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Systems, Components and Technological Discontinuities: The Case of the Semiconductor Industry

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Research Paper

Systems, Components and Technological Discontinuities: The Case of the Semiconductor Industry

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ABSTRACT This paper uses the semiconductor industry to describe a model of technological change that sheds light on the mechanism by which many technological discontinuities occur. The model combines two arguments: (1) incremental improvements in a system's components impact on the performance and design of systems; and (2) these incremental improvements in components can lead to discontinuities in system design through their impact on the design tradeoffs that are inherent in all systems. Components are defined loosely as any subsystem in a nested hierarchy of subsystems where the most important component in the semiconductor industry is semiconductor manufacturing equipment. Improvements in this equipment and the processes they are used in have changed (and continue to change) the tradeoffs that firms make in their choices of semiconductor materials, transistor designs and system designs, and thus led to a number of technological discontinuities. The model is described using the discontinuities that are the most widely emphasized in histories of the semiconductor industry.

KEY WORDS: Technological discontinuities, dominant designs, components, hierarchies

1. Introduction

In spite of the recognized importance of technological discontinuities both in the business press and in the existing literature on technological innovation, the three most widely used models of industry evolution do not directly address them. Technological discontinuities are considered an exogenous variable in the product life cycle model (Abernathy and Utterback, 1978; Utterback, 1994; Klepper, 1997), Anderson and Tushman's cyclical model of technological change (1990) and Christenson's model of disruptive change (1997). Instead, these models and those that are built on top of them (Teece, 1986; Henderson and Clark,

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1990; Afuah and Bahram, 1995; Adner, 2002; Suarez, 2004) primarily focus on the mechanisms by which incumbents succeed or fail in these technological discontinuities.

The lack of models that directly address technological discontinuities limits our ability to understand how industries form and evolve. This is a particularly large limitation since it appears that the frequency of discontinuities (Gilder, 2000; Kurzweil, 2005; Kressel and Lento, 2007) is increasing. Without models that directly address the potential sources of technological discontinuities, how can entrepreneurs, governments, research institutions, firms and universities understand the formation and evolution of industries and how this evolution may impact on the design of systems? For universities, how can they help their students understand how existing industries evolve and how new ones may emerge unless they directly address the mechanisms through which technological discontinuities occur?

This paper introduces a model that is a first step towards better understanding the mechanisms by which many technological discontinuities occur while at the same time representing the emergence of dominant designs. Two key aspects of the model are how incremental improvements in a system's components impact on the performance and design of systems and how these incremental improvements can lead to discontinuities in system design through their impact on the design tradeoffs (Rosenberg, 1963, 1969; Alexander, 1964; Dosi, 1982; Sahal, 1985) that are inherent in all systems. A third key aspect of this model is the concept of product design and customer choice hierarchies (Alexander, 1964; Clark, 1985). The concept of hierarchies enables one to consider how new products reinforce or overturn existing designs (Henderson and Clark, 1990) or linkages with customers (Abernathy and Clark, 1985; Christensen, 1997). Large movements up the product design hierarchy overturn existing designs and are defined as technological discontinuities while large movements down this hierarchy reinforce existing designs and are defined as a dominant design path, thus mimicking Anderson and Tushman's cyclical model of technological change (1990). This paper's model includes the concept of dominant designs because the existing literature strongly emphasizes a distinction between them and technological discontinuities (Anderson and Tushman, 1990; Murmann and Frenken, 2006) and this paper focuses on a definition of them that is consistent with Suarez and Utterback's emphasis (1995) of multiple design decisions within Clark's product design hierarchies (1985).

It is argued that the emergence of many discontinuities is driven by incremental improvements in components where it is assumed that components can be defined for any nested hierarchy of subsystems (NHOS). All products, including basic materials such as glass and chemicals can be represented as an NHOS in which all inputs, even equipment, are defined as components (Simon, 1962). Although other scholars have linked radical innovations in components with radical or modular innovations in systems (Tushman and Murmann, 1998; Malerba *et al.*, 1999; Lee and Veloso, 2008), this paper focuses on *incremental* improvements in components and how they drive changes in a system's design tradeoffs (Rosenberg, 1963, 1969; Alexander, 1964; Dosi, 1982; Sahal, 1985) and thus can lead to technological discontinuities in systems. Reinterpreting Christensen's concept of technology overshoot (1997) as changes in the tradeoffs that users make between price and different measures of performance (Adner, 2002), incremental improvements in components can change the tradeoffs that both users and designers make with respect to systems. Large changes in these design tradeoffs can require firms to redesign the systems and sometimes consider new customers, which reflect movements back up the product design and customer choice hierarchies, respectively.

