The Sources and Timing of Technological Discontinuities and Dominant Designs

by

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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 four different industries. 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.

Keywords: technological discontinuities, dominant designs, hierarchies, design tradeoffs modular designs, incremental improvements

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) cyclical model by showing examples of 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 four industries to demonstrate this model of technological change. Due to limitations in page numbers and the application of the model to multiple industries, there is not sufficient space to address how and why different firms responded differently to changes in the design tradeoffs in terms of their movements (or lack thereof) back up the product design and customer choice hierarchies. It is hoped that readers will recognize that the paper's insights into how discontinuities and dominant designs occur outweigh the disadvantages of not having a more detailed discussion of these firm decisions, particularly since the proposed model shows how future research can apply existing research on firm responses (to discontinuities) to the model. Following a description of the proposed model and research methodology, this paper applies the model to the semiconductor, computer, music, and mobile phone industries.

2. Proposed Model

The proposed model builds on the concepts of hierarchical decision making in complex systems (Simon, 1962; 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 independent 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 different firm's products in terms of 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), where "design rules" define how these different modules interact, thus ensuring compatibility between them (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 situation, dominant designs will differ in terms of the relative importance of alternative designs and sub-problems within a specific design path and the number of levels to which a dominant design proceeds down the design hierarchy (i.e., the degree of commonality between the design paths of different firms). The latter will depend on both the flexibility/robustness of the technology and the extent of common needs among users. The extent of common needs among users sounds similar to the second half of Suarez and Utterback's (1995) definition: "a dominant design will embody the requirements of many classes of users, even though it may not meet the needs of a particular class to quite the same extent as would a customized design."

On the other hand, incremental improvements in a product's components, a material's processes, or in the equipment used in these processes drive changes in 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. Both popular journalists (e.g., Gilder, 1990, 1992) and scholars have used similar concepts to explain the impact of technological change on society. For example, incremental 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, incremental improvements in transportation, communication, and computer systems in the last 10 years have changed the tradeoffs for production systems where one result has been the increased globalization of them (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). This 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, which are addressed in this paper. 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 and create a critical mass of users (Rohlfs, 2001). Customers 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).

If we focus on the compatibility aspects of modular designs, Shapiro and Varian's tradeoff between performance and compatibility can also be applied to movements down the hierarchy that deal with defining sub-problems in a modular way and that involve network effects. This paper focuses on the definition of sub-problems in a modular way due to the large emphasis many scholars place on modularity (Langlois and Robinson, 1992; Ulrich, 1995; Sanchez and Mahoney, 1996; Baldwin and Clark, 2000). Following the introduction of a new product class, there is decreasing marginal utility from increases in product performance (Anderson and Tushman, 1990) from an integral design and increasing marginal utility from any network effects that may be part of a modular design. Although network effects are typically modeled in terms of the number of users, we can plot the marginal utility as a function of time since the number of users increase in a growing market, where this marginal utility eventually declines as shown in Figure 2 (Rohlfs, 2001). Figure 2 summarizes this tradeoff over time and helps us better understand how, when and why the emergence of a dominant design lags the emergence of a technological discontinuity/new product class (Anderson and Tushman, 1990).

Place Figure 2 about here

3. Research Methodology

The author chose four industries that represent a wide range of industry characteristics including process (semiconductor), product (computer, music), and service (mobile phone) ones where the computer and music industries involve both hardware and software. There are also large amounts of technological change and large literatures on these industries. The lack of randomness in the choice of industries suggests that we must be careful about generalizing to other industries.

The author analyzed the primary and secondary literature on these four industries 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 changes in product class through major movements back up the product design or customer choice hierarchies or changes in business models and sales channels; 2) the incremental improvements in a product’s components, a material’s processes, or 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 in each product class in terms of alternative designs and definitions of sub-problems in a modular way; and 4) the dominant designs for each product class and the incremental improvements that have impacted on the timing of those dominant designs that involve both modular designs and network effects.

4. Semiconductors

Table 1 summarizes the evolution of product classes in the semiconductor industry and the movements back up the product design and customer choice hierarchies for them. These product classes are defined in terms of the use of semiconductors in final products such as computers. In addition to changes in material design (from germanium to silicon transistors) and in transistor design from bipolar to MOS (Metal-Oxide Semiconductor) and CMOS (Complementary MOS), there has also been an evolution in the use of semiconductors in these final products (i.e., system design) from “combinations of discrete devices” to “combinations of ICs and discrete devices” and later to combinations of more complex ICs such as microprocessors and now SoC (System on Chip). All of these changes in material, transistor, and system designs represent large movements back up the product design hierarchy. The MOS (pocket calculators), CMOS (digital watches), and microprocessor (low-volume equipment) product classes also involved movements back up the customer choice hierarchies in that there was a different set of initial customers (shown in parentheses) for these product classes than the main customers for the previous product classes.

Table 2 summarizes the incremental improvements in equipment and their related processes that have driven changes in the design tradeoffs and thus caused movements back up the product design and customer choice hierarchies and the emergence of new product classes in the semiconductor industry. For example, improvements in silicon crystal growing (Riordan and Hoddeson, 1997) and oxidation processes and the equipment used in these processes led to the first large change in the design tradeoffs shown in Table 2 and the emergence of a new product class of semiconductors called silicon transistors (See Table 1). In terms of design tradeoffs, the benefits from being able to cover a silicon wafer with a thin layer of oxidation (i.e., planar process) finally exceeded the higher costs associated with the higher melting point of silicon (i.e., the higher costs of furnaces) (Bassett, 2002; Tilton, 1971) and led to the replacement of germanium with silicon in most semiconductor products beginning with ones for military applications.

