System-on-a-Chip Integration in the Semiconductor Industry: Industry Structure and Firm Strategies

Article *in* Industrial and Corporate Change · June 2003

DOI: 10.2139/ssrn.259878 · Source: RePEc

2 authors, including:

Deepak Somaya
University of Illinois, Urbana-Champaign
78 PUBLICATIONS **2,758** CITATIONS

SEE PROFILE

Industrial and Corporate Change, Volume 12, Number 3, pp. 545–576

System-on-a-chip integration in the semiconductor industry: industry structure and firm strategies

Greg Linden and Deepak Somaya

Miniaturization has spurred ever-increasing on-chip integration in the semiconductor industry so that large-scale electronic systems can now be put on a single chip. The proliferation of such 'systems-on-a-chip' has important repercussions for the structure of the electronics industry, and the strategies of electronics firms. In a detailed case study, we apply a theoretical framework developed in Somaya and Teece ['Combining inventions in multi-invention contexts: organizational choices, intellectual property rights, and public policy,' SSRN Working Paper (available at: www.ssrn.com) 2001] to understand how system-on-a-chip integration is altering the balance between integrated approaches, components trading, and the licensing of 'design modules' (DM) in the semiconductor industry. Consistent with the framework, we observe a burgeoning market for licensed DMs in the industry, along with the primarily in-house design approach being pursued by large integrated firms. Important technical and institutional factors that are shaping industry structure, and the strategies being pursued by different types of firms are documented. Based on the framework, implications are drawn for firm strategy in response to technological shifts of the kind engendered by system-on-a-chip in the semiconductor industry. We extend the Somaya–Teece framework to include firm strategies that seek to influence the institutional environment in which they operate, and thus alter the balance between competing organizational modes.

1. Introduction

The semiconductor industry is undergoing yet another strategic revolution that is poised to transform existing business models. Ever-advancing miniaturization continues to increase the number of design elements that can be placed on an integrated circuit (IC), creating the opportunity to build large-scale electronic systems on a single chip. This 'system-on-a-chip' (SOC) movement is engendering a marked shift in the approach towards creating, reusing and licensing designs for ICs. In this increasingly complex world of system chips, a market for sub-chip design modules (DMs) has begun to develop, which could lead to new patterns for the division of labor in the industry.

Our analysis of this emerging phenomenon revolves around the functional design

inventions that we call DMs. These DMs are combined in different ways to make marketable electronic end-products, which typically include a very large number of these inventions. We analyze the SOC phenomenon by using a theoretical framework developed in Somaya and Teece (2001), which describes how such multi-invention products may be assembled using three generic alternative organizational modes. First, firms may utilize only internally developed technologies to build integrated products entirely in-house. Second, specialized component firms may market inventions in embodied component form to system integrators, who make the end-products. Finally, firms may specialize in making only the inventions, which are then licensed and integrated into products by other firms.

We analyze the emerging shift in the semiconductor industry through a comparison of the costs and benefits of making electronic products using these alternative organizational modes, namely, internal organization, component markets or licensing markets. We find that the SOC paradigm makes the licensing of semiconductor designs attractive, and that industry players are fostering institutional changes to reduce further the transaction costs entailed in licensing. At the same time, many large semiconductor firms are pursuing a more established integrated model based on in-house designs, and are competing for dominance with the licensing approach. But there are also complementarities between the two approaches, with the integrated firms being increasingly open to licensing external designs.

The rest of this paper is organized as follows. Section 2 describes the development of system-on-a-chip integration and design trading in the semiconductor industry. Section 3 explores the implications of this phenomenon for the organizational modes used in building electronic systems. Section 4 examines the strategic responses of various industry participants to this shift. Section 5 summarizes our analysis of system-on-a-chip in semiconductors, discusses its implications for industry structure and firm strategy in multi-invention contexts generally, and concludes.

2. System-on-a-chip and design trading in the semiconductor industry

In the semiconductor industry, the drive to exploit ever-increasing miniaturization has led to a new trend towards putting large-scale electronic systems on a single chip. For over three decades, following the well-known 'Moore's Law', the number of transistors on an IC has more or less doubled every 18 months.[1] In the early 1960s, digital ICs contained fewer than 50 transistors. According to the 2001 International Technology Roadmap for Semiconductors (SIA, 2001), the number of transistors that will be feasible on a single logic chip in 2004 will be 1 bn.[2] As in the past, this increasing 'silicon

[1]Moore's law was articulated by Dr Gordon Moore, one of the founders of Intel, in 1965.

[2]Continuing miniaturization has been the *sine qua non* of change in the semiconductor industry, and has given rise to episodes of industry-wide restructuring in the past. A wave of start-ups, including

real estate' is being used to enhance the functionality of specialized components, e.g. a higher capacity memory IC or a more powerful processor. But increasingly, it is also being used to combine multiple functions on one IC called an SOC.[3]

An SOC incorporates at least one processor, memory and any number of other functions, such as protocol converters, signal processors, and input and output controllers. While the semiconductor industry has witnessed various levels of on-chip functional integration in the past,[4] the recent focus on SOC promises significant improvements in cost, portability and functionality of electronic end-products.

System integration on an IC has several advantages over integration on a conventional printed circuit board (PCB). First, it increases operating speeds, as on-chip integration bypasses the congested data buses on PCBs and enables data transfer at faster clock speeds. A related advantage is lower power consumption, as lower voltages are required for each signal. A third major advantage of SOCs is a reduction in the size and complexity of end-use products resulting from fewer chips and minimal off-chip circuitry. Fourth, the consolidation of functions on a single chip can lead to lower unit manufacturing costs relative to fabricating several separate chips.[5] Fifth, the replacement of PCB interconnects with pathways on a single chip improves system reliability.

Despite these advantages, the SOC approach also requires additional fixed investments in development to integrate the multiple functions into a single-chip design, making it unattractive for low-volume applications. Moreover, SOC is currently uneconomical for the *entire* system in many cases (despite the name 'system-on-a-chip'), and certain specialty functions that require non-CMOS manufacturing technologies are often integrated into the final product through separate ICs. Nonetheless, the many advantages of SOCs are not only enabling downstream electronics manufacturers to improve the performance and reduce the size and cost of existing end-products, but also opening up new applications where bulky PCBs are unusable.

The enthusiasm for SOC in the semiconductor industry is being driven, in part, by a shift in the electronics market from performance-oriented, computer-centric devices to

---

Intel, appeared between 1966 and 1972 to exploit the new IC technology, and again a new wave, including LSI Logic, entered in the early 1980s to specialize in ASICs (application specific ICs).

[3]System-on-a-Chip is also called system-LSI, system-ASIC, or system-on-silicon.

[4]System-level integration in semiconductors has a long history, but the systems in question have become more complex. As far back as 1969, for example, a company called Mostek produced the first single chip calculator, which integrated basic functions such as addition, subtraction, multiplication and division (Borrus, 1988: 77). The current SOC movement reflects a qualitatively different level of integration, however, holding out the possibility of putting highly complex, multifunction electronic circuits entirely on a single chip.

[5]These cost advantages stem from fewer total silicon processing steps and lower chip-packaging costs required in the manufacture of a system-level chip compared with the multiple subsystem chips and components that it replaces. The system integrator also experiences cost savings by avoiding the integration and management of multiple chips from several suppliers.

other applications that include low-end computers, intelligent consumer products, and a plethora of wireless and broadband communication devices. As long as the high-end PC industry was the primary driver of the IC business, semiconductor firms competed aggressively to be the first to market with cutting edge 'performance components' that were able to earn a premium over current technology. But recently, price-sensitive households eager to access the internet have assumed a larger share of the PC consumer base,[6] and portable electronic devices have grown into an important emerging market segment.

SOC-based systems fit excellently into this emerging market scenario. Philips Semiconductors, for example, has announced a single-chip solution for in-car navigation systems that incorporates the main processor for Global Positioning System (GPS) data, embedded memory, and specialized interconnects for a gyroscope system and cellular phone. The chip, small and inexpensive enough to be incorporated in a car radio, can enable a range of services, such as automatic emergency calling, receipt of traffic data and locating stolen vehicles (Philips Semiconductors, 2002). Cellular telephony and hand-held devices, where small size and low power consumption are significant differentiating factors, are leading examples of SOC use. Other applications where the chip count has been steadily reduced by greater integration on fewer chips include personal computers, cordless telephones, internet set-top boxes, video game consoles and disk drives.

As these markets grow, SOC is steadily expanding its share of the semiconductor market. According to Dataquest (Table 1), SOC revenue in 1997, the first year the data were collected, was $7.6 billion, and grew faster than the industry as a whole through 2001 to reach roughly 14% of total chip revenues. Dataquest predicted in November 1999 that SOC would account for 40% of chip revenues by 2010 (*Electronic Buyers' News*, 1999).

The SOC movement interacts with an important design problem being faced by the semiconductor industry. While the complexity and density of ICs has increased rapidly in keeping with Moore's law, improvements in the productivity of IC designers have failed to keep up. This has resulted in a so-called design productivity gap in the industry (Figure 1), which has grown substantially through the 90s. One way out of this situation could be the brute-force application of more engineers to design work. However, IC designers are already highly paid and in short supply, and increasing the size of design teams poses additional problems due to rapidly rising team co-ordination costs. Semiconductor firms hope that the reuse of existing designs in SOC products will help bridge this productivity gap. We find, however, that large chip firms have run into some problems with their attempts to institute design reuse (see Section 4.1).

Even if firm-level reuse of designs is established, many elements needed for an SOC

[6]In 1996, the 'sub-$1000' PC became the fastest growing segment of the PC industry, and PCs began penetrating into a broader range of US households. Then, in 1999, low-end PCs began to be offered as incentives in exchange for subscriptions to internet service providers or to enhanced services, such as AOL.

Table 1 System-on-a-chip (SOC) revenues (US$ billions)

Year	SOC revenue	Total semiconductor revenue	SOC share (%)
1997	7.6	147	5.17
1998	9.4	135	6.96
1999	14.3	165	8.67
2000	23.1	227	10.17
2001	21.1	152	13.88

Source: Dataquest (May 2002).

