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Creating Technologies For Disruptive Innovation: Practical R&D Approaches

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Abstract

The literature has addressed many aspects of Disruptive Innovation from a business model innovation and organizational management perspectives. The specific technology itself has been assumed to emerge from the R&D labs once in a while. In this paper, we shall move upstream to study empirically how one may create technologies in the R&D Lab which have potentials for subsequent exploitation using the Disruptive Innovation approach. We have revisited the issue of what the typical characteristics of the candidate technologies are, and then distilled a number of generic, major technological improvements which could lead to desired disruptive characteristics for such innovative products. Based on the detailed study of 5 diverse cases in the electronics industry, we have proposed broad approaches which could drive the purposeful creation of these technologies at the front end of R&D. These propositions include vision-driven technology creation, reshaping of a high-end technology, augmenting a sustaining technology with disruptive features and exploiting technological progress from another application. The general applicability of these proposed approaches to other cases in the electronics and other industries was further examined using 30 relevant cases cited in Christensen's books. The frequencies of their utilization were also compiled and the implications studied. During the general validation process, a fifth proposition of developing technologies which are inherently disruptive was identified. All the five broad R&D approaches were then deliberated with appropriate examples to further clarify their applicability.

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1. INTRODUCTION

Owing to strong competition in the market, companies would need to develop technologies continuously to foster improved product performance. They are known as sustaining technologies as they involve either incremental or radical innovations to fend off competitions by continuous or periodic improvement of established products. Occasionally, a disruptive technology would emerge [1], [2]. It results in worse product performance, at least in the near-term, when compared with current technologies used in the established market. It is hence largely ignored by incumbents who are preoccupied in developing sustaining technologies in competition with others to maintain or grow their market shares in the mainstream business. However, such a disruptive technology could provide other product features, such as being cheaper, smaller, simpler to use, etc, which allow it to be used by new entrants at the lower end or in a new, niche market. Meanwhile, the keen competition in the mainstream market could have caused the performance of the sustaining technology to overshoot what the customers could utilize or absorb. The disruptive technology will continue to improve over time. When its performance could meet the performance of the mainstream market, customers may rapidly switch over to the product based on this new technology which they have ignored in the past, hence causing a fairly quick and surprised “disruption” to the incumbents. This dynamic innovation process is illustrated in Figure 1. More recently, some enlightened incumbents have also learnt the above lesson and are better prepared to exploit disruptive innovation against entrants and other reluctant incumbents [2], [3]. Even without eventual disruptions of incumbents, the new market created by the disruptive technology/products could grow to become very significant [4], [5]. Disruptive innovation has thus been increasingly regarded as a promising discontinuous technological innovation approach or strategy to create new products/services to sustain growth of companies. It is noted that the more recent research of Christensen has extended the model of disruptive innovation to services and other opportunities where business model innovation is the key while technology may or may not be an enabler [2]. In this paper, we shall confine our study to the original disruptive technological innovation in which the technology is a primary enabler.

The literature on disruptive technological innovation has assumed that a particular technology would emerge from the R&D Labs once in a while. Such a technology, which is called disruptive technology, would facilitate the commercialization and innovation path of a disruptive innovation. The research focus to-date has therefore correctly addressed the management challenges of exploiting the disruptive technology for successful innovation. Topics such as business model, leadership, organizational competence, market learning and disruptiveness of innovation have been well studied in the literature [4] - [9]. One exception was the work on "disruptive technology roadmaps" [10] which outlined a more systematic search for possible candidates of disruptive technology through text-mining of literature and subsequent roadmapping workshop/exercise.

In this paper, we shall move upstream to study empirically how one may intentionally create disruptive technologies in the R&D Lab. Our research covers the following. First we need to understand what the typical characteristics of the candidate technologies are. Second, we shall distill a number of generic, major technological improvements which will enhance such characteristics. Third, we shall discuss the results of a detailed study of 5 diverse cases in the electronics industry and propose approaches at the fuzzy front end of R&D which could drive the purposeful creation of such disruptive technologies. The general applicability of these proposed approaches to other cases in the electronics and other industries was then studied through examining 30 relevant and distinct cases cited in the famous books of Christensen.

During this general validation process, the notion of developing technologies which are inherently disruptive was found to be an additional distinct approach. While they have inherent weaknesses in the conventional application domain, such technologies could create disruptive opportunities in certain application domains if explored purposefully. The frequencies of past applications of all these five broad approaches were then compiled, and the implications discussed. More detailed deliberations with appropriate examples were made to highlight the potential of these broad R&D approaches. How they might be used together with market learning in a fourth generation R&D organization was then discussed.

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 [11], [12].

2. LITERATURE REVIEW OF TECHNOLOGICAL DIMENSION OF DISRUPTIVE INNOVATION

Although Christensen [1] has first coined the term disruptive technology, he and other scholars have subsequently focussed on the management challenges in disruptive innovation, assuming that the suitable technology is available. Technological uncertainty was thus not considered a major issue, unlike radical technology/ innovation [13] - [15]. In addition, the initial performance of disruptive technology is indeed inferior when compared to existing technology which sustains the mainstream market. All these contribute to the current 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. Another perception is that since it is relatively inferior, disruptive technology is not a worthwhile R&D goal in universities and industrial R&D Labs, which in turn reinforces the pattern that disruptive technology only occurs by chance or only occasionally.

At this juncture, it is useful to clearly differentiate the term "disruptive" from "radical" as they were used quite loosely in the literature and had created some confusion since both have the potential to cause incumbents to fail in the mainstream market and both could be used to create new markets. For disruptive technological innovation, we are using the definition originally given by Christensen [1], which refers to the potential disruption of incumbents by companies which employ a technology which is initially inferior in the mainstream market. As such, in its early development, a disruptive innovation only serves niche segments that value its non-standard performance attributes; subsequently, its further development also raises the performance valued by the mainstream customers. It is hence an "attack from below" when the disruption eventually occurs. It is noted that Intel has referred to it as the "Christensen's Effect" to avoid possible confusion during internal discussions [7]. For radical innovation, we are using the definition given by Leifer et. al [14], which could lead to the toppling of incumbents by competitors which employ a superior technology (either in performance or in costs). It is hence a direct "attack from the top" when it occurs. Both disruptive and radical innovations are discontinuous and share similarities such as difficulties in management at the fuzzy front end, internal resistance by managers who are focusing on immediate market demands, uncertainty in the market place, etc. However, there are important differences as well, such as the following. While a disruptive technology could be initially inferior in the mainstream market (but has other special features appreciated in niche or low-end markets), a radical technology creates superior performance in the mainstream market, or achieves significant cost reduction without sacrificing performance. While disruptive innovation was often ignored by incumbents owing to its initial inferiority in performance, radical innovation was often avoided by incumbents owing to the large R&D investment needed and the long period of R&D and product development involved in spite of its superior performance and potential benefits. In the literature [8] – [10], the above differentiation was not very clearly discussed. One way to make the differentiation clearer would be to use a more definite but longer term such as "initially inferior but potentially disruptive technology". Owing to its already popular usage, we shall use the shorter term "disruptive technology" with the above implicit understanding.

