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EXPLORING THE RISKS OF VALUE CHAIN MODULARITY: ELECTRONICS OUTSOURCING DURING THE INDUSTRY CYCLE OF 1992-2002

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This paper focuses mainly on the issues of supply-base concentration and increased buyer-supplier lock-in through an examination of recent trends in what is perhaps the best case of value chain modularity, product-level electronics. Wherever possible, the discussion is placed in the context of the huge industry cycle that began its upward swing in 1992, peaked in late 1999, and is currently working its way downward in search of a bottom. This cycle has created an excellent opportunity to explore the performance of value chain modularity under extreme conditions.

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Introduction

Elsewhere I have argued that a new system of industrial organization, the modular production network, has recently emerged on the global economic scene, driven largely by the strategies of firms based in North America. This change in industry structure has been entwined with the spatial processes of geographic dispersion, re-location, and regionalization—in short, globalization (Sturgeon, 2002). For the past three years (1999-2002), a team of 24 researchers from MIT's Industrial Performance Center (IPC) has been investigating the confluence of globalization and industry reorganization in several sectors, including electronics, motor vehicles, software, and textile/apparel.[1] One important finding of this research is that one of the key features of value chain modularity, high levels of outsourcing to very competent, independently operating suppliers, increased dramatically during the 1990s, especially in complex assembly sectors such as electronics and motor vehicles.[2] In modular production networks firms with a high degree of autonomy rely on standardized protocols to exchange codified

[1] Field research for the IPC Globalization Study has consisted of semi-structured qualitative interviews with company personnel and relevant individuals from government agencies, labor unions, and academia. In-person interviews and plant tours have been conducted in Canada, Mainland China, France, Germany, Indonesia, Ireland, Israel, Italy, Japan, Korea, Malaysia, Mexico, the Philippines, Singapore, Taiwan, Thailand, and the United States. As of this writing we have conducted more than 350 interviews, which have been written-up and stored in a searchable database. One hundred eight of these interviews were conducted in the electronics industry, 72 were conducted in the textile/apparel industry, and 61 were conducted in the motor vehicle industry. For more information about the IPC Globalization Study, including our methodology and detailed research findings, see http://globalization.mit.edu.
[2] In others industries, such as apparel, horticulture, and household goods, some aspects of value chain modularity is in evidence but the supply-base remains fragmented and the role of intermediaries such as brokers, buyers, and trading companies are important.

knowledge, sometimes on a on a global scale. This feature inhibits the build up of asset specificity in the network, which in turn dampens inter-dependence and keeps supplier switching costs low.

Even as we have identified value chain modularity as a distinct mode of industrial organization, ongoing changes are at work that may undermine it. Extreme levels of outsourcing and growing reliance on a large, increasingly powerful suppliers, for all the advantages it offers and problems it solves, is not without its own risks and pitfalls. At the most basic level, how firms create and capture value in modular value chains is poorly understood. This is a view that is shared by the members of our research team, and has also been articulated by some company managers during our interviews. The risks and uncertainties are manifold. Will the outsourcing of key activities hamper lead firms' ability to innovate and to create and control key intellectual property? Will the commodification of key value chain activities, such as global manufacturing and product design, lower barriers to entry for future competitors? Has the introduction of new layers in the value chain created forecasting distortions that make inventory gluts and shortages more likely and more severe? Will the reliance on fewer, larger suppliers create dependencies that will undermine the fluidity of the system and allow suppliers to raise their prices with impunity? As suppliers become more involved in the strategic elements of their customers business, such as product design and distribution, will the transactions in the network become de-codified and therefore more asset-specific?

This paper focuses mainly on the latter questions of supply-base concentration and increased buyer-supplier lock-in through an examination of recent trends in what is perhaps the best case of value chain modularity, product-level electronics.[3] Wherever possible, the discussion is placed in the context of the huge industry cycle that began its upward swing in 1992, peaked in late 1999, and is currently working its way downward in search of a bottom. This cycle has created an excellent opportunity to explore the performance of value chain modularity under extreme conditions.

