Systems, Components, and Modular Design:

The case of the U.S. semiconductor industry

by

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Abstract

While existing research on modular designs and vertical disintegration primarily focuses on a single industry, this paper looks at the interaction between modular design and vertical disintegration in both electronic system (e.g., computers, telecommunications, broadcasting) and electronic component (i.e., semiconductors) industries. It uses data on the top ranked firms in the U.S. semiconductor industry to show how this interaction has evolved over the last 50 years in two ways. First, it shows how the development of "industry standard" components for use in "open-system" modular designs of electronic systems facilitated vertical disintegration between electronic systems and component suppliers. Second, it shows how vertical disintegration in electronic components (between semiconductor design houses and foundries) in the 1980s strengthened modular designs at the electronic systems level and further encouraged vertical disintegration between system and component suppliers by reducing the entry barriers for design houses and foundries. These results have implications for research on the industry dynamics that result from interactions between modular designs,

design rules, and several aspects of the product life cycle, including dominant designs, increasing returns to scale, and firm shakeouts and industry consolidation.

I. Introduction

Research on vertical disintegration has steadily increased over the last 15 years as its increasing occurrence and importance have become widely recognized. The visible hand (Chandler, 1978) has been replaced by the virtual hand (Langlois, 2003; Chesbrough, 2003a) where the evolution of individual industries is often represented by the emergence of modular designs (Langlois and Robertson, 1992; Brusoni and Prencipe, 2001) and design rules (Baldwin and Clark, 2000) that define how different modules within a system (Langlois, 1992) or stages in a value chain interact (Jacobides, 2005). This literature almost always focuses on a single industry. For example, analyses of modular designs and vertical disintegration have been done on the mainframe (Baldwin and Clark, 2000) and personal computer (Langlois, 1992), semiconductor (Macher et al, 2002), mortgage banking (Jacobides, 2005), and telecommunication (Steinmueller, 2003) industries.

Other research has looked at the interaction between different levels in a nested hierarchy of sub-systems. Beginning with Herb Simon (1962), many scholars have noted that all products, including basic materials such as glass and chemicals can be represented as multiple levels of subsystems that are organized in a hierarchical fashion (Tushman and Murmann, 1998). In these multiple levels of subsystems, radical or architectural (Henderson and Clark, 1990) innovations at one level can are typically thought of as modular innovations at the next higher level (Murmann and Frenken, 2005).

This paper combines the concepts of modular design, vertical disintegration, and nested hierarchies of subsystems in order to look at the interaction between modular design/vertical disintegration at the system and component levels using the interaction between electronic systems (i.e., computers, telecommunications) and components (i.e., semiconductors) as industry contexts. Contrary to prior research on nested hierarchies of subsystems, technological discontinuities in such semiconductor industry products as logic chips, microprocessors, memory, application specific integrated circuits (ASICs), and application specific standard products (ASSPs) are found to constitute architectural innovations for electronic systems products. Discontinuities in semiconductors changed the architectures of electronic systems by enabling new designs using new combinations of “standard” modules.

This paper also suggests how the emergence of modular designs at the electronic systems level (in the form of new combinations of new standard modules) facilitated vertical disintegration between electronic systems and components. Furthermore, vertical disintegration in the value chain for semiconductors (between design houses and foundries) in the 1980s is shown to have strengthened modular design at the electronic systems level—and thereby to have enabled vertical disintegration between system and component suppliers by reducing entry barriers for design houses and foundries.

This paper uses histories of the semiconductor industry, readings of trade journals, and classifications of the top ranked (in terms of sales) U.S. semiconductor firms to describe this interaction between modular design and vertical disintegration at the electronic systems and component levels. Drawing on literature on the early years of the industry (Tilton, 1971; Braun and MacDonald, 1982), industry reports (UN, 1986; ICE, 1996), and other data sources, the top ranked firms (numbers of firms are shown in parentheses) in 1955 (12), 1965 (15), 1983/84 (35), 1995 (35), and 2005 (35) are classified in three different ways: 1) as system captive, system merchant, or independent merchant; 2) as integrated producer, design house, or foundry; and 3) as a producer/designer of standard “modules” (i.e., logic, memory, microprocessors, ASICs, and ASSPs), or producer/designer of a broad line of products. Analysis then shows that the top ranked firms changed from integrated producers that designed and manufactured a broad line of semiconductors and electronic systems to firms that specialize in specific modules and often just in the design of modules.

Information from trade journals and industry histories enable a rich and systematic description of the co-evolutionary progression of vertical disintegration, modular design, and design rules that support modular design over the last 50 years. A focus on U.S. firms, which have undergone vertical disintegration much faster than firms in other countries, reveal this progression much more clearly than research that has analyzed, for example, the global ASIC industry (Linden and Somaya, 2003; Dibiaggio, 20007). These results suggest important implications for further research on modular designs, design rules, and several aspects of the product life cycle including dominant designs, increasing returns to scale, and the reduced likelihood of firm shakeouts.

2. Theoretical discussion

The product life cycle (PLC) model (Abernathy and Utterback, 1978; Utterback, 1994; Suarez and Utterback, 1995) and Anderson and Tushman’s (1990) cyclical model of technological change suggests ways in which industries evolve. Both models focus on dominant designs and how they emerge at a single point of time. The PLC focuses on the role these dominant designs play in a shakeout (firm failures and take-overs) of vertically integrated manufacturers while Anderson and Tushman’s (1990) cyclical model of technological change suggests how technological discontinuities provide opportunities for new entrants.

Klepper (1997) and Klepper and Simons (1997) developed an alternate version of the PLC model that uses increasing returns to scale in product and process R&D to explain a shakeout of vertically integrated manufacturers. Klepper’s (1997) analysis of 46 industries found that in 19 industries increasing returns to scale did not emerge when sub-markets for specialized products exist or when process specialists emerge. The existence of sub-markets reduces the returns to scale on R&D and thus enables small firms to survive or new firms to enter these sub-markets, as analyses of the camera (Windrum, 2005), hard disk, computer, and other (Christensen, 1997) industries have found. The emergence of process specialists can also reduce the barriers to entry for new entrants and thus facilitate the entrance of new firms even after an industry shakeout and consolidation has occurred. The emergence of process specialists is an important form of vertical disintegration that enables a separation between equipment and product manufacturers, as in Klepper's (1997) examples, or between design and manufacturing, as this paper will show has occurred in the semiconductor industry. This aspect of vertical disintegration may also be encouraged by the existence of sub-markets in which firms use modular designs to serve demand for heterogeneous product variations (Sanchez and Mahoney 1996; Schilling, 2000). For example, specialist contract manufacturing is more likely to be found in industries with heterogeneous demand than in markets for homogeneous outputs (Schilling and Steensma, 2001).

Two key concepts for analyzing vertical disintegration are *modular design* (Sanchez and Mahoney, 1996) and *design rules* (Baldwin and Clark, 2000; Langlois, 2003). Modular designs are those in which the interfaces that determine how the functional components or "modules" in a product, process, or organization design will interact are specified to enable the substitution of component variations within the design (Sanchez and Mahoney 1996). A modular design approach enables compatibility among functional component variations in configuring design variations to meet different market demands or incorporate new component variations (Sanchez 1999). "Design rules" constrain the ways interfaces can be specified between different modules within a product (Sanchez 2004) or stages in a value chain interact (Jacobides, 2005) to ensure compatibility between them (Baldwin and Clark, 2000; Langlois, 2003). Design rules may be defined to maintain proprietary interfaces that result in "closed system" designs in which only a specific manufacturer's components will be compatible, or they may be defined to establish "industry standard" interfaces that create "open system" designs in which many manufacturers' "industry standard" components will be compatible (Sanchez and Collins 2001). The locus of control over design rules—i.e., whether a single firm developing a proprietary system product or a collective of firms creating an open system design—determines the degree of independence firms in an industry will have in developing modules and thus the extent of opportunities for vertical disintegration within that industry.