In a recent exploratory study [16], it has been found that the creation of certain disruptive technologies could indeed be extremely challenging as well, especially if it is based on a new scientific discovery. The introduction of the world's first transistor radio by Sony, an innovative disruptive product as analyzed by Christensen [1], [2], was found to clearly demonstrate such a challenge. First, the time frame achieved was unprecedented: a successful commercial product 8 years after the breakthrough invention of point-contact transistor by Bell Labs (which later won a Nobel Prize for its three inventor-scientists) and only 3 years after Sony licensed the patent from Western Electric (holder of the transistor patent from Bell Labs) and then started its indigenous R&D to produce a transistor radio product [17], [18]. As the transistor at that time could handle only audio frequencies, and the production yield was very poor, the R&D team at Sony (which was only a new tiny company back in the 1950s) had to overcome many technical hurdles to redesign the transistor for the much higher radio frequencies (including the use of advanced materials science and the virtual reinvention of the transistor), to create new circuit designs at radio frequencies, to pioneer the use of printed circuit board and other manufacturing technologies to get it finally production-ready. Another evidence which indicated the great technological challenges faced and overcome by Sony was that it had attracted outstanding scientists to join the R&D team [19]. For instance, one of the team members was Leo Esaki, a bright physicist with a PhD from Tokyo University, who eventually won the 1973 Nobel Prize for his discovery of the tunnel diode. The R&D achievements and technology created not only gave Sony a big lead over other competitors (as it inadvertently created a disruptive technology ahead of others and enjoyed the lead for several years), it also created new core competences to build other innovative products which later made Sony a global multinational giant.

While it is true that once a suitable disruptive technology is available, the success of the disruptive innovation would then depend largely on a suitable business model and other management excellence, the deeper investigation of the technological dimension has provided the following important perspective. The example of Sony's transistor radio and other examples of disruptive technologies [2] have indicated that: 1) the R&D leading to the creation of disruptive technologies may indeed be extremely challenging and is hence suitable as agenda for use-inspired upstream research in companies as well as in universities, and 2) by creating disruptive technologies ahead of competitors, the company could command a substantial lead in exploiting them for subsequent disruptive innovations and building unique core competences.

In the literature, it is also not very clear how one may qualify a specific technology as disruptive, other than broadly defining disruptive technology as one which possesses certain characteristics which could be used as a candidate technology for disruptive innovation. These characteristics are: 1) it initially has inferior performance compared to that used in the mainstream market, and 2) it has "good enough" performance with some special features which are appreciated in other niche markets or in the low-end of the mainstream market (for instance, it is smaller, simpler to use and cheaper). As many inferior technologies created by poor R&D or other reasons indeed have little value, the second characteristics needs to be carefully examined with regard to its potential for disruptive applications.

The revisit of the transistor radio R&D would give an excellent insight into the question of how disruptive technologies were created by some companies in the past, while many other companies including the dominant incumbents failed to recognise or tap their potentials. It has become evident that when new scientific/engineering breakthroughs such as the invention of transistor occurred, the basic science/ engineering itself might be rather neutral. Depending on the subsequent R&D goals and strategic approaches, it could either lead to the development of a radical technology to facilitate successful radical innovation, or a disruptive technology to facilitate successful disruptive innovation, provided of course that the radical or disruptive innovation was executed correctly with appropriate business model and management practice. In the case of transistor invention, incumbent companies in the vacuum-tube based consumer electronics sector such as RCA and Westinghouse would naturally want to ensure that they themselves were the first to replace vacuum tubes by the new transistors which had very promising potentials. Being well-managed successful companies, they bravely pursued the radical approach in order to sustain their mainstream businesses. However, the radical/sustaining approach needed very substantial R&D investments and long period of R&D and product development. They eventually abandoned the R&D effort to tame the transistor to create a radical technology after more than 10 years of intensive effort without producing any commercially viable product. Sony did the opposite against the wisdom of that time and pursued the disruptive approach to create good enough transistors and associated technologies to first launch an affordable transistor radio product which was commercially a success, and then repeat with transistor TV and other subsequent consumer products successfully [19].

A more recent counter-example is an engineering breakthrough called Micro-Electro-Mechanical Systems (MEMS). It involved miniaturizing electro-mechanical systems using microelectronics fabrication processes hence achieving drastic cost reduction while maintaining excellent performance if mass-produced. Analog Devices took more than 9 years of sustained effort and very substantial R&D investments to create and successfully commercialize MEMS acceleration sensors for automobile air-bag crash sensing applications [14]. As they were for use in automobiles, the performance had to be high and the volume had to be large for low-cost production. Hence Analog Devices had to use the radical innovation approach with very substantial investments in R&D and manufacturing to create the necessary breakthrough technology. But once successfully developed, the company could use the same basic MEMS technology to revolutionize other application domains such as optical switches and digital light processing. MEMS was first successfully developed through the radical rather than the disruptive route. It is also important to note clearly that once the radical MEMS technology is commercially available, it could also be used to facilitate the development of new disruptive products (see Section 3.4 for an example).

Although basic scientific/engineering breakthroughs are mostly neutral at their initial discovery stage, there are some which would be better developed as radical technologies owing to the inherent higher performance and extremely long duration and high cost of R&D investments needed. Examples included the exploitation of plasma to create flat-panel TV to replace the CRT-based TV display, and the development of CT scanner and many high-end biomedical instruments. They would attract much attention by companies as they could readily appreciate the commercial potentials.

Yet there exist scientific/engineering discoveries which are inherently more compatible with a disruptive approach as their initial performance is inferior in the mainstream technology/application space. Arguably, all digital equivalents of their analogue counterparts are in this category. Examples include digital watches, digital phones, digital cameras, etc. Other inherently disruptive inventions/discoveries include fuzzy logic, personal computers, short message system (SMS), wireless devices, artificial intelligence, etc.

There are other opportunities where existing technologies, either incremental or radical in nature could be adapted, simplified or combined to yield potentially disruptive technologies. This will become clearer in the next section. Once the disruptive technologies are created, they would become technology options which could facilitate the next step of technology integration in a formal product development process [20], [21].

In view of its increasing importance, there were indeed two recent attempts in the literature to propose systematic approaches to create disruptive technologies. Kostoff et.al [10] 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. Walsh [22] modified the emerging technology roadmapping tool to guide the development and commercialization of disruptive technologies for the microsystems industry. These approaches aimed to address discontinuous innovations which are different from continuous/incremental type of sustaining innovation. However, there was no clear differentiation of radical versus disruptive technology approaches within discontinuous innovation. A more detailed analysis of these roadmapping approaches shows that they are indeed more applicable to radical technology creation, but not to the "initially inferior" disruptive technology creation. The explicit identification of strategic approaches specific to the creation of disruptive technology creation on purpose has remained as a research gap.

3. IDENTIFICATION OF APPROACHES FOR CREATION OF DISRUPTIVE TECHNOLOGIES

As discussed in the previous section, it is more likely that companies, both incumbent and new start-ups would approach the subsequent R&D and product development of new scientific/engineering discoveries from a sustaining and radical innovation point of view as they could readily appreciate the eventual market potential of higher performing products/services. Even if these discoveries would better be initially developed as disruptive technologies, many companies do not have the tradition or discipline to be proactive to grasp the opportunity. The creation of disruptive technologies from purposeful R&D to provide additional technology options [11], [12] and to enhance the company's dynamic capabilities [23] was rare and needs to be promoted.

As disruptive technologies are typically cheaper, smaller and simpler to use, the more relevant capabilities and R&D activities are in the areas of miniaturization, simplification and other more generic ways of reducing both size and cost through component/function integration, shifting of certain functions to software, introduction of technologies originally developed from other industries (e.g. video games technology which will be elaborated later), new materials, improvement of user-interface through architectural changes, etc. While all these types of R&D activities are easily appreciated in sustaining innovation as there are clear market demands, pursuing them to create disruptive technologies for potential applications in low-end or niche markets without clear market demands initially would require very brave commitment from the top management of innovative companies. The specific R&D activities may also seem to be similar to those in sustaining technology creation although the goals are quite different. Hence there is a need for R&D management to provide strategic approaches to guide the R&D activities towards creating the targeted disruptive technologies. Our research leading to the identification of such broad approaches to potential disruptive technology creation through purposeful R&D will be presented in the following.

