Technical, Organizational and Business Model Modularity:
Evidence from the Fabless Semiconductor Industry

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March 31, 2021

Abstract:

Modular interfaces enable decentralized creativity and thus rapid innovation. Here we highlight a previously unremarked prerequisite to the benefits of technical and organizational modularity: the need for business model modularity. Using data on fabless semiconductor firms from 1980-2020, we demonstrate how the success of the fabless model required two compatible business model innovations. Our study highlights the potential chicken-and-egg challenge of business model modularity, and suggests the role of industry associations as coordinating mechanisms for resolving such a challenge.

Key words: modularity, business model innovation, semiconductors, trade associations

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1. Introduction

The scholarly interest in modularity in the early 2000s was driven by growing product complexity and questions about how technology development processes might support that trend (Baldwin and Clark, 2000; Schilling, 2000; Langlois, 2002; Pil and Cohen, 2006). Viewed through a modularity lens, the decades that followed were a triumph of modularization, evident both in the technology, in the form of standard technical interfaces, and in the organization of industry, with the entry of specialized firms occupying successful niches (Baldwin and Clark, 2000; Macher and Mowery, 2006). Moreover, innovation that resulted from modularization enabled complex products and novel functionality for a dizzying variety of industries, defying the risk that increasingly complex products would be late to the market (Schilling, 2000).

Indeed, in a focal industry of Baldwin and Clark's (2000) seminal book, *Design Rules*, semiconductors have leapt the bounds of the computer industry and entered such unanticipated realms as transportation, social media, and retail sales. Is variety a trivial, if under-explored, dimension of complexity or is it a distinct phenomenon with its own dynamics? In the semiconductor industry, we trace variety's historical origins and find that the requisite organizational modularity involved the right business models and incentives to create new customer markets.

We follow the ongoing modularity research, which views technical interfaces as *enabling* the partitioning of tasks between organizations, while recognizing that this partitioning is not inevitable (Baldwin, 2012, 2020; Colfer & Baldwin, 2016; MacCormack et al, 2012). We delve into the coordination challenges of an industry in which organizational modularity seems so straightforward as to be taken for granted: fabless semiconductors. Indeed, well-defined technical interfaces allowing for the separation of design from fabrication were assumed to have led to organizational modularity (Mead & Lewicki, 1982; Baldwin & Clark, 2000; Sturgeon, 2007; Funk, 2008; Shih et al, 2009) both within vertically integrated semiconductor firms and, at the industry level, with design-only (“fabless”) and manufacturing-only (“foundry”) firms (Mowery and Macher, 2006; Kapoor, 2013).

But upon further investigation, the industry’s earliest business model experiments suggest that the fabless and foundry industry structure was far from obvious, let alone inevitable. For example, one popular arrangement that the new technical interface enabled had computer makers (customers of semiconductor firms) designing chips and semiconductor firms manufacturing them. The business models of new stand-alone design firms were precariously dependent on the availability of contractible fabrication services at a time when manufacturers preferred design customers with proven demand, such as existing computer makers. The solution to this conundrum was the manufacturing-only “pure-play” semiconductor foundry business model, which required and would seek out a large pool of fabless customers. This chicken-and-egg problem was eventually solved by an industry association that coordinated fabless firms on one side of the technical interface and foundries on the other side, legitimating both business models and helping both sides to survive and thrive.

Our study thus focuses on two questions. First, what factors delayed and later promoted the development of compatible business models that would enable the organizational modularity that had been predicted since the 1970s? Second, what impact did business model modularity have on horizontal specialization and, in turn, variety? A notable aspect of the leading foundry’s business model is to consistently set aside capacity for new firms, thereby supporting newcomers to the fabless industry. Fabless firms continue to occupy largely distinct niches in semiconductor product markets, producing exactly the type of technical modularity that Baldwin and Clark (2000) viewed as essential to supporting complexity.

In updating the familiar story of semiconductors, highlighted by Baldwin & Clark (2000), we trace the changes to business models and industry structure in the 21st century. Our study highlights a previously unremarked aspect of inter-organizational modularity: the need for modular business models that are compatible between the two types of organizations on either side of a technical interface. Business models have been largely understudied in the modularity literature, even though they are recognized as playing an important role in commercializing new technologies (Chesbrough and Rosenbloom, 2002). We thus contribute to the business model innovation literature by identifying a chicken-and-egg problem that can arise across a technical interface. Finally, we document a role for industry associations in coordinating and navigating this chicken-and-egg problem, thereby unleashing unanticipated levels of innovation, variety, and market expansion.

2. Background

The question of how innovation happens engages several levels of analysis. At the individual level, scientists and engineers might create new knowledge. However, commercializing a new invention usually requires a firm to organize the necessary activities, complementary assets, and strategies to convert an invention into profits (Teece, 1986). Such firms operate within industries, which include competitors, customers, suppliers and more: the modularity literature has bridged these levels of analysis, starting with new knowledge in the form of a new technical interface, and tracing its effect on firms and across industries (Brusoni & Prencipe, 2001; Galvin & Morkel, 2001; Colfer & Baldwin, 2016). Here we highlight a key mediator of such transformation: a firm's business model. Business model fit and business model innovation has long been regarded as critical to the success of a new technology (e.g., Chesbrough, 2010); we show that they can also be the key to achieving organizational modularity from a new technical interface.