While some of the literature on modular designs analyzes firm strategies to establish new design rules *versus* following another firm’s design rules in creating closed system designs (Baldwin and Clark, 2000), this paper elaborates the conditions that lead to the emergence of open system design rules that enable vertical disintegration within an industry. When the final producers largely control the design rules for a system design, they may define the design rules in ways that enable them to retain control over the modules used in such system products, and there may be few or no new entrants able to provide modules for such products. In combination with increasing returns to scale (Klepper, 1997), control of design rules for modules may lead to the concentration of the industry into a few final producers. However, the greater the extent to which design rules governing component interfaces maintain open system designs, the greater the extent to which new entrants may emerge to provide modules and services and thus to occupy new positions in vertically disintegrated layers of the industry (Sanchez and Mahoney 1996; Baldwin and Clark, 2000; Langlois, 2003; Jacobides, 2005).

Open knowledge about the interactions between components (Chesbrough, 2003b) and the different stages in an industry’s value chain (Jacobides, 2005), or possible government regulations to separate ownership of stages in the value chain or to unbundle products (Steinmueller, 1996), can cause an industry’s design rules to become more open. In these cases, the locus of control over design rules may shift from vertically integrated manufacturers to other firms or collections of firms at various positions in the vertically disintegrated layers of an industry. Such shifts have been observed, for example, in microprocessors and operating systems for PCs (Langlois, 1992). Subsequently, control of design rules may interact with increasing returns to scale (Klepper, 1997) to cause a shakeout in these new vertically disintegrated layers, or further disintegration may take place within layers for the reasons just mentioned.

These dynamics of vertical disintegration may be driven by the interactions between systems and components throughout a nested hierarchy of subsystems. In such a nested hierarchy, radical or architectural innovations (Henderson and Clark, 1990) at one level are typically seen as modular innovations at the next higher level in these subsystems (Tushman and Frenken, 1998; Murmann and Frenken, 2006). A parallel hierarchy of firms may also form around these nested subsystems. Differences in the structures of the hierarchies of subsystems and firms will depend on the extent of vertical integration of firms within the hierarchies of subsystems at any point in time (Christensen and Rosenbloom, 1995).

As the discussion of modular designs suggests, the degree of vertical integration *versus* disintegration within the hierarchy of firms will depend on the extent to which closed system *versus* open system design rules emerge for the modules that make up the hierarchy of subsystems. In this study, the emergence of open design rules for “industry standard” components and modular designs (Sanchez 2002) led to the design of electronic systems composed of industry standard modules such as logic chips, memory, microprocessors, ASICs, and ASSPs *and* the vertical disintegration of semiconductor industry value chains into separate design houses and foundries specializing in specific modules. The emergence of open system design rules enabled the separation of system and component design activities, the separation of semiconductor design and fabrication, the entry of independent firms, and the eventual domination of the U.S. semiconductor industry by independent firms, many of whom only do design. Consistent with the notion that open design rules may be created by a set of cooperating partners (Sanchez 2002; Dibiaggio, 2007), the emergence of open system design rules in the semiconductor industry is found to involve important interactions between firms at the system, component, and other levels.

Two aspects of this story contradict the existing literature. First, the emergence of industry standard modules such as logic chips, memory chips, microprocessors, ASICs, and ASSPs are observed to be technological discontinuities in the semiconductor industry that represent true *architectural* rather than modular innovations for the electronic systems industries. Successive emergence of new standard modules has changed and continues to change the architectures of electronic systems by enabling these systems to be designed around new combinations of standard modules. Second, the emergence of industry standard semiconductors is observed to lead to reduce the entry barriers for designers and fabricators of the components and to lead to subsequent vertical disintegration among firms at the component level of semiconductors. These dynamics are also observed to facilitate evolutions in modular designs at the systems level that led to further vertical disintegration between systems and component firms.

3. Methodology

Lists of the top U.S. semiconductor suppliers in terms of sales were gathered from many sources including Tilton (1971), Braun and MacDonald (1982), the United Nations (UN, 1986), Dataquest (HBS, 1993), ICE (1996), Electronic Business (Edwards, 2006) and Compustat. From these sources, lists of the top suppliers were assembled for 1955 (12 firms), 1965 (14 firms), 1983/4 (35 firms), 1995 (35 firms), and 2005 (35 firms). In many cases multiple sources were used in order to create a longer list of firms for a single year than any single sources contained. For example, the top 25 U.S. firms in 2005 were identified from the top 25 ones that were in the top 50 global semiconductor firms in 2005 (Edwards, 2006) and the 26th to 35th U.S. firms were identified using Compustat’s listing of firms in the semiconductor industry. Firms in Compustat’s list that only do assembly or test were excluded. Because Compustat only classifies firms as semiconductor firms if they are primarily semiconductor producers, the rankings for 2005 may have overemphasized the importance of firms that only produce semiconductors. However, since there was only one systems firm in the top 25 U.S. semiconductor suppliers in 2005 (IBM), this variation in data classification probably does not pose a problem.

Largely using the sources mentioned, each firm was classified in terms of three variables: 1) as system captive (SC) producing semiconductors for own use, system merchant (SM), or independent merchant (IM); 2) as integrated producer (IP), design house (DH), or foundry (F); and 3) as a producer/designer of either standard modules or a broad line of products. Firms were classified as independent merchants if more than 50% of their sales were from semiconductors. Firms were classified as broad line producers if less than 50% of their sales were from a specific standard module. Firms were only classified as suppliers of ASSPs if their products could be associated with a specific standard module within a specific product. Because this has occurred to a much greater extent in digital products than in analog products (Malerba; 1985; Kressel and Lento, 2006), this paper primarily focused on digital products in order to be conservative in our estimates of the emergence of standard modules.

The sources used to classify firms depended on the year of the rankings. The classifications of firms in the 1955 and 1965 rankings were fairly trivial since firms only differed in terms of the first variable. The classifications of firms in the 1983/4 rankings largely depended on the descriptions in the UN report (1986). The classifications of firms in the 1995 rankings largely depended on the classifications and descriptions used in the ICE (1996) report. Ones for the 2005 rankings relied on annual reports that were largely found on the Internet. These sources were supplemented with the most often referenced histories of the semiconductor industry (Tilton, 1971; Braun and MacDonald, 1982; Malerba, 1985; Borrus, 1987), insider accounts (Walker, 1992), and a search for the top ranked firms in almost every issue of the industry publications *Electronics* and *Electronic Business* between 1960 and 2005.

4. Results

Table 1 summarizes the growth in semiconductor sales from 1965 to 1988. More recent data on sales from other sources are discussed in the sub-sections below. Tables 2-5 classifies the top ranked U.S. semiconductor suppliers (in terms of sales) for 1955/1965, 1983/4, 1995, and 2005 in three different ways. Figures 1, 2, and 3 plot the evolution in the percentages of firms that are classified in these three different ways. Figure 4 shows the number of producers of ASSPs by the systems industry that consumes their ASSPs. Figure 5 summarizes the evolution in modular designs for the electronic systems and semiconductor industries.

The continued changes in the composition of top ranked U.S. semiconductor suppliers and the role that new startups have played (Braun and MacDonald; 1982; Borrus, 1987; Saxenian, 1994; Angel, 1994) and continue to play (e.g., see Roelandts, 2005; Clark, 2006) in the changes in this composition suggests that shakeout and consolidation in the industry have in fact not occurred. For example, of the 18 de novo firms in the top 35 semiconductor suppliers in 1983/4, only 6 of them were still in the top 35 suppliers in 2005. Of the 24 de novo firms in the top 35 semiconductor suppliers in 1995, only 13 of them were still in the top 35 suppliers in 2005.

4.1 Early years of the semiconductor industry

The semiconductor industry was formed in the early 1950s and it was initially dominated by firms that produced military, television, and telecommunication systems (Tilton, 1971; Macher et al, 2002). The only non-systems (merchant) producers in the top 12 ranked U.S. semiconductor firms in 1955 were Transitron, TI (Texas Instruments), and Clevite, and in 1965 were Fairchild, TI, General Instruments, and Sprague. As shown in Figure 1, most of the systems producers only produced semiconductors for internal use (i.e., captive producer).

