Technological Discontinuities and Dominant Designs:

The Case of the Broadcasting Sector

by

Jeffrey L. Funk

Professor

Hitotsubashi University

Institute of Innovation Research

2-1 Naka, Kunitachi, Tokyo 186-8603 Japan

Telephone: 81-42-580-8430

Facsimile: 81-42-580-8410

funk@iir.hit-u.ac.jp

Title:

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Abstract:

This paper demonstrates a model of technological change that addresses the sources and timing of technological discontinuities and dominant designs using data from the broadcasting industry. 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 back up the hierarchies are defined as technological discontinuities 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, customers, and business models 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 [7] 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 [1] [32] [70] 73]. Still others have extended Anderson and Tushman's model by showing examples of interactions between component and system innovations/discontinuities [71] [42] and how dominant designs can exist at multiple levels in a single product [46] [71].

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 [6] [17], design tradeoffs [19] [52] [53] [57], 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 back up the hierarchies are defined as technological discontinuities 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 [71] [42], by showing the specific changes that occur in the designs, customers, and business models during the emergence of the discontinuity.

This paper uses data from the broadcasting sector, particularly from the U.S. one, to demonstrate this alternative viewpoint of technological change. The broadcasting sector is an appropriate application for the model due to large amounts of technological change, large literatures, and large differences between the relative successes of various technological discontinuities. 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 broadcasting sector.

2. Proposed Model

The proposed model builds on the concepts of hierarchical decision making in complex systems [6] [61] 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 [17]. 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 [17]. The interaction between these hierarchies also includes the determination of a business model [14] and sales and service channels [1].

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 [70], customer segments begin to emerge and design activity moves from higher-level to lower-level problem solving [71] [46] 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 the different firm's products in both alternative designs and the definition of sub-problems (product design hierarchy) [17]. In terms of sub-problems, the coalescence of customer needs around a few related dimensions and pressures to reduce cost and standardize [2] may cause firms to redefine the sub-problems in terms of independent modules [72]. These modular designs may also enable new forms of business models to emerge [8] [39] [58].

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 [66] 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 [19] 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 [7] and the possibility that such a stable architecture can extend to sub-systems and components within a system [46] [71].

However, depending on the industry, dominant designs will differ in terms of both the relative importance of alternative designs and sub-problems 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 [66] 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 components in a product's components, a material's processes, or in the equipment used in these processes, which may be driven by other industries, can change the "design tradeoffs" that are implicit at all levels in the product design hierarchy and thus lead to movements *back up* the hierarchies of both product design and customer choice and the emergence of a technological discontinuity. Both popular journalists [24] [25] 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 [23].

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 [4] [27] [38], to tradeoffs at each level in a product design hierarchy [6]. This concept of design tradeoffs is similar to Dosi's [19] characterization of a technology paradigm, which "defines its own concepts of progress based on its specific technological and economic tradeoffs," to Rosenberg's [52] [53] concepts of imbalances and technical disequilibria between machines and between the components within them, and to Sahal's [57] concept of how innovations "overcome the constraints that arise from the process of scaling the technology under consideration."

The degree to which incremental improvements in a product's components, a material's processes, and the equipment used in these processes change the design tradeoffs for the product/system as a whole will also impact on the degree of success of the technological discontinuity through their impact on the relative advantages and disadvantages of the new product with respect to existing products. The concepts of value trajectories and indifference curves can be used to model competition between the existing products and the new products resulting from the technological discontinuities [4]. New products must also overcome the network effects of the existing products [60] and create a critical mass of users [51] where customers perceive a tradeoff between the performance advantages of a new product and its level of compatibility with existing products. Without compatibility with existing products, the new product must have a large performance advantage over existing products in order for users to forgo the network effects, including both indirect (complementary) and direct ones, of the existing products [60].

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 [7] [70], these discontinuities clearly involve smaller movements back up the hierarchies than the introduction of mainframe, mini-, and personal computers. In terms of the largest movements back up the hierarchies, technological discontinuities that are primarily due to movements back up the customer choice hierarchy are often called niche innovations [1] or disruptive technologies [15]. Ones that are primarily due to movements back up the product design hierarchy are often called revolutionary [1] or architectural [32] 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 [32], capabilities [5] [70], complementary assets [67], and managerial cognitive representations [37] [69].

3. Research Methodology

The author analyzed the primary and secondary literature on the broadcasting sector including academic papers and books from the management, economic, and historical fields, practitioner-oriented accounts, and encyclopedic histories. Through analysis of this literature, the author identified: 1.) the technological discontinuities that involved major movements back up the product design or customer choice hierarchies or changes in business models and sales channels; 2.) the incremental improvements in a product's components, a material's processes, or in the equipment used in these processes that have changed the design tradeoffs thus leading to movements back up the hierarchies; 3.) the movements down the hierarchies following each technological discontinuity in terms of both alternative designs and definitions of sub-problems in a modular way; and 4.) the dominant designs.

4. Results: Brief History of the Broadcasting Industry

Table 1 summarizes the major technological discontinuities in the broadcasting industry and the changes in the product design and customer choice hierarchies and business models for them. Table 1 divides the product design hierarchy into content production/recording, transmission, and receivers and the customer choice hierarchy focuses on the initial applications and users. Many technological discontinuities involved coordinated movements back up the product design hierarchy for all three aspects of it along with changes in the early applications (e.g., main types of programs or content), users, and business models (e.g., advertising, national networks of affiliates and sponsors). Some technological discontinuities have not involved changes in all three aspects of the product design hierarchy (e.g., new forms of transmission) and still others have but not in a coordinated fashion. For example, solid state devices, video recording/playback, high definition television (HDTV), and digitalization have involved movements back up each aspect of the product design hierarchy but these movements have occurred at different times and in a somewhat independent manner.

