Technological Change within Hierarchies:

The Case of the Semiconductor Industry

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Abstract

This paper uses the semiconductor industry to demonstrate a model of technological change that addresses the sources and timing of technological discontinuities and dominant designs. The model emphasizes product design and customer choice hierarchies, design tradeoffs, and technological improvements at lower levels in the product design hierarchy (e.g., improvements in process equipment for components). Improvements at lower levels in a product design hierarchy drive changes in the design tradeoffs for the product as a whole, which affects the movements up and down the product design and customer choice hierarchies. Movements up the hierarchies may lead to the emergence of a technological discontinuity, which this paper calls a new product class, while movements down the hierarchies may result in the emergence of a dominant design. The use of product design and customer choice hierarchies and the concept of design tradeoffs provide additional insight into how a discontinuity occurs, including the specific changes that occur in the designs and customers during the discontinuity.

1. Introduction

In spite of the recognized importance of technological discontinuities and dominant designs in the existing literature on technological innovation, there are few models that address the sources and timing of them. Anderson and Tushman's (1990) seminal article articulated a cyclical model of technological change where competition between alternative designs, the emergence of a dominant design, and incremental progress follow a technological discontinuity. They and others have shown the difficulties incumbents experience in responding to these discontinuities (Abernathy and Clark, 1985; Tushman and Anderson, 1986; Henderson and Clark, 1990; Utterback, 1994; Chesbrough and Kusunoki, 2001). Still others have extended Anderson and Tushman's (1990) model by showing some 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 (Utterback, 1994; 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 (Clark, 1985), design tradeoffs (Alexander, 1964; Dosi, 1982; Rosenberg, 1963, 1969; Sahal, 1985), and technological improvements at lower levels in the product design hierarchy (e.g., improvements in process equipment for components). Improvements at lower levels in a product design hierarchy 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. Movements up the hierarchies may lead to the emergence of a technological discontinuity, which this paper calls a new product class, while movements down the hierarchies may result in the emergence of a dominant design. 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 and the factors driving these changes.

This paper uses the semiconductor industry to demonstrate this model of technological change. The semiconductor industry is an appropriate industry to apply the model due to the large amount of technological change and literature and the author's experience (as an engineer and a researcher) in the industry. The lack of randomness in the choice of industry suggests that we must be careful about generalizing to other industries. The paper first describes the proposed model followed by the research methodology and the application of the model to the semiconductor industry.

2. Proposed Model

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

The introduction of new products and services reflect movements both down and up the hierarchies of product design and customer choice in the industry as depicted in Figure 1. Following a technological discontinuity, design activity shifts from core to periphery at one particular level of the product design hierarchy and it also 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 design decisions made at higher levels in the hierarchy. The amount of movements down the hierarchies reflects the degree of similarity between different firm's methods of segmenting customers (customer choice hierarchy) and the different firm's products in both alternative designs and the definition of sub-problems (product design hierarchy) (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 (Baldwin and Clark, 2000). The emergence of independent modules can cause vertical disintegration to occur and thus lead to large changes in market structure (Langlois and Robertson, 1992; Sanchez and Mahoney, 1996; Baldwin and Clark, 2000; Brusoni and Prencipe, 2001).

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(s) 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 or the emergence of sub-product classes define the emergence of independent design paths. Defining a dominant design as a path is consistent with Dosi's (1982) notion of technological trajectories, which define the direction of advance within a technological paradigm (see below), and with other research on dominant designs that emphasizes a stable architecture (Anderson and Tushman, 1990) and the possibility that such a stable architecture can extend to sub-systems and components within a system (Tushman and Murmann, 1998; Murmann and Frenken, 2006).

However, depending on the industry, dominant designs will differ in terms of both the relative importance of alternative designs and sub-problems and the number of levels to which a dominant design proceeds down the design hierarchy. The latter can be defined in terms of the similarities between the physical components, overall architecture, and design "concepts" in different firm's products where Polanyi's (1962) concept of "operational principle" can be used to define the degree of "conceptual" similarity between products such as helicopters and aircraft (Murmann and Frenken, 2006). The similarities between the physical components, overall architecture, and design "concepts" in different firm's products will depend on 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.”

Returning to movements within the hierarchies, technological improvements at lower levels in the product design hierarchy can change the “design tradeoffs” that are implicit at all levels in this hierarchy and thus lead to movements *back up* the hierarchies of both product design and customer choice. Both popular journalists (e.g., Gilder, 1990, 1992) and scholars have used similar concepts to explain changes at both the macro- and micro-level. At the macro-level for example, improvements in automobiles in the second half of the 20^{th} century changed the design tradeoffs for cities and thus enabled many countries to redesign them to include suburbs and extended commuting. Similarly, improvements in transportation, communication, and computer systems in the last 10 years have changed the tradeoffs for production systems and one result has been the increased globalization of 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 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. 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; Chesbrough and Kusunoki, 2001) 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 or have not 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), modularity traps (Chesbrough and Kusunoki, 2001) and managerial cognitive representations (Kiesler and Sproull, 1982; Tripsas and Gavetti, 2000).