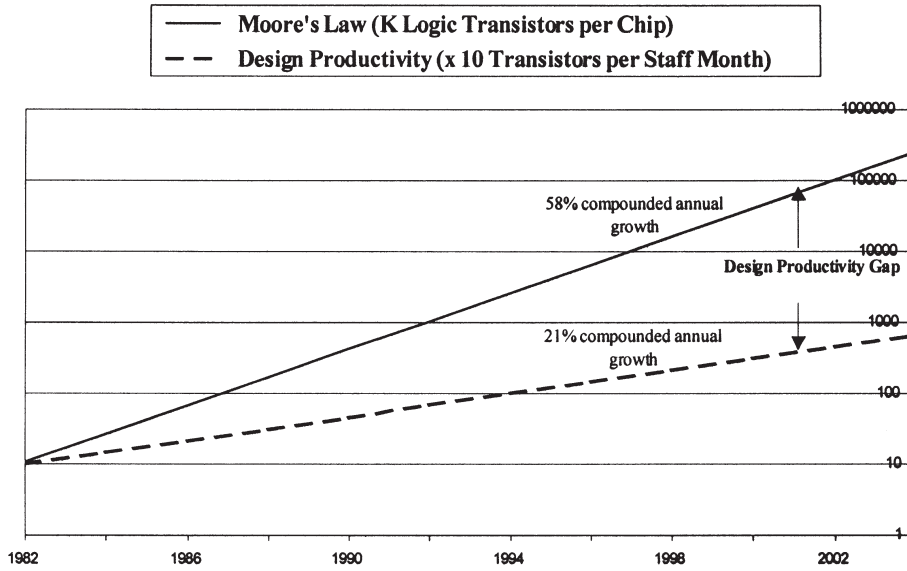

Figure 1 Widening design productivity gap in integrated circuits. Source: SIA (1999).

may not be available in-house and will need to be built afresh, causing delays in new product introduction. Moreover, as SOCs become larger and more complex, it will become increasingly difficult for firms to remain competitive in all the functional design elements that are being integrated into SOCs. The solution to these problems appears to lie in the young and fast-growing market for DMs, known in the industry as 'IP blocks,' 'design cores' or 'virtual components'.[7] According to Dataquest, trade in

[7]The many names and acronyms used for DMs in the industry can lead to much confusion, which is compounded when they have different meanings in other contexts. For example, what is commonly referred to as IP in the industry (a circuit design that performs some function) is not legally IP (intellectual property) at all. Similarly, virtual components are not components in the conventional sense, and are therefore inconsistent with the concept of components as used later in this paper. We therefore prefer our neutral term 'design module' (DM).

Table 2 Licensing revenue from DMs (US$ millions)

Year	Amount
1998	330
1999	442
2000	714
2001	892

Source: Dataquest (April 2002).

DMs more than doubled from $330 million in 1998 to $892 million in 2001 (Table 2).[8] Most of these traded DMs are being offered by so-called 'chip-less' firms, which sell no physical semiconductor product of their own and rely entirely on one-time license fees and/or running royalty revenue from their designs.

SOC integration and design trading in semiconductors may be seen as complementary developments. The market for DMs could be instrumental in the effective orchestration of the industry's innovative resources in making SOC products. As we explain in the next section, institutional underpinnings such as industry-wide compatibility standards and market intermediaries are necessary if DM trading is to occur on a large scale. The growth in traded DMs is in part a reflection of the fact that these structures are being put in place. Later in this paper, we examine how these changes have unfolded, and the ways in which various industry players have responded strategically to them.

3. Organizational choices in system-on-a-chip design

The emerging SOC-based industry structure typifies the historical shifting between integrated and ever more fragmented organizational modes of production in the electronics industry. Just as specialization in components proliferated in PCB-based electronic systems, the SOC era is showing signs of industry fragmentation driven by specialization in the disembodied semiconductor designs that are being licensed between firms. We analyze this shift in organizational modes in the industry using a framework for such 'multi-invention products' introduced in Somaya and Teece (2001)—henceforth the Somaya–Teece framework. Using the framework, we describe

[8]Personal communication with Dataquest. Dataquest's definition of 'a semiconductor intellectual property block' is 'a pre-designed function to be implemented in a semiconductor device. . . These functions include physical library functions (analog or digital), basic blocks (such as counters and MUXs) and system level macros (also known as cores or virtual components)—including memory blocks.'

alternative organizational approaches to commercializing electronic end-products, and compare the organizational costs between the two alternatives that apply to SOC. The section concludes with a discussion of the industry initiatives that seek to reduce transaction costs in the licensing mode of organization.

3.1 The semiconductor industry in the PCB paradigm

Most electronic products contain a PCB on which individual components are placed and interconnected by wiring. If electronic functions are not integrated with each other on the chip itself, PCB-level integration of these functions using individual components is the likely alternative, and we refer to this stylized model of integrating physically separable inventions as the 'PCB paradigm'.

Until fairly recently, large firms, such as IBM, DEC, AT&T (Lucent) and Motorola were highly integrated, manufacturing not only their final, proprietary PCB-based systems in-house, but also the most important ICs involved. Independent component manufacturers operated in this environment by specializing in general-use ICs—microprocessors, memory, graphics, etc.—which were traded in component markets for assembly onto PCBs by other firms.

As open architectures proliferated in electronic systems industries generally, and especially in computers through the 1980s, component specialists increased their share of revenues at the expense of the more integrated players. Component specialists that provided superior functionality and especially those that controlled important standards—such as Intel—also managed to capture a significant share of the rents from the systems business. In response, integrated systems firms started to compete directly with component firms by selling to outside customers while continuing to commercialize end-products.

This history can be seen as a competition between two modes of organization in commercializing electronic products—an integrated mode, and a more fragmented one based on a components market. Under the PCB paradigm, both 'integrated modes' and 'component modes' of organizing electronics production co-exist (Figure 2). But, over time, the component mode has been gaining an upper hand as many system firms—particularly in the USA—have spun off their component operations (Hewlett-Packard, Rockwell, Siemens) or are in the process of doing so (Lucent). When our attention turns from the PCB paradigm to SOC, the competition will be between integration and a 'licensing mode'.

Integrated, component and licensing modes are three generic alternatives for commercializing products that combine a large number of inventions, so-called 'multi-invention products.' The licensing mode was mostly absent under the PCB paradigm. This does not mean that there was no licensing between semiconductor firms. Licensing occurred through broad cross-licensing deals, sharing of process IP or within strategic alliances. But, with the exception of alliances (which were quite rare), these were typically passive, IP-only licenses that merely removed impediments to

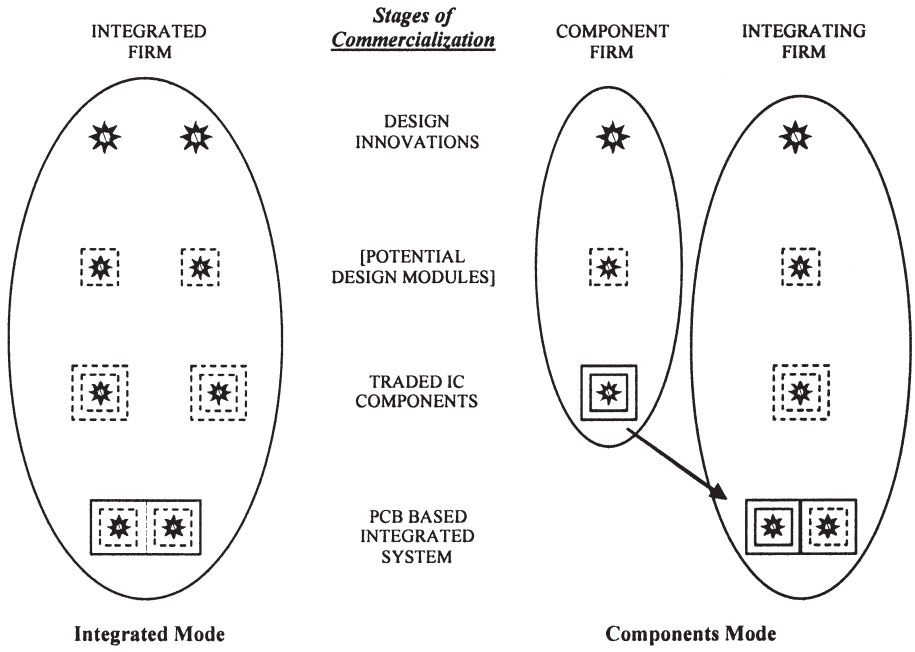

Figure 2 Integrated and component modes under PCB integration.

commercialization posed by blocking legal IP rights (Grindley and Teece, 1997), and did not involve any actual transfers of know-how or designs between firms.[9]

3.2 Organizational trade-offs in the Somaya–Teece framework

The Somaya–Teece framework uses a transaction cost approach to compare alternative ways of combining multiple inventions to make end-products, and we use it to analyze the organizational choices entailed in building electronic systems. Consistent with our discussion of organizational alternatives in electronics products in the previous section, three generic approaches to commercialization are suggested by the framework, respectively labeled *integrated*, *licensing* and *component* modes.

One way to understand the framework is through the stages at which inventions may be organizationally combined with others as one progresses towards commercialization of the end-product (Figure 3). First, all relevant inventions may be combined within the same firm, where they are used internally to make the end-product, resulting in an integrated mode. Integrated modes can include mergers and acquisitions through which the ownership of inventions is consolidated into a single firm, and they may also witness some passive licensing to obtain access to IP rights held by others.[10] Second, in a

[9]The need to ensure access to such blocking IP rights led to very aggressive patenting practices among semiconductor firms (Hall and Ham, 1999).

