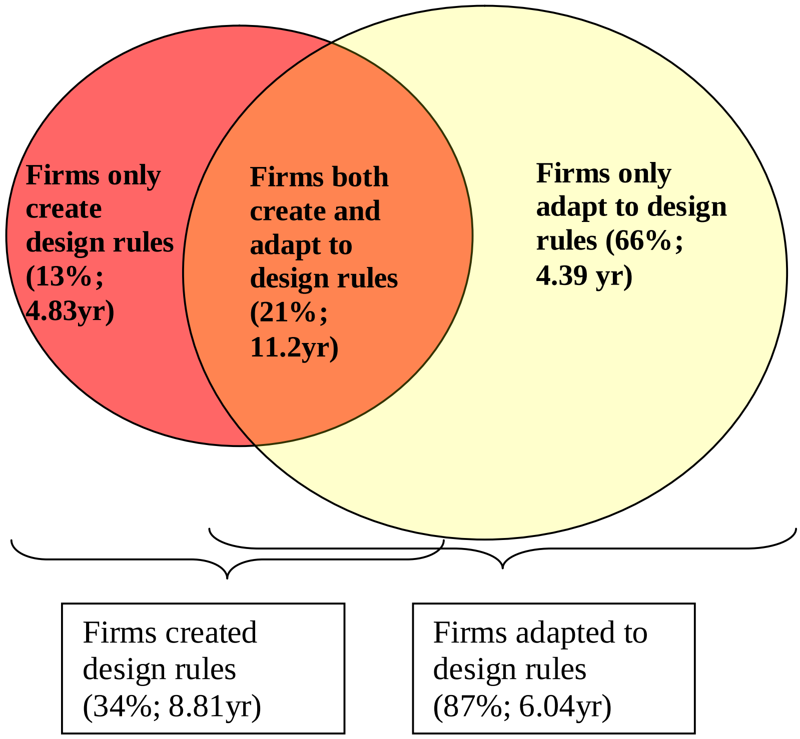
TABLE 5. 10
Comparison between creation and discovery of entrepreneurial opportunities

Importance comparison	**Create entrepreneurial opportunities** **ONLY create new modules and changed the design rules**	**Discover entrepreneurial opportunities** **ONLY adapt to emerging design rules**	**Both create and discover entrepreneurial opportunities** **Create certain design rules and adapt to other design rules**	**All de-novo startup firms**
Number of firms	6	31	10	47
Percentage	13%	66%	21%	100%
Survival years on average	4.83	4.39	11.2	5.89

	Create design rules irrespective of adaptation or not (2nd plus 4th columns above)	**Adapt to design rules irrespective of creation or not(3rd plus 4th columns above)**
Number of firms	16	41
Percentage	34%	87%
Survival years on average	8.81	6.04

Source: The number and percentage of firms and their survival years are calculated based on data shown in Tables 5.6-5.9.
Survival years on average are defined as the sum of the survival years of all firms in a special group, divided by the number of firms in this group.

FIGURE 5. 5
Comparison between creation and discovery of entrepreneurial opportunities

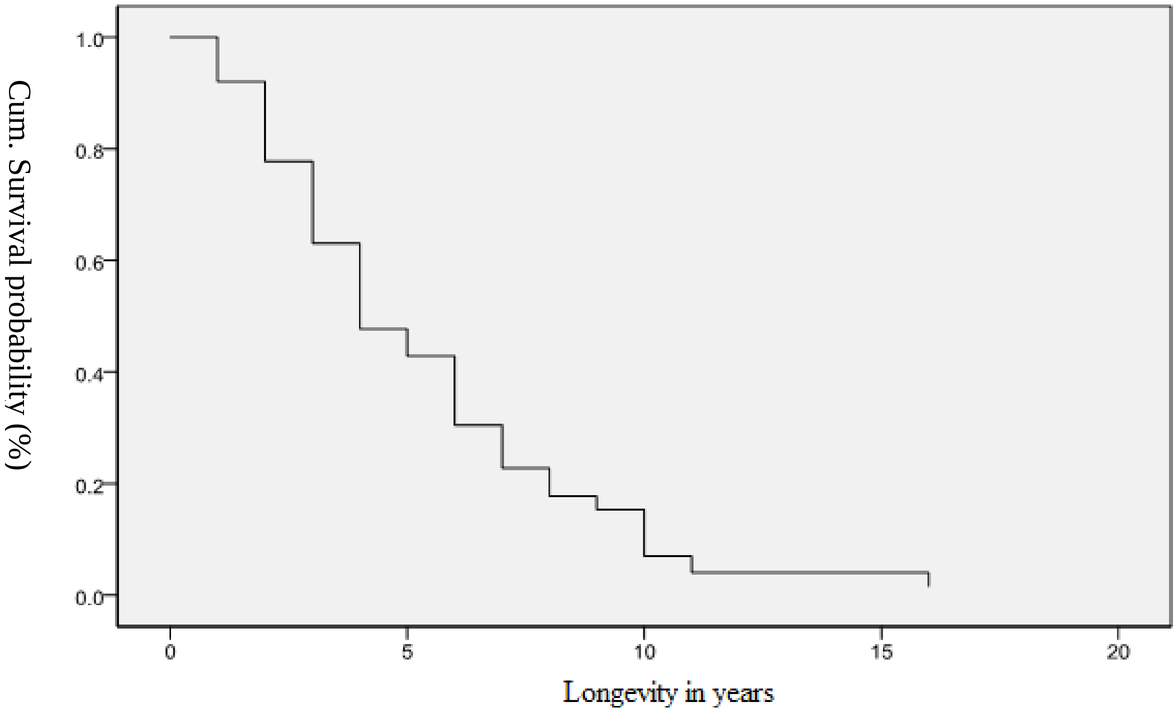


Notes: The left circle represents all of the de-novo small startups that created certain design rules irrespective of whether they only created or also adapted to other design rules. The size of the circle is proportional to the percentage of firms, which means 34% of de-novo startup firms created the design rules, and their survival years is 8.81 on average. The right ball represents all firms that adapted to design rules with a percentage of 87%, and an average survival year 6.04.

Source: The percentage and survival years are calculated based on the data presented in Tables 5.6 to 5.9.

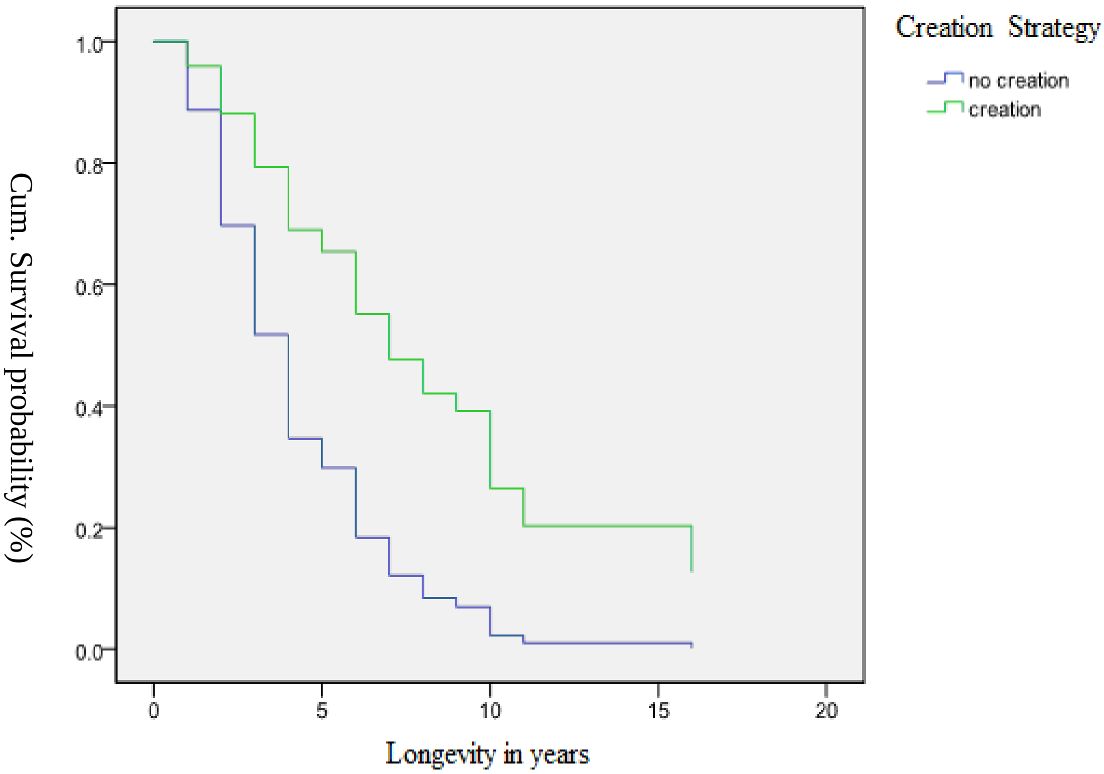
For multivariate survival analysis, Cox proportional hazard regression model should be used to analyze the effect of creation of or adaptation to design rules on firms' survival. Figure 5.6 presents that the number of firms that survive in the overall active firms has decreased along years.

FIGURE 5. 6 Survival probability function on time



Firms that created design rules (irrespective of adaptation or not) had an average survival length at 8.81, while firms that never created design rules had an average survival length at 4.39 (Table 5.10 and Figure 5.5), which implies significant difference. This is demonstrated by Cox regression model in Figure 5.6. At the same longevity in years, survival probability of firms that created design rules is significantly higher than that of firms that never created design rules. Furthermore, the 3 firms that created 2 or more new design rules had an exceptional long presence in the industry. The average survival years are 10 for Rodime (Table 5.6), 25 for Maxtor (Table 5.7), and over 27 for Seagate (Table 5.6), compared to 5.89 for the average of all startups that entered the industry from late 1978 to 1999. Hence, creation of design rules is one significant factor for long-term survival (significant level 0.016). I found similar results with respect to adaptation.