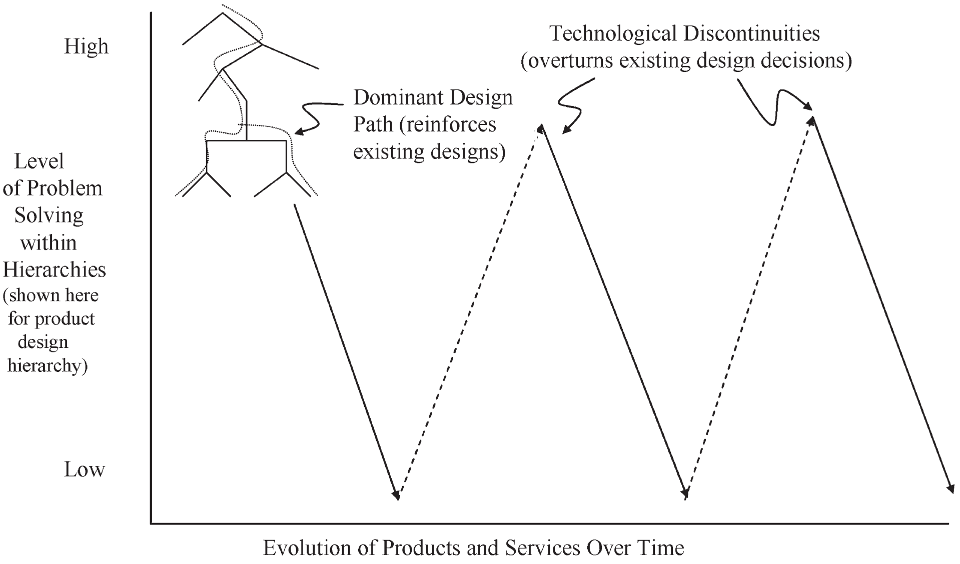
This paper uses the semiconductor industry to demonstrate this model of technological change. Like other industries for which the model has been applied (Funk, 2007, forthcoming), the semiconductor industry is an appropriate industry to apply the model due to the large number and variety of technological discontinuities and the key role that improvements in one component in the NHOS for semiconductors, the equipment that are used to manufacture them, has played in fostering these technological discontinuities. Improvements in this equipment and the processes they are used in have changed the tradeoffs that firms have made in their choices of semiconductor materials, transistor designs and system designs. The model is described using the discontinuities that are the most widely emphasized in histories of the semiconductor industry. 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 concept of hierarchical decision making in complex systems (Alexander, 1964; Simon, 1996) and on Clark's use of this concept (1985) to represent the translation of customer needs into products over time in terms of customer choice and product design hierarchies. A customer choice hierarchy represents a firm's perception of the ways in which customers make choices in a market and thus how firms define market segments and the problems to be solved in each segment. A product design hierarchy defines the methods of problem solving for the market segments and it includes both alternative choices about technology and definitions of sub-problems in terms of independent modules (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).

Looking at these hierarchies from a broad perspective, the introduction of new products and services reflect movements both down and up the hierarchies of product design and customer choice as depicted in Figure 1. Large movements down the hierarchies reinforce existing designs (Henderson and Clark, 1990) or linkages with customers (Abernathy and Clark, 1985; Christensen, 1997) while large movements back up the hierarchies overturn them and are often called technological discontinuities. Technological discontinuities that are primarily due to movements back up the customer choice hierarchy are sometimes called niche innovations (Abernathy and Clark, 1985) or disruptive technologies (Christensen, 1997) while ones that are primarily due to movements back up the product design hierarchy are often called revolutionary or architectural innovations (Abernathy and Clark, 1985; Henderson and Clark, 1990).

Looking at the movements down the hierarchies from a more detailed perspective, following a technological discontinuity and a period of intense technical variation (Tushman and Anderson, 1986) customer segments begin to emerge and design activity moves from higher-level to lower-level problem solving (Tushman and Murmann, 1998; Murmann and Frenken, 2006) where these movements down the hierarchies reinforce the decisions made at higher levels in the hierarchies. The amount of movement down the hierarchies reflects the degree of similarity between different firm's methods of segmenting customers



Note: Within the dominant design path, the sloping lines represent alternative choices about technology and the straight ones the definition of sub-problems in terms of independent modules.

Figure 1. Evolution of level of problem solving in industry over time. *Note:* Within the dominant design path, the sloping lines represent alternative choices about technology and the straight ones the definition of sub-problems in terms of independent modules.

(customer choice hierarchy) and between different firm's product designs in both the choices of technologies and the definitions of sub-problems (product design hierarchy) (Clark, 1985).

The choice of technologies and the definition of sub-problems in terms of independent modules represent a dominant design path for the industry, which is consistent with the first half of Suarez and Utterback's definition (1995): "a dominant design is a specific path along an industry's design that establishes dominance among competing paths". As shown in the upper left-hand side of Figure 1, the choice of a specific design alternative defines a single path while the definition of sub-problems in terms of independent modules defines the emergence of multiple and relatively independent design paths. Defining a dominant design as a path(s) is consistent with Dosi's notion of technological trajectories (1982), which define the direction of advance within a technological paradigm (see below) in terms of both performance and design decisions. It is also consistent 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 subsystems and components within a system (Tushman and Murmann, 1998; Murmann and Frenken, 2006).

Depending on the industry, dominant designs will differ in terms of both: (1) the relative importance of alternative designs and defining sub-problems in terms of independent modules; and (2) the number of levels to which a dominant design path proceeds down the product design hierarchy. Independent modules often emerge (Sanchez and Mahoney, 1996) and lead to vertical disintegration (Langlois, 1992; Langlois and Robertson, 1992) where their emergence depends on the creation of ‘‘design rules’’ that determine how these independent modules interact (Baldwin and Clark, 2000; Brusoni and Prencipe, 2001). The number of levels to which a dominant design path proceeds down the design hierarchy 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 concept of ‘‘operational principle’’ (1962) 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 may also depend on the extent of common needs among users (Suarez and Utterback, 1995) and the number of sub-markets in the overall industry (Klepper, 1997).

Looking at the movements back up the hierarchies from a more detailed perspective, large movements back up them are defined as technological discontinuities. The central argument in this paper is that many of these discontinuities are the result of technological improvements in components (i.e. at lower levels in an NHOS). Improvements in these components change the ‘‘design tradeoffs’’ for systems (i.e. higher levels in an NHOS) and thus require firms to move *back up* the hierarchies of product design and/or customer choice at the higher level in the NHOS.