2.1. Technical and Organizational Modularity

Beyond the level of a single firm, industry-level innovation and economic growth typically require decentralized innovation efforts. Within a firm, modularity allows a firm to break down a problem into manageable pieces (Sanchez & Mahoney, 1996). Within an industry, such decentralized innovation requires task partitioning between organizations, which in turn is made possible by modularity of technology, IP and organizational boundaries (Henkel et al, 2013; Parker et al, 2017). Such modularity allows firms to develop complex large-scale systems such as airplanes and computers (Prencipe, 2000; Baldwin & Clark, 2000). Baldwin & Clark (2000) term modularity to manage organizational complexity "modularity in production".

Baldwin (2008, 2012, 2020; Baldwin & Clark, 2000; Colfer & Baldwin, 2016) has studied how partitioning of the technical and organizational complexity enables such decentralized innovation. Key to that is her concept of a "thin crossing point":

> If labor is divided between two domains and most task-relevant information hidden within each one, then only a few, relatively simple transfers of material, energy and information need to pass between the domains. The overall network will then have a *thin crossing point* at the juncture of the two subnetworks. Having few dependencies, the two domains will be modules within the larger system. In the task network, modules are separated from one another by thin crossing points and hide information. (Baldwin, 2020: 10).

The interaction of modules at these crossing points is controlled by an interface (Baldwin & Clark, 2006). Such interfaces make possible a complex ecosystem of decentralized innovation and customer choice that Baldwin & Clark (2000) term "modularity in use"; examples including computer platforms (Garud & Kumaraswamy, 1993; Bresnahan & Greenstein, 1999; Baldwin & Clark, 2000) and audio products (Langlois & Robertson, 1995).

Research has long shown that the creation of interfaces impacts firm boundaries and industry structure via vertical specialization, which can also enable new entry (Langlois & Robertson, 1995; Baldwin & Clark, 2000; Langlois, 2002; Colfer & Baldwin, 2016). Previous research has tended to focus on the industry impact of interfaces created by firms, such as proprietary standards (Langlois & Robertson, 1992), open standards promoted by a single firm (West & Dedrick, 2000; Kenney & Pon, 2011), or multilateral standards that reconcile various corporate interests (Leiponen, 2008; Bekkers et al, 2011; Simcoe, 2012). In these cases, standards are strategically created to coordinate economic activity including the entry of new firms that will adhere to standards (David & Greenstein, 1990; Bresnahan & Greenstein, 1999).

While Baldwin & Clark (2000) emphasize the inherent advantages of technical and organizational modularity, subsequent has suggested conditions where an integral strategy may provide superior innovation and financial results. Beyond the technical opportunities for partitioning the design efforts, other moderators of potential modularity benefits include competencies, the business model of the firm and its complementors, and firm strategy (Fixson & Park, 2008; Cabigiosu et al, 2013; MacDuffie, 2013; Jacobides et al, 2018). Thus, understanding the limits of the benefits of modularity remains an important question in modularity research (Colfer & Baldwin, 2016).

2.2. Business Model Innovation in Modular Industries

Prior research has repeatedly demonstrated how the ability to produce a technical innovation does not assure a profitable product or successful business venture. Instead, new technologies that disrupt existing value creation and industry structure often require new business models.

Facing potential disruption, incumbent firms constrain their business model search, filtering out options incompatible with their "dominant logic" (Chesbrough, 2010).

Instead, new business models often emerge from new, less constrained firm that seek a path to commercialize a new technology (Chesbrough & Rosenbloom, 2002; Zott et al., 2011). These firms engage in search for a new business model that fits with the firm, its technology and its markets (Moeen & Agarwal, 2017; Hannah & Eisenhardt 2018; Zuzul & Tripsas, 2020). Given limited resources and the liability of newness, these firms face a particularly urgent need to find such a fit (Massa & Tucci, 2013; Felin et al, 2020; McDonald & Eisenhardt, 2020).

The business model of one firm often depends on the business model choices of competitors and complementors. New business models are most likely to be needed when the business models of related firms or industries are also disrupted (Chesbrough & Rosenbloom, 2002; Kodama, 2003). In some cases, there is deliberate collaboration between firms to select complementary business models (Kapoor, 2014). Such collaboration is particularly true within ecosystems, when multiple interdependent firms collaborate to jointly create value (Bogers et al, 2019). Finding a successful business model is more challenging when the firm is highly dependent on external actors, or when more such actors are involved (Berglund & Sandström, 2013).

A specific form of such interdependent business model innovation is that for industries or segments where responsibilities are subdivided based on organizational modularity. Only a limited amount of work has examined the relationship of interfirm technical and organizational modularity to business model innovation, including the initial causes and long-term impacts.

In an extended essay, Ernst (2005) argued that in electronics, modularity enabled the emergence of the electronic contract manufacturing industry. Meanwhile, Kodama (2004) showed how modularity enabled related industries to have differing rates of market growth by attracting new uses.[1]

Other research has examined the effect of a firm's intrafirm modularity upon its business model choices. Krikke et al (2004) showed modular product design allows firms to lease remanufactured products based on reverse logistics sourcing previously leased products. Building on this evidence, Agrawal et al (2021) offered a theoretical model of how the choice of a modular (vs. integral) systems architecture influences the profitability of leasing rather than selling a systems product. Other research has looked at how modularity can be used *within* a given business model to enable business model evolution (Aversa et al, 2015). Finally, one study considered how IP and technical modularity could be aligned to support a particular business model (Waltl et al, 2012).