Incremental improvements in a larger variety of processes, the equipment used in those processes, and their impacts on feature size (See Figure 3) have led to further changes in the design tradeoffs and thus the emergence of new product classes in the semiconductor industry. For example, the early reductions in feature size in the late 1950s caused engineers such as Jack Kilby of Texas Instruments to recognize that the advantages of producing resistors, capacitors, and transistors with the same material (i.e., silicon) in a so-called integrated circuit (IC) outweighed the advantages of using the optimal material for capacitors (Mylar) and resistors (carbon) in discrete components (Reid, 1985; Riordan and Hoddeson, 1997). Further reductions in feature sizes (See Figure 3) along with reductions in defect densities and increases in die size (IC Knowledge, 2005) increased the number of transistors on a chip (See Figure 4) and thus the heat production of ICs. This caused the benefits of lower power and heat production from MOS and later CMOS transistors to outweigh the processing speed advantages of bipolar transistors in the 1970s and 1980s respectively (Langlois and Steinmueller, 1999; Riordan and Hoddeson, 1997). Simultaneously, these reductions in feature size have also made it economical to waste silicon space in return for lower user development costs through semi-custom designs such as microprocessors and SoC (System on Chip). Both microprocessors and SoC fill a gap between general-purpose logic chips, which have low development costs, and full-custom chips, which use silicon space efficiently (Borrus, et al, 1983; Bass and Christensen, 2002; Thomke, 2003).

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

Table 3 lists the dominant designs for each product class and where possible the multiple movements down the product design hierarchy that define the dominant designs. Multiple design decisions represent the multiple movements down the product design hierarchy for both germanium and silicon transistors. For bipolar ICs, the multiple movements are represented by the emergence of multiple sub-product classes that reflect the emergence of specific market segments within the customer choice hierarchy. A dominant design can be defined at levels further down the product design hierarchies for some of these sub-product classes/market segments than others, which reflects the greater importance of standardization and thus modular designs for some sub-product classes/market segments than others. The advantage of defining a dominant design at lower levels in the product design hierarchy is that it helps us understand the sources of competitive advantage for firms, in this case those of Fairchild and Texas Instrument (Borrus, 1987), while the disadvantage is that it may cause blanks to appear for some sub-product classes/market segments.

The dominant designs that represent a new definition of the sub-problem are digital IC logic families, microprocessors, and scalable design rules where the first two involve network effects. For both of these product classes, the emergence of the modular design can be described in terms of a tradeoff between the decreasing marginal utility from improved performance via an integral design and the increasing marginal utility from network effects via a modular design (See Figure 2). For example, the marginal benefits from being able to use the same digital IC logic families in multiple applications increased (more modular design for customers) while the marginal benefits of greater performance through small changes in the design of these families declined over time. Similarly, the increasing installed base of for example PCs increased the need for software reuse and thus a modular design for the microprocessor and operating system while the marginal utility from performance increases in microprocessors (and also PCs) was falling (Langlois, 1993; Steffens, 1994).

5. Computers

Table 4 summarizes the major product classes in the computer industry and the changes in product design and customer choice hierarchies, initial sales channels, and business models when compared to the previous product class. Each product class involved movements back up the product design hierarchy where the mini-computer and personal computer (PC) represented a scaled down version of the previous class. These scaled-down versions used slower processors, smaller memory, shorter word lengths, and smaller instruction sets, and thus had significantly lower performance than the previous product class (Smith, 1989). There were also movements back up the customer choice hierarchy (including early users and initial applications) and changes in the sales channels and business models for the mini- and personal computer.

The incremental improvements in components that have driven changes in the design tradeoffs and caused movements back up the product design and customer choice hierarchies and thus the emergence of new product classes include improved vacuum tubes, semiconductors, and magnetic recording media. Incremental improvements in vacuum tubes enabled the development of the first mainframe computer (Flamm, 1988; Ceruzzi, 1998). Incremental improvements in ICs and microprocessors, which were driven by the improvements in equipment and processes that were discussed in the last section, changed the design tradeoffs, caused movements back up the product design hierarchy, and led to the emergence of mini-computers and PCs (Langlois, 1993; Rifkin and Harrar, 1983). Both mini-computers and PCs also provided a different tradeoff to users between performance in million instructions per minute (MIPs) and the ratio of price to performance (See Figure 5), which is partly why there were movements back up the customer choice hierarchy as shown in Table 4. Furthermore, incremental improvements in the recording density of magnetic tape, drums, and particularly disks (Stevens, 1999, Figure 18-1) have also changed the design tradeoffs for magnetic storage, which have led to smaller form factors for them and thus changed the design tradeoffs for computers and contributed to the emergence of mini-computers and PCs (Christensen, 1997).

The incremental improvements in components, particularly those that involved semiconductors, also played a role in the determination of the dominant designs for computers, which all involve network effects and defining sub-problems in a modular way. Table 5 summarizes the dominant designs, the multiple movements down the product design hierarchy that culminated in these modular designs, and the tradeoff between the decreasing marginal utility from increases in product performance via an integral design and the increasing marginal utility from network effects via a modular design (See Figure 2). For mainframes, increasing hardware speeds and memory capacity in the 1950s and 1960s enabled the use of more complex software programs through an integral design while the marginal utility to users of this greater complexity was falling. At the same time, the increasing installed base of computers and their applications increased the need for the reuse of software (i.e., network effects and compatibility) (Campbell-Kelly, 2003) and thus a modular design like the IBM System/360 (Flamm, 1988; Pugh, 1995).

Place Tables 4 and 5 and Figure 5 about here

In mini-computers the tradeoff revolved around word length. Although IBM's

System/360 had defined word lengths with multiplies of 8-bits (now considered one byte) as an industry standard, DEC had initially introduced a 12-bit machine (PDP-8) in 1965 and soon after introduced computers that doubled and tripled this word length. However, DEC finally made its mini-computers compatible with the 8-bit word length through the introduction of its PDP-11 line of 16-bit machines in 1970, which reflected the increasing importance of compatibility (i.e., network effects) between mini- and mainframe computers (Rifkin and Harrar, 1988).