3.1 Empirical Research Methodology

As there was no prior research on purposeful R&D to help companies create disruptive technologies more regularly and ahead of competitors, we have adopted an empirical approach to conduct detailed studies of 5 diverse cases of electronics companies which had successfully created disruptive technologies which were followed by successful commercialization as disruptive innovations. There were some 30 disruptive technological innovation cases discussed in the two famous books of Christensen [1], [2]. From these 30 cases, we have chosen 2 widely used cases in the electronics industry for our detailed study. The other 3 cases are more recent and wellknown cases in the electronics industry not yet covered by Christensen’s books. The 5 selected cases were transistor radio (Sony), hard disk drive (Seagate), Wii

Games Console (Nintendo), Digital Camera (Casio) and Automatic External Defibrillator (Philips). The detailed studies were facilitated by their public reports, literature on their technology developments, and some special interviews of their CEOs or key decision makers [24] – [28]. For instance, in the case of Seagate, while lots of data were available in the first generation disruption from 5.25 inch to 3.25 inch technology, the emergence of 2.5 inch technology is more recent. We expended much effort visiting the company many times to hold interviews and in-depth discussion with their senior managers. These companies were also chosen based on their diversity within the electronics industry. Transistor radio and hard disk drive were classical examples used by Christensen. They are quite different as transistor radio was based on a new scientific breakthrough, whereas the hard disk drive was based primarily on advances in engineering technology. These 2 cases were also examples from very different periods. The other 3 cases, Wii Games Console, Digital Camera and Automatic External Defibrillator are more recent examples and they are for different markets. The 5 selected cases also cover the different nature of entrant and incumbent firms. The most unique case is Seagate as the 3.5 inch disruptive technology was originally pioneered by a start-up spun off from Seagate, while the current 2.5 inch potential disruption is being pursued by Seagate as an incumbent. The diversity is clearly shown in Table 1.

Based on extensive studies of these cases, we have deduced the strategic approaches which these companies used at the fuzzy front end of R&D to guide the development of the needed disruptive technologies. These identified approaches were then made into propositions which would be further verified with regard to their generality using 30 distinct cases of disruptive innovation as follows. We have selected all the 30 distinct cases of disruptive technological innovations from the 2 well known books of Christensen [1], [2] to examine if the propositions were applicable to the creation of disruptive technologies. These 30 cases were from diverse industries and much information about them were available in the literature and websites, and hence the study could be readily facilitated. In studying these 30 cases, two steps were taken. First, we investigated whether these propositions could have been verified based on the information gathered about each company and the particular disruptive innovation it introduced. Second, we investigated if there were any additional broad approach which could have been consciously or unconsciously applied during the R&D process and this might suggest an additional proposition which was not discovered from the original 5 cases studied in detail. The process was then repeated. The generation of propositions from the 5 detailed case studies is elaborated in the following.

3.2 Study of Transistor Radio

Sony's technology development for transistor radio could be traced in two stages – transistor technology and transistor radio.

When the transistor invention was first announced by Bell Laboratories in 1948, all major vacuum tube manufacturers were excited as there was a great likelihood that the vacuum tubes could eventually be replaced by transistors. Hence large incumbent firms in US such as Westinghouse and RCA invested heavily in transistor technology development. Large Japanese firms such as Toshiba, Mitsubishi Electric and Hitachi also tried to get a foothold by investing significantly in transistor technology development. There were no logical reasons to enter into transistor technology development for a tiny Sony which had only a small team for audio tape recorder R&D. But when Mr Masaru Ibuka, Sony's co-founder, first went to visit the US to promote its audio tape recorder business, he was alerted to the news that the Western Electric, the patent company of Bell Laboratories, had just made the transistor patent rights available to anyone who would pay royalties. As only the patents rights were licensed, the licensee would still need to invest heavily to develop the technology needed for manufacturing and engineering performance enhancement. On a restless night when he could not sleep well and was pondering the future of Sony, an idea flashed through his mind: "We will work on transistor. It will require many engineers and researchers as well. Thank God those new Totsuko people relish a new challenge. This is just right for them [17]". Sony was then called Totsuko. It had hired a team of specialists in an effort to advance the company's tape production technology. Mr Ibuka was pondering some new project which would galvanize and best utilize the diverse strength of these engineering and specialist talent. "What kind of work should I give them?" Mr Ibuka kept asking himself. Such a situation and the availability of transistor patent licensing triggered him to form a vision that Sony would develop transistor technology, even against the objection of Japan's Ministry of International Trade and Industry which controlled the license for manufacturing the transistor as it could not understand how a small factory could produce such a complex thing as the transistor.

After making the visionary decision to go into transistor technology development, the next big question was what should be the first product. Sony was advised at that time by Western Electric executives to make hearing aids with transistors, because it was said at that time that transistors could not be used for a radio. They further informed him that the transistors would be expensive to produce, and it was no match to the portable vacuum tube radio either technically or cost-wise. Sony had, however, decided to challenge itself to be the first in the world to design and manufacture a transistor radio. Morita even had a vision of a “pocket-sized” radio. The small team of scientists and engineers went ahead to beat the odds to reinvent the transistor for radio frequencies, solve all the miniaturization problems to produce the successful, five-transistor “pocket radio”, the TR-55 in 1955, followed by a ground-breaking “TR-7”, a seven-transistor portable with a performance which could compete with the vacuum-tube portables. The rest was history and the transistor radio example helped other Japanese companies to develop the concept and vision of miniaturized electronics products. More details of the transistor radio development and also an interview of a Sony’s senior executive are reported in [24].

According to all the conventional wisdom and theory of competitive strategy [29], a tiny company like Sony in the 1950s should not commit its limited resources first into the new transistor technology itself and next to develop the transistor radio product. The daring goal of producing an affordable, reliable and portable product, to realize the world’s first “pocket radio” which was regarded by experts at that time to be unrealistic, could only be conceived by Sony’s visionary founders. They inspired and led Sony engineers to overcome all the odds to complete the almost impossible mission of commercial production of both the transistors and the transistor radio within a short period of 3 years.

Proposition 1: Disruptive technology creation is vision-driven.

3.3 Study of Hard Disk Drive

Seagate is the world's largest computer hard disk manufacturer and the oldest independent hard disk maker still in operation.

In early 1985, Seagate engineers had developed a 3.5-inch prototype drive. It was requested by their largest customer, IBM, whose product planners were considering replacing the 5.25-inch drive in their PC-AT desktop computer with the smaller 3.5-inch drive. When IBM evaluated the 3.5-inch prototype and understood its capacity was limited to 10 and 20 MB models, the product planners decided to go with the next-generation 5.25-inch drive instead. The IBM people felt that the AT's customers wanted 40 and 60 MB of disk storage in the next AT models to be released, rather than any new, less tangible benefits of a physically smaller drive housed within the large AT box on their desktops.

Having been abandoned by IBM, Seagate tried to market the 3.5-inch design to other customers. As these customers were also manufacturers of full-sized desktop computer systems, they were similarly looking for next generation products with 40 to 60 MB capacity. However, the 3.5-inch drive could only provide 20 MB and at higher costs. The little interest from Seagate's existing customers made the program manager at Seagate lower his 3.5-inch sales estimates, and subsequently the senior executives shelved the 3.5-inch program.

It was not until early 1988 when 3.5-inch drive became firmly established in portable and laptop application that Seagate responded to it. Fortunately, Seagate was very fast to innovate and became the major player of 3.5-inch drive. Seagate learnt a valuable lesson as it was not sufficiently proactive when the dominant design of hard disk drive changed from 5.25 inch to 3.5 inch.

