Technological Discontinuities and Dominant Designs:

The case of audio and video magnetic recording equipment

by

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Abstract

This paper uses the audio and video magnetic recording equipment industry to demonstrate a 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, design tradeoffs, and incremental improvements in a product's components, a material's processes, or in the equipment used in these processes. These incremental improvements 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. Large movements up the hierarchies are defined as technological discontinuities, which this paper calls new product classes, while large movements down the hierarchies are defined as dominant designs. The use of product design and customer choice hierarchies and the concept of design tradeoffs provide additional insight into how a discontinuity occurs, including the specific changes that occur in the designs and customers during the discontinuity.

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. Anderson and Tushman's (1990) seminal article articulated a cyclical model of technological change where competition between alternative designs, the emergence of a dominant design, and incremental progress follow a technological discontinuity. They and others have shown the difficulties incumbents experience in responding to these discontinuities (Abernathy and Clark, 1985; Tushman and Anderson, 1986; Henderson and Clark, 1990; Utterback, 1994). Still others have extended Anderson and Tushman's (1990) model by showing examples of the interactions between component and system innovations/discontinuities (Tushman and Murmann, 1998; Malerba et al, 1999) and how dominant designs can exist at multiple levels in a single product (Tushman and Murmann, 1998; Murmann and Frenken, 2006).

This paper builds on this literature to present a model of technological change that provides greater insights into the sources and timing of technological discontinuities and dominant designs than does the existing literature. The proposed model emphasizes product design and customer choice hierarchies (Alexander, 1964; Clark, 1985), design tradeoffs (Dosi, 1982; Rosenberg, 1963, 1969; Sahal, 1985), and incremental improvements in a product's components, a material's processes, or in the equipment used in these processes. These incremental improvements drive changes in the design tradeoffs for the product/system as a whole, which affects the movements up and down the product design and customer choice hierarchies. Large movements up the hierarchies are defined as technological discontinuities, which this paper calls a new product class, while large movements down the hierarchies are defined as dominant designs. The use of product design and customer choice hierarchies and the concept of design tradeoffs provide additional insights into how discontinuities occur, including ones that involve an interaction between component and system innovations (Tushman and Murmann, 1998; Malerba et al, 1999), by showing the specific changes that occur in the designs and customers during the emergence of the discontinuity.

This paper uses data from the audio and video magnetic recording equipment industry to demonstrate this alternative viewpoint of technological change. This industry is an appropriate application for the model due to large amounts of technological change, large literatures, and the importance of interface standards (i.e., dominant designs). 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 audio and video recording equipment industry including the recent competition with optical and semiconductor recording media.

2. Proposed Model

The proposed model builds on the concepts of hierarchical decision making in complex systems (Simon, 1996; Alexander, 1964) and the use of product and customer choice hierarchies to represent the process by which by which firms translate customer needs into products over time (Clark, 1985). The customer choice hierarchy represents a firm's perception of the ways in which customers make choices in the market and thus how firms define market segments 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 and processes (Clark, 1985). The interaction between these hierarchies also includes the determination of a business model (Chesbrough, 2003) and sales and service channels (Abernathy and Clark, 1985).

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 depicted in Figure 1. Following a technological discontinuity and a period of intense technical variation (Tushman and Anderson, 1986), customer segments begin to emerge and design activity moves from higher-level to lower-level problem solving (Tushman and Murmann, 1998; Murmann and Frenken, 2006) where these movements down the hierarchies reinforce the decisions made at higher levels in the hierarchies. The amount of movements down the hierarchies reflects the degree of similarity between different firm's methods of segmenting customers (customer choice hierarchy) and between the different firm's products in both alternative designs and the definition of sub-problems (product design hierarchy) (Clark, 1985). In terms of sub-problems, the coalescence of customer needs around a few related dimensions and pressures to reduce cost and standardize (Abernathy and Utterback, 1978) may cause firms to redefine the sub-problems in terms of independent modules (Ulrich, 1995; Baldwin and Clark, 2000).

Place Figure 1 about here

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." As shown in the upper left hand side of Figure 1, the choice of a specific design alternative defines a single path while the definition of sub-problems into independent modules defines the emergence of multiple and relatively independent design paths. Defining a dominant design as a path is consistent with Dosi's (1982) notion of technological trajectories, which define the direction of advance within a technological paradigm (see below), and with other research on dominant designs that emphasizes a stable architecture (Anderson and Tushman, 1990) and the possibility that such a stable architecture can extend to sub-systems and components within a system (Tushman and Murmann, 1998; Murmann and Frenken, 2006).

However, depending on the industry, dominant designs will differ in terms of both the relative importance of alternative designs and sub-problems in 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."

On the other hand, incremental improvements in a product's components, a material's processes, or in the equipment used in these processes can change the "design tradeoffs" that are implicit at all levels in a product design hierarchy and thus lead to movements *back up* the hierarchies of both product design and customer choice where many of these improvements may be driven by other industries or even sectors. Both popular journalists (e.g., Gilder, 1990, 2002) and scholars have used similar concepts to explain changes at both the macro- and micro-level. At the macro-level for example, improvements in automobiles in the second half of the 20th century changed the design tradeoffs for cities and thus enabled their inhabitants to redesign some of them to include suburbs and extended commuting. Similarly, improvements in transportation, communication, and computer systems in the last 10 years have changed the tradeoffs for production systems and one result has been the increased globalization of production systems (Friedman, 2005).

In terms of the academic literature, the concept of design tradeoffs extends the notion of performance and cost tradeoffs at the customer level, which is widely used in the marketing, decision science, and economics literature (Adner, 2002, Lancaster, 1979; Green and Wind, 1973), to tradeoffs at each level in a product design hierarchy (Alexander, 1964). The concept of design tradeoffs is similar to Dosi's (1982) characterization of a technology paradigm, which "defines its own concepts of progress based on its specific technological and economic tradeoffs," to Rosenberg's (1963, 1969) concepts of imbalances and technical disequilibria between machines and between the components within them, and to Sahal's (1985) concept of how innovations "overcome the constraints that arise from the process of scaling the technology under consideration."