Table 2 summarizes the incremental improvements in components, a material's processes, or in the equipment used in these processes that have changed the design tradeoffs and thus enabled movements back up the product design hierarchy and the emergence of technological discontinuities in the broadcasting sector. For the second half of the 20th century, the most important improvements were in integrated circuits (ICs) (See Figure 2) and magnetic recording density. The changes in design tradeoffs for a specific row in Table 2 primarily refer to comparisons with the above row. Exceptions include: 1) comparisons between AM radio and both FM radio and black and white television (TV); 2) between both solid state radios and TVs with their non-solid state versions; and 3) between video recording and film recording for broadcasters, and video recording and regular TV viewing for consumers.

Table 3 summarizes the dominant designs for each aspect of the product design hierarchy in each technological discontinuity. Although some analyses (e.g., [74]) argue that national networks can be seen as a form of dominant design, Table 3 focuses on the technical standards including the frequency band and format for transmitting and receiving images partly for reasons of conciseness. Instead, this paper considers these national networks to be part of the business model (See Table 1) and several sections of this paper discuss the interaction between them and movements down the product design hierarchy, particularly those that involve modular designs.

Place Tables 1 – 3 and Figure 2 about here

4.1. AM Radio

Incremental improvements in alternators, magnetic coils, magnetic diaphragms, vacuum tubes, and microphones enabled the creation of the first commercial radio services in the early 1920s [35]. Improvements in alternators were driven by the electric power industry and enabled the creation of high power transmitters [40] [64]. Improvements in magnetic coils, diaphragms, vacuum tubes, and microphones were driven by the telephone industry where the former three made speakers and amplification possible in the receivers and the fourth, microphones, expanded the range of possible live broadcasts to sporting and other public events [35].

The debate about business users versus consumers and the merits of user fees versus advertising represented the first moves down the customer choice hierarchy and the interaction between the hierarchies and business models. The leading incumbent, Marconi, focused on business users and all European countries chose user fees where taxes were levied on radio receivers [10] [62]. It was not until Frank Conrad began transmitting music and advertisements for radios on the same program in Pittsburgh in 1921 that the outlines of the current business model for radio broadcasting began to emerge [10] [35] [40] [62]. So-called "radio heads," who had used the early crystal sets as "ham" radios and had stubbornly refused to comply with the regulation of radio spectrum (e.g., in the Radio Act of 1912), provided an enthusiastic audience for the music programs [59] and helped created a critical mass of listeners and radio broadcasters in the early 1920s. The success of music and later other programs such as comedies, dramas, educational talk, and news shows [40] [62] [64] reflect the emergence of well-defined segments in the customer choice hierarchy.

The resulting growth in the market led to interference between stations and the regulation of frequencies by the U.S. government beginning in 1927 [29] [64] where the selection and licensing of frequency spectrum was the first step down the product design hierarchy and the emergence of a dominant design. Unlike subsequent broadcasting technologies, the simplicity of radio technology did not require any technical specifications for the interface between the transmitter and the receiver [35], which is why radio heads were able to construct their own radio sets from inexpensive crystals and cereal boxes [74]. Nevertheless, vacuum tubes provided superior sound quality particularly through the use of them in the superheterodyne circuit. Along with electrical plugs and speakers, they formed the dominant design for receivers where RCA was the main beneficiary through its ownership of key patents [40].

The U.S. government's opposition to ownership of multiple stations in a single market and its perceived opposition to AT&T's entry into the broadcasting field also impacted on the overall dominant design and business model for radio broadcasting. The former opposition promoted competition and the latter, perceived opposition caused AT&T to reach an agreement with RCA in 1926 where AT&T agreed to sell its stations to RCA and allow RCA and other broadcasters to send their programs to local affiliates over AT&T's telephone lines [10] [35] [40]. The open use of AT&T's telephone lines can be considered one part (a modular part) of the dominant design for radio broadcasting and it enabled national networks of affiliates and sponsors to emerge where these national networks can be considered part of the business model for AM radio broadcasting [10] [20] [35] [62] [64].

4.2. FM Radio

Incremental improvements in vacuum tubes, other components, and transmitters [10] [35] [40] [62] led to the first changes in the design tradeoffs shown in Table 2 for radio broadcasting and thus to movements back up the product design and customer choice hierarchies and the emergence of FM radio as a technological discontinuity in the 1950s (See Table 1). Improvements in vacuum tubes, other components, and transmitters, particularly low frequency ones, were driven by the use of AM radios and black and white TVs (see below). The improvements in vacuum tubes and other components enabled engineers to dramatically reduce the number of vacuum tubes that were needed to construct the limiter and discriminator circuits, which were used to process the FM signals. By the 1950s it was possible to design these circuits for a fraction of the almost 100 vacuum tube that would have been required to construct them in the 1920s [35].

