Technological Change within Nested Hierarchies:

The Case of the Information Technology 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 using data from the information technology (IT) sector. The model emphasizes nested hierarchies of subsystems, product design and customer choice hierarchies, design tradeoffs, and incremental improvements at lower levels in the nested hierarchy. This paper defines the nested hierarchy of the IT sector using both the physical relationships between subsystems and the parallel hierarchy of firms where product design and customer choice hierarchies are defined at each level in the nested hierarchy of subsystems. Incremental improvements at one level of a nested hierarchy drive changes in the design tradeoffs at both higher and adjacent levels of the nested hierarchy and thus require firms to rethink the product design and customer choice hierarchies for their level in the nested hierarchy of subsystems. The use of product design and customer choice hierarchies and the concept of design tradeoffs provide greater insight into how a discontinuity occurs (including the specific changes that occur in the designs and customers during the discontinuity) than does the existing literature.

1. Introduction

In spite of the recognized importance of technological discontinuities in the existing literature on technological innovation, including their increasing occurrence, there are few models that address the sources and timing of them. Technological discontinuities are often defined in terms of an innovation's impact on a technological system, on a technological system's linkages to a market (Abernathy and Clark, 1985), and on a firm's competencies (Tushman and Anderson, 1986) where it is implied that the greater the impact, the greater the discontinuity. Henderson and Clark (1990) further divided the impact of innovations on a technological system into their impact on the concepts that underlay the system and the linkages that connect components within the system. These and other scholars have also shown the difficulties incumbents experience in responding to those innovations that represent the largest discontinuities (Abernathy and Clark, 1985; Tushman and Anderson, 1986; Henderson and Clark, 1990; Utterback, 1994).

A related literature on technological change has emphasized the decomposable nature of artifacts and the complex systems they comprise (Simon, 1962; Langlois and Robertson, 1992; Ulrich, 1995; Sanchez and Mahoney, 1996; Baldwin and Clark, 2000). Artifacts, including basic materials such as glass and chemicals (Utterback, 1994), can be represented as multiple levels of subsystems that are organized in a hierarchical fashion (Tushman and Murmann, 1998) where a parallel hierarchy of firms can also be defined (Christensen and Rosenbloom, 1995; Murmann and Frenken, 2006). Some scholars have linked this research on the decomposable nature of complex systems with that of discontinuities by showing examples of interactions between component and system level innovations including those that can be defined as discontinuities (Tushman and Murmann, 1998; Malerba et al, 1999).

This paper builds on this literature to present a model of technological change that provides greater insights into how a discontinuity occurs than does the existing literature. The proposed model emphasizes nested hierarchies of subsystems (Tushman and Murmann; Murmann and Frenken, 2006), product design and customer choice hierarchies (Clark, 1985), design tradeoffs (Alexander, 1964), and incremental improvements at lower levels in a nested hierarchy of subsystems. Incremental improvements in one level of a nested hierarchy (e.g., components) drive changes in the design tradeoffs at both higher (e.g., an assembled product) and adjacent levels (e.g., other components) of the nested hierarchy and thus require firms to rethink the product design and customer choice hierarchies for their level in the nested hierarchy of subsystems. The use of product design and customer choice hierarchies and the concept of design tradeoffs provide additional insights into how a discontinuity occurs by showing the specific changes that occur in the designs and customers during the discontinuity. The emphasis on incremental improvements is also different from the emphasis by others on the interaction between modular, architectural and radical innovations in a nested hierarchy of subsystems (Tushman and Murmann, 1998; Malerba et al, 1999).

This paper uses data from the information technology (IT) sector, with a focus on the fifty year period covering 1945 to 1995 (until the emergence of the Internet), to demonstrate this model of technological change. This paper defines the nested hierarchy of the IT sector using both the physical relationships between subsystems and the parallel hierarchy of firms where product design and customer choice hierarchies are defined at each level in the nested hierarchy of subsystems. The IT sector was chosen because it has experienced large amounts of technological change at multiple levels in the nested hierarchy and there is a large literature on this technological change. Due to limitations in page numbers and the application of the model to multiple levels in the nested hierarchy of the IT sector, 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 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 decisions to the model. Following a description of the proposed model and research methodology, the paper applies the model to the IT sector.

2. Proposed Model

Hierarchies of subsystems and firms reflect the interactions between artifacts (i.e., products) and markets (Christensen and Rosenbloom, 1995; Tushman and Murmann, 1998; Murmann and Frenken, 2006). At a given level in a hierarchy of subsystems (See Figure 1), firms introduce products that are evaluated by markets and a specific firm's introduction of products reflects its perception of customer needs and how best to translate those needs into products. Following previous work on hierarchical decision making (Simon, 1962; Alexander, 1964), we can represent this process in terms of an interaction between two other hierarchies, which are called the customer choice and product design hierarchies (Clark, 1985). The interaction between these two hierarchies also includes the determination of a business model (Chesbrough, 2003) and sales and service channels (Abernathy and Clark, 1985).

In the customer choice hierarchy, firms develop a conceptual framework for how customers evaluate competitive offerings where they divide users and applications into different 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 (Clark, 1985, Figure 1) and processes (Durand, 1992). One way to represent both product and process design choices in a single product design hierarchy is to use the concept of dual-technology trees. Products and processes are represented by horizontal and vertical branches respectively where the closeness of the branches represents the degree of commonality in competences (Durand, 1992, Figure 4).

At one level in a nested hierarchy, the introduction of new products and services reflect movements both down and up the hierarchies of product design and customer choice hierarchies (See Figure 2). 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 (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 two 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). The choice of design alternatives and the definition of sub-problems represent a dominant design path down the product design and customer choice hierarchies, which can be defined as a dominant design for the industry (Suarez and Utterback, 1995, Figure 1)[1].