The extent of the movements back up the product design and customer choice hierarchies define the degree of the technological discontinuity. For example, although some research has defined the introduction of transistors, integrated circuits (ICs), and semiconductor memory in mini-computers as technological discontinuities (Tushman and Anderson, 1986; Anderson and Tushman, 1990), these discontinuities clearly involve smaller movements back up the hierarchies than the introduction of mainframe, mini-, and personal computers did. In terms of the largest movements back up the hierarchies, 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, 1990) innovations.

By showing how these discrete innovations fit within the proposed model, future research with the proposed model can refer to the research on these discrete innovations when analyzing how firms have moved back up the product design and customer choice hierarchies in response to changes in the design tradeoffs. Future research with the proposed model should consider the roles of organizational structure (Henderson and Clark, 1990), capabilities (Tushman and Anderson, 1986; Afuah and Bahram, 1995), complementary assets (Teece, 1986), and managerial cognitive representations (Kiesler and Sproull, 1982; Tripsas and Gavetti, 2000).

There are several concepts and related mathematical models that can help us further understand the timing of both technological discontinuities and dominant designs. The concepts of value trajectories and indifference curves can be used to model competition between different product classes (Adner, 2002). New product classes must also overcome the network effects of the existing product class (Shapiro and Varian, 1999) and create a critical mass of users (Rohlfs, 2001). Customers often perceive a tradeoff between the performance of a new product class and its level of compatibility with the 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).

This tradeoff between performance and compatibility can also be applied to the emergence of dominant designs that represent modular designs and in particular ones that represent interface standards. Although most of the literature on dominant designs suggests that a single dominant design emerges following a discontinuity (Anderson and Tushman, 1990), the tradeoff between performance and compatibility suggests that an interface standard (i.e., dominant design) is updated more times within a specific product class for applications that favor performance (e.g., industrial ones) than those that favor network effects and thus compatibility (e.g., consumer applications). The smaller network effects for industrial than consumer applications may reflect the difference between internal (to a single consumer or firm) and external (between people or organizations) network effects (Liebowitz, 2002) where industrial applications may primarily involve internal network effects.

3. Research Methodology

The author analyzed the primary and secondary literature on the audio and video recording equipment industry including academic papers and books from the management, economic, and historical fields, practitioner-oriented accounts, and encyclopedic histories of which Daniel et al's (1999) edited volume *Magnetic Recording: The First 100 Years* was particularly valuable. 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; 2.) the incremental improvements in components or materials that have changed the design tradeoffs thus leading to movements back up the hierarchies for the product/system; 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.

4. Results: A Brief History of the Audio and Video Recording Equipment Industries

Table 1 summarizes the major product classes in the audio and video magnetic recording equipment industry and movements back up the product design and customer choice hierarchies for them where Table 1 broadly separates these product classes into audio versus video and also analog versus digital. Movements back up the product design hierarchy include changes not only from audio to video and analog to digital but also between magnetic tapes and disks; between single stationary, single rotary, and multiple rotary magnetic heads; and recent changes to optical and semiconductor recording media. Movements back up the customer choice hierarchy primarily involve changes in applications; major applications include editing by broadcasting and music firms or playback and recording for consumers.

Table 2 summarizes the incremental improvements in components or materials that have changed the design tradeoffs for audio and video recording equipment and led to movements back up the product design and to a lesser extent customer choice hierarchies and the emergence of new product classes. The single most important improvement has been in the magnetic recording density of tape (See Figure 2). Improvements in the recording density of magnetic tape have changed both the internal (to the equipment) and external (that users make) design tradeoffs for equipment and thus caused multiple movements back up the hierarchies.

Users make tradeoffs between storage capacity, data transfer rate, size (e.g., portability), cost, removability, and access time (to a specific memory location) when considering audio and video recording equipment (Esener et al, 1999; Monson, 1999). Magnetic tape has been widely used in audio and video recording systems because it scores high on most of these measures of performance except access time and to a lesser extent portability and removability. Improvements in the recording density of magnetic and optical disks and semiconductor memory have closed the gap between these new formats and magnetic tape in most of these measures of performance thus causing the weaknesses of magnetic tape (access time, portability, and removability) to become more important measures of performance (i.e., changes in the external design tradeoffs). This has caused hard disks to be used for editing applications (e.g., by music companies), optical disks such as DVDs (Digital Video Disks) to be sold as pre-recorded videos, and small hard disks and semiconductor flash memory to be used for portable applications (e.g., in i-Pod or in mobile phones).

Table 3 summarizes the dominant designs for each product class and if applicable the specific market. All of these dominant designs reflect movements down the product design hierarchy that deal with defining sub-problems in a modular way. This includes how a magnetic head interacts with tape, how a laser interacts with an optical disc, or how the data on hard disks or flash memory are transferred between computers, portable devices, and other equipment. Although some of these modular designs emerged as defacto standards through competition between different consumer products in the marketplace, most of them were chosen and updated in committees.

Place Tables 1-3 and Figure 2 about here

4.1 Analog audio

Oberlin Smith combined key components from the telephone (magnetic coil, microphone, and speakers) with piano wire to create the first device for recording sound with magnetic material in 1878. Sound vibrations were recorded on a magnetic wire with a magnetic coil and the wire was moved between two spools. Although the device was first applied to dictation by Smith and others, the lower cost of tin foil recorders (Clark, 1999a), which were also only marginally successful in this market (Read and Welch, 1976), prevented the market for wire recorders from experiencing much growth.

4.1.1 Reel-to reel magnetic tape

Incremental improvements in coating technology, iron particles, magnetic coils, polyvinyl chloride (PVC) plastics, and vacuum tube amplifiers in the 1930s 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 magnetic tape (plastic coated with magnetic material) as a new product class for audio recorders in the 1930s (in Germany) and 1940s (in the U.S.). Improvements in coating technology were driven by efforts to attach a gold foil to cigarettes in order to prevent ugly residues from being left on cigarette smoker’s lips. Improvements in iron particles and magnetic coils were driven by the market for telecommunications equipment (Engel, 1999), in PVC they were driven by consumer products, and in vacuum tubes they were driven by the market for radios and music players (Millard, 1995).