3. Context and Research Design

We situate our study in the growth of the fabless semiconductor industry from 1980 to 2020. While Baldwin and Clark (2000) recount the emergence of technical and organizational modularity at the beginning of this period, our focus is on the changes in industry structure before and after the publication of their book and the need for business model compatibility.

A cornerstone of Baldwin and Clark's (2000) analysis is the work of Carver Mead and Lynn Conway. During the 1970s, Mead had advocated a technical and organizational division of labor between those who designed semiconductors and those that manufactured them (Mead, 1972; Sutherland & Mead, 1977). Building on this and other work, Mead and Conway created a

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[1] Kodama uses "business model" innovation to refer to new ways of using a technology, which is inconsistent with — in what became the dominant design for business model theory — the idea of business model innovation as being new ways of creating and appropriating value from a technology (cf. Chesbrough & Rosenbloom, 2002; Zott et al, 2011; Massa & Tucci, 2013).

method of designing semiconductor chips that was independent of fabrication methods, documented that method in a textbook that became the standard of the 1980s (Mean & Conway, 1980), and prototyped a modular fabrication service for their own and other American university student designs. Together, this meant that the formally vertically integrated process of semiconductor design was modularized, allowing design and fabrication to performed by different organizations.

Design Rules called out how Mead and Conway modularized design itself, both with their textbook, and with the process they created for their early classes to allow students to separately design their specialized chips while fabricating those designs as a complex, multi-project wafer:

> The example we offer is Carver Mead and Lynn Conway's approach to very-large-scale integrated (VLSI) chip designs. In choosing this example, we are admittedly guilty of overkill. Theirs was not a simple modularization, as might happen with laptop computers. Mead and Conway did not pursue modularity piecemeal; instead they totally reconceptualized chip designs in terms of nested, regular, modular structures. Their rethinking of the process of creating chips encompassed all levels of the design, from the location of single transistors and the layering of material, to the economic arrangements that linked chip designers, maskmakers and fabricators. (Baldwin & Clark, 2000: 79)

In the early 2000s, the semiconductor industry had become shaped by Mead and Conway's invention, with the original vertically integrated firms that did both design and manufacturing now joined by a variety of design-only "fabless" firms supported by a handful of manufacturing-only ("pure-play") foundries (Kapoor, 2013). But while the semiconductor industry had, since its inception, been distinguished by high levels of innovation, nevertheless, by the early 2000s, growth had largely slowed (Macher and Mowery, 2006).

What could scarcely be imagined, therefore, was the expansion into new markets that occurred over the next decade, driven primarily by the wide array of small fabless firms that were supported by an ever-improving foundry, Taiwan Semiconductor Manufacturing

Corporation (TSMC). The fabless business model facilitated entry by eliminating the need to build manufacturing capabilities, and allowed a plethora of specialized firms to try new product ideas. One industry insider remarked that as recently as six years ago, it was unclear that Nvidia would survive let along become the world's most valuable semiconductor company (Shelton, 2021, author interview).

What allowed Nvidia to overtake Intel in terms of market valuation was Nvidia's identification of new customer markets. As a leading producer of graphics processing units (GPUs), Nvidia was founded to supply the personal computer (PC) industry with better gaming capabilities. But the company realized that their chips were ideally suited to artificial intelligence, a type of computation activity that involves parallel processing. With high-paying users like Google, Amazon, and Netflix all requiring extensive computation power, Nvidia's chips suddenly found a new, valuable, and growing use that incumbent firms could not supply.

But Nvidia is just one example of fabless firms' technological niches combining with business incentives to create and supply enormous new markets. We argue that this extent of economic activity was unanticipated by Baldwin and Clark (2000). On the one hand, they estimated the economic effects of organizational modularity in the computer industry and the creation of value through innovation.

> [W[e show that the modular operators create options for designers, options that…may have led to a fivefold increase in value over previous designs. But there is more. By combining a modular design structure (splitting) with independent, parallel experimentation on modules (substitution), we find that designers can create as much as a twenty-five-fold increase in system value. (p. 14)

On the other hand, the innovation and value creation that Baldwin and Clark (2000) describe occurs *within* the computing industry. What was under-explored was the value creation caused by computing's expansion beyond computers. Industry reporting and analysis provide a current snapshot of the semiconductor industry. Figure 1 shows a large but declining market for "Standard PCs", the main market for semiconductors in Baldwin and Clark's (2000) study. Communications, especially cellphones, are already a larger market than PCs, with continuing high growth. This segment is supported by specialized fabless firms, too, Qualcomm and Broadcom (Table 1).

Another indication of the growth of new markets is the creation of two new interest groups by the Global Semiconductor Alliance, formerly the Fabless Semiconductor Association. The Automotive Interest Group was formed in 2017 and includes 300 participants from the semiconductor and automotive sectors. And the Internet of Things (IoT) Ecosystem Security Group was created in 2018 and brought together 102 participants in the fastest segment in Figure 1.

To understand the dynamics behind the largest and the fastest growing customer markets (communications and IoT, respectively), we investigate the fabless and foundry business models and uncover the nearly forgotten obstacles to both types of firms, including the well-justified doubts that observers had. We employ historical methods, including interviews, oral histories, and memoirs listed in Table 2, to show that the full benefits of modularity were delayed by almost a decade as various firms struggled under a chicken-and-egg problem. A nonprofit industry association, the Fabless Semiconductor Association (now, the Global Semiconductor Alliance), eventually facilitated the creation of compatible business models for fabless and foundry counterparts across the new technical interface, after which the semiconductor industry could generate high levels of variety and innovation across both sides of the technical interface.