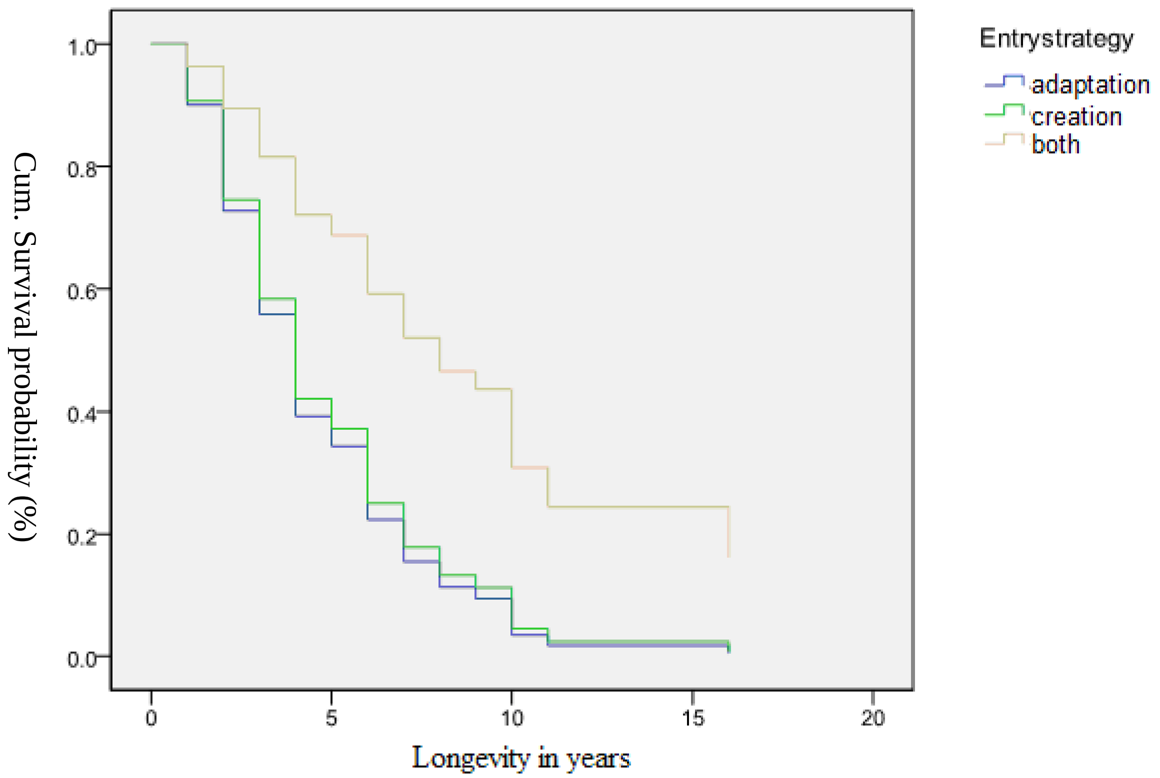
FIGURE 5. 7 Survival probability function for firms that created design rules vs. firms that never created design rules



The average survival length of firms that only created design rules is 4.83 years, while the average survival length of firms that only discovered design rules is 4.39 years. Although there is much more literature supporting discovery than creation process for entrepreneurial firm success, the result did not show significant difference between the survival length of creation vs. discovery of design rules. The result of cox regression model in Figure 5.8 also shows no significant difference between only creation of vs. only adaptation to new design rules.

However, the average survival length of firms that both created and adapted to new design rules is 11.2 years (Table 5.10, Column 4), which is over 2 times larger than the survival years of firms that either only create or only adapt to design rules. The result of Cox regression in Figure 5.8 also shows significant difference between the function curve of "both" vs. only "adaptation" or "creation".

FIGURE 5. 8 Survival probability function for firms that only create/adapt to design rules or both



5.5 Discussion

The purpose of this essay is to empirically examine the relative contribution of creation versus discovery of entrepreneurial opportunities to success of entrepreneurial firms. My first major finding shows five times more firms entered the industry by discovery rather than creation of entrepreneurial opportunities.

It is found that more firms discover than create because it is easier to discover than create. This is consistent with the finding in the broadcasting industry (Funk, 2007). Both entrepreneurship literature and modular design literature lead a solid support to the finding. First, consistent with the entrepreneurship literature, the challenges of creation process such as complexity and ambiguity in market feedback, the path-dependence of creation actions (Arthur, 1989; Choi, 1993) makes creation of entrepreneurial opportunities much harder than discovery. The negative feedback from mainstream customers on the smaller form factors has been extensively discussed in the disruptive innovation theory (Christensen, 1997), which explained the ambiguous and sometimes wrong signals from market could make creation of new design rules much harder. Second, consistent with the modular design literature, adapting to (i.e., discover) design rules is much easier and can be done much faster than creating design rules (Baldwin & Clark, 1997). This is particularly true given the technical complexity of hard disk drives. In many instances, the development of new modules was a “vertically integrated” R&D process, when basic scientific research, engineering, system design, product design all had to come together. The degree of complexity makes more startup firms adapted to rather than created design rules.

However, there is no significant difference in longevity of firms that only did discovery or only did creation. Moreover, firms both create and adapt to design rules survived significantly longer than firms only created or discovered. These firms constitute the most successful group of firms, suggesting firms should pursue both creation and discovery of entrepreneurial opportunities to achieve long survival periods.

On one hand, discovery does not lead to long survival periods because it is easier for firms to discover than create. Just as the ease of discovery enables many more firms to discover than create, it also increases competition among firms and thus reduces their survival period. As explained in Discovery theory of entrepreneurship literature, in a setting where everyone could potentially become aware of and exploit an opportunity, it would be difficult for anyone to generate sufficient profits to continuously produce new product or services (Aldrich & Fiol, 1994; Barney, 1986; Schumpeter, 1939). Only the firms that can differentiate themselves by creating new opportunities could survive and grow in the long run. Modular design literature also emphasizes creation for long survival because creating design rules enables firms to control the architecture and thus the direction and pace of innovation, which further leads to above average profits (Baldwin & Clark, 2001).

On the other hand, systems and environments are too complex for firms to create everything by themselves. They must create some design rules and discover other ones. This is why the firms that only created design rules did not have as long a survival period as those that both create and discover. The result is consistent with Dibiaggio (2007): In Application-Specific Integrated Circuits (ASICs) industry, the design rule adaptors are gaining market shares from the design rule creators and do not hesitate to embark on the design of leading-edge rules, and these firms grew fast and survive longer. Christensen et al. (2004) also pointed out that companies should not employ a one-size-fits-all-forever strategy for capturing value cross the life cycle of technologies after studying three advanced technology industry including the hard disk drive industry. Interestingly in the literature, certain attentions have been paid to creation of entrepreneurial opportunities (Alvarez & Barney, 2005; Gartner, 1985; Venkataraman, 2003), much more research has focused on discovery of entrepreneurial opportunities (Gaglio & Katz, 2001; Kirzner, 1973; Levinthal, 1997; Shane, 2003; Venkatraman, 2003), and the literature so far only use a single-side theory to explain the entrepreneurial action to produce new products and services. However, no single theory can fully explain the entrepreneurial actions in reality. In the hard disk drive industry, some de-novo startup firms both created and discovered entrepreneurial opportunities and they were the most successful firms. For example, Seagate introduced new design rules in 5.25 inch form factor and ST506 interface upon entry, which are less sophisticated and less time-consuming, thus more appropriate for small startup firms. Meanwhile, for complicated R&D on creation of design rules of Read/Write heads and error detection codes, they adapted to design rules mostly developed by incumbents to be faster to market ahead of competitors. Therefore, they both enjoy the benefits of creators and discovers. In addition, *Effectuation theory* (Sarasvathy, 2001) also shows that the entrepreneurial opportunities available to entrepreneurs and their startup firms will shift over time, based on the market and their growing expertise; therefore firms could not survive in the long run if they only create or discovery entrepreneurial opportunities. Hence, Discovery and Creation Theory of entrepreneurship are complementary in nature (Alvarez & Barney, 2006), and they could be combined to explain the entrepreneurial actions.

These results suggest that firms must balance their degree of discovery and creation. While the entrepreneurship literature emphasizes discovery vs. creation, it is really about the degree of discovery versus creation. Since creation and discovery are complementary rather than exclusive with each other, firms must find the equilibrium of the two under different conditions. Systems and environments are so complex that we need better theories of creation versus discovery that discuss how firms choose when and which entrepreneurial opportunity to create and when and which one to adapt to.

Research on exploration versus exploitation supports my proposal on balancing creation and adaptation and may shed light on how to achieve the balance between the two. When the analysis is confined to a single domain, exploitation and exploration are conceptualized as two ends of a common continuum. Logic dictates that punctuated equilibrium should be viewed as the appropriate adaptation mechanism for balancing exploration and exploitation (Gupta, et al., 2006). Similarly, when the analysis focuses only on one type of design rules (e.g. design rules between read/write heads and disks), firms can create one generation and adapt to another generation of design rule changes based on capabilities of firms, applying punctuated equilibrium. When the analysis involves action in multiple domains within a system, exploitation and exploration are conceptualized as orthogonal. Logic dictates that ambidexterity be viewed as the appropriate adaptation mechanism for balancing the two. In the same vein, when viewing hard disk drives as a hierarchical systematic innovation, firms could choose to create some design rules (e.g. design rules between servo systems and disks) and to adapt to other design rules (e.g. design rules between read/write heads and disks) simultaneously, applying ambidexterity.