These improvements changed the design tradeoffs for magnetic recording equipment and because the new product class appealed to a new set of users, there were movements back up both the product design and customer choice hierarchies. Although the first magnetic tape players were used by the German government in the 1930s to support mass rallies and other aspects of its propaganda machine (Engel, 1999), it was not until after WWII that the above-mentioned improvements enabled tape players to be used in the first successful commercial application, pre-recorded radio broadcasts in the U.S. The ability to pre-record radio programs reduced the programming costs and eased the work schedule of popular entertainers such as Bing Crosby. Although Crosby had quit radio in 1944 because he was tired of live performances, improvements in magnetic recording equipment convinced him to return to radio and offer a national radio show in 1947. By focusing on radio broadcasters as opposed to consumers as many other manufacturers did, Ampex became the leader in magnetic tape recorders (Gooch, 1999). By the early 1950s, magnetic tape was used by most radio broadcasters for time delayed broadcasts and by music companies for editing music before a record master was created (Gooch, 1999; Millard, 1995).

The definition of these market segments and thus movements down the customer choice hierarchy coincided with movements down the product design hierarchy. The decisions by German companies to use a "ring head," a base film of cellulose acetate in the tape, and ferric oxide as the magnetic material on top of the cellulose acetate, and later decisions by many firms to use AC bias and synchronous motors can be interpreted as moves down the product design hierarchy and the emergence of a dominant design for reel-to reel magnetic tape players. While the above movements down the product design hierarchy can be interpreted as choices of alternative designs, decisions about the size and speed of the tape can be interpreted as defining sub-problems in terms of relatively independent modules and thus a definition of the dominant design for them.

A desire for interoperability within the radio broadcasting and music industries caused firms to agree on tape size and speed and update these standards several times. Although both industries primarily used 1/4” tape with Dolby noise reduction, music companies used faster speeds due to their higher quality requirements. They initially used 30 inches per second (ips) and later updated the speed to 15 ips (Gooch’s, 1999; Sadashige, 1999) while radio broadcasters initially used a combination of 15.0 and 7.5 ips and later updated these standards to 7.5 and 3.75 ips (Inglis, 1999). The music industry also used a larger variety of tape sizes than the radio industry did partly due to music industry’s use of multi-track systems (Clark, 1999b).

Educational and training markets later emerged for reel-to reel tape as the prices for the recording machines fell (Clark, 1999); the definitions of these markets reflect further movements down the customer choice hierarchy. Although Ampex later introduced some products for these markets, Japanese firms entered first and by the 1960s controlled most of the low-end market for these tape recorders (Rosenbloom and Freeze, 1985). Nevertheless, the difficulties of threading tape and accessing specific songs caused consumers to remain a niche market until 8-track and cassettes eliminated the tape threading problem (Clark, 1999b).

4.12 8-Track and Cassette Tape

Further improvements in the recording density of magnetic tape and heads and in the strength and cost of plastics led to a second round of changes in the design tradeoffs (See Table 2) and thus to movements back up the product design and customer choice hierarchies and the emergence of a new product class of tape player (See Table 1) in which the tape is enclosed in a plastic case. The improvements in recording density, which were driven primarily by the use of multi-track systems in musical recording studios (Clark, 1999b) enabled the use of thinner and narrower tape. The improvements in the cost and strength of plastics, which were driven by a number of consumer products, enabled plastics to be used for special runners, hubs, guides, and spools that enclosed and guided the movement of tape within a case (Millard, 1995).

The move back up the customer choice hierarchy involved a new application, portable tape players. Beginning with Ford, U.S. automobile manufacturers began offering tape players as an option and music companies beginning with RCA began offering pre-recorded 8-track cartridges with 1/4" wide tape. Although a critical mass of users for these 8-track cartridges emerged, the inability to fast forward and reverse (i.e., long access times) and the smaller size of cassette tapes (1/8" wide tape) and thus players, which were driven by additional improvements in magnetic recording density and plastics (and also transistors) caused cassette tapes to replace 8-track cartridges in the mid-1970s. The liberal licensing policies of Philips helped make its technology the dominant design for cassette tapes (Clark, 1999b). Continued miniaturization and Sony's release of its Walkman player in the late 1970s reinforced Philips' cassette tape as a dominant design (Sanderson and Uzumeri, 1995). Miniaturization reflected a specific design path by manufacturers and the emergence and definition of such market niches as the Walkman reflected further moves down the customer choice hierarchy for cassette players.

4.2 Analog Video

Incremental improvements in magnetic recording density and later transistors and ICs led to several changes in the design tradeoffs (See Table 2), repeated movements back up the product design and to a lesser extent customer choice hierarchies, and to several new product classes within the general category of video recording (See Table 1). Improvements in recording density were driven by the market for audio tape recorders and computers while improvements in transistors and ICs were initially driven by military applications. The improvements in magnetic recording density were particularly important because video requires more than 250 times the bandwidth of audio. Therefore, the use of existing stationary head reel-to reel systems would have required tape speeds that could not be reliably handled with the existing technology and for obvious reasons television broadcasters placed a large emphasis on reliability (Mallinson, 1999). For example, even after several years of trying to apply such a stationary head system to video recording (often called the longitudinal approach), RCA's system still required tape speeds of 360 inches per second (ips) and a 17-inch reel could only hold four minutes of playing time in 1953 (Jorgensen, 1999; Inglis, 1991).

4.2.1 Quadruplex

Ampex was the first firm to go back up the product design hierarchy and create a design that could effectively handle the higher bandwidth of video recording. Named for its four rotating heads (Mallinson, 1999), the Quadruplex only required tape speeds of 15 ips as compared to the 360 ips for RCA's system and thus enabled the use of much simpler tape handling system, whose benefits outweighed the extra cost of multiple heads (Rosenbloom and Freeze, 1985; Inglis, 1991). Ampex demonstrated the system to CBS and ABC executives in early 1956, it began deliveries in 1957, and it was the sole supplier until RCA introduced a compatible system in 1959 (Inglis, 1991).