[10]When passive (IP) licensing is used, the firms typically already possess internally developed versions

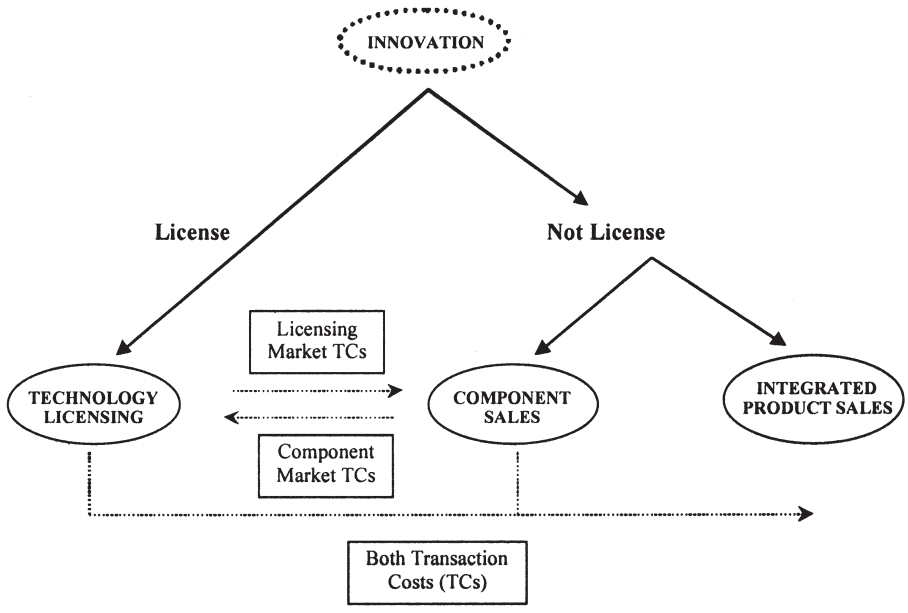

Figure 3 Innovation, licensing and integration in multi-invention products.

licensing mode, inventions actually reside in separate firms, but are combined through 'active' licensing that entails the transfer of technologies between firms. Third, firms may embody their inventions in components that are then sold to firms that build the multi-invention end-product, resulting in a component mode.

In the case of SOC integration, we define DMs as the relevant 'unit of invention'.[11] Under the PCB paradigm, IC designs are typically used to make separate ICs that are then assembled with others on a PCB. Depending on whether the ICs are freely traded or not, a component mode or integrated mode prevails in the industry. With SOC, componentization of DMs is no longer technically feasible as the modules have to be intermingled in a single design, and manufactured jointly in integrated form (literally, as they are fabricated on the same silicon wafer). The organizational choices available to the industry for designing and producing SOCs are thus reduced to integrated or licensing modes.[12]

---

of the licensed technology (sometimes even before the owners of the IP rights are known), and hence can be described as 'integrated'.

[11]Each DM may be covered by several different pieces of intellectual property, including multiple patents and copyrights. But it is DMs, as against patented inventions, that offer the possibility of reuse and licensing, and are therefore the appropriate unit of analysis.

[12]Multi-chip modules (MCMs), also called systems-in-a-package (SIPs), offer a different technique for accessing many of the benefits of SOC while retaining the option for component trade. Here, each chip

We evaluate which organizational mode is likely to predominate by examining their relative organizational effectiveness, where effectiveness is measured by the advantages gained and costs incurred when using each mode. Such a 'transaction cost' approach, exemplified in the work of Williamson and others (Hart and Moore, 1990; Williamson, 1991, 1998), examines organizational choice through the costs and benefits of organizing the associated transactions within firms or across firm boundaries. As illustrated in Figure 3, markets are superior to bureaucratic internal organization within firms when transaction costs are low, but as transaction costs rise, internal organization becomes more attractive.

In SOC products, the transaction of interest is the licensing of inventions (DMs), whereas in the PCB paradigm, it is the sale of component products embodying the inventions. Early in the PCB era, high transaction costs associated with components sourcing led to internalization of the most important chip design and manufacturing stages, especially among leading mainframe computer firms. These transaction costs arose primarily from the systemic nature of the technology (Teece, 1996), which required substantial co-ordination of innovation, and the associated problems of acquiring capabilities or components from relatively underdeveloped external markets in real-time, so-called 'dynamic transaction costs' (Langlois, 1991; Langlois and Robertson, 1995).[13] By contrast, the development of the electronic systems of the time could be co-ordinated quite effectively through intra-firm teams. As these products became more and more complex, however, the bureaucratic costs of such co-ordination became quite onerous, especially when compared with the modular strategies being pursued by entrants.

Modularization, spurred by increasing standardization of PCB interfaces, improvements in the capabilities of specialized semiconductor firms, and proliferation of open systems in the microcomputer era (such as those for the PC and client-server architectures), helped reduce transaction costs in components markets. Soon, component modes were widely adopted because they had strong advantages stemming from the strength of decentralized innovation in modular industrial systems (Langlois, 1992a; Langlois and Robertson, 1992). IC component markets offered the benefits of high-powered market incentives, with the best-in-class (or lowest-in-cost) IC suppliers being rewarded with large market shares. Integrated manufacturers who continued to

is fabricated separately on silicon, but the separate ICs are integrated within a single chip package. MCMs have not yet become popular in the industry, but they may be used in emerging applications where size and power consumption is critical (e.g. in portable devices), and the SOC approach is impractical for technical or cost reasons. In this paper, we focus on SOC alone because it is a significant recent development that is qualitatively different from a theoretical standpoint.

[13]The transaction costs in this context are more difficult to characterize in terms of Williamsonian asset specificity (Williamson, 1985); alternative descriptions such as those used here, appear to point more directly to their source.

employ inefficient internal divisions that were not competitive with market performance did so at their own peril.[14]

While licensing modes provide similar benefits from modular innovation, they also entail many transaction costs, which we describe below. Comparatively, the transaction costs in components markets are low, reflecting the conventional co-ordination costs of exchanging goods between suppliers and integrators. These include the problems of ensuring quality and delivery from closely tied suppliers, and the difficulties of co-ordinating design changes across a market interface, which are not too cumbersome when compared with licensing. Owing to the relative effectiveness of component markets, the 'active' licensing of design elements was virtually absent in PCB-based systems.

However, two crucial historical developments in the semiconductor industry created the context conditions for an effective licensing market in designs. The first of these was the establishment around 1980 of silicon-based CMOS technology as a dominant design in semiconductor process technology.[15] If many different process technologies were in use, standardization in DM interfaces, an important precondition for DM licensing, would have been very difficult to achieve. The second key development was the emergence of design software that was capable of characterizing the CMOS process limits of different chip plants. This enabled the de-linkage of design and manufacturing in CMOS ICs, as reflected in the emergence, beginning in the early 1980s, of a burgeoning 'fabless' segment—semiconductor design firms that outsource chip fabrication to 'foundry' manufacturers (Macher *et al.*, 1998).[16]

3.3 The semiconductor industry in the systems-on-a-chip paradigm

Despite its advantages with PCB-based systems, the component mode becomes untenable when an SOC approach is used. Not only does on-chip integration require the simultaneous fabrication of all hypothetical components (as they are now on the same chip), but it also entails non-trivial integration of the designs into a single system, so that the SOC cannot be readily subdivided into physical components. While the SOC is ultimately assembled on a PCB with other components (including passives and some

[14]During this phase, large firms such as IBM and DEC that continued to rely on integrated structures, saw erosion of their market positions, despite large installed bases. DEC has (from a variety of causes) ceased to exist; IBM revived its business in part by forcing its captive divisions, including semiconductors, to compete in component markets.

[15]The temperature stability of silicon and low heat generating properties of CMOS ('complementary metal oxide semiconductor', a semiconductor device design that incorporates both p-channel and n-channel transistors) has made it the process of choice for all but a few specialized applications.

[16]The authors suggest (p. 134, endnote 35) that the 'diffusion of MOS production technology facilitated the division of labor between device designers in fabless firms, who were able to operate within relatively stable design rules, and foundries, who were able to incrementally improve their process technologies to accommodate a succession of new device designs.'

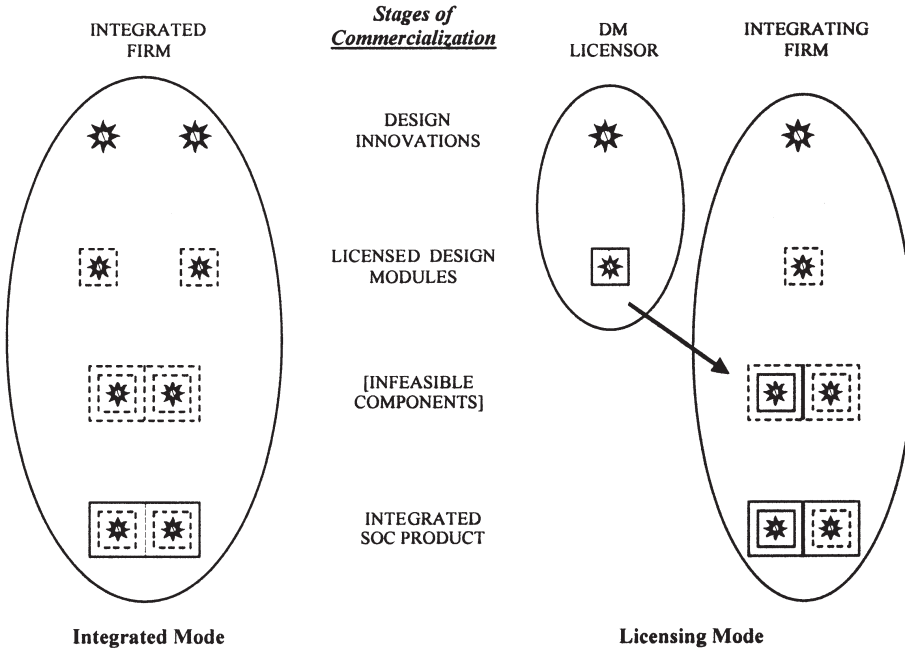

Figure 4 Integrated and licensing modes under SOC integration.

specialized chips), the critical change being witnessed is the migration of a substantial portion of the circuitry, the heart of the system, on to the SOC.