The paper is organized as follows. First, I briefly present the general features of value chain modularity, and follow up with a discussion of its theoretical advantages, buttressing the arguments where possible with findings from our recent field research in the electronics industry. I then present a brief historical account of the rise of value chain modularity in the electronics industry, followed by a overview of the recent industry cycle and a discussion of how modular production networks appear to faring in its wake. I then briefly explore four broad areas of risk raised by value chain modularity in the electronics industry: intellectual property (IP) risk, inventory risk, market entry risk, and asset specificity risk, as summarized in Table 1. Some of these risks have been exposed and worsened by the recent cycle, and others appear to be inherent to the system. After discussing each risk in turn, the paper explores the question of asset specificity risk in more detail, focusing on the interface between tacit and codified information in electronics outsourcing. The approach taken is to trace how the linkages between American electronics firms and their largest contract manufacturers are evolving. I conclude with some reflections on the likely trajectory of value chain modularity in the electronics industry.

[3] For a definition and discussion of product-level electronics as a unit of analysis, see the appendix.

Table 1. Four Types of Risk Raised by Value Chain Modularity

Type of Risk	Description
1. IP Risk	Value chain modularity increases the potential for IP leakage to competitors through shared suppliers and customers.
2. Market Entry Risk	Value chain modularity can invite new competitors into the market by commodifying essential value chain functions, such as manufacturing.
3. Inventory Risk	In complex assembly industries where hundreds or perhaps thousands of individual parts must be purchased and brought together for sub- and final-assembly, value chain modularity introduces forecasting distortions as estimates of what needs to be produced gets passes along the value chain in what can be likened to an industry-level game of "telephone."[4]
4. Asset Specificity Risk	As suppliers consolidate in order to scale-up, provide a wider range of services, and establish global operations, the possibility of increased asset specificity and supplier lock-in is increasing, a trend that could lead to decreased network flexibility and increased cost.

The Concept of Value Chain Modularity and the Rise of the Global Supplier

Value chain modularity emerged during the late 1980s and 1990s from the break-up of vertically integrated corporate structures and the horizontal aggregation of activities around specific sets of closely related value chain functions. Out of this change two broad sets of firms can be identified, lead firms, focused on product development, marketing, and distribution, and sometimes some late-stage manufacturing steps such as final assembly, and turn-key suppliers focused on selling, as services, many of the value chain activities that lead firms have decided to outsource. This pattern appears to be most common in complex assembly industries, where vast numbers of parts and subassemblies must be specified, manufactured, and brought together for final assembly, and in

[4] Telephone is a child's game were a phrase is passed from child to child. The more children that play, the more altered the phrase is likely to be by the time it is uttered by the last child.

industries, such as semiconductors, where fixed capital costs are extremely high. In both cases there are substantial advantages that accrue from sharing the competencies and fixed capital of suppliers across a broad customer base.

The shift from vertical integration to value chain modularity has been especially pronounced since the early 1990s. In product-level electronics, for example, firms as different as Hewlett Packard and Ericsson have sold off their most of their worldwide manufacturing infrastructure to contract manufacturers such as Solectron and Flextronics. In semiconductors we have seen the emergence of "fabless" design that relies on semiconductor foundries such as TSMC, UMC, and IBM for production. In the auto industry, Ford and GM have retained vehicle design and final assembly, spun off their internal components divisions as the independent suppliers Visteon and Delphi, and outsourced an increasing volume of component and module design and production to "first tier" suppliers such as Lear, Johnson Controls, Magna, and TRW.

We call these new arrangements value chain modularity because distinct breaks in the value chain tend to form at points where information regarding product and process specifications can be highly formalized. We posit, following the literature on modular product design (Ulrich, 1995; Sanchez and Mahoney, 1996; Meyer and Lehnerd, 1997; Thomke and Reinertsen, 1998; Shilling, 2000), that within functionally specialized value chain nodes activities tend to remain tightly integrated and based on tacit linkages. Between these nodes, however, linkages are achieved according to widely agreed-upon protocols. Linkages based on codified knowledge provide many of the benefits of arms-length market linkages—speed, flexibility, and access to low-cost inputs—while allowing for a rich flow of information between firms. Such transactions, however, are not the same as classic market exchanges based on price. When a computerized design file is transferred from a lead firm to a supplier, for example, there is much more flowing across the inter-firm link than information about prices. The locus of these value chain break points appear to be largely determined by technical factors, especially the open and *de facto* standards that determine the protocol for the hand-off of codified specifications.[5] The network architecture that arises from such linkages has many of the advantages of modularity in the realm of product design, especially the conservation of human effort through the re-use of system elements— or modules—as new products are brought on-stream (Langlios and Robertson, 1995).[6]