Ampex's early lead and the need for compatibility, primarily among machines within a single broadcaster, enabled Ampex's product to become the dominant design in the television broadcasting industry, which helped Ampex dominate the industry until its design was replaced by the helical design in the late 1970s (see below). For example, even though RCA had strong advantages in color technology, RCA had to trade its color-related patents for Ampex's recorder-related patents in order to make its machines compatible with those of Ampex. On the other hand, industry wide committees such as those in the Society Motion Picture Television Entertainment (SMPTE) focused on other aspects of video recording equipment such as tape size and speed and updated standards for them several times (Inglis, 1991; Sugaya, 1999).

4.2.2 Helical Scan

Incremental improvements in magnetic recording density continued to change the design tradeoffs in the 1960s and 1970s thus requiring movements back up both the product design and customer choice hierarchies for video recording. These improvements enabled the development of simpler systems whose low cost appealed to new applications and customers where these new applications and customers represented movements back up the customer choice hierarchy. These applications included training and education and the new customers were sports teams, airlines, and universities. The most successful of these new designs used one instead of four heads and was called the helical-scan recorder because of the way the tape wraps around a rotating head in a helix (Rosenbloom and Freeze, 1985; Rosenbloom and Cusumano, 1987).

Japanese firms introduced helical scan recorders in the early 1960s and quickly dominated these new markets partly because Ampex and RCA continued to focus on their existing customers (Rosenbloom and Cusumano, 1987). Several Japanese firms including Sony, Panasonic and JVC also agreed in 1969 to a standard for the helical scan recorder, which is called the U-Format and the definition of this standard can be interpreted as movements down the product design hierarchy. These firms first released products based on the U-Format in 1971 and for several years offered compatible products. However, Sony was unable to convince Panasonic and JVC to introduce products that were compatible with Sony's updated version of the U-Format, Beta. Instead, Panasonic and JVC introduced products based on a standard called VHS that eventually became the dominant design for video recording and playback machines (Rosenbloom and Cusumano, 1987; Sugaya, 1999). There is large literature on the competition between Beta and VHS where there has been a long debate between the relative importance of recording time and openness in the victory of VHS over Beta (Rosenbloom and Cusumano, 1987; Cusumano et al, 1992; Grindley, 1995; Rohlfs, 2001).

The key point here is that the helical design diffused in these new applications much more than the Quadruplex did as improvements in magnetic recording density eliminated the image quality disadvantages of the helical design and thus changed the mode of competition from image quality to price. Japanese firms were much faster to recognize the importance of these new applications and thus the need to move back up both the product design and customer choice hierarchies than Ampex and RCA were. Further improvements in magnetic recording density also caused the television broadcasters to replace their Quadruplex machines with helical design machines that were modified for the broadcasting market partly through standards set by the SMPTE (Sadashige, 1999). Nevertheless, the similarity between the designs enabled Japanese firms like Sony to also dominate the broadcasting market for video recorders (Cusumano et al, 1992).

4.2.3. Camcorders

Incremental improvements in magnetic recording density continued to change the design tradeoffs for video recording in the 1970s and 1980s and along with incremental improvements in charge coupled devices (CCD) and liquid crystal displays (LCDs) enabled movements back up the product design and to a lesser extent customer choice hierarchies and the emergence of a new class of video recorders, which are called camcorders (combination of cameras and recorders). Improvements in recording density first changed the design tradeoffs for news organizations that had been using 35 mm film cameras to record video for news programs where these improvements finally caused the benefits (faster editing) of magnetic tape to exceed their higher costs in the 1970s. Although initially the recorder was kept in a van and connected to a camera with a cable, improvements in magnetic recording density gradually reduced the size of the recording equipment so that it could be carried (Inglis, 1991). In the late 1970s, the SMPTE designated one of Sony's products as the Type L Format, one of Panasonic's early products as the Type M format, and one of Panasonic's subsequent products as a Type M-II format (Sugaya, 1999).

Further improvements in magnetic recording density, CCDs (first used in facsimiles), and LCDs (first used in watches and calculators) finally enabled a consumer market to emerge for camcorders in the early 1980s (Johnstone, 1999). Sony's introduction of a hand-held movie camera that used 8 mm wide tape led to a standard for this format in 1984. Although JVC developed a compact cassette (12 mm) that could be played in a VHS machine using an adapter, Sony eliminated this advantage by including a VHS player mechanism and circuitry in its product (made possible through improvements in ICs) thus enabling a direct connection between their product and the VHS player. Sony's use of smaller tape is one reason why it and its partners regularly introduced products with longer recording time and smaller size than the JVC-led group and why the 8mm wide tape emerged as a dominant design for camcorders (Grindley, 1995). This dominant design can be defined in terms of several movements down the product design hierarchy including the use of a VHS player mechanism and circuitry in the camcorder.

4.3. Digital Audio

Incremental improvements in magnetic recording density, lasers, metallic coatings, microprocessors, and ICs have led to continuous changes in the design tradeoffs, repeated movements back up the product design and to a lesser extent customer choice hierarchies for audio recording systems (See Table 1), and thus enabled several new product classes to emerge that can be classified as digital audio systems. The tradeoffs between analog and digital systems revolve around the superior sound quality and editing capability of digital recording versus its higher data requirements. When an analog signal is converted to a binary form, it is called a pulse-code-modulated (PCM) signal. This conversion requires a data rate of about one million bits per second per video channel or about 30 times that of analog audio and a one hour audio recording requires about 500 megabytes of data. Although pulse code modulation (PCM) was developed by telephone companies in the 1930s in an attempt to get more messages over their wires, it has taken many decades for the above-mentioned improvements to occur and thus enable the practical use of digital audio recording systems (Millard, 1995; Watkinson, 1999).

4.3.1 Professional applications

Music companies and to a slower extent radio broadcasters started moving from analog to digital in the 1970s and they did this at various levels in their "hierarchies" of recording and storage systems[1]. Like other users of information technology, music companies use a hierarchy of storage systems where access times are more important than cost at the top and costs are more important than access times at the bottom of these hierarchies (Watkinson, 1999). The music companies still use hard disks at the top of their hierarchies in combination with PCs. Improvements in the recording density of hard disks have caused their costs to dramatically fall over the last 40 years where these improvements were driven primarily by the computer industry (Christensen, 1997). These and other improvements have caused the PC to become the interface between the recording engineers and digital synthesizers, the MIDI (Music Instrument Digital Interface) sequencer to become the word processor for music, and various disks (e.g., 3.5") and USB devices disks to become the mediums for transferring data between the PC, digital synthesizers and other equipment (Millard, 1995).