Lacking the possibility of a components mode, the emerging SOC-based segment of the semiconductor industry features a healthy competition between a networked industry structure based on the licensing of DMs and firms pursuing integrated modes using largely in-house designs (Figure 4). Which of these two structures will eventually dominate, and how this is likely to vary by industry segment, can be evaluated by comparing their associated organizational costs. Moreover, these organizational costs are likely to change over time as initiatives to reduce the transaction costs in licensing that we discuss in Section 3.5 play out, and organizational capabilities in integrating outsourced DMs evolve.

An integrated mode for SOC anticipates the design of entire ICs within a single firm that has all the requisite technology in-house. These technologies may have either been developed internally or obtained through the acquisition of innovative firms. However, other firms may own legal IP rights that can block the use of these technologies, making passive, IP-only licenses (typically, as a part of cross-licensing arrangements) necessary to use them. In general, the integrated mode is a workable model for SOCs, and corresponds to the approach that many large semiconductor firms have initially taken. Integrated modes economize on the many transaction costs of (active) licensing markets for DMs discussed below. Integrated firms also typically own their own manufacturing facilities, which can provide further co-ordination

advantages over licensing when there are complementarities between design and production (Monteverde, 1995; Macher, 2001). In addition, they can use more flexible intra-firm design interfaces, thus avoiding the performance penalties imposed by inflexible and slow-moving industry wide standards.[17]

Despite these apparent advantages, the integrated mode has some critical drawbacks. Integrated firms may not have all the required technologies in-house to design certain SOC products. Even if in-house development is possible without infringing on the intellectual property rights of other firms, the duplicative re-engineering (or inventing around) required may still be costly and time consuming. 'Buying' the needed technologies by acquiring other firms is also somewhat costly, involving the use of highly imperfect merger markets. Most importantly, integrated modes sacrifice the benefits of modular innovation, namely, targeted market incentives for excellence in each DM (as against the end-product), and fertile experimentation in alternative technologies and approaches. Furthermore, the internal political status quo that typically facilitates co-ordination across design domains under the integrated model can become a liability as it may actually block the adoption of best-in-class design elements from outside.

3.4 Transaction costs in SOC licensing markets

In comparison, the licensing of DMs may appear to be an attractive alternative to integrated modes, but licensing markets are also plagued with many transaction costs, to which we now turn in detail. These contractual difficulties are aggravated by the fact that innovation in the industry is extremely fast paced and licensing delays cannot be easily countenanced. An industry group estimates that the time required to locate, evaluate and license a DM is currently on the order of 5 months.[18] By contrast, the time between introductions of new models of personal computers, an indicator of the pace of innovation in electronic systems, has shrunk in recent years to 3 months (Curry and Kenney, 1999).

Licensing markets in DMs are plagued by four types of interrelated transaction cost problems described in Somaya and Teece (2001)—respectively: technological interconnectedness; diffuse entitlements; value allocation; and monitoring and metering.[19] These problems can be indirectly linked to the sources of transaction cost

[17]Because the interests of participants may diverge, industry standard-setting organizations can suffer from some of the more severe costs of bureaucracy. In particular, it may take longer to reach initial agreement and to implement changes than in a hierarchical organization because of the difficulty of establishing a consensus. For these reasons, consensual standards tend not to evolve quickly enough to meet the needs of fast moving technology domains, and individual firms can often design higher performing systems if they do not conform to the standard.

[18]Virtual Component Exchange presentation in Santa Clara, CA, July 27, 1999.

[19]Two other types of transaction cost, relating to the *transfer of tacit know how* and the *strategic isolation of rents* from complementary assets (Somaya and Teece, 2001), are less relevant in DM licensing. We have also excluded from our analysis here the ordinary market-making transaction costs of locating

cited in the traditional literature; however, the archetypes presented here are more analytically useful in the high-tech context. Each of these, in turn, are slowing down the adoption of DM trading in the industry and forcing market players to seek out solutions to mitigate them.

When implemented in the same SOC, DMs need to be adapted and integrated with each other. Typically, these needs cannot be entirely foreseen, and consequently such *technological interconnectedness* implies that licensing contracts are somewhat open-ended, making it ambiguous as to who is responsible for solving problems that arise in integration. Licensing problems due to technological interconnectedness are reflected in the high levels of warranties and after-sales engineering support that DM suppliers are required to provide, and in the frequent complaints heard from licensees about lack of 'co-operation' from DM suppliers in solving their design problems. While 'plug and play compatibility' standards for DMs are a stated industry goal, it is still some distance from realization. Moreover, industry-wide standardization may not be a panacea for all cases. Where the technology is extremely fast moving, bureaucratic, politics-ridden public standards bodies may be too slow to co-ordinate the development of cutting edge design platforms.

A second source of transaction costs—*diffuse entitlements*—arises from the typically unclear allocation of IP rights for inventions in the industry. It is usually very difficult to identify beforehand all firms that own the IP rights that cover any given technology, leaving the parties exposed to substantial liabilities in the event of future litigation. This ambiguity arises not only because the technological domain is complex and rich in patents, but also because uncovering applicable IP rights is expensive and time consuming, especially when many relevant patents are yet to be issued. Further, patentees have incentives to delay, strategically, issue of their patents in order subsequently to hold up potential IP licensees for more rents after they have committed to a particular technology. Consequently, the DM licensing arena has seen licensee demands for indemnity against IP litigation, which can be very expensive to provide, especially for small independent DM suppliers.[20]

Given the large uncertainties in the commercial prospects of technologies, *valuation* differences between the parties are notorious for causing impediments in licensing transactions between firms (Merges and Nelson, 1990, 1994). Moreover, this is compounded by the fact that in multi-invention products, any technology is by definition used jointly with other technologies, making it difficult to evaluate any single

and matching buyers and sellers, which are rapidly being reduced by the internet and B2B market-places.

[20]Protection is being sought not only for design patents, but also for related process patents needed to fabricate the chips ('Legal designs,' *Electronics Times*, March 30, 1998). Nascent insurance markets have begun to form in this area ('Want insurance with that chip,' *Electronic News*, December 3, 2001), including both third party insurance and indemnification offered by mainstream IC manufacturers such as TI. However, it remains to be seen how effective IP insurance is in overcoming critical market inefficiencies.

technology's contribution to the generated surplus. Legal uncertainties about the strength and scope of IP protection covering an invention further compound the valuation problem.

Finally, transaction costs also accrue from the *monitoring and metering* needs of licensing agreements, which exacerbate the contracting problems in each of the categories above. When DMs are licensed, it is very difficult to determine, in advance, appropriate measures for its use (of concern to the licensor) or its performance (of concern to the licensee). Although 'field of use' (i.e. application, region, etc.) may be limited by contract, the licensee invariably has some room to maneuver, which can cause unanticipated losses to the licensor. Monitoring and auditing problems also make it difficult to evaluate which ICs actually use the licensed DMs, and to determine appropriate license fees if licensees reverse engineer or modify the licensed design. Absent robust tools to verify the performance of licensed DMs, licensors may also be concerned about the 'quality' of designs they are getting, and about 'allocating blame' for failures down the road. Technologies are being developed to address some of these measurement issues by defining objective specifications for evaluating and testing DMs. For example, one start-up, SiidTech, markets 'silicon fingerprinting' technology that can be used for tracking the use of Dms (*Semiconductor Business News*, 2000a).

The second and third columns of Table 3 summarize the discussion so far, highlighting both the nature of organizational costs and well as their source.

3.5 Dynamic shifts in transaction costs of licensing

The framework we have used has so far adopted a somewhat static view of comparative transaction costs among alternative organizational modes. However, as Williamson emphasizes, transactions operate within an institutional environment, which is susceptible to strategic influence by the transacting parties (Williamson, 1993). The framework can thus be extended to serve as a guide for strategy development, particularly in a dynamic context, through its implications for institutional changes that firms may support in order to advance (or not) the licensing mode, which is currently disadvantaged by various transaction costs. Chip firms and their partners are currently pursuing a combination of technical and institutional changes to reduce the costs of licensing relative to those of the integrated mode.

First, DM providers are experimenting with licensing different kinds of DMs to mitigate licensing costs. DMs come in three formats that are differentiated by their extent of embodiment, in increasing order, as 'soft', 'firm' and 'hard' DMs.[21] Soft modules and hard modules reflect the advantages and disadvantages associated with markets for the ideal-type 'inventions' and 'components' respectively. Hard modules permit the fastest implementation because they have been verified for performance,

[21]Hard DMs are provided as mask-level data that is specially adapted to the process technology of a particular manufacturer, such as a foundry, while less embodied soft DMs provide a more abstract description of architecture and algorithm with no physical layout information. Firm DMs lie somewhere in between.

Table 3 Relative costs and benefits of licensing and integrated modes

Mode	Costs	Source of cost	Potential mitigating factors
Licensing mode	Problems with co-ordinating and solving design problems across firm boundaries	Technological interconnectedness	Effective 'modularizing' public standards
	Inability to identify and contract with IP owners, without opportunism	Diffuse IP entitlements	Early verifiable IP disclosures; corrective DM trading norms/rules
	Time-consuming disputes over DM valuation	Valuation difficulties	Valuation intermediaries; well defined IP rights; trading rules and arbitration
	Inability to quantify and detect breach of contract	Monitoring and metering problems	Technological monitoring solutions; standardized performance metrics; trading rules
	Slow-moving industry standards for DMs that compromises performance	Bureaucratic and political public standards bodies	No real solution
Integrated mode	Lacks targeted incentives for creating cutting edge innovative DMs	Governance-based co-ordination within the firm	Lower costs to acquiring and integrating innovative start-ups
	Poor experimentation with alternative innovative solutions to design problems	Governance-related intra-firm cognitive limitations	
	Less likely to incorporate (or license out) best-in-class DMs	Internal political opposition	No real solution

NB: This table appears to document only costs and no benefits, but the benefits of the licensing mode show up as costs of the integrated mode, and vice versa.

area and timing, which eliminates some of the most time-consuming tasks of SOC design. Soft modules, by contrast, offer much greater flexibility for adaptation to a specific application, but they have only been verified for functionality and require lengthy additional design and verification work. Soft modules also entail higher

licensing costs, due to the risk from reverse engineering, and problems associated with technological interconnectedness and diffuse entitlements.