For PCs, in addition to other factors (Malerba et al, 1999; Langlois, 1993), the IBM PC provided a superior tradeoff between performance and software reuse than other PCs through the use of a hybrid 8- and 16-bit microprocessor. The 8-bit capability enabled the use of existing packaged software (i.e., compatibility and network effects) while the 16-bit capability enabled the use of new software and thus increased performance. The success of WordPerfect and Lotus provide evidence of this increased performance. These firms introduced word processing and spreadsheet software that were customized for the 16-bit microprocessor and thus ran faster than the then popular WordStar and Visicalc did on the IBM PC. Both WordStar and Visicalc had been optimized for the 8-bit microprocessors used in existing computers, e.g., Apple’s computers and those computers that ran the CP/M operating system (Steffens, 1994).

6. Music

Table 6 summarizes the major product classes in the music industry and movements back up the product design and customer choice hierarchies for them. Table 6 divides the product design hierarchy into recording media (e.g., cassette tapes), recording units (e.g., recording studios with tape recorders), and playback units (e.g., tape players) and the customer choice hierarchy into initial applications/users and type of music. Only electrical recording (it used the same records) and transistor players (they used the same records and recording units) did not involve movements back up all three aspects of the product design hierarchy. On the other hand, only transistors players (young people) and magnetic tapes (use in automobiles) required movements back up the customer choice hierarchy where they involved new applications or users. Interestingly, new music did not have an impact on the *initial* emergence of any new product class.

A variety of incremental improvements in components and materials have changed the design tradeoffs and enabled movements back up the product design hierarchy and the emergence of new product classes. As shown in Table 7, these components and materials have changed from electro-magnetic and mass production ones in the late 19th and early 20th century; to vacuum tubes in the 1920s; transistors, ICs (See Figure 4), magnetic tape, and plastics in the 1960s (American Plastics Council, 2004); and microprocessors in the 1980s and 1990s. For example, at the turn of the 19th century the benefits from incremental improvements in the recording density of shellac eventually outweighed the cost of reducing the rotational speed of the disc as the stylus approached the end of it, a problem that did not exist with cylinder players (Read and Welch, 1976). The benefits from incremental improvements in vinyl recording density eventually outweighed the cost of new styli in the change to vinyl LPs in the 1940s and the increasing data requirements of stereo music in stereo LPs in the 1950s (and the cost of consumers replacing their record collections in both cases) (Millard, 1995). Incremental improvements in transistors (both cost and performance) eventually outweighed their high price and the initially poor sound quality of the players. The benefits from incremental improvements in magnetic tape recording density (portability) and the strength of plastics eventually outweighed the initially poor sound quality of the tape players. The benefits from improved microprocessors eventually compensated for the increased data processing requirements of digital recording (Chanan, 1995; Millard, 1995).

Table 8 lists the dominant designs and movements down the product design hierarchies for them in each product class. Except for electrical recording and transistor players, all of the dominant designs shown in Table 8 involved network effects and defining sub-problems in a modular way due to the change in the recording medium. Electrical recording did not involve a new recording medium and it only involved the replacement of some parts with new ones (i.e., alternative designs). Transistor players also did not involve defining sub-problems in a modular way and instead improvements in semiconductors enabled a continuous reduction in the number of electronic components that are needed to handle the playback function.

Place Tables 6, 7 and 8 about here

For the dominant designs that involved defining sub-problems in a modular way, it is possible to describe the tradeoffs between decreasing marginal utility from increases in product performance via an integral design and increasing marginal utility from network effects via a modular design (See Table 8 and Figure 2). In cylinders and both shellac and vinyl discs, firms competed to increase recording density until the increasing returns from the choice of a single standard exceeded the decreasing marginal utility from improvements in the recording density. Firms also competed to reduce the tape size and thus player size via improvements in recording density until the increasing returns from the choice of single standard exceeded the decreasing returns from further miniaturization. Similar things occurred with stereo records and compact discs (CDs) albeit the tradeoffs were primarily carried out inside firms and committees as opposed to in the market place (Chanan, 1995; Millard, 1995). For example, all of the manufacturers delayed the introduction of stereo records until the vinyl recording density was sufficient to make stereo LPs possible and until they had agreed upon a standard for stereo LPs (Chanan, 1995; Millard, 1995; Robertson and Langlois, 1992).

7. Mobile Phones

Table 9 summarizes the major product classes in the mobile phone industry and movements back up the product design and customer choice hierarchies for them. The product design hierarchy is divided into base stations, switching equipment, and phones while the customer choice hierarchy is divided into early users and applications. Every change in product class involved movements back up the product design hierarchy (in particular base stations and phones) but not the customer choice hierarchy. Although the mobile phone industry has experienced a large expansion in the number of users, the applications (only the *addition* of data in 3G) and early users of each new product class were not much different from those of the previous product class.

Place Table 9 about here

Like the computer and to some extent the music industry, the incremental improvements in components that have changed the design tradeoffs and thus enabled movements back up the product design hierarchy and the development of new mobile phone product classes primarily involved vacuum tubes and semiconductors and to a lesser extent batteries and displays. Improvements in vacuum tubes enabled the introduction of pre-cellular phones, sometimes called private mobile radio (Garrard, 1998) for military, police, fire, taxi, and later consumer applications in the first half of the 20th century.

Incremental improvements in semiconductors enabled digital switching to be developed in the 1970s (Fransman, 1995) and the availability of digital switching changed the design tradeoffs in a mobile phone system and led to the introduction of analog cellular systems. The slow speed of analog switching systems had caused most private mobile systems to use a single transmitter for a wide geographical area. Digital switching enabled a mobile phone system to be divided into multiple cells (thus the name cellular phone) where the frequency spectrum is reused in each cell and digital switches automatically "switched" the users to new base stations as they crossed into a new cell. The use of cells dramatically increased the capacity of the system (Garrard, 1998).

