Technological Change within Hierarchies:

The Case of the Music Industry

by

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Abstract

This paper uses the music industry to demonstrate a model of technological change that explains the sources and timing of technological discontinuities and dominant designs. The process by which firms translate customer needs into products can be represented in terms of an interaction between customer choice and product design hierarchies. Technological improvements at lower levels in the product design hierarchy can change the design tradeoffs and thus affect movements up and down the hierarchies. Movements up the hierarchies lead to the emergence of new product classes (i.e., technological discontinuity) while movements down the hierarchies may result in the emergence of a dominant design in a specific product class.

Keywords: technological discontinuities, dominant designs, hierarchies, products, customers, music industry.

Journal of Economic Literature classifications: O32, O33

1. INTRODUCTION

In spite of the recognized importance of technological discontinuities and dominant designs in the existing literature on technological innovation, there are few models that address the sources and timing of them. The existing literature on technological discontinuities emphasizes individual genius, their rarity (Tushman and Anderson, 1986), their heavy impact on technical progress in the industry (Anderson and Tushman, 1990), and the difficulties of responding to them (Utterback, 1994). The literature on dominant designs emphasizes social factors (Anderson and Tushman, 1990), their lack of existence in some industries (Klepper, 1996), and problems with defining and identifying them (Utterback, 1994; Murumann and Frenken, 2005).

This paper presents an alternative model of technological change that addresses the sources and timing of technological discontinuities and dominant designs. The model emphasizes product design and customer choice hierarchies (Clark, 1985) and technological improvements at lower levels in the product design hierarchy, e.g., performance trajectories for components (Christensen, 1997). By definition, the performance trajectories for components involve continuities and it is the cumulative nature of the improvements along these trajectories that drive technical progress in the industry. These component-based trajectories also drive changes in the design tradeoffs for the product as a whole, which affects the movements up and down the product design and customer choice hierarchies. Movements up the hierarchies may lead to the emergence of a technological discontinuity, which this paper calls a new product class, while movements down the hierarchies may result in the emergence of a dominant design.

This paper uses data from the music industry to demonstrate this alternative viewpoint of technological change. The music industry is an appropriate industry to apply the model due to large amounts of technological change, large literatures, and the wide agreement between sources for the variables used in the proposed model. The lack of randomness in the choice of industry suggests that we must be careful about generalizing to other industries. Following a description of the proposed model and research methodology, this applies the model to the music industry.

2. PROPOSED MODEL

The process by which firms translate customer needs into products can be represented in terms of an interaction between customer choice and product design hierarchies (Clark, 1985), where the interaction between them also includes the determination of a business model (Chesbrough, 2003) and sales and service channels (Abernathy and Clark, 1985). In the customer choice hierarchy, firms develop a conceptual framework for how customers evaluate competitive offerings. In doing this, they divide users and applications into different segments (this paper focuses on users and applications) and the problems to be solved in each segment. The product design hierarchy defines the method of problem solving and it includes both alternative designs and sub-problems for both products (Clark, 1985, Figure 1) and processes (Durand, 1992).

Place Figure 1 about Here

The introduction of new products and services reflect movements both down and up the hierarchies of product design and customer choice in the industry. As design activity shifts from core to periphery at one particular level of the product design hierarchy, it also moves from higher-level to lower-level problem solving (Murmann and Frenken, 2005) in both the product design and customer choice hierarchies as depicted in Figure 1. The coalescence of customer needs around a few related dimensions and pressures to reduce cost and standardize (Abernathy and Utterback, 1978) cause firms to redefine the sub-problems in terms of independent modules (Ulrich, 1995) where "design rules" define how these different modules interact, thus ensuring compatibility between them. Competition among alternative module designs can only occur after "splitting" occurs, where splitting is the equivalent of defining independent sub-problems (Baldwin and Clark, 2000).

The choice of design alternatives and the definition of sub-problems represent a dominant design for the industry, which is consistent with the first half of Suarez and Utterback's (1995, Figure 1) definition: "a dominant design is a specific path along an industry's design that establishes dominance among competing paths." Defining a dominant design as a path implies that a stable and open architecture might exist at multiple levels in a single product design hierarchy. This is consistent with other research on dominant designs that emphasizes a stable architecture (Murmann and Frenken, 2005) and the possibility of such an architecture existing at multiple levels in a single product design hierarchy (Tushman and Murmann, 1998).

However, depending on the industry, dominant designs will differ in terms of the relative importance of alternative designs and sub-problems within a specific design path and the number of levels to which a dominant design proceeds down the design hierarchy (i.e., the degree of commonality between the design paths of different firms). The latter will depend on both the flexibility/robustness of the technology and the extent of common needs among users. The extent of common needs among users sounds similar to the second half of Suarez and Utterback's (1995) definition: "a dominant design will embody the requirements of many classes of users, even though it may not meet the needs of a particular class to quite the same extent as would a customized design." Although this paper implies that dominant designs have impacted on competition in the music industry, it is still unclear whether and how they impact on competition in all industries (Teece, 1986) and other concepts such as increasing returns to scale may play a larger role (Klepper, 1996, 1997, 2002).

Returning to the movements within the hierarchies, technological improvements at lower levels (e.g., performance trajectories for components in an assembled product) in the product design hierarchy can change the design tradeoffs that are implicit at all levels in this hierarchy and thus lead to movements *back up* the hierarchies of both product design and customer choice. These improvements can change these tradeoffs at any level in the product design hierarchy and changes in the tradeoffs at the highest levels in this hierarchy (e.g., between different measures of cost and/or performance) may be accompanied by movements back up the customer choice hierarchy.