One theoretical basis for this argument is that economic, marketing and information science scholars have long used the concept of tradeoffs between cost and various measures of performance to define specific market segments and the demand for specific products and services in each segment (Green and Wind, 1973; Lancaster, 1979; Adner, 2002). These segments and the tradeoffs users make in each segment can be considered part of Clark’s customer choice hierarchy (1985). Engineers combine such information about customer needs with information about the tradeoffs between different engineering variables in order to consider tradeoffs between different types of components and different types of materials, processes and equipment for these components (Rosenberg, 1963, 1969; Dosi, 1982; Sahal, 1985) all of which can be considered part of Clark’s product design hierarchy (1985). A casual look at any engineering journal will find figures that display the tradeoffs between different engineering variables albeit in a simplified manner due to the two-dimensional nature of figures. Formal engineering techniques such as value engineering, quality function deployment (Cohen, 1995) and design structure matrixes (Ulrich and Eppinger, 2007) also provide insights into how engineers translate the information about tradeoffs between engineering variables and those that customers make between price and performance into engineering decisions about components, materials and processes.

However, these tradeoffs are not constant. Incremental improvements at lower levels in an NHOS can change the ‘‘design tradeoffs’’ for higher levels in an NHOS and thus require firms or even societies to move *back up* the hierarchies of both product design and customer choice at the higher level in the NHOS. Although other scholars have noted that radical innovations in components can lead to modular innovations in systems (Tushman and Murmann, 1998; Malerba *et al*., 1999), this paper argues that incremental improvements at lower levels in an NHOS can explain the emergence of many discontinuities, including radical, modular and architectural ones, through the impact of these incremental improvements on the design tradeoffs that are inherent in any NHOS.

These changes in tradeoffs represent a more general mechanism of technology ‘‘overshoot’’ in Clayton Christensen’s concept of disruptive technologies (1997). Disruptive technologies often occur when an existing technology “overshoots” existing customer needs where this paper argues that such “overshoots” represent changes in the tradeoffs customers make between performance and price or between different measures of performance (Adner, 2002). In this paper’s proposed model, however, the changes in design tradeoffs can occur at both an internal (engineering tradeoffs internal to the product) and an external (tradeoffs made by customers) level and in some cases such changes can ripple through multiple levels in an NHOS. 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 them to include suburbs and extended commuting. Similarly, improvements in transportation, communication and computer systems (shown below to have come from improvements in components) in the last 10 years have changed the tradeoffs for production systems and one result has been that some think that the “World is Flat” (Friedman, 2005).

3. Research Methodology

I 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, encyclopedic histories and the two main industry journals (*Electronics* and *Electronic Business*), some of which are referenced below. Through analysis of this literature, I identified the: (1) technological discontinuities; (2) movements down the product design and customer hierarchies in terms of the choice of alternative designs, definitions of sub-problems and customer segments in each technological discontinuity; (3) technological improvements at lower levels in the NHOS (i.e. improvements in equipment) that have changed the design tradeoffs thus leading to movements back up these hierarchies; and (4) the dominant design path for each technological discontinuity.

4. Brief History of the Semiconductor Industry

Table 1 summarizes the technological discontinuities that have occurred in the semiconductor industry and the movements back up the product design and customer choice hierarchies that they represent. Taking a broad view of the electronics industries, there have been large movements back up the product design hierarchy for semiconductors in terms of changes in material, transistor and electronic system design. There were changes in materials from germanium to silicon in the 1950s and in transistors from bipolar to MOS (Metal-Oxide Semiconductor) and later CMOS (Complementary MOS) in the 1970s. There have also been changes at the electronic systems level from “combinations of discrete devices” to “combinations of ICs (integrated circuits) and discrete devices” and later to combinations of more complex ICs such as memory, microprocessors, application specific integrated circuits (ASICs) and application specific standard products (ASSPs). The MOS and CMOS ICs and microprocessors also involved changes in the customer choice hierarchies in that there was a different set of initial customers (listed in parentheses) for MOS chips (calculators, computer memory), CMOS chips (digital watches) and microprocessors (low-volume equipment) than there were for the previous generations of semiconductors.

Table 1. Technological discontinuities and their movements back up the hierarchies for the semiconductor industry

Technological discontinuity	First introduced	Movements back up the hierarchies	
		Product design	Customer choice (early users)
Germanium bipolar transistor	Early 1950s	Change in material, transistor and system design (from vacuum tubes)	Military and later transistor radios
Silicon bipolar transistors	Mid-1950s	Change in material	No changes (still primarily military)
Bipolar integrated circuits (ICs)	Early 1960s	Changes in system design	No changes (still primarily military)
Metal-Oxide Semiconductor ICs	Early 1970s	Changes in transistor design	Calculators, computer memory
Complementary MOS ICs	Mid-1970s	Changes in transistor design	Watches and calculators
Microprocessors	Mid-1970s	Changes in system design	Aviation, medical, test equipment
Application specific ICs	Mid-1980s	Changes in system design	Many products/systems
Application specific standard products	Mid-1990s	Changes in system design	Many products/systems

Sources: Tilton (1971), Braun and MacDonald (1982), Malerba (1985), Borrus (1987), Turley (2002), Rowen (2004).

Table 2 summarizes the technological improvements at lower levels in the NHOS that have driven changes in the design tradeoffs and thus movements back up the product design and customer choice hierarchies and the emergence of technological discontinuities in the semiconductor industry. The middle column defines the improvements in equipment that have driven many of the technological discontinuities in the semiconductor industry. This equipment has reduced defect densities (IC Knowledge, 2005) and feature sizes (Figure 2) where 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 (Flamm, 2004). The right column summarizes the impact of these improvements on the design tradeoffs that are inherent within the semiconductor industry. These tradeoffs include those between manufacturing cost, chip density, speed, power/heat dissipation and development cost. Changes in these tradeoffs required firms to move back up the product and customer choice hierarchies and led to the technological discontinuities that are summarized in Table 1.