The growth in the market for FM radio was also delayed by a lack of available frequencies and a type of music that could benefit from the high fidelity of FM broadcasting. The FCC did not allocate appropriate frequencies until the end of the 1940s partly because the incumbent radio broadcasters opposed the awarding of new licenses. Since the popular music of the early 1950s, Jazz, did not sound better with FM than AM radio, it was the emergence of rock and roll music in the 1950s that finally created a critical mass of FM radio receivers and programs where the rock music can be considered a move back up the customer choice hierarchy. Rock music lovers like loud music and lots of percussion, both of which required high-fidelity transmission [13] [44]. And since rock music was opposed by much of the mainstream media in the 1950s, local FM radio stations provided rock music with a necessary outlet that was not available on national or even local AM radio [35]. In retrospect, proponents of FM broadcasting were slow to recognize the need to move back up the customer choice hierarchy and find those people who would benefit from the specific advantages of FM broadcasting and instead primarily focused on the technical (i.e., product design hierarchy) and regulatory aspects of making FM broadcasting possible.

Furthermore, an interaction between the dominant design, business model and these movements back up the customer choice hierarchy strengthened the FM broadcasters. Improvements in vacuum tubes and transistors enabled the introduction of multiplexing, better known as stereo broadcasting, which represents the dominant design for FM radio. Stereo broadcasting further improved the sound quality of rock and roll music and thus increased FM radio's ratings, advertising revenues, and revenues from music companies for playing their music in a system called "payola" [35] [44] These additional revenues caused national networks and national programs to initially play a less important role in the business model for FM than AM broadcasting (See Table 1) [35].

4.3. Black and White TV

Incremental improvements in transmitters, vacuum tubes, photo-emissive materials, and electron guns led to the second round of changes in design tradeoffs shown in Table 2 for broadcasting and thus to movements back up the product design and to a lesser extent customer choice hierarchy and the emergence of black and white TV as a technological discontinuity in the 1940s. Improvements in transmitters were driven by the radio and electric power industries, vacuum tubes by the market for radio receivers [35], and photo-emissive materials and electron guns by the market for oscilloscopes [63]. The electron guns and photo-emissive materials were used in a cathode ray tube (CRT) that worked far better than Nipkow's spinning disks, which had been used on a limited basis in the 1930s for U.S. [35] and British [12] broadcasts. In a CRT, an electron gun generates the electron beam while vacuum tubes and other components focus and deflect the beams [35]. The photoemissive materials were also used in a cathode ray scanning tube, known as the iconoscope, which gave the television camera an electronic eye [3] [35]. Farnsworth added the image dissector, which dissected the electronic image into picture elements, and then transmitted them through a small aperture in an electrical shutter [10].

While the overall change from radio to TV represents a movement back up the product design hierarchy, many of the design decisions described in the last paragraph represented movements down the product design hierarchy where the specification of the density of scanning lines and the number of picture frames transmitted between the broadcast station and receiver by governments represents the dominant design for black and white TVs [35] [47]. In the U.S., the FCC chose a standard in 1941 that was similar to one introduced by RCA two years earlier [35] (Inglis, 1991) and awarded licenses to the big three radio broadcasters (NBC, CBS, ABC). Although the U.S. government prohibited the production of TVs during WWII, the market began to rapidly grow once the government rescinded the ban following the end of the war [10] [29] [62]. Part of the growth was due to the improvements in CRTs that had been made in wartime applications such as radar and in other electronic measuring and sensing devices [35].

In addition to these movements up and subsequently down the product design hierarchy, there were also movements up and down the customer choice hierarchy albeit many of them were fairly obvious. While music and comedies were the most successful radio programs in the 1940s [40] [62], sports and news were initially the most popular TV programs where specific types of programs and sponsors for the programs reflect the emergence of well-defined segments in the customer choice hierarchy. Like radio, these programs were distributed to local broadcasters via telephone lines that were updated with coaxial cables (an inner conductor surrounded by an insulating material) [35]. This enabled the big three TV broadcasters to create a national network of affiliates and sponsors, just as they had done in radio broadcasting. However, the existence of the film industry and later the requirement by the U.S. government in the 1960s that the three major TV broadcasters source a high proportion of their programming from independent producers [20] caused these networks to be less vertically integrated than the ones that existed in radio broadcasting.

4.4. Color TV

Incremental improvements in cameras, photo-emissive materials, electron guns, and vacuum tubes led to the third round of changes in the design tradeoffs shown in Table 2 for broadcasting and thus to movements back up the customer choice and product design hierarchies and the emergence of color TV as a technological discontinuity in the 1950s. These incremental improvements were driven by both black and white TVs and defense applications such as radar and other electronic measuring and sensing devices [35]. Like black and white TV, the value of color TV was widely recognized. And although there were issues about the types of color programs that would drive the purchase of color TVs (see below), the main challenges involved the specific standards (i.e., dominant designs) and business models that would enable the additional cost of colorizing programs to be financed.

Partly due to CBS's efforts to challenge RCA, which was the leader in black and white TV, the U.S. moved much more quickly to set standards for color TV than the rest of the world. The U.S. government initially chose CBS's system as a standard in 1951 but its poor quality, lack of backward compatibility, and other reasons prevented a critical mass of programs and receivers from emerging. After relieving CBS of its responsibility to make color sets when the Korean War started [35] [60], the U.S. government chose RCA's system in December 1953 partly since it was compatible with existing black and white systems [29] [60].

However, even with the backward compatibility of this system, creating a critical mass of receivers and programs proved difficult. Receivers were expensive and sponsors refused to pay more for air time in color than in black-and white. The first problem was solved by the passage of time; improvements in vacuum tubes, transistors (see next section), and other components along with economies of scale caused the factory price of receivers to drop by 40% between 1955 and 1965 even as their screen size increased [74] and more color than black and white receivers were sold for the first time in 1968 [35]. The second problem, which also occurred in high-definition and digital TV, required RCA to absorb the additional cost (about 25%) of colorizing programs in the hope of selling color TV receivers. It also required RCA's subsidiary, NBC to find those programs that would benefit the most from colorization, which can be interpreted as a small movement back up the customer choice hierarchy. It is generally agreed that NBC's decision to colorize the popular Walt Disney TV program after purchasing it from ABC in 1960 accelerated the diffusion of color TVs [60].