Reflecting this trade-off, Advanced RISC Machines (ARM), an experienced vendor of 'reduced instruction-set computing' (RISC)-based processor modules, only makes hard versions of its DMs available in the early stages of the product cycle. As the design becomes more commonly used and experience with it accumulates, ARM starts making 'softer' versions available and allowing licensees to adapt it more closely to their needs.

Some firms have also developed technological solutions that, as suggested by researchers in other contexts (von Hippel, 1998), can help reduce transactions costs in licensing. Artisan Components, a provider of design libraries, has created a software tool that places a 'watermark' on DMs, which can be used to overcome monitoring problems in tracking their use.[22] IP Valuation, a Silicon Valley start-up, markets an algorithm for valuing DMs based on the use to which it will be put and the structure of the deal (e.g. whether it is based on up-front fees or running royalties) (Goering, 1999b). A New Hampshire firm, Topdown Design Solutions, has generated a 'simulation model' that allows a soft DM to be evaluated by potential customers without revealing the code in which it is written, thus reducing concerns about reverse engineering (Steffora, 1999a)

Meanwhile, various industry-wide consortia have taken on the challenge of reducing the transaction costs of DM licensing by creating industry-wide standards for SOC design and reuse and new institutional arrangements for DM trading. The current institutional drive for SOC standards is led by a broad coalition of firms who came together in the Virtual Socket Interface Alliance (VSIA) to establish open, plug-and-play compatibility standards (so called 'virtual sockets') in semiconductor designs.[23] When established in September 1996 with 35 founding members, VSIA was largely comprised of leading electronic design automation (EDA) software firms, DM vendors, and several prominent Japanese electronics firms. But other firms, including the large integrated industry leaders, soon joined in, and VSIA now includes virtually every significant player in the semiconductor industry.

VSIA's work, while still incomplete and subject to the normal delays and conflicts of consensual standard-setting, promises to lower the costs of reusing and trading designs not only by reducing the technological interconnectedness between DMs, but also by setting up techniques for testing and measuring the performance of designs. By February 2002, VSIA had released its specifications for 17 standards,[24] including on-chip buses, system level hardware description, and mixed signal ICs, and was engaged in efforts to encourage their use by participating firms.

[22]The company has also submitted the technology to VSIA as a possible future standard (Goering, 1999a).

[23]See the VSIA website: www.vsi.org/about.htm. The VSI Alliance is chartered to define, develop, authorize, test and promote open standard specifications relating to data formats, test methodologies, and interfaces.

[24]Personal communication with VSIA spokesperson, February 12, 2002.

A market-place for the trading of DMs has been built by another industry group, the Virtual Component Exchange (VCX), which was created in October 1998 through the joint initiative of 'Scottish Enterprise' (a Scottish economic development agency), and a few major players from VSIA.[25] VCX has addressed business and legal issues related to trade in DMs through the development of standard contracts, monitoring systems and customized arbitration services. Since October 2000, the VCX has also been operating an on-line exchange where potential customers can evaluate and license DMs. By June 2002, they had 350 DMs listed for trading.[26]

Other institutional efforts at promoting a DM market are also underway. In May 2000, some major Japanese electronics firms formed a Japan-centric DM exchange called IPTC. Meanwhile, a plethora of private efforts have also mushroomed, including 'EDA portals' such as SiliconX, SpinCircuit and Toolwire, and licensing intermediaries such as HelloBrain.com and Yet2.com. So far, these ventures claim, at least publicly, to be working together on complementary aspects of creating a DM market. However, in March 2000, Design and Reuse, a B2B licensing firm with its own DM catalog, split away from the Silicon Integration Initiative (SI2) led industry group (which includes VCX) that was developing a common XML tagging schema for classifying DM catalogs.[27]

By reducing transaction costs, these technical and institutional solutions are collectively fostering the growth of the nascent market in DM licensing. For SOC-focused firms, both integrated and licensing modes are feasible, but each brings different organizational costs and benefits. Further, as summarized in the right-hand column of Table 3, various managerial, technical and institutional efforts can mitigate specific organizational costs in each of these modes. In the next section, we look at the strategic responses of various actors in the industry to this emerging SOC scenario in the context of their historical capabilities and the opportunities to tilt the organizational advantage in their favor.

4. In search of strategy

Organizational modes in semiconductors are naturally chosen based on more than just the costs and benefits described in Section 3. In particular, pre-existing differences in capabilities and DM ownership have had an important impact on organizational choices. Based on these differences, the semiconductor industry has broadly split into two camps with respect to strategies for the SOC era. The first camp consists of large integrated firms that currently own the bulk of the industry's DMs. These firms are

[25]See VCX website: www.thevcx.org. As of June 2002, VCX had forty-four members, including a broad range of semiconductor manufacturers and designers.

[26]VCX statistic from IP Direct Newsletter (VCX newsletter), June 7, 2002, accessed June 8, 2002 on-line at http://www.thevcx.com/web/vcx_press.nsf/webipdirectall/ipirect16!OpenDocument

[27]Clarke (2000). SI2 represents 'industry-leading silicon systems and tool companies focused on improving productivity and reducing cost in creating and producing integrated silicon systems' (online at: www.si2.org).

maintaining their emphasis on designing and manufacturing internally, taking advantage of external capabilities, i.e. traded DMs, only when necessary. The second camp consists of several specialized players, including smaller design-only firms, customer systems firms, chip foundries and EDA software suppliers, which are developing a relatively new, networked business model of SOC design and manufacture configured around licensing markets for DMs. However, the stark differences between the integrated and networked groups mainly represent starting positions reflecting their respective historical capabilities, and these differences appear to be narrowing over time.

The initial differences between the two camps and their subsequent reduction are evident in the history of VSIA. When VSIA was established in 1996, several large semiconductor firms, led by IBM, Motorola and LSI Logic, expressed reservations about its standardization efforts and continued to pursue their own internal SOC business plans.[28] Even though VSIA's proposals promised industry-wide benefits, integrated firms that were already able to achieve SOC designs with in-house technologies were hesitant to encourage competition in SOCs by facilitating a market for DMs. But as VSIA's standardization efforts made headway, it drew in most integrated firms, including the early dissenters.[29] By August 1999, VSIA's membership included over 180 firms and institutions, reflecting a broad commitment to common standards from all significant players in the industry.

4.1 Integrated firms

To be considered 'integrated' by our definition, semiconductor firms need only *design* their SOC products with little or no external licensing. However, in addition, many integrated firms also have their own in-house manufacturing divisions. Integrated SOC firms usually fall into one (or both) of two categories: those with strong historic ties to electronic systems divisions in the same company, and those with extensive experience creating application-specific ICs (ASICs) for various end-use markets. Firms falling in the first category, some of which are also leading ASIC suppliers, include IBM, Lucent and Motorola in the USA, NEC, Hitachi and Toshiba in Japan, and Infineon (formerly the semiconductor division of Siemens) and Philips in Europe. ASIC suppliers with no connection to internal systems divisions include LSI Logic and Texas Instruments in the USA, and STMicroelectronics in Europe.

An important subset of these firms, shown in Table 4, have long relied on

[28]Brown (1996). This response on the part of large integrated firms is not unusual, and parallels the initial response of integrated firms in the automobile industry (Langlois and Robertson, 1995: chapter 5) and Applied Materials, the most integrated firm in the semiconductor equipment industry (Langlois, 1992b), to interface standardization efforts undertaken by the Society of Automotive Engineers (SAE) and Semiconductor Equipment and Materials International (SEMI), respectively.

[29]In March 1999, VSIA removed one of the last barriers to full participation of the major firms, such as IBM, by permitting members to specify which patents would be made available to other members as part of a standard, instead of operating under a presumption of contribution.

Table 4 Worldwide standard cell sales (US$ millions)

1997	1998	Company	1997	1998	% change
1	1	IBM	1532.90	1742.80	13.70
2	2	Lucent Technologies	1318.30	1554.50	17.90
4	3	LSI Logic	724.00	1241.00	71.40
3	4	NEC	938.10	893.60	–4.70
5	5	Texas Instruments	620.20	697.30	12.40
6	6	VLSI Technology	595.00	601.70	1.10
7	7	Hitachi	495.70	401.90	–18.90
9	8	ST Microelectronics	264.70	298.80	12.90
10	9	Alcatel Microelectronics	215.00	260.00	20.90
8	10	Toshiba	273.20	243.80	–10.80
		Top 10 total:	6977.00	7935.40	13.70
		Total market:	9112.80	9729.10	6.80
		Total semiconductor market:	137 203.00	125 612.00	–8.40

Source: Cahners In-stat Group (Arnold, 1999).

pre-configured 'standard cells' (the larger of which are roughly equivalent to DMs) that can be reused in multiple designs, suggesting that they were already well positioned for system-level integration. But even in many of these firms, little communication occurred between IC design teams serving different end-user markets. Consequently, a single function could be re-designed several times within the same company instead of being designed once and reused. However, integrated firms have now recognized the need to adjust their internal organization and design practices to take advantage of SOC opportunities.