Furthermore, the findings confirm some arguments on the hard disk drive industry. For example, Christensen (1992: 98-101) has found that established firms tended to be more aggressive and successful in introducing the very complex and risky innovations such as read/write heads and disks than entrants. My finding is consistent, as it shows that if de-novo startup firms created design rules, those design rules are mostly limited to ones caused by relevant innovations in form factors and interfaces.

For another example, I also used Cox proportional hazard regression model to examine whether there is a significant difference of longevity between firms that participated (either create or adapt to) versus firms that never participated in design rules changes led by disruptive innovations. In the hard disk drive industry, the disruptive innovations particularly refer to the form factor changes, or architectural changes (Henderson & Clark, 1990), and the rest are non-disruptive innovations. The result shows significant difference (significant level 0.02) of longevity between the two groups — disruptive vs. non-disruptive innovations and it implies entry firms based on disruptive/architectural innovation tend to perform better than those did not. This finding is consistent with Christensen (1993, 1998) and Henderson and Clark (1990).

Finally, Chesbrough & Kusunoki (2001) have found that the technology development in the industry is marked by shifts between integral and modular stages. The shift in technology stimulated the alignment of organizational strategies between creating an integral system of all design rules and adapting to some design rules not developed in house. The discussion is based on large incumbent firms such as IBM, NEC and Fujitsu. My study is focused on the entrepreneurial firms and they also faced the challenge of balancing creation versus discovery/adaptation, rather than the question of positioning either as a creator or as a discoverer.

5.6 Conclusion

Stimulated by the comparison between creation and adaptation, and leveraging the literature on system innovation, modular design and design rules as the theoretical lens, this chapter is devoted to empirically examine the relative importance of creation versus discovery of entrepreneurial opportunities in the HDD industry. The first contribution is to extend Alvarez & Barney's theoretical differentiation and comparison between "Creation Theory of Entrepreneurship" and "Discovery Theory of Entrepreneurship" into an empirical context. My research shows that many more firms entered the industry by discovering the entrepreneurial opportunities, however, doing both creation and discovery significantly increases survival period. Discovery provides more entry opportunities due to the complexity of systems. But these greater opportunities also intensify competition and reduce survival periods. Therefore, firms must create some of the design rules. Second, my research suggests that the emergence and evolution of modular designs should be part of models that attempt to address how entrepreneurial opportunities appear and disappear. Third, while existing literature explained the entrepreneurial action wholly based on either creation or discovery theory of entrepreneurship, it is really about the degree of discovery and creation. Firms should find the balance of the two under different conditions in various forms such as punctuated equilibrium and ambidexterity.

This study hopes to stimulate more empirical research in other contexts to compare “Creation Theory of Entrepreneurship” and “Discovery Theory of Entrepreneurship” and explain how firms could achieve the balance between creation and discovery.

Chapter 6

Summary of Contributions

6.1 Overall Contribution

The thesis has identified and performed the pioneering work of the research on the technological perspective of disruptive innovation, which complements the literature focus to date on business models and other aspects. Furthermore, it is also one of the initial studies that move from theoretical descriptions to empirical comparison between creation and discovery of entrepreneurial opportunities. The specific contributions of the 3 essays are detailed in the next three sections.

6.2 Contributions of the essay on a reflective review of disruptive innovation literature

The first essay aims to critique and integrate current studies in this domain, and raise questions to initiate future research. The basic definition and potential misinterpretations have been clarified at the beginning. Following the viewpoint that the disruptive innovation theory has predictive value on firm performance, I then summarized and critiqued the research on the front-end challenge of how to enable potential disruptive innovation from internal, external, marketing and technology perspectives. The finding shows that the extant studies turned out to be quite unbalanced in favor of internal and marketing perspectives.

The different perspectives have inspired me to identify 7 key research directions within the disruptive innovation research domain. For example, the literature has shown that keeping the size of business units reasonably small would contribute to the development of disruptive innovation, but this also causes cost increases and difficulties in architectural interdependence. Hence, how to optimize the number and the size of business units in a large organization could be an important topic for future research.

I also briefly discussed potential future research by integrating disruptive innovation with 4 other research domains. To begin with, an implication from the literature of *Open Innovation* may be that disruptive innovations could benefit by collaboration between incumbents and startup firms. Second, the review on marketing perspective has suggested that an orientation toward small but emerging customer segments advances the development of disruptive innovations. The techniques of understanding customer needs such as focus groups may provide potentially effective tools to find emerging markets and understand the latent needs of customers. Third, research questions in technology perspective could be addressed by introducing the literature in technology forecasting. The techniques such as technology roadmapping could be applied to create a potential disruptive technology or find new application for existing technology and product. Fourth, there is another convergence of literature between disruptive innovation and the *Bottom of the Pyramid* (Prahalad, 2004). In fact, the bottom of the pyramid could be an ideal target market for disruptive technologies because nonconsumption is usually abundant at the bottom of the pyramid. Future research could study how to use the disruptive innovation as an approach to tap the business potential of the majority at the bottom.

Finally, besides theoretical contributions, I also made practical contributions in the first essay by outlining a series of potential inhibitors and enablers of disruptive innovation as managerial "take-aways".

6.3 Contributions of the essay on the development of R&D strategies for potential disruptive innovation

The reflective review shows several promising future research directions, and one direction is the creation of technology candidates for potential disruptive innovation, which is the 2nd essay in this thesis.

For a start, it is found that technologies indeed played very important roles in a representative technological disruptive innovation -- transistor radio. The exploratory case study clearly demonstrates the challenging nature of technology in a technological disruptive innovation. The simplicity and user-friendly characteristics of most disruptive innovations are the outcome of disruptive R&D, rather than disruptive R&D itself. In consistence with some authors (Kostoff et al., 2004; Walsh, 2004), I believe the important role of technology could not be underestimated. I then reviewed papers in the literature on the purposeful creation of DI from the technology perspective. Unfortunately, their attempts failed to observe the initially "inferior performance" of DI; thus the explicit identification of R&D strategies specific to the creation of disruptive technologies and product candidates has remained as a research gap.

My research aims to address this important gap. Based on the intensive case studies, 4 R&D strategies have been identified: miniaturization, simplification, augmentation and exploitation for another application. Two cases were used to explain each of the 4 strategies in detail, and cases such as Wii game consoles and tank gauging machine are recent examples empirically studied by myself in the Asian context. These 4 R&D strategies were further verified by means of Delphi method with a panel of 25 experts who agreed to assess if these strategies were likely to be used in another 30 technological disruptive innovations cited in the extant literature. The answers from the expert panel mainly show that “simplification” and “miniaturization” are more frequently applied than the rest, implying the lifestyle change towards convenience and agility in the fast-paced world today. Meanwhile, little utilization of “augmentation” and “exploitation for another application” suggests potentially untapped disruptive opportunities.

This essay is believed to be a first study to clearly highlight the enabling role of technology in disruptive innovations, which is important yet not well addressed. Furthermore, the 4 R&D strategies would form a more deliberate and systematic strategy framework to create disruptive technology candidates which would in turn help firms to become disruptors or serial disruptors.

As the cases used in this study are all from the physical science and engineering areas, they may not be as useful in the biological science and engineering areas. It is expected that more proactive applications of the proposed R&D strategies will be applied in future. Hence they will be opportunities to observe any failures or difficulties in applying these strategies, which could create future academic research agenda.

6.4 Contributions of the essay on creation versus discovery of entrepreneurial opportunity in hard disk drive industry

In the 3rd essay, using rich data on the de-novo startups that were established between 1978 and 1999 in hard disk drive industry, I was able to empirically compare the relative importance of creation versus discovery of entrepreneurial opportunities to startup firms' longevity. Borrowing from the literature on modular design, de-novo startup firms can be divided into those that create design rules and those that discover them (i.e. adapt to them). Technological innovations force changes of design rules, and new design rules bring forward entrepreneurial opportunities for startup firms. When new firms participated in certain change in design rules, this change in the design rules presents a potential entrepreneurial opportunity. Cases in which firms entered the industry by creating new design rules can be considered as creation of an entrepreneurial opportunity. Cases in which firms entered the industry by adapting to design rules can be considered as discovery of an entrepreneurial opportunity. The initial result shows that more de-novo startups can be classified as ones that only discovered (31 firms) than only created (6 firms) entrepreneurial opportunities, while 10 firms both created and discovered them. Further analysis by Cox proportional hazards model indicates that longevity of firms that both created and discovered entrepreneurial opportunities is significantly longer than firms that only discover or create them. However, there is no significant difference of longevity between firms that only create and firms that only discover entrepreneurial opportunities.

The 3rd essay is one of the first academic studies to empirically contrast the relative contribution of creation vs. discovery of entrepreneurial opportunities to startup firms' longevity, following conceptual differentiation between the two alternatives by Alvarez and Barney (2005). While the entrepreneurship literature has paid much more attention to discussing discovery rather than creation of entrepreneurial opportunities, there is no supporting evidence that discovery of entrepreneurial opportunities contributed more to longevity. In addition, the literature so far only uses a single-side theory to explain the entrepreneurial action to produce new products and services. However, no single theory can fully explain the startup firms that survived the longest since the most successful firms both create and discovery entrepreneurial opportunities in reality. It is really about the degree of discovery versus creation or the balance between the two. Ambidexterity and punctured equilibrium are two mechanisms to solve the problem of balancing creation and discovery. Future research could study whether the conclusions are generalizable to other industries or contexts.

REFERENCES

Abramovitch, D.Y. & Bushnell, L.G. 1999. Report on Fuzzy versus Conventional Control Debate, ***IEEE Control Systems***, Jun.: 88-91.

Adner, R. 2002. When are technologies disruptive? A demand-based view of the emergence of competition, ***Strategic Management Journal***, 23(8): 667-688.