While many new products and services involve small movements back up the hierarchies, we are mostly interested in large movements back up the hierarchies (i.e., technological discontinuities), which we define as new product classes. New product classes that are primarily due to movements back up the customer choice hierarchy are often called niche innovations (Abernathy and Clark, 1985) or disruptive technologies (Christensen, 1997). Ones that are primarily due to movements back up the product design hierarchy are often called revolutionary (Abernathy and Clark, 1985) or architectural (Henderson and Clark, 1985) innovations while ones that involve movements back up both hierarchies are often called radical innovations (Abernathy and Clark, 1985). By showing how these discrete innovations fit within the proposed model, future research on the success or failure of incumbents with the proposed model can refer to the research on these discrete innovations. This research on the success or failure of incumbents with discrete innovations includes the roles of organizational structure (Henderson and Clark, 1990), capabilities (Tushman and Anderson, 1986; Afuah, 1995), complementary assets (Teece, 1986), and managerial cognitive representations (Kiesler and Sproull, 1982; Tripsas and Gavetti, 2000).

In all cases, the successful emergence of a new product class is followed by a period of intense technical variation (Tushman and Anderson, 1986). The technological improvements at lower level components in the hierarchy can extend the period of ferment and temporarily prevent movements down the design hierarchy where firms emphasize integral design. Nevertheless, as is discussed above, design activity eventually shifts from higher-level to lower-level problem solving.

There are a number of mathematical models that can be applied to the movements up and down the hierarchies. Competition between product classes, which represent movements back up the hierarchy, can be modeled using value trajectories and indifference curves (Adner, 2002). New product classes must also overcome the economies of scale (both supply and demand ones) of the existing product class and create a critical mass of users (Rohlfs, 2001). For example, in the case of demand-based ones, customers perceive a tradeoff between the performance of a new product class and its level of compatibility with an existing product class. Without compatibility with the existing product class, the new product class must have a large performance advantage over the existing product class in order for users to forgo the network effects, including both indirect (complementary) and direct ones, of the existing product class (Shapiro and Varian, 1999).

If we focus on the compatibility aspects of modular designs, Shapiro and Varian's tradeoff between performance and compatibility can also be applied to movements down the hierarchy that deal with defining sub-problems in a modular way. This paper focuses on the definition of sub-problems in a modular way due to the large emphasis many scholars place on modularity (Langlois and Robinson, 1992; Ulrich, 1995; Sanchez and Mahoney, 1996; Baldwin and Clark, 2000). Following the introduction of a new product class, there is decreasing marginal utility from increases in product performance (Meyer and Johnson, 1995) via an integral design and increasing marginal utility from economies of scale via a modular design. Although this increasing utility from economies of scale is typically modeled in terms of the number of users for demand-based ones and the number of units for supply-based ones (Shapiro and Varian, 1999), we can plot this marginal utility as a function of time since the number of users and units increase over time in a growing market, where this marginal eventually declines as shown in Figure 2 (Rohlfs, 2001). Figure 2 summarizes this tradeoff over time and helps us better understand how and why the emergence of a dominant design often lags the emergence of a technological discontinuity/new product class (Tushman and Anderson, 1986).

Place Figure 2 about Here

3. RESEARCH METHODLOGY

The author analyzed the primary and secondary literature on the music industry including academic papers and books from the management, economic, and historical fields, practitioner-oriented accounts, and encyclopedic histories, which are referenced below. Through analysis of this literature, the author identified: 1.) the changes in product class through major movements back up the product design or customer choice hierarchies or changes in business models and sales channels; 2.) the technological improvements at lower levels in the product design hierarchy (i.e., performance trajectories for components) that have changed the design tradeoffs thus leading to movements back up the hierarchies; 3.) the movements down the hierarchies in each product class in terms of both alternative designs and definitions of sub-problems in a modular way; and 4.) the dominant designs, particularly ones that deal with defining sub-problems in a modular way and the trajectories impacting on them.

4. RESULTS: BRIEF HISTORY OF THE RECORDED MUSIC INDUSTRY

Table 1 summarizes the major product classes in the music industry and key aspects of their product design and customer choice hierarchies. It divides the product design hierarchy into recording media, recording units, and playback units and the customer choice hierarchy into initial applications and type of music. Most changes in product class involved movements back up the product design hierarchy for all three aspects of it while only two changes in product class involved changes in the main customers (i.e., customer choice hierarchy).

Table 2 summarizes the technological improvements at lower levels in the product design hierarchy (e.g., component performance trajectories) that have changed the design tradeoffs and enabled movements back up the product design hierarchy and the emergence of new product classes. The key component performance trajectories have changed from electro-magnetic and mass production ones in the late 19th and early 20th century, to vacuum tubes from the 1920s, transistors, integrated circuits (ICs) (See Figure 3), magnetic tape (See Figure 4), and plastics from the 1960s (American Plastics Council, 2004), and variety of ones in the 1990s. Table 3 summarizes the dominant designs for each product class and for the ones that involved defining sub-problems in a modular way, the tradeoffs between the decreasing marginal utility from increases in product performance and the increasing marginal utility from economies of scale.

Place Tables 1 – 3 and Figures 3 and 4 about here

4.1 Acoustic cylinders

Improvements in electro-magnetic devices such as magnetic diaphragms, magnetic coils, and clockwork motors and mass-production techniques such as lathes enabled Alexander Graham Bell and Thomas Edison to create the first phonographs in the 1880s. These first phonographs carried out both recording and playback functions. Every recording was an original, there was no means of replication, and the quality of the cylinders quickly deteriorated (due to the stylus). Basically, a horn containing a diaphragm was located close to the sound to be recorded. The diaphragm moved a mechanical stylus, which etched the spiral analog of the sound waves onto the soft metal foil that covered a cylinder either in a vertical- or lateral-cut format. For playback, the stylus was moved over the indentations in the foil to vibrate the diaphragm in the same way that the recording had been made. Both the stylus and reproducing arm moved precisely along the cylinder by a lead screw assembly. Later, the tin foil was replaced by wax and an electric motor was used in place of hand power (Millard, 1995: Read and Welch, 1976).