3. Research Methodology

The author analyzed the primary and secondary literature on the semiconductor industry including academic papers and books from the management, economic, and historical fields, practitioner-oriented accounts, technical accounts, and encyclopedic histories, some of which are referenced below. Through analysis of this literature, the author identified the: 1.) changes in product class through major movements back up the product design or customer choice hierarchies; 2.) technological improvements at lower levels in the hierarchy (i.e., improvements in process equipment) that have changed the design tradeoffs thus leading to movements back up the hierarchies; 3.) the movements down the hierarchies in terms of the choice of alternative designs and definitions of sub-problems in each product and in some cases sub-product and sub-sub product classes; and 4.) the dominant designs for each product class (and in some cases sub- and sub-sub-product classes).

4. Brief History of the Semiconductor Industry

Table 1 summarizes the evolution of product classes in the semiconductor industry and the movements back up the product design and customer choice hierarchies that they represent. 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 integrated circuits (ICs) and discrete devices” and later to combinations of more complex ICs such as microprocessors and now SoC (System on Chip). The changes in materials represent the largest movements back up the product design hierarchy followed by changes in transistor and system design. The MOS IC, CMOS IC, and microprocessor product classes also involved changes in the customer choice hierarchies in that there was a different set of initial customers for these product classes than the main customers for the previous product classes.

Table 2 summarizes the technological improvements at lower levels in the hierarchy that have driven changes in the design tradeoffs and thus movements back up the product design and customer choice hierarchies and the emergence of new product classes in the semiconductor industry. These include improvements in processes and the equipment used in these processes, which have reduced defect densities (IC Knowledge, 2005) and feature sizes (Figure 2). The reduction in defect densities has enabled a 30-fold increase in die size over the last 25 years (ICEC) and both larger die sizes and reduced feature sizes have increased the number of transistors that can be placed on a single IC chip (See Figure 3), which is often called Moore's Law. All of these improvements have changed the design tradeoffs for semiconductors (Gilder, 1990) and required manufacturers to go back up the product design and customer choice hierarchies many times.

Table 3 lists the dominant designs for each product class and whether they represent alternative designs or modular ones. The dominant designs that are defined as alternative designs represent the results of competition between different transistor (and their supporting processes) designs and the dominant designs that are defined as modular ones represent a new definition of the sub-problem and they include ones for bipolar digital IC logic families, semi-custom MOS and CMOS ICs, and microprocessors.

Place Tables 1-3 and Figures 2-3 about here

4.1 Discrete transistors

Improvements in processes such as crystal growing and high-temperature processing (and an improved understanding of semiconductor physics) enabled Walter Brattain and John Barden to create a point-contact transistor in 1947 and William Shockley to create a junction-transistor in 1949 using single crystal germanium. Pure semiconductor material and thus crystal growing are essential to the creation of semiconductors and few people realized this until these rudimentary transistors were successfully constructed. For example, the junction-grown transistor depended on the revival of Czochralski's crystal growing approach, which was originally developed in 1917. Combined with zone refining, which was also developed at Bell Labs in 1950, these techniques enabled the manufacture of germanium that has less than 1 in 10 billion impurities by 1950 (Braun and MacDonald, 1982; Riordan and Hoddeson, 1997; Tilton, 1971).

The initial research on these germanium transistors was driven by military applications where the improvements in them can be interpreted as moves down the product design and customer choice hierarchies. For example, further improvements in high-temperature processing and germanium purity enabled Bell Labs to create the diffused transistor, which can be defined as the dominant design for germanium transistors (See Table 3) (Riordan and Hoddeson, 1997). The emergence of this dominant design also coincided with the emergence of well-defined consumer market segments in the customer choice hierarchy such as transistor radios and hearing aids. Although the poor frequency response of these diffused transistors initially prevented the production of transistor radios with high sound quality, young people still bought transistor radios in order to listen to rock- and roll music and improvements in the transistors gradually led to improved frequency response and thus higher sound quality (Christensen et al, 2001).

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 finally exceeded the higher costs associated with the higher melting point of silicon (and thus 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 that still drove research spending on semiconductors (Tilton, 1971).