4. Business model innovation and the need for coordination

New organizational configurations have been observed as a response to the introduction of technical interfaces or technical modularity. Such organizational modularity is neither assumed nor inevitable; rather, it is acknowledged to be merely possible. In the semiconductor setting, Baldwin and Clark (2000) observed that fabless semiconductor design firms and dedicated foundries co-exist with vertically-integrated incumbents. The former occupied small, specialized niches that provided variety in an industry dominated by large firms supplying a mass-market. This peaceful coexistence of firm types corresponded to differing strategies and advantages (Kapoor, 2013) and capabilities (Macher & Mowery, 2006).

Decades later, those fabless firms at the fringes of the industry now occupy the high-growth, high-profit sectors of the semiconductor market. These former niche players have proven themselves astute at identifying growth opportunities and at moving quickly to dominate those market segments, while incumbents are at risk of losing their technological edge. While modularity theory predicts vertical specialization on either side of a technical interface, there are open questions about the nature of the innovation that technical modularity enables and how much of that innovation depends upon organizational modularity. Our historical scope uncovers the business model experimentation on both sides of a new technical interface and considers the variety of innovation that results from different organizational configurations.

We first discuss manufacturing business models, including the pure-play foundry that was the target of much skepticism (Table 3). We then consider the business models for design (Table 4). Next, we analyze each combination of manufacturing and design business models in terms of their compatibility (Table 5). Finally, we explain what the Fabless Semiconductor Association did to coordinate fabless and foundry business models to generate compatibility.

Note that while the literature does not provide a single definition for "business model," we identify dimensions of firms' operations that, taken together, comprise what we refer to as a business model: firm capabilities and services, information set, intellectual property rights, revenue model, and resulting incentives to innovate and market products.

4.1. Manufacturing Business Models

Table 3 shows that while all semiconductor manufacturers have manufacturing capabilities, they differ in their complementary capabilities. Vertically integrated firms, exemplified by Intel, design and market chips, as well. A limitation of this business model is that the design is unlikely to be optimal for computer-maker customers because the designers in a semiconductor firm know less about the desired functionality than their customer (Sutherland and Mead, 1977).

This problem was solved somewhat by application-specific integrated circuit (ASIC) companies, which manufactured chips designed by their computer-maker customers. In this business model, ASIC companies served existing computer makers that wanted to update their products with new, customer chips. These customers would buy a quantity of chips priced to cover the fixed costs of setting up manufacturing. In some cases, the ASIC firm retained the rights to further market the chips to other customers, which could boost demand for the chip and lower the unit cost of manufacturing. But if the custom chip were a strategic advantage of the computer maker, price declines might be outweighed by competition from a rival using the same chip.

Note that some integrated firms did manufacture designs from other companies, but only when it complemented their own product strategy. Because integrated firms designed and marketed their own chips, they would only partner with customers whose chips filled gaps in their existing product line. This outcome ran contrary to Mead's hope that semiconductor firms would help computer makers create more tailored products (Mead & Lewicki, 1982).

This changed in 1987 with the founding of Taiwan Semiconductor Manufacturing Company (TSMC), the world's first pure-play foundry. A firm that would take on all customers was hitherto unheard of outside of the university-based prototyping service, MOSIS.[2] TSMC took the basic idea of manufacturing other people's chips to production-scale, offering its services from prototyping to full-scale manufacturing to any firm, from startup to established firm. TSMC provided no marketing or design services, in large part because the local human capital in Taiwan, while strong in manufacturing, was weak in design and marketing.

TSMC is now the market leader, and technology leader, in semiconductor manufacturing, but there was considerable uncertainty around its manufacturing-only business model. When TSMC was founded, before the fabless industry existed, potential customers were vertically integrated firms with overflow demand or ad hoc capacity shortages for older products. What observers did not know was that Chang had heard about latent demand for a foundry from engineers at his former employer, Texas Instruments, who wanted to leave to start their own firms. Morris Chang describes the skepticism about the foundry business model:

> There was no market because there was very little fabless industry, almost none. No fabless industry. So who are you going to sell these wafers to? Who are you going to manufacture the wafers for? (Chang, 2007: 13)

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[2] MOSIS is a manufacturing brokerage service for prototypes based at the University of Southern California. Initially funded by the Defense Advanced Research Projects Agency (DARPA), MOSIS was another brainchild of Lynn Conway, who established the service to produce student projects. Thus, generations of chip designers were trained using the prototyping service, which also produced small-scale military projects and later start-up firm prototypes.

4.2. Design Business Models

On the other side of the technical interface is design. As Sutherland, Mead and Everhardt (1976) pointed out, the technical interface Mead and Conway created was meant to address the manufacturing problem of increasingly complex chips as well as the design problem of understanding what computer makers needed. Thus, in addition to the vertically integrated firms that designed their own chips, computer makers also got into the business of designing bespoke chips for their products. This "tall thin man" could see both the computer side of the chip and could do the design work needed to bring the chip to life (Fairbairn, 2021).

However, the technical interface enabled entry from fabless firms, which designed special-purpose chips to sell to computer makers or other customers. Fabless firms were highly attuned to the needs of various niches within the industry. They were also aware of the weaknesses of existing products for certain customers. Dozens of firms, each with their own ideas for better, specialized chips entered to address a market demand.