Hence, in the next wave technological innovation of 2.5 inch drive, Seagate proactively pursued the potential trajectory as a disruptor. In 1990 and 1991, when Conner Peripherals first introduced and controlled over 85% of the 2.5 inch market, it was a sustaining innovation because the application of 2.5 inch drive was in the low-end market of laptop and notebook computers with the same customers[†]. Seagate subsequently bought Corner Peripherals and benefitted from its technological team. It also quickly spotted new applications of 2.5 inch drive in Consumer Electronics products such as handheld digital audio or video players. In 1998, Seagate established its advanced research center at the Data Storage Systems Center of Carnegie Mellon University founded by Prof Mark Kryder in 1990. Subsequently, Seagate has become a technology leader in small form factors: with totally new 2.5 inch, 1.8 inch and even 1 inch hard disc drives for the Consumer Electronics market, hence well positioning itself for a potential disruption to 3.5 inch in the mainstream storage market in future. The detailed study of Seagate on its serial transitions is captured in [25].

[†] Clayton Christensen, *The Innovator's Challenge: Understanding the Influence of Market Environment on Process of Technology Development in the Rigid Disk Drive Industry*, DBA thesis of Harvard University, 1992, P150.

Unlike most of its competitors which were disrupted, Seagate has succeeded to survive and grow as its engineers were excited by the challenge to reshape its high-end 3.5 inch technology into smaller dimension applications for new or low-end markets. The 2.5 inch and 1.8 inch technologies may become disruptive technologies in the mainstream computer market and the mobile PC market in due course. In addition to supporting Proposition 1, this case suggests a new proposition.

Proposition 2: Disruptive technology could be created by reshaping a high-end sustaining technology.

3.4 Study of Games Console

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: the synergistic processing elements, the parallel floating-point shader pipelines and the high-definition graphics. 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 encourages people around world to play video games regardless of their age, gender or cultural background. "Our goal is to expand the gaming population". (Message from the President, Annual report 2006 of Nintendo.)

In terms of the traditional hardware specification, Wii's features are obviously inferior compared with PS 3 and Xbox 360. For examples, Wii's "Broadway" CPU (central processing unit) is clocked at 729MHz. By contrast, Xbox360 is powered by a custom-made IBM PowerPC-based three symmetrical cores running at 3.2 GHz each, and PlayStation 3's new cell processor is jointly developed by IBM, Sony and Toshiba Corporation, which is made up of a PowerPC-based core running at 3.2 GHz. And the Wii's ATI-provided "Hollywood" GPU (graphics processing unit) only clocks in at 243MHz. In contrast, Xbox 360's ATI-provided GPU is clocked at 500MHz and for PlayStation 3, the GPU is based on the NVIDIA G70 architecture, making use of 256 MB GDDR3 VRAM clocked at 550 MHz. Furthermore, the audio for Xbox 360 is impressive with Dolby Digital's multi-channel surround sound output, and it is designed to work with both Standard-Definition and High-Definition TV, providing at least 720p resolution. PlayStation 3 supports 7.1 digital Dolby TrueHD, and full High-Definition TV resolution from 480p to 1080p, also a superb audio and video effect. By contrast, Wii has only stereo sound and features a resolution of 480p.

However, Wii Remote features a new gaming interface which makes game control intuitive. According to Financial Times, approximately 9 million Wiis were purchased across the globe as of end of July, 2007, overtaking the 360's sales of 8.9 million units during the same period. Both platforms were far ahead of the PlayStation 3, which sold only around an estimated 3.7 million units worldwide.

How Nintendo formulated this new visionary strategy has been studied in detail in [26]. It is evident that Nintendo focused on winning "fringe" customers through the new games interface [30]. Its new Wii games console only has the normal incremental features over its predecessor product, the Games Cube, avoiding the higher cost of vastly enhanced graphics and much faster microprocessor as in Sony PS3 and Microsoft Xbox360. However, the affordable Wii includes an affordable 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. This product with such disruptive features has brought a huge market success for Nintendo. In addition to supporting Proposition 1, this case suggests a new proposition.

Proposition 3: Disruptive technology could be created by augmenting a sustaining technology with disruptive features.

3.5 Study of Digital Camera

Japan is well-known as an early adopter of cool, technology-intensive consumer electronics products in the world. And Casio Computer has been one of the trail-blazers in this fiercely competitive market and was best known for its pocket-size electronic calculators, digital watches and electronic musical instruments. With its core competence in electronics design, miniaturization and mass-manufacturing, it started to look at the potential of digital cameras in the 1990s.

The feasibility of commercial electronic still camera based on the Charge Couple Devices (CCD) image sensor (which converts light into digital pictures) was first explored globally in the early 80s. Truly digital models were then produced by Toshiba and Fujifilm in 1989. These products did not gain immediate consumer market success owing to their high price and unavailability of sufficiently well-developed peripherals, i.e. PCs. The first successful digital cameras for the consumer-level market that worked with a home computer via a serial cable were the Apple Quicktake 100 camera (Feb 1994), the Kodak DC40 camera (March 1995), the Casio QV-11 (with LCD monitor, late 1995) and Sony's Cyber-shot digital still camera (1996).

In 1995, Casio launched the QV-10 without the benefit of a market survey. Its engineers focused on designing a user-friendly and affordable digital camera which could be used by the increasingly PC-savvy customers in Japan and the US. In addition to using its miniaturization and mass-manufacturing expertise to achieve drastic weight and price reduction, its engineers added a 1.8 inch active matrix LCD display for instant playback. This proved to be a great feature as users could immediately delete unwanted shots and retake pictures of importance and eliminated the inconvenience to access a PC for viewing – its introduction forced competitors to do likewise and the LCD digital camera became a new dominant design. Although such an innovative product could not compete head-on even with a much cheaper conventional film-based camera in terms of picture quality (resolution and colour intensity), it became a big hit for consumers who liked a fun product which was good for taking snap shots at parties or special occasions, and gave digital cameras a strong-enough foothold to begin the disruption. Over the next few years, the CCD resolutions rapidly improved, from 0.3 megapixels to more than 2 megapixels (becoming sufficiently good for normal consumers); the storage improved drastically using first hard-disk microdrives and then affordable, removable flash-memory cards/sticks – enabling storing of thousands of pictures; the battery price dropped while recharging intervals lengthened and weight reduced, all very significantly. Coupling with zero developing cost and film cost, and the emergence of photo-printing service from memory cards/sticks, the digital cameras started to disrupt film-cameras since 2002 [27].

In addition to competing with other digital camera manufacturers which joined the race to capture the consumer camera market, Casio engineers continued to innovate by introducing the Exilim series starting 2002 again without a market survey. Using their core competences in miniaturization and mass-manufacturing developed from other successful consumer products, these engineers worked with suppliers of lenses and CCDs to further squeeze out space between parts to produce a stunning ultra-thin camera – just 13 millimeters, front to back. It could easily slip into a pocket, heralding in the new era of pocket-camera. The Exilim Z3 became the hottest-selling model of the year.

Proposition 4: Disruptive technology could be created by exploiting technological progress from another application.

3.6 Study of 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, whether or not they have a diagnosed heart condition. In USA alone, every year more than 250,000 die from SCA. 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.

Up to the early 1950s, defibrillation of the heart was performed as a major open chest surgery. Dr Bernard Lown invented the “Lown Waveform” technology in 1961 and this quickly became the dominant standard until the 1980s. It was replaced by “Biphasic Truncated Waveform” technology. Despite the technology being portable, manual defibrillators still required users to have extensive medical knowledge to operate it. A major breakthrough came with the introduction of the Automated External Defibrillator (AED). AED is a portable defibrillator designed for minimally-trained or untrained non-medical personnel.

Although the performance of AED was not comparable to the hospital-based machine, its mobility and ease of usage are the great attributes well suited for saving lives as the likelihood for successful resuscitation of a Sudden Cardiac Arrest (SAC) patients would decrease by approximately 7 to 10% with each minute following the SCA. After 10 minutes, very few resuscitations attempts would be successful. AED would shorten the response time to defibrillation and this fits into the American Heart Association’s target to increase the survival rates for SCA victims from 5% to 49% through bringing defibrillation response time to less than 4 minutes.