One of the largest reasons why system-captive producers dominated the early years of the semiconductor industry was the large amounts of uncertainty in both applications and in product and process design. Semiconductors were initially designed for special military applications and even those used in consumer applications such as transistor radios were often designed in close cooperation between system and semiconductor designers. This close cooperation was needed to match the capabilities of semiconductors with the relevant applications in systems. The interaction between product and process design was even closer. Virtually every history of the semiconductor industry emphasizes a close relationship between product and process design and the key role that system producers such as Western Electric/AT&T, RCA, General Electric, and Philco played in these early developments. Improved diffusion, etching, masking, and oxidation processes enabled new forms of transistors to be made. The sum of these improvements is often called the *planar process*, which enabled the development of the planar transistor in the late 1950s (Tilton, 1971; Malerba, 1985; Braun and MacDonald, 1982; Anderson and Tushman, 1990). Although TI and Fairchild made some of the key developments in the planar transistor and the ICs (integrated circuits) that resulted from this transistor, they were the only two independent merchants represented in the top 20 patent recipients through 1968, where they ranked fifth and 19th respectively (Tilton, 1971, Table 4-2).

The emergence of the planar process defined the basic steps for producing semiconductors and the basic requirements for manufacturing equipment. Public knowledge of the planar process led to open design rules for planar transistors, which stimulated the first step in the vertical disintegration in the industry. Although the descriptions of the semiconductor industry in the 1950s (Tilton, 1971; Malerba, 1985; Braun and MacDonald, 1982) do not mention any equipment firms and thus suggest that equipment sales were very small in the 1950s, equipment sales had reached 7% of semiconductor industry sales by 1988 (U.S. DOC, 1990) and 26% by 1996 (ICE, 1997). Descriptive summaries (Saxenian, 1994) and analyses (von Hippel, 1983) of innovation in the semiconductor industry also emphasize the increasing role of independent semiconductor equipment suppliers from the 1960s onwards.

4.2 ICs, logic chips, and the modular design of electronic systems

The first integrated circuits (ICs) were independently developed by Jack Kilby of Texas Instruments and Robert Noyce of Fairchild in the late 1950s. ICs can be divided into analog and digital types (Malerba, 1985). Early applications for analog ICs include military, broadcasting (both radio and television), and telecommunication systems in which the ICs process audio and video signals. Because of the initial difficulties in defining standard analog functions, the development of early analog ICs required close cooperation between system and IC design activities. Understanding which kinds of functions the chips needed to provide required knowledge about the system they were to be used in, and understanding which functions chips could be developed to provide required an understanding of ICs (Steinmueller, 1987). The need for this close cooperation between system and IC design is one reason why the top 15 semiconductor producers in 1965 (See Table 2) included manufacturers of broadcasting equipment and systems (Motorola, RCA, GE, Sylvania, Philco-Ford, Westinghouse, Delco Radio), telecommunication systems (Western Electric), and defense systems (TRW and Raytheon). Only two of the leading producers of analog ICs were independent merchants (Fairchild and TI).

Digital ICs were initially used for logic functions in computers and defense products, though now they are used in virtually every type of electronic product. Combinations of resistors, diodes, and later only transistors were used to produce ICs that perform simple logic functions (e.g., AND, NAND, NOR, and OR gates in which Boolean Logic can be used to combine gates into more complex systems, such as those that add and multiply). The rapidly increasing number of transistors that could be placed on a chip, commonly referred to as Moore’s Law, enabled semiconductor manufacturers to place more complex systems of logic gates on a single chip in the 1970s.

System firms began to create systems in the 1960s with Boolean Logic (Malerba, 1985; Borrus, 1987; Kressel and Lento, 2006), and standard input and output interfaces for digital ICs (Murphy et al, 2000) emerged through competition between different IC logic families

(Malerba, 1985; Borrus, 1987). The emergence of these standard input and output interfaces in effect constituted the emergence of a relatively open set of design rules that enabled the modular design of electronic systems (Sanchez 2002). The emergence of modular electronic system designs in turn facilitated both growth in the market for logic chips and rising market shares of independent semiconductor merchants.

As shown in Table 1, by 1971 logic chips represented 70% of IC sales and 36% of total semiconductor sales (including both discrete chips and ICs). TI was the leading producer of semiconductors in the U.S. from 1965 until the early 1990s partly because the standard input and output interfaces for logic chips were largely defined by the interfaces used for TI's logic chips. Fairchild's 920 series had initially defined the interfaces and design rules for an early type of logic chip called Diode-Transistor Logic (DTL), and this control helped its share of the semiconductor market to rise from 18% in 1964 to 24% in 1967. However, TI became dominant in a new form of logic chip called Transistor-Transistor Logic (TTL) that replaced DTL in the late 1960s (Malerba, 1985), and TI's 7400 series defined a new set of interfaces and design rules. Other independent merchants such as National Semiconductor, Signetics, and even Fairchild became second sources to TI (Borrus, 1987; UN, 1986). TI and Signetics are classified as logic producers for 1983/84 while the other two firms are classified as broad producers of semiconductors. The only major supplier of logic chips that is classified as a systems supplier in 1965 is Rockwell. Most logic chips were gradually replaced by ASICs and ASSPs in the 1980s (see below).

4.3 Processors, Memory, and the Modular Design of Electronic Systems

The increasing number of transistors on a chip gradually enabled semiconductor manufacturers to introduce a growing variety of semiconductor memory chips and processors during the 1970s by increasing the number of bits that could be saved in memory or processed by a processor, and to increase the speed with which these functions were carried out. The increasing number of transistors on a chip was also facilitated by the introduction of Metal Oxide Semiconductor (MOS)-based ICs, which had lower power requirements (albeit with lower speeds) and higher packing densities than did bipolar ICs (Bassett, 2002; Ernst and O'Connor, 1982). Semiconductor memory gradually replaced magnetic memory and also expanded the total market for memory in computers and other products such as telecommunication and broadcasting systems. Standard microprocessors also provided a new form of IC that filled the space between standard logic chips and custom application chips (Borrus, 1987) and thus enabled new kinds of modular designs in electronic systems. The programmability of standard microprocessors enabled their development costs to be lower than those for full-custom chips and their levels of design integration into electronic systems to be higher than that of logic chips. Pure logic chips then tended to become more specialized as the number of transistors on them increased (Jackson, 1998; Steinmueller, 1987).

Providers of computer, telecommunication, broadcasting, and other consumer products and systems began to design their systems around standard microprocessors and memory chips in the 1970s (Steinmueller, 1987; Jackson, 1998). Although the first order for a microprocessor was made to meet the needs of Japanese calculator manufacturers, and although microprocessors were initially used in a large number of low- to mid-volume applications such as aviation, medical, and test equipment (Jackson, 1998), by the 1980s microprocessors were used in a wide variety of computer, telecommunication, and consumer electronic products and systems (Borrus, 1987; Steinmueller, 1987; Jackson, 1998; Turley, 2003). The emergence of programming tools such as assemblers and higher-level programming languages like PASCAL further enhanced the advantages of microprocessors (Jackson, 1998).

The success of microprocessors caused a variety of microprocessors and memory chips to emerge in the 1970s and 1980s that supported the modular design of electronic systems. Simple forms of microprocessors, called micro-controllers, evolved from the first microprocessors and are still used in a large variety of non-computer applications. Digital signal processors emerged for applications that required the processing of audio and video digital signals. They became widely used in CD players, mobile phones, and video graphic chips (Turley, 2003) and are now generally classified as ASSPs (see below).

The wide use of microprocessors also caused new forms of memory to emerge. While the early programs for microprocessors were stored in so-called Read-Only Memory (ROM), the ability to program the memory in so-called Programmable ROMs (PROMs) and to change the program with ultraviolet light in Erasable PROMs (EPROMs) and later with electrical signals in Electrically Erasable PROMs (EEPROMs) reduced the cost of using microprocessors and further expanded modular designs for electronic systems. Other forms of memory such as DRAMs (Dynamic Random Access Memory), SRAMs (Static Random Access Memory), and flash memory also emerged (Borrus, 1987; Jackson, 1998; Gruber, 1994; Turley, 2003). As shown in Table 1, the sales of microprocessors, memories, and logic chips represented 12%, 36%, and 25% respectively of total IC sales and 56% of total semiconductor sales in 1984.

In combination, the new forms of modular system designs based on these industry standard components (See Figure 5) increased the number of opportunities for entry by independent merchant suppliers, because modular designs based on standard components relieved component firms of the need to understand how specific systems were being designed. The number of independent merchant suppliers in the top 15 rose from four in 1965 to eight in 1983/4 (shown in percentages in Figure 1). TI and Fairchild were the only two independent merchant suppliers from the top 15 in 1965 that were still in the top 15 in 1983/84. TI was the leader in logic chips, while Fairchild was a leader in several other types of standard modules (bipolar memories, logic chips, and microprocessors) and is therefore classified as a broad producer of semiconductors.