Adner, R. 2006. Match your innovation strategy to your innovation ecosystem. ***Harvard Business Review***, 84(4): 98-107.

Ahuja, G. & Lampert, C.M. 2001. Entrepreneurship in the large corporation: A longitudinal study of how established firms create breakthrough discoveries. ***Administrative Science Quarterly***, 38: 51-73.

Aldrich, H.E. & Fiol, C.M. 1994. Fools rush in? The institutional context of industry creation, ***Academy of Management Review***, 19(4): 645-670.

Alvarez, S.A, & Barney, J. 2005. How entrepreneurs organize firms under conditions of uncertainty. ***Journal of Management***, 31(5): 776-793.

Alvarez, S. A., & Barney, J. 2006. ***Discovery and Creation: Alternative Theories of Entrepreneurial Action.*** Fisher College of Business Working Paper, No. 2006-01-005, The Ohio State University.

Anderson, P. & Tushman, M.L. 1990. Technological discontinuities, dominant designs: A cyclical model of technological change. ***Administrative Science Quarterly***, 35, 604-633.

Arthur, W.B. 1989. Competing technologies, increasing returns, and lock-in by historical events. ***Economic Journal***, 99(394): 116.

Augsdorfer, P. 2008. Managing the unmanageable, ***Research Technology Management***, Jul/Aug: 41-47.

Baker, W.E. & Sinkula, J.M. 2005. Market Orientation and the New Product Paradox. ***Journal of Product Innovation Management***, 22, 483-502.

Baker, T., & Nelson, R. 2005. Creating something from nothing: Resource construction through entrepreneurial bricolage**.** ***Administrative Science Quarterly***, 50: 329-366.

Baldwin, C. & Clark, K. 1997. Managing Modularity, ***Harvard Business Review***, Sep-Oct: 84-93.

Baldwin, C. & Clark, K. 2000. ***Design Rules, Volume 1: The Power of Modularity***. Cambridge, MA: MIT Press.

Barney, J.B. 1986. Strategic factor markets: expectations, luck, and business strategy. ***Management Science,*** 32(10): 1231-1241

Barney, J.B. 1997. On flipping coins and making technology choices: Luck as an explanation of technological foresight and oversight. In Garud, R., Nayyar, P. and Shapira, Z. (eds.), ***Technological Innovation: Oversight and Foresights.*** New York: Cambridge University Press, 13-19.

Benner, M.J. & Tushman, M.L. 2003. Exploitation, exploration, and process management: The productivity dilemma revisited. ***Academy of Management Review***, 28(2):238-256.

Bhide, A.1999. ***How Entrepreneurs Craft Strategies That Work.*** Boston: Harvard Business School Press.

Bower, J.L. & Christensen, C.M. 1995. Disruptive technologies: Catching the wave. ***Harvard Business Review***, 73(1):43-53.

Brusoni, S. & Prencipe, A. 2001. Unpacking the Black Box of Modularity: Technologies, Products and Organizations. ***Industrial*** *and* ***Corporate Change***, 10(1):179-205.

Campo A.D., Sparks A., Hill R.C. & Keller R.T.1999. The Transfer and Commercialization of University-Developed Medical Imaging Technology: Opportunities and Problems, ***IEEE Trans. on Engineering Management***, 46(3):289-298.

Claude-Gaudillat, V. & Quelin, B.V. 2006. Innovation, new market and governance choices of entry: The Internet brokerage market case. ***Industry and Innovation,*** 13(2), 173-187.

Chandy, R.K. & Tellis, G.J. 1998. Organizing for radical product innovation: The overlooked role of willingness to cannibalize. ***Journal of Marketing Research***, 35(4), 474-487.

Chao, R.O. & Kavadias, S. 2007. A theoretical framework for managing the NPD portfolio: When and how to use strategic buckets, ***Management Science***, 54(5), 907-921.

Charitou, C. & Markides, C. 2003. Responses to disruptive strategic innovation. ***Sloan Management Review***, 44(2), 55-63.

Chesbrough, H. 1999. Arrested development: The experience of European hard disk drive firms in comparison with US and Japanese firms. ***Journal of Evolutionary Economics***, 9, 287-329.

Chesbrough, H.W. 2003. Environmental influences upon entry into new sub-markets. Evidences from the worldwide hard disk drive industry conditionally, ***Research policy***, 32: 659-678.

Chesbrough, H. W. 2001. Assembling the elephant: A review of empirical studies on the impact of technical change upon incumbent firms. In Chesbrough, H. and Burgelman, R. (eds.), ***Comparative Studies of Technological Evolution***, Oxford UK: Elsevier: 1-36.

Chesbrough, H.W. & Kusunoki, K. 2001. The Modularity Trap: Innovation, Technology Phase Shifts and the Resulting Limits of Virtual Organizations. In Nonaka, I. & Teece, D.J.(Eds.) ***Managing Industrial Knowledge: Creation, Transfer and Utilization***: 203-230, London: Sage.

Chesbrough, H. 2003. ***Open innovation: The new imperative for creating and profiting from technology***. Boston: Harvard Business School Press.

Chesbrough, H. and Crowther, A.K. 2006. Beyond high tech: early adopters of open innovation in other industries. ***R&D Management***, 36(3): 229-236.

Choi, Y.B. 1993. ***Paradigms and Conventions: Uncertainty, Decision Making and Entrepreneurship.*** Ann Arbor: University of Michigan Press.

Christensen, C.M. 1992. ***The Innovator's Challenge: Understanding the Influence of Market Environment on Processes of Technology Development in the Rigid Disk Drive Industry***. Doctoral dissertation. Harvard University, Massachusetts.

Christensen, C.M. 1993. The rigid disk drive industry: A history of commercial and technological turbulence. ***Business History Review***, 67(4): 531-589.

Christensen, C. M. & Rosenbloom R.S., 1995. Explaining the attackers advantage: technological paradigms, organizational dynamics, and the value network, ***Research Policy,*** 24: 233-257

Christensen, C.M. 1997. ***The innovator's dilemma: When new technologies cause great firms to fail.*** Harvard Business School Press.

Christensen, C.M., Suarez, F. F. & Utterback J.M. 1998. Strategies for Survival in Fast-Changing Industries. ***Management Science***, 44(12): 207-221.

Christensen, C.M. Verlinden, M. & Westerman, G. 2002. Disruption, disintegration and the dissipation of differentiability, ***Industrial and Corporate Change***, 11(5): 955-993.

Christensen, C.M. & Bower, J. L. 1996. Customer power, strategic investment, and the failure of leading firms. *Strategic Management Journal*, **17**(3), 197-218.

Christensen C.M. & Raynor, M**.** 2003. ***The Innovator's Solution: Creating and sustaining successful growth.*** Harvard Business School Press.

Christensen, C.M. 2004. Maximizing the returns from research, ***Research Technology Management***. 47(4): 12-18.

Christensen, C.M. 2006. The ongoing process of building a theory of disruption. ***Journal of Product Innovation Management***, 23: 39-55.

Cohen, W. M. & Klepper, S. 1996. Firm size and the nature of innovation within industries: the case of process and product R&D. ***Review of Economics and Statistics,*** 78: 232-243.

Daniel, E.D., Mee, C.D. & Clark, M.H. 1998. ***Magnetic Recording, The first 100 Years.*** NY: IEEE Press.

Danneels, E. 2002. The dynamics of product innovation and firm competences. ***Strategic Management Journal***, 23(12): 1095-1121.

Danneels, E. 2004. Disruptive technology reconsidered: A critique and research agenda. ***Journal of Product Innovation Management***, 21(4): 246-258.

Day, G.S. 1999. Misconceptions about market orientation. ***Journal of Market-focused Management***, 4(1): 5-16.

Denning, S. 2005. Why the best and brightest approaches don't solve the innovation dilemma. ***Strategy & Leadership***, 33(1): 4-11.

DeTienne, D.R. & Koberg, C.S. 2002. The impact of environmental and organizational factors on discontinuous innovation within high-technology industries. ***IEEE Transactions on Engineering Management,*** 49(4): 352-364.

Druehl, C.T. & Schmidt, G.M. 2008. A strategy for opening a new market and encroaching on the lower end of the existing market. ***Production and Operations Management,*** 17(1): 44-60.

Edmondson A.C. & McManus S.E. 2004. Methodological fit in organizational field research, ***working paper of Harvard Business School***, May 14

Sarasvathy, S.D. 2001. Causation and effectuation: Toward a theoretical shift from economic inevitability to entrepreneurial contingency, ***Academy of Management Review***, 26(2): 243-263.

Eisenhardt, K. 2007.Theory Building From Cases: Opportunities and Challenges, ***Academy of Management Journal,*** 50(1): 25-32.

Florida, R. & Kenney, M. 1990. ***The Breakthrough Illusion.*** New York: Basic.

Foster, R. N. 1986. ***Innovation: The attacker's advantage*****.** New York: Summit Books.

Funk, J.L. 2007. Vertical Disintegration and Entrepreneurship: The Case of Broadcasting, ***Best paper proceedings for the Academy of Management***, Philadelphia, PA.

Gaglio, C.M., & Katz, J.A. 2001. The Psychological Basis of Opportunity Identification: Entrepreneurial Alertness. ***Small Business Economics***, 16(2): 95.

Ganco, M. & Agarwal, R. 2009. Performance differentials between diversifying entrants and entrepreneurial startups: A complexity approach. ***Academy of Management Review***, 34(2): 228-252.

Gartner, W.B. 1985. A conceptual framework for describing the phenomenon of new venture creation. ***Academy of Management Review***, 10(4): 696-706.

Gillbert, C. 2003. The disruption opportunity. ***MIT Sloan Management Review***, 44(4): 27-32.

Govindarajan, V. & Kopalle, P. K. 2004. How legacy firms can introduce radical and disruptive innovations: Theoretical and empirical analyses. ***AOM 2004 Conference best paper***, BPS: A1-A6.