Place Figures 1 and 2 about here

On the other hand, incremental improvements at lower levels in a nested hierarchy of subsystems can change the design tradeoffs that are implicit at all levels in this nested hierarchy and thus lead to movements *back up* the hierarchies of both product design and customer choice at higher (See Arrow 1 in Figure 1) and adjacent (combination of all three arrows) levels in this nested hierarchy and thus the emergence of technological discontinuities. Both popular journalists (e.g., Gilder, 1990, 1992) and scholars have used similar concepts to explain the impact of technological change on society in particular for the mechanism represented by Arrow 1. 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 (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

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[1] A separate paper by the author describes the emergence of a dominant design in terms of the proposed model in much more detail.

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 for a specific level in the nested hierarchy 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, technological discontinuities 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).

Returning to the proposed model, incremental improvements at one level of a nested hierarchy of subsystems can also impact on adjacent levels (combination of all three arrows in Figure 1) in the nested hierarchy of subsystems. For example, if incremental improvements in subsystem “A” change the design tradeoffs for system “A” to such an extent that suppliers of system “A” move back up the product design hierarchy (Arrow 1), suppliers of subsystem “B” may also be required to change their designs and consider new customers (i.e., move back up their product design and customer choice hierarchies) (Arrow 2). Furthermore, incremental improvements in component “B” may simultaneously change the design tradeoffs for subsystem B (Arrow 3) and thus increase the extent to which suppliers of subsystem “B” must move back up their product and customer choice hierarchies.

The impact of the design of system “A” on subsystem “B” highlights both how customer choice hierarchies at one level in a nested hierarchy of subsystems are related to the product design hierarchies in the next higher level of the hierarchy of subsystems and the impact system integrators (in this case suppliers of system “A”) can have the evolution of a nested hierarchy of subsystems (Hobday et al, 2005). Since both consumers (Earl and Potts, 2004) and firms design processes and systems (i.e., product design hierarchies) to solve problems and meet various needs, a firm’s customer choice hierarchy reflects its perceptions of its customers’ product design hierarchies. Therefore, a firm could attempt to understand customer needs by analyzing the product design hierarchies of potential customers. However, it is also important for firms to understand the *identity* of the potential customers, which also reflects changes in the customer choice hierarchy. This requires firms to understand how incremental improvements at lower levels in the hierarchy of subsystems drive changes in design tradeoffs and thus require them to consider both new customers and designs (i.e., movements back up the customer choice and product design hierarchies).

3. Research methodology

The author analyzed the primary and secondary literature on the IT 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 top four levels in the nested hierarchy of subsystems for the IT sector; 2.) the technological discontinuities that have occurred in each level of the nested hierarchy; and 3.) the incremental improvements that have driven changes in the design tradeoffs at higher and adjacent levels of the nested hierarchy.

With respect to number 1, this paper has defined the top four levels of the nested hierarchy of the IT sector using both the physical relationships between subsystems and the existing hierarchy of firms (See Figure 3). For example, although a few firms such as IBM have participated in multiple levels of the nested hierarchy, the largest users of computers (top level) and the largest producers of them (second level), electronic components such as semiconductors (third level), and semiconductor manufacturing equipment (fourth level) are for the most part separate firms and are defined as separate industries by for example the U.S. Bureau of Economic Analysis. Within each level of the nested hierarchy shown in Figure 3, the paper focuses on the subsystems and components that have received the most emphasis in the literature on the IT sector.

With respect to number 2, each of the technological discontinuities that are defined by the author for computers, semiconductors, and photolithographic equipment have been characterized by other scholars in the academic literature as either disruptive, architectural, or radical innovations using Christensen's (1997), Henderson and Clark's (1990), and Abernathy and Clark's (1985) frameworks respectively. On the other hand, consistent with the literature on the IT sector, this paper describes the changes in a "firm's use of IT" in terms of an evolution rather than a series of technological discontinuities.

4. Results

Table 1 summarizes the technological discontinuities for each level in the nested hierarchy of subsystems for the IT sector (See Figure 3). Firms have used IT in the second half of the 20th century to automate and integrate different functions where most descriptions of IT emphasize the evolution of IT systems and technological discontinuities of other systems that are shown in Table 1. Improvements in electronic components such as vacuum tubes and semiconductors have had the largest impact on the emergence of technological discontinuities for computers through their impact on the design of central processing units (CPU) and primary memory (Flamm, 1988). Although from the viewpoint of artifacts the most important physical inputs for semiconductors are materials such as silicon, it is the interaction between the product and process designs for semiconductors in general that have driven the largest improvements in the performance of semiconductors (Braun and MacDonald, 1982; Malerba, 1985; Borrus, 1987) where improvements in equipment, particularly photolithographic equipment (Henderson, 1995), have driven both improvements in processes and the interactions between process and product designs; this is consistent with Durand's (1992) dual-technology trees.

Place Figure 3 and Table 1 about here

The remainder of this paper looks more closely at how incremental improvements at lower levels of the nested hierarchy shown in Figure 3 have driven changes in the design tradeoffs at both higher and adjacent levels the in the nested hierarchy and thus required semiconductor and computer manufacturers and users of IT to rethink their product designs and customers (i.e., movements back up the product design and customer choice hierarchies) for their level in the nested hierarchy of subsystems. Each sub-section begins with improvements in equipment and their impact on the design tradeoffs for semiconductors where the titles for each of the four sub-sections roughly correspond to the major technological discontinuities in the semiconductor industry: 1) discrete germanium and silicon transistors; 2) bipolar ICs; 3) MOS and CMOS ICs; and 4) microprocessors. These sub-sections also contrast the proposed model's emphasis on incremental improvements with the emphasis by other scholars on the interaction between modular, architectural and radical innovations in a nested hierarchy of subsystems (Tushman and Murmann, 1998; Malerba et al, 1999).