Further improvements in semiconductors enabled digital signals to be transmitted between phones and base stations where sophisticated "digital receiver algorithms" convert analog signals to digital signals and visa versa. These algorithms are defined in the "air-interface" standards that define how signals are transmitted between phones and base stations in both analog and digital systems (Garrard, 1998). The sophistication of the algorithms determines the capacity of a specific cell and more sophisticated algorithms require faster microprocessors and other digital chips in the same way that digital music players required advanced microprocessors and other digital chips (Calhoun, 1988). In this way, improvements in semiconductors have also enabled the introduction of third generation mobile phone systems (Sharma and Nakamura, 2003).

Table 9 also summarizes the dominant designs for the cellular phone systems, which are the result of global competition between systems that used different air-interface standards. Since the determination of these open air-interfaces enabled the definition of independent sub-problems for the design of phones and base stations, we can define them as modular designs. Firms, often in collaboration with governments, introduced these modular designs before the services were started. Although in some cases governments mandated a single standard and in other cases they did not mandate a single standard, in all cases firms introduced systems that defined the interface between the phone and base stations in order to obtain forward compatibility of phones (Funk and Methe, 2001; Funk, 2002; Lyytinen and Fomin, 2002).

Individual firms, with the consent of governments, could have initially introduced a succession of systems in a specific product class (e.g., first generation analog cellular systems) that were incompatible or at the best partially compatible with the previous systems as the computer and music player manufacturers did. They did not do so for reasons that are consistent with the tradeoffs embedded in Figure 2. The cost of introducing a succession of initially incompatible mobile phone systems would have been many orders of magnitude larger than it was with computers and music players. The large scale of these systems caused all parties to realize that the indirect network effects (between phones and services) from a modular design were far larger than the performance benefits of an integral design (Funk, 2002). Similar things occurred in other large scale systems such as radio and television (Shapiro and Varian, 1999).

8. 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 small number of industries and the lack of randomness in their choice suggest 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 and the concept of design tradeoffs provide insights that are not found in the existing literature. Table 10 categorizes some of the ways in which improvements in a product's components, a material's processes, or the equipment used in these processes changed a product's internal or external (involving users) design tradeoffs and thus required firms to rethink the product designs and customers. For example, the tradeoffs between different materials, parts, and shapes were impacted on by the different rates of improvements in manufacturing processes for these different materials, parts, or shapes. Changes in external design tradeoffs include those between price and performance, different measures of performance, and different types of costs for users. The tradeoffs between price and processing speed for computers, between price and sound quality for music players, and between price and spectrum efficiency for mobile phones were impacted on by improvements in semiconductor components. For semiconductors, the tradeoffs between component (discrete components) and system (integrated circuits) performance, between heat production and speed, and between performance and development cost (for users of chips) were also impacted on by reductions in feature size and their associated increases in the number of transistors per chip.

Place Table 10 about here

In addition to these design tradeoffs that are inherent in the product design hierarchy, the exact timing of the discontinuity depended on how firms used these improvements to rethink their products, customers, business models, and sales channels. For products, firms were forced to rethink the material, transistor, and system designs for semiconductors, the word length and instruction sets for computers, the recording media and recording and playback units for recorded music, and the design of handsets and infrastructure for mobile phone systems. 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 class to occur. For example, the demand for portable calculators made it possible for MOS ICs and the demand for electronic watches made it possible for CMOS ICs to diffuse before their performance had reached the level of the previous product class. The demand for various types of low-volume aviation and other equipment made it possible for microprocessors to diffuse before their performance had reached the level of central processing units in mainframe or mini-computers. The existence of scientific and engineering applications made it possible for mini-computers and the existence of hackers made it possible for PCs to diffuse before the performance of mini-computers or PCs 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). For example, Malerba et al (1999) describe how innovations such as the microprocessor enabled the development of the PC. The proposed model represents this phenomenon at a much deeper level and shows how there were *independent* movements back up the product design and customer choice hierarchies for both semiconductors and computers. Incremental reductions in feature size changed the design tradeoffs for semiconductors, which required manufacturers to redefine the concept of ICs in a microprocessor and initially target a new set of customers that included low-volume aviation, medical, and test equipment. In turn, incremental improvements in these microprocessors changed the design tradeoffs for computers, which required manufacturers to redefine the concept of computers and initially target a new set of customers that included hackers, university professors, and small firms.

With respect to dominant designs, this paper extends Suarez and Utterback's (1995) concept of a dominant design as a design path by showing how dominant designs that are widely cited in the business and economics literature can be described in terms of multiple movements down the product design hierarchy. It also shows how this definition enables dominant designs to be defined for product classes in the music and semiconductor industries in which dominant designs have not been previously identified. In transistor players, many small design changes define the dominant design for them where these design changes have reduced the size of a player to one that can be placed in for example a mobile phone. In the semiconductor industry, dominant designs can be defined for bipolar ICs in terms of the emergence of specific market segments, which enable us to better define the sources of competitive advantage for firms such as Fairchild and Texas Instrument (Borrus, 1987).

A second contribution to the area of dominant designs concerns the timing of dominant designs. All of the dominant designs that involve defining sub-problems in a modular way and that involve network effects showed the tradeoff between decreasing marginal utility from increases in product performance and increasing marginal utility from network effects. The improvements in a product's components, a material's processes, or the equipment used in these processes drove improvements in overall product performance and thus delayed the emergence of *most* dominant designs. This highlights the differences between how dominant designs may emerge from competition to define sub-problems in a modular way as opposed to how competition between alternative designs occurs.

The tradeoff between decreasing marginal utility from increases in product performance and increasing marginal utility from network effects also help us understand why a dominant design would not lag the emergence of a technological discontinuity/ new product class, something which the existing literature suggests would not happen (Anderson and Tushman, 1990). For example, the emergence of dominant designs for stereo records, CDs, and mobile phones did not lag the emergence of a technological discontinuity. The literature on the music industry strongly suggests that firms delayed the introduction of the stereo records and CDs until their performance advantages outweighed the user's cost of buying new players (network effects) and until they agreed upon standards, i.e., dominant designs (Robertson and Langlois, 1992). Similarly, the literature on the mobile phone industry suggests that firms defined modular designs (i.e., independent design of phones and base stations) in the first systems due to their large scale (Funk, 2002; Funk and Methe, 2001; Garrard, 1998). All of these cases suggest that firms were aware of the tradeoffs between the decreasing marginal utility from increases in product performance and the increasing marginal utility from network effects when defining sub-problems in a modular way.