4.5. Solid state radios and TVs

Improvements in transistors and later ICs (See Figure 2), both of which were driven by military applications [41] [68], changed the design tradeoffs shown in Table 2 for both radios and TVs and led to the emergence of solid state radios and TVs as technological discontinuities. The use of transistors and other new components to dramatically reduce the size of a radio represent movements back up the product design hierarchy while the new users represent movements back up the customer choice hierarchy. The first transistor radios initially had inferior sound quality to the vacuum tube-based ones [48] and young people that wanted to listen to rock-and roll music outside of ear-shot of their parents were the initial purchasers of these radios. Minor producers and new entrants such as Regency, Texas Instruments, and Japanese manufacturers went back up both hierarchies faster than the major incumbents did to target this low-end market [16].

Further improvements in silicon transistors enabled the design of transistor TVs where the low voltage of these transistors initially only allowed the design of small TVs [48]. Sony was the first firm to sell such a TV in the U.S. where its small size and thus portability was a major selling point [34]. Like the transistor radios, this portability required movements back up both the product design and customer choice hierarchies where it was mostly Japanese firms that made these moves and introduced transistor TVs [16] [49].

ICs also changed the design tradeoffs for radios and TVs and required movements back up the product design hierarchy in two ways. First, because the cost of ICs was driven more by the number of external connections than the number of transistors on them, TV designers had to minimize the number of external connections (i.e., number of pads) on an IC as opposed to reducing the number of circuit elements, which had been the rule when designing TVs with vacuum tubes [48]. Second, the use of ICs basically involved an increased integration of functions, which required TV manufacturers to discard the modular design approach that had been used to facilitate maintenance. The Japanese manufacturers quickly discarded modularity and pursued integration with ICs to improve reliability partly since they did not have a network of service facilities like the U.S. manufacturers did [49]. Furthermore, improvements in ICs still continue to drive changes in the design of radios and TVs by enabling a reduction in the number of chips needed for a radio or TV tuner with the most recent example being mobile phones that contain these tuners. This continued integration can be defined as the dominant design (path) for solid state radios and TVs.

4.6. Video Recording and Playback

Incremental improvements in magnetic recording density and later transistors and ICs changed the design tradeoffs shown in Table 2 for broadcasters, manufacturers, and consumers and thus led to multiple movements back up the customer choice and product design hierarchies and the emergence of video recording equipment as a technological discontinuity the 1950s for TV broadcasters and for consumers in the 1970s. Improvements in recording density in the 1930s and 1940s were driven by the German government's use of tape players in mass rallies and in other aspects of its propaganda machine [22] and these improvements eventually led to the post-war use of magnetic tape recorders by radio broadcasters to produce national programs and by music companies to edit recordings [26] [44]. These magnetic tape recorders were first used in Bing Crosby's popular radio program thus enabling Crosby to reduce the number of his live performances [26].

Further improvements in magnetic recording density also led to changes in the design tradeoffs for TV broadcasters and thus additional movements back up the product design hierarchy for both manufacturers and broadcasters. Other than live broadcasts, film was initially used to record the first programs where the development of film involved time-consuming chemical processing steps thus making editing very difficult [50]. The challenge for video recording was that it required 250 times the bandwidth of audio applications [35] and thus the initial attempts to record video in the same manner as audio failed. For example, RCA's prototype in the summer of 1953 still required a tape speed of 360 inches per second (ips) and a 17-inch reel only contained four minutes of playing time. 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 [43], 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 [35] [55]. Ampex's Quadruplex was the dominant design until it was replaced by the helical design in the late 1970s.

Further improvements in magnetic recording density changed the design tradeoffs for a second time and thus caused another movement back up both the product design and customer choice hierarchies for video recorder manufacturers. Japanese firms introduced a single head recording format in the 1960s called helical scan that is much simpler, less expensive, but had lower image quality than the Quadruplex design. Japanese firms sold these systems to firms for education and training where these applications had a different tradeoff between quality and price and thus also represented movements back up the customer choice hierarchy. Later, consumers purchased them for time-shifted recording [54] and the expansion of these markets reflects the emergence of well-defined segments for the customer choice hierarchy of video recording and playback.

Although the agreement by Japanese firms to support the so-called "U-Format" in 1969 can be interpreted as movements down the product design hierarchy, the divergence of Sony's and JVC's designs in the mid-1970s ended these movements down the hierarchy. Although there is a large literature [18] [28] [51] [54] on the competition between these two designs – Beta versus VHS – the important points for this paper's proposed model are that the differences between Beta and VHS represent different movements down the product design hierarchy and overall Japanese firms moved back up the product design and customer choice hierarchies more effectively than Ampex and RCA did. Not only were Ampex and RCA unsuccessful in the consumer segment, improvements in magnetic recording density eventually caused the quality of the helical scan machines to become acceptable to broadcasters and the last sale of equipment based on the Quadruplex format occurred in 1981 [35] [54].