While Tables 1 and 2 are concerned with movements back up the product design and customer choice hierarchies and the technological discontinuities that they represent, Table 3 is concerned with the movements down these hierarchies. It lists some of the design decisions that constitute a dominant design path for each technological discontinuity and whether these design decisions represent alternative choices of technology or defining sub-problems in terms of independent modules. The design decisions that are defined as alternative choices of technology include different types of transistor (and their supporting processes) designs and the design decisions that are defined in terms of independent

Table 2. Technological improvements changing the design tradeoffs and driving moves back up the hierarchies for the semiconductor industry

Technological discontinuity	Technological improvements at lower levels in the NHOS (i.e. improvements in process equipment)	Eventual impacts of technological improvements on design tradeoffs at higher levels in the NHOS and thus emergence of technological discontinuities at higher levels in the NHOS
Silicon bipolar transistor	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
Bipolar IC	Improvements in equipment that led to 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 and also lower yields
MOS ICs CMOS ICs	Improvements in equipment that led to reductions in feature size and the increasing number of transistors on a chip	Increasing number of transistors made the lower heat production of MOS (and later CMOS) more important than the faster speeds of bipolar ICs
Microprocessors ASICs		Reductions in feature size decreased the cost of transistors and thus made the lower development costs of microprocessors and ASICs more important than the efficient use of silicon space
ASSPs		Increases in the number of transistors per chip increased the development costs and thus the need to amortize these costs over larger production volumes

IC= integrated circuit; MOS= Metal-Oxide Semiconductor; CMOS= Complementary MOS; NHOS= nested hierarchy of subsystems.

Sources: Tilton (1971), Malerba (1985), Reid (1985), Borrus (1987), Riordan and Hoddeson (1997), Turley (2002), Rowen (2004).

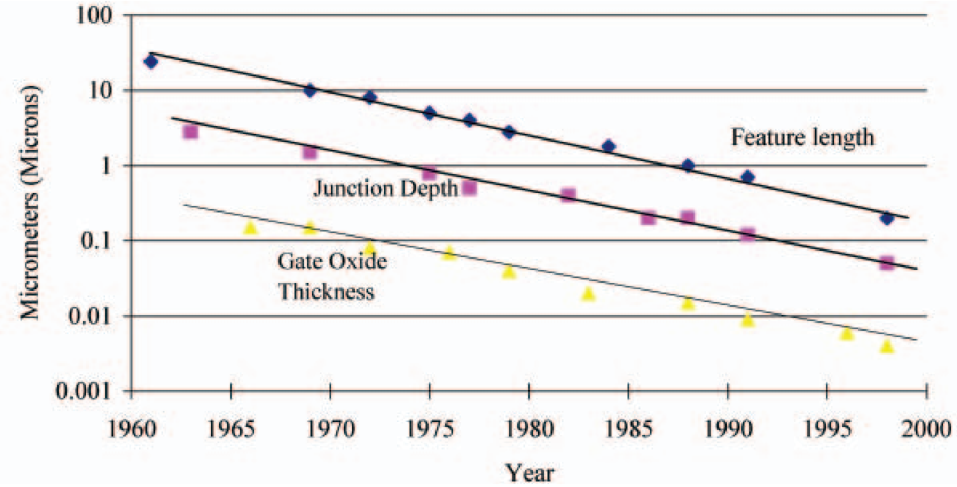


Figure 2. Declining feature size. *Source:* O'Neil (2003).

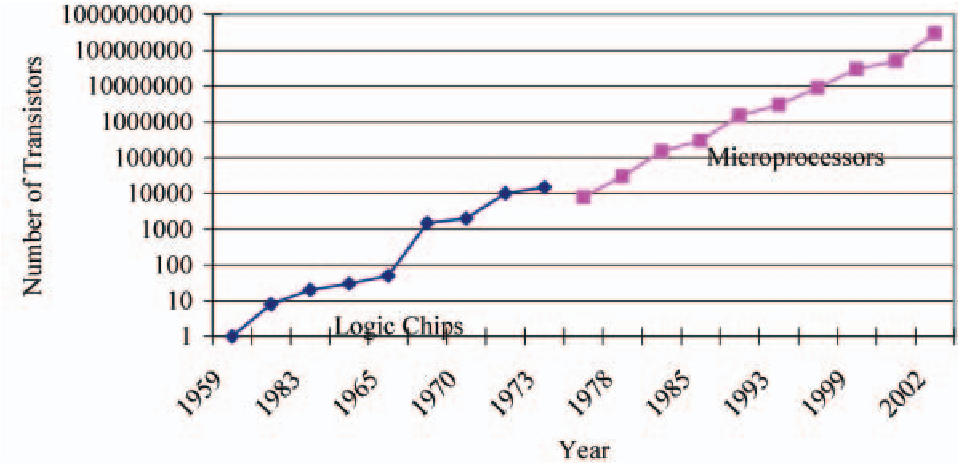


Figure 3. Number of transitions per chip. *Source:* Moore (2004).

modules represent different types of design rules for how bipolar digital IC logic families, microprocessors, ASICs and ASSPs operate in electronic systems.

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 condition until 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 (Tilton, 1971; Braun and MacDonald, 1982; Riordan and Hoddeson, 1997).