Philips Medical Systems entered the AED market by acquiring Agilent Technologies' Healthcare segment in 2000 and inherited both good technologies and patents in AED [31]. It rapidly became the number two medical equipment supplier with a market share of 36.5% in 2004. It invested substantially into R&D and innovation and introduced a specially designed defibrillation pads to reduce the energy shock to infants and children less than 8 years, hence expanding the AED application reach. It recognized that with about 121 million homes in the US, a new and large home sub-segment could be created. It hence worked closely with the regulator while reshaping the AED for use in homes. In 2004, it successfully introduced the first ever FDA approved Heartstart Home Defibrillator through over-the-counter sales without the need for prescriptions. It significantly broadens the access to AEDs. In 2005, it introduced the first commercial use Heartstart OnSite Defibrillator without prescriptions, successfully extending AED applications in communities, schools and businesses. More details about Philips' success and strategy are given in [28].

The portable Automated External Defibrillator (AED) was originally developed [31] as a high-end medical equipment to help start a person's stopped heart, for use in ambulances and high-traffic areas such as stadiums, airports and shopping malls. Philips Medical Systems had successfully sold more than 150,000 units since the late 1990s. What's next? Its high price and the need for a doctor's prescription to purchase had prevented portable AEDs to be made available to individuals. Using a disruptive approach to compete against non-consumption, Philips Medical Systems further simplified the portable AEDs to have an easy-to-use user interface that provides audio cues and guidance throughout the emergency response, defibrillation and cardiopulmonary resuscitation (CPR) process, giving even ordinary users the power to help save lives. The resultant HeartStart Home product was an instant market success as it was affordable, could be purchased over the counter, and was able to satisfy an unmet demand – to save lives at home, schools, etc as there are increasing cases of sudden cardiac arrest (in the order of few thousand cases per year in the US alone). This case clearly supports Proposition 2.

3.7 Verification of the Propositions for Broad Applicability

The four propositions and the five cases leading to their proposals as broad R&D approaches are listed in Table 2. As outlined in Section 3.1, the 30 technological innovation cases in Christensen books were used to study the general validity of these propositions. In the process of this verification, we have found a fifth proposition which will be further substantiated in Section 4.5:

Proposition 5: There exists inherently disruptive technology which may be gainfully employed if explicitly identified and developed.

The overall results are summarized in Table 3 which confirm that the different cases indeed could have used one or more of these broad strategic approaches as proposed. The application frequencies of these 5 approaches when applied in these 30 cases are shown in Table 4. The differences in the application frequencies are indeed very substantial which not only show how often these different R&D approaches were used in the past, but also suggest that certain approaches could be applied more frequently in future if they are better understood. This potential will be discussed in Section 4.

Another observation from Table 3 is the following. Many disruptive technologies which were vision-driven could also apply additional approaches of Reshaping, Augmenting or Borrowing. This type of disrupting technologies will therefore be pursued quite systematically once the vision was set. There were 5 cases (Inkjet printer, Bell Telephone, Google Search, Seiko Quartz Watches and LCD Flat-panel Display) which could not use the additional approaches of Reshaping, Augmenting and Borrowing. Two of them were also inherently disruptive. The implication is that these 5 cases of vision-driven approaches may call for a great deal of fundamental research and hence may favour larger firms with sufficient R&D resources and financial capital. The benefit is, however, that the resultant disruptive technologies would be more unique and harder to be pursued by imitators in due course.

4. FURTHER ELABORATION OF THE BROAD R&D APPROACHES

We shall next further elaborate on the five broad R&D approaches identified in the previous section and include additional examples of creating disruptive technologies for illustration and further strengthening of the generality of the propositions.

4.1 Vision-driven Disruptive Technology Creation

As discussed earlier, it is usually counter-intuitive to have an R&D goal which does not aim to achieve high-performance in a mainstream market, especially at the early stage of a science/engineering breakthrough. Hence the setting of an R&D goal to enhance the disruptive dimension of a new discovery has to be purposeful with the strongest support of the top management. It is also often very challenging at this early stage to aim for low-cost while maintaining an adequate performance. In the case of the transistor radio, it is clear from the literature [17] - [19] that its success depended critically on the top management's commitment driven by such a vision.

Many pioneering disruptive products such as minicomputers, personal computers, inkjet printers, etc were indeed results of vision-driven purposeful R&D against very high odds. A most recent and still emerging product is the $100 laptop from the one-laptop-per child (OLPC) project of MIT's Media Lab [32]. Its specification of a 500 MHz processor, 1 GB of memory and a 12-inch dual-mode display which can be used in full colour mode, or in a black-and-white sunlight-readable mode, and running under a Linux operating system is extremely ambitious especially with a target price of US$100. The low-cost 12-inch dual-mode display alone is already a challenging mountain for the small team of R&D engineers in the OLPC project to scale. Its recent successful development has led to a number of patents which could revolutionalize the design of displays for other applications. The graphical user interface, called Sugar, represented yet another revolutionary attempt to rethink and redesign the PC user interface which would allow children in third-world countries to operate it easily. While OLPC project may not succeed as originally planned, the disruptive technologies inspired by the visionary project have started to attract attention of other innovators as there could be other application opportunities as well (see Section 4.4). Incumbents such as Intel also could not afford to ignore this potential challenge and has introduced a similar, low-cost Classmate PC for children in the developing countries [33], while an innovative Taiwanese company, Asus, has responded with a good enough $250 ultramobile PC called Eee PC [34] by end of 2007.

As shown earlier in Table 4, vision-driven disruptive technology creation was the most frequently used approach. In retrospect, it is not entirely a surprise as disruptive innovation applications are not obvious, and visions based on intuition of leaders could help to interpret the weak market signals and guide the next risky step of technology development. Indeed many of the 30 disruptive technological innovation examples were created by visionary entrepreneurs. They either spotted the potential of such technologies when the emerging enabling science was developed, or they developed early visions of the products they wished to bring to markets, and they interacted with the R&D teams to guide them towards the appropriate technology development paths ahead of others. This type of visionary leadership is well documented in the literature [35] as it is largely identical to that needed in radical innovation except that the target/goal of disruptive innovation is different as discussed earlier in Section 2. Instead of aiming to achieve superior performance as in a radical technology, the R&D in disruptive innovation aims to create a “good enough” technology which has other “disruptive” features appreciated in a niche or low-end market.

Finally, the vision of a new product could be unconsciously formed as the leader would respond to weak market signals in daily life, and it becomes clearer when a special event triggers its emergence. The case of the invention of Walkman [19], [36] would illustrate this point. In 1978, Sony engineers managed to shrink a tape recorder into a specified footprint, but failed to fit the recording mechanism into it. When Sony’s co-founder and Honorary Chairman, Mr Masaru Ibuka, popped into their laboratory one day, he saw this failed product. As he remembered an unrelated development of a lightweight portable headphone elsewhere in the building, he asked “what if you combined them?” He then brought the resultant prototype to demonstrate to the other co-founder and Chairman, Mr Akio Morita. Morita tried and found it an excellent audio experience. It turned out that Morita was already pondering an idea for a while, and it came into focus as Ibuka talked. Morita was observing that young people could not seem to live without music. He saw people with big tape players and radios perched on their shoulders blaring out music. He also remembered that his daughter once came home from a trip and rushed upstairs before even greeting her mother and then put a cassette in her stereo. A vision for portable music with privacy was formed in his mind. He immediately issued instruction to develop the prototype Walkman into a commercial product. The rest was history.

The example of Walkman also tells us that failure of a normal R&D project could produce results which may be exploited to create a disruptive product – provided such failures are communicated to visionary leaders in the company who are always on the look out for new products and services enabled by new technologies which may arise from unexpected results [37].