4.7. New forms of transmission

Incremental improvements in cables, vacuum tubes, ICs, microwave transmission, and satellites [25] continue to change the design tradeoffs shown in Table 2 for broadcasters, manufacturers, and consumers thus leading to continued movements back up the product design and to a much lesser extent the customer choice hierarchy and the emergence of technological discontinuities (See Table 1). These discontinuities include cable, microwave, satellite, fiber optics, and new forms of wireless. Although these improvements largely impact on only the transmission aspect of the product design hierarchy, they also require adapters for receivers.

First, improvements in coaxial cable and IC-based amplifiers, both of which were driven by the telephone industry, enabled mom-and-pop cable companies to extend the range of local TV stations with cable. Cable was popular in remote and/or mountainous regions where it was difficult for residents to obtain a signal from the local stations. The cable companies provided this service for an installation and monthly fee beginning in the early 1950s [35]. Second, the cable companies began importing programs using microwave transmission systems in the late 1950s and using satellites in the 1970s, both of which became cheaper than laying cables [25] [33] [65]. The ability to cheaply import programs caused national providers such as HBO (Home Box Office) and Viacom [35] to emerge just as they had in radio and TV broadcasting and like broadcasting, the use of national programs represented a new business model for cable and also satellite services.

Third, further improvements in satellites services, fiber optics, and wireless continue to shape competition in the "last mile" and require additional sets of movements back up the product design and customer choice hierarchies. As consumers began using satellite antennas or dishes to directly access programs from satellites for free, cable operators began introducing scrambling techniques such as VideoCipherII and satellite operators began offering paid services that also used these scrambling techniques [9]. These services strengthened the importance of national programs and a business model that supported them. Later, these analog services were replaced with digital services that use the digital video broadcasting (DVB) standard.

The rates of improvements in satellite, fiber optic, and new forms of wireless services and the cost of implementing them (e.g., the construction costs of fiber optics) continue to impact on the design tradeoffs and the movements back up the product design and perhaps customer choice hierarchies for these new forms of transmission and the competition between them. Fiber optics offers 10-20 times the bandwidth (20-40 gigabits) of coaxial cable but has higher implementation costs than either satellite or wireless services in the "last mile." The costs of satellite services are driven by the cost of launching satellites and receivers, which depend on the cost of rockets and electronics [25] [35][36] [75].

4.8. HDTV

Unlike the other technological discontinuities discussed in this paper, the case of HDTV shows how incremental improvements in components have largely been insufficient to dramatically change the design tradeoffs for TV broadcasting and thus lead to movements back up the product design hierarchy. Compression techniques, which depend largely on improvements in ICs, were initially not capable of reducing the bandwidth requirements of HDTV to the level of existing TV and allocating new frequencies to HDTV during the transition from conventional to HDTV meant that the total spectrum allocated to TV broadcasters would have to be more than doubled. This was politically difficult, particularly in the U.S. and Europe given the many demands for frequency spectrum from other applications such as mobile phones. Even the TV broadcasters were opposed to HDTV because they wanted to use the spectrum to expand the number of programs as opposed to improve the image quality of them [11] [28] [29].

HDTV also requires larger TV screens in order for users to receive the full benefits of the higher resolution. However, improvements in cathode ray tubes have occurred at a much slower rate than those of ICs over the last 40 years. Thus prices for wide-screen TVs have fallen very slowly even in Japan where manufacturers and broadcasters agreed on standards, Japan's public broadcaster (NHK) has offered programming, and a strategy of incremental improvements was adopted [28] [51]. For example, prices for 40-inch CRT televisions have never dropped below US $1000 and the slow diffusion of these wide-screen televisions has discouraged other broadcasters from offering high-definition programs.

This slow diffusion in Japan suggests that a lack of inexpensive large-screen CRTs would probably have slowed diffusion in the U.S. and Europe even if standards had been agreed upon, which they were not [29] [51] [64]. In fact, one reason why HDTV had trouble generating support by the 1990s and one reason why computer manufacturers argued for a digital standard that is compatible with computer monitors in the mid-1990s is that many people believed that continued improvements in ICs such as microprocessors and digital signal processors would quickly make both digital TV and its compatibility with computer monitors technologically and economically possible [29] [51].

4.9. Digitalization

Improvements in magnetic and optical recording density and ICs have led to continuous changes in the design tradeoffs and thus to multiple movements back up the product design and to a lesser extent customer choice hierarchies for digital broadcasting that have varied in their degree of success. The most successful movements have been in the content production part of the product design hierarchy where improvements in magnetic recording density enabled broadcasters to introduce digital magnetic recording in the early 1980s for its advantages in editing [35] [56]. Later, improvements in optical storage including improved lasers, rotation speeds, error correction codes, and servo systems, which were driven by the use of compact discs in the music industry, led to the replacement of home VCRs with digital video disks (DVD) in the 1990s [22]. Improvements in semiconductors, which were driven by the personal computer industry, were also needed before digital recording could be used in both magnetic and optical recording [28] [44] [56].

Dominant designs for both digital recording and DVDs have emerged. The Society for Motion Pictures, Television, and Entertainment (SMTE) has introduced multiple generations of standards for digital recording beginning in the early 1980s that are based on differential pulse code modulation (DPCM) and MPEG (Moving Picture Experts Group) formats. The SMPTE has introduced ones for studio, portable (electronic news gathering) and high definition applications and updates of them to include for example new MPEG formats [56]. As for DVD, a consortium of manufacturers and movie companies called the DVD forum published the 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 [21].