Building on their internal culture of modular design, integrated ASIC suppliers are reinforcing their design reuse practices to bridge the design productivity gap. According to a Dataquest survey, the average proportion of an ASIC that was reused from previous designs jumped from 22% in 1997 to 33% in 1998 (Clarke, 1999). Integrated firms are also addressing the tougher challenge of building reusable modules from their vast product portfolios, which were not originally designed for reuse. Firms such as NEC, Motorola and Alcatel Microelectronics even created special task forces for this purpose.[30] However, the initiatives to unpack legacy DMs and make them reusable have often encountered difficulties. For example, the DSP group in Lucent Technologies reportedly opposed efforts to make its designs available to other Lucent ASIC groups because it feared that this would undermine the market for its own stand-alone

[30]Alcatel Microelectronics established an internal 'design factory' and tried to involve the original engineers in the redesign and documentation (Collins, 1998). NEC assembled teams of engineers from different divisions to build up rapidly a portfolio of reusable modules (Cataldo, 1998). And, in 1998, Motorola formed the Advanced Systems Technology Laboratory with an expected staff of about 300 engineers working on both, reclaiming legacy designs and supporting reusability of new designs (Lammers, 1998a).

products (Ristelhueber, 1998). Such conflicts of interest arising out of the diffuse and somewhat long-term benefits of reuse are typical, requiring innovative organizational solutions from many integrated firms.[31]

Integrated firms have also been struggling with transforming internal design practices to enable reuse of *new* DMs. This transformation not only requires otherwise independent design units to adhere to a common design methodology, but also necessitates a major cultural change in the work habits of design engineers. Designing for reuse can almost double the work required to design a DM, while the benefits of reuse are realized later and possibly in some other part of the company. This makes it very difficult to convince design engineers to put in the extra effort. Design engineers also appear to have a 'cultural' bias against using DMs designed by other divisions because they fear unforeseen problems in SOC integration that they are not equipped to fix. LSI Logic and Texas Instruments, which were pioneers in design reuse, had a head start in dealing with many of these problems,[32] but other firms, such as IBM and NEC, are catching up.[33]

The emphasis on design reuse in integrated firms underscores the preference for in-house capabilities in their SOC strategy. When gaps in internally available intellectual property are perceived, integrated firms often prefer to augment their DM portfolio through acquisitions or joint ventures rather than turn to licensing. Intel, for example, entered into a joint design project with Analog Devices and acquired DSP Communications to bolster its capabilities in the area of digital signal processing (DSP) (Lammers and Ohr, 1999). Lucent and Motorola are similarly collaborating in their StarCore joint venture to develop DSP DMs (Fuller and Gold, 1998). And major ASIC suppliers such as LSI Logic have been reinforcing their stock of analog DMs through acquisitions.[34] Prima facie, it appears that acquisitions and collaborations have provided a viable mechanism for integrated firms to remain effective in the SOC world by absorbing new technologies developed externally.

Integrated firms are also awakening to the value of the emerging market in DMs to address SOC opportunities. In most cases, this appears to be a one-way street, with integrated firms licensing external DMs for use in their own IC products but not

[31]For example, NEC faced problems convincing its business units to devote resources to developing DMs that would mostly benefit parts of the company outside their own divisional profit centers. Toshiba sought to overcome similar internal organizational resistance by adopting an internal licensing program that enabled business units to internalize the company-wide benefits (Cataldo, 1998).

[32]LSI Logic started a DM reuse program called 'CoreWare' in the early 1990s. Texas Instruments also began early, and had made a company-wide database of about 100 DMs available to its engineers by 1998. The company also maintains a slim 'IP rescue squad' of about a dozen engineers to help engineers deal with the problems of reusing DMs (Lammers, 1998b).

[33]Arensman (1999). The number of cores available in IBM's core library rose from 30 in 1996 to about 100 in 1999. NEC set up a 50-person group at its US subsidiary to help the company convert from custom ASIC design work to a more reuse-oriented approach.

[34]LSI Logic bought the optical read channel division of NeoMagic (*Electronic Buyers' News*, 2000).

licensing out. LSI Logic, for example, used the MIPS RISC processor DM in its IC design for Sony's highly successful PlayStation video game (Clarke, 2000). Over time, this trend appears to be intensifying; IBM expects that up to half its DMs will eventually come from outside vendors (Wade, 1999).

Integrated firms do not necessarily view the use of external DMs as a threat to their dominance of the SOC market. SOC solutions require significant expertise in application-specific system design, as well as a deep understanding of the interactions between DMs and other elements, including software—areas where integrated firms have much to offer. Some integrated firms also see their competitive advantage in leveraging unique, high-value DMs that they own, and see no harm in licensing the more commodity portions of the chip design from external sources to economize on the use of valuable internal engineering resources. Moreover, only integrators who have a good system-level understanding of the design and have contributed a significant fraction of the actual DMs used can provide chip-level assurances, which are currently valued highly by customers. Thus, according to the prevailing view, an in-licensing program is a useful complement to the integrated firms' primarily in-house strategic approach.

Integrated firms currently seem reluctant to license their DMs separately from their integration and fabrication services. In July 2000, Motorola decided to start an out-licensing program for its DMs,[35] but this has so far remained an isolated case. Integrated firms generally regard their key DMs as core company assets, and are hesitant to license them, especially in the face of opposition from internal groups that rely on these DMs for their competitive edge in building SOC solutions. In addition, licensing out incurs all the transaction costs of licensing markets discussed above. Integrated firms are particularly wary of dedicating the engineering support required to overcome problems with technological interconnectedness, as these resources are scarce and have higher-value uses in designing the integrated company's own chips.

A related barrier to licensing out by integrated firms is the fear among potential licensees of opportunistic behavior by the integrated firm, who may also be a competitor. This is a problem similar to that addressed by prior research in the context of component procurement (de Figueiredo and Teece, 1996), and is driven by the weaker incentives the integrated firm has to provide the necessary support to external engineers, relative to its own. In two cases where a particular DM has shown sufficient promise to merit a licensing program (Philips' TriMedia multimedia processor core and Hitachi's SuperH embedded processor core) (*Semiconductor Business News*, 2000b, 2001), it has been spun off into a separate company so that the risk of opportunism by the parent (integrated) firm would be reduced.

Looking ahead, however, the hand of integrated firms could eventually be forced in this matter. If the markets for DMs are successful and licensing becomes routine and low-cost, integrated firms may be compelled to compete DM for DM (much as

[35]Edwards (2000). Motorola was motivated by its keenness to retain erstwhile customers of its ICs, who are migrating to an SOC business model that involves DM providers and foundries.

vertically integrated system firms were eventually obliged to compete in component markets) by competition from the networked (dis-integrated) firms to which we now turn.

4.2 Networked firms

Start-ups and other firms that lack all the in-house capabilities of integrated firms have been experimenting with a licensing mode approach of the type discussed theoretically in Section 3. These firms execute SOC projects through a networked value chain involving some combination of design firms, customer systems firms, EDA software firms, integrators and contract manufacturers. The networked business model is still in its early stages, and depends critically on the growing standards and institutions described in Section 3.5. Moreover, it emerged during one of the worst downturns in the industry's history, and perhaps only after the current downturn (which began in 2001) plays out will we be able to evaluate its success.

Independent DM providers. As the industry's attention turned to third-party DMs in the 1990s, many independent DM firms mushroomed, and over 200 were set up by 1998 (Brown, 1998). However, several of these firms focused on commodity DMs, such as those meeting new public standards (e.g. USB), and did not have defensible long-term appropriability positions. Faced with the many difficulties of making DM licensing work in a nascent market, many firms failed or were acquired, and their number quickly fell to less than 100 (Steffora, 1999b).

In fact, only a very small number of start-up firms have actually been successful as DM providers. In 2001, three such firms, ARM, Rambus and MIPS, together accounted for above 40% of the DM licensing business (Gartner Dataquest press release, April 30, 2002, Egham, UK). A second group of firms, including inSilicon,[36] and EDA software firms Synopsys and Mentor (discussed below), have built a successful 'commodity DM warehouse' model based on licensing a broad range of relatively low-value DMs, many of which were acquired by buying out start-up firms.

ARM, established in 1990 in the UK to develop RISC microprocessor designs, was one of the earliest entrants into DM licensing. With over fifty licensees and a strong presence in many application markets, it is arguably the most successful firm in this business.[37] Two other processor DM companies, MIPS and DSP Group, are also considered successful today, but they took many years to develop their designs and customer relationships into a sustainable business. Rambus, a 1990 California start-up,

[36]inSilicon, formerly the semiconductor IP division of Phoenix Technologies, has a large customer base, including Compaq, Fujitsu, Hewlett-Packard, Hitachi, Intel, LSI Logic, Lucent, Philips, Siemens, Sony, STMicroelectronics and Toshiba, and has been adding to its DM library through acquisitions of smaller firms (Goering and Quan, 1998).

[37]In September 2000, the company had a market capitalization of over $10bn on half yearly (2000) revenues of $65.4m.

has capitalized on Intel's selection of its PC memory interface as the next-generation standard, and built up a substantial licensee base.[38]

These successful start-up DM firms appear to have pursued a number of key strategies. First, they focused on design niches that have multiple disparate applications, where licensing modes have an advantage over integration due to the ability to access a broader market. Second, they have avoided DMs that rapidly lose value through easy duplication of their functionality, e.g. public standards-based one-time designs. Instead, they have preferred 'architectural' modules, such as processors, which improve over successive generations. Third, these firms have implemented effective appropriability strategies to protect rents from their knowledge assets. Not only have they used legal intellectual property protection where possible, but also harnessed other mechanisms such as rapid time-to-market, complementary capabilities in sales and support, and network effects.[39] In particular, network effects resulting from the growth of compatible IC software and DM-specific engineering talent in system integration, as well as the DM's proven robustness in multiple applications, have been significant success factors.

Successful firms have also been diligent in providing adequate sales and support. In a business where technological interconnectedness is a pervasive problem, these firms have committed the resources to help diagnose and solve customer problems, even though the ratio of support to design effort can often be as high as three-to-one. DM providers with a commodity warehouse model have also been attentive to these needs, typically capitalizing on scale and scope economies in providing support for multiple DM offerings, which are not available to start-up DM providers. In addition, these commodity warehouse firms offer designs that are considered more reliable and proven, and provide credible warranties (i.e. someone to sue) in the event of unforeseen problems with the design.