Music companies and later radio broadcasters also introduced a variety of magnetic tape systems for the backup of music and programs respectively, which are considered the lowest levels in the hierarchy of storage systems for these companies. The first

[1] While is possible to define product design hierarchies for the music companies and customer choice hierarchies for the equipment suppliers in terms of these hierarchies of recording and storage systems, the possible confusion to readers probably exceeds the benefits of doing so.

systems used stationary heads like those used in cassette tapes, of which the most successful format was the digital audio stationary head (DASH). However, the large amounts of data that must be stored in a digital format required very fast tape speeds and thus like the case of analog video systems for television broadcasters, digital tape was not widely used until a more complex tape system, in this case a rotary head system called digital audio tape (DAT) was developed in the early 1980s. Further improvements in recording density finally enabled a return to stationary heads in the 1990s when a new format called digital compact cassette (DCC) was introduced (Watkinson, 1999). These improvements continue to change the design tradeoffs for music companies and radio broadcasters and thus the mix of different digital media that they use within their hierarchy of recording and storage systems.

4.3.2 Consumer applications

Incremental improvements in magnetic recording density, lasers, metallic coatings, microprocessors, and ICs have also led to changes in the design tradeoffs and repeated movements back up the product design hierarchy for consumer applications. The first successful digital recording medium for consumers was optical discs, which are better known as compact discs (CDs) (Millard, 1995; Grindley, 1995). Laser beams record bits of information on a coated disc by thermally heating very small areas on the disc. This heating changes the reflectivity of these areas, which can be sensed by the combination of a laser and photodiode (Esener et al, 1999). Improvements in semiconductor lasers and light-sensitive photodiodes were driven by their use in bar code readers in the 1970s (Millard, 1995; Grindley, 1995). Introduced in late 1982, the superior sound quality and smaller size of CDs caused a critical mass of users to emerge for them and for their sales to exceed those of records by the late 1980s (Grindley, 1995).

Digital audio tape (DAT), digital compact cassettes (DCC), and mini discs have been much less successful than the CD. None of these products have been able to overcome the network effects 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, DAT was not backward compatible with cassette tapes, and firms have not found a way to move back up the customer choice hierarchy. Other than the use of DAT and DCC in recording studios and of Sony's minidisk (miniature version of CDs) by consumers to record rented CDs in Japan, these products have not found new customers or created new applications or music (Rohlfs, 2001; Grindley, 1995).

Improvements in microprocessors, magnetic disks, and flash memory have also played a role in the diffusion of the Internet and are now impacting on the downloading of music via the Internet. The PC is becoming the main music player in the home where like the music companies, hard disks have become the main form of storage. In portable devices, Apple's i-Pod and mobile phones use small hard disks and flash memory where the music is transferred to PCs with a USB (Universal Serial Bus), memory card, or similar device. As for competition between the i-Pod and phones, continued improvements in the capacity and price of flash memory and other chips may cause mobile phones to eventually become the dominant form of portable music player.

4.4. Digital Video

Incremental improvements in magnetic and optical recording density, microprocessors, and other ICs have led to continuous changes in the design tradeoffs, repeated movements back up the product design and to a lesser extent customer choice hierarchies for video recording systems (See Table 1), and thus enabled several new product classes to emerge that can be classified as digital video systems. The impact of these improvements on the tradeoffs between analog and digital systems revolves around the superior image quality and editing capability of digital recording versus its higher data requirements. Once an image has been transformed into 1s ands 0s, it is easy to alter its size, aspect ratio, brightness, color, and linearity. On the other hand, data rates in the 100 Mb/s range are needed to access videos that have been stored in a digital format and this requires higher recording densities, faster microprocessors, and more sophisticated compression techniques (Sadashige, 1999).

4.4.1. Professional Applications (Broadcasters)

The first digital video recording systems were used by broadcasters to record and edit television programs. Insufficient magnetic recording density caused the first digital systems to be used for so-called "component" as opposed to "composite" recording. In component recording, each of the three components of the composite color signal (brightness, brightness minus blue, and brightness minus red) are recorded separately and recombined later. Sony's product became the standard for component recording while in composite recording, Ampex and Sony reached agreement on a standard called SMPTE D-2 in 1986 that used 0.75 inch tape (Inglis, 1991) after Ampex's system had been the basis of a much less used D-1 standard (Sadashige, 1999).

The next step for broadcasters was electronic news gathering, which required smaller systems and thus thinner tape. A line of products released by Panasonic became the basis in the early 1990s for the SMPTE D-3 format, which used 0.5 inch tape. However, demands for further miniaturization and higher resolution, which are conflicting goals, required firms to explore various compression techniques via the motion picture experts groups (MPEG) and create new formats. Many of these formats were based on differential pulse code modulation (DPCM) where only the difference between the preceding and present samples is recorded. The SMPTE ratified several digital formats for electronic news gathering in the early 1990s including D-5, D-6, and D-7 (Sadashige, 1999).

The tape systems for electronic news gathering were just one part of a hierarchy of storage systems that were used by television broadcasters. Like the music companies, television broadcasters use hard disks in those applications that require the shortest access times while tape or more recently optical systems are used where access time is less important. For example, raw news footage that was collected with a magnetic-tape based camcorder in the late 1980s was transferred to a magnetic disk on a personal computer (PC) with an appropriate reader as soon as it was received by the station. The development of smaller hard disks has enabled them to be used in some portable devices thus further simplifying the transfer of data to PCs via for example USBs in electronic news gathering (Sadashige, 1999).

4.4.2 Consumer Applications

Electronic news gathering applications drove improvements in digital compression techniques and magnetic recording density that enabled digital to also be used in consumer products such as camcorders. Video recorder manufacturers agreed on a standard called DV in 1994 and products based on this standard appeared in 1995. Combined with the CCDs, the use of digital recording on tape made the camcorder an all-digital device.