On the other hand, in spite of its greater efficiency in the usage of the frequency spectrum as compared to analog technology, the application of digital technology to the actual transmission and reception of signals has been stalled by a lack of standards, un-aggressive time-tables for broadcasters to return analog frequencies, and expensive receivers. Long debates about standards, which began when a digital system was proposed as an alternative to HDTV, occurred in the U.S., Europe, and Japan and resulted in the emergence of dominant designs in Europe and Japan but not in the U.S. where 18 formats were approved by the government in 1996 [29] [31]. Broadcasters may not return the analog frequencies before 2010 or almost 15 years after the digital formats were determined. One reason for the lack of aggressive time-tables for the return of analog frequencies has been uncertainty about how quickly the price of digital receivers will drop and thus the receivers will diffuse. They have diffused much more quickly for cable and satellite services through their special set-up boxes and antennas than for terrestrial services [30] [31], probably because cable and satellite services have subsidized them through their subscriber services. The success of set-top boxes suggests that high prices for digital technology have not been as large a reason for the slow diffusion of digital TV as high prices for large-screen CRTs have been for the slow diffusion of HDTV.

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, the use of product design and customer choice hierarchies and the concept of design tradeoffs provide insights that are not found in the existing literature. Incremental improvements in a product's components, a material's processes, or in the equipment used in these processes change the design tradeoffs and thus require firms to rethink the product design and customers. This paper identified several kinds of changes in design tradeoffs of which three are focused on here. First, the tradeoffs between price and quality (both sound and image) for consumers were impacted on by improvements in transistors and ICs that enabled the production of smaller and cheaper radios and TVs and by improvements in magnetic recording density that enabled the production of inexpensive VCRs.

Second, the tradeoffs between price and performance were also changed in the opposite direction where improvements in recorders (for broadcasters), transmitters, and receivers (both radios and CRTs) enabled the recording, transmission, and reception of additional information (e.g., stereo sound, color images, and later high-density color images) in return for higher prices. In each of these cases, the new product initially had higher prices but also higher performance in terms of information than the existing product. Third, the tradeoff between the price of receivers and spectrum efficiency was changed by improvements in ICs where it appears that ICs have finally made low-price digital receivers and transmitters possible.

In addition to these design tradeoffs that are inherent in the product design hierarchy, the exact timing of the discontinuity will depend on how firms use these improvements to rethink their products, customers, business models, and sales channels. For products, firms were forced to rethink the methods of production/recording, transmission, and reception. In terms of customers, 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 to occur. For example, the demand for rock-and roll music made it easier for FM radio to overcome the network effects of AM receivers. The demand for small and inexpensive radios, TVs, and VCRs made it possible for solid state radios and TVs and helical design VCRs to diffuse before their performance had reached the level of the previous product.

These results go beyond those of previous research that have linked innovations in components to those in systems [42] [71]. The proposed model represents this phenomenon at a much deeper level by showing the specific changes that occurred in the product design and customers during the emergence of the technological discontinuity and how firms can both underestimate and overestimate the impact of the improved components on the design tradeoffs. On the one hand it appears that many firms underestimated the extent to which improvements in vacuum tubes, transistors, ICs, and magnetic recording density would require changes in the design and more importantly in the customers during the technological discontinuity. Examples include failures by Marconi in AM radio, many AM broadcasters in FM radio, and U.S. manufacturers in solid state radios and TVs and in video recorders. On the other hand it appears that many firms and even governments overestimated the extent to which other improvements would occur, for example in spinning disks for black and white TV and in CRTs for both color and HDTV. Some firms wasted large amounts of resources on for example the spinning disk format and HDTV.

One of the reasons for the errors of overestimation was that many firms assumed the emergence of the technological discontinuity would drive improvements in components as opposed to visa versa [29]. The proposed model suggests that firms and governments should place greater emphasis on how incremental improvements in these components can change the design tradeoffs than how new products and components for a technological discontinuity can be simultaneously created. This is particularly true when the improvements in the components are driven by other industries, which was often the case for the broadcasting sector.

For example, radio benefited from improvements in vacuum tubes that were made for telephones, black and white TVs benefited from improvements in CRTs that were made for oscilloscopes and military applications, video tape recorders benefited from improvements in magnetic recording density that were made for cassette tapes, cable TV benefited from improvements in coaxial cable that were made for telephones, DVDs benefited from improvements in lasers and related technologies that were made for CDs, and digital TV now benefits from improvements in semiconductors and liquid crystal displays that have been made for personal computers. The importance of improvements that are driven by other industries and sectors also suggests that the concept of a critical mass [61] must also be reconsidered. Although the history of the broadcasting sector suggests that the performance of a new product must overcome the network effects of the existing product, it is important to consider how other industries can drive these improvements in performance.

With respect to dominant designs, this paper extends Suarez and Utterback's [66] concept of a dominant design as a design path. For example, radio manufacturers pursued a similar design path in vacuum-tube based units where they used "standard" circuits such as a limiter, discriminator, and a multiplexer. Successful TV manufacturers pursued a similar design path with CRTs, photoemissive materials, and an image dissector. Video recording manufacturers pursued a similar design path with the U-Format until differences emerged between VHS and Beta. Radio and TV manufacturers pursued a similar design path in solid state units that has led to continuous reductions in the number of components in radio and TV tuners and the emergence of single chip tuners that are now in phones and other portable devices.

Furthermore, while using the definition of a "stable architecture" for a dominant design [7] in the broadcasting industry would focus attention on the interface between the radio and TV transmitter and receiver, using the concept of a dominant design as a path enables us to consider the impact of a number of design decisions, particularly modular ones, on competition including the business models that were used in the broadcasting industry. For example, the availability of AT&T's telephone lines, which goes beyond the interface between transmitters and receivers, enabled radio broadcasters to create national networks of affiliates and advertisers. Coaxial cable and later satellites enabled these national networks to be extended to broadcast, cable, and satellite TV.