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Table 1. Major Product Classes and Movements back up the Hierarchies
for the Semiconductor Industry

New Product Class (emphasis on underlined terms)	First Introduced	Movements back up the Hierarchies	
		Product Design	Customer Choice (early users)
Combinations of discrete germanium bipolar transistors and other discrete devices	Early 1950s	Change in material, transistor, and system design (from vacuum tubes)	Military and later transistor radios
Combinations of discrete silicon bipolar transistors and other discrete devices	Mid-1950s	Change in material	No changes (still military)
Combinations of bipolar ICs and discrete devices	Early 1960s	Change in system design	No changes (still military)
Combinations of MOS ICs and discrete devices	Early 1970s	Changes in transistor design	Pocket calculators, computer memory
Combinations of CMOS ICs and discrete devices	Mid-1970s	Change in transistor design	Watches and pocket calculators
Combinations of microprocessor, memory, and discrete devices	Mid-1970s	Changes in system design	Aviation, medical, and test equipment
SoC (System on Chip)	Early 2000s	Change in system design	Complex systems

IC: integrated circuit; MOS: Metal-Oxide Semiconductor; CMOS: complementary MOS. Sources: (Tilton, 1971; Braun and S. MacDonald, 1982; Malerba, 1985; Borrus, 1987; Jackson, 1997; Bass and Christensen, 2002)

Table 2. Incremental Improvements Changing the Design Tradeoffs and Driving Moves Back up the Hierarchies for the Semiconductor Industry

New Product Class (emphasis on underlined terms)	Incremental Improvements in a Product's Processes or Related equipment	Eventual Impacts of Incremental Improvements on Design Tradeoffs and thus Emergence of New Product Class
Combinations of discrete silicon bipolar transistors and discrete devices	Higher temperature furnaces and processes for the oxidation of silicon	Benefits from improvements in silicon crystal growing and oxidation exceeded the cost of higher temperature furnaces
Combinations of bipolar ICs and discrete devices	Reductions in feature size and thus increasing circuit density	Benefits from placing transistors, resistors, and capacitors on the same chip outweighed the use of sub-optimal materials for resistors and capacitors
Combinations of MOS ICs and discrete devices	Reductions in feature size and the increasing number of transistors on a chip	Increasing number of transistors made the lower heat production of MOS (and later CMOS) more important than the faster speeds of bipolar ICs
Combinations of CMOS ICs and discrete devices		
Combinations of microprocessor, memory, and discrete devices		Reductions in feature size made it possible to waste silicon space in return for lower development costs
SoC (System on Chip)		

IC: integrated circuit; MOS: Metal-Oxide Semiconductor; CMOS: complementary MOS. Sources: (Bass and C. Christensen, 2002; Borrus, 1987; Malerba, 1985; Reid, 1985; Riordan and Hoddeson, 1997; Tilton, 1971)

Table 3. Dominant Designs for Major Product and Sub-Product Classes
in the Semiconductor Industry

Product Class (emphasis on underlined terms)	Dominant Design: alternative or modular ones that involve multiple moves down the product design hierarchy
Combinations of discrete germanium bipolar transistors and discrete devices	Alternative designs: Use of single crystal growing and diffusion processes culminated in the diffused transistor
Combinations of discrete silicon bipolar transistors and discrete devices	Alternative designs: Use of silicon crystal growing, diffusion, and oxidation processes culminated in the planar process and planar transistor
Combinations of Bipolar ICs and discrete devices and their sub-product classes:	Modular designs for sub-product classes:
1. Digital IC logic families	1. Digital IC logic families:
a. RTL (Resistor-Transistor Logic)	a. none
b. DTL (Diode- Transistor Logic)	b. Fairchild’s 920 series
c. TTL (Transistor-Transistor Logic)	c. Texas Instrument’s 7400 series
2. Linear ICs	2. Linear ICs: none due to little standardization
3. Custom (and semi- custom) ICs: many types	3. Custom ICs: none due to little standardization
Combinations of MOS ICs and discrete devices	Modular designs: many dimensionless, scalable design rules that define geometrical relationships between widths, thicknesses, power, and speed
Combinations of CMOS ICs and discrete devices	
Combinations of a microprocessor, memory, and discrete devices	Modular designs: Intel’s microprocessor in PCs. Other designs for other applications

IC: integrated circuit; MOS: Metal-Oxide Semiconductor; CMOS: complementary MOS.

Sources: (Tilton, 1971; Braun and S. MacDonald, 1982; Malerba, 1985; Borrus, 1987)

Table 4. Major Product Classes in the Computer Industry and Relevant Changes

Product Class	Movements back up the Hierarchies and Other Changes				
	Product Design	Customer Choice		Sales Channels	Business Model
		Early Users	Applications		
Main-Frame	Add vacuum tubes to punch card equipment	No changes (Existing punch-card users and their business systems)		No changes (Existing sales force)	No changes (Lease computers and software)
Mini-Computer	Scaled-down version of mainframes	Scientific & engineering companies	Engineering analysis and process control	Corporate mail orders, later sales force	Sell not lease. Extensive documentation.
Personal Computer (PC)	Scaled-down version of mini-computers	Individuals (home, university, small business)	Games spreadsheet, word processing	Individual mail order and later retail, Internet	Modular and open systems, sale of packaged software

Sources: (Rifkin and Harrar, 1983; Flamm, 1988; Langlois, 1993; Ceruzzi, 1998; Campbell-Kelly, 2003.)