Like germanium transistors, many of the improvements in silicon transistors can be interpreted as moves down the product design hierarchy. After Texas Instruments (TI) created a single-crystal growth process to create the world's first silicon transistor in 1954 (Braun and MacDonald, 1982; Tilton, 1971), Bell Labs created the first diffused process, diffused silicon transistor, and silicon dioxide in 1955. In combination with photo-resist technology, which was borrowed from the printing and graphics industry, these developments led to the creation of the mesa transistor in 1955 and the planar transistor in 1958 (Braun and MacDonald, 1982; Tilton, 1971; Riordan and Hoddeson, 1997). Adding an additional layer of silicon dioxide to the planar transistor stabilized the transistor's surface and is called the planar process (Malerba, 1985; Tilton, 1971). Because each of these process improvements built upon the previous processes for silicon transistors, each of the improvements can be interpreted as moves down the product design hierarchy and together they can be considered a dominant design for silicon transistors. Furthermore, the military's funding of this research enabled it to define the specifications for these transistors and thus the U.S. military's needs initially defined the market segments and thus the customer choice hierarchy for discrete silicon transistors.

4.2 Bipolar ICs

Improvements in a large variety of processes and the equipment used in these processes (e.g., planar and metal deposition processes) led to a second round of changes in the design tradeoffs (See Table 2) and the emergence of a third product class of semiconductors called ICs in the early 1960s (See Table 1). The early reductions in feature size and defect density 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) outweighed the disadvantages of not being able to use the optimal materials for capacitors (Mylar) and resistors (carbon) as was done with discrete components. Similarly, the early reductions in defect density in the late 1950s caused engineers such as Robert Noyce of Fairchild to recognize that these improvements would eventually cause the advantages of using a metal layer to connect multiple transistors on a single device (and thus not connecting individual transistors with wires) to outweigh the disadvantages of lower yield from placing multiple transistors on a single device. In spite of initial opposition to ICs by many scientists, including those in the military (Reid, 1985; Riordan and Hoddeson, 1997; Murphy et al, 2000), the increasing yields of transistors had justified the move to ICs by the early 1960s (Tilton, 1971).

Because the military was the first customer for ICs and still the main customer for silicon transistors and research on them (Malerba, 1985; Reid, 1985), ICs only required semiconductor manufacturers to go back up the product design and not customer choice hierarchies. However, the diverse demand for ICs both in the military and other applications caused a number of sub-product and sub-sub-product classes to emerge (See Table 3) for ICs that can be interpreted as a splintering of movements down the product design and customer choice hierarchies and the emergence of multiple design paths (See Figure 1) where the application (Murmann and Frenken, 2006) of Polanyi's (1962) operational principle defines the similarities between these paths. Digital ICs (which were demanded by the military and later computer markets), linear ICs, and also semi-custom ICs emerged as the three main sub-product classes within the product class of IC where each of them operated under the same principle of multiple transistors on a single device.

The existence of Boolean Logic made it easier to standardize digital than linear ICs (Malerba, 1985) thus causing greater movements down the product design hierarchy (i.e., dominant design) for digital than linear or custom ICs (See Table 3). Users of digital IC logic families designed their products with Boolean Logic functions where standard input and outputs (Murphy et al, 2000) for them emerged through competition between different IC logic families. Semiconductor manufacturers designed families of digital ICs that could perform these Boolean logic functions using repeated combinations of resistors, diodes, and/or transistors (Borrus, et al, 1983; Malerba, 1985).

The short life-span of resistor-transistor logic and the greater difficulties with defining standard building blocks for linear and custom ICs than for digital ICs prevent the definition of dominant designs for them. However, if we move one step back up the product design hierarchy, we could define transistor-transistor logic as a dominant design for the product class “combinations of ICs and discrete devices.” This would be consistent with this paper's and the first half of Suarez and Utterback’s (1995) definition of a dominant design (“a dominant design is a specific path along an industry’s design that establishes dominance among competing paths”) in that the issue is how far down the product design hierarchy we can define a dominant design.

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 while the disadvantage is that it may cause blanks to appear in our summaries of the industry. For example, the benefits to firms from using IC logic families that had standard inputs and outputs (Murphy et al, 2000) caused certain families to emerge as dominant designs. Fairchild’s 920 series emerged as the dominant design for the DTL sub-product class in the period from 1965 to 1967 and this caused its share of the semiconductor market to rise from 18% in 1964 to 24% in 1967. However, the move from DTL to TTL and the emergence of TI’s 7400 series as the dominant design in TTL caused TI to become the global leader in the 1970s (Malerba, 1985).

4.3 MOS and CMOS ICs

Further improvements in processes, the equipment used in these processes (e.g., photolithographic equipment), and their resulting impact on feature sizes (See Figure 2) and the number of transistors per chip (See Figure 3) led to further changes in the design tradeoffs for semiconductors (See Table 2) and the emergence of two new product classes of them (See Table 1) that involved new transistor designs. Although the reductions in feature size and their associated increases in heat dissipation eventually caused designers to favor the lower power consumption (and thus lower heat production) but slower speeds of MOS and later CMOS over bipolar ICs, initially these improvements in processes merely made the design of MOS and CMOS transistors possible in the early 1960s. For example, improvements in the oxidation process, which was a critical part of the planar process, led to improved control over the thickness of the silicon oxide that separates the gate and channel in these transistors and the almost elimination of the semiconductor surface problems that had plagued the industry since the invention of the point-contact transistor by Bell Labs in 1947 (Bassett, 2002).