Govindarajan V. & Kopalle P.K. 2006. Disruptiveness of Innovations: Measurement and Assessment of Reliability and Validity, ***Strategic Management Journal***, 27: 189-199.

Govindarajan, V. & Kopalle, P. K..2006. The usefulness of measuring disruptiveness of innovations ex post in making ex ante predictions, ***Journal of Product Innovation Management***, 23:12-18.

Grisham T. 2009, The Delphi technique: a method for testing complex and multifaceted topics, ***International Journal of Managing Projects in Business***, 2(1), 112-130.

Gupta, A.K., Smith, K.G. & Shalley, C.E. 2006. The interplay between exploration and exploitation, ***Academy of Management Journal***, 49(4): 693-706.

Hang, C.C., Yu, D. & Chai, K.H. 2007. ***An Exploratory study on Understanding the Technological Dimension in Disruptive Innovation,*** The 5th International Symposium on Management of Technology, China/Zhejiang, Jun 1-3.

Hart, S. L. & Christensen, C.M. 2002. The great leap: Driving innovation from the base of the pyramid. ***MIT Sloan Management Review***, 44(1): 51-56.

Henderson, R. M. & Clark, K. B. 1990. Architectural innovation: the reconfiguration of existing product technologies and the failure of established firms. ***Administrative Science Quarterly***, 35: 9-30.

Henderson, R.M. 2006. The innovator's dilemma as a problem of organizational competence. ***Journal of Product Innovation Management***, 23: 5-11.

Henry C. L. & Goh J.M. 2009. Disruptive technology: How Kodak missed the digital photography revolution, ***Journal of Strategic Information Systems***, 18(1): 46-55.

Hill C.W.L. & Rothaermel F.T. 2003. The Performance of Incumbent Firms in the Face of Radical Technological Innovation. ***Academy of Management Review***, 28(2), 257-274.

Hogan, J. 2005. Being successfully disruptive. ***Medical Device Technology***, 16(5): 21-23.

Husig S., Hipp, C & Dowling, M. 2005. Analyzing disruptive potential: The case of WLAN and the mobile telecommunications network companies. ***R&D Management***, 35: 17-35.

Jacobides, M. 2005. Industry Change through Vertical Disintegration: How and why markets emerged in mortgage banking, ***Academy of Management Journal***, 48 (3): 465-498.

Kanellos M. 2003. Intel Wireless Plans Begin With New Chip, ***ZDNet News***, March 10, 2003. http://news.zdnet.com/2100-9584-22-991566.html.

Khessina, O.M. & Carroll, G.R. 2008. Product Demography of De Novo and De Alio Firms in the Optical Disk Drive Industry, 1982-1999. ***Organization Science***, 19(1): 25-38.

King, A.A. & Tucci, C.L. 2002. Incumbent entry into new market niches: The role of experience and managerial choice in the creation of dynamic capabilities. ***Management Science***, 48(2): 171-186.

Kirzner, I. 1973. ***Competition and Entrepreneurship***. Chicago and London: University of Chicago Press.

Kostoff R.N., Boylan, R. & Simons, G. R., 2004. "Disruptive Technology Roadmaps," ***Technological Forecasting and Social Changes***, 71:141-159.

Langlois, R. 1992. External Economics and Economic Progress: the case of the Microcomputer Industry, ***Business History Review***, 66: 1- 50.

Langlois, R.N. & Robertson, P.L. 1992. Networks and Innovation in a modular system: Lessons from the microcomputer and stereo component industries, ***Research Policy***, 21: 297-313.

Langlois, R.N. 2003. The vanishing hand: the changing dynamics of industrial capitalism, ***Industrial and Corporate Change***, 12(2): 351-385.

Lee, R. & Chen, Q. M. 2009. The Immediate Impact of New Product Introductions on Stock Price: The Role of Firm Resources and Size. ***Journal of Product Innovation Management***, 26(1): 97-107.

Leifer R., McDermott C.M., O'Connor G.C., Perters L.S. & Rice M. 2000. ***Radical Innovation.*** Harvard Business School Press.

Lejarraga, J. & Martinez-Ros, E. 2008. Comparing Small versus Large Firms' R&D Productivity through a Dual Process Perspective. ***Academy of Management Proceedings***, 1-6.

Levinthal, D. 1997. Adaptation on Rugged Landscapes. ***Management Science***, 43(7): 934-950.

Lynn L. H. 1998. The Commercialization of the Transistor Radio in Japan: The Functioning of an Innovation Community, ***IEEE Trans. on Engineering Management***, 45(3): 220-229.

Macher, J.T. & Richman, B.D. 2004. Organizational responses to discontinuous innovation: A case study approach. ***International Journal of Innovation Management***, 8(1): 87-114.

Markides, C. 1998. Strategic innovation in established companies. ***Sloan Management Review***, 39(3): 31-42.

Markides, C. 2006. Disruptive Innovation: In need of better theory. ***Journal of Product Innovation Management***, 2: 19-25.

McKendrick, D.G., Doner, R.F. & Haggard, S. 2000. ***From Silicon Valley to Singapore, Location and competitive advantage in the head disk drive industry***. California, Stanford University Press.

Mohr, J. J., Sengupta, S. & Slater, S. 2004. ***Marketing of High Technology Products and Innovations***, 2nd edition. Upper Saddle River, NJ: Prentice-Hall.

Morita A., Reingold E. & Shimomura, M.1987, ***Made In Japan***. EP Dutton.

Morone, J. 1993. ***Winning in High Tech Markets*.** Boston, MA: Harvard Business School Press.

Murase, E. M. 2003. **Keitai Boomu: The case of NTT DOCOMO and innovation in the wireless internet in Japan**. Unpublished Doctoral Dissertation, Department of Communication, Stanford University.

Myers, D.R. 2002. A practitioner's view: Evolutionary stages of disruptive technologies. ***IEEE Transactions on Engineering Management,*** 49(4): 322-329.

Narver, J. C., Slater, S.F. & MacLachlan, D.L. 2004. “Responsive and Proactive Market Orientation and New Product Success”, ***Journal of Product Innovation Management***, 21(5): 334-347.

Nayak R. & Ketteringham J. M.1994, ***Breakthroughs***. San Diego, CA: Pfeiffer and Co..

Nelson, R. R. & Winter, S.G. 1982. The Schumpeterian tradeoff revisited. ***American Economic Review***, 72(1): 114-133.

O’Connor G.C. & Ayers A.D. 2005. Building a Radical Innovation Competency, ***Research Technology Management***, 48(1): 23-31.

Paap, J. & Katz, R. 2004. Anticipating disruptive innovation. ***Research Technology Management***, 47(5): 13-22.

Pfeffer, J. & Salancik, G.R. 1978. ***The External Control of Organizations: A Resource Dependence Perspective***. New York: Harper & Row.

Prahalad C. K. 2004. ***The fortune at the Bottom of the Pyramid: Eradicating poverty through profits***. Upper Saddle River, NJ: Wharton School Publishing.

Rao, B. Angelov, B. & Nov, O.2006. Fusion of Disruptive Technologies: Lessons from the Skype Case. ***Journal of European Management***, 24(2-3): 174-188.

Roger S., 2007. “The Disruptive Potential of Game Technologies,” ***Research Technology Management***, 50(2): 57-64.

Rothaermel, F.T. 2001. Incumbent's advantage through exploiting complementary assets via interfirm cooperation. ***Strategic Management Journal,*** 22(6-7), 687-699.

Rothaermel, F.T. 2002. Technological discontinuities and interfirm cooperation: What determines a startup's attractiveness as alliance partner? ***IEEE Transactions on Engineering Management,*** 49(4), 388-397.

Sahlman W.A. & Stevenson H.H. 1985. Capital Market Myopia, ***Journal of Business Venturing,*** 1: 7-30.

Sanchez, R. & Mahoney, J.T. 1996. ***Modularity, Flexibility, and Konwledge Management in Product and Organization Design,*** Nedlands, W.A. : Graduate School of Management, University of Western Australia

Schiffer, M. B. 1991.***The Portable Radio in American Life.*** Tucson: University of Arizona Press.

Schmidt, G.M. 2004. Low-end and high-end encroachment strategies for new products. ***International Journal of Innovation Management***, 8(2), 167-191.

Schmidt G. M. & Druehl C.T. 2008. When is a disruptive innovation disruptive? ***Journal of Product Innovation Management***, 25: 347-369.

Schumpeter, J.A. Business Cycles. ***A Theoretical, Historical, and Statistical Analysis of the Capitalist Process***. New York and London: McGraw-Hill.

Shane, S. 2003. ***A General Theory of Entrepreneurship. The individual-opprotunity Nexus.*** Massachusetts: Edward Elgar Publishing, Inc.

Simon, H. 1962. The Architecture of Complexity: Hierarchic Systems, ***Proceedings of the American Philosophical Society*** 106: 467-482.

Simon, H. 1996. ***The Sciences of the Artificial***, 3rd Edition, Cambridge: MIT Press.

Slater S. & Mohr J. 2006. Successful Development and Commercialization of Technological Innovation: Insights Based on Strategy Type, ***Journal of Product Innovation Management,*** 23: 26-33.

Smith, P.G. 2005. Book reviews. ***Journal of Product Innovation Management***, 22: 213-220.

Tellis, G.J. 2006. Disruptive technology or visionary leadership? ***Journal of Product Innovation Management***, 23, 34-38.

Tsai, K. H. & Wang, J.C. 2005. Does R&D performance decline with firm size?—A re-examination in terms of elasticity. ***Research Policy***, 34(6), 966-976.

Tushman, M. & Anderson, P. 1986. Technological discontinuities and organizational environments. ***Administrative Science Quarterly,*** 31(3), 439-466.