EDA software suppliers. EDA software, which automates various stages of chip design, simulation and verification, emerged as a separate industry segment in the 1980s. EDA firms also help engineers develop design methodologies, and have been in the vanguard of promoting design practices that would support a DM licensing market.[40]

EDA firms have long provided libraries of pre-tested design elements (called 'cells') for use with their tools. Typically, these cell libraries are tailored to the design rules of

[38]Rambus' position in the industry is highly controversial and the company is facing multiple lawsuits challenging its patents and practices.

[39]DMs can be legally protected by an overlapping set of patent, copyright and semiconductor maskworks protection rights, but none of these are a good fit to the precise kind of 'invention' involved in creating DMs. That is not to say they are irrelevant. ARM has acquired over 60 patents, and recently sued another firm, picoTurbo, over elements of the latter's microprocessor design.

[40]Michael Keating and Pierre Bricaud, respectively from Synopsys and Mentor Graphics, two leading EDA firms, literally 'wrote the book' on design reuse (Keating and Bricaud, 1998).

one or more semiconductor manufacturers. Library cells can be as small as a few dozen logic gates, and are the basic building blocks from which modules and entire chip designs are constructed.[41] As we have seen in the previous section, EDA firms, such as Mentor Graphics and Synopsys, have been quick to make the jump from library provision to DM distribution, in part by acquiring other DM firms and licensing their DMs along with quality customer support. Mentor sold its cell libraries in early 2000 and is now only in the DM business, but Synopsys continues to license both.

The third major EDA firm, Cadence Design Systems, has adopted a very different strategy, acquiring no DMs for its own portfolio, but specializing in design integration services for SOC products using third-party and customer modules. The design services business appears to have been a success for Cadence, and in July 2000, the company spun out the design services division as a stand-alone company under the name Tality.

Foundries. Earlier in this paper, we discussed how the emergence of the CMOS standard in semiconductor manufacturing and improvements in design software led to the creation of a 'fabless' segment in the semiconductor industry. Early fabless firms relied on the excess capacity of vertically integrated chip manufacturers, but dedicated contract manufacturers (known as 'foundries') were soon established, beginning in the late 1980s.

Foundries rely entirely on IC manufacturing contracts from other firms to keep their rapidly depreciating capital equipment in constant use. To attract and retain these customers, many of whom are working on SOC products, foundries have started acting as brokers for DMs and offering design services. Their key allies in this endeavor have been independent cell library providers that tune their products to the design rules of the sponsoring foundry. A notable deal between TSMC, a leading Taiwanese foundry, and Artisan Components of California in August 1998 offered 'free IP', for which Artisan forgoes the up-front licensing fee that is typical in the industry, and instead receives royalties from TSMC for each chip fabricated using its design cells. The free IP model was quickly copied by TSMC's chief rival United Microelectronics (UMC), also of Taiwan, who has IP arrangements with Artisan and Silicon Access, among others.

Artisan's new strategy led many small cash-constrained cell library providers to exit the business, and even large firms such as Mentor sold out to focus their energies elsewhere. Independent DM providers initially looked askance at the 'free IP' model, and questioned whether foundry relationships added as much value as their other licensing deals (Brown, 1998). Nevertheless, most DM firms, including ARM, ultimately decided that they could not ignore the rapidly growing customer base of the foundries and signed deals to make foundry-specific versions of their modules available.

To complement this DM licensing activity, foundries have also set up design services

[41]Logic gates are the basic building blocks of ICs and consist of approximately four transistors that deliver a binary output in response to inputs received.

businesses that Dataquest has dubbed 'ASIC Lite' because they do not offer the full range of design services available from regular ASIC suppliers (Smith, 1999). For the time being, the emphasis at the foundries is on doing what is necessary to keep capacity utilized, with other businesses developing into profit centers only in the distant future (Lapedus and Chen, 1998). Nonetheless, the new foundry model has increased competitive pressure on integrated ASIC firms because it siphons off customers who might otherwise absorb some of their manufacturing capacity or even buy their SOC chips (Fraone, 1999).

Systems firms. Systems firms, the assemblers and marketers of electronics end-products to consumers, are confronted with difficult choices in the SOC world. Complete SOC solutions offered by integrated firms not only diminish the role of their system-level know-how and system design capabilities, but also limit their ability to differentiate effectively their products.

However, systems firms can also exploit opportunities emerging from the networked side of the SOC industry. The availability of design integration services from foundries and specialized firms, such as Tality, along with the availability of licensed DMs, allows systems firms to exercise more control over the SOC design process for their products. Moreover, many systems firms have long had their own IC design teams, which are being positioned to act as internal SOC integrators, using licensed-in DMs. For example in 1999, Quantum Corporation, the volume leader in hard disk drives (HDD) at the time, licensed a microcontroller module from NEC, a DSP module from Texas Instruments, and a 'read-channel' module from Lucent to create a single-chip solution for its drives.[42] The company's strategy is to control the design to leverage its system-level understanding of the application, and dual-source the fabrication to maximize its leverage in price negotiations.

But not all system companies choose to tap into the networked business model in this way; some are content to fine-tune an application-specific reference design from an (integrated) SOC supplier.[43] These firms are then free to focus their energies on the marketing end of the business—identifying consumer preferences, and harnessing emerging technologies to satisfy them. Moreover, reference designs can typically be adapted to meet a systems firm's product differentiation needs by using proprietary software. For example, Cirrus Logic, a fabless firm that introduced the data storage industry's first single-chip solution, allows its customers to port their own software to the SOC's microcontroller, providing Quantum's competitors with a somewhat different commercialization alternative to the one used by Quantum (Lammers, 1999).

[42]Lammers (1999). In October, 2000, Maxtor, a rival firm, announced that it was acquiring Quantum's HDD business.

[43]A reference design of this type is known as a 'customizable ASSP' (application-specific standard product).

5. Discussion and conclusions

Firms experiencing technological change of the type driving the SOC movement typically face two central sets of strategic questions.[44] First, they would like to know how their industry is likely to be transformed by such an environmental shift. How will industry structure change? Which sets of business models are likely to win out? And, which external developments are likely to alter the balance between these business models? Second, they would like to know how best to respond to the technological change. What products, markets and technologies should they focus on, and what competencies or resources would they need? How can they reinforce these strategic positions? Should they consider acquisitions, licensing (both in and out), or divestment?

The framework we have employed in this paper highlights organizational choice as a key variable in these strategic calculations. An SOC design can be completed within an integrated organization, through a series of transactions between licensing entities, or using a combination of the two modes The analysis summarized in Table 3, above, shows that transaction costs stemming from various sources discussed earlier are the primary drawbacks of using licensing modes. However, through modularization, licensing markets also provide more targeted economic incentives, facilitate greater innovative experimentation, and enable widespread use of best-in-class DM technologies in SOC commercialization.

Integrated modes currently enjoy the upper hand in SOC, primarily due to the initial distribution of industry assets and the lack of supporting licensing institutions at the dawn of the SOC era. However, various factors may shift the balance over time. The success of standardization efforts in modularizing IC design and the growth of institutional arrangements (and technologies) that support DM trading are likely to lower transaction costs in licensing modes, allowing them to become more effective than governance-intensive integrated modes.

Integrated modes, in turn, may benefit from other developments, such as the emergence of effective markets for mergers and acquisition. If new technologies can be successfully absorbed within integrated firms through such markets, some—but not all—of the natural advantages of licensing modes could be neutralized. Moreover, even if SOC standardization efforts succeed, technological developments may render bureaucracy-laden public standards too ineffective in some IC products where technological interconnectedness is high, giving integrated modes, with their internally governed proprietary interfaces a distinct competitive edge.

In response to the second set of strategic questions we posed, firms in the

[44]It is worth noting here that SOC integration may not be attractive for all segments of the industry, or even for all components in a system. Technical hurdles and competition from PCB-based component modes may be a significant factor in many cases. Where the cost and functional (size, power and system speed) advantages offered by SOC are not significant, and fast-paced innovation requires the freedom to mix and match components, PCB-based component architectures are likely to continue (e.g. high-end, short-cycle products, such as servers and Internet routers).

semiconductor industry are clearly pursuing strategies consistent with that mode, licensing or integrated, which favors their own capabilities. Historically integrated firms, for example, currently view their high-quality DM libraries, system design capability, and connections to in-house fabrication as distinct advantages in pursuing an integrated approach to SOC commercialization. By contrast, smaller firms and start-ups, recognizing their limited capabilities, have sought to fill key roles (e.g. processor modules) in the emerging networked licensing mode, and, in some cases, have even extended themselves into allied activities (e.g. integration services) where they have perceived opportunities. As the context conditions for more effective licensing modes improve, integrated firms will need to become more open to the licensing (in and out) of DMs, and loosen their ties to in-house DMs that do not measure up to market alternatives. Similarly, if ongoing efforts are unable to mitigate transaction costs in licensing markets, many network-side firms may be forced to rethink their focused strategies and consolidate into more integrated structures.

The framework also provides an insight into the strategic positioning of different firms within the SOC market. The choice of integrated firms to remain within the integrated mode has spurred them to identify lacunae and build new capabilities to fill them. Many large firms, for example, acquired or jointly developed new DMs to address gaps in their technology portfolio and leverage themselves into the integrated SOC business. By contrast, firms on the networked side have pursued strategies to improve their collective performance by taking the lead, for example, in standardizing design modularity. In many cases, networked firms, such as foundries, EDA suppliers and systems integrators, have also enhanced their own value propositions by providing services that are in demand in the licensing market.

The framework also suggests ways in which firms can influence their institutional environment to their advantage. For example, the standardization efforts to make licensing more effective are open to strategic influence from industry participants. Firms may choose to encourage or impede these efforts depending on whether or not a licensing mode will benefit them. Indeed, we have seen that large integrated firms were not very helpful to VSIA in its early stages. Only when it became evident that there was considerable momentum behind VSIA did they join in to make sure that the new standards would not be detrimental to their interests. Similarly, networked firms were in the vanguard of organizations such as VSIA and VCX as they had the most to gain from the success of licensing markets.