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 (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 2 and the emergence of the second technological

Table 3. Dominant design paths for the major technological discontinuities in the semiconductor industry

Technological discontinuity	Dominant design path (designs associated with alternative designs and/or defining sub-problems in a modular way)
Germanium bipolar transistors	Dominant alternative design: diffusion process and diffused transistor
Silicon bipolar transistors	Dominant alternative design: planar process and transistor
Bipolar integrated circuits (ICs):	1. Logic families
1. Digital IC logic families	Dominant alternative designs: TTL (transistor–transistor logic) Dominant modular designs: inputs and outputs for Texas Instrument's (TI) TTL 7400 series
2. Linear and semi-custom ICs	2. Linear and semi-custom ICs: none due to little standardization
Metal Oxide Semiconductor (MOS) ICs	Dominant alternative designs: poly-silicon gates and multiple metal layers
Complementary MOS (CMOS) ICs	Dominant modular designs: inputs and outputs for specific generations of memory ICs and specific logic families
Microprocessors	Dominant modular designs: Intel's 8080, Motorola's 6500 series and other designs for other applications
Application specific integrated circuits (ASICs)	Dominant modular designs: Mead and Conway's high-level symbolic design methods, dimensionless and scalable design rules, standard arrays and libraries, CAD design tools
Application specific standard products (ASSPs)	Dominant modular designs: different designs for different system applications

Sources: Tilton (1971), Braun and MacDonald (1982), Malerba (1985), Borrus (1987), Turley (2002), author's research.

discontinuity 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) (Tilton, 1971; Bassett, 2002) 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) used a single-crystal growth process to create the world's first silicon transistor in 1954 (Tilton, 1971; Braun and MacDonald, 1982), 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 (Tilton, 1971; Braun and MacDonald, 1982; 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 (Tilton, 1971; Malerba, 1985). 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 (i.e. the planar process) can be considered a dominant design for silicon transistors (Anderson and Tushman, 1990). Although the military's funding of this research enabled it to define the specifications for these transistors and thus the US military's needs initially defined the market segments and thus the customer choice hierarchy for discrete silicon transistors, the emergence of other applications in computers, broadcasting and telecommunications caused this customer choice hierarchy to become more complex and differentiated.

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 technological discontinuity called ICs in the early 1960s (see Table 1). These improvements caused Jack Kilby of Texas Instruments to recognize that the advantages of producing resistors, capacitors and transistors on the same substrate material (i.e. silicon) in a so-called bipolar integrated circuit (IC) would *eventually* outweigh the advantages of using the optimal material for capacitors (Mylar) and resistors (carbon) in discrete components. It also caused Robert Noyce of Fairchild to recognize that the advantages of using a metal layer to connect multiple transistors on a single IC chip (and thus not connecting individual transistors with wires) would *eventually* outweigh the disadvantages of lower yields from placing multiple transistors on a single IC chip. The key word is *eventually*. While other researchers were focused on the day-to-day problems of how to best design and fabricate capacitors, resistors and transistors according to existing tradeoffs, Jack Kilby and Robert Noyce considered the implications of improvements in semiconductor manufacturing equipment for how combinations of these capacitors, resistors and transistors would be best designed in the future (Tilton, 1971; Reid, 1985; Riordan and Hoddeson, 1997; Murphy *et al.*, 2000).

Subsequent improvements in processes and their associated equipment have reduced feature sizes by more than 100 times and defect densities by more than 1,000 times in the last 45 years. The implications of these trends were noted by Gordon Moore in his famous 1965 article in *Electronics Magazine* that led to the term ''Moore's Law''. Slightly modified from Moore's original figure, Figure 4 shows the evolution in the ''optimal'' level of integration (see U-shaped curves) over time where reductions in feature size and defect density pushed this optimal level of integration towards the lower-right part of the figure. The optimal level of integration represents the tradeoffs between the benefits and costs of increased integration that are discussed in the last paragraph and that were analyzed by Robert Noyce and Jack Kilby as they were developing the first ICs. Their efforts reside in the upper left-hand corner of Figure 4 in the move from one to multiple transistors on a single IC.

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 hierarchy. However, the increasing number of applications for ICs in the military and other industries caused a variety of ICs to emerge (see Table 3) that can be interpreted as an increasing breadth and depth to the customer choice hierarchy. This increasing breadth and depth also increased the number and complexity of design paths where the application (Murmann and Frenken, 2006) of Polanyi's operational principle (1962) helps us understand the similarities between these different paths (see Figure 1). Digital ICs (which were demanded by the military and later computer markets), linear ICs and also semi-custom ICs

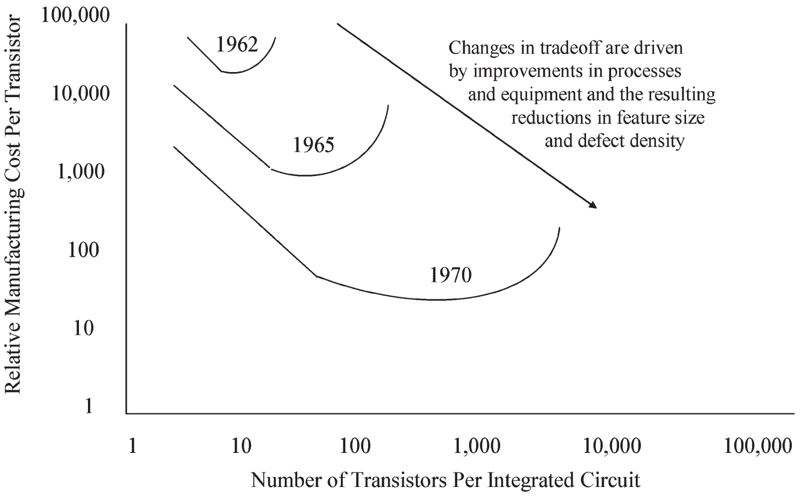


Figure 4. Evolution in the tradeoff (reflected in U-shaped curves) between the benefits and costs of integration in integrated circuits. *Source:* Adapted from Moore, G., Cramming more components onto integrated circuits, *Electronics*, 19 April 1965.