New markets such as calculators, computer memory, and watches initially drove the demand for MOS and CMOS ICs and thus required semiconductor manufacturers to move back up both the product design and customer choice hierarchies (i.e., new customers). In spite of their slower speeds, only MOS ICs could provide the level of power consumption that was demanded in pocket calculators. U.S. manufacturers such as TI and Rockwell made the first MOS ICs for calculators (Malerba, 1985) and they were quickly followed by Japanese firms, who were helped by the global success of Japanese calculator manufacturers (Majumder, 1982). Calculators provided Japanese semiconductor manufacturers with a foothold in the MOS market (Malerba, 1985) and represented more than 50% of Japanese IC production in the early 1970s (Watanabe, 1984).

Memory ICs for computers also drove demand for MOS ICs particularly in the U.S. and like calculators they represented a new market for semiconductors and thus they required semiconductor manufacturers to move back up the customer choice hierarchy. With the increasing speeds of bipolar ICs in the 1960s, magnetic core memory became the bottleneck in computers and MOS ICs were more appropriate for this memory than bipolar ICs (Jackson, 1998; Murphy et al, 2000). The success of Intel's 1K DRAM (Dynamic Random Access Memory) led to a doubling in the size of them every 1-2 years and the introduction of many variations of memory (see below).

Like the MOS ICs, the CMOS ones required a new type of transistor design (Bassett, 2002) and initially depended on a new type of customer thus requiring semiconductor manufacturers to again move back up both the product design and customer choice hierarchies. In spite of the slower speeds and higher costs (more process steps were required) of CMOS than of MOS ICs, it was the only technology that could provide the low power consumption that was needed to produce digital watches (Ernst and O'Connor, 1982) where Seiko was the first watch manufacturer to use CMOS ICs in 1974 (Johnstone, 1999).

Further improvements in processes, the equipment used in these processes (e.g., photolithographic equipment), and their resulting impact on feature sizes (See Figure 2), the number of transistors per chip (See Figure 3), and power consumption eventually favored CMOS over MOS and both of them over bipolar ICs. The reductions in feature size and thus the increasing number of transistors on a chip caused power consumption to become a major problem in many electronic products and thus favored the lower power consumption of MOS ICs over the faster speeds of bipolar ones and later the lower power consumption of CMOS ICs over the lower cost and faster speeds of MOS ones (Langlois and Steinmueller, 1999; Riordan and Hoddeson, 1997). CMOS transistors were first used in DRAMS in the 1MB device in 1986 and the percentage of IC production represented by CMOS rose from 40% in 1988 to 80% in 1994 (Langlois and Steinmueller, 1999).

Aside from microprocessors, which are dealt with in the next section, memory, digital logic, and semi-custom ICs were and still are the main markets for MOS and CMOS ICs (Turley, 2002) and many variations of them existed in the 1970s and 1980s. These different variations represent sub-sub-product classes within the product classes of MOS and CMOS ICs (See Table 3) and they can be interpreted as a splintering of movements down the product design and customer choice hierarchies and the emergence of multiple design paths (See Figure 1) where the application of Polanyi's (1962) operational principle (Murmann and Frenken, 2006) defines the similarities between these paths. The different variations of memory include ROMs (Read Only Memory), SRAMs (Static Random Access Memory), PROMs (Programmable ROMs), EPROMs (Erasable PROMs), and flash memory (Borrus, 1987; Jackson, 1997) where each of them operate under the same principle of memory storage. The applications for these memory products can be defined as different segments within the customer choice hierarchy of memory applications.

There is also a large variety of logic ICs, which were referred to in the previous section on bipolar ICs. The existence of Boolean Logic and the demand for standard inputs and outputs caused dominant designs to emerge for MOS and CMOS-based IC logic families as they did with bipolar logic families. TI's effective move from bipolar ICs to both MOS and CMOS ICs and the network effects (Shapiro and Varian, 1999) associated with TI's bipolar logic families enabled its logic families to remain dominant designs for some of the niche markets within MOS and CMOS digital IC logic families (not shown in Table 3) (Malerba, 1985).

Although there are also a variety of semi-custom ICs, they are described in section 4.5. Instead, this section focuses on the emergence of “dimensional, scalable design rules” as the dominant design for semi-custom ICs where these rules have facilitated the separation of design and manufacturing and thus vertical disintegration in the form of independent foundries and design houses (Baldwin and Clark, 2000). Such a market structure first emerged in the U.S. and contributed towards the resurgence of the U.S. semiconductor industry (Macher et al, 1999; Arora, et al, 2001). “Dimensionless, scalable design rules” define geometrical relationships between line widths, material thicknesses, power consumption, and speed (Baldwin and Clark, 2000; Murphy et al, 2000; Critchlow, 1999). These dimensional scalable design rules emerged through a long period of experimentation in the 1970s and continue to be modified. Initially these rules were created to more easily update semi-custom designs as feature sizes were reduced (See Figure 2) but they gradually facilitated the separation of design and manufacturing into modular sub-problems (Critchlow, 1999). Like the dominant designs for germanium and silicon transistors and other product classes, this definition of a dominant design for semi-custom ICs reflects multiple movements down the product design hierarchy in this case for a specific segment (semi-custom ICs) in the customer choice hierarchy for MOS and CMOS ICs.