Because of the important role that American firms have played in the twin processes of deverticalization and globalization, both as lead firms and as suppliers, I have elsewhere characterized value chain modularity as a "new American model" of industrial organization (Sturgeon, 1997, 1999, 2000a, 2002a). The turn-key suppliers in this model contain "generic" productive capacity that can easily be re-deployed to serve a range of lead firms as conditions change. The term "turn-key" stems from the large size, broad capabilities, and independent stance of the largest suppliers. The services of turn-key suppliers are generally available to lead firms on short notice with relatively little prior interaction. The fluidity of the network is supported by the ability to hand-off

[5] Standardized protocols do not arise spontaneously, but are part of the historical processes of industrial development. Standards can be agreed upon by committees (open standards), or they can arise from the codification of the routines of dominant firms or from equipment or software vendors (*de facto* standards). Their establishment is often contentious and part of the competitive positioning of firms. Standards are also dynamic. They change as new component, product, and process technologies emerge.

[6] The set of ideas underpinning the notion of modular production networks has much in common with Langlios and Robertson's (1995: 68-100) discussion of external capabilities, modular systems, and the rise of "decentralized networks," except that value chain modularity in their framework arises from lead firms' reliance on outside component suppliers and does anticipate the possibility that lead firms might outsource processes steps and even the entire manufacturing process itself. Their focus is on component modularity, not the process modularity that underlies the modular production network.

relatively codified product and process specifications at the inter-firm link, which has the effect of reducing asset specificity and making suppliers and lead firms substitutable. Asset specificity is also lowered and substitutability enhanced by the "generic" production capacity of turn-key suppliers, capacity that is essentially shared by the supplier's customers.

In other work (Sturgeon, 2002b; Gereffi, Humphrey, and Sturgeon, 2003), value chain modularity is contrasted to more "relational" network models that have been developed in the literature where lead firms and suppliers are more locked into their trading relationships, either through social and spatial propinquity, as in industrial districts (Piore and Sabel, 1984), or though a high level of supplier dependence on dominant lead firms, as in Japanese-style "captive" production networks (Dore, 1986). In relational networks, product and process specifications remain relatively tacit, and therefore more intense interaction between firms is required, which in turn leads to greater asset specificity in the inter-firm relationship (Williamson, 1975, 1981, 1985). Spatial clustering in industrial districts is one mechanism to suppress transaction costs in the face of asset specificity (Scott, 1988) and the power relationships and equity ties between lead firms and suppliers in captive networks are another (Jarillo, 1988).

The process of industry re-organization that has given rise to modular production networks has been occurring at the same time that firms from nearly all advanced economies, and many developing economies, have been increasing their direct and indirect involvement in the global economy.[7] International production has long been a hallmark of American firms, but today, because of "deverticalization," global reach is

[7] There are two main routes to global integration, indirectly through buying or selling across borders, or directly though cross-border production. This paper principally concerns itself with the latter.

increasingly achieved with the help of a wide range of intermediaries, partners, and suppliers who support and even proxy for lead firms in far-flung locations (Gereffi, 1994). To try to solve some of the coordination problems that have arisen from outsourcing to multiple partners in a growing number of locations, many American lead firms have an active program in place to outsource to fewer, larger suppliers. In complex assembly industries, such as electronics and autos, this confluence of deverticalization, outsourcing, and supply-base consolidation has created a new set of important actors in the global economy, the "global suppliers" (Sturgeon and Florida, 1999, forthcoming; Sturgeon and Lester, forthcoming). Global suppliers introduce a high degree of value chain modularity into industry structure because the large scale and scope of their operations create comprehensive bundles, or modules, of value chain activities that can be accessed by a wide variety of lead firms. To put it differently, global suppliers are nearly always turn-key suppliers. Value chain modularity can be conceptualized and observed entirely at the local level (e.g., Saxenian, 1994), but in practice industry re-organization has become deeply entwined with the processes of globalization, and it is global suppliers that perhaps best exemplify this connection.

The combination of productive scale, geographic scale, and value chain scope that has been achieved by global suppliers in only a few short years is striking. Solectron, a provider of manufacturing and engineering services for the electronics industry, grew from a single Silicon Valley location with 3,500 employees and $256M in revenues in 1988 to a global powerhouse with more than 80,000 employees in 50 locations and nearly $20B in revenues in 2000.[8] During the same period Solectron increased its offering of

[8] Notably, Silicon Valley employment had increased to 6,000 by 2000.

services related to its traditional manufacturing function to include, among others, product (re)design-for-manufacturability, component purchasing and inventory management, test routine development, final assembly, global logistics, distribution, and after-sales service and repair. Lear, a Detroit-based automotive seating supplier that generated $1.1B in revenues in 1991 grew to $14.5 in annual sales by 2000, and now operates 400 plants in 33 countries and employs 125,000. At the same time, Lear expanded its product offering to include entire automotive interior systems, including headliners, carpets, cockpit modules, and interior panels.