emerged as the three main types of ICs 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 or semi-custom ICs (Malerba, 1985) thus causing greater movements down the product design hierarchy (i.e. dominant design path) 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, that is, open design rules, emerged through competition between different IC logic families. A dominant design for these logic families can be defined in terms of both choices of alternative technologies and the definition of sub-problems in a modular way. Transistor–transistor logic (TTL) emerged as the choice of technology for these logic families and the inputs and outputs of Texas Instrument's (TI) 7400 series defined the design rules for how these logic chips interfaced with each other and other ICs in an electronic system (Borrus *et al.*, 1983; 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 technological discontinuities (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. US 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 logic chips for the MOS market (Malerba, 1985) and they represented more than 50 percent of Japanese IC production in the early 1970s (Watanabe, 1984). Their success in these logic chips enabled them to partly redefine the inputs and outputs for these logic chips and thus a new form of dominant design for them (see Table 3).

Memory ICs for computers also drove demand for MOS ICs particularly in the USA and like calculators they represented a new market for semiconductors and thus they required semiconductor manufacturers to move back up the customer choice hierarchy. Improvements in processes and the equipment used in these processes finally made it possible to manufacture memory chips that provided a higher ratio of performance to costs than magnetic core memory (Jackson, 1998; Murphy *et al.*, 2000). The success of Intel's 1K DRAM (Dynamic Random Access Memory) was followed by a doubling in the size of DRAMs every 1–2 years and the introduction of many variations of memory. These 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, 1998). This increased variation can be interpreted as increased breadth and depth in the customer choice hierarchy of memory applications and the emergence of many design paths where each of the designs operate under the same "principle" of memory storage (Polanyi, 1962; Murmann and Frenken, 2006). Nevertheless, different types of dominant designs emerged for some of these memory chips or sometimes only for a single generation in a memory chip (Utterback, 1994).

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, 1992) 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 (Riordan and Hoddeson, 1997; Langlois and Steinmueller, 1999). 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 percent in 1988 to 80 percent in 1994 (Langlois and Steinmueller, 1999). Many of these improvements in CMOS transistors involved the use of common processes among firms, which can be defined as a dominant design path (see Table 3). The expansion in the number of applications for MOS and CMOS ICs reflected an increased breadth and depth to the customer choice hierarchy for them.

4.4. Microprocessors

At the same time that 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) were impacting on the tradeoffs inherent in the use of bipolar, MOS and CMOS transistors in the 1970s, these same improvements were also impacting on the tradeoffs inherent in the design of electronic systems (see Table 2). The increasing number of transistors on a chip finally reached the level at which a computer, that is, microprocessor, could be economically placed on a single IC chip and this microprocessor is defined as the sixth technological discontinuity in the semiconductor industry (see Table 1). Since markets other than the ones driving the demand for bipolar, MOS or CMOS 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 where the emergence of programming tools such as assemblers and higher-level programming languages such as PASCAL expanded the advantages of microprocessors (Jackson, 1997).

Although microprocessors are now customized for a large variety of different applications, microprocessors and a low-end version of them called micro-controllers were initially marketed as a general solution for many types of electronic systems where the network effects associated with programming languages, assemblers and hardware design caused dominant designs to emerge for some of them. Intel's 8080 and Motorola's 6500 series had emerged as dominant designs for microprocessors by the late 1970s where the interaction between the hardware, assemblers and programming languages was defined by design rules that were proprietary to Intel's and Motorola's microprocessors. Similarly Japanese firms became the leaders in low-end micro-controllers for many consumer markets (Borrus, 1987; Gruber, 2000). The key operational principle (Polanyi, 1962;

Murmann and Frenken, 2006) in all of these processors and controllers is programmable semiconductors and the market segments for them represent an increasing breadth and depth to the customer choice hierarchy for microprocessors and micro-controllers.

4.5. Application Specific Integrated Circuits (ASICs)

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 sixth round of changes in the design tradeoffs (see Table 2) and the emergence of a seventh technological discontinuity called ASICs (see Table 1) in the early 1980s. Although some producers of electronic systems had been designing ASICs for their low-volume systems (e.g. computer, telecommunication, instrument and military systems) since the 1960s (Walker, 1992), the increasing number of transistors on a chip (i.e. Moore's Law) enabled ASICs to replace logic chips in many applications since the increasing number of transistors on a chip made it difficult to design logic chips that both used the full extent of integration possible from Moore's Law and that still could be considered "general-purpose ICs" (Mead and Lewicki, 1982; Walker, 1992).

Since ASICs primarily replaced existing semiconductors rather than created new markets, their emergence only required movements back up the product design hierarchy, which involved several new methods of designing ICs (see below). The key operational principle (Polanyi, 1962; Murmann and Frenken, 2006) for these different types of ASICs is semi-custom design and the new markets for them in higher-volume products such as personal computers, cordless telephones and video games (Mead and Lewicki, 1982; Walker, 1992) represent an increasing breadth and depth to the customer choice hierarchy for them.