4.2 Reshaping of a high-end technology

Christensen [2] has advocated the application of the 80/20 rule to simplify a high-end sustaining or even a radical technology 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 technology could be created. There are many examples of disruptive products created through this approach [2], including that of Galanz of China. When Galanz first decided to enter the microwave oven market in the 90s, it did not emulate other Chinese companies to manufacture the matured high-end oven under license and for export back to the developed countries. Instead, Galanz redesigned and created a simple, energy-efficient microwave oven that was cheap and small enough for the tiny kitchens in most Chinese homes. The affordable product was well received in China and sales grew steadily, allowing the company to take advantage of economies of scale to reduce the product's price even further to reach more in the mass market. By 2000, it owned the Chinese market with a 76% market share. In 2000, Galanz began trying to replicate its success in the home air conditioning market. Again, it first redesigned and built a simple, affordable, energy-efficient product that was good enough to cool the small homes and apartments in which most Chinese live. To these non-consumers, even a relatively limited product seems like a gift from above. The strategy worked and Galanz has quickly established another foothold in the air conditioning market.

What we could observe from the simplification of the mighty corporate mainframe computers to minicomputers, personal computers, laptop computers, personal digital assistants, and subsequently to many mobile internet appliances was indeed the reshaping of the original, sophisticated digital computers (which required professional computer programmers or engineers to use them) so that non-professionals down to laypersons could use the power of the digital computing engines. In the process, the digital computers were increasingly hidden behind simpler and more intuitive userinterfaces, progressively achieving the ultimate vision of invisible (but pervasive) computers [38]. In the broader industry setting, some of these macro changes which also brought along architectural changes and innovation [37] could be tracked and their trend predicted. Reshaping to create the next generation of disruptive technology may hence be feasible in some industry sectors although the accurate timing of their occurrence may still be rather difficult.

Although reshaping could be as simple as using the 80/20 rule as proposed by Christensen [2], it could also be extremely difficult in some cases. The recent experience of Seagate in the development of the 2.5 inch drive is a good example here [25]. Although Seagate was the leader in 3.5 inch drive business back in the 90s, it realized that it had to become a technology leader to compete and lead in the 2.5 inch business as the smaller dimension and the need for extra reliability for mobile applications were creating very challenging technological hurdles. Seagate hence created an Advanced Concepts Laboratory and a new Seagate Research Lab in 1997/8 to take up this challenge [25]. By means of vision and long-term strategic investment, Seagate is thus uniquely positioned as it has developed the state-of-the-art 2.5 inch drive technology for the new mobile storage market and is able to participate in the impending disruption of the 3.5 inch drive mainstream business by the 2.5 inch drive innovation.

As there exist many high-end sustaining technologies, both incumbents and entrants could proactively reshape them to create potentially disruptive technologies. This approach was the second most frequently used among the 30 cases as shown in

Table 3. It is anticipated that companies will find this strategy to be in line with the new trend of open innovation [40] as the high-end technology (before reshaping) 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) [41]. There exists good potential to overcome this problem if the Universities/Research Institutes proactively reshape their high-end technologies, in consultation with the SMEs to better appreciate the "job-to-be-done" market needs, to create appropriate disruptive technologies for the SMEs which will in turn use them in introducing disruptive innovation.

4.3 Augmenting a sustaining technology with disruptive features

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 [30] discussed earlier in Section 3.4 demonstrated that it was possible to set and realize such a R&D goal.

Another successful case was that of the Intel R&D Centre in Haifa, Israel. 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 [42] 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.

It is noted that this R&D approach 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 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 approach and hopefully more applications in the near future.

4.4 Exploiting technological progress from another application

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 revolutionalised 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 [43]. They are also good enough to be used as a recruiting tool for new soldiers. 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. A potential disruption could be taking place in the low-end of this industry using borrowed technologies from the games industry [43].

The $100 laptop originally developed for use in the third world [32] could possibly facilitate another emerging example. With a capability quite close to the normal $1000 machine, this $100 laptop or its imitator would provide significant improvement in price-performance. It may then be used also by other industry which will exploit it as a low-cost, good enough off-the-shelf robust industrial component (including both hardware and software), in data-logging, monitoring, programmable instrument sub-system to automate their products or incorporate more intelligent functions at affordable prices. Even at the sub-component level, such as its innovative dual-mode display, some could find new applications far beyond the original laptop applications.

Finally, there is a possibility of leveraging on progress of certain sustaining or even radical technology 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 [19] was one classical example. The MEMS accelerometer [26] was another example as it could find new applications beyond its original purpose in automobile crash-sensing. With its reliable and affordable price by now, such affordable accelerometers have found new disruptive applications in games consoles such as the Nintendo Wii, could find opportunities in disruptive products for monitoring of aged folks, and facilitate other new market creations by entrepreneurs. Perhaps the approach of text-mining of literature coupled with roadmapping [10], [22] could be applied here to help search for appropriate technology candidates as disruptive technology options .

From Table 4, 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 technologies. It is also anticipated that the new trend of Open Innovation [40] would spur more interest in this R&D approach for disruptive technology creation.

4.5 Identifying/developing inherently disruptive technologies

This approach as indicated by Proposition 5 is not so obvious initially. Indeed, there may exist many other inherently disruptive technologies which have not been analyzed or developed purposefully from a disruptive innovation angle. We have mentioned in Section 2 that all digital equivalents of analogue counterparts are inherently inferior owing to finite quantization and hence could be easily ignored by R&D departments which are tuned to pursue higher product performance. If the R&D managers could pay more attention to their potential, they could significantly enhance the chance of creating more novel applications ahead of competitors based on such disruptive technologies. The following give two more examples, one classical and one emerging.

When fuzzy logic was first introduced by Lotfi Zadeh in 1965, both the academic and industry communities ignored it as it was obviously inferior to precision logic in all the mainstream control applications [44]. Whereas digital logic recognizes only two values, zero or one precisely, which is a fundamental requirement in conventional control theory and applications, fuzzy logic enables software developers to program computers that can handle vagueness and uncertainty such as “slightly”, “hot”, “many”, “few” inherent 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 in 1988 to provide smooth acceleration/deceleration control of subway trains. Since then, Japanese and other companies globally have introduced numerous fuzzy control applications in auto-focus in cameras/camcorders, wash-cycle control in washing machines, and many other consumer products with these “good enough” and “intelligent” features that are affordable. Progressively, fuzzy logic/control has become a pervasive and basic technology to create new feedback control applications previously not possible owing to high cost or the need of a dynamic mathematical model of a complex process [44], as there are many consumer and industrial automation applications which do not require extreme precisions.

An emerging example of a technology which is inherently inferior/disruptive is the probabilistic chip invented by Krishna Palem in 2004 [45]. Unlike precision digital logic and fuzzy logic, it uses probabilistic bits which take on a logic value of 0 or 1 but only with a probability of ‘p’. Current computing hardware, using conventional bits, expends large amounts of energy calculating with absolute certainty. With probability, the computing hardware uses much less energy with decreasing probability as the voltage level is reduced correspondingly. Another idea in its implementation is that it makes use of the noise inherent in semiconductor hardware as a “free” source of the randomization needed in the probabilistic algorithm. An example of a probabilistic adder is shown in Fig. 2. Using such probabilistic computing hardware, Palem hopes to create a disruptive technology which is just good enough for many commercial applications, but with the potential, order-of-magnitude saving in energy consumed. He envisages its applications in robotics, natural language processing, data mining, signal processing and bio-engineering. It could also have pervasive mobile device applications owing to the much reduced power consumption [46]. The probability chip has just been rated by MIT's Technology Review as one of the top 10 emerging technologies of 2008 [47].