What is important about the geography of global suppliers is that they are firmly embedded in locations with both low and high operating costs. Locations in advanced economies, such as Detroit and Silicon Valley, support the set of important interactions between lead firms and suppliers that resist codification, such as co-design, prototype development, and manufacturing processes validation. Such locations are also used for the manufacture of high value and/or low volume products. Engineering changes tend to occur more frequently in these products and their high unit value makes the marginal savings garnered by low-cost locations less compelling. Global turn-key suppliers provide a mechanism to bridge the tacit and proprietary with the codified and generic, as well as a mechanism to integrate high-cost locations with low.

This section has discussed the elements of value chain modularity in general terms. The following section offers a more fine-grained illustration of value chain modularity through the case of the electronics industry. Although value chain modularity appears to be increasing in other industries as well (Sturgeon, 1999; Sturgeon and Lester, 2002; Sturgeon and Florida, forthcoming), the electronics industry, thanks in part to relatively well developed standards surrounding design processes, component characteristics, and manufacturing process technologies, provides an excellent illustration of this emergent system of industrial organization.

Value Chain Modularity and the Rise of Global Contract Manufacturers in the Electronics Industry

Markets for electronics-based products, and the value chains that serve them, are extremely diverse, complex, and dynamic. Hardware and software applications are very broad and new applications and products continue to be invented. The result is an industry characterized by overlapping sets of value chains and a variegated and dynamic set of actors. Still, the organizational structure of the electronics industry in the United States has changed enormously since the industry's birth in the late 19th century and broad historical patterns of organizational change can be identified.[9] After a brief period of infant industry fragmentation, the electronics industry in the US came to be dominated by large, vertically integrated firms, first in the telephone industry (e.g., ATT) and then the radio industry (e.g., RCA), out of which grew other consumer electronics sectors such as television and eventually, computers (e.g., IBM). In the 1960s and 1970s, with the push for better semiconductors for military and aerospace applications, an independent, or "merchant," components industry (e.g., Texas Instruments) gathered steam with the Air Force and NASA playing the role of "lead firm" (Markusen, et al, 1991). In the 1980s, as the civilian electronics industry began to grow rapidly with the personal computer, a range of other value chain functions were outsourced, beginning with production equipment for both semiconductor fabrication and circuit board assembly, and then spreading to the manufacturing process itself in a practice called "contract manufacturing."

Today, the structure of the electronics industry is increasingly modular. Process technology is being driven in large part by the vendors of production equipment such as Applied Materials (for semiconductor fabrication) and Fuji, Matsushita, and Siemens (for circuit board assembly). The use of semiconductor foundries for chip fabrication and full-service contract manufacturers for circuit-board and final product assembly is widespread and increasing (Electronic Trends Publications, 2000). Most recently, even the design process is being "unbundled," with repetitive and specialized design tasks being turned over to external suppliers, especially in semiconductors where "system-on-a-chip" integration has increased the range of design competencies required to produce a single device (Linden and Somaya, 2002). This industry structure allows "virtual" lead firms and "fabless" component design houses to be regularly founded with no intention of ever establishing in-house production, a feature that has long been part of the organizational landscape of the electronics industry in places like Silicon Valley (Davidow 1992; Saxenian, 1994; Sturgeon, 2000b) and Taiwan (Lee and Chen, 2000), but which has now been fully embraced by many large electronics firms that have historically been more vertically integrated, such as Nortel, IBM, and Ericsson (Serant 2000a).

The general organizational pattern that has resulted from these changes can be described as a shift away from vertical integration toward horizontal specialization. This is not to say that value chains have fragmented into smaller elements. While value chains

[9] The geography and organization of the electronics industries emanating from Japan, Europe, and Korea are not intended to be included in this section's description.