Although Bell, Edison, and others initially believed that business applications like transcribing would be the initial applications for these devices, most of the devices were used for musical entertainment. This included both home and more importantly coin-operated machines where Edison's machine was more successful than Bell's machine since the former relied on an electric motor rather than a foot treadle for power (Read and Welch, 1976; Chanan, 1995). The poor sound quality of the first phonographs restricted the type of music that could be played on them. Artistic whistling records, the banjo, the xylophone, and only later military music became popular in the 1890s (Millard, 1995).

The identification of musical entertainment as the major application for phonographs led to movements down the product design and customer hierarchies in the late 1800s and early 1900s. Spring-driven and later clockwork motors and pre-recorded cylinders became standard items on phonographs. However, the competition between different diameters, numbers of grooves per inch, and cutting formats (lateral versus vertical cuts) were still occurring in cylinders several years after discs had replaced cylinders as the dominant product class for recorded music. As Millard (1995) says about the situation in 1908, "If you bought a record made by one company, you were lucky if it played on the machine of another."

4.2 Acoustic discs

Improvements in materials such as ebonite and shellac and mass-production techniques such as molding led to the first change in design tradeoffs shown in Table 2 and thus to movements back up the customer choice and product design hierarchies and the emergence of acoustic discs as a new product class of music players in 1895.

Although the sound was still recorded via a horn, diaphragm, and stylus (Read and Welch, 1976), it was recorded on a disc as opposed to a cylinder where discs were easier to duplicate, use, and store than cylinders. Initially the narrow bandwidth of the acoustic needle and horn favored the singing voice over instruments and the first million-selling record was from one of the leading opera singer's, Enrico Caruso (Chanan, 1995).

The problem with disc players was that it was necessary to reduce the rotational speed of the disc as the styli approached the end of it. Many firms including Thomas Edison's company stuck with the cylinder because they believed that the additional cost of sophisticated motors did not justify the benefits of the disc player (Read and Welch, 1976). However, improvements in motors and in the recording density of discs changed the design tradeoffs for music players in that the improved recording density of the discs eventually outweighed the costs of the improved motors where consumers could store 50 discs in the same space as four regular or one concert cylinder (Read and Welch, 1976). As part of these improvements entrepreneurs such as Emile Berliner and Eldrige Johnson, who formed the Victor Talking Machine in 1901, experimented with different types of materials for masters (zinc, wax, and phenol resins) and mixed shellac, which had been used to make buttons, with a number of other substances to form a lacquered plastic (Chanan, 1995; Read and Welch, 1976).

The emergence of a dominant design in discs can be seen in terms of a tradeoff between decreasing marginal utility from increases in product performance via an integral design and increasing marginal utility from economies of scale via modularity, as is represented by Figure 2. Firms stopped trying to increase the recording density of shellac discs because the benefits of a modular design for discs and players exceeded the performance improvements via an integral design. Small improvements in recording density required new players (including stylus, tone arm, and magnetic pickup) and thus made it difficult to play old discs on them.

The emergence of a dominant design for discs along with the expiration of most patents in 1917 had a dramatic impact on competition. The number of independent producers of records and record players in the U.S. market to rise from 18 in 1914 to 166 in 1918. This caused the price of records, record players, and profits to drop (Millard, 1995). The big loser was Thomas Edison. While Columbia Manufacturing had introduced discs soon after Victor did, Edison did not introduce a disc player until 1913 and when he did, he chose to continue using the vertical-cut as opposed to the lateral-cut format, which had become the dominant design for discs. This prevented users of Edison's disc player from accessing the large amount of pre-recorded music that existed for the lateral-cut format (Millard, 1995). Coupled with Edison's slow move to furniture-type cabinets and to electrical recording, Thomas A. Edison, Inc. ceased the manufacture of recorded-sound products in 1929 (Read and Welch, 1976).

4.3. Electrical recording

Improvements in vacuum tubes and to a lesser extent microphones and speakers led to a second round of changes in the design tradeoffs (See Table 2) and thus to movements back up the product design and to a lesser extent customer choice hierarchies and the emergence of a third class of music recording and players called electric recording in the early 1920s (See Table 1). Improvements in vacuum tubes were initially driven by attempts to increase the range of telephone calls but by the early 1920s the radio industry had become the major driver of improvements in them (Inglis, 1991). These improvements eventually enabled the advantages of vacuum tubes to outweigh the costs of them and also the costs of microphones and speaker, which together replaced the horn. The use of microphones meant that the performers and recording equipment could be separated and orchestras could be more widely dispersed during a recording session. The greater responsiveness of microphones also enabled the use of lighter cutters, which reduced noise and thus improved the quality of music (Read and Welch, 1976; Millard, 1995).

The improved quality was particularly evident in the lower end of the frequency range (i.e., the bass sounds) and enabled the recording of a new type of music called Jazz, which became the rage of the 1920s (Chanan, 1995). This new music and the reduced cost of these playback machines opened up a new market and encouraged many people to replace their old collections of discs with the new ones. Furthermore, the new condenser microphones and speakers enabled the recording studios to begin creating an "illusion" as opposed to a "perfect" reproduction in records (Chanan, 1995).

Western Electric created the technologies for electrical recording and licensed them to other firms in the early 1920s. The new technologies required new discs and although it was possible to play an electrically recorded disc on an acoustic machine, they sounded better on a new player (Read and Welch, 1976; Chanan, 1995). The adoption of a common standard by the major record companies guaranteed the interchangeability of records and record players where the 78-rpm became the dominant design for records (Robertson and Langlois, 1992). However, unlike discs, electrical recording did not involve defining sub-problems in a new modular way. It did not involve a new recording medium and it only involved the replacement of existing parts with new ones (i.e., alternative designs). Therefore, the tradeoff represented in Figure 2 did not occur with electrical recording.