Tushman, M. & Murmann, P. 1998. Dominant Designs, Technology Cycles, and Organizational Outcomes, ***Research in Organizational Behavior***, 20: 231-266.

Tushman, M. L. & O'Reilly, III C. A. 2002. ***Winning through Innovation: A Practical Guide to Leading Organizational Change and Renewal***. Boston, Massachusetts: Harvard Business School Press.

Ulrich, K. 1995. The role of product architecture in the manufacturing firm, ***Research Policy***, 24(3): 419-440.

Utterback, J.M. 1994. ***Mastering the Dynamics of Innovation.*** Boston, MA: Harvard Business School Press.

Utterback, J.M. & Acee, H.J., 2005. Disruptive Technologies: An Expanded View, ***International Journal of Innovation Management***, 9(1): 1-17.

Van Orden, J., Schmidt, G. & Van Der Rhee, B. 2008. Encroachment patterns of the 'Best products' from the last decade, *15th International Annual EurOMA Conference*.

Venkataraman, S. 2003. Preface. In, Shane(Eds.), ***A General Theory of Entrepreneurship. The individual-opprotunity Nexus.*** Massachusetts: Edward Elgar Publishing, Inc.

Vojak, B.A. & Chambers, F.A. 2004. "Roadmapping disruptive technical threats and opportunities in complex, technology-based subsystems: The SAILS methodology", ***Technological Forecasting and Social Change***, 71(1-2): 121-139.

Walsh, S.T., Kirchhoff, B.A. & Newbert, S. 2002. Differentiating market strategies for disruptive technologies. ***IEEE Transactions on Engineering Management,*** 49(4): 341-351.

Walsh, S.T. 2004. Roadmapping a disruptive technology: A case study of the emerging microsystems and top-down nanosystems industry. ***Technological Forecasting and Social Change,*** 71, 161-185.

Yin R.K. 2003. ***Case study Research Design and Methods,*** *3rd edition*, Sage Publications, Inc

Yoon, B., Phaal, R. & Probert, D. 2008. Morphology analysis for technology Roadmapping: application of text mining, ***R&D Management***, 38(1): 51-68.

Young, G.K., Jong, H.S. and Sang, C.P. 2008. Visualization of patent analysis for emerging technology. ***Expert Systems with Applications,*** 34, 1804-1812.

Yoon, B. & Lee, S. 2008. Patent analysis for technology forecasting: Sector-specific applications. ***Proceedings of IEEE Engineering Management Conference***, Portugal, Jun. 28-Jul.1, 1-5.

Yu, D. & Hang, C.C. 2008. Creating candidate technologies for potential disruptive innovations: A case study approach, ***Proceedings of IEEE International Conference on Management of Innovation and Technology***, Thailand, Sep. 21-24: 65-70.

Yu, D. & Hang, C.C. 2009. A reflective Review of Disruptive Innovation Theory, ***International Journal of Management Review***, accepted.

PUBLICATIONS

(Relevant to the contents in the thesis)

Journal:

- Dan Yu and Chang Chieh Hang, 2009. A Reflective Review of Disruptive Innovation Theory, ***International Journal of Management Review***, accepted.
- Dan Yu and Chang Chieh Hang, 2009. Creating Technology Candidates for Disruptive Innovation: Practical R&D Strategies, submitted to ***R and D Management***.

Conference:

- Dan Yu and Chang Chieh Hang; *An Empirical Study on Purposeful Creation of Potential Disruptive Innovation*, Academy of Management Annual Meeting 09, USA/Chicago, Aug 7-11, 2009.
- Dan Yu and Chang Chieh Hang; *Creating Product Candidates for Potential Disruptive Innovation: Practical R&D Strategies*, International Society for Professional Innovation Management, Singapore, Dec 14-17, 2008.
- Dan Yu and Jeffrey Funk; *Creation or Discovery of Entrepreneurial Opportunities: The Case of Hard Disk Drive Industry,* International Society for Professional Innovation Management, Singapore, Dec 14-17, 2008.

- Dan Yu and Chang Chieh Hang; *Creating Candidate Technologies for Disruptive Innovation: A case study approach*, The 4th IEEE International Conference on Management of Innovation and Technology, Thailand/ Bangkok, 21-24 Sep 2008.
- Dan Yu and Chang Chieh Hang; *A Reflective Review of Disruptive Innovation Theory*, Portland International conference of Management of Engineering and Technology 08, South Africa/ Cape Town, Jul 27-31, 2008
- Chang Chieh Hang, Dan Yu and Kah Hin Chai; *An Exploratory study on Understanding the Technological Dimension in Disruptive Innovation*, The 5th International Symposium on Management of Technology, China/Zhejiang, Jun 1-3, 2007.
- Frans Carpay, Chang Chieh Hang and Dan Yu; *Management of Outsourcing R&D in the Era of Open Innovation*, The 5th International Symposium on Management of Technology, China/Zhejiang, Jun 1-3, 2007.

APPENDICES

Appendix 1-----The expert panel profile

No. of experts	Technical area	Organization	Position	Experience in their special technical area (years)
				Working
1	Robotics; Automation	NUS	Assoc Prof	28
2	Electrical & Computer Engineering	NUS	Assoc Prof	20
3	Electronics Engineering & Instrumentation	NUS	Assoc Prof	40
4	Consumer electronics	A*STAR,IIR	Science & Engineering Research Council	31
5	Communications Engineering	NUS	Prof	19
6	Microelectronics	A*STAR, IME	Director	27
7	Communications Networks	NUS	Assoc Prof	25
8	Control and robotics	NUS	Prof	15
9	Electronics instrumentation	NUS	Assoc Prof	25
10	Computer Science & Engineering	Rice U	Prof	23
11	Mechanical engineering	ST Kinetics	CTO	25
12	Biomedical engineering	Micropoint technologies	CEO	10
13	Manufacturing & Materials Engineering	A*STAR, IMRE	Executive Director	25
14	Biomedical Engineering	AWAK Technologies	CEO	20
15	Interactive Digital Media	NUS	Research Fellow	3
16	Physics & Data Storage Technology	NUS	Prof	30
17	Communication and networks	MediaTek	Senior Advisor	30
18	Automation	NUS	Assoc Prof	11
19	Mechanical engineering	Gilbarco Veeder-root Asia	Technical director	29
20	Computer Science & Engineering	NUS	Assoc Prof	28
21	Wireless Communications	A*STAR,IIR	Program mgr &Dept Head	19
22	Human Factor Engineering	NUS	Adjunct Prof	20
23	Communications Engineering	NUS	Professor & Head of Dept	29
24	Control and Automation	NUS	Prof	30
25	Interactive Digital Media	NUS	Assist Professor	11
Average				**22.92**

Appendix 2-----The first round questionnaire using Delphi method

Dear Sir or Madam:

We cordially seek your kind participation in a study on the "**Purposeful creation of product candidates for potential disruptive innovation**".

This questionnaire is designed by the Division of Engineering and Technology Management, NUS. It aims to cross validate 4 R&D strategies proposed by our extensive studies. The questionnaire contains 3 parts and the estimated completion time is **15-20 minutes**.

Introduction

Disruptive Innovation (DI) Theory has attracted much attention due to its great power in explaining how some seemingly inferior products may find a market foothold, improve subsequently, and either replace dominant products eventually or create new high-growth market. Creating potential disruptive innovation has thus been increasingly regarded as a promising strategy to achieve successive growth of companies. Since academic research has been focusing mainly on business models and other implementation challenges of disruptive innovation so far, we believe it is timely to conduct research on the front-end issues of relevant R&D which would lead to timely creation of promising disruptive technology/innovation. Specifically, from our extensive research, we have proposed 4 R&D strategies for creating disruptive products for DI, and now we want to cross validate these strategies in various industries. It is hoped that the findings of this research will be helpful to technology managers in pursuing the strategic intent of creating disruptive technologies to enhance the technology options of the company.

Your Benefits

For each valid returned questionnaire, we will provide accordingly a full report on our studies as well as the results and analysis of this questionnaire. If you are industrial technology professionals, we wish our findings on R&D strategies would inspire you with creative ideas of disruptive technologies and products.

Please do not hesitate to contact us if you need further information. Your time and efforts are greatly appreciated. We can be reached at

PhD Candidate: Ms. YU Dan;
yudan@nus.edu.sg Office: 6516 6722

Sincerely yours,
Dan

Questionnaire on R&D Strategies of Disruptive Innovation

This questionnaire investigates how R&D strategies have been used to create technological disruptive innovations.

I. Background Knowledge

(We hope that the following background knowledge would help you to better understand the questions in the main body of the questionnaire.)

1. <u>What is Disruptive Technology?</u>

Definition of Disruptive Technology: Disruptive Technologies happen in a process. Disruptive technologies are those which initially do not meet the performance requirements of the established customers and markets of the threatened firm. Therefore, the products based on disruptive technologies can only be applied initially in new or certain low-end markets. In these new or low-end markets, the different product attributes of the disruptive technology present an advantage that can redefine the value and significance of certain performance dimensions. They are typically cheaper, smaller, or easier to use. Gradually, these technologies continue to improve and when their performance is good enough to meet the performance requirements of the mainstream market, they may start to penetrate the mainstream market. Meanwhile, the existing technology has also improved such that their performance has overshot that required by the mainstream customers. In this situation, mainstream customers are likely to switch to the new products based on the cheaper and good-enough disruptive technologies, causing the dethronement of the established firms. Nowadays, a disruptive technology could also be used to create a new high-growth niche market even without disrupting the established firms.