Of the six new members to the top 15 in 1983/4 that were independent merchant suppliers, five of them were primarily producers of microprocessors, memory, and/or logic chips. Intel and AMD focused on microprocessors, while Signetics focused on logic chips. Although two of the other new members (National Semiconductor and Monolithic Memories) are classified as broad producers of semiconductors in Table 3, National Semiconductor was a leader in logic chips, Fairchild in both logic chips and microprocessors, and Monolithic Memories in all three of these products (UN, 1986). Only one of the six new members (Analog Devices) was primarily a producer of semiconductors other than these standard modules.

4.4 ASICs and the Modular Design of Electronic Systems

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). However, the increasing number of transistors on a chip gradually opened up new markets for ASICs in the late 1970s and early 1980s in higher volume products such as personal computers, video games, and other digital products. In some cases, microprocessors could not provide the necessary levels of specialization that ASICs could provide. In other cases, the increasing use of microprocessors and memory created a bottleneck in high-volume systems design in which 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 could still be considered “general-purpose ICs” (Mead and Lewicki, 1982; Walker, 1992).

There are several kinds of ASICs (See Table 6), and each type requires a different kind of basic design and design tool in which both result in a different form of modular design for electronic systems. In general, the highest volume applications are likely to use full custom-designed chips, while standard cell designs and gate arrays tend to be used for lower volume applications (Posa, 1980; Fields, 1982; Bogle, 1984; Bourbon, 1984; Thomke, 2003). Programmable logic devices (PLDs) emerged as another design alternative in the 1990s, and more recently Systems on Chip (SoC) have become more widely used.

While full custom chips are by definition a custom and not a modular design for electronic systems, ASICs do represent a new form of modular design in which their design tools and standard interfaces define the new modular designs for electronic systems. With standard cell designs, design engineers select pre-designed blocks that have increased in complexity as the number of transistors on a chip has 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 light (similar to EPROMs) and later with electrical signals (similar to EEPROMs) (Cole, 1988; Ristelhueber, 1996; Thomke, 2003).

The emergence of these ASICs with their new design tools and interfaces required a new set of design rules in both IC design and fabrication. Since traditional logic design was too-time consuming and expensive for low-volume ASICs, it was replaced with higher-level symbolic methods that were developed by Carver Mead and Lynn Conway and that substantially reduced the cost of designing complex ICs (Beresford, 1983a; Bourbon, 1984; Baldwin and Clark, 2000).

The traditional integration of design and fabrication within one company was also too expensive for potential producers of ASICs (Macher et al, 2002). The cost of a new fabrication facility had reached $200 million by 1982 (or about ten times what it had been ten years earlier) and $1 Billion by 1995 (ICE, 1997). Although the rising cost of fabrication facilities had become a major barrier for new entrants and had caused leading integrated producers to produce a broad line of ICs, some of these integrated producers and later independent foundries began to provide fabrication services to independent design firms. These services were helped by the development of so-called “dimensionless and scalable design rules.” These rules define the minimum feature sizes on an IC such as line width and material thicknesses and the geometrical relationships between them, and power consumption and speed. Although these rules were initially created to more easily update semi-custom designs as feature sizes were reduced over time, in combination with Mead and Conway’s standardized design approach, they gradually facilitated the vertical disintegration between design and fabrication (Baldwin and Clark, 2000; Murphy et al, 2000; Critchlow, 1999; Macher et al, 2002).

Mead and Conway’s high-level design approach, dimensionless scalable design rules, and specific design tools emerged from a long period of experimentation in the 1980s (Walker, 1992). The most successful ASIC suppliers developed standard arrays and libraries, sets of design tools, and relationships with foundries in which licensing played a key role. They licensed standard arrays, libraries, and individual design tools from smaller firms, recombined these individual design tools into system design tools, and then re-licensed system design tools to systems firms so that systems firms could design ASICs themselves (Barney, 1986; Walker, 1992). Systems firms welcomed the availability of these design tools, since these tools enabled them to maintain a viable presence in the IC design stage of the industry that had been significantly weakened by the wide availability of microprocessors and memory ICs from independent merchants (Bourbon, 1984).

Some of these ASIC suppliers forward integrated into fabrication, but most did not. The two leading suppliers of ASICs in the 1980s and 1990s (See Tables 3-5), VLSI Technologies and LSI Logic, forward integrated into fabrication before the former was acquired by Phillips and the latter went fabless in the late 1990s. On the other hand, hundreds of so-called “design houses” entered the ASIC market in the late 1970s and early 1980s as “fabless” firms

(Beresford, 1983a; Borrus, 1987) and by 2005 there were more than 600 fabless design firms (Roelandts, 2005). Two of these fabless design houses, Altera and Xilinx, created a new form of ASICs called PLDs (described above); they were ranked in the top 35 firms in both 1995 and 2005 (See Tables 4 and 5). On the fabrication side, as of late 2007 there were more than 150 foundries, many of them specialized in different types of materials, processes, transistors, and logic families[1]. The three largest independent foundries in the world in 2006 were Taiwanese (Edwards, 2006).

The success of fabless design houses and independent foundries was also helped by the success of computer-aided design (CAD) suppliers such as Cadence. Acting as both a partner and a competitor to LSI Logic and VLSI Technologies, Cadence acquired a number of small CAD suppliers in the late 1980s and integrated their individual design tools into a CAD system that could be easily implemented by design houses and foundries (Walker, 1992). More recently, the Internet is being used by CAD suppliers and foundries to provide and update their design tools for system designers (Macher et al, 2005). Both CAD tools and Internet-based tools represent a more open form of design rules that is facilitating modular design within the semiconductor value chain.

In summary, each form of ASIC has led to a new form of modular design in electronic systems (See Figure 5) and has further facilitated vertical disintegration between system and semiconductor design. The market for ASICs grew from $0.07B in 1976 to $30.1B in 1998, and the percentage of the total IC market represented by ASICs grew from 5% in 1976 to 25% in 1998 (Arnold, 1999). Two ASIC suppliers were in the top 15 U.S. semi- conductor suppliers by 1995, and the number of ASIC suppliers in the top 35 U.S. semi- conductor suppliers had grown from three in 1983/4 to five in 1995 (shown in percentages in Figure 3). The number of independent merchants in the top ten global producers of ASICs had also

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[1] For example see: http://electronic-contract-manufacturing.globalspec.com/LearnMore/Electrical_Electronic_Contract_Manufacturing/Semiconductor_Foundry_Services

grown from one (European) firm in 1982 (Beresford, 1983b) to four in 1998 (Arnold, 1999), partly because independent merchants were faster than system suppliers to provide customers with design tools and to outsource their own manufacturing (Walker, 1992).

The increasing presence of independent merchants of ASICs, along with firms that focused on microprocessors, logic chips, or memories, also caused the number of system suppliers in the top ranked U.S. semiconductor suppliers to decline. The only systems suppliers in the top 15 U.S. semiconductor suppliers in 1995 were IBM, Motorola, Lucent, HP, and Rockwell, and the percentage of the top 35 semiconductor suppliers in the U.S. that were systems suppliers had fallen from 46% in 1983/4 to less than 25% in 1995 (See Figure 1). Furthermore, the easier access to ASIC designs facilitated by the vertical disintegration between semiconductor design and fabrication contributed to the growing importance of ASICs as the basis for a new form of modular design, and thereby contributed to vertical disintegration between system and component design. The emergence of a new form of ASICs called PLDs was led by two fabless design houses, Altera and Xilinx, and their success encouraged other semiconductor suppliers (including ASIC suppliers) to go “fabless.” The number of fabless firms in the top 35 U.S. semiconductor suppliers had grown from zero in 1983/4 to 20% in 1995 and to more than 30% by 2005 (See Figure 2).

4.5 ASSPs and the Modular Design of Electronic Systems

The increasing number of transistors on an IC chip continued to change the bottlenecks in system design. As described in the last section, the increasing number of transistors had changed the bottleneck in electronic system design during the early 1980s to logic chips that were used in combination with microprocessors and memory to customize an electronic system for a specific application. While ASICs provided one solution to this problem, this section describes a second and related solution, which is called application specific standard products (ASSPs). 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. They are often designed using ASIC-design techniques, and their key difference with ASICs is that they are sold as standard rather than custom (“application-specific”) products in the market (Walker, 1992). The growing market for PCs and other digital products and the emergence of open standards for these products enabled ASSPs to be used in a wide variety of digital products (See Figure 4). At the same time, increasing vertical disintegration in semiconductor design and fabrication has reduced the barriers to entry for new suppliers of ASSPs.