The ascendance of radio in the 1920s and the similarities between phonographs and radios also impacted on the dominant design for phonographs and led to partial movements back up the product design and customer hierarchies and the emergence of a new business model for the music companies. Vacuum tubes and speakers were used in both record players and radios and the sales of dual use units rose dramatically in the late 1920s. The greater sales of radio caused its leaders, RCA and Columbia Broadcasting, to purchase the recording companies Victor and Columbia Phonograph Company and use radio (and to a lesser extent film) to promote the sales of music. Although some performers resisted the free use of their music over the radio waves, a series of court cases in 1940 ruled that property rights to a recording ended when it was sold and it quickly became clear that performers benefited from these free advertisements. In fact, there were so many benefits to having records played on radio programs that some record companies paid disc jockeys to play their records, which became known as payola (Millard, 1995).

4.4. Vinyl records and the LP

Improvements in vinyl materials and pickups led to a third round of changes in the design tradeoffs (See Table 2) and thus to movements back up the product design and to a lesser extent customer choice hierarchies and the emergence of a new product class called vinyl records in the late 1940s. The vinyl resins were first used in cabinets for radios and parts for telephones in the early 1930s. Because vinyl contains no abrasives, like those found in shellac, vinyl enabled the use of a permanent jeweled stylus with a synthetic sapphire or diamond. The lightness of this stylus and the use of piezo-electric crystal pickups doubled the signal-to noise ratio of these records (Millard, 1995).

The improvements in vinyl materials drove the emergence of a new product class and impacted on the timing of the dominant design for it. The emergence of Columbia's LP as the dominant design for vinyl records can be seen as a tradeoff between decreasing marginal utility from increases in product performance via an integral design and increasing marginal utility from economies of scale via modularity, as is represented by Figure 2. While RCA introduced 33-rpm vinyl records and compatible players before the vinyl records had a substantial advantage in recording density over shellac records and thus had to quickly pull them from the market (Langlois and Robertson, 1990), Columbia Records introduced vinyl records in 1948 or 16 years after RCA did. By this time, Columbia's vinyl records (224 to 260 grooves per inch) had almost three times the recording density of shellac records (80 to 100 groves per inch), which enabled Columbia to dramatically improve both the quality and the number of songs on a single record (Millard, 1995); the latter improvement caused the new record to be called the LP (long playing). These advantages were particularly important to buyers of classical records (Langlois and Robertson, 1990).

There were two other critical parts of Columbia's success. First, it made the records partially compatible with existing phonographs. Columbia offered an inexpensive attachment that enabled the new records to be played on existing phonographs for $9.95. Second, Columbia also licensed its microgroove technology to other record makers like Philco (Langlois and Robertson, 1990).

The big loser was RCA, which introduced its own micro-groove vinyl records and players that used a 45-rpm format, thus starting the "battle of the speeds." Although this second standard did confuse some consumers (Millard, 1995), there were enough sales of classical music to create a critical mass of users with the 33-rpm vinyl records

(Rohlfs, 2001). Furthermore, the incompatibility between 33- and 45-rpm records turned out to be one way. Not only was it possible to play 45-rpm records with a stylus designed for a 33-rpm record, by placing a plastic adapter in the hole of a 45-rpm record, it was possible to listen to the 45-rpm records on a 33-rpm record player (Langlois and Robertson, 1990).

The introduction of vinyl records also played a role in the introduction of magnetic reel-to reel tape for recording music and thus magnetic reel-to reel tape is considered part of the same product class as vinyl records in Table 1. The higher cost of recording "masters" for vinyl than shellac records increased the need for editing (Chanan, 1995) and improvements in the recording density of magnetic tape during the 1930s by German firms for governmental applications eventually provided sufficient recording capability to provide this editing capability and thus changed the design tradeoffs for recording studios in the early 1950s. New entrants or so-called independents adopted magnetic tape faster than the large firms did due to the lower cost but lower recording quality of the tape and they used the tapes to sell their music to the major recording companies that controlled the distribution of music (Millard, 1995; Huygens et al, 2001). Improvements in the tape caused all of the music companies to use magnetic tape to record with multiple microphones and mixing consoles by the early 1960s (Millard, 1995).

4.5 Stereo music and hi-fidelity

Improvements in both vinyl recording density and electrical components led to a fourth round of changes in the design tradeoffs (See Table 2) and thus to movements back up the product design and to a lesser extent customer choice hierarchies and the emergence of a fifth product class called stereo LPs in the mid-1950s. Although the record companies had been doing research on stereo since the early 1930s, the improvements in vinyl recording density made the recording of stereo music on LPs, not just stereo singles, possible (Millard, 1995). As for stereo players, although improvements in vacuum tubes and other discrete components were made throughout the 1920s and 1930s, they were not introduced on a wide scale until the emergence of vinyl records exposed the poor quality of the record players and expanded the interest in hi-fidelity from amateur phonograph builders to regular consumers (Robertson and Langlois, 1992).

Like vinyl records, there was a tradeoff between the decreasing marginal utility from increases in product performance via an integral design and increasing marginal utility from economies of scale via modularity in the introduction of stereo records. However, the costly "battle of the speeds" caused this tradeoff to be carried out inside firms and committees as opposed to the in the marketplace. The costly "battle of the speeds" encouraged the record companies to agree on a standard that was also backward compatible with non-stereo records and delay the release the stereo records until the recording density of vinyl records had reached the level at which backward compatibility could be achieved in the mid-1950s. Purchases of stereo records exceeded those of non-stereo records by the late 1950s (Millard, 1995).