4.3. Business Model (In)compatibility

With our set of manufacturing business models and design business models, we can generate seven design and manufacturing combinations. Table 5 summarizes these combinations, some of which are inferior to others, and so are unstable in equilibrium.

4.3.1. Vertically integrated firm – Successful but with technical limitations

The industry's initial business model was that of the vertically integrated semiconductor manufacturer, which performs all of the activities involved in creating and selling chips: design, manufacturing, and marketing. Firms in this category, of which Intel is an exemplar, do not manufacture chips for other firms. As the preeminent firm for decades, Intel produced high volumes of general-purpose central processing units (CPUs) for personal computer (PC) makers.

Intel regularly improved product performance or processing speed by miniaturizing chips, and doubling performance every two years, i.e., Moore's Law.

4.3.2. Systems integrator and Integrated foundry – Successful but with business limitations

With the new technical interface introduced by Mead and Conway, new sources of design were enabled. The first of these was predicted by Mead in the form of the "tall thin man," computer designers who designed chips but hired others to manufacture those chips. Initially, options were limited to vertically integrated firms that were also willing to manufacture another firm's chips. In such cases, several considerations went into the formation of partnerships. First, the computer maker's own demand for a chip would make a partnership more attractive to a manufacturer. Thus, typical customers were established computer companies, like Sun Microsystems, that wanted to develop a next-generation chip for competitive reasons. Second, the proposed customer chip should fit strategically with the vertically integrated firm's product line. Finally, the integrated firm had to have capacity for an outsider's chip.

VLSI Design magazine's year-end report from 1983 listed 38 foundries, all of which were vertically integrated firms (Werner, 1983). But the foundry's own product line affected the type and size of clients they would engage, thereby limiting the effect of the technical interface to incumbent firms only, i.e., existing computer makers and existing manufacturers.

4.3.3. Systems integrator and ASIC manufacturers – Successful but with business limitations

These limitations made room for a new kind of manufacturer to enter, the ASIC company. ASICs are designed by the customer and produced by the ASIC firm, which had no designs of its own. However, ASIC firms would retain the right to market and sell the chips, thereby giving them an additional source of revenue on top of selling to the designing firm. As with integrated foundries, ASIC firms faced financial risks devoting resources to a customer without proven demand. Other conflicts also existed between the manufacturer's incentive to market a chip to the customer's potential competitors and the cost of investing in marketing capabilities.

In practice, ASIC firms had weak incentives to market customer chips and instead focused on acquiring customers for new, custom chips. Successful technical marketing would have require additional sets of skills that the ASIC firms did not possess or acquire.

4.3.4. Systems integrator and pure-play foundry - Successful

While similar to ASIC companies in providing contract manufacturing, pure play foundries lacked any claim to marketing capabilities and thus retained no marketing rights. This hands-off approach was a good fit for systems integrators whose custom-designed chips could confer a strategic advantage over competitors. Pure-play foundries also had an incentive to work with new customers of any size.

4.3.5. Fabless firm and integrated foundry – Unsuccessful

Fabless firms have design capabilities and product ideas but no manufacturing capabilities. These firms must *sell* their chips to systems integrators as their primary source of revenue. With integrated foundries as the only manufacturing option, fabless firms must fit within the integrated foundry's product line. An example of this arrangement is Nvidia's first few chips in partnership with SGS Thompson. Nvidia specialized in graphics chips, which was also a gap in SGS Thompson's product line. SGS Thompson had a strong marketing presence in Europe, so it sold the chips in that market while Nvidia marketed the chip in the US. The first two chips failed to sell well, but the third chip saw unexpected success. SGS Thompson was unable to manufacture enough of the chips to meet demand, so Nvidia renegotiated the marketing and manufacturing rights and moved production to TSMC, where Nvidia's production has remained ever since.

4.3.6. Fabless firm and ASIC firm - Unsuccessful

For specialized fabless firms, especially startups, covering an ASIC firm's set up costs could be considerable. Thus Nvidia, whose founder came from an ASIC firm, chose an integrated foundry, and later a pure-play foundry, over an ASIC producer. The high set-up cost increased the business risk for a fabless startup with uncertain demand.

4.3.7. Fabless firm and pure-play foundry - Successful

Pure-play foundries need sufficient demand in order to cover costs and survive. Because they have no other sources of revenue, pure-play foundries have a strong incentive to invest in manufacturing quality and to support entry by fabless firms, in the hopes that they will survive and grow into a customer base. At the same time, fabless firms have unproven products with uncertain demand. A flexible manufacturing partner that could support various levels of production would allow a fabless firm to try new product ideas at low cost, lowering the cost of entry.

In equilibrium, a flourishing ecosystem of fabless firms could support a foundry, while a profitable foundry could improve its technology to meet the ongoing needs of an ever-growing set of fabless entrepreneurs. But coordination was needed to address the pre-equilibrium scaling process, or chicken-and-egg problem.

4.4 Fabless Semiconductor Association: Coordination to Solve Chicken-and-Egg Problem

The success of two emerging business models—the fabless and the pure-play foundry—was hastened and supported by an industry association, the Fabless Semiconductor Association (FSA), created in 1994. Co-founder and president, semiconductor marketing executive Jodi Shelton, recognized the potential of the fabless industry but also its struggle to achieve critical mass (Shelton and Pepper, 2011). She and co-founder Robert Pepper recruited fabless firms, many of which saw themselves as competitors, to come together to discuss, analyze, and strategize. “FSA was populated by pioneers who recognized the industry could be strengthened if its rigid adherence to an outmoded business model could only be shaken,” (Shelton and Pepper, 2011, p. 27).