There are several kinds of ASICs and there are tradeoffs between them and with full-custom ICs (see Table 4). In general, the highest volume applications use full-custom chips followed by standard cell designs and gate arrays for lower volume applications (Posa, 1980; Fields, 1982; Bogle, 1984; Bourbon, 1984; Thomke, 2003). Programmable logic devices (PLDs) emerged as another alternative in the 1990s and more recently System on Chip (SoC). With standard cell designs, design engineers select pre-designed blocks that have increased in complexity as the number of transistors on a chip (i.e. Moore's Law) has

Table 4. Comparison of custom and semi-custom design methods

	Programmable logic device	Gate array	Standard cell	Full custom
Prototype cost	Lowest ($1,000)	Medium	High	Highest (>$50,000)
Prototype time	Lowest (minutes)	Medium	High	Highest (>8 weeks)
Variable cost	Highest	Medium	Lower	Lowest
Complexity, performance	Lowest	Medium	Higher	Highest
Market (2000)	$5.4 billion	$2.7 billion	$9.5 billion	>$10 billion

Source: Thomke (2003).

increased (Fields, 1982). The term SoC is now used when these pre-designed blocks include microprocessors and large blocks of memory (Linden and Somaya, 2003; Thomke, 2003; Rowen, 2004). With gate arrays, a design engineer only customizes the final metal layer(s) in order to determine those transistors that will be connected on the chip (Posa, 1980; Bogle, 1984; Bourbon, 1984).

The level of standardization is taken one step further with so-called programmable logic devices (PLDs). Design engineers can customize these "standard" products in a matter of minutes by connecting specific "fuses"; this was initially done with ultraviolet (similar to EPROMs) and later with electrical signals (similar to EEPROMs) (Cole, 1988; Thomke, 2003). The continued improvements in manufacturing equipment have reduced the cost of silicon space and thus favor the lower development costs of PLDs over the greater transistor density of other semi-custom techniques (Ristelhueber, 1996). Similar factors are at work in the move from relatively simple standard cell designs to SoC (Rowen, 2004).

These different types of ASICs represent different ways to define sub-problems in modular ways for the design of electronic systems. Therefore, the emergence of design rules that determine the interaction between different stages in the design and production of ASICs and electronic systems can be interpreted as the emergence of a dominant design path for each type of ASIC. First, the most successful suppliers of ASICs did not design or manufacture ASICs; instead they sold design tools and databases that were used by electronic system suppliers to design the ASICs. Suppliers of gate arrays and PLDs defined standard arrays and suppliers of standard cell designs defined the libraries of design functions that they offer where the greater success of some arrays and cells (Barney, 1986; Walker, 1992) can be defined as the emergence of a dominant design path.

Second, the emergence of so-called "dimensionless and scalable design rules" enabled the separation between the design and manufacture of ASICs. These rules define geometrical relationships between line widths, material thicknesses, power consumption and speed, and their emergence reduced the need for communication between design and fabrication even as designs had to be updated for smaller feature sizes (Critchlow, 1999; Baldwin and Clark, 2000; Murphy *et al*., 2000; Macher *et al*., 2002). The separation between design and fabrication was also driven by the rising cost of new fabrication facilities that had become a barrier to entry for the new suppliers of ASIC design tools and databases (Macher *et al*., 2002). Furthermore, the emergence of standard CAD tools and the Internet further support the separation between design and fabrication and the separation between suppliers and users of ASIC design tools and databases (Walker, 1992; Macher *et al*., 2002).

4.6. Application Specific Standard Products (ASSPs)

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 seventh round of changes in the design tradeoffs (see Table 2) and the emergence of an eighth technological discontinuity called ASSPs (see Table 1) in the 1990s. The term ASSPs refers to standard IC chips that are designed for a specific system/product and often for a specific standard module in that system/product. Since many of them are microprocessors that are customized for a specific application and often done so using ASIC design techniques, the movements back up the product design hierarchy for them represent differences between them and both microprocessors and ASICs (Walker, 1992; Turley, 2002). Like ASICs, since ASSPs primarily replace existing semiconductors rather than create new markets, their emergence did not involve movements back up the customer choice hierarchy and their diffusion (several examples are described below) represents an increasing breadth and depth to the customer choice hierarchy for them.

Changes in the market for electronic products also contributed towards the emergence of ASSPs. Until the market for personal computers began to grow in the 1980s electronic products that were both complex and produced in high volumes did not exist. Digital calculators and watches were produced in high volumes but by the 1980s did not require the full number of transistors that could be placed on a single IC. On the other hand complex electronic products such as mainframe computers and telecommunication switches were only produced in low volumes and thus were assembled from a combination of ASICs and standard logic chips, microprocessors and memory. The emergence of high-volume digital electronic products has caused firms to design complex ICs for specific products where these ICs are defined as ASSPs.

ICs for personal computers became the largest example of ASSPs as Intel and other firms began to customize processors and other chips for the PC. Intel gradually customized its microprocessors for PCs as the market for PCs grew in the 1980s. Chips and Technologies and Cirrus Logic successfully reverse engineered IBM’s so-called BIOS chips in the early 1980s. As the falling prices for memory chips enabled bit-map displays, other firms such as S3 and Nvidia offered special processors that handled this data and that were compatible with Intel’s microprocessors (Takahashi, 1999). Other ASSPs that supported PCs, that required IC controllers compatible with a specific standard and that dominated a single firm’s sales include those for modems (Lineback, 1987), Ethernet local area networks (Hindin, 1982) and hard disks (McLeod, 1987). The sum total of these design decisions for PCs constitutes a dominant design path for the ASSPs used in PCs.