4.6 Transistor players

Improvements in transistors, which were driven by military applications, and plastics led to a fifth round of changes in the design tradeoffs (See Table 2) and thus to movements back up the product design and to a lesser extent customer choice hierarchies and the emergence of a new class of inexpensive music player that is based on transistors. Young people were the major purchasers of these inexpensive players that initially had inferior sound quality to the vacuum tube-based devices. Japanese firms went back up the hierarchies fasters than U.S. firms did to target this low-end market (Christensen et al, 2001) and introduce the first transistorized phonographs in 1961 (Millard, 1995) after they already dominated the market for transistor radios (Lynn, 2000). Improvements in the quality and cost of transistors and later ICs continued to change the design tradeoffs for music players over the next 40 years and unlike the product classes that involved new recording mediums, strong demand-based economies of scale did not exist with transistor players. These improvements led to a continuous reduction in the number of components in a music player; a single chip in a phone can now carry out these functions (Funk, 2004).

4.7 Portable tape players

Continued improvements in the recording density of magnetic tape and plastics led to a fifth round of changes in the design tradeoffs (See Table 2) and thus to movements back up the product design and to a lesser extent customer choice hierarchies and the emergence of a new product class called portable tape players in the 1960s. The improvements in recording density, which were driven primarily by the computer industry and to a lesser extent by the musical recording studios (Daniel, et al, 1999), enabled the use of thinner and narrower tape. The improvements in the cost and strength of plastics enabled plastics to be used for special runners, hubs, guides, and spools and thus eliminated the need to thread tape as with reel-to reel players.

The emergence of Philip's 1/8" cassette tape as the dominant design for portable players can be analyzed in terms of a tradeoff between decreasing marginal utility from increases in product performance via an integral design and increasing marginal utility from economies of scale via modularity (See Figure 2)[1]. There were decreasing returns from reductions in player size via smaller tape and increasing returns from a single standard for cassette tapes. While the first tape players (e.g., 4-track and 8-track systems) were primarily used in automobiles (Millard, 1995), cassette tapes dramatically increased the portability of music players.

4.8 Digital

Improvements in microprocessors, magnetic recoding density, lasers, metallic coatings, and ICs have led to continuous changes in the design tradeoffs and thus to repeated movements back up the product design and to a lesser extent customer choice hierarchies for digital music players (See Table 4). Although pulse code modulation (PCM) was developed by telephone companies in the 1930s in an attempt to get more messages on their wires, it has been improvements in microprocessors and semiconductor memory that have made the use of PCM possible (Millard, 1995). Improvements in lasers and metallic coatings drove the introduction and improvements in both compact discs (CDs) (Millard, 1995; Grindley, 1995) and Minidiscs, improvements in magnetic recording density have driven the introduction and improvements in both digital tape players and digital hard disk players (Grindley, 1995), and improvements in ICs are driving the use of USB devices and semiconductors in portable devices. There is competition between these different product classes and competition within each one to determine a dominant design for each product class.

[1] A similar argument can be made for the emergence of a dominant design for reel-to reel tape.

The first successful digital playback machines (See Table 5) used compact discs (CDs) that were developed by Philips and Sony. Semiconductor lasers and light-sensitive photodiodes are the critical technologies (Millard, 1995; Grindley, 1995) and they were the result of improvements in semiconductor processing and the use of lasers for bar code readers in the 1970s. Introduced in late 1982, their superior sound quality and smaller size caused them to overtake record sales by the late 1980s (Grindley, 1995). Like the vinyl records, classical music buyers were the first to purchase these CD players (Robertson and Langlois, 1992).

Place Table 5 about here

Digital audio tape (DAT), digital compact cassettes (DCC), and mini discs have been much less successful than the CD. None of these products were able to overcome the demand-based economies of scale that exist with CDs and create a critical mass of users. Their performance advantages over CDs are small, music companies have not strongly supported them, and firms have not found a way to move back up the customer choice hierarchy. Other than the use of DCC in recording studios and Sony's minidisk (miniature version of CDs) for recording rented CDs, these products have not found new customers or created new applications or music (Rohlfs, 2001; Grindley, 1995).

Digital technologies probably had a larger impact on recording equipment than on recording media and playback units in the 1980s and early 1990s. Improvements in microprocessors and semiconductor memory continue to change the design tradeoffs for recording studios and have made personal computers (PC) the interface between the recording engineers and digital synthesizers, the MIDI (Music Instrument Digital

Interface) sequencer the word processor for music (Millard, 1995), and led to the introduction of new types of music such as reggae and rap (Millard, 1995).

Improvements in microprocessors and magnetic and semiconductor memory have also played a role in the diffusion of the Internet and are now impacting on the downloading of music on the Internet. Such improvements have had a large impact on the design of public switched networks (Gilder, 2000), local area networks (LANs), and devices such as modems (von Burg, 2001). For example, packet switched networks required much more computer processing than circuit-switched networks but provide much more efficient data transmission (Abatte, 1999). The PC is becoming the main music player in the home and new forms of portable units that rely on downloads over the internet are replacing CD-based players. The success of file sharing services, better digital copyright management, and potential new revenues have also caused music companies to more aggressively embrace the Internet.

For example, Apple's i-Tunes and similar services for mobile phones represent a new business model and offer new revenues to music companies. Downloading short songs wirelessly on phones to be used as ringing tones in Japan had a similar level of downloads as i-Tunes did in globally in 2003 and 2004 and Japanese service providers improved this service to include full songs for less than $3.00 in November 2004 (Funk, 2004). In Korea, lower copyright protection and the earlier introduction of MP3 functions on phones has already made phones a popular device for listening to music that has been downloaded for free from the Internet[2]. It is likely that continued improvements in semiconductor memory will have a large impact on competition between i-Pod-type devices and mobile phones in the playing of music and may cause

[2] Personal communication, Moon Suh Park, Vice President, Qualcomm, October 20, 2004)

the mobile phone to eventually become the dominant product class for portable music players.