Place Tables 2-4 about here

4.1 Discrete germanium and silicon transistors

Improvements in the equipment for producing pure germanium and the processes they are used in (e.g., crystal growing and high-temperature furnaces) enabled physicists at Bell Labs to develop the point-contact and junction transistors in the late 1940s.

Other equipment and the processes they are used in enabled other researchers to make further improvements in these germanium transistors, which led to their usage in military products and transistor radios (Braun and MacDonald, 1982; Riordan and Hoddeson, 1997; Tilton, 1971).

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 3 and the emergence of a technological discontinuity called silicon transistors in the mid-1950s (See second line of Table 2). The benefits from being able to cover a silicon wafer with a thin layer of oxidation (via higher temperature furnaces) finally exceeded the higher costs associated with these higher temperature furnaces (Bassett, 2002; Tilton, 1971) and led to the replacement of germanium with silicon in most semiconductor products beginning with ones for military applications.

The introduction and improvement of these silicon transistors was occurring at the same time that vacuum tube-based computers were being introduced and improved. Improvements in vacuum tubes, which were driven by their use in radios and televisions, changed the design tradeoffs for office equipment (e.g., punched-card equipment) and caused the emergence of mainframe computers in the early 1950s. Although the emergence of these mainframe computers can be interpreted as a movement back up the product design hierarchy for office equipment, the fact that the initial customers for these vacuum-based mainframe computers were well-established users of punched-card equipment (Pugh and Aspray, 1996; van den Ende and Dolfsma, 2005) suggests that the hierarchy of customer choice for computers was initially similar to the one for punched-card equipment. This is one reason IBM was able to transfer its domination of punched card equipment into mainframe computers (Pugh and Aspray, 1996; Pugh, 1995; Flamm, 1988).

Silicon transistors certainly impacted on the performance of mainframe computers. However, they did not require the large changes in the design (i.e., large movements back up the product design hierarchy) of computers that improvements in vacuum tubes (and later ICs and microprocessors) did and it is generally considered that they did not lead to a technological discontinuity in computers (Flamm, 1988; Pugh, 1995; Ceruzzi, 1998). Similarly, it was not the introduction of silicon-transistor-based mainframe computers that had the largest impact on a firm's use of IT.

Consistent with this paper's proposed model, it is more accurate to say that incremental improvements in mainframe computers and their peripherals changed the design tradeoffs for users of office equipment (including punch-card equipment) and led to some movements back up of the product design hierarchies for a "firm's use of IT." Incremental improvements in mainframe computers and peripherals gradually enabled firms to automate administrative functions such as accounting, order processing, billing, and payroll and some manufacturing functions such as inventory control. In doing so, firms created highly centralized departments where typically only personnel from these departments were allowed to handle hardware and software that was leased from large manufacturers such as IBM (Campbell-Kelly, 2003; Ceruzzi, 1998; Cortada, 2005).

The growing market for mainframe computers also created a need for new peripherals where the emergence of these needs reflects the impact of incremental improvements in one subsystem on adjacent subsystems in a nested hierarchy and the interaction between the three arrows shown in Figure 1. The emergence of mainframe computers, which were enabled by improvements in vacuum tubes (See Arrow 1), changed the customer choice hierarchy for peripherals (Arrow 2) thus requiring the suppliers of these peripherals to go back up their product design hierarchies and introduce for example line printers and magnetic storage systems of which several generations (e.g., magnetic tape, cores, and drums) of the latter systems are often interpreted as technological discontinuities (Flamm, 1988; Daniel et al, 1999). Although incremental improvements in for example recording density can be said to have *enabled* (Arrow 3) the movements up the product design hierarchies by the producers of magnetic storage systems, we can say that it was the emergence of mainframe computers that *caused* (Arrow 2) some manufacturers of peripherals to move back up the product design hierarchy for this equipment.

4.2 Bipolar integrated circuits

Improvements in semiconductor manufacturing equipment and the processes they are used in (e.g., planar and metal deposition processes) led to a second round of changes in the design tradeoffs for semiconductors (See second line of Table 3) and the emergence of a third technological discontinuity (See Table 2) called integrated circuits (ICs). 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 ICs would eventually outweigh the advantages of using the optimal material for capacitors (Mylar) and resistors (carbon) in discrete components (Reid, 1985; Riordan and Hoddeson, 1997). Similarly, the early reductions in defect density in the late 1950s caused engineers such as Robert Noyce of Fairchild to recognize that the advantages of using a metal layer to connect multiple transistors on a single chip (and thus not connecting individual transistors with wires) would eventually outweigh the disadvantages of lower yields from placing multiple transistors on a single chip (Reid, 1985; Riordan and Hoddeson, 1997).

The first market for these ICs was in military applications, which was still the largest market for silicon transistors (Malerba, 1985; Reid, 1985). Thus the introduction of ICs required movements back up the product design but not customer choice hierarchy. Military markets such as missiles and satellites drove improvements in ICs and these improvements in ICs also changed the design tradeoffs for computers, which led to movements back up the customer choice and product design hierarchies and the emergence of a technological discontinuity called mini-computers in the 1960s. These mini-computers were a scaled down version of mainframe computers where the shorter word lengths, instruction sets, and slower processing speeds of them represented movements back up the product design hierarchy for computers. Mini-computers also provided a different tradeoff between performance in million instructions per minute (MIPs) and the ratio of price to performance to users (See Figure 4) and thus the initial customers for them were very different from the customers for mainframe computers (See Table 4). In scientific and engineering applications such as product design and process control, users developed their own software and modified the input-output devices where these new users represented movements back up the customer choice hierarchy for computer manufacturers.