The need for the FSA was evidenced by the continuing skepticism and fluidity of the fabless business model, even seven years after TSMC’s founding. As Pepper recalls, “Quite frankly, my board thought I was crazy. ‘This could never work,’ they said. ‘Not just the organization but also the long-term vision of fabless.’ We came up against this prejudice a lot,” (Shelton and Pepper, 2011, p. 27). As fabless firms tried to gain a foothold, Shelton and Pepper realized that they needed to include foundries in their strategizing. This extension of membership, too, was unobvious at the time.

> As a result, FSA undertook projects that would welcome and integrate partner companies, primarily the manufacturing foundries…Unfortunately, this collaborative approach was not an easy decision. At the time, many member companies saw the FSA board as a place to share ideas, best practices, and experiences. Inviting foundries or other partners to be part of the board meant a real change in the dynamics of the leadership. But Pepper and Shelton realized they couldn’t hold on to this “us-versus- them” undertone if they wanted to meet the challenges ahead (p. 29).

With the relevant parties in place in the FSA, coordination of businesses and business models could take place. One of the first decisions the FSA made was what its goals were. While outward-facing issues were considered, including greater representation in Washington and a higher profile among venture capitalists, the founding group instead focused on inward-facing problems, such as how fabless firms and foundries should work together. For example, an early initiative of the FSA was its test chip process. Fabless firms need to fabricate prototypes, but doing an entire manufacturing run for a prototype can be costly. MOSIS solved this problem with its multi-project chip program, which placed multiple student projects onto a single wafer.

Fabless firms wanted a similar process at foundries, and fabless members of the FSA worked with foundries to create a solution to a prevailing problem.

> One pivotal project was the start of the Standard Process Qualification Committee, which would create a test chip that could be used by multiple companies in place of the redundant individual process qualifications used by fabless companies' foundries. This project achieved the support and leadership of the foundries. (p. 29)

Fabless members of the FSA also identified capabilities and technologies that they considered priorities for foundries, and were successful in influencing foundries' investments. Exposure to fabless firms and their concerns was also valuable to foundries and shaped their strategies and policies. For example, Morris Chang, TSMC's founder, maintained a policy of reserving production capacity for startups, even when existing customers like Nvidia grew to be large enough to claim all of TSMC's capacity. This practice would help ensure that new fabless firms would always have a chance to start, survive, and grow.

The effectiveness of the FSA was aided by the leadership skills of the FSA's longtime executive director:

> But as time went on, one of her other talents was revealed: a unique ability to manage a lot of egos and competing interests and inspire them to work together on behalf of an industry. She sometimes even got them to perform unexpectedly altruistic acts! …She continued to grow in the job and inspire all of us to work cooperatively. She could talk anybody into doing anything. The amazing thing was she did not have a technical background, was not an engineer, and yet managed to earn the respect of these very technical leaders. It was quite unusual (Shelton and Pepper, 2011, p. 27).

Over time, FSA membership grew to top out at around 350 fabless firms. Other, non-fabless members include service providers like investors, bankers, and lawyers, as well as industry partners like foundries, customers, software tool providers, etc. Figure 2 shows the growth from its inception to 2005 when membership reached its current level.

4.5 Impact on Industry Growth

One of the hallmarks of the semiconductor business in the twenty years since Baldwin and Clark (2000) is the growth of new customer markets. The chips made by fabless firms that were once the preserve of specialized users are now an essential component in cloud computing, communications, entertainment, transportation and more. This type of rapid innovation is precisely the phenomenon that Baldwin and Clark (2000) predicted would arise from modular organization. The marketing ability of fabless firms, and the strong incentives they face to find and support new markets for their products, lie in stark contrast to incumbent firms that have repeatedly failed to discover and fuel new applications for semiconductor chips. Thus, organizational modularity encouraged and permitted the entry of diverse new firms implementing new ideas and finding new markets.

This expansion of innovation is visible in the FSA, which became the Global Semiconductor Association (GSA) in 2008. New members now include formerly-unlikely firms like car company Tesla and e-commerce giant Alibaba. The ubiquity of semiconductor chips has been driven by firms on both sides of the technical interface, and we suggest that the emergence of two independent but compatible business models would not have happened without coordination supplied by the nonprofit industry association. Indeed, for over a decade, the wrong business model prevailed, as firms with old, incompatible business models struggled.

5. Discussion

Baldwin and Clark (2000) launched two decades of research into how modularity facilitates innovation across broad swaths of the economy. During this period, numerous new examples have emerged of decentralized modular innovation, as cloud computing, artificial intelligence, smart phones and apps reshape whole industries and how we travel, consume entertainment, communicate, gather, and conduct business.

Both then and now, many of these innovations have been driven by consistent improvements in semiconductor technology. Here we show how the shifts of the current century have been enabled by the modular division of labor between the fabless and foundry semiconductor. Our study probes the origins of business model innovation that enabled such firms, and shows the crucial importance of the coordination provided by a nonprofit industry association so solve the chicken-and-egg problem that delayed realization of the potential benefits of such modularity.