5. DISCUSSION

The purpose of this paper was to introduce a model of technological change that explains the sources and timing of technological discontinuities and dominant designs where technological discontinuities are defined as new product classes. The use of a single industry suggests that we must be careful about generalizing to other industries. With this caveat in mind, this paper has made two contributions to our understanding of technological change.

First, this paper helps us better understand the sources and timing of technological discontinuities. It showed how improvements at lower levels in the product design hierarchy (i.e., improvements in component performance) changed the design tradeoffs and led to the emergence of new product classes that involve movements back up the product design and customer choice hierarchies. Contrast this with the existing literature which focuses on firm reaction to discontinuities as opposed to the sources of them.

One implication of the dynamic nature of design tradeoffs is that industries are not in equilibrium. Firms must constantly respond to changes in the design tradeoffs, which are being driven by improvements at lower levels in the product design hierarchy. Contrast this with the punctuated equilibrium model (Tushman and Anderson, 1986), which implies that industries are often operating near equilibrium. The steeper the performance improvements at lower levels in the hierarchy, the farther the industry will likely operate from equilibrium, the greater the chances of a technological discontinuity (i.e., new product class), and the greater the importance of understanding the sources of these technological discontinuities.

A second implication of focusing on design tradeoffs is that we are able to more closely link the managerial and economic literature on innovation with that of engineering fields. Engineering education, textbooks, and trade journals readily use the terms design tradeoffs, product design, and customer needs; the latter two are a central part of product design and customer choice hierarchies. Although forecasting technological change is highly problematic, decisions about firm R&D budgets implicitly reflect technological forecasts and the size of these budgets suggests that firms need better tools to analyze the future. By using variables and logic that are widely used by engineers, an emphasis on design tradeoffs provides firms with a methodology for analyzing the future of their industry.

The second key contribution of this paper involves the concept of dominant designs. Although other scholars have noted the existence of dominant designs at multiple levels in a nested hierarchy (Tushman and Murmann, 1998; Murmann and Frenken, 2005), the proposed model takes this one step further by defining a dominant design in terms of a path, which is consistent with Utterback and Suarez's (1995) definition. The case of transistor players highlights the advantage of this definition. Firms have pursued a similar design path that has led to continuous reductions in the number of components in a player and the emergence of single chip players that are now in phones and other portable devices.

A second contribution to the area of dominant designs concerns the timing of dominant designs that involve defining sub-problems in a modular way. All but three of the relevant product classes showed the tradeoff between decreasing marginal utility from increases in product performance and increasing marginal utility from economies of scale. In cylinders and discs, there were decreasing returns from improvements in their recording density and increasing returns from the choice of a single standard. In cassette tapes, there was also decreasing returns from reductions in tape size and increasing returns from the choice of single standard. Furthermore, when one considers the decisions to delay the release of vinyl discs, stereo systems, and CDs, these cases are also consistent with the tradeoffs between decreasing marginal utility from increases in product performance and increasing marginal utility from economies of scale. For example, Columbia delayed the introduction of its vinyl records until the performance advantages in terms of recording density outweighed the cost of buying new players and replacing ones collection of records. All of the manufacturers delayed the introduction of stereo records until the vinyl recording density was sufficient to make stereo LPs possible.

Further research should apply the model to other industries and use it to analyze the success or failure or firms in combination with previous research on discrete innovations. For example, in the music industry it appears that some firms moved more effectively back up the hierarchies than others in discs (Edison failed), vinyl LPs (Columbia), transistor players (Japanese manufacturers), and in the use of reel-to reel tape players (Capitol Records). Analyzing these and other examples using the previous research on discrete innovations in combination with the proposed model can increase our understanding of how and why incumbents succeed or fail.

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Table 1. Major Product Classes in the Music Industry

Date of Intro-duction	Product Class	Product Design Hierarchy			Customer Choice Hierarchy	
		Recording Media	Recording Unit	Playback Unit	Early Application	Types of Music
1880s	Acoustic Cylinders	Tin foil, Wax cylinder	Stylus etches wave form on cylinder	Movement of stylus drives horn	Juke Box, Home listening	Expansion of folk to classical
1900s	Acoustic Discs	Shellac record	Stylus etches wave form on discs	Different stylus and player	Home listening	Addition of Opera
1920s	Electrical Recording	Shellac record	Electrical recording from microphones	Movement of stylus drives speakers	Home listening	Addition of Jazz
Late 1940s	Vinyl (Micro-Groove) LPs	Vinyl record	Move to magnetic tape for editing	Narrower stylus, lighter pickups	Home listening	Initially classical, later Rock & Roll
Late 1950s	Stereo music	Vinyl with lateral and vertical cuts	Continued move to magnetic tape	Stereo players	Home listening	Rock & Roll
1960s	Transistor players	Not applicable	Not applicable	Transistor players	Young users tolerated poor sound quality	Rock & Roll
Mid-1960s	Magnetic Tapes	8-track and cassette	Integrated and separate recording and playback machines		Cars, other portable	Rock & Roll
Late 1970s	Digital	Compact discs (CD) and others	Digital recording	CD and other players	Home listening and portable	Addition of disco, rap

Sources: Read and Welch, 1976; Robertson and Langlois, 1992; Langlois, and Robertson, 1992; Chanan, 1995; Millard, 1995.