Canon's introduction of slower but inexpensive tabletop photocopiers in the late 1970s relative to Xerox's high-speed big copiers is an example of disruptive technology/innovation. The tabletop copiers were rapidly accepted by small businesses and individuals who appreciated the convenience and price despite poor resolution. At the time of their introduction, the mainstream market (large firms) still preferred the large copiers because of speed, resolution, collation, etc. However, over time, further developments in small copiers allowed Canon to improve quality, speed, and features and offer them at a price point that was sufficient to satisfy the needs of mainstream market.

2. <u>What are the 4 R&D Strategies?</u>

Strategy 1 Miniaturization--Miniaturization Strategy is defined as the strategy to design and produce products to achieve reduction in size and weight so as to increase the benefits of portability and convenience. *For example*, transistor radios vs. vacuum tube radios. Because of the dramatic size difference between transistors and vacuum tubes, transistor radios were portable with lighter weights while vacuum tube radios were bulky and clumsy. The small size and light weight allowed transistor radios to gain a foothold in the niche market where people could listen to radio whenever and wherever they want. Gradually, the sound quality and reliability of transistor radios improved to be good enough for mainstream customers and transistor radios started to penetrate the mainstream market. Nowadays, transistor radios have replaced vacuum tube radios in most applications.

Strategy 2 Simplification--Simplification Strategy is used to create potential disruptive products based on the current products of overly high complexity and performance which also cause the high price. *For example*, Heartstart Home Defibrillator vs. Manual External Defibrillators (MED). MEDs are highly priced, full functional defibrillators that support multifunctional operations, making it only suitable for highly-skilled medical personnel. However, Heartstart Home Defibrillators, the world's first over-the-counter AED devices, are simplified portable defibrillators with voice instruction and automatic activation to save lives at home or schools, designed for minimally-trained or untrained non-medical personnel.

Strategy 3 Augmentation--Augmentation Strategy suggests firms can augment an existing sustaining product with a disruptive feature. The traditional primary performances that mainstream customers historically valued still maintain a satisfactory level of performance, while the creative disruptive features are derived from the R&D efforts. *For example*, Nintendo Wii Game Console vs. Microsoft Xbox 360 and Sony PlayStation 3. Nintendo Wii maintained just good enough performances on primary dimensions such as processing speeds of CPU and resolution and realism of graphics, but created a disruptive feature of a new game interface. The new game interface is a 3-dimensional motion-sensitive wireless remote controller, which utilizes a commercially available MEMS acceleration sensor to enable such actions like racing-game steering and a tennis swing to be done through simple natural movements of the gamers' hands rather than just their skillful fingers.

Strategy 4 Exploitation for another application— In many cases, disruptive innovations are not completely new technologies, and may consist of off-the-shelf technologies from technology advances in other seemingly unrelated areas. It was originally improved for other applications, and then used for creating disruptive technologies by chance. Exploitation for another application Strategy encourages incumbent firms to reposition their existing products targeting another application, where it would be just good enough. *For example*, a class of mainstream simulator devices is gradually disrupted by entertainment games. PC-based games which were developed for the entertainment market were found to be "good enough" as training tools for less demanding customers and as recruiting tool for new soldiers in recent years.

3. <u>What should I do if I do not understand the details of the cases under examination?</u>

This survey is targeted to examine 30 technological disruptive innovation cases. For each case, we provide background information in a *manual* together with the questionnaire. Please feel free not to respond to any cases which you think are outside your expertise or interest. We are sure that there are at least some cases which you could confidently respond and we wish to thank you for your input!

II. Main Body of the Questionnaire

(Please answer the questions in this section.)

We greatly appreciate your answers to the following 3 questions in the table below:

1. For Case X, which of the 4 R&D strategies has (have) been used for creating the disruptive product X? Notice that 2 or more strategies can be used for a single case.

2. To what extent are you confident in your answers? A or B.
   A = I'm very confident/ I'm professional in this technical field or industry;
   B = I get the answer based on my analysis although I'm not professional in this technical field or industry.

3. Do you find other patterns or possible R&D strategies from the existing cases which are different from the 4 proposed strategies?

Demo: For the 1st case 3.5 inch Hard Disk Drive that disrupted 5.25 inch Hard Disk Drive, if you think it has applied *Miniaturization Strategy*, please kindly put either A or B in the 3rd column, and leave the other columns blank. Take a step further, if you draw the conclusion based on your own analysis but not professional experience, please put B in the 3rd column. In the same vein, if you give A to the 2nd case, it means you are a professional in PC industry and agree the case has used *Simplification Strategy*. If you find other patterns or possible R&D strategies from the existing cases which are different from the 4 proposed strategies, please put down your notes in the last column named "Other potential strategies".

Demo Table

Examples		**Choices of Strategies**				
Disruptive Product	**Mainstream Product**	**Miniaturization**	**Simplification**	**Augmentation**	**Exploitation for another application**	**Other potential strategies**
3.5 inch Hard Disk Drive	5.25 inch Hard Disk Drive	**B**				
Minicomputer	Mainframe		**A**			
Microcomputer	Minicomputer					This case used the strategy which I would call…because …

Section II (A)

Name: ____________________________

Email: ___________________________
Organization: _____________________
Position: _________________________
Education in Science and Engineering field: ____ years
Working experience in Science and Engineering field: ____ years

Section II(B) **30 Technological Disruptive Innovations for Examination**

Category 1--Industrial / Commercial Computer Hardware and Software

Examples		**Choices of Strategies**				
Disruptive Product	**Mainstream Product**	**Miniaturization**	**Simplification**	**Augmentation**	**Exploitation for another application**	**Other potential strategies**
3.5 inch Hard Disk Drive	5.25 inch Hard Disk Drive					
Minicomputer	Mainframe					
Microcomputer	Minicomputer					
Palm pilot, RIM blackberry	Notebook computer					
Microprocessor	Complex logic circuits based on PWB					
RISC microprocessors	Normal Microprocessors					
Small business accounting software QuickBooks	Mainstream accounting software					
Google search engine	Yellow pages					
Oracle's relational database software run on minicomputer	Incumbents' relational database software run on mainframe					
SQL database software	Oracle database software					
Email	Postal Service					
Linux	UNIX					
Digital animation	Full-length animated movie					

Category 2—Consumer Electronics

Examples		**Choices of Strategies**				
Disruptive Product	**Mainstream Product**	**Miniaturization**	**Simplification**	**Augmentation**	**Exploitation for another application**	**Other potential strategies**
Canon photocopiers	High-speed Xerox machine					
Point and shoot Brownie camera	Expensive complicated photography					
Raku-Raku phones for silver-hair people	Multifunctional mobile phone					
Walkman	Traditional music player					
Small-sized microwave oven	Normal-sized microwave oven					

Category 3—Communications/Networking

Examples		**Choices of Strategies**				
Disruptive Product	**Mainstream Product**	**Miniaturization**	**Simplification**	**Augmentation**	**Exploitation for another application**	**Other potential strategies**
Wireless telephony	Wireline phones					
802.11	Local-area wireline network					
Routers based on packet-switching technology (enable VOIP)	Routers based on traditional circuit-switching equipment					

Category 4—Healthcare and Medical Equipment

Examples		**Choices of Strategies**				
Disruptive Product	**Mainstream Product**	**Miniaturization**	**Simplification**	**Augmentation**	**Exploitation for another application**	**Other potential strategies**
Endoscopic surgical equipments	Complicated heart procedures					
Portable diabetes blood glucose meters	Large blood glucose testing machines					
Sonosite	Professional ultrasound device					

Category 5—Process and Mechanical Engineering

Examples		**Choices of Strategies**				
Disruptive Product	**Mainstream Product**	**Miniaturization**	**Simplification**	**Augmentation**	**Exploitation for another application**	**Other potential strategies**
Minimill	Integrated mill					
Blended plastics	Engineering plastics					
Plastic-encased tools with universal motors	Handheld electric tools before 1960					
50cc Supercub	Traditional motorcycle					
Hydraulically actuated excavator	Cable-actuated excavator					
Digital watches	Mechanical watches					

Appendix 3-----The second round questionnaire using Delphi method

Dear Friend

I greatly appreciated your 1st round participation in our study on the "**Purposeful creation of product candidates for potential disruptive innovation**". We have more than 25 experts who have kindly provided their answers and some proposed valuable comments for further improvements. We have revised them accordingly in the 2nd version.

In order to increase the accuracy and reliability of our research findings, we plan to use the so called **Delphi method** and conduct a 2nd round survey. The Delphi method is a systematic, interactive method of making judgments that relies on a panel of independent experts. The carefully selected experts answer questionnaires in two or more rounds. After each round, a facilitator provides an anonymous summary of the experts' judgments from the previous round. Thus, experts are encouraged to revise their earlier answers in light of the replies of other members of their panel. It is believed that during this process the range of the answers will decrease and the group will converge towards the "correct" answer. Finally, the process is stopped after a pre-defined stop criterion, for example, number of rounds or achievement of consensus. In this particular case, there is already good convergence in most of the results and hence we only expect you to participate in this 2nd and possibly a third round.

I am pleased to attach the 2nd round questionnaire. I sincerely hope that you will continue to support us by kindly accepting our invitation to participate in this 2nd round. As you are now familiar with the contents, it would take you **less than 10 minutes to** complete the questionnaire. We shall be most grateful to receive your completed return by **15 Sep.**

Again, many thanks for your kind effort in advance!

Regards,
Dan YU

Questionnaire on R&D Strategies of Disruptive Innovation

I. Main Body of the Questionnaire

(Please answer the questions in this section.)

We have summarized the answers of all experts from the 1st round in the 5 tables below. The **convergent answers** that most experts selected are highlighted in **gray**. This 2nd round survey using Delphi method invites you to answer the questionnaire again based on all other experts' judgments. In case you forget the contents of the 1st questionnaire, we also provide background knowledge following this section and the reference manual as appendix.