Table 5. Dominant Designs for the Major Product Classes in the Computer Industry

Product Class	Dominant design	Movements down the product design hierarchy	Decreasing Marginal Utility from Increases in Product Performance	Increasing Marginal Utility from Network Effects
Main-frame	IBM 360	Stored program control, magnetic core memory, transistors	Improved hardware and thus more complex software	Rising installed base and need for software reuse
Mini-	DEC's 16-bit PDP-11	MOS memory, magnetic disk storage	Above manifested in form of longer word length	Above manifested in increased need for compatibility
Personal (PC)	IBM PC	Monitor, keyboard, mouse, floppy disk, packaged software	Above manifested in more complex software	Above manifested in increased need for compatibility

Sources: (Rifkin and Harrar, 1983; Flamm, 1988; Langlois, 1993; Steffens, 1994; Ceruzzi, 1998; Campbell-Kelly, 2003)

Table 6. Major Product Classes and Movements back up the Hierarchies for the Music Industry

Decade of Introduction	Product Class	Movements Back up the Hierarchies				
		Product Design			Customer Choice	
		Recording Media	Recording Unit	Playback Unit	Early Application/ User	Types of Music
1880s	Acoustic Cylinders	Cylinder (various materials)	Input to horn, stylus etches wave form on cylinder	Movement of stylus on cylinder drives horn	Juke Box, Home listening	Expansion of folk to classical
1900s	Acoustic Discs (records)	New shape, material (shellac)	Stylus etches wave form on disc	New stylus and player	Home listening	Addition of Opera
1920s	Electrical Recording	No changes	By using vacuum tubes for amplification, replaced horn with speaker & microphone		Same	Addition of Jazz
Late 1940s	Vinyl LPs (long playing)	New material (Vinyl)	Change to magnetic tape for editing	Adapter with new stylus and pickup	Same	Initially classical, later Rock and Roll
Late 1950s	Stereo music	New types of cuts in vinyl	No changes	New stylus, electrical components	Same	Rock and Roll
1960s	Transistor Players	No changes	No changes	Replaced vacuum tube w/ transistor	Home listening with young users	Rock & Roll
Mid-1960s	Magnetic Tapes	New media (8-track, cassette)	Units with either or both recording and playback functions		Cars, other portable	Rock and Roll
Late 1970s	Digital	New media (e.g., CDs)	Digital recording	CD (compact disc) and other players	Home listening and portable	Addition of disco, rap

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

Table 7. Incremental Improvements Changing the Design Tradeoffs and Driving Movements Back up the Hierarchies for the Music Industry

New Product Class	Incremental Improvements in Components or Materials	Eventual Impacts of Incremental Improvements on Design Tradeoffs and thus Emergence of New Product Class
Acoustics Discs	Materials such as shellac, mass-production techniques such as molding, and motors	Benefits from improvements in shellac recording density finally outweighed the costs of variable speed controls that were needed with discs (not needed with cylinders)
Electrical Recording	Vacuum tubes, microphones, and speakers	Benefits from vacuum tubes (amplification) finally outweighed their costs and the costs of speakers and microphones
Vinyl LPs (long playing)	Vinyl materials and lighter pickups	Benefits from improvements in vinyl recording density finally outweighed the costs of new styli (and replacement of record collections)
Stereo music	Vinyl recording density and electrical components	Improvements in vinyl recording density compensated for increased information to be recorded with stereo music
Transistor Players	Transistors and later ICs	Improvements in transistors (both cost and performance) finally outweighed their cost and initially poor sound quality of players
Cassette Tapes	Magnetic tape recording density and strength of plastics	Benefits from improvements in tape recording density and strength of plastic (smaller size and thus portability) finally outweighed the poor sound quality of tape
Digital	Microprocessors, magnetic recoding density, lasers, metallic coatings, and ICs	Improvements in data handling technology compensated for the increased data processing requirements of digital over analog recordings

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

Table 8. Dominant Designs for Major Product Classes in the Music Industry

Product Class	Dominant Design	Movements Down Product Design Hierarchy	Decreasing Marginal Utility from Increases in Performance	Increasing Marginal Utility from Network Effects
Acoustic Cylinders	Long-playing Edison cylinder (Amberol plastic)	Wax originals, electroplated metal negatives	Recording density	Compatibility between recorded cylinders, players
Acoustic Discs	Lateral cut disc (shellac)	New types of wax originals, metal negatives	Recording density	Compatibility between recorded discs and players
Electrical Record-Ing	Lateral cut disc using Western Electric technology	Condenser microphones, light cutters, transducer loudspeakers	Not applicable due to choice of alternative design as opposed to redefinition of sub-problem in a modular way	
Micro-Groove Vinyl Records	33-rpm long-playing (LP) and 45-rpm (for singles) vinyl record with lateral cuts	Permanent jeweled stylus, piezoelectric crystal pickup	Recording density	Compatibility between recorded discs (records) and players
Stereo records	Westrex stereo disc system	Not applicable - no lag between discontinuity and dominant design		
Transistor Players	Continuous reduction in the number of components	Continuous reductions in the number of components required many small changes in integral design, which also prevented emergence of modular design		
Magnetic Tapes	Philips Cassette	Materials for tape and shapes of plastic parts	Recording density	Compatibility between recorded tapes and players
Digital	CDs with continued competition from new designs	For CDs, no lag between discontinuity and dominant design		

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

Table 9. Major Product Classes and Movements back up the Hierarchies for the Mobile Phone Industry

Product Class	Movements back up the Hierarchies					Dominant Designs (air-interface standards)
	Product Design Hierarchy			Customer Choice		
	Base stations	Switching equipment	Phones	Early Users	Major Applications	
Pre-Cellular	Single analog ones	None	Radio phones	Business users	Voice	Many different standards
1G Analog Cellular	Multiple analog-based ones	Digital (similar to wireline)	Analog ones	Business users	Voice	AMPS
2G Digital Cellular	Multiple Digital-based ones	Digital (similar to wireline)	Digital ones	Business users	Voice	GSM
3G Digital Cellular	Multiple 3G-based ones	Internet protocol	3G ones	Business users and consumers	Voice and data	Wide-Band CDMA