5.1 Contributions of the Concept of Business Model Modularity

Baldwin & Clark (2000) developed a nuanced theoretical explanation for technical and organizational modularity, and demonstrated the innovation and economic outcomes made possible by such modularity. We contribute to this literature by highlighting a previously unremarked aspect of organizational modularity: business model modularity, or the compatibility of business models across an organizational boundary. Our analysis shows that business model innovation is not always needed to support organizational modularity. For example, the Mead and Conway technical interface ushered in a successful set of firms that helped computer makers improve and differentiate their products. Thus entry occurred on both sides of a new technical interface. However, the magnitude of this entry and the level of economic activity it enabled, while substantial, pale in comparison to what the fabless and foundry firms were able to achieve.

Our examination of business model challenges builds on work on innovation and business model fit, in which new innovations often require new business models in order to generate profit (Chesbrough & Rosenbloom, 2002; Chesbrough, 2010; Schneider, 2019).

Consistent with that literature, we show that technical compatibility without business model compatibility across an interface can enable creation of modular product without a viable way to profit from such products. We extend that literature by introducing the added complexity of upstream or downstream partner relationships with which business models must also fit together.

A third contribution relates to the particular problem fabless and foundry firms faced, the chicken-and-egg problem. Chicken-and-egg problems are common in multi-sided platforms or two-sided markets (Caillaud and Julien, 2003; Parker and Van Alstyne, 2005). But in those cases, the multi-sided platform is often controlled by a single firm that coordinates the creation of both sides of the market, such as the iPhone app store (West & Mace 2010). For ecosystems without the central control of a platform sponsor, we show that an industry association can overcome the collective action problem of coordinating simultaneous business model development. We thus link research on technical coordination (Baldwin & Clark, 2000; Kapoor, 2013) with research on coordination in value creation and value capture (Lavie, 2007; Bogers et al, 2019). This includes using industry associations to provide decentralized leadership for a modular (Wareham et al, 2014) or diverse ecosystem (Hiatt and Carlos, 2015) and goes beyond their previously identified role in industry legitimation (Aldrich et al, 1994; Esparza et al, 2014; Lee, Hiatt and Lounsbury) and political activity (Walker & Rea, 2014).

5.2 Future Research

Our goal was to explore how coordinating business model innovation impacts the benefits of technical and organizational modularity. Our example now raises several questions for future work. First, how widespread is the problem of business model incompatibility? Our data suggest that this can be difficult to recognize if less that fully-modular business models work successfully for a limited number of firms, as when computer makers of the 1990s contracted with foundries under restrictive business models. However, as Baldwin and Clark demonstrate, a successful form of organizational modularity will — by its very nature — enable entry, specialization and variety, as demonstrated by the 21st century fabless model. Future research could probe the relationship between business model modularity and variety, where variety is the desired outcome of business model innovation and fit.

A related question is what type of innovation incumbent firms perform compared with entrants (Kapoor, 2013). Our inside look at changes to the semiconductor industry over time shows vertically integrated firms were unable or unwilling to meet the needs of new growth markets. Additional research might therefore also connect with work on Schumpeterian innovation or the innovator's dilemma (Breschi et al, 2000; Christensen, 1997).

Finally, our study raises questions about when and how coordination is necessary or possible. Must firms recognize the need to evolve their business models? What role do entry barriers play for the business models on either or both sides of the interface? In our setting, the surprising level of success may have been due to strong leadership, as noted earlier. Thus, future research could improve our understanding of the conditions and mechanisms of cooperation and cooperative strategy.

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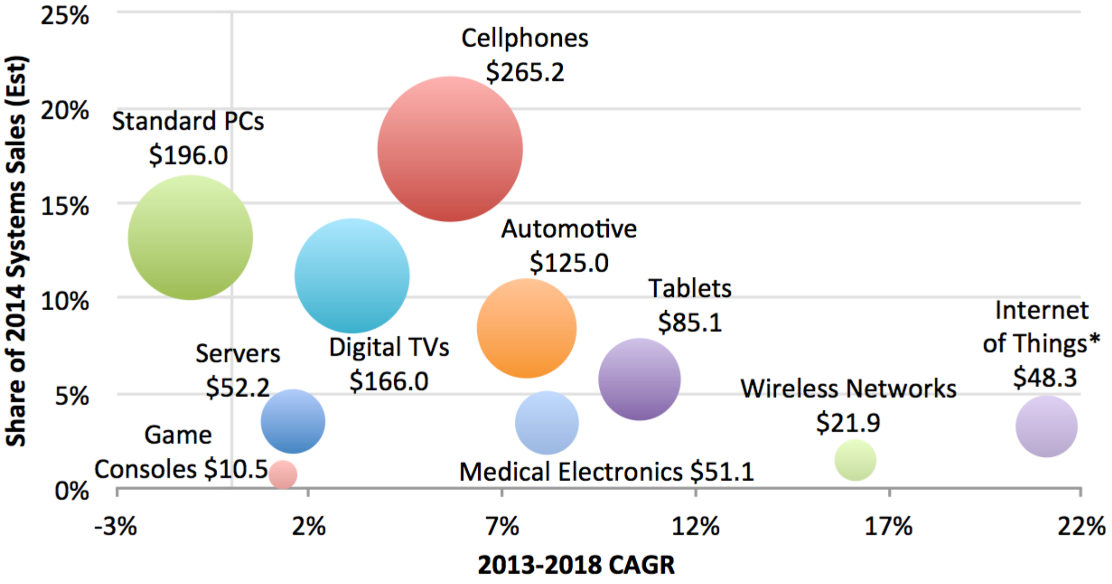
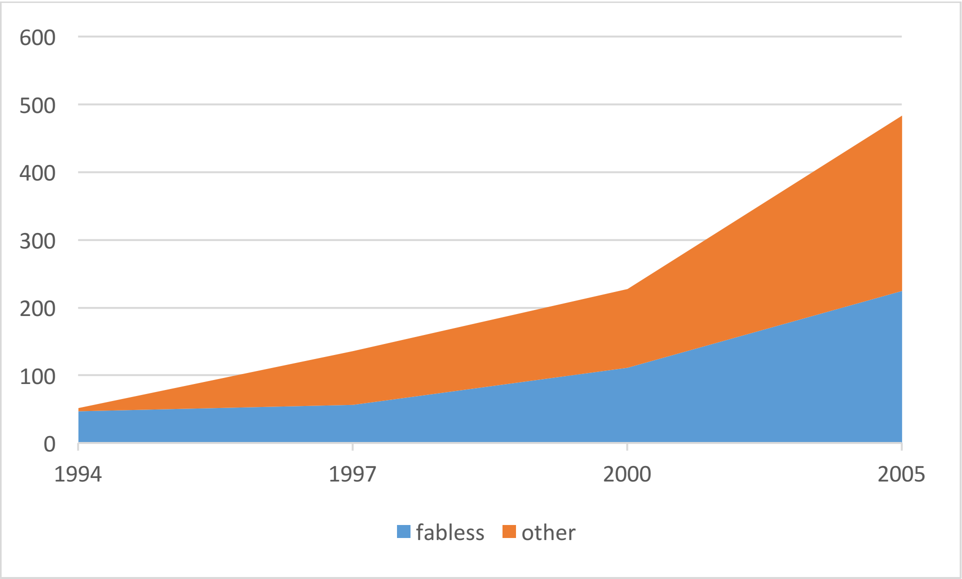
Figure 1: Semiconductor end-use markets (2014)