However, it was the replacement of tape with flash memory beginning in the late 1990s that brought the largest benefits to digital camcorders. Not only did the use of flash memory dramatically reduce the size of camcorders, by placing the flash memory in a protective casing like a memory stick or compact flash card, the use of flash memory also enabled users to more easily transfer the videos to PCs for editing. Furthermore, as improvements in CCDs enabled the replacement of film with CCDs in digital still cameras, it became possible to combine still and video cameras in a single device that was easily connected to your PC for editing, storage, and sending of photos and videos to friends via electronic mail.

Further improvements in flash memory and other semiconductors continue to change the design tradeoffs for video recorders and players. Camera phones were successfully introduced in 2001 in Japan, video phones followed in 2002, and they are both now available in most of the world. Video viewing capability has recently been introduced in the i-Pod. Videos can be transferred to PCs with a USB, memory card, or similar device. Like portable music players, improvements in flash memory and other chips may cause mobile phones to become as widely used as the i-Pod for watching videos. Of course, this will take much longer than it will for music and the length of this time will probably depend on the rate of improvements in recording density for magnetic disks and flash memory and the relative sizes of the i-Pod and mobile phone screens.

The other major consumer product that uses digital video technology is of course the digital video disk (DVD). Improvements in lasers, rotation speeds, error correction codes, and servo systems, most of which are driven by the market for CDs have changed the design tradeoffs for video recording systems and caused movements back up the product design hierarchies. Shorter wavelength lasers and a higher numerical aperture lens have reduced the size of the memory spot and improvements in ICs enabled more powerful error correction codes, and faster servo systems. In the ten years that followed the introduction of the CD, these improvements increased the capacity of CDs by more than 10 times, reduced the access times by 2/3, and increased the transfer rate by 1000 times (Esener et al, 1999).

A dominant design for DVDs emerged in 1998 and a second one is currently being debated. A consortium of manufacturers and movie companies called the DVD forum published specifications in September 1996, manufacturers released the first players in early 1997, and by mid-1998 pre-recorded movies has been released by most movie companies (Dranove and Gandal, 2003). Subsequent improvements such as the ones discussed in the previous paragraph have caused manufacturers to work on a new standard for DVDs. As of early 2006, two different consortiums of firms had still not reached agreement and were ready to release products based on these different formats.

Of course, the life of DVDs may be short as it appears that the life of CDs will be. The ability to download music from the Internet and the greater portability of magnetic disks and semiconductor memory is eliminating the need for CDs and DVDs face a similar problem. The main advantage of optical storage (and tapes) over magnetic disks has been their greater removability. Increasing the recording density of magnetic disks requires a reduction in the separation between heads and disks, which increases the difficulty of removing the disk. As data is transferred via the Internet or transferred via flash memory, the removability advantage of optical disks becomes less relevant and the market for optical storage may disappear over the next ten years (Esener et al, 1999).

5. Discussion

The purpose of this paper was to introduce a model of technological change that addresses the sources and timing of technological discontinuities and dominant designs better than the existing literature. 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 several contributions to our understanding of both technological discontinuities and dominant designs.

With respect to technological discontinuities, which this paper calls new product classes, the use of product design and customer choice hierarchies provide insights that are not found in the existing literature. Incremental improvements in components or materials change the design tradeoffs and thus require firms to rethink the product design and customers where many of these improvements are driven by other industries. For example, the improvements in coating technology, magnetic coils, and plastics that made the first reel-to reel tape players possible were driven by the cigarette, telecommunication, and radio industries respectively. Further improvements in magnetic recording density were partly driven by data applications in the computer industry as were many of those in microprocessors and ICs. Those in CCDs were driven by the facsimile industry, those in LCDs by the digital watch and calculator industries, and those in lasers by the retail industry.

These incremental improvements changed the tradeoffs between price and various measures of performance in at least four ways. First, improvements in magnetic recording density changed the tradeoffs between equipment cost and editing in both the initial use of analog recorders by radio broadcasters and music companies and in the change from analog to digital recording by these companies. Second, improvements in magnetic tape recording density reduced the need for complex tape handling systems that had been introduced to provide adequate sound or image quality. This was the case with 8-track/cassettes and the helical scan design that is used in VHS. Third, in 8-tracks/cassettes and camcorders, the improvements in magnetic tape recording density also changed the tradeoffs between quality and portability where users were willing to sacrifice quality for portability. Fourth, many of these improvements in magnetic recording density, in particular hard disks and flash memory, have placed magnetic recording equipment within a larger system of products; this includes the hierarchies of storage systems used by firms and now the Internet, which may eliminate the physical distribution of music and video.

In addition to the design tradeoffs that are inherent in the product design hierarchy, the exact timing of the discontinuities has depended on how firms use these improvements to rethink their products and customers. For products, firms were forced to rethink the shape of the magnetic medium, the type and number of heads, the use of analog or digital, and beginning with the CD a broader range of product designs. Movements back up the customer choice hierarchy reflect changes in the users and applications and any movements back up this hierarchy may reduce the improvements in performance and cost that are needed for growth in the new product class to occur. For example, the first users of new audio product classes changed from radio broadcasters with the reel-to reel tape players to automobile owners with 8-track/cassette players, and to a mixture of music companies and consumers with the different types of digital recording and playback product classes. The first users of new video product classes changed from television broadcasters with the Quadruplex to education and training for helical scan, to news gathering for the camcorder, and to a mixture of television broadcasters and consumers for different types of digital recording and playback product classes. Each set of new users enabled the new product class to diffuse before its performance had reached the level of the previous product class.

These results go beyond those of previous research that have linked innovations in components to those in systems (Tushman and Murmann, 1998; Malerba, et al, 1999). The proposed model represents this phenomenon at a much deeper level by showing how incremental improvements in components and materials change the design tradeoffs, how the specific changes in the product designs and customers are a result of these changes in the design tradeoffs, and how firms do or do not move back up the product design and customer choice hierarchies. In responding to these changes in the design tradeoffs for audio and video recording equipment, firms had more trouble moving back up the customer choice hierarchies than the product design hierarchies, which is consistent with Christensen (1997). For example, Ampex and RCA successfully introduced several different product classes of audio and video recorders for broadcasters but were much less successful at redesigning them for other customers. New entrants, both Japanese firms and Philips, moved faster to introduce simpler designs for these other customers and then used the improvements in components (i.e., improvements in magnetic recording density) to sell improved designs to for example broadcasters.