Place Figure 4 about here

DEC was the first manufacturer to offer an appropriate business model and architecture for these scientific and engineering applications (Flamm, 1988). Although it had sold logic modules from the late 1950s, the PDP-8, which was released in 1965, is usually considered DEC's first computer (Rifkin and Harrar, 1988; Baldwin and Clark, 2000). The PDP-8 and DEC's subsequent mini-computers changed the design tradeoffs for many users of IT and thus enabled many firms to utilize IT differently from existing users of mainframe computers. The PDP-8's modular design (Baldwin and Clark, 2000) and extensive documentation made it easy for users to develop their own software and modify existing input-output devices (Rifkin and Harrar, 1988). And DEC's use of ICs and a shorter word length (12-bits) and list of instructions enabled DEC to sell the PDP-8 for a fraction ($18,000) of the price of the smallest IBM System 360 (Ceruzzi, 1998). These changes enabled engineering and manufacturing departments to manage their own computers, develop their own software and peripherals, do more experimentation with them, and bypass the "accounting mentality" of the data processing departments that used mainframe computers (Ceruzzi, 1998; Cortada, 2005).

The growing market for mini-computers also created a need for smaller and cheaper peripherals where the emergence of these needs and the products that filled these needs reflect the impact of incremental improvements in one subsystem on adjacent subsystems in a nested hierarchy of subsystems and the interactions between the three arrows shown in Figure 1. The emergence of mini-computers, which were enabled by incremental improvements in ICs (Arrow 1), changed the customer choice hierarchy for peripherals thus requiring peripheral suppliers to go back up their product design hierarchies and offer scaled-down versions of peripherals for mini-computers (Arrow 2) where for example smaller hard drives are defined as technological discontinuities. Although incremental improvements in for example recording density can be said to have *enabled* (Arrow 3) the movements back up the product design hierarchy, we can say that it was the emergence of mini-computers that *caused* (Arrow 2) some manufacturers of magnetic storage equipment to move back up the product design hierarchy for this equipment (Christensen, 1997).

4.3 MOS and CMOS ICs

Like discrete transistors and bipolar ICs, improvements in semiconductor manufacturing equipment and the processes they are used in led to further changes in the design tradeoffs for semiconductors (See Table 3) and the emergence of two new technological discontinuities for them (See Table 2) that both involved movements back up both the product design and customer choice hierarchies. Improvements in oxidation equipment and the processes they are used in led to improved control over the thickness of the silicon oxide that separates the gate and channel in transistors thus making the design of MOS (metal-oxide semiconductor) and CMOS (complementary MOS) transistors possible (Bassett, 2002). The use of MOS instead of bipolar transistors and later CMOS instead of MOS transistors in an IC represented two movements back up the product design hierarchy and the new markets for the MOS and CMOS ICs represented two movements back up the customer choice hierarchies. The MOS ICs were more appropriate for pocket calculators and computer memory than were bipolar ICs due to their lower power consumption (but slower speeds) (Malerba, 1985; Watanabe, 1984). Similarly, CMOS ICs consumed less power than both bipolar and MOS ICs and were the only ICs that could provide the low power consumption that was needed to produce digital watches (Ernst and O’Connor, 1992).

Further improvements in equipment and the processes they were used in continued to change the design tradeoffs for semiconductors in the 1970s through their impact on defect densities and feature size, which caused MOS to gradually replace bipolar ICs and later CMOS to gradually replace MOS ICs in most applications. Reduced defect densities have enabled an increase in die size and both larger die sizes and reduced feature sizes have increased the number of transistors that can be placed on a chip, which is often called Moore's Law. The increasing number of transistors on a chip has led to increases in heat production on an IC and thus changed the design tradeoffs for semiconductors ICs. The increasing number of transistors per chip favored the lower power consumption and thus lower heat production of MOS over the faster speeds of bipolar ICs in the 1970s and there was a move from MOS to CMOS ICs in the 1980s for similar reasons. By the mid-1980s, both memory chips and microprocessors used CMOS transistors (Langlois and Steinmueller, 1999; Riordan and Hoddeson, 1997).

Interestingly, the improvements in photolithographic equipment that have driven many of these reductions in defect density and feature size also involved technological discontinuities and these discontinuities were driven by improvements in the equipment's components and the impact of these improved components on the design tradeoffs for the equipment itself (See Figure 3 and Table 1). For example, shortening the wavelength of light used to expose wafers, expanding the numerical aperture from which this light emerges (Henderson, 1995), and improving the accuracy of alignment systems have changed the design tradeoffs and thus required equipment manufacturers to move back up the product design hierarchy several times for photolithographic equipment in what Henderson and Clark (1990) call architectural innovations.

As for the impact of incremental improvements in MOS and CMOS ICs on the design tradeoffs for computers and for firm's use of IT, the impacts on the design tradeoffs did not lead to any technological discontinuities. Similar to how discrete silicon transistors improved the performance of mainframe computers without leading to large movements back up the product design hierarchy for them, MOS and CMOS ICs, which can be defined as radical innovations using certain frameworks (Abernathy and Clark, 1985; Henderson and Clark, 1990), did not directly lead to technological discontinuities for computers or large changes in ‘firm use of IT.” Instead, there is more complex story, which is told in the next section.

4.4 Microprocessors

Further improvements in processes, the equipment used in these processes (e.g., photolithographic equipment), and the resulting increase in the number of transistors on a chip led to a fifth round of changes in the design tradeoffs (See Table 3) and the emergence of a sixth technological discontinuity for semiconductors (See Table 2). The increasing number of transistors on an chip, which was decreasing the cost of space on this chip, made it economical to design a general-purpose chip like the microprocessor that could be programmed to perform various functions. In the 1970s firms began to design their products around these microprocessors, memory, and other support chips (Borrus, et al, 1983) where the development of programming tools such as assemblers and higher-level programming languages such as PASCAL supported the diffusion of microprocessors (Jackson, 1997).