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 (See Figure 3) led to a fifth round of changes in the design tradeoffs (See Table 2) and the emergence of a sixth product class of semiconductors called microprocessors (See Table 1) in the early 1970s. The increasing number of transistors on a chip finally reached the level at which a computer, i.e., microprocessor, could be economically placed on a single IC chip. Since markets other than the ones driving the demand for bipolar and MOS logic, and memory ICs drove the initial demand for microprocessors, we can say that semiconductor firms had to go back up both the product design and customer choice hierarchies to develop microprocessors. Although the first order for a microprocessor was driven by the needs of Japanese calculator manufacturers (Aspray, 1997), the rapidly growing market for calculators enabled special purpose ICs to be used in them 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 digital IC logic families and custom/semi-custom ICs (Borrus et al, 1983). Microprocessors had higher performance than logic families and better programmability (i.e., lower development costs) than custom and semi-custom ICs in the mid-1970s where the emergence of programming tools such as assemblers and higher-level programming languages such as PASCAL expanded the advantages of microprocessors (Jackson, 1997).

Technically speaking, microprocessors are the largest sub-product class within a broader class of products called processors. Different sub-product classes have emerged within processors and as previously discussed for other semiconductor product classes, the emergence of these sub-product classes can be interpreted as a splintering of movements down the product design and customer choice hierarchies and the emergence of multiple design paths (See Figure 1) where the application (Murmann and Frenken, 2006) of Polanyi's (1962) operational principle defines the similarities between these paths. In addition to microprocessors, processors can be subdivided into digital signal processors (DSPs), microcontrollers, and programmable peripheral ICs (Turley, 2002) where the key operational principle in all of these processors is programmable semiconductors. The emergence of these sub-product classes has coincided with the emergence of market segments such as personal computers, workstations, audio products, digital mobile phones, servers, and industrial and automotive products (there are more than 65 microprocessors in a BMW) within the customer choice hierarchy for processors (Turley, 2002).

Dominant designs have emerged for many of these market segments where the network effects associated with providing compatible hardware and software have enabled some firms to make higher than average profits (Shapiro and Varian, 1999). Although Intel's domination of the personal computer market is the most famous example (Langlois, 1993; Malerba et al, 1999), there are others. TI is the leading supplier of digital signal processors, which were developed to handle the real-time processing of audio and visual signals in for example music and video players and mobile phones. ARM and Qualcomm are also leading suppliers of IC designs for GSM and CDMA (Code Division Multiple Access) phones respectively (Poe, 2003; Roberts, 2003). Japanese firms have been the leaders in low-end micro-controllers for many consumer markets (Borrus, 1987; Takahashi, 2003).

4.5 System on Chip

Improvements in processes, the equipment used in these processes (e.g., photolithographic equipment), and the resulting reduction in feature sizes (See Figure 2) continue to drive changes in the design tradeoffs for semiconductor products where semi-custom ICs such as system-on-a-chip (SoC) products probably represent the next product class in the semiconductor industry (Arora et al, 2001; Bass and Christensen, 2002; Christensen et al, 2004). Smaller feature sizes reduce the importance of silicon space and thus increase the importance of development costs where semi-custom ICs such as SoC have lower development costs than do custom and even programmable ICs such as microprocessors. For example, according to the national technology roadmap for semiconductors, the number of transistors that could be put on a die was increasing at a rate of about 60% a year while the number of transistors that circuit designers could design into new independent circuits was going up at only 20% a year (Bass and Christensen, 2002).

As mentioned above, microprocessors filled a gap in the market between digital IC logic families and custom/semi-custom ICs where one type of semi-custom IC is called "standard cell designs." Because with "standard cell designs" manufacturers can design products from a set of building blocks that go beyond the logic functions used in digital logic families, these designs have largely replaced digital IC logic families except for simple applications (Thomke, 2003). SoC takes these standard cell designs one step further in that designers can place more complex functions such as an entire 32- or 64-bit microprocessor and a memory chip on a single IC chip and thus are replacing standard cell designs in complex applications (Bass and Christensen, 2002; Christensen et al, 2004).