With respect to dominant designs, this paper extends Suarez and Utterback's (1995) concept of a dominant design as a design path where several examples of how slight differences between designs played a key role in the audio and video recording industry highlight the advantages of using the "design path" definition. The first dominant design for reel-to reel players represented several movements down the product design hierarchy such as the choice of a ring head, cellulose acetate and ferric oxide in the tape, AC bias, and synchronous motors. Second, there was often small differences in the tape size and speed that were used by radio broadcasters and music companies in several product classes. Third, although both consumers and broadcasters ended up using the helical design and U-Format for video recording, there were small differences between for example VHS and Beta that made them incompatible. Fourth, although both DASH and DCC used stationary heads, other differences made them incompatible. Fifth, for camcorders, 8mm and VHS-C achieved backward compatibility with the VHS standard in different ways. Sixth, dominant designs for digital systems represented a combination of PCM, specific MPEG formats, different methods of transferring data between fixed and portable devices, and other design decisions.

The second implication for the dominant design literature is that a larger number of interface standards (i.e., dominant designs) emerged for industrial than consumer applications due to the greater importance of performance and the lower importance of network effects for industrial than consumer applications. For example, while only three audio (8-track, cassette, CD) and four video (VHS, 8mm, DV, DVD) recording formats had become dominant designs for consumers as of early 2006, committees representing broadcasters and music companies continuously updated formats for analog and digital audio and analog and digital video and had thus defined more than 20 formats between the mid-1950s and the early 2000s.

The difference between the number of interface standards for industrial and consumer applications reflects the tradeoff between performance and compatibility. Industrial applications emphasize performance more than compatibility and consumer applications do the opposite thus leading to the definition of a greater number of updates in interface standards for industrial than consumer applications. Although definitions of a dominant design that emphasize market share, e.g., Anderson and Tushman (1990) require a 50% share, would not define many of these interface standards for the industrial applications as dominant designs, definitions that emphasize interface standards (Shapiro and Varian, 1999) would probably do so. The tradeoff between performance and compatibility and the definition of a dominant design as a path helps us reconcile these different definitions, the way these standards are determined in industrial and consumer applications, and the implications these differences have for competition.

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Table 1. Major Product Classes and Movements back up the Hierarchies in Audio and Video Magnetic Recording Equipment

Product Classes	Decade Intro-duced	Movements Back up the Hierarchies	
		Product Design	Customer Choice (Early applications)
Analog Audio		Magnetic wire/tape passes a magnetic head or coil	
1. Wire	1880s	Wire on a spool	Dictation
2. Reel-to reel tape	1930s	New material (tape); open reels, manual threading	Pre-recorded radio broadcasts
3. 8-Track, cassette tape	1960s	Smaller tape with enclosed reels and fixed threading	Pre-recorded music for car/portable users
Analog Video		Magnetic tape and head	
1. Quadruplex	1950s	Four recording heads	Pre-recorded television broadcasts
2. Helical scan	1960s	Single recording head	Education and training
3. Camcorder	1980s	Added camera and display	News gathering
Digital Audio		Magnetic heads, lasers/photo-diodes, ICs read/write data	
1. Hard disk	1980s	Magnetic head and disk	Editing by music firms, broadcasters
2. Stationary head cassette	1980s	Replaced disk with tape	
3. Optical discs	1980s	New disc (metal), read/write method (lasers/photodiodes)	Pre-recorded music
4. Rotary head cassette	1980s	Returned to magnetic head and tape but with rotary head	Editing by music firms
5. Flash memory	2000s	All done by integrated circuits	Mobile phones
Digital Video		Magnetic heads, lasers/photo-diodes, ICs read/write data	
1. Tape	1980s	Magnetic head and tape	Editing by TV broadcasters
2. Hard disks	1980s	Replaced tape with disk	
3. Optical disks	1990s	New disc (metal), read/write method (lasers/photodiodes)	Pre-recorded movies
4. Flash memory	2000s	All done by integrated circuits	Portable camcorders

Sources: (Inglis, 1991; Millard, 1995; Sadashige, 1999; Sugaya, 1999; Grindley, 1995; web pages)

Table 2. Incremental Improvements Changing the Design Tradeoffs and Driving Movements back up the Hierarchies for Audio/Video Magnetic Recording Equipment