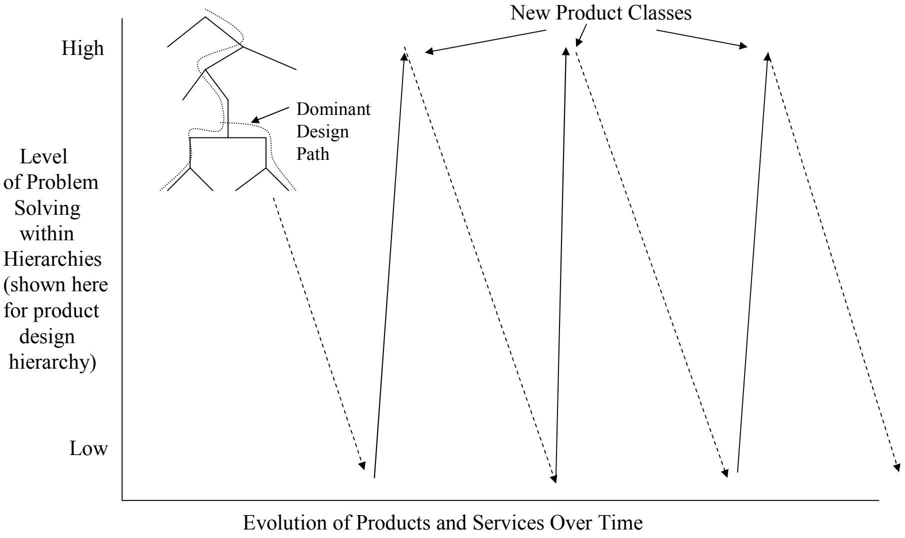
Sources: (Garrard, 1998; Funk and Methe, 2001; Funk 2002; Lyytinen and Fomin, 2002)

G: Generation; AMPS (Advanced Mobile Phone System); GSM (Global System Mobile); CDMA (Code Division Multiple Access)

Table 10. Categorizing the Changes in Design Tradeoffs that led to New Product Classes/Technological Discontinuities

General Tradeoffs	Detailed Tradeoffs	Incremental Improvements Driving Changes	Industry or Product Class
Internal design tradeoffs; between			
Different types of parts	Vacuum tubes, transistors, and ICs	Different rates of improvement for different equipment and processes	All four industries
Different types of materials	Germanium and silicon Shellac and vinyl		Semiconductors Music
Different types of shapes	Cylinders and discs		Music
External design tradeoffs; between			
Price and performance	Price and processing speed	Better ICs	Mini-, personal computers
	Price and sound quality	Better transistors/ICs	Transistor music players
	Price and spectrum efficiency	Better ICs	Mobile phones
	Price and sound quality	Better ICs	Digital music players
Different measures of performance	Performance of component (e.g., resistor) and system (IC)	Reductions in feature size	Bipolar ICs
	Heat production and speed	Reductions in feature size	MOS and CMOS ICs
Different types of user costs	Between fixed (development costs) and variable costs (efficient use of silicon space)	Increased in the number of transistors per chip	Microprocessors and System on Chip (SoC)

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



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

Figure 2. Tradeoff Between Product Performance via an Integral Design and Network Effects via a Modular Design