5. Discussion

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

With respect to technological discontinuities the use of product design and customer choice hierarchies and the concept of design tradeoffs provide insights that are not found in the existing literature. Technological improvements at lower levels in the product design hierarchy change the design tradeoffs and thus require firms to rethink the product designs and customers. This paper identified three kinds of changes in design tradeoffs. First, the tradeoffs between different materials were impacted on by the different rates of improvements in manufacturing processes for these different materials, in this case germanium and silicon. Second, the tradeoffs between different measures of performance were changed at least two times. Reductions in the defect density of transistors caused firms to value integration over the performance of individual components such as resistors and capacitors. Similarly, increases in the number of transistors per chip (i.e., Moore's Law) caused the lower power consumption of MOS and CMOS ICs to become more important than the higher speeds of bipolar ICs. Third, the tradeoff between performance and development costs were also impacted on by the increases in the number of transistors per chip at least two times. Increases in the number of transistors per chip enabled microprocessors to provide an intermediate solution between digital logic bipolar IC families and semi-custom ICs. Further increases in the number of transistors per chip have continued to change this tradeoff between performance and development cost where the latest product class is SoC.

In addition to the design tradeoffs that are inherent in the product design hierarchy, the exact timing of the discontinuities has depended on how firms use these improvements to rethink their products and customers. For products, firms were forced to rethink the material, transistor, and system designs and thus go back up the product design hierarchy several times. 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 and electronic watches made it possible for MOS and CMOS designs to diffuse before their performance had reached the level of the previous product class. The demand for various types of low-volume equipment made it possible for microprocessors to diffuse before their performance had reached the level of central processing units in mainframe or mini-computers.

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, although the impact of improvements in semiconductor equipment on semiconductor processes sounds similar to the impact of components on systems, the use of product design and customer choice hierarchies and the concept of design tradeoffs enable the proposed model to represent the phenomenon of technological change at a much deeper level. For similar reasons this paper also goes beyond Sahal's (1985) focus on "scaling" and Clark's (1985) focus on the interaction between product and process designs. Changes in scale were just one way in which the tradeoffs were changed and it was not just specific innovations in processes that drove improvements in products (Clark, 1985), it was improvements in the process equipment that continuously changed the design tradeoffs in semiconductors and this required firms to move back up *both* the product design and customer choice hierarchies multiple times.

By linking movements back up the product design hierarchies with new product classes and thus technological discontinuities, this paper also illuminates some of the issues associated with a modularity trap (Chesbrough and Kusunoki, 2001). Firms that were slow to move from discrete components to ICs and from bipolar logic to MOS logic families or microprocessors focused too much on the modularity of the existing product class. The new product classes not only sometimes destroyed the existing definition of modularity, product classes such as microprocessors or sub-product classes such as MOS or CMOS semi-custom ICs defined new forms of modularity.

With respect to dominant designs, this paper extends Suarez and Utterback's (1995) concept of a dominant design as a design path. For example, because many of the improvements in processes used to make the planar transistors built upon many previous processes for silicon transistors, each of them can be interpreted as moves down the product design hierarchy and together they can be considered a dominant design for silicon transistors. Similar arguments can be made for germanium transistors and dimensionless, scalable design rules for MOS and CMOS semi-custom ICs where this paper's characterization of how dimensionless, scalable design rules emerged agrees with much of the research on modular design and vertical disintegration (Langlois, 1993; Brusoni and Prencipe, 2001).

The discussion of dominant designs within the product class "combinations of bipolar ICs and discrete devices" also highlights the advantage of this paper's definition of a dominant design. Although this paper was not able to define a dominant design for several sub-product classes such as resistor-transistor logic families and linear and custom ICs, moving back to the level of product class made it possible to define TTL's digital IC logic family as a dominant design for the entire product class. Efforts to better understand the sources of competitive advantage encourage us to look for dominant designs at lower levels in the product design hierarchy such as Fairchild's DTL 920 series and TI's TTL 7400 series (Borrus, 1987). However, we should not expect that all dominant designs can be defined at the same level in the product design hierarchy in the same way that competitive advantage is not always determined at the same level in this hierarchy.

These results suggest that defining a dominant design in terms of a path will help clarify the role of dominant designs in the competition between firms in many industries including the semiconductor industry. The inability to define a dominant design or find a link between one and the number of firm exits or specific winners in many industries (Klepper, 1997) makes this an important issue. For example, it is likely that further sub-divisions of the product classes in Table 1 into for example types of memory, logic, and semi-custom ICs would probably provide additional insights into the sources of success for the leading semiconductor providers. Other industries will probably also benefit from such an analysis.

The dynamic nature of this paper's characterization of dominant designs as a design path complements Murmann and Frenken's (2006) characterization of dominant designs as core components with stable interfaces and their use of Polanyi's (1962) operational principle to define the similarities and differences between designs. In terms of representing technological change, Suarez and Utterback's (1996) emphasis on a dominant design path enables us to better capture the dynamic nature of dominant designs than one that emphasizes stable interfaces; Murman and Frenken's definition is probably more appropriate for understanding competition at a single point in time.