We greatly appreciate your answers to the following 2 questions in the tables below:

1. For Case X, based on the answers of all experts in the 1st round, would you please reconsider which of the 4 R&D strategies has (have) been used for creating the disruptive product X? If you are different from the convergent answers, please kindly provide your reasons in the last column.

2. To what extent are you confident in your answers? A or B.
   A = I'm very confident/ I'm professional in this technical field or industry;
   B = I get the answer based on my analysis although I'm not professional in this technical field or industry.

Section I (A)

Name: ____________________________

Section I (B) **30 Technological Disruptive Innovations for Examination**

Category 1--Industrial / Commercial Computer Hardware and Software

Examples		**Answers from the experts panel in 1st round**				**Answers from the experts panel in 2nd round**				
Disruptive Product	**Mainstream Product**	**Miniaturi-zation**	**Simplifi-cation**	**Augmen-tation**	**Exploitation for another application**	**Miniaturi-zation**	**Simplifi-cation**	**Augmen-tation**	**Exploitation for another application**	**Why different from convergent answers**
3.5 inch Hard Disk Drive	5.25 inch Hard Disk Drive	8A,12B		A,B	2B					
Minicomputer	Mainframe	5A,5B	8A,7B	A	3B					
Microcomputer	Minicomputer	10A,6B	8A,3B	A,B	A,2B					
Palm pilot, RIM blackberry	Notebook computer	8A, 6B	7A,4B	A,B	A,4B					
Microprocessor	Complex logic circuits based on PWB	9A,4B	3A, 7B	2A,B	2A,6B					
RISC microprocessors	Normal Microprocessors	3A,2B	5A,8B	A,4B	A,B					
Small business accounting software QuickBooks	Mainstream accounting software	2B	A,16B	A,B	2B					
Google search engine	Yellow pages	A,	3A,3B	3A,4B	5A,4B					
Oracle's relational database software run on minicomputer	Incumbents' relational database software run on mainframe		A,10B	A,B						
SQL database software	Oracle database software	B	8B	A,B	2B					
Email	Postal Service		2A,4B	3A,5B	4A,4B					
Linux	UNIX	B	A,8B	2A,3B	2A,B					
Digital animation	Full-length animated movie		3A,5B	4B	2A,2B					

Category 2—Consumer Electronics

Examples		Answers from the experts panel in 1st round				Answers from the expert panel in 2nd round				
Disruptive Product	**Mainstream Product**	**Miniaturi -zation**	**Simplifi-cation**	**Augmen -tation**	**Exploitation for another application**	**Miniaturi zation**	**Simplifi -cation**	**Augmen -tation**	**Exploitation for another application**	**Why different from convergent answers**
Canon photocopiers	High-speed Xerox machine	4A,7B	A,11B	B						
Point and shoot Brownie camera	Expensive complicated photography	2A,6B	A,14B	A	2B					
Raku-Raku phones for silver-hair people	Multifunctional mobile phone		4A,11B	A,B	3B					
Walkman	Traditional music player	7A,8B	2B	3B	4A,2B					
Small-sized microwave oven	Normal-sized microwave oven	3A,12B	A,6B	A,2B	2B					

Category 3—Communications/Networking

Examples		Answers from the experts panel in 1st round				Answers from the expert panel in 2nd round				
Disruptive Product	**Mainstream Product**	**Miniaturi -zation**	**Simplifi-cation**	**Augmen -tation**	**Exploitation for another application**	**Miniatu-rization**	**Simplifi-cation**	**Augmen -tation**	**Exploitation for another application**	**Why different from convergent answers**
Wireless telephony	Wireline phones	5A,3B	B	5A,7B	2A,2B					
802.11	Local-area wireline network	4A	A,B	4A,5B	2A,B					
Routers based on packet-switching technology (enable VOIP)	Routers based on traditional circuit-switching equipment	A	A	4A,8B	5A,2B					

Category 4—Healthcare and Medical Equipment

Examples		**Answers from the experts panel in 1st round**				**Answers from the expert panel in 2nd round**				
Disruptive Product	**Mainstream Product**	**Miniaturization**	**Simplification**	**Augmentation**	**Exploitation for another application**	**Miniaturization**	**Simplification**	**Augmentation**	**Exploitation for another application**	**Why different from convergent answers**
Endoscopic surgical equipments	Complicated heart procedures	2A,8B	5B	3B	3B					
Portable diabetes blood glucose meters	Large blood glucose testing machines	2A,12B	A,11B		2B					
Sonosite	Professional ultrasound device	2A,9B	A,7B		2B					

Category 5—Process and Mechanical Engineering

Examples		**Answers from the experts panel in 1st round**				**Answers from the expert panel in 2nd round**				
Disruptive Product	**Mainstream Product**	**Miniaturi-zation**	**Simplifi-cation**	**Augmen-tation**	**Exploitation for another application**	**Miniatu-rization**	**Simplifi-cation**	**Augmen-tation**	**Exploitation for another application**	**Why different from convergent answers**
Minimill	Integrated mill	7B	7B	B	3B					
Blended plastics	Engineering plastics		2B	8B	B					
Plastic-encased tools with universal motors	Handheld electric tools before 1960	2B	A,7B	A,B	b					
50cc Supercub	Traditional motorcycle	5B	10B	B	5B					
Hydraulically actuated excavator	Cable-actuated excavator		5B	A,4B	4B					
Digital watches	Mechanical watches	3B	4B	A,4B	A,6B					

II. Background Knowledge

(We hope that the following background knowledge would help you to better understand the questions in the main body of the questionnaire.)

1. What is Disruptive Technology?

Definition of Disruptive Technology: Disruptive Technologies happen in a process. Disruptive technologies are those which initially do not meet the performance requirements of the established customers and markets of the threatened firm. Therefore, the products based on disruptive technologies can only be applied initially in new or certain low-end markets. In these new or low-end markets, the different product attributes of the disruptive technology present an advantage that can redefine the value and significance of certain performance dimensions. They are typically cheaper, smaller, or easier to use. Gradually, these technologies continue to improve and when their performance is good enough to meet the performance requirements of the mainstream market, they may start to penetrate the mainstream market. Meanwhile, the existing technology has also improved such that their performance has overshot that required by the mainstream customers. In this situation, mainstream customers are likely to switch to the new products based on the cheaper and good-enough disruptive technologies, causing the dethronement of the established firms. Nowadays, a disruptive technology could also be used to create a new high-growth niche market even without disrupting the established firms.

Canon’s introduction of slower but inexpensive tabletop photocopiers in the late 1970s relative to Xerox’s high-speed big copiers is an example of disruptive technology/innovation. The tabletop copiers were rapidly accepted by small businesses and individuals who appreciated the convenience and price despite poor resolution. At the time of their introduction, the mainstream market (large firms) still preferred the large copiers because of speed, resolution, collation, etc. However, over time, further developments in small copiers allowed Canon to improve quality, speed, and features and offer them at a price point that was sufficient to satisfy the needs of mainstream market.

2. What are the 4 R&D Strategies?

Strategy 1 Miniaturization--Miniaturization Strategy is defined as the strategy to design and produce products to achieve reduction in size and weight so as to increase the benefits of portability and convenience. *For example*, transistor radios vs. vacuum tube radios. Because of the dramatic size difference between transistors and vacuum tubes, transistor radios were portable with lighter weights while vacuum tube radios were bulky and clumsy. The small size and light weight allowed transistor radios to gain a foothold in the niche market where people could listen to radio whenever and wherever they want. Gradually, the sound quality and reliability of transistor radios improved to be good enough for mainstream customers and transistor radios started to penetrate the mainstream market. Nowadays, transistor radios have replaced vacuum tube radios in most applications.

Strategy 2 Simplification--Simplification Strategy is used to create potential disruptive products based on the current products of overly high complexity and performance which also cause the high price. *For example*, Heartstart Home Defibrillator vs. Manual External Defibrillators (MED). MEDs are highly priced, full functional defibrillators that support multifunctional operations, making it only suitable for highly-skilled medical personnel. However, Heartstart Home Defibrillators, the world's first over-the-counter AED devices, are simplified portable defibrillators with voice instruction and automatic activation to save lives at home or schools, designed for minimally-trained or untrained non-medical personnel.

Strategy 3 Augmentation--Augmentation Strategy suggests firms can augment an existing sustaining product with a disruptive feature. The traditional primary performances that mainstream customers historically valued still maintain a satisfactory level of performance, while the creative disruptive features are derived from the R&D efforts. *For example*, Nintendo Wii Game Console vs. Microsoft Xbox 360 and Sony PlayStation 3. Nintendo Wii maintained just good enough performances on primary dimensions such as processing speeds of CPU and resolution and realism of graphics, but created a disruptive feature of a new game interface. The new game interface is a 3-dimensional motion-sensitive wireless remote controller, which utilizes a commercially available MEMS acceleration sensor to enable such actions like racing-game steering and a tennis swing to be done through simple natural movements of the gamers' hands rather than just their skillful fingers.

Strategy 4 Exploitation for another application— In many cases, disruptive innovations are not completely new technologies, and may consist of off-the-shelf technologies from technology advances in other seemingly unrelated areas. It was originally improved for other applications, and then used for creating disruptive technologies by chance. Exploitation for another application Strategy encourages incumbent firms to reposition their existing products targeting another application, where it would be just good enough. *For example*, a class of mainstream simulator devices is gradually disrupted by entertainment games. PC-based games which were developed for the entertainment market were found to be "good enough" as training tools for less demanding customers and as recruiting tool for new soldiers in recent years.

3. <u>What should I do if I do not understand the details of the cases under examination?</u>

This survey is targeted to examine 30 technological disruptive innovation cases. For each case, we provide background information in a *manual* together with the questionnaire. Please feel free not to respond to any cases which you think are outside your expertise or interest. We are sure that there are at least some cases which you could confidently respond and we wish to thank you for your input.