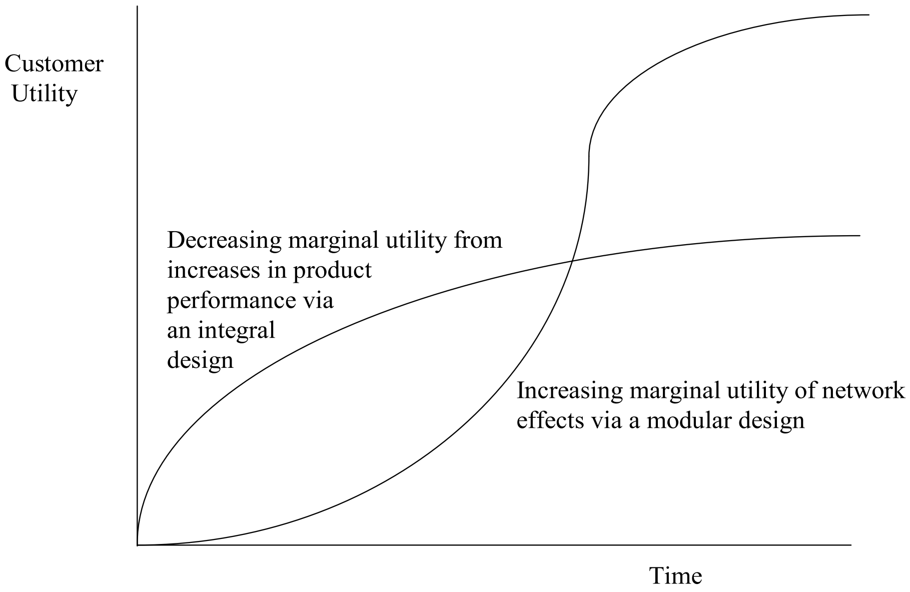
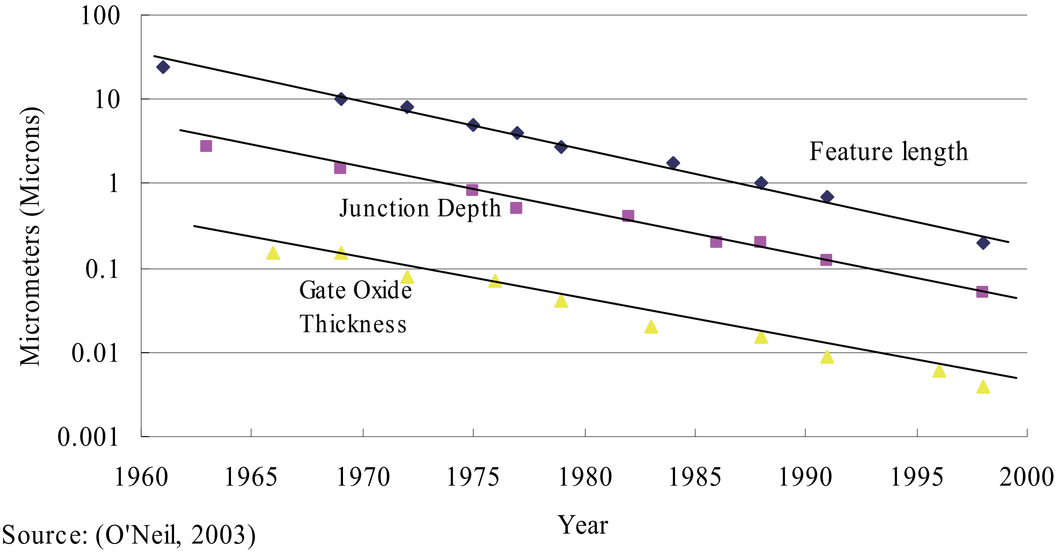
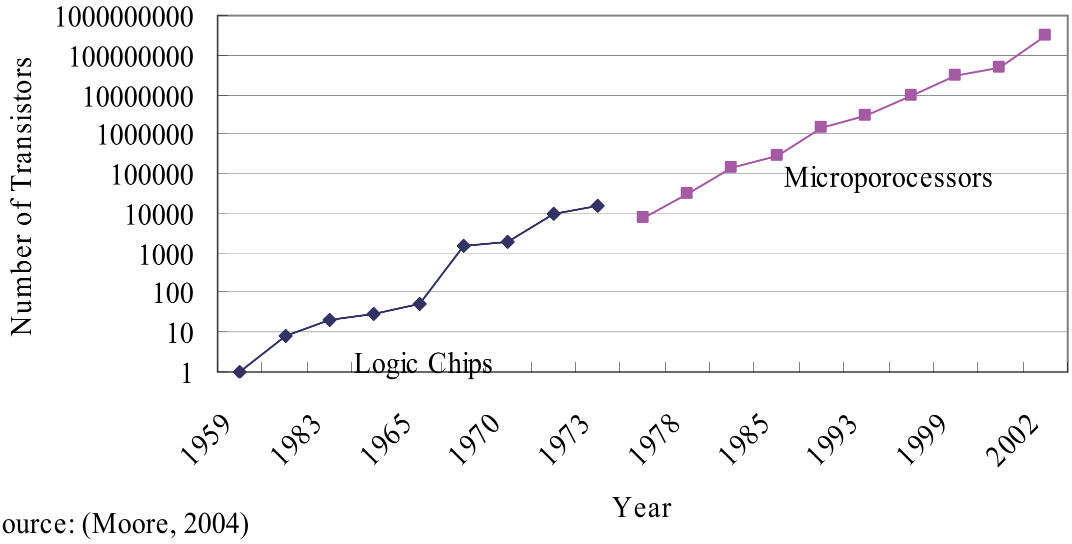


Figure 3. Declining Feature Size



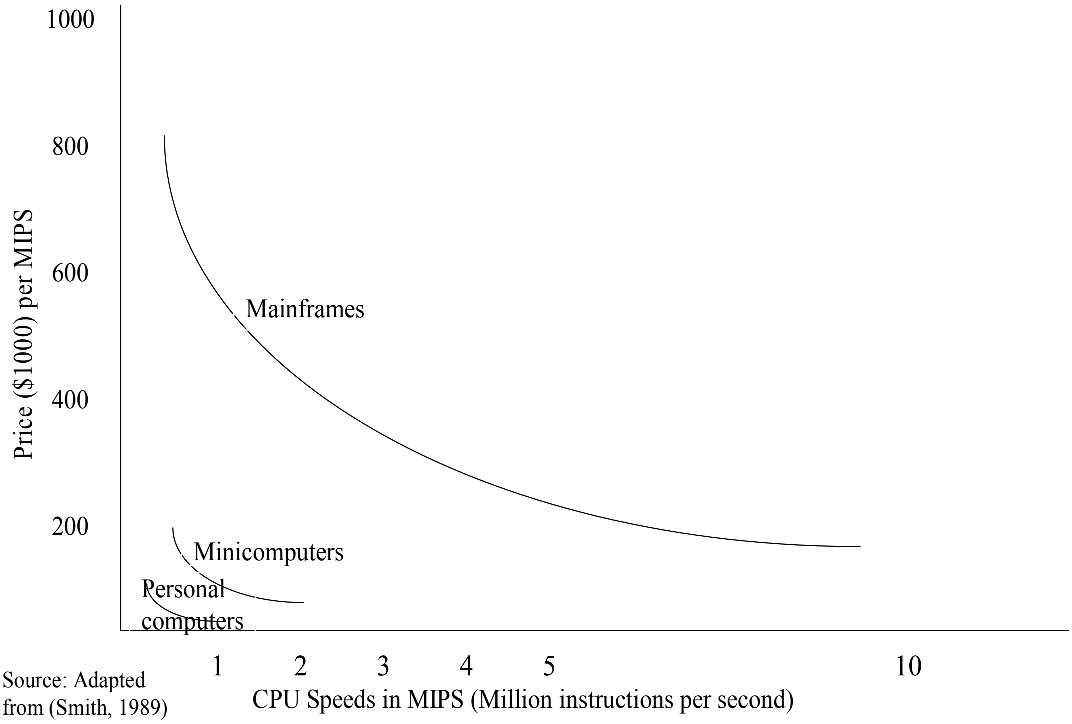
Source: (O'Neil, 2003)

Figure 4. Number of Transistors Per Chip



Source: (Moore, 2004)

Figure 5. Relationship Between Prices and Performance (1981 data) for Different Product Classes of Computers that Reflect the User's Different Tradeoffs Between Price and Performance for Different Product classes of computers (1981 data)



Source: Adapted from (Smith, 1989)