ICs for personal computers became the largest use of ASSPs as Intel and other firms that were fabless from their start 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 (#19 in 1991) and Cirrus Logic (#11 in 1995) successfully reverse engineered IBM’s so-called BIOS chips. As the falling prices for memory chips enabled bit-map displays, other firms offered special processors that handled this data and that were compatible with Intel’s microprocessors (Takahashi, 1999). Examples include S3 (#26 in 1995) and Nvidia (#10 in 2005) (See Tables 4 and 5).

Other ASSPs that supported PCs, that required IC controllers compatible with a specific standard, and that dominated a single firm’s sales include those designed for modems (Lineback, 1987), Ethernet local area networks (Hindin, 1982), and hard disks (McLeod, 1987). For example, although initially the ASSPs for controlling hard disks were largely supplied by a firm (Western Digital) that also supplied hard disks, independent merchant suppliers such as Silicon Systems (#24 in 1995) and later Marvel Technology (#10 in 2005), of which the latter was fabless from the beginning, gradually came to dominate the market in the 1990s (ICE, 1996).

The adoption of open standards in the move to digital technology has also made telecommunications systems a large market for ASSPs and for fabless suppliers that found market niches. Successful new entrants that started as fabless firms include Broadcom (#8 in

2005), Marvel Technology (#19 in 2005), and QLogic (#35 in 2005). Broadcom was founded in 1991 to provide chips for Ethernet LANs, cable modems, ADSL trans-receivers, and digital set top boxes in cable systems. Marvel Technology was founded in 1995 to provide chips for LANs (and hard disk controllers as described above). The success of such fabless ASSP suppliers and the increasing cost of fabrication facilities also encouraged other suppliers of ASSPs for telecommunication systems such as Standard Microsystems (#25 in 1995) and Rockwell (#13 in 1995) to go fabless and for Rockwell to spin off its semiconductor operations as Conexant Systems (#31 in 2005).

In the mobile phone industry, open standards for digital technology have also led to an increased usage of ASSPs. The most critical open standards are so-called “air-interface standards” that define how signals are transmitted between base stations and mobile phones in a specific frequency band. The most successful of these firms is Qualcomm, which was founded as a fabless firm in 1985 to promote a specific standard called CDMA (code division multiple access) and later to provide chip design, intellectual property rights, and for a time equipment compatible with CDMA. It was the 7th largest U.S. semiconductor firm in 2005 and the only fabless supplier of mobile phone chips that is in the top 35 U.S. semiconductor firms. Other top 35 ranked firms in 2005 that supply ASSPs for mobile phones include RF Micro Devices (#29), Skyworks Solutions (#30), and TI (#2). The first two firms are the only suppliers of analog devices that are also defined as suppliers of ASSPs; their devices have become standard modules in mobile phones, because they in turn adhere to specific standards and frequencies in use in the mobile telephony industry. TI is the leading provider of digital signal processors for phones. These processors have represented about 1/3 of its sales over the last 10 years, and TI is defined as a supplier of a broad product line of ICs in Table 5.

Figure 3 and Table 7 summarize the results from this sub-section. The number of top 35 U.S. semiconductor firms that can be classified as suppliers of ASSPs increased from 2 in 1983/4 to 9 in 1995 and 10 in 2005 (percentages are shown in Figure 3). As shown in Table 7, the percentage of these firms that are fabless increased from zero in 1983/4 to 58% in 2005, and the percentage of firms formed since 1984 that were fabless from the beginning increased from zero in 1985 to 50% respectively in 2005. This reflects the increasing interaction between vertical disintegration in semiconductors (in particular design houses that were fabless from the beginning) and in electronic systems (based on modular design with ASSPs – See Figure 5). The vertical disintegration between semiconductor design and fabrication reduced the barriers to entry for fabless design houses, which made it easier for newly created independent merchants to find specific niches associated with ASSPs. On the other hand, the success of ASSPs further reduced the need for semiconductor suppliers to be vertically integrated into supply of electronic systems.

4.6 IP and new layers of modular design

This sub-section deals briefly with the apparent next stage in vertical disintegration just beginning in the semiconductor and electronic systems industries. More than 200 firms have begun to sell their designs as intellectual property (IP). System and IC designers purchase such IP in order to reduce the development time and cost of their systems and/or ICs (Sanchez 1995; Dibiaggio, 2007). The leading supplier of semiconductor IP is a British firm ARM, which sells configurable processors to mobile phone suppliers. The mobile phone suppliers customize these processors for their phones (Harbert, 1999). ARM had $312M in sales in 2004 (D&R, 2005) or about 1/3 the sales of the 50th largest semiconductor supplier in the world or the 30th largest supplier in the U.S. Many observers expect that IP will play a particularly important role in the SoC business where suppliers of SoC design tools will offer some designs in their libraries that they have purchased as IP (Rowen, 2004). Open sales of IPs that become de facto industry standard designs can be expected to lead to further vertical disintegration, this time within semiconductor design firms themselves.

5. Discussion

This paper has explored the interaction between modular designs, design rules that use modularity to create open systems, and vertical disintegration at system and component levels in the context of the semiconductor industry. Contrary to prior research on nested hierarchies of subsystems, this research has suggested that technological discontinuities in a component (semiconductor) industry actually led to architectural innovations in the (electronic) systems industry, rather than simply being considered a modular innovation as current theory would predict. Each technological discontinuity in semiconductors has changed the architecture of electronic systems by enabling these systems to be designed around a new combination of "industry standard" modules.

The resulting changes in the architectures of these systems may be one reason why there have been significant changes in the composition of top U.S. suppliers. Incumbents may have been constrained by their success in and focus on existing architectures and their associated problem solving strategies (Henderson and Clark, 1990). Changes in architecture may have posed particularly difficult problems for the semiconductor divisions inside the suppliers of electronic systems, since these divisions were focused on using their current architectures to meet the needs of their internal customers rather than developing new standard modules that would enable new architectures that would appeal to external customers.

This paper develops this argument by suggesting (i) how new modular open system designs based on new standard components facilitated vertical disintegration between electronic systems and electronic components activities, and (ii) how subsequent vertical disintegration between design and fabrication in semiconductors facilitated both the emergence of new forms of modular designs at the electronic systems level and the further vertical disintegration of firms specializing in new standard components. The latter effect is particularly evident in one type of ASIC (PLDs) where both of the market leaders started as fabless firms and in ASSPs where 50% of the eight ASSP firms in 2005 started as fabless firms. Taking these interactions between systems and components into account seems essential to explaining the evolution of modular designs and vertical disintegration in the semiconductor and electronic systems industries.

The interpretation of system and component interactions mediated through modular designs presented here differs from existing models of industry evolution in at least four ways. First, it clarifies the application of the two concepts of technological discontinuities and dominant designs to the semiconductor industry. As mentioned above, innovations in logic chips, memory, microprocessors, ASICs, and ASSPs can be characterized as technological discontinuities that changed the architectures of electronic systems by enabling new forms of modular design to emerge in electronic systems.

Second, this interpretation raises questions about the application of the concept of dominant designs in the context of the semiconductor industry. Although the literature on dominant designs emphasizes a single architecture that emerges at a single point in time, a single architecture did not emerge for the range of electronic systems covered in this research. Moreover, it is not even possible to identify a single architecture that became dominant in one type of electronic system (such as the PC) or within the semiconductor industry. For example, although Intel’s microprocessor is usually said to be the dominant design for the hardware of the “Wintel PC,” this paper’s interpretation of the semiconductor industry suggests that other aspects of the PC design also form an essential part of this architecture, such as BIOS and video graphic chips, and that these components were subject to change and evolution. Similarly, a single architecture did not emerge at a single point in time in the process of vertical disintegration between semiconductor design and fabrication. Instead, this vertical disintegration can be more accurately represented as resulting from multiple design decisions influenced by the emergence of Mead and Conway’s high-level design methodology, dimensional scalable rules, and CAD systems.