*Covers only the Internet connection portion of systems

Source: IC Insights (2015)

Figure 2: FSA membership by category



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Source: FSA member lists

Table 1: Top 10 semiconductor firms by revenue, 1990 and 2020

Rank by revenue	1990	Firm type	2020	Firm type
1	NEC	Vertically integrated	Intel	Vertically integrated
2	Toshiba	Vertically integrated	Samsung	Vertically integrated
3	Hitachi	Vertically integrated	TSMC	Foundry
4	Intel	Vertically integrated	SK Hynix	Vertically integrated
5	Motorola	Vertically integrated	Micron	Vertically integrated
6	Fujitsu	Vertically integrated	Qualcomm	Fabless
7	Mitsubishi	Vertically integrated	Broadcom	Fabless
8	TI	Vertically integrated	Nvidia	Fabless
9	Philips	Vertically integrated	TI	Vertically integrated
10	Matsushita	Vertically integrated	Infineon	Vertically integrated

Source: IC Insights, 2011; 2020

Table 2: Primary Data

Name	Role	
Carver Mead	Coauthor of *Introduction to VLSI Systems;* Professor emeritus, Caltech	Interview 3 oral histories Published works
Lynn Conway	Coauthor of *Introduction to VLSI Systems;* Professor emeritus, University of Michigan	Published works
Marina Chen	Carver Mead grad student, Chair emeritus, Boston University Computer Science Dept.	Interview
Morris Chang	Founder, TSMC	Oral history
Douglas Fairbairn	Computer History Museum historian, founder of VLSI Technologies and *VLSI Design*	Interview
Robert Garner	Engineer in Lynn Conway's group at PARC, later at Sun	Interview
Peter Tong	Early Nvidia engineer	Interview
Rick Whitacre	Early Nvidia operations engineer	Interview
Jodi Shelton	Founder and Chair, Fabless Semiconductor Association	Interview
Gina Gloski	Early board member, Fabless Semiconductor Association	Interview

Table 3: Manufacturing Business Models

Business Model	1 Vertically integrated	2 Integrated firm with foundry business	3 Foundry Broker	4 ASIC	5 Pure-play foundry
Exemplar	Intel	Fujitsu, Cypress	MOSIS	LSI Logic	TSMC
Capabilities					
• Design	**	**			
• Manufacturing	**	**	**	**	**
• Marketing	**	**		--	
IP rights	**	--		--	
Knowledge of customer need	--	--			
Source of revenues	Own chip sales	Own + customer chip sales	Government subsidy	Customer chip sales	Customer chip sales

Table 4: Design Business Models

Business Model	A Vertically integrated	B System integrator (computers, devices)	C Fabless
Exemplar	Intel	Sun, SGI, Tesla	Nvidia, Qualcomm
Capabilities			
• Design	**	**	**
• Manufacturing	**		
• Chip marketing	**		**
IP rights	**	--	--
Knowledge of customer need	--	**	**
Source of revenues	Chip sales	System sales	Chip sales

Table 5: Business model combinations

Design	Manufacture	Strengths	Weaknesses
Vertically integrated*	Vertically integrated	Large volumes	Knowledge of customer need
Systems integrator	Integrated foundry	Leverages, increases scale economies	Strategic partners only
Systems integrator*	ASIC firm	Customization for customer	Weak marketing incentives
Systems integrator*	Pure-play foundry	Accept any customer	No marketing incentive
Fabless	Integrated foundry	Existing manufacturing capacity	Strategic partners only
Fabless	ASIC firm	Customization for customer	Weak marketing incentives
Fabless*	Pure-play foundry	Strong incentive for fabless to market chips	Chicken and egg dilemma

* Stable configuration