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Table 1. Technological Discontinuities and Movements back up the Hierarchies in the Broadcasting Sector and Changes in Business Models

<table>
<tr><th rowspan="3">Date of Intro-duction</th><th rowspan="3">Techno-logical Disconti-nuity</th><th colspan="4">Movements back up the Hierarchies</th><th rowspan="3">Business Model (1)</th></tr>
<tr><th colspan="3">Product Design</th><th rowspan="2">Customer Choice (1)</th></tr>
<tr><th>Production/ Recording</th><th>Transmission</th><th>Receiver</th></tr>
<tr><td>1920s</td><td>AM Radio</td><td>Live with microphones, later records, magnetic tape</td><td>AM broadcast and telephone lines</td><td>Crystals, vacuum tubes</td><td>Music and variety programs</td><td>National network of affiliates, advertisers</td></tr>
<tr><td>1940s/ 1950s</td><td>FM Radio</td><td>No change</td><td>Changed to FM broadcast</td><td>New receiver</td><td>Rock and Roll Music</td><td>Network less needed</td></tr>
<tr><td>1940s</td><td>Black & White TV</td><td>Added camera & film, later magnetic tape</td><td>Changed to TV broadcast and coaxial lines</td><td>New receiver</td><td>Sports, variety</td><td>New national network</td></tr>
<tr><td>1950s</td><td>Color TV</td><td>New camera or tape equipment</td><td>Changed to color broadcast</td><td>New receiver</td><td>New programs</td><td>Same</td></tr>
<tr><td>1950s, 1960s</td><td>Solid state</td><td colspan="3">Application of solid state devices (transistors and integrated circuits) to recording, transmission, and receiving equipment</td><td>Low end of consumer market (2)</td><td>New service network (2)</td></tr>
<tr><td>1950s-1970s</td><td>Video Recording/ playback</td><td>See B&W TV above</td><td>Use of tapes from 1970s</td><td>Connect recorder to TV</td><td>Time-shifted recording</td><td>Sale of pre-recorded tapes</td></tr>
<tr><td>1960s – now</td><td>New forms of trans-mission</td><td>Not applicable</td><td>Cable, micro-wave, fiber optics, satellite</td><td>Added adapter to TV</td><td>Initially rural areas</td><td>New nat'l network, paid subscribers</td></tr>
<tr><td>1980s-now</td><td>HDTV</td><td colspan="3">High definition recording, transmission, and receivers (greatest success in recording)</td><td>Same as color TV</td><td>Same as color TV</td></tr>
<tr><td>1990s – now</td><td>Digital</td><td colspan="3">Application of digital technology to recording (e.g., DVDs), transmission, and receivers</td><td>Uncertain</td><td>Uncertain</td></tr>
</table>

Abbreviations: AM (amplitude modulation); FM (frequency modulation); TV (television); B&W (black &white); DVD (digital video disc); HDTV (high definition TV);

Sources: [10] [29] [45] [50] [72]; Notes: 1) from standpoint of broadcasters unless otherwise noted; 2) from standpoint of receiver manufacturers.

Table 2. Incremental Improvements Changing the Design Tradeoffs and Driving Movements Back up the Hierarchies for the Broadcasting Sector

Technological Discontinuity	Incremental Improvements	Eventual Impact of Incremental Improvements on the Design Tradeoffs
FM Radio	In vacuum tubes, other components, and lower frequency transmitters	Benefits of fewer vacuum tubes for necessary circuits eventually outweighed the increased complexity of these circuits
B&W TV	In transmitters, vacuum tubes, photo-emissive materials, electron guns	Benefits of images from use of improved components eventually outweighed their increased costs
Color TV	In cameras, photo-emissive materials, electron guns, cathode ray tubes (CRTs), vacuum tubes	Benefits of color images from improved photo-emissive materials and electron guns (in CRTs) eventually outweighed their increased costs
Solid State Radios, TVs	In manufacturing processes for transistors and integrated circuits (ICs)	Improvements in transistors (both cost and performance) eventually outweighed their cost and the initially poor performance of the radios and TVs
Recording and Playback	In magnetic recoding density and later transistors and ICs.	Benefits from improvements in magnetic recording density (editing for broadcasting, recording for consumers) eventually outweighed the initially poor image quality and high costs
New forms of transmission	In cables, microwave transmission, and satellites.	Benefits from improvements in components caused the benefits of the new system (access to remote areas) to eventually outweigh their increased costs
High Definition TV (HDTV)	In transmitters, ICs, and CRTs	Benefits of increased image quality have only partly outweighed costs of larger CRTs
Digitalization	In ICs, optical and magnetic recording,	Benefits of digitalization (ease of editing and more efficient use of frequency spectrum) are gradually outweighing their increased costs

Sources: [10] [25] [45] [50] [58] [66] [72]