Although the first order for a microprocessor was driven by the needs of Japanese calculator manufacturers, the rapidly growing market for calculators enabled special purpose ICs to be used instead of microprocessors thus preventing calculators from becoming a major driver of the microprocessor market. Instead it was a large number of low- to mid-volume applications such as aviation and medical and test equipment that initially drove the market for microprocessors (Jackson, 1997) where microprocessors provided an intermediate solution between general purpose logic ICs and custom/semi-custom ICs. Except in cases where the customers are relatively insensitive to price like the military, the high development costs for custom or semi-custom IC designs required large markets to justify their development costs and thus a large gap had existed in the market until microprocessors appeared in the 1970s (Borrus et al, 1983).

Incremental improvements in the microprocessor also changed the design tradeoffs for computers (See Figure 6) and enabled firms to go back up the product design and customer choice hierarchies and introduce the personal computer (PC). These PCs provided a different tradeoff between performance and the ratio of price to performance to users (See Figure 4) and thus the initial customers, applications, and business models for them were very different from those for mini- or mainframe computers (See Table 4). Individuals and small firms were the initial customers while the initial applications included game and education software. The new business model was the sale of PCs and pre-packaged software through the mail and in retail outlets such as Computerland (Langlois, 1993; Campbell-Kelly, 2003;).

Since the emergence of the PC also led to the emergence of new peripherals, the PC is also an example of how incremental improvements in one subsystem drove changes in adjacent subsystems through the interactions between the three arrows shown in Figure 1. For example, the emergence of the PC, which was a result of incremental improvements in microprocessors (Arrow 1), led to the need for small and inexpensive disk drives and printers (Arrow 2). The need for small and inexpensive disk drives caused disk drive manufacturers to go back up their product design and customer choice hierarchies and develop a 5.25 inch disk drive for PCs and later smaller ones. Although it can be said that incremental improvements in recording density *enabled* (Arrow 3) the movements, we can also say that it was the emergence of the PC that *caused* (Arrow 2) the movements back up the product design hierarchy for hard disk drives (Christensen, 1997).

Similarly, the need for small and inexpensive printers caused printer manufacturers to go back up the product design and customer choice hierarchies and develop laser printers. As with the hard disk drives, although incremental improvements in lasers, which were driven by the use of bar code readers in retail check-out counters, *enabled* (Arrow 3) the movement, we can say that it was the emergence of the PC that *caused* (Arrow 2) the movement back up the product design hierarchy for printers. Furthermore, it was the use of laser printers that drove the introduction of local area networks (LAN), which were eventually connected to the Internet (von Burg, 2001).

In addition to their impact on LANs, the PC drove more fundamental changes in the design tradeoffs associated with a firm's use of IT. The relatively high price of mainframes and even mini-computers had required a high utilization of them and thus multiple people had shared a single computer. The low price of PCs reduced the need for high utilization and enabled employees to own their own computers and thus directly handle them. Although many employees were gaining access to mainframe and mini-computers in the 1970s through time-sharing systems, PCs provided faster responses to user inputs, which were essential to the use of business software such as spreadsheets, word processing, and the preparation of overhead slides (e.g., power point) (Campbell-Kelly, 2003).

Similarly, the combination of PCs, EDI (Electronic Data Exchange), LANs and packet-switched systems have fundamentally changed the tradeoffs for supply chain management, cross-functional integration, inter-firm and inter-industry cooperation, and economies of scale and scope where all of these were now considered at the global and not just national levels (McKenney, 1995; Cortada, 2005; Friedman, 2005). Improvements in EDI, LANs and packet-switched systems were driven by the same factors that drove improvements in PCs and other computers. Incremental improvements in ICs drove improvements in modems, which together with computers were needed to implement EDI, and made packet switching[2] and LANs economical. These changes also caused the data processing departments of the 1950s to become a firm-wide organization and their managers to become chief information officers in the 1990s (Cortada, 2005; McKenney, 1995).

5. Discussion

The purpose of this paper was to introduce a model of technological change that explains the sources and timing of technological discontinuities. The use of a single sector and the lack of randomness in its choice suggest that we must be careful about generalizing to other sectors. With this caveat in mind, two contributions to the field of technological change are summarized.

First, the use of product design and customer choice hierarchies and the concept of design tradeoffs provide additional insights into how a technological discontinuity occurs. Incremental improvements at lower levels in a nested hierarchy of subsystems change the design tradeoffs and thus require firms at higher levels in the nested

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[2] Packet switched networks required much more computer processing than circuit-switched networks but provided much more efficient data transmission (Abatte, 1999).

hierarchy to rethink their product designs, customers, business models, and sales channels. Table 5 categorizes some of the ways in which incremental improvements at lower levels in a nested hierarchy of subsystems changed internal and external design tradeoffs and thus required firms to rethink the product designs and customers in the IT sector. For example, the tradeoffs between different materials and between different parts were impacted on by the different rates of improvements in manufacturing processes for these different materials or parts. 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 were impacted on by improvements in semiconductor components. For semiconductors, the tradeoffs between component (discrete components) and system (integrated circuit) performance, between heat production and speed, and between performance and development cost were also impacted on by reductions in feature size and their associated increases in the number of transistors per chip.

In addition to these design tradeoffs that are inherent in the product design hierarchy, the exact timing of the discontinuity depends on how firms use these improvements at lower levels in the nested hierarchy of subsystems 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 and the scale (i.e., word length and instruction sets) of the computers; all of these changes can be interpreted as large movements back up the product design hierarchy. In terms of customers, movements back up the customer choice hierarchy reflect changes in the users and applications and movements back up this hierarchy reduced the improvements in performance and cost that were needed for growth in the product representing the technological discontinuity 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 bipolar and MOS ICs respectively. 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 mainframe and mini-computers respectively.