4.6 The process of R&D for Disruptive Technology Creation

It is timely now to discuss the process of R&D to examine which and when each of the broad R&D approaches could be deployed by itself or in combination at the fuzzy front end. First, it should be noted that strategic decision makings in R&D are not independent of marketing. Technology and market development are often combined and iterated [48], [49] to create new winning products as recommended in the established 4th Generation R&D Practice [50]. Purposeful creation of disruptive technology also does not imply that R&D has to be done ahead of or independent of marketing. This is not contradictory to what the Innovator's Dilemma [1] indicates: that the direct feedback from incumbent's customers could not tell us the potential need of any discontinuous product. Instead, market demand has to be created and market learning with "job-to-be-done" analysis will be essential and they are used implicitly when leaders create the vision of a discontinuous product. While a disruptive technology finds applications in a niche market, it will need continuing improvement to overcome competition. Its initially inferior performance relative to the mainstream technology would thus improve with time. Furthermore, the new value creation for the niche products may be fed back to influence customer preferences even in the mainstream business and help to accelerate the occurrence of potential disruption [6]. The above process is shown in Fig. 3. The relevant role of open innovation is increasing and indicated as shown. Nowadays it is also feasible for a large incumbent, or university/research institute to use its core capability to collaborate with a start-up company led by entrepreneurs who have the compelling vision of a new product/service. In this case, the first strategic approach (vision-driven disruptive technology creation) would be formulated and executed by the external company. When a more straightforward R&D without the vision-driven part is engaged to create disruptive technology, the process is simplified to that of Fig. 4.

Christensen has identified two types of disruptive innovation [1], [2]. In low-end disruption, the market is more clear-cut and the focus of the R&D is to ensure that the cost is affordable to this market segment while the performance is adequate. In the case of the steel minimill [1], which is an example of low-end disruption, the initial target was to win the low-end rebar market and the R&D strategy was to simplify the manufacturing process to focus on just this product segment to reduce cost. In the case of the inkjet printer, which is both low-end and new market disruptions, however, the resources needed for R&D were huge [16]. Initially, it was vision-driven in that John Vaught, who led a research team in HP [16], [51] was envisaging a thermal inkjet printer which was simple, low-cost and with reasonable performance although many past attempts failed. He figured out that it would need a solid-state print head that would experience less wear and no clogging, but still be able to spit ink out fast enough for the job. Returning to the laboratory after Christmas in 1978, he realized in enlightenment from watching the coffee percolator that the answer was to use the ink itself to shoot dots on the paper. After many attempts, he found that it was feasible to vaporize and spit out the ink as a droplet and a suitable means of heating the ink with a high degree of control was thin-film resistor. A lot of R&D was then expended to develop quick-drying and light-fast inks, better mechanisms for feeding the paper, new design to lighten the print-head mechanism while increasing the number of nozzles, etc. After the extensive R&D to create the dream product, a significant amount of market development and technology refinement had to be expended before the inkjet printer business took off commercially [16]. In new-market disruption, technology and market development have to be closely coordinated and iterated as prototypes need to be created for market testing/learning. Other examples include disk drive, mobile phones and other mobile devices, Google search engine, Walkman, etc.

An interesting model which is slightly different from low-end and new-market disruptions, is the R&D approach 3: augmenting a sustaining technology with disruptive features. In this approach, an existing sustaining technology or its incrementally improved version is used in the new product. New disruptive features are then added to appeal to non-consumption creating new growth for the business. In situations in which there are limited growth in the conventional market, cramming more technology into an existing product like games consoles would only make it more expensive, harder to use, and worst of all, less fun – as declared by Nintendo's CEO Satoru Iwata [52]. This approach is also much harder for new entrants to follow as they do not have the strong base of core sustaining technology, the brand name and other business development resources. It will also create fewer objections to senior management of incumbent firms who are more hesitant to support the classical disruptive technology approach which is associated with inferior performance relative to sustaining technology.

5. SUMMARY AND CONCLUDING REMARKS

We have discussed the strategic intent of developing disruptive technologies which could serve as technology options to be used in conjunction with a suitable business model/strategy to create successful products leading to disruptive innovation. The technological dimension of disruptive innovation and the candidates of disruptive technologies have been studied. We have also identified five broad R&D approaches which could be used individually or in combination in an appropriate R&D process to purposefully create disruptive technologies as additional technology options often ahead of competitors. Adopting such a systematic and explicit framework would hopefully help companies to share and internalize their experiential learning which would in turn help them to become serial disruptors.

But knowing what to do is not enough, especially if the doing part is difficult. The purposeful approaches/methods of creating disruptive technologies are certainly challenging although the fuzzy front end of disruptive technology creation is not as severe as that of radical innovation [13], [14]. It is imperative for the R&D management to adopt a deliberate, strategic goal of creating disruptive technologies. This goal could be a result of a higher level vision of creating a new product which may have a promising high-growth market, such as a pocket radio which is affordable, a mobile office on laptops, etc. But very often, the market needs are tacit and unless the technologies/prototypes are in the hands of the consumers, the killer applications may not be obvious initially. Examples include email, sms, and mobile phone in the early days. In order not to confuse with radical technology/innovation, it is thus important for the R&D management to keep two points in mind: one is that the disruptive technology must be affordable with good enough performance; the other is that it should create new features valued by the current non-consumers. It is pertinent that the R&D managers/engineers be familiar with tacit market demand issues of disruptive innovation.

Finally, the initial market for disruptive technology/innovation may not be confined to developed economies as in the case of radical technology/innovation. The speed and extent of the mobile phone market development in China, which has created opportunities for high-end as well as disruptive products, serves as a good example. Indeed, some multinational companies have established new R&D centres in the developing economies not only to appropriately adapt technologies/products imported from the developed economies, but also to explore the development opportunities for new products first developed for the very large mass-markets of these emerging economies [3], [53]. These R&D efforts targeting the high-growth local markets at the "Bottom of Pyramid" [54], 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. They are by no means easy and it is hoped that the 5 strategic approaches presented in this paper will assist in their implementations. In addition, the so called “Silver Market” or “Greying Market” fast emerging in both developed as well as developing countries [55], [56] offers another golden opportunity for companies which could conduct purposeful R&D for creating appropriate disruptive technologies to address such potentially high-growth but price-sensitive markets which simultaneously demand adequate performance.

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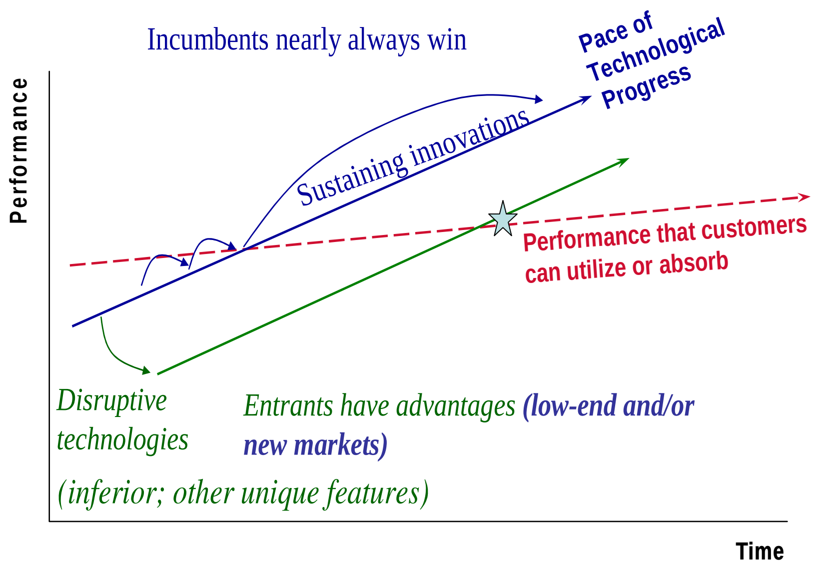