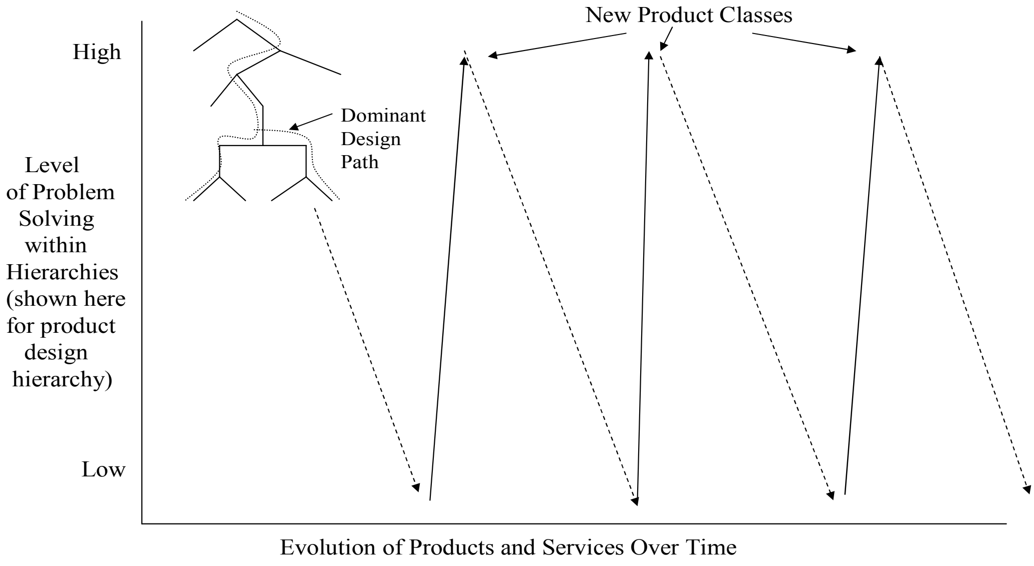
Table 3. Dominant Designs for Major Technological Discontinuities in the Broadcasting Industry

Disconti Nuities	Production/Recording	Transmission	Receiver
AM Radio	Carbon microphone, later LP record, 1/4" reel-to reel tape recorder	For transmission and receiver: 500 to 1,500 KHz band; For receiver: vacuum tube and superheterodyne circuits	
FM Radio	Same except for different microphone	88 MHz – 108 MHz frequency band; multi-plexing and stereo for transmission; limiter and discriminator circuits for receivers	
B&W TV	Iconoscope, later Ampex Quadruplex recorder	30 frames; 441 scanning lines per second; 54-88 MHz; CRT, vacuum tubes in receivers	
Color TV	Replaced iconoscope with Orthicon and later new type of camera	U.S. and Japan: NTSC (6MHz wide channels in 54-88 MHz band), Europe: PAL, SECAM	
Solid State	Continuous integration (i.e., miniaturization) of solid state components in cameras, recorders, transmitters, radios, and televisions		
Recording & Playback	Broadcasters: see B&W TV above; Consumers: VHS	Video rental stores	VHS Player
New forms of transmission: 1. Cable 2. Satellite	Not applicable	1. Coaxial cable and set-top boxes; later DVB-C and set-top boxes 2. Analog (same as color TV plus VideoCipherII); later DVB	
HDTV	SMPTE recording formats	Japan: Enhanced Definition TV; U.S.: none; Europe: none	
Digital	Broadcasters: SMPTE D-1 to D-7 formats Consumers: DVD	U.S.: 18 formats approved in 1996; Europe: DVB; Japan: Integrated Service Digital Broadcasting Terrestrial	

Abbreviations: NTSC (National Television Standards Committee); PAL (Phased-Attenuation by Line); SECAM (Sequential Couleur a Memoire); SMPTE (Society Motion Picture Television Entertainment); DVD (Digital Video Disk); DVB (Digital Video Broadcasting); VHS (Video Home System); LP (long playing)

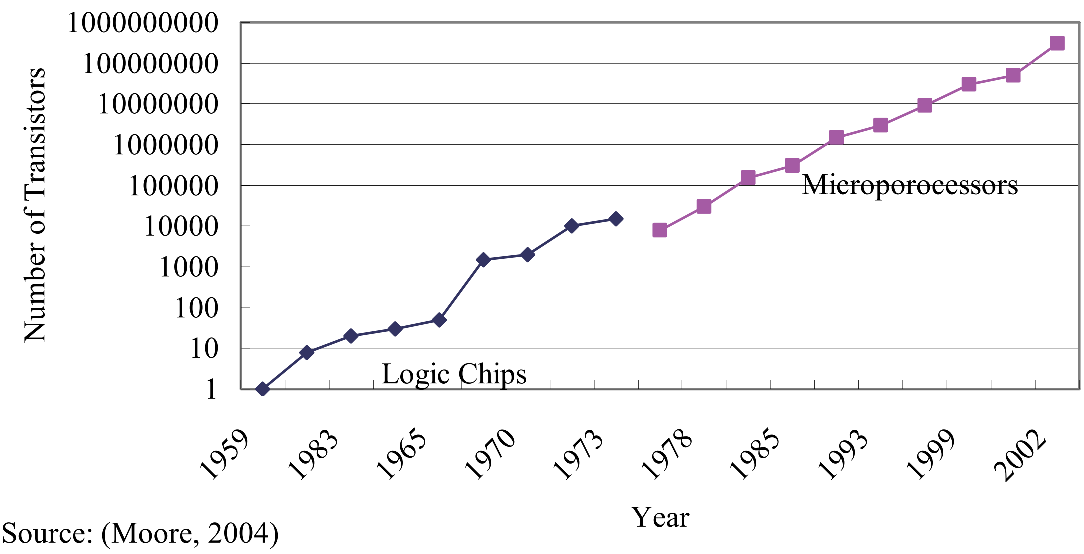
Sources: [9] [10] [29] [33] [45] [50] [72] [75]

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. Number of Transistors Per Chip



Source: (Moore, 2004)

Source [55]