Moreover, once such market facilitating efforts gain momentum, individual firms and other new coalitions begin to address gaps in the evolving structure, thus creating positive spillovers for the entire process. For example, as the licensing of third-party DMs made inroads, new design portals, DM catalogs, and DM evaluation and encryption firms have mushroomed, which in turn has begun to lower transaction costs further in DM licensing markets. Thus, individual strategic actions can have a disproportionate impact on eventual industry outcomes.

In this article, we have provided an analysis of the early-stage industry structure and

resulting firm strategies for SOC integration in the semiconductor industry. Based on our research in the trade press and interviews with a small number of experts, we have sought to present systematically a number of key facts about the SOC phenomenon, and inductively organize them around an emerging theory of organizational choice in highly innovative contexts. We believe that the general approach of our analysis can be extended to other multi-invention industries (such as biotechnology), although our specific conclusions may have little external validity outside the SOC-centric electronics industry.

Overall, the theoretical premise that both integrated and licensing modes have their merits for SOC integration appears to have been borne out. While historically integrated firms began with an integrated approach to SOC, smaller design firms, foundries, customer systems firms and EDA software producers appear to be successfully pioneering a networked model based on licensing markets. The success of ongoing institutional and infrastructure developments will determine the prominence of each of these organizational modes in the future.

We have also extended the Somaya–Teece framework to include dynamics (in the endogenous relationship between firm behavior and evolving industry structure) and history (in the role of pre-existing capabilities when discontinuous change occurs). Although we have not focused on it in this paper, the framework could also be extended to address important questions of public policy.

Acknowledgements

Some data were generously provided by Dataquest, part of the Gartner Group. Linden gratefully acknowledges support from the Alfred P. Sloan Foundation through grants to the Competitive Semiconductor Manufacturing Center's E-Commerce Project and HR Group at UC Berkeley, and to the Berkeley Roundtable on the International Economy (BRIE). Somaya gratefully acknowledges research support from the UC President's Initiative for University-Industry Research and the Ryoichi Sasakawa Young Leaders Foundation. Useful comments were provided by Fabrizio Cesaroni, Larry Goldstein, Bronwyn Hall, David Mowery, Peter Sandborn, three anonymous referees and conference participants at the Academy of Management meetings (Toronto, 2000), and an anonymous referee for *Industrial and Corporate Change*.

Address for correspondence

Deepak Somaya, R. H. Smith School of Business, University of Maryland, College Park, MD, USA. Email: dsomaya@rhsmith.umd.edu

References

Arensman, R. (1999), 'In silicon's vise,' *Electronic Business*, March.

Arnold B. (1999), 'It was a very bad year,' *Electronic Business*, May.

Borrus, M. (1988), *Competing for Control: America's Stake in Microelectronics*. Ballinger Publishing: Cambridge, MA.

Brown, P. (1996), 'Cautious approach to VSIA,' *Electronic News*, September 23.

Brown, P. (1998), 'Changing IP market might mean trouble,' *Electronic News*, September 7.

Cataldo, A. (1998), 'Japan struggles with design reuse in SOC era,' *Electronic Engineering Times Interactive*, December 3.

Clarke, P. (1999), 'Early users of IP cores could gain an edge from design reuse,' *Electronic Engineering Times Interactive*, June 22.

Clarke, P. (2000), 'Design and reuse exits IP catalog standards program,' *Electronic Engineering Times*, March 20.

Collins, L. (1998), 'Europeans capitalize on design's new world order,' *Electronic Engineering Times Interactive*, March 13.

Curry, J. and M. Kenney (1999), 'Beating the clock: Corporate responses to rapid change in the PC industry,' *California Management Review*, **42**, 8–36.

de Figueiredo, J. M. and D. J. Teece (1996), 'Mitigating procurement hazards in the context of innovation,' *Industrial and Corporate Change*, **5**, 537–559.

Edwards, C. (2000), 'Motorola to step up licensing of its semiconductor IP cores,' *Electronics Times*, July 3.

Electronic Buyers' News (1999), 'SOC market opportunities favor fewer players, says research firm,' November 11.

Electronic Buyers' News (2000), 'LSI Logic acquires design team from NeoMagic,' April 14.

Fraone, G (1999), 'Is the ASIC business model broken?,' *Electronic Business*, January.

Fuller, B. and M. Gold (1998), 'DSP rivals, Motorola and Lucent, become partners,' *Electronic Engineering Times Interactive*, June 2.

Goering R. (1999a), 'IP99: Exec extols free-library model', *Electronic Engineering Times Interactive*, March 25.

Goering R. (1999b), 'Startup looks to put price tags on IP cores,' *Electronic Engineering Times*, February 8.

Goering, R. and M. Quan (1998), 'Phoenix, Sand merge to attain IP critical mass,' *Electronic Engineering Times Interactive*, September 18.

Grindley, P. C. and D. J. Teece (1997), 'Managing intellectual capital: licensing and cross-licensing in semiconductors and electronics,' *California Management Review*, **39**(2), 8–41.

Hall, B. H. and R. M. Ham (1999), 'The patent paradox revisited: determinants of patenting in the US semiconductor industry, 1980–94.' IBER working paper, Department of Economics: Berkeley, CA.

Hart, O. and J. Moore (1990), 'Property rights and the nature of the firm,' *Journal of Political Economy*, **98**, 1119–1158.

von Hippel, E. (1998), 'Economics of product development by users: the impact of 'sticky' local information,' *Management Science*, **44**, 629–644.

Keating, M. and P. Bricaud (1998), *The Reuse Methodology Manual*. Kluwer Academic Publishers: Dordrecht.

Lammers, D. (1998a), 'Motorola sets up lab aimed at systems-on-chip,' *Electronic Engineering Times Interactive*, July 14.

Lammers, D. (1998b), 'Design reuse rules at TI's ASIC operation', *Electronic Engineering Times Interactive*, December 3.

Lammers, D. (1999), 'Cost crunch creates push for single-chip drive,' *Electronic Engineering Times*, May 31.

Lammers D. and S. Ohr (1999), 'Intel, ADI ally to develop DSP core,' *Electronic Engineering Times*, February 8.

Langlois, R. N. (1991), 'Transaction cost economics in real time,' *Industrial and Corporate Change*, **1**, 99–127.

Langlois, R. N. (1992a), *Capabilities and Vertical Disintegration in Process Technology: The Case of Semiconductor Fabrication Equipment*. Center for Research in Management, University of California at Berkeley: Berkeley, CA.

Langlois, R. N. (1992b), 'External economies and economic progress: the case of the microcomputer industry,' *Business History Review*, **66**, 1–50.

Langlois, R. N. and P. L. Robertson (1992), 'Networks and innovation in a modular system: lessons from the microcomputer and stereo component industries,' *Research Policy*, **21**, 297–313.

Langlois, R. N. and P. L. Robertson (1995), *Firms, Markets, and Economic Change: A Dynamic Theory of Business Institutions*. Routledge: London.

Lapedus, M. and S. Chen (1998), 'The wafer chase,' *Electronic Buyers' News Online*, December 16.

Macher, J. T. (2001), 'Vertical disintegration and process innovation in semiconductor manufacturing: foundries vs. integrated producers,' working paper, Georgetown University.

Macher, J. T., D. C. Mowery and D. A. Hodges (1998), 'Reversal of fortune? The recovery of the U.S. semiconductor industry,' *California Management Review*, **41**, 107–136.

Merges, R. P. and R. R. Nelson (1990), 'On the complex economics of patent scope,' *Columbia Law Journal*, **90**, 839–916.

Merges, R. P. and R. R. Nelson (1994), 'On limiting or encouraging rivalry in technical progress: The effect of patent scope decisions,' *Journal of Economic Behavior & Organization*, **25**, 1–24.

Monteverde, K. (1995), 'Technical dialog as an incentive for vertical integration in the semiconductor industry,' *Management Science*, **41**, 1624–1638.

Philips Semiconductors (2002), 'Philips Semiconductors first to market with fully integrated telematics processor,' press release, February 28.

Ristelhueber, R. (1998), 'Shaking up the old order,' *Electronic Business*, January.

Semiconductor Business News (2000a), 'SiidTech rolls out "silicon fingerprinting" for chip tracing, fraud fighting,' February 7.

Semiconductor Business News (2000b), 'Philips spins off TriMedia processor technology as separate company,' March 29.

Semiconductor Business News (2001), 'STMicro, Hitachi plan new company to develop RISC cores,' April 3.

SIA (1999), *International Technology Roadmap for Semiconductors, 1999 Edition*. Semiconductor Industry Association: San Jose, CA.

SIA (2001), *International Technology Roadmap for Semiconductors: 2001 Edition*. Semiconductor Industry Association: San Jose, CA.

Smith, G. (1999), 'Confusion in the "IP" market,' *Electronic News*, March 15.

Somaya, D. and D. J. Teece (2001), 'Combining inventions in multi-invention contexts: organizational choices, intellectual property rights, and public policy.' SSRN working paper (available at: www.ssrn.com).

Steffora, A. (1999a), 'Core evaluation made easy,' *Electronic News*, July 5.

Steffora, A. (1999b), 'IP cores at the crossroads,' *Electronic News*, March 29.

Teece, D. J. (1996), 'Firm organization, industrial structure, and technological innovation,' *Journal of Economic Behavior & Organization*, **31**, 193–224.

Wade, W. (1999), 'Design reuse revolution still trying to get off the ground', *Semiconductor Business News*, March 15.

Williamson, O. E. (1985), *The Economic Institutions of Capitalism*. Free Press: New York.

Williamson, O. E. (1991), 'Comparative economic organization: the analysis of discrete structural alternatives,' *Administrative Science Quarterly*, **36**, 269–296.

Williamson, O. E. (1993), 'Transaction cost economics and organizational theory,' *Industrial and Corporate Change* **2**, 107–156.

Williamson, O. E. (1998), 'Transaction cost economics: how it works; where it is headed,' *Economist-Leiden*, **146**, 23–58.