This research suggests that dominant designs may encompass multiple design decisions that would be more consistent with Suarez and Utterback's (1995) definition of dominant designs: "a dominant design is a specific path along an industry's design that establishes dominance among competing paths." However, in contrast to Suarez and Utterback's emphasis on technological choices, complementary assets, and their impact on firm shakeouts, the motive suggested here for reconceptualizing a dominant design in terms of multiple design decisions is the co-evolutionary dynamics of modular design and vertical disintegration. Drawing from Clark (1985), while the choice of a specific technology might define a single path for design evolution, efforts to solve sub-system problems related to independent modules may result in the emergence of multiple and relatively independent design paths. Clearly, further research is needed to clarify the concept of a dominant design in various technical and industry contexts.

Third, this paper's interpretation of the semiconductor and electronic systems industries provides a richer description and more insightful analysis of how open-system design rules emerge than would an analysis of either as a single industry. For example, this dual analysis shows that the design rules that emerged to support the modular design of systems using logic chips, microprocessors, and memory largely came from component designers and not from system designers. For example, independent merchants such as TI and Intel largely created the design rules that define how logic chips, digital signal processors, and microprocessors are used in electronic systems. If one presumes that these firms defined design rules in ways that reflected their respective technological strengths, this may be one reason why these two firms are still leading producers of semiconductors.

The interactions between systems and components become even more complex when we consider ASICs and ASSPs. Here new design rules emerged through multilateral interactions between design houses, foundries, systems producers, and CAD suppliers. Further research is needed on how some firms managed to define the new design rules and why others merely responded to their emergence (Baldwin and Clark, 2000) in both ASICs and ASSPs.

Fourth, this paper's interpretation of the semiconductor industry sheds light on why shakeout and consolidation has not occurred in the semiconductor industry, and may shed light on why a shakeout has not occurred in other industries. The existing literature emphasizes either the impact of a dominant design (Abernathy and Utterback, 1978; Utterback, 1994; Suarez and Utterback, 1995) or increasing returns to scale (Klepper, 1997; Klepper and Simons, 1997) in explaining a shakeout of firms. This paper's analysis provides more support for the role of increasing returns to scale than for the role of dominant designs as a reason for a shakeout in the number of firms. In particular, it explains how the existence of sub-markets (Windrum, 2005; Christensen, 1997) and process specialists prevent or minimize the effects of increasing returns to scale (Klepper, 1997). In the semiconductor industry, sub-markets initially existed in the form of special designs that were implemented by system firms for their proprietary closed systems. The emergence of standard logic chips, memories, microprocessors, ASICs, and ASSPs created sub-markets that change and evolve. Although shakeouts have occurred in specific sub-markets of the semiconductor industry that are often attributed to increasing returns to scale (Gruber, 1994; Flamm, 1996), the continued evolution of these sub-markets may explain why there has not been an overall shakeout and consolidation in the semiconductor industry and why there have been significant changes in the firms holding leading positions in the industry.

Klepper (1997) suggested that an absence of shakeout may be due to the emergence of process specialists. In the semiconductor industry, process specialists emerged in the form of foundries in the 1980s, and their emergence reduced the barriers to entry for (and thus facilitated the entry of) design houses. This effect is similar to, but somewhat different from, Klepper's (1997) analysis of the effects of the emergence of independent equipment suppliers, in that the emergence of independent foundries arguably reduced the barriers to entry for design houses more than the emergence of independent equipment suppliers reduced barriers to entry to semiconductor manufacturers.

The influences of sub-markets and process specialists proposed by Klepper (1997) appear to be compatible with the influences of modular designs, the interaction between vertical disintegration at the systems and component levels, and the role of heterogeneity in outputs proposed by Schilling and Steensma (2001). The evolution in modular designs in electronic systems and their impact on vertical disintegration between electronic systems and semiconductors was paralleled by the evolution of sub-markets for semiconductors. The emergence of process specialists (foundries) described by Klepper parallels the vertical disintegration in the value chain for semiconductors into foundries and design houses described here. Finally, the emergence of foundries and design houses often reflected the heterogeneity in their sub-markets (Schilling, 2000; Schilling and Steensma, 2001) and their subsequent evolutions. Foundries and design houses have decided to focus on specific sub-markets that become increasingly complex. Changes in materials, processes, and transistor designs drive changes in the sub-markets for foundries, while changes in ASICs, ASSPs, and the modules they represent within electronic systems drive changes in the sub-markets for design houses. In this way, the vertical disintegration into separate foundries and design houses appears to support the growth of heterogeneity in their sub-markets.

Finally, the interpretation presented here suggests that a shakeout in the semiconductor industry may not occur unless these sub-markets, design houses, and foundries stop evolving and stabilize. Moore’s Law continues to drive the emergence of new designs in ASSPs, and related changes in technology continue to drive the increasing specialization of foundries in different materials, processes, and transistor designs, and both of these processes support and co-evolve with each other. Furthermore, new forms of modular design stimulated by the rise of IP designs may further contribute to the growth of sub-markets. All of these factors suggest that shakeout remains only a distant possibility in the semiconductor industry. In this regard, the semiconductor industry may continue to provide a rich area for research on the interactions of modular design and vertical disintegration in industry evolution for many years to come.

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Table 1. Global Sales (Billions of US$) of Semiconductors

Year	Discrete & Hybrid	Analog ICs	Digital ICs					Total ICs
			Logic	Memory	Processors	Custom/ ASIC	ASSPs	
1966	1.3							.15
1971	.0.7	.07	.36	.06				.51
1976	.89	.38	.68	.51	.11	.07	.16	1.9
1980	1.3	.68	1.3	1.9	.64	.30	.53	5.2
1984	1.7	1.3	3.0	3.5	1.7	1.3	2.1	13.0
1988	2.1	2.4	1.8	3.7	1.6	2.4	.67	13.1

Source: Various issues of Electronics and Electronic Business

Table 2. Classifications of Top Ranked U.S. Semiconductor Suppliers in 1955 and 1965

1955			1965		
Rank	Firm	Classification	Rank	Firm	Classification
1	Hughes	SC, IP, Broad	1	TI	IM, IP, Broad
2	Transistron	IM, IP, Broad	2	Motorola	SM, IP, Broad
3	Philco	SC, IP, Broad	3	Fairchild	IM, IP, Broad
4	Sylvania	SC, IP, Broad	4	General Instruments	SM, IP, Broad
5	TI	IM, IP, Broad	5	GE	SC, IP, Broad
6	GE	SC, IP, Broad	6	RCA	SC, IP, Broad
7	RCA	SC, IP, Broad	7	Sprague	IM, IP, Broad
8	Westinghouse	SC, IP, Broad	8	Transitron	IM, IP, Broad
9	Motorola	SM, IP, Broad	9	Raytheon	SC, IP, Broad
10	Clevite	IM, IP, Broad	10	Western Electric	SC, IP, Broad
11	Western Electric	SC, IP, Broad	11	Sylvania	SC, IP, Broad
12	Raytheon	SC, IP, Broad	12	Westinghouse	SC, IP, Broad
			13	TRW	SC, IP, Broad
			14	Delco Radio	SC, IP, Broad

Abbreviations: 1) system captive (SC), system merchant (SM), independent merchant (IM); 2) integrated producer (IP); 3) broad line of products (Broad)

Sources: Tilton, 1971; Malerba, 1985, and author's analysis

Table 3. Classifications of Top Ranked U.S. Semiconductor Suppliers in 1983/4

Rank	Firm	Classification	Rank	Firm	Classification
1	TI	IM, IP, Log	19	Mostek	IM, IP, Mem
2	IBM	SC, IP, Broad	20	International Rectifier	IM, IP, Broad
3	Motorola	SM, IP, Broad	21	Unitrode	IM, IP, Broad
4	National Semiconductor	IM, IP, Broad	22	Siliconix	IM, IP, Broad
5	Intel	IM, IP, Micro	23	NCR	SC, IP, Broad
6	AMD	IM, IP, Micro	24	Sprague	IM, IP, Broad
7	Fairchild	IM, IP, Broad	25	LSI Logic	IM, IP, ASIC
8	Signetics	IM, IP, Logic	26	VLSI Technology	IM, IP, ASIC
9	Western Electric	SC, IP, Broad	27	Honeywell	SC, IP, Broad
10	General Instruments	SM, IP, Mem	28-35	Burr-Brown	IM, IP, Broad
11	Harris	SM, IP, Broad		Precision Monolithics	IM, IP, Broad
12	Analog Devices	IM, IP, Broad		Raytheon	SM, IP, Broad
13	Delco	SC, IP, Broad		Zilog	IM, IP, Micro
14	Monolithic Memories	IM, IP, Broad		Western Digital	SM, IP, ASSP
15	HP	SC, IP, Broad		DEC	SC, IP, Broad
16	American Microsystem	IM, IP, ASIC		Burroughs	SC, IP, Broad
17	TRW	SM, IP, Broad		Silicon General	IM, IP, Broad
18	General Electric	SM, IP, Broad			

Abbreviations: 1) system captive (SC), system merchant (SM), independent merchant (IM); 2) integrated producer (IP), design house (DH), foundry (F); 3) broad line of products (Broad), Mem (Memory), Log (Logic), Micro (Microprocessor)

Sources: UN, 1986; HBS, 1993; and author’s analysis.