have “disintegrated” vertically, there has been a great deal of horizontal consolidation to achieve external economies of scale and scope.[10] Horizontal specialties sometimes constitute a single value chain function, but recent trends suggest that under certain conditions, this may be giving way to more “vertical bundling” within the horizontal pattern (Calderon, 2001; Serant and Shah, 2001). Hence, the electronics value chain is coming to be made up of a shifting set of “value chain modules,” each containing sets of closely related activities. The parameters of these modules are in part determined by technical factors, such as the standards that characterize product and process technologies, and in part by the strategies of participating firms. It is important to recognize that the parameters of value chain modules are highly dynamic; they can and do change as technology and strategies change. In our interviews; many lead firms managers stated their desire to integrate downstream from their “core” activities of product development, sales, and marketing by developing new capabilities in “value-added” services such as system integration and custom application development. These strategies are being pursued even as upstream activities such as manufacturing are shed. For turn-key suppliers, rapid expansion has led some toward upstream integration to ensure the supply of components that are unique to specific product models, such as bare circuit boards and enclosures, especially in remote locations with poorly developed supply-bases.

This paper is mainly concerned with product-level electronics, and in this part of the electronics value chain it is the rise of contract manufacturers that has been one of the most notable features of organizational change over the past fifteen years. As the

[10] Economies of scale are said to be “external” in this case because they are generated at the industry-, not the firm-level (Langlois and Robertson, 1995). External economies of scale arise because the capacity of

outsourcing of manufacturing gathered steam in the late 1980s, clusters of regional contractors emerged in a variety of locations, with Silicon Valley, California, Hunstville, AL, Singapore, Hong Kong, Taiwan, and Scotland being notable early centers (Sturgeon, 1999). Within the past five years there has been a striking process of consolidation and the largest five contractors, all based in North America, have expanded globally, in part through the acquisition of competitors from Europe and Asia.[11] Today the world's largest five contract manufacturers are Solectron, based in Milpitas, California; Flextronics International, incorporated in Singapore but managed from its San Jose, California, headquarters; Sanmina/SCI, also based in San Jose; Celestica, based in Toronto, Canada; and Jabil Circuit, based in St. Petersburg, Florida. A few of these firms have had global-scale operations for some time, but others have established global footprints quite suddenly through the acquisition of competitor and customer facilities as well as the establishment of new, "greenfield" facilities.

As Table 2 shows, largest five contract manufacturers collectively grew at an average annual rate of 36% per year since from 1994 to 2001. Estimates by Technology

modular suppliers is essentially shared at the industry-level.

[11] The description in this section cover the North American-based contract manufacturers only. A set of smaller, highly sophisticated electronics contract manufacturers also emerged in Taiwan in the 1990s (Dedrick and Kraemer, 1998; Lee and Chen, 2000). Taiwanese contract manufacturers, widely known in the industry as original design manufacturers (ODMs) have a much narrower product focus (i.e., on low- to mid-range personal computers), generate more revenue from design services, and have shown a greater penchant to compete with their customers in end markets than North American contract manufacturers. Although the Taiwanese ODMs make up an important part of the shared, modular supply-base for electronics production, and have developed in large measure in response to the outsourcing strategies of American personal computer firms such as Compaq and Dell. Sturgeon and Lee (2001) argue that the above characteristics have caused the Taiwanese contract manufacturers to grow more slowly than their American counterparts. Between 1993 and 1999 total revenues of the largest five ODMs—Acer, Quanta, HonHai, First International Computer, and Mitac—increased 35.5% annually from $1.7B to $10.3B. In the same period, total revenues of the top five American contractors increased 47.7% per year, from $3.3B to $33B. Along with slower growth, institutional factors in Taiwan, such as an undercapitalized financial market, legal constraints on mergers and acquisitions, and a shortage of international management experience outside of East Asia appear to have put limits on the ODMs' ability to expand globally (Sturgeon and Lester, 2002).

Forecasters, IDC, and Prudential Financial all peg contract manufacturers' penetration of the total available market for circuit-board and product-level electronics manufacturing in 2000 at roughly 13%, leaving a great deal of room for continued growth. A recent Bear Stearns survey of lead firms in the electronics industry concluded that the rate and size of outsourcing agreements will continue to increase, with 85% of the firms interviewed planning on further increases in production outsourcing. The lead firms surveyed expected to outsource 73% of total production needs on average, and 40% stated their intention ultimately to outsource 90% to 100% of final product manufacturing.