The importance of open standards and the move to digital technology has also made telecommunications systems, both fixed and mobile, a large market for ASSPs. Examples include ICs for cable modems, ADSL trans-receivers and digital set top boxes for cable systems. In the mobile phone industry, standards and digital technology have also led to an increased usage of ASSPs. The most critical standards are so-called ‘‘air-interface standards’’ that define how signals are transmitted between base stations and mobile phones in a specific frequency band. Qualcomm supplies many of the ASSPs for mobile phones that use a standard called CDMA (code division multiple access). TI is the leading provider of digital signal processors for phones, these processors handle the real-time processing of audio and visual signals in not only mobile phones but also music and video players (Poe, 2003; Roberts, 2003). The sum total of these design decisions constitutes a dominant design path for either fixed or mobile telecommunications.

Further improvements in processes, the equipment used in these processes and the resulting increase in the number of transistors on a chip (see Figure 3) will probably lead to the increased usage of ASSPs, ASICs and in particular one type of ASIC called SoC, and probably the emergence of other technological discontinuities. Candidates for technological discontinuities include configurable processors on an SoC, the customization of such processors for specific applications, the integration of antennas on these chips, the reconfiguration of these chips wirelessly after they have been installed in the field, the use of a broader number of materials on these chips, the placement of test and other laboratories' facilities on a single chip and the smart delivery of drugs via ingested chips. With respect to the latter two cases, a variety of sensors and machines can be placed on a chip and chemicals can be placed in a cavity of a chip where both of these features enable the production of small portable testers and of drugs that can target specific parts of the body and often the infected parts of the body (Rowen, 2004; Roelandts, 2005; Sargent, 2006). This paper's model can help students and managers analyze how these types of discontinuities may emerge.

5. Discussion

This paper uses the semiconductor industry to demonstrate a model of technological change that addresses the mechanisms by which many technological discontinuities occur while differentiating between them and the concept of 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 an NHOS change the design tradeoffs at higher levels in an NHOS 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 2 times. Reductions in the defect density of transistors caused firms to value integration over the performance of individual components such as resistors and capacitors, which led to the emergence of the IC. 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 3 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 technological discontinuities are ASICs and ASSPs.

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 type of transistor design. 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, Malerba *et al*. (1999) describe how a technological discontinuity (microprocessor) in a component (IC) led to a technological discontinuity in a system (computers). The proposed model represents this phenomenon at a much deeper level by describing the interaction between *incremental* improvements in components, design tradeoffs and movements back up product design and customer choice hierarchies for systems where there were *independent* movements back up them for both computers and semiconductors. Incremental improvements in equipment (and the processes they are used in) led to the development of the microprocessor and incremental improvements in microprocessors led to the development of the personal computer. The initial use of microprocessors in calculators and aviation and scientific instruments represents the movements back up the customer choice hierarchy for semiconductor manufacturers and the initial use of PCs by hackers and hobbyists (not covered in this paper) represents similar movements back up the customer choice hierarchies for computer manufacturers (Langlois, 1992). For similar reasons this paper also goes beyond Sahal's focus on ''scaling'' (1985) and Clark's focus on the interaction between product and process designs (1985). 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 equipment that continuously changed the design tradeoffs in semiconductors and thus required firms to move back up *both* the product design and customer choice hierarchies multiple times.

This paper also goes beyond the research cited in the last paragraph by presenting a general model that can be used by students and managers to think about the future. Just as the emergence of microprocessors, ASICs and ASSPs are in retrospect not surprising given the increases in the number of transistors per chip (Moore's Law), it is likely that many of the discontinuities summarized at the end of Section 4.6 will occur. The exact markets and designs, the first customers, the timing, and whether and how incumbents will be able to adapt to these discontinuities are separate questions that can be better addressed when we understand what is technologically driving the emergence of them as possible discontinuities. Students and managers can use this paper's model to create a list of possible discontinuities and then use other concepts/models (Teece, 1986; Anderson and Tushman, 1990; Afuah and Bahram, 1995; Adner, 2002; Suarez, 2004) to address how incumbents should respond to them and/or might fail to effectively respond to them.

With respect to dominant designs, this paper extends Suarez and Utterback's concept (1995) 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 path for silicon transistors. Similar arguments can be made for the other technological discontinuities where both choices of technology and the definition of sub-problems in terms of independent modules constituted these dominant design paths.

By explicitly addressing movements down and up the product design hierarchies and the role of modular design in movements down the product design hierarchy, 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 may have focused too much on the modularity of the existing technology. The technological discontinuities not only often destroyed the existing definition of modularity; they also often defined new forms of modularity that represented a new dominant design path.

Defining a dominant design in terms of a path may help clarify the role of dominant designs in the competition between firms in many industries. 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 possible that more detailed analyses of the dominant design paths for each of the technological discontinuities shown in Table 3 would 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 characterization of dominant designs (2006) as core components with stable interfaces and their use of Polanyi's operational principle (1962) to define the similarities and differences between designs. In terms of representing technological change, Suarez and Utterback's emphasis (1996) on a dominant design path enables us to better capture the dynamic nature of dominant designs than one that emphasizes stable interfaces; Murmann 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, processors and ASICs, and thus the dominant design path for each discontinuity. 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 discontinuity. In particular, an increasing number of markets/applications within a specific technological discontinuity can be interpreted as an increasing breadth and depth in the customer choice hierarchy where different designs are often needed for each market that is defined in the customer choice hierarchy.

Future research should attempt to apply the model to other industries. Computers, mobile phones and other electronic products that use semiconductors are obvious candidates (Funk, 2007, forthcoming). Other candidates are products that are impacted on by improvements in magnetic or optical recording density, in plastics or other engineered materials, in any type of manufacturing equipment or in gene sequencing (Kurzweil, 2005).

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