The second contribution of this paper involves how incremental improvements in one subsystem drive changes in adjacent subsystems. Like the first contribution, the use of product design and customer choice hierarchies and the concept of design tradeoffs provide additional insights into how these changes, including ones that can be defined as technological discontinuities, occur. Incremental improvements in electronic components such as semiconductors (subsystem “A” in Figure 1) drove changes in the design tradeoffs for computers and the emergence of technological discontinuities (Arrow 1) where the producers of them (e.g., of System “A”) can be considered the new system integrators (Hobday et al, 2005) in the nested hierarchy of subsystems. From the standpoint of suppliers of peripherals such as magnetic memory and printers (suppliers of subsystem “B”), these technological discontinuities represented changes in their customer choice hierarchies and required them to move back up their product design hierarchies (Arrow 2). The degree to which they must move back up their product design hierarchies depends on the extent to which improvements in component “B” change the design tradeoffs for subsystem “B” (Arrow 3). For example, incremental improvements in magnetic recording density changed the design tradeoffs for magnetic storage systems to such an extent that large movements back up the product design hierarchies were required and thus these magnetic storage systems can be defined as technological discontinuities.

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). Although component innovations did enable system innovations in the IT sector, the linkage between these component and system innovations is much more complex than the previous research suggests. For example, it is not possible to find a direct link between component innovations such as silicon bipolar, MOS, and CMOS transistors and system innovations such as new computers. Even the first ICs and microprocessors are only indirectly linked to the mini-computer and the PC respectively since the first applications of ICs and microprocessors were not in mini-computers and PCs. Instead, military products and a variety of test and aviation equipment were the first applications for ICs and microprocessors respectively and it was only after these applications encouraged manufacturers to make incremental improvements in ICs and microprocessors that these improved ICs and microprocessors drove changes in the design tradeoffs of computers and thus the emergence of mini-computers and PCs.

The proposed model represents this phenomenon at a much deeper level and sheds light on how spillovers occur between industries and how firms should be careful not to define their nested hierarchy of subsystems too narrowly. It shows how there were *independent* movements back up the product design and customer choice hierarchies for both semiconductors and computers, which reflects the fact that different markets have driven most of the technological discontinuities. For example, the radio and television industries drove improvements in vacuum tubes, which enabled the development of the mainframe computer. Military applications drove improvements in discrete transistors and ICs where the latter enabled the development of the mini-computer. Aviation and other special applications drove improvements in microprocessors, which enabled the development of the PC. Improvements in MOS and CMOS transistors also played a role in the improvements of microprocessors where the initial improvements in MOS and CMOS were driven by the markets for portable calculators and digital watches.

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Table 1. The Technological Discontinuities in each Level of the Nested Hierarchy shown in Figure 3

Level in Nested Hierarchy	Technological Discontinuity
Firm's Use of Information Technology (1)	1. Automation of administrative functions 2. Automation of engineering functions 3. Integration of administrative and engineering functions
Computers	1. Mainframe computer 2. Mini-computer 3. Personal Computer (PC)
Telecommunication	1. Circuit switching for voice 2. Circuit switching for electronic data interchange (EDI) 3. Packet switching
Magnetic Storage	1. Magnetic Core 2. Magnetic tape 3. Magnetic drum 4. Magnetic hard disks, including different form factors (e.g., 14", 8", 5.25", 3.5")
Electronic technologies (particularly semiconductors)	1. Vacuum tube 2. Germanium bipolar transistor 3. Silicon bipolar transistor 4. Bipolar integrated circuit (IC) 5. MOS transistor 6. CMOS transistor 7. Microprocessor
Photolithographic Equipment	1. Contact aligner 2. Proximity aligner 3. Scanning projection 4. Stepper

Abbreviations: MOS (Metal-Oxide Semiconductor); CMOS (complementary MOS)

Sources: see text

(1) The technological discontinuities shown for a "firm's use of information technology" actually represent an evolution in the IT systems for firms.

Table 2. Technological Discontinuities and Movements back up the Hierarchies for the Semiconductor Industry

Technological Discontinuity (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 calculators
Combinations of microprocessor, memory, and discrete devices	Mid-1970s	Changes in system design	Aviation, medical, test equipment

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 3. Incremental Improvements Changing the Design Tradeoffs and Driving the Emergence of Technological Discontinuities for the Semiconductor Industry

Technological Discontinuity (emphasis on underlined terms)	Incremental Improvements at Lower Levels in the Nested Hierarchy of Subsystems	Eventual Impacts of Incremental Improvements on Design Tradeoffs and thus Emergence of Technological Discontinuities
Combinations of discrete silicon bipolar transistors and discrete devices	Improved 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 through improved equipment	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 through improved equipment in particular photolithographic equipment	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 decreased the cost of transistors and thus made the development costs more important than the efficient use of silicon space

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 4. Technological Discontinuities in the Computer Industry and Relevant Changes

Technological Discontinuity	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. Categorizing the Changes in Design Tradeoffs that led to Technological Discontinuities

General Tradeoffs	Detailed Tradeoffs	Incremental Improvements Driving Changes	Industry or Technological Discontinuity
Internal design tradeoffs; between			
Different types of parts	Vacuum tubes, transistors, and ICs	Different rates of improvement for different equipment and processes	Computers
Different types of materials	Germanium and silicon		Semiconductors
External design tradeoffs; between			
Price and performance	Price and processing speed	Better ICs	Mini-, personal computers
Different measures of performance	Performance of component (e.g., resistor or capacitor) 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	Fixed (development costs) and variable costs (efficient use of silicon space)	Increased in the number of transistors per chip	Microprocessors