Fig. 1 Disruptive Innovation [1]

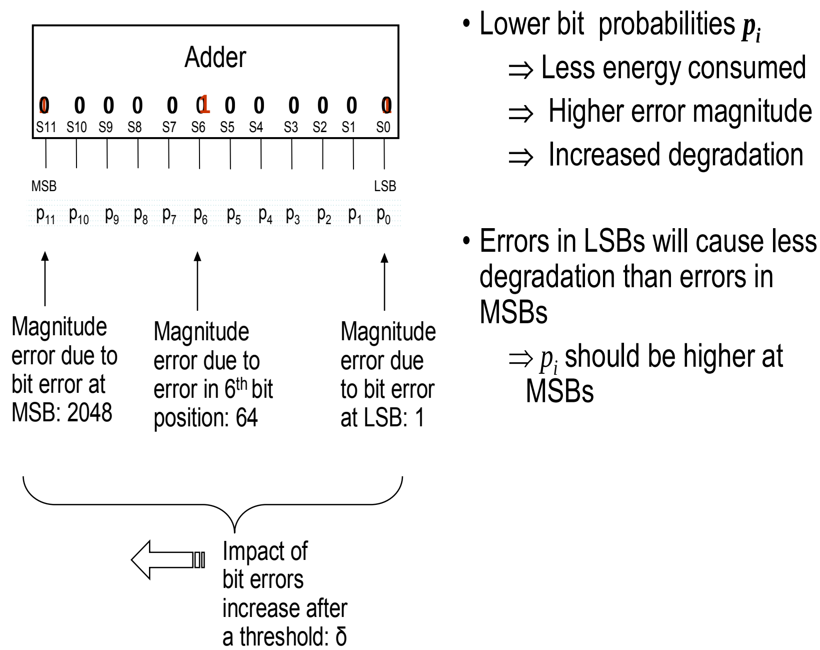

Fig. 2 A Probabilistic Adder

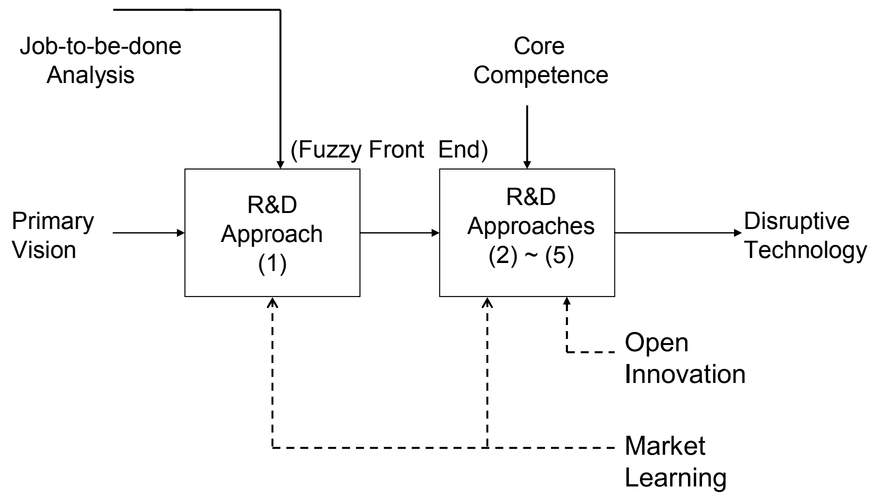

Fig. 3 A Fourth Generation R&D Process

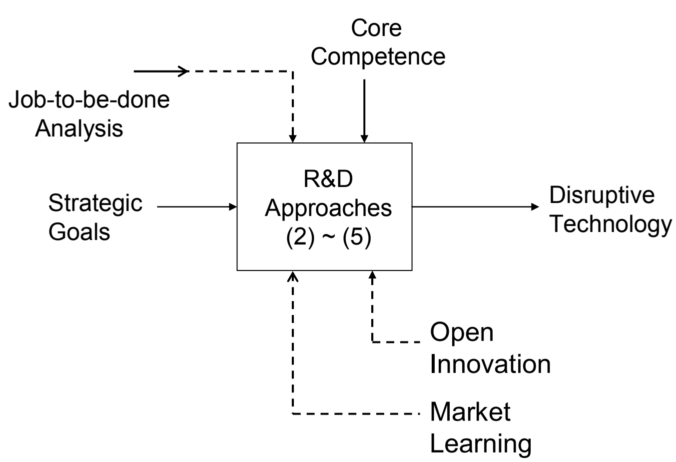

Fig. 4 A Shorter R&D Process

Cases	Period	Market	Company
Transistor Radio	1950s	Mobile Music	Entrant
Hard Disk Drive	1980s – Present	Mass Data Storage	Entrant / Incumbent
Wii Games Console	Present	Games	Incumbent
Digital Camera	Present	Photography	Entrant/Incumbent
Auto. Ext. Defibrillators	Present	Medical Device	Incumbent

Table 1: Diversity of the Cases

Cases	Broad R&D Approaches			
	Vision-driven	Reshaping a high-end technology	Augmenting a sustaining technology	From other Applications
Transistor Radio	√			
Hard Disk Drive	√	√		
Wii Games Console	√		√	√
Digital Camera	√			√
Auto. Ext. Defibrillators		√		

Table 2: Broad R&D Approaches Used

Approaches	Frequency of Usage
i. Vision-driven	22
ii. Reshaping	17
iii. Augmenting	2
iv. From other applications	8
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v. Inherent	3

Table 4: Application Frequencies of the 5 Broad R&D Approaches

Examples						
Disruptive Technology	**Mainstream Technology**	**Vision-driven**	**Reshaping a High-end Technology**	**Augmenting with disruptive features**	**Borrowed from another application**	**Inherently disruptive**
3.5 inch HDD	5.25 inch HDD		Y		y	
Hydraulically actuated excavator	Cable-actuated excavator	Y			y	
Minimill	Integrated mill		Y			
Minicomputer	Mainframe	y	Y			
Personal Computer	Minicomputer	y	Y			
Inkjet printer	Laser Printer	y				
Programmable controllers	Electromechanical	y				
Endoscopic surgical equipments	Complicated heart procedures	y	Y		Y	
50cc Supercub	Traditional motorcycle		Y			
Microprocessor	Complex logic circuits based on PWB	y			Y	
Routers based on packet-switching technology(enable VOIP)	Routers based on traditional circuit-switching equipment	y		y		y
Small business accounting software Quickbooks	Mainstream accounting software		Y			
802.11	Local-area wireline network	y	Y			
Bell telephone	Long-distance telegraphy	y				
Plastic-encased tools with universal motors	Handheld electric tools before 1960		Y		Y	
Blended plastics	Engineering plastics				Y	
Canon photocopiers	High-speed Xerox machine	y	Y			
Digital animation	Full-length animated movie	y			Y	
Small-sized microwave oven	Normal-sized microwave oven	y	Y			
Google search engine	Yellow pages	y				
Point and shoot Brownie camera	Expensive complicated photography	y	Y			
Oracle's relational database software run on minicomputer	Incumbents' relational database software run on mainframe	y	Y			
Palm pilot, RIM blackberry	Notebook computer		Y			
Portable diabetes blood glucose meters	Large blood glucose testing machines		Y			
Seiko quartz watches	Mechanical watches	y				y
Transistor radio	Vacuum tube radio	y				
Walkman	Traditional audio player	y	Y		y	
SQL database software	Oracle database software	y	Y			
Wireless telephony	Wireline phones	y		y		
LCD Flat-panel Display	CRTs	y				y

Table 3: R&D Approaches Used In Disruptive Innovation Cases in Christensen’s Books

Revised 29 Sept 08/Ver 2