Table 4. Classifications of Top Ranked U.S. Semiconductor Suppliers in 1995

Rank	Firm	Classification	Rank	Firm	Classification
1	Intel	IM, IP, ASSP	19	Xilinx	IM, DH, ASIC
2	TI	IM, IP, Broad	20	Symbios Logic	IM, DH, ASIC
3	Motorola	SM, IP, Broad	21	Altera	IM, DH, ASIC
4	IBM	SC, IP, Broad	22	Cherry Semiconductor	IM, IP, Broad
5	Micron Technology	IM, IP, Mem	23	International Rectifier	IM, IP, Broad
6	AMD	IM, IP, Broad	24	Silicon Systems	IM, IP, ASSP
7	National Semiconductor	IM, IP, Broad	25	Standard Microsystems	IM, DH, ASSP
8	Lucent	SM, IP, Broad	26	S3	IM, DH, ASSP
9	LSI Logic	IM, IP, ASIC	27	Hughes	SC, IP, Broad
10	HP	SC, IP, Broad	28	Digital Semiconductor	SC, IP, ASSP
11	Cirrus Logic	IM, DH, ASSP	29	Micro Chip Technology	IM, IP, Micro
12	Analog Devices	IM, IP, Broad	30	Burr-Brown	IM, IP, Broad
13	Rockwell	SM, IP, ASSP	31	Linear Tech.	IM, IP, Broad
14	VLSI Technology	IM, IP, ASIC	32	Zilog	IM, IP, Micro
15	Integrated Devices Tech.	IM, IP, Mem	33	Siliconix	IM, IP, Broad
16	Harris Semiconductor	SM, IP, Broad	34	Maxim Integrated Products	IM, IP, Broad
17	Atmel	IM, IP, Mem	35	Dallas Semiconductor	IM, IP, Broad
18	Cypress Semiconductor	IM, IP, Mem			

Abbreviations: 1) system captive (SC), system merchant (SM), independent merchant (IM); 2) integrated producer (IP), design house (DH), foundry (F); 3) broad line of products (Broad), Mem (Memory), Log (Logic), Micro (Microprocessor)

Sources: ICE, 1996 and author’s analysis

Table 5. . Classifications of Top Ranked U.S. Semiconductor Suppliers in 2005

Rank	Firm	Classification	Rank	Firm	Classification
1	Intel	IM, IP, ASSP	19	Marvel Technology	IM, DH, ASSP
2	TI	IM, IP, Broad	20	LSI Logic	IM, DH, ASIC
3	Freescale	IM, IP, Broad	21	Fairchild	IM, IP, Broad
4	Micron	IM, IP, Mem	22	ON Semi	IM, IP, Broad
5	AMD	IM, IP, Micro	23	Vishay	IM, IP, Broad
6	IBM	SM, IP, Broad	24	Altera	IM, DH, ASIC
7	Qualcomm	IM, DH, ASSP	25	International Rectifier	IM, IP, Broad
8	Broadcom	IM, DH, ASSP	26	Linear Tech. Corp.	IM, IP, Broad
9	Analog Devices	IM, IP, Broad	27	Microchip Tech. Corp.	IM, IP, Micro
10	Nvidia	IM, DH, ASSP	28	Cypress Semiconductor	IM, IP, Mem
11	Sandisk	IM, DH, Mem	29	RF Microdevices	IM, IP, ASSP
12	National Semiconductor	IM, IP, Broad	30	Skyworks Solutions	IM, IP, ASSP
13	Spansion	IM, IP, Broad	31	Conexant Systems	IM, DH, ASSP
14	Avago	IM, IP, Broad	32	Intersil Corp.	IM, IP, Broad
15	Atmel	IM, IP, Broad	33	Integrated Devices Tech.	IM, IP, Mem
16	Maxim Integrated	IM, DH, Broad	34	QLogic Corp.	IM, DH, ASSP
17	Agere	IM, IP, Broad	35	Omnivision Technologies	IM, DH, ASSP
18	Xilinx	IM, DH, ASIC			

Abbreviations: 1) system captive (SC), system merchant (SM), independent merchant (IM); 2) integrated producer (IP), design house (DH), foundry (F); 3) broad line of products (Broad), Mem (Memory), Log (Logic), Micro (Microprocessor)

Sources: Edwards, 2006; Compustat, and author’s analysis

Table 6. Comparison of Custom and Semi-Custom Design Methods

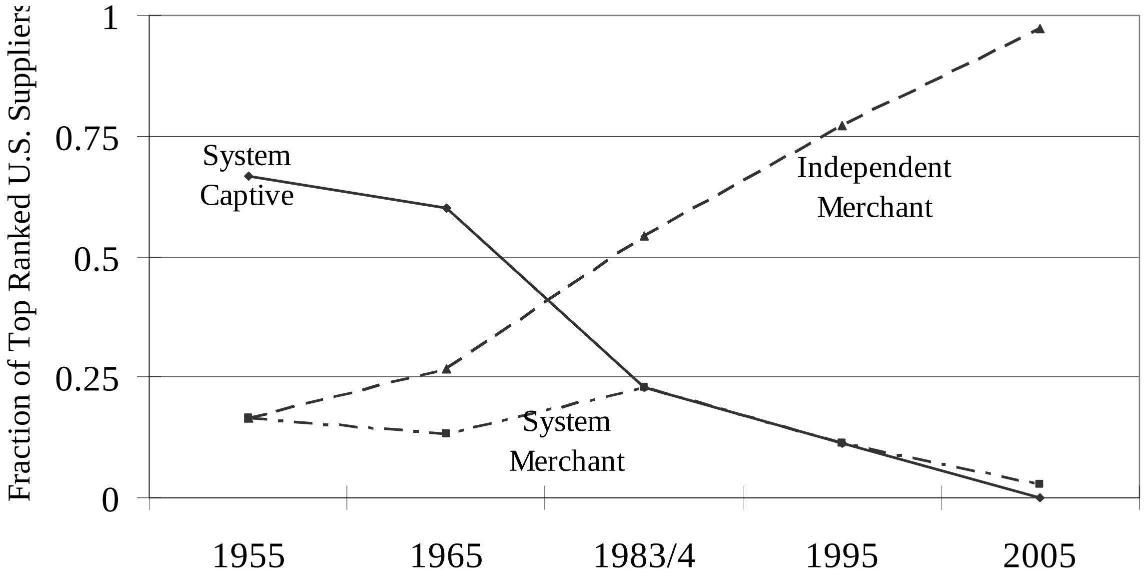
	PLD	Gate Array	Standard Cell	Full Custom
Prototype Cost	Lowest ($1000)	Medium	High	Highest (>$50,000)
Prototype Time	Lowest (minutes)	Medium	High	Highest (>8 weeks)
Variable Cost	Highest	Medium	Lower	Lowest
Complexity, Performance	Lowest	Medium	Higher	Highest
Market (2000)	$5.4 Billion	$2.7 Billion	$9.5 Billion	>$10 Billion

Source: Thomke, 2003; Abbreviations: PLD (Programmable Logic Devices)

Table 7. Selected Data on Top Ranked U.S. Suppliers that are classified as Producers of Application Specific Standard Products (ASSPs)