Table 2. Technological Improvements Changing the Design Tradeoffs and Driving Movements Back up the Hierarchies for the Music Industry

Product Class	Technological Improvements	Eventual Impacts on Design Tradeoffs
Acoustics Discs	Materials such as ebonite and shellac and mass-production techniques such as molding	Benefits from improvements in shellac recording density outweighed the costs of variable speeds
Electrical Recording	Vacuum tubes, microphones, and speakers	Benefits from vacuum tubes (amplification) outweighed their costs
Vinyl LPs	Vinyl materials and lighter pickups	Benefits from improvements in vinyl recording density outweighed the costs of new styli (and replacement of record collections)
Stereo music	Vinyl recording density and electrical components	Improvements in vinyl recording density compensated for increased information to be recorded in stereo music
Transistor Players	Transistors	Improvements in transistors (both cost and performance) outweighed their cost and initially poor sound quality
Cassette Tapes	Magnetic tape recording density and strength of plastics	Benefits from improvements in tape recording density and strength of plastic (smaller size and thus portability) outweighed their poor sound quality
Digital	Microprocessors, magnetic recoding density, lasers, metallic coatings, and ICs	Improvements in data handling technology compensated for the increased data processing of digital over analog recordings

Sources: (Read and Welch, 1976; Chanan, 1995; Millard, 1995).

Table 3. Dominant Designs for Major Product Classes in the Music Industry

Product Class	Dominant Design	Decreasing Marginal Utility from Increases in Product (Hardware) Performance	Increasing Marginal Utility from Economies of Scale (Ability to play music on all machines)
Acoustic Cylinders	Long-playing Edison cylinder	Recording density	Ability to play cylinders on all players
Acoustic Discs	Lateral cut disc	Recording density	Ability to play discs on all players
Electrical Recording	Lateral cut disc recorded with Western Electric technology	Not applicable due to choice of alternative design as opposed to redefinition of sub-problem in a modular way	
Micro-Groove Vinyl Records	33-rpm long playing (LP) and 45-rpm (for singles) vinyl record with lateral cuts	Recording density	Ability to play discs on all players
Stereo records	Westrex stereo disc system (combined vertical and lateral cuts)	Recording density	Ability to play discs on all players
Transistor Players	Continuous reduction in the number of components	Not applicable due to continuous changes in integral design that has led to all playback functions on a single chip	
Magnetic Tapes	Philips Cassette	Recording density	Ability to play tapes on all players
Digital	CDs with continued competition from new designs	Recording density	Ability to play CDs on all players

Sources: (Read and Welch, 1976; Robertson and Langlois, 1992; Langlois, and Robertson, 1992; Chanan, 1995; Millard, 1995).

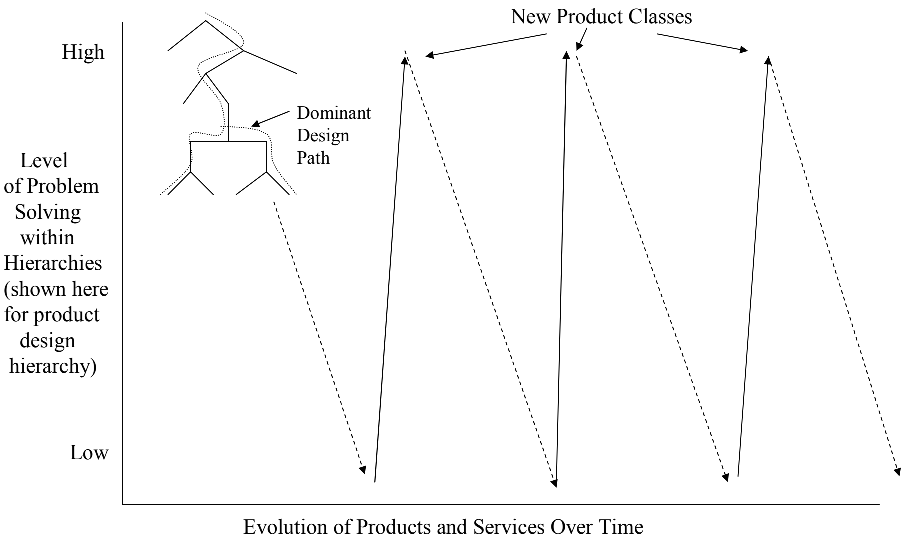
Table 4. A Summary of Digital Mediums and Their Functions and Performance

Medium	Functions and Performance					
	Play-back	Recording	Backward compati-bility (1)	Portability	Sound Quality	Random Access
Compact Disc (CD)	Yes	Initially no	No	Average	Superior	Yes
Digital Audio Tape (DAT)	Yes	Yes	No	Good	Same as CDs (2)	No
Digital Compact Cassette (DCC)	Yes	Yes	Yes	Good	“	No
Minidisc	Yes	Yes	No	Good	Same as CDs	Yes
Hard Disk (in PCs or handheld devices)	Yes	Via the Internet	Via the Internet	Good	Same as CDs	Yes
Mobile Phones	Yes	Via the Internet	Via the Internet	Very good	Same as CDs	Yes

(1) The comparisons are between CDs and records, between Minidiscs and CDs, and between the two tape formats (DAT, DCC) and cassette tapes

(2) but superior to analog cassette tapes

Figure 1. Evolution of Problem Solving in Hierarchies as a Function of Time



Note: Dotted lines represent movements down the hierarchies and solid lines represent movements back up the hierarchies

Figure 2. Tradeoff Between Product Performance via an Integral Design and Economies of Scale via a Modular Design