Table 2. Revenue at the Top Five Electronics Contract Manufacturers, 1994 and 2001, $M

COMPANY	1994	2001	Average Annual Growth Rate
Solectron	1,641,617	18,692,000	42%
Flextronics	210,700	12,110,000	78%
Sanmina/SCI	2,363,581	11,248,651	25%
Celestica	1,989,000	10,004,000	26%
Jabil Circuit	404,056	4,331,000	40%
TOTAL	6,608,954	56,385,651	36%

* All Celestica revenues in 1994 were from IBM.
Source: Company annual and quarterly reports

Electronic Trend Publications (2000) estimates that the top five contract manufacturers had captured 38% of the electronics contract manufacturing market by 1999, and expect this share to grow to 65% by 2003. This rapid consolidation, fueled by the acquisition of competitors and customer facilities as well as internal expansion in existing and newly established facilities, was aided by the US stock market run up in the late 1990s, which concentrated 90% of the market capitalization in the top five CMs.

The geographic pattern that has resulted from this consolidation and reorganization is as follows. The handful of dominant contract manufacturers have their headquarters in North America. New product introduction (NPI) centers, where prototypes and volume manufacturing processes for new products are worked out in concert with lead firms, are located in advanced economies.   Contractor NPI centers tend to be located in places where there are concentrations of lead firms, such as Silicon Valley and the Boston region, or adjacent to the design centers of important customers. Advanced economies also house "high-mix" production lines tuned to manufacturing a wide variety of high-value products in small batches. These are often co-located with NPI activities. High-volume manufacturing of price-sensitive products is generally located in locations with low operating costs. Such products fall into two broad categories. Products that have short lead times and have requirements for last-minute configuration tend to be produced in lower-cost locations within regional trade blocs, such as Mexico and East Europe. As a result, many older plants in Scotland, Ireland and Continental Europe and Scandinavia are being closed, scaled back, and/or re-focused on new product introduction and low-volume, high-mix production. In North America this has meant a shift of production from US and Canadian plants to Mexico, especially Guadalajara. The most standardized, highest-volume, price-sensitive products such as personal computers, cell phones, and consumer electronics are manufactured in Asia. Southeast Asia has long been an important manufacturing location for the most standardized and price sensitive electronics products, such as parts for hard disk drives and personal computers, but nearly all new capacity in Asia is now being established in Mainland China, especially in the southern province of Guandong Province near Hong Kong.

The Electronics Industry Cycle of 1992-2002

The electronics industry has historically been extremely cyclic. The most dramatic business cycles have been associated with the appearance of what are referred to in the industry as "killer applications;" that is, applications, products, and technologies that have a wide range of potential end uses and the ability to change the way wide swaths of the population live and work. The personal computer was certainly such a product. The boom in sales that followed the introduction of the original IBM PC in 1981, as well as its open architecture, led to a rush of market entrants and an overproduction cycle that peaked in late 1984 (Rogers and Larson, 1984). The subsequent market slowdown led to a fierce shake-out of fledgling PC companies and a brutal whipsawing of various component sectors, from disk drives to semiconductors.

In the late 1980s, the industry gradually picked up steam again as the client-server model of computing caught hold, driving sales of PCs, servers, and local area networking gear to connect them. The general economic slowdown in the early 1990s was felt in the industry as corporate IT budgets were cut, and there was much hand-wringing over the need for a new "killer application" to drive growth, but markets continued to expand after the recession as analog telephone infrastructure was converted to digital, local area data networks were connected through routers and bridges to create wide area networks, and products as diverse as medical equipment, motor vehicles, and household goods began to incorporate a significant amount of electronics.

While there was much discussion in the early 1990s about how the convergence of communications and computing would provide computer users with ubiquitous access to rich "multi-media" content, there was no agreement about how that content would be delivered. In the mid-1990s the Internet provided that delivery system quite suddenly, and the industry, fueled by an unprecedented flow of capital into venture capital funds and securities markets, took off on a boom of epic proportions. The Internet drove many parts of the electronics industry to new heights, especially PCs but even more so Internet-capable communications equipment.

The to meet the boom in demand for Internet-related hardware, highly successful lead firms in the communications and data storage sectors with little in-house manufacturing such as Cisco Systems, Juniper Networks, and EMC placed large orders with contract manufacturers. Telecommunications equipment firms with in-house production such as Nortel, Lucent, Alcatel, and Ericsson, Nokia sealed multi-billion dollar outsourcing deals with the largest contract manufacturers that coupled 2-5 year contracts with the sale of dozens of production facilities and process technology centers. By engaging in these deals, lead firms claimed to be focussing their efforts on winning new business in the seemingly limitless market for Internet-related switching gear and optical transport.