The operational principle helps us to better understand the similarities and differences within for example bipolar ICs, memory ICs, and processors and thus the dominant design path for each product class. Combined with the concept of movements down both the product design and customer choice hierarchies, the operational principle can help us better understand the evolution of technology, markets, and competition within a single product class. On the one hand, the emergence of sub- and sub-sub-product classes can be interpreted as a splintering of movements down the product design and customer choice hierarchies and the emergence of multiple design paths where different firms have tended to dominate various niches within the customer choice hierarchy (i.e., horizontal disintegration). On the other hand, network effects can cause a specific design to provide a firm with a competitive advantage in a specific market segment. In the semiconductor industry, this occurred in digital IC logic families for TI and in processors for many firms including Intel, TI, and Qualcomm.

6. References

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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 primarily military)
Combinations of bipolar ICs and discrete devices	Early 1960s	Change in system design	No changes (still primarily military)
Combinations of MOS ICs and discrete devices	Early 1970s	Changes in transistor design	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
SoC (System on Chip)	Early 2000s	Change in system design	Unclear

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

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

New Product Class (emphasis on underlined terms)	Technological Improvements at Lower Levels in the Product Design Hierarchy	Eventual Impacts of Technological 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 drove emergence and diffusion of MOS ICs, CMOS ICs, microprocessors, and SoC	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 (lower with microprocessors and SOC) more important than the efficient use of silicon space
SoC (System on Chip)		

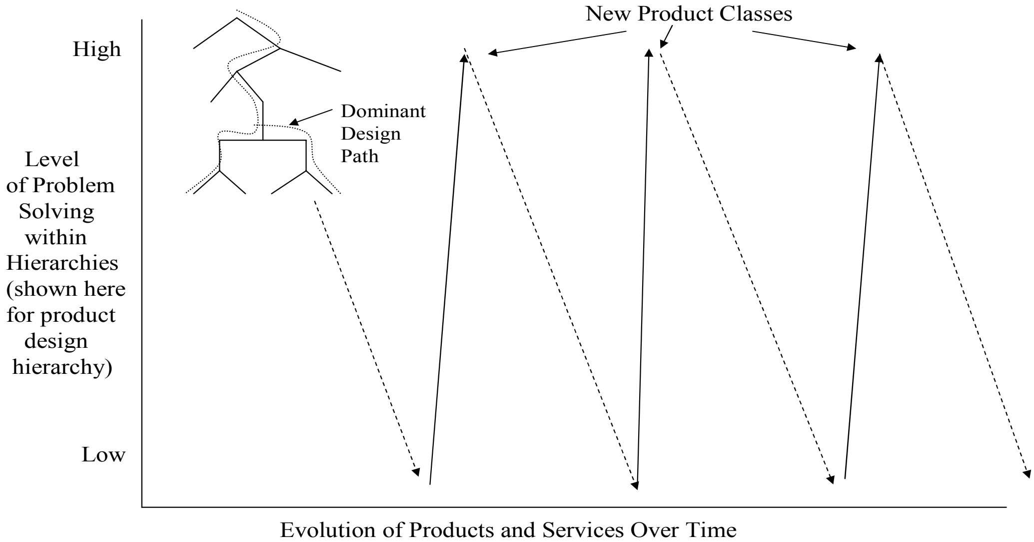
IC: integrated circuit; MOS: Metal-Oxide Semiconductor; CMOS: complementary MOS. Sources: (Bass and C. Christensen, 2002; Borrus, 1987; Malerba, 1985; Reid, 1985; Riordan and Hoddeson, 1997; Tilton, 1971)

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

Product Class (emphasis on underlined terms)	Dominant Design (defined as alternative designs or defining sub-problems in a modular way)
Combinations of discrete germanium bipolar transistors and discrete devices	Dominant alternative design: Diffusion process and diffused transistor
Combinations of discrete silicon bipolar transistors and discrete devices	Dominant alternative design: Planar process and transistor
Combinations of Bipolar ICs and discrete devices and their sub-product classes: 1. Digital IC logic families a. RTL (Resistor-Transistor Logic) b. DTL (Diode- Transistor Logic) c. TTL (Transistor-Transistor Logic) 2. Linear ICs 3. Custom (and semi- custom) ICs: many types	Dominant modular designs for sub-product classes: 1. Digital IC logic families: a. none b. Fairchild's 920 series c. Texas Instrument's (TI) TTL 7400 series 2. Linear ICs: none due to little standardization 3. Custom ICs: none due to little standardization
Combinations of MOS ICs and discrete devices	Dominant modular designs: 1. memory ICs: many designs (see text) 2. logic ICs: TI's chip families 3. semi-custom ICs: dimensionless, scalable design rules
Combinations of CMOS ICs and discrete devices	
Combinations of a microprocessor, memory, and discrete devices	Dominant modular designs: Intel's microprocessor in PCs. Other designs for other applications