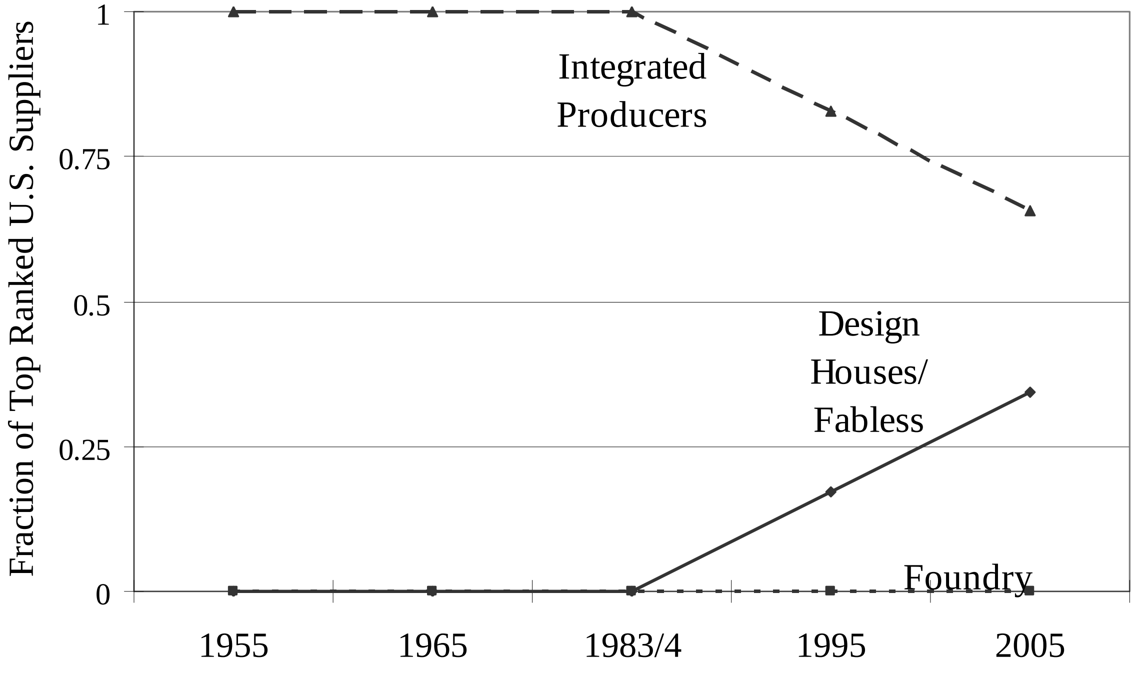
	1983/84	1995	2005
Number of Firms	1	7	10
Percent Fabless	0%	43%	70%
Percent Fabless and Formed Since 1984	0%	22%	50%

Figure 1. Vertical Disintegration Between Semicondcutors and Electronic Systems



Top 12 for 1955, top 15 for 1965 and Top 35 for 1981-2005

Figure 2. Vertical Disintegration Between Design and Fabrication



Top 12 for 1955, top 15 for 1965 and Top 35 for 1981-2005

Figure 3. Fraction of Top Ranked U.S. Suppliers that are Classified as Producers of Specific Modules or a Broad Product Line

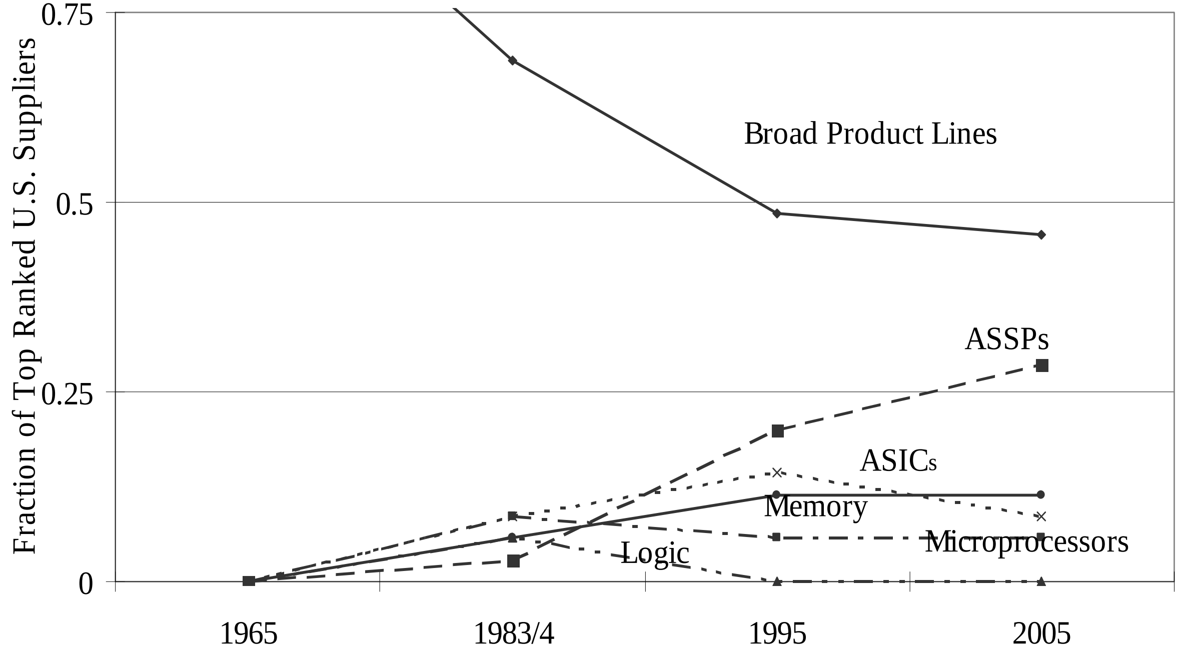


Figure 4. Number of Top Ranked U.S. Suppilers that are Classified as Producers of ASSPs by End User/Product

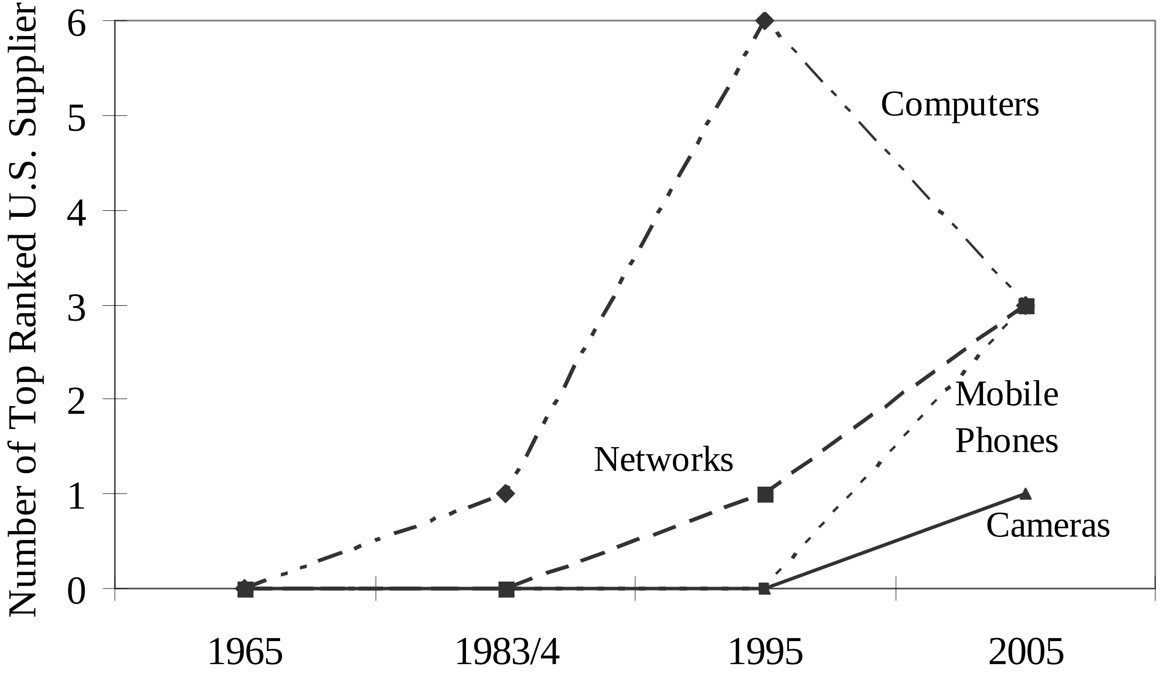


Figure 5. General Evolution of "Modular Design" in the Electronic Systems and Semiconductor Industries