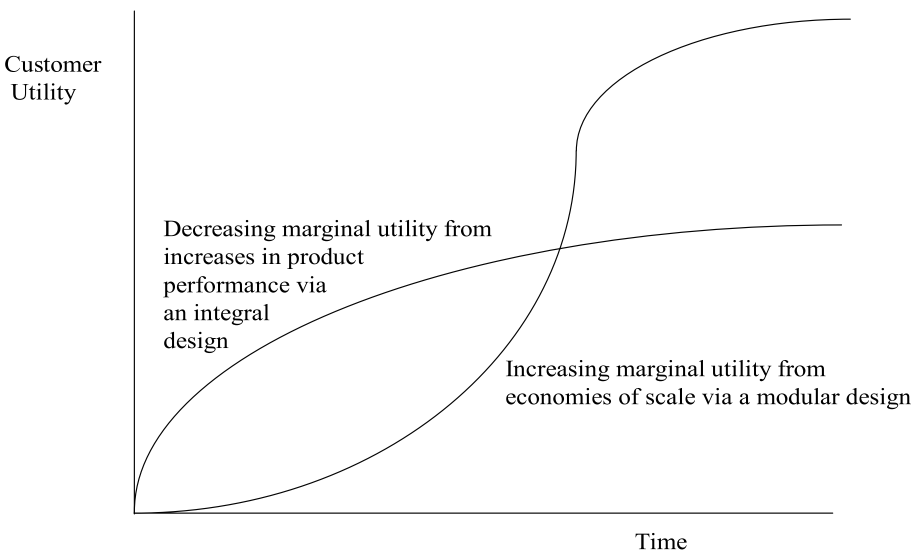
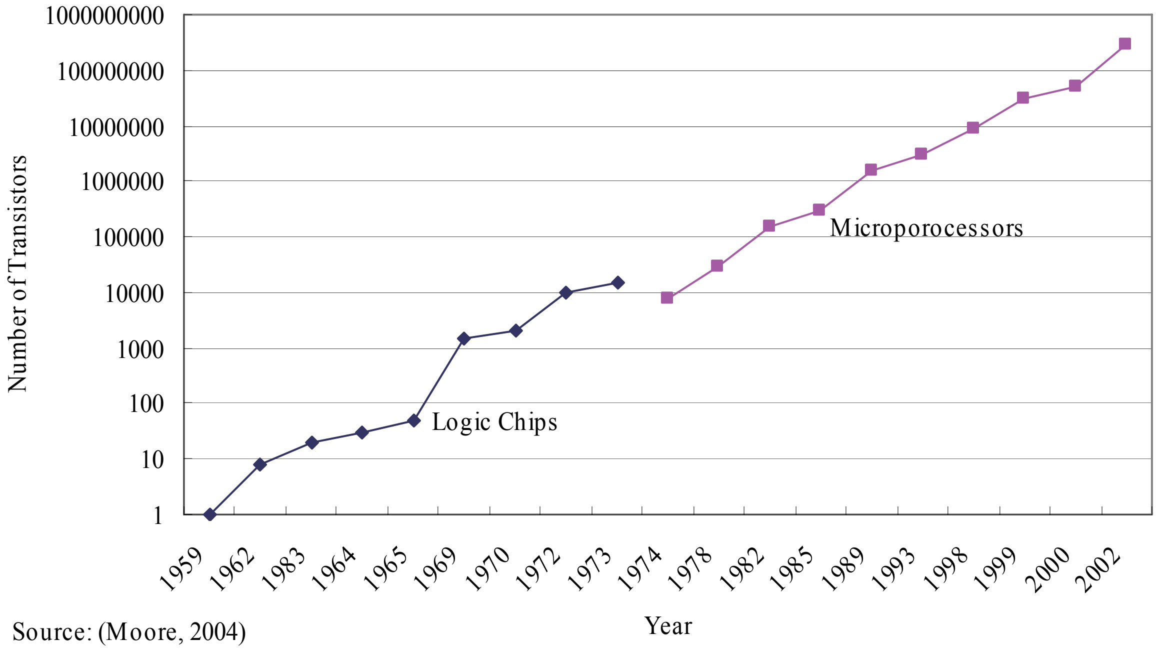
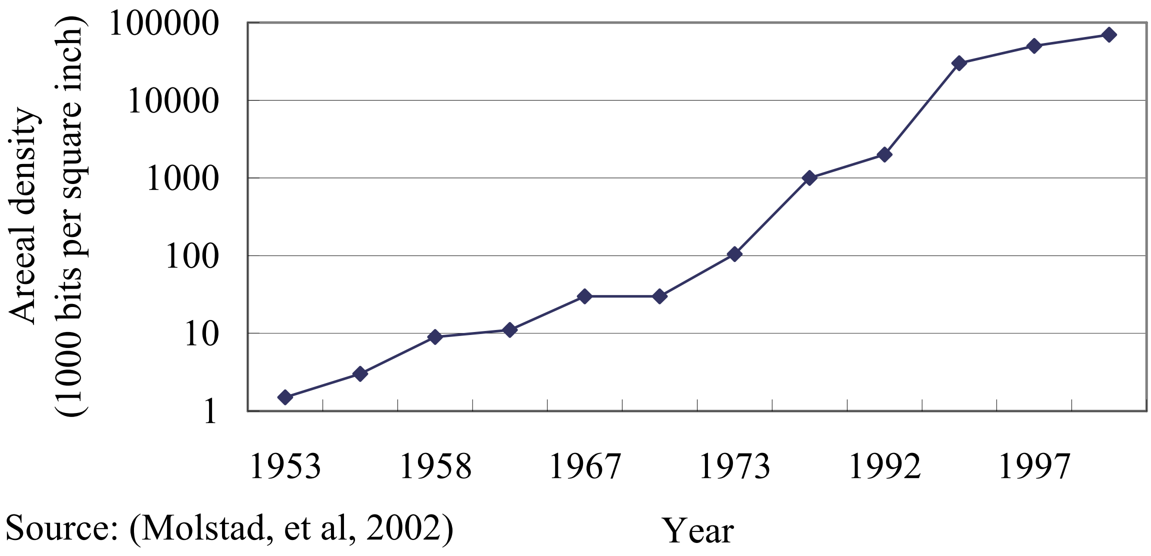


Figure 3. Number of Transistors Per Chip



Source: (Moore, 2004)

Figure 4. Growth in Magnetic Tape Areal Density



Source: (Molstad, et al, 2002)