In can be safely said that outsourcing became a "fad" in American business during the boom years of the late 1990s. Wall Street rewarded lead firms' for the sale of fixed assets (plant and equipment) to suppliers and rewarded suppliers for their rapid growth; their accumulation of fixed capital was either overlooked, or seen as unproblematic because of capacity pooling. As share prices skyrocketed lead firms used the cash to acquire smaller firms that would help them develop new products and services for the Internet, and the largest contractors made additional acquisitions of customer factories and competitors on a global scale. On the announcement of large outsourcing deals, the share prices of both lead firms and contractors tended to increase.

Then, in late 1999, the boom began to stall. It became clear quite suddenly that the Internet, while still growing with extreme rapidity, would not utilize the huge volume of communications infrastructure that had already been deployed for many, many years, and capital spending on communications and information technology ground to an abrupt halt. Since the bulk of their growth had been in the communications sector, the crisis was immediately felt by the largest contract manufacturers. Although this industry slowdown has certainly been painful—Solectron has cut its worldwide workforce by 20,000—the crisis also created new business for contract manufacturers. Large outsourcing deals have continued to be announced, with most of the new business going to the very largest firms. On average, sales of the largest 50 CMs declined only 6.5% in 2001 from the previous year (from $77.9B to 72.8B). According to John Tuck, publisher of the industry newsletter Manufacturing Market Insider (Tuck, 2002), "If some [additional] outsourcing had not occurred in 2001, the decline would have been worse." Our recent field interviews with the largest contractors have shown that these firms are pushing hard, and are being pushed, to take on additional functions, especially build-to-order final assembly and design services for low-end products. Furthermore, the downturn is causing lead firms to ask their contractors to shift production from advanced to emerging economies as rapidly as possible (Manufacturing Market Insider, 2002). This is especially true of China where a critical mass of low cost components is becoming available.

With the industry downturn there have been a new attempts to shift the production of the lower ranges of higher-value products, such as the most basic Internet routers and telecommunications switches, to lower-cost locations. Still, it is important to note that the share of electronics manufacturing in high-wage economies remains significant. During field interviews, managers at the largest contract manufacturers stated that 50-70 percent of their revenues were derived from producing in advanced economies and although they were rapidly building up additional capacity in low-cost locations, the share of revenues generated in high-cost locations was unlikely to fall below 30 percent. Some managers also suggested that the shift to low-cost locations could be slowed or reversed if capacity utilization rates were to increase with an upturn in the industry.

The (Theoretical) Advantages of Value Chain Modularity

Why has value chain modularity emerged so suddenly in the American electronics industry? The herd mentality of managers can help to explain such fads in corporate practices, but there are usually sound theoretical notions underpinning such extremely popular business strategies. The question of performance then, comes down to execution of those ideas and the tendency for very popular ideas to overwhelm other important business fundamentals. This section presents the theoretical advantages of value chain modularity, but it is important to bear in mind that these advantages do not accrue automatically and can only be reaped by firms that recognize both the advantages and the pitfalls and act accordingly.

The theoretical advantages of value chain modularity can be divided into two broad categories, cost advantages and dynamic advantages. A long-standing question in the electronics industry is if using contract manufacturers costs lead firms less than in-house production (see Sturgeon, 1991, for an early discussion). Our recent research suggests that the answer to this question is yes. For example, a respondent at a large, diversified lead firm in the electronics industry who had seen a large share of his company's manufacturing facilities sold to contract manufacturers stated that "contract manufacturers reduce the cost of good sold 10-15%."[12]

Using turn-key suppliers for production lowers costs in two ways, human resource "un-bundling" and capacity pooling. Production workers at lead firms typically enjoy benefit packages and, to some degree, wages that are set by higher-paid employees at the firm, such as managers and engineers. The ARISSA laws, which have effect in the US since 1975, make it illegal for firms to have two-tier benefit systems. When production jobs are outsourced, then, production workers, because they are in a different company, can earn wages and benefits inferior to the design, management, and marketing staff that remain at the lead firm.[13] In addition to paying lower wages and providing inferior benefits to permanent employees, contract manufacturers make heavy use of temporary workers in places were it is easy to do so (it is easier to use temporary workers in North American and Japan than in Europe, for example). Our interviews found that temporary workers typically comprise 10-50% of the workforce at the largest contract