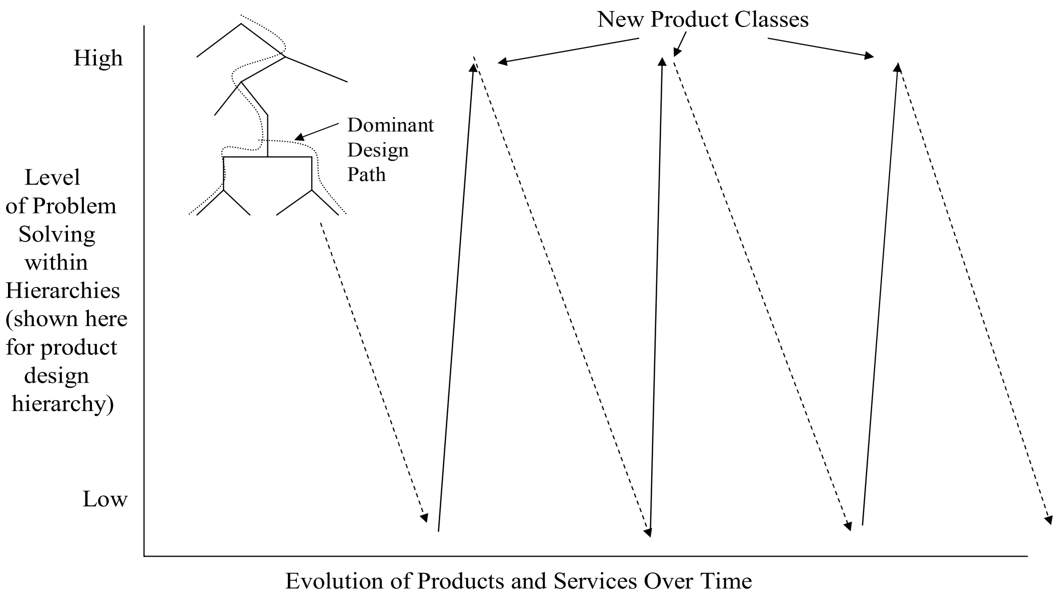
Audio/ Video	Incremental Improvements	Eventual Impacts on Design Tradeoffs for some of the Product Classes shown in Table 1
Audio	In coating processes, magnetic coils/ heads/tape, plastics, synchronous motors, amplifiers	1. Change from wire to tape: Benefits in tape handling and magnetic recording density eventually outweighed the costs of replacing readily available steel wire with tape 2. Change from reel-to reel tape to 8-track/cassette: Benefits from improvements in tape recording density and in strength of plastics (smaller size and thus portability) eventually outweighed the initially poor sound quality and higher costs of 8-Track and cassette. 3. Change from analog to digital: Improvements in magnetic recording density and ICs caused the benefits from digital editing to eventually outweigh the initially high costs of processing the increased data volumes.
Video	In recording density of magnetic tape, accessing density of heads, and integrated circuits	1. Emergence of first video recorder: Benefits (video) from improvements in recording density eventually outweighed the costs of a more complex tape handling system. 2. Change from Quadruplex to helical scan: Improvements in recording density caused the benefits from using a simpler tape handling design to eventually outweigh the inferior image quality of the simpler design. 3. Change from helical scan to camcorder: Benefits from improvements in magnetic recording density and in strength of plastics (smaller size and thus portability) eventually outweighed the initially poor video quality. 4. Change from analog to digital: Improvements in increased magnetic recording density and ICs caused the benefits from digital editing to eventually outweigh the initially high costs of processing the increased data volumes.

Table 3. Dominant Designs for Specific Product Classes and Markets in Audio and Video Magnetic Recording Equipment

Product Class and if Applicable, Market		Dominant Design (mostly defines relationship between the writing/reading mechanism and storage medium)
Analog Audio	1. Reel-to reel	1. 1/4” tape with Dolby (updated many times)
	a. Radio broadcasters	a. Initially 15 and 7.5 ips, updated to 7.5 and 3.75 ips
	b. Music companies	b. Initially 30 ips, later updated to 15 ips
	2. 8-Track, cassette	2. Philips Compact Cassette
	a. music consumers	a. 1/8” tape, 1.875 ips
	b. music companies	b. many tape sizes and speeds
	c. broadcasters	c. 1/8” tape; 1.875 and 0.938 ips
Analog Video	1. Quadruplex	1. Initially Ampex design with 2” tape and 15 ips; updated several times by SMPTE
	2. Helical Scan	2. Helical Scan
	a. Consumers	a VHS (Video Home System), 0.5” tape
	b. TV broadcasters	b. SMPTE formats
	i. news gathering	i. Type L and M Formats
	ii. studios	ii. Type C Format
	3. Camcorder (portable)	3. VHS-C, 8-mm
Digital Audio	General design	Pulse Code Modulation (PCM), MPEG compression
	1. Hard disk	1. 3.5” disk, later USB (Universal Serial Bus)
	2. Stationary head cassette	1. Digital Audio Stationary Head (DASH) and later digital compact cassette (DCC)
	3. Optical discs	3. Sony-Phillips compact disc (CD)
	4. Rotary head cassette	4. Digital Audio Tape (DAT)
	5. Flash memory	5. Memory cards, USB, or similar device
Digital Video	General design	MPEG (including Digital PCM) compression formats
	1. Magnetic tape	1. SMPTE D-1 to D-7 formats for professional applications and DV for camcorders
	2. Hard Disks	2. 3.5” disk, later USB and similar devices
	3. Optical discs	3. Digital video disks (DVDs)
	4. Flash memory	3. Memory cards, USB, or similar device

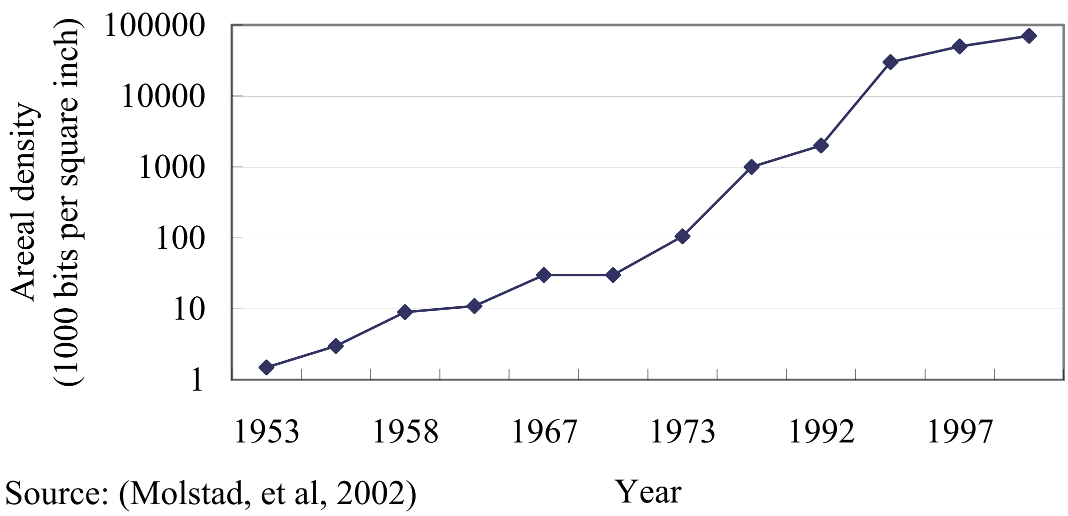
Abbreviations: SMPTE (Society Motion Picture Television Entertainment), MPEG (Moving Picture Expert Groups), ips (inches per second). Sources: (Inglis, 1991; Clark, 1999; Millard, 1995; Sadashige, 1999; Sugaya, 1999; Grindley, 1995; Web pages)

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. Growth in Magnetic Tape Areal Density



Source: (Molstad, et al, 2002)