Figure 1. Hierarchy of Sub-Systems and Firms

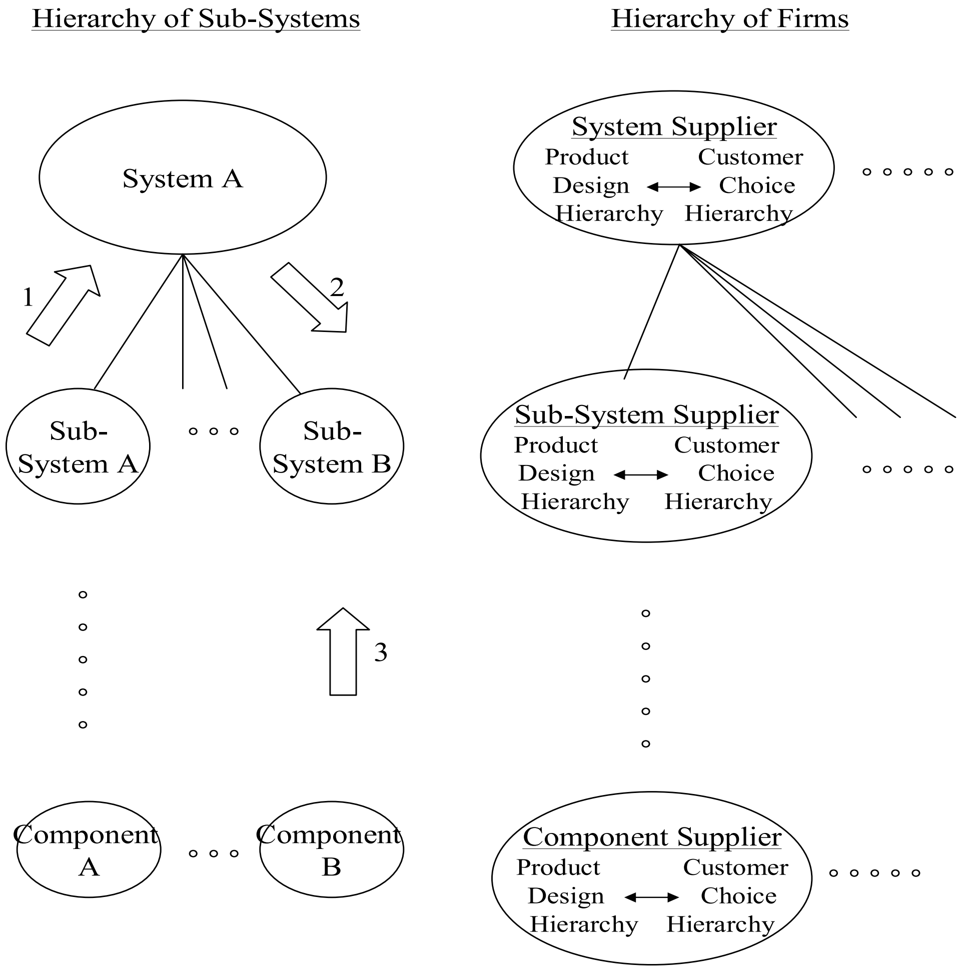
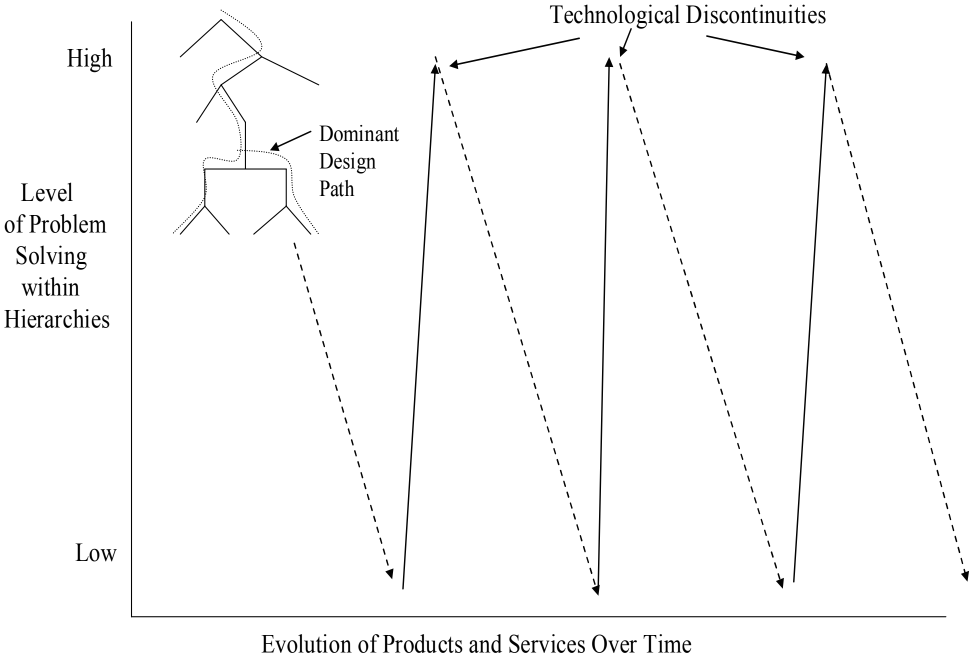
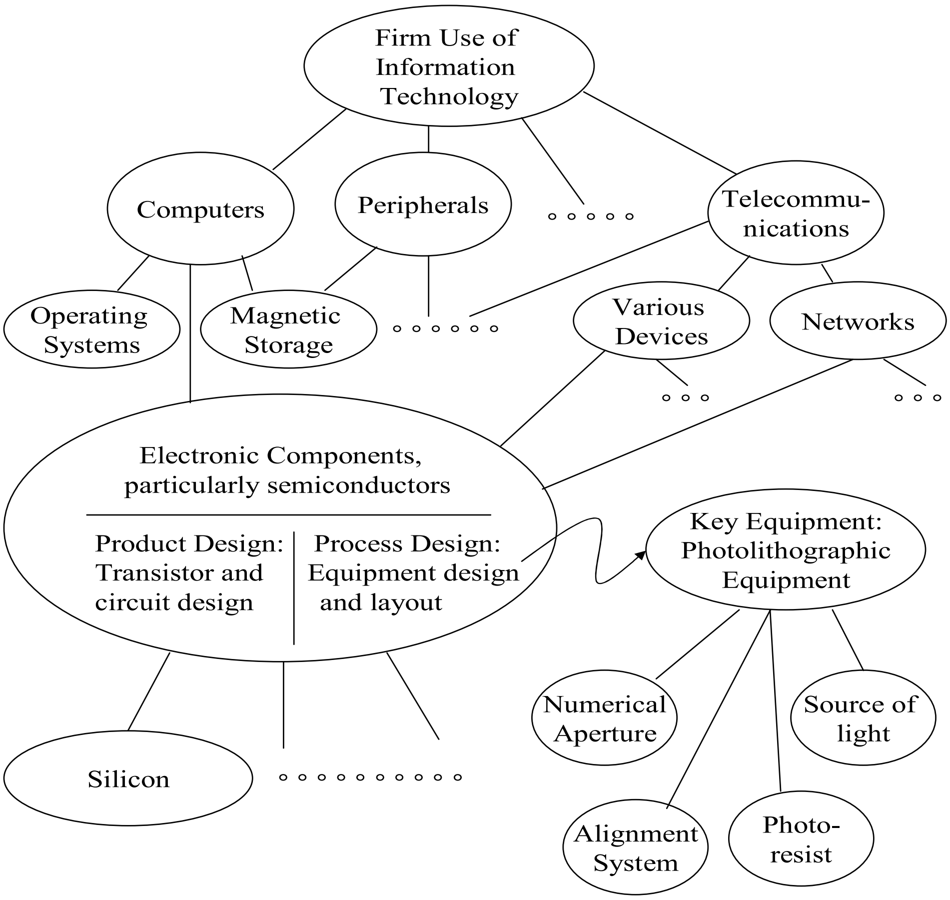