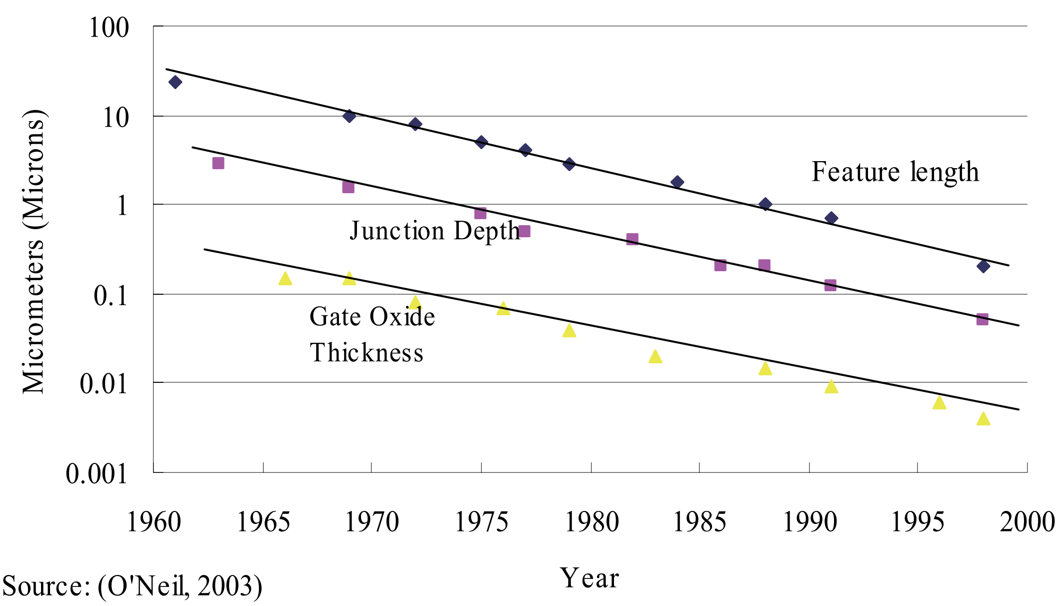
Sources: (Tilton, 1971; Braun and S. MacDonald, 1982; Malerba, 1985; Borrus, 1987)

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



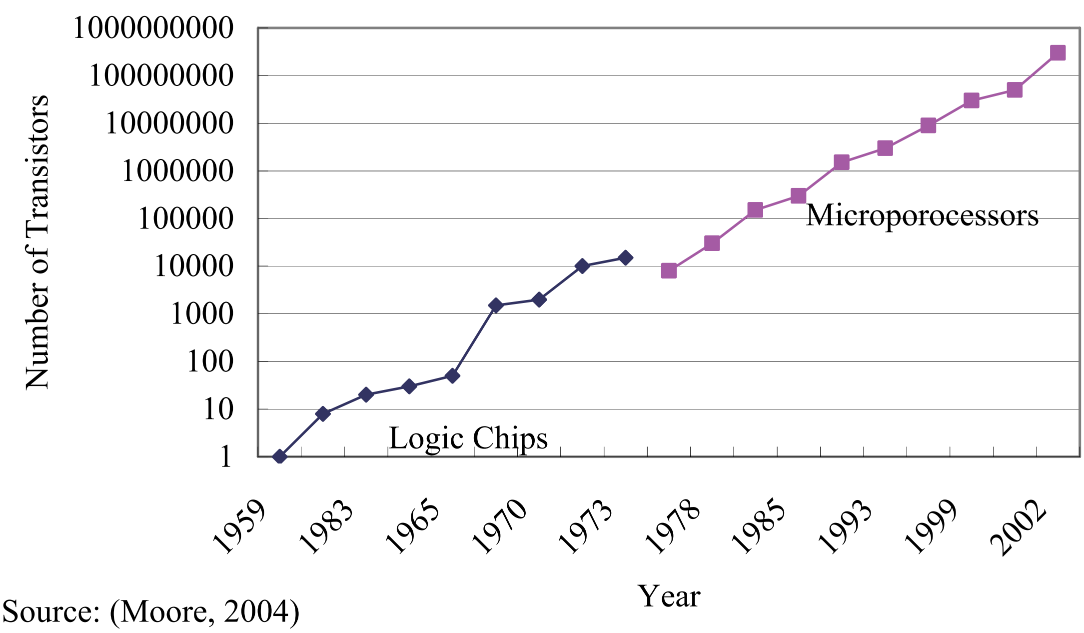
Note: Dotted lines represent movements down the hierarchies and solid lines represent movements back up the hierarchies

Figure 2. Declining Feature Size



Source: (O'Neil, 2003)

Figure 3. Number of Transistors Per Chip



Source: (Moore, 2004)