Figure 2. Evolution of Problem Solving in Hierarchies (shown here for product design hierarchy) as a Function of Time



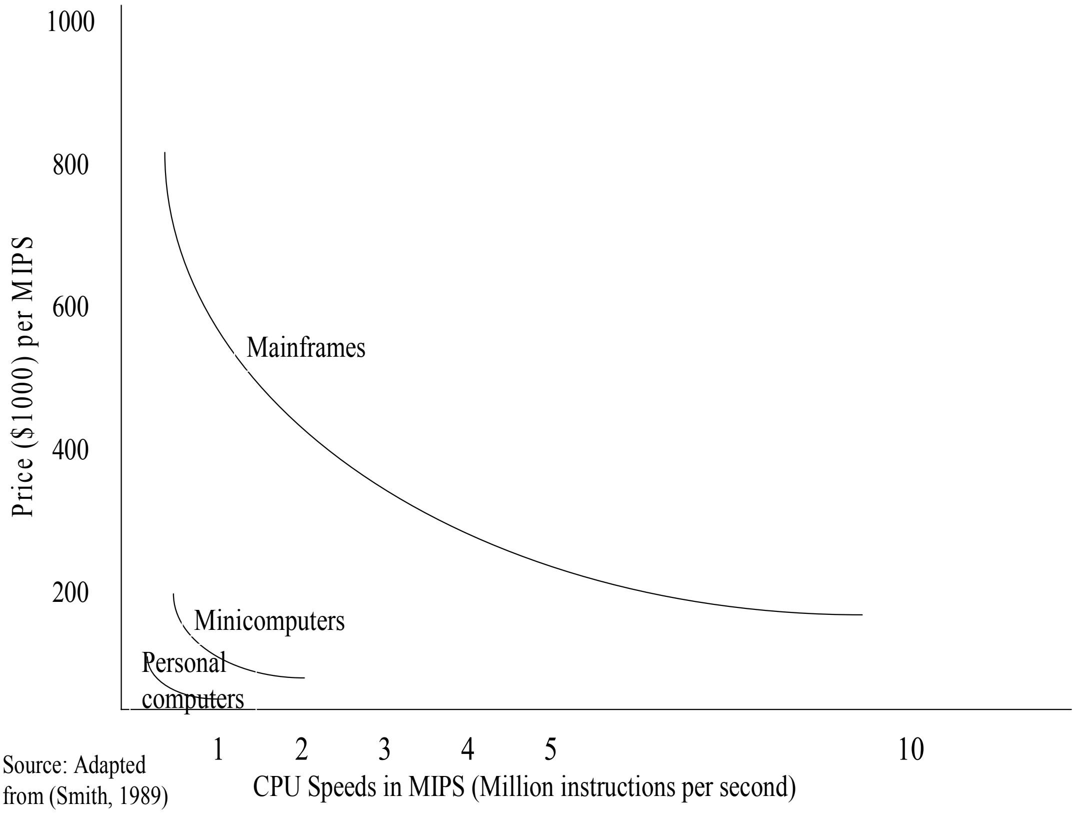
Note: Dotted lines represent movements down the hierarchies and solid lines represent movements back up the hierarchies

Figure 3. Nested Hierarchy of Sub-Systems in the IT Sector



Note: Although they are not shown, there are both product design and customer choice hierarchies in each circle.

Figure 4. 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)