[12] These savings are shared between lead firms and the contractors though a process (often contentious) that is negotiated as each new product is brought into the system.
[13] In the US motor vehicle industry, where industry structure has shifted dramatically toward value chain modularity since 1985, employees at suppliers, on average, earn far less than those at lead firms, the automakers. Average hourly wages at suppliers were almost on par with those at automakers between 1958 and 1978, when they ranged from 93 percent-97 percent of wages paid by automakers. This rough parity

manufacturers.[14] Temporary workers provide contractors with a buffer to compensate for demand fluctuations. As the human resources director a one large contract manufacturer put it during an interview, "We want to give employment to permanent employees permanently, but temporary workers are at the mercy of our customers."[15]

The second source of lower costs at suppliers in modular production networks are what one lead firm manager referred to during an interview as the "natural efficiencies" that arise from shared production capacity, namely better utilization of plant and equipment and component purchasing scale economies. The base processes and services offered by turn-key suppliers, because they are generic, have large economies of scope and so can be offfered to a wide range of lead firms within their industry. In product-level electronics, manufacturing plants for circuit board and final product assembly can produce products for a very wide range of customers and end-markets. Such scope economies lead to better asset utilization as human effort and fixed capital are pooled, conserved, and (re)deployed across a broad customer base. High asset utilization comes from running plant and equipment for long hours. Since contract manufacturers have many customers, there is greater scope to balance manufacturing loads than with in-house facilities, which are usually dedicated to the manufacture of products for the firm that owns the plant.

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began to erode after 1978, and by 2000 average wages at suppliers stood at an all-time low of 74 percent of those paid by automakers. (Sturgeon and Florida, forthcoming).

[14] Temporary workers are found through employment agencies, student internship programs, and "retiree-on-call" programs.

[15] Not surprisingly, labor unions take a dim view of outsourcing unionized manufacturing jobs to non-union contract manufacturers. Although unionization rates in the electronics industry have been low historically, there are places, such as the Northeast United States and in Europe, where labor unions have been important. A union Secretary interviewed in the Northeast US who had seen his local's membership shrink from 4,000 to 1,000 between the mid 1985 and 2001 as the local telecommunications plant outsourced more and more jobs to contract manufacturers stated, "The companies are going to use the contract

Purchasing scale economies come from the pooling of component orders. Simple electronics components, such as resistors, capacitors, and connectors are required for the manufacture of nearly all electronics products, and contract manufacturers can get better terms from component manufacturers and distributors than their customers because they can pool orders. As the buying power of contract manufacturers has increased, many component manufacturers and distributors have created dedicated sales teams to cater to them (Serant, 2000b).

The second broad category of advantages are dynamic in nature. In what is often referred to in the industry as "upside and downside flexibility;" contract manufacturers provide lead firms with the ability to ramp production output levels up and down without installing or idling in-house capacity. This is especially important in volatile industries such as electronics. During an interview we were told by a lead firm manager that, "[Our firm] was selling 24,000,000 [units] each year in the mid-1990s and this increased to 40,000,000 in just a few years. This ramp-up could never have been done in-house. The administrative time alone for getting new in-house capacity on-line is six months, forget about construction. So, upside flexibility is important. And when business is down, you are sitting on underutilized factories that may be in the wrong location."[16]

The geographic scale of global turn-key suppliers plays into both cost and dynamic advantages. Since their largest and most important customers require goods and services delivered in a range of geographic locations, turn-key suppliers have worked to rapidly establish a global footprint. A global footprint allows a supplier's customers to

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manufacturers to bust the unions." Shortly after the interview, the plant was sold to a leading contract manufacturer.

[16] To protect the confidentiality of the organizations and individual respondents, we mask company names and exact products.

locate production in a variety of places with less, or even no, direct investment, lowering the risk of globalization. Many of these places have lower operating costs than locations where lead firms have facilities. Lower operating costs come from lower prevailing wage rates, taxes, component prices, and less stringent environmental and labor standards. The volatility of the global economy in general, and in particular in the specific industries where global suppliers are important, has only made the dynamic advantages they afford more attractive.

There are questions about the magnitude of the advantages of using global suppliers in the realm of global integration. Conceivably, global suppliers might be able to pool activities such as logistics and materials management to provide scale efficiencies that would be out of reach for any single customer. During an interview, one lead firm manager stated, "The global nature [of the largest contract manufacturers] is truly unique, and this is an extraordinary value added. Activities such as distribution and tooling are still very regional. Even OEs [lead firms] are more regional because they have to sell to different end markets. These global competencies give contract manufacturers a huge opportunity to 'roll up' [consolidate through acquisition] other regional industries [to create global-scale, centrally managed systems]." Others argue that it is possible to deploy in-house assets globally, as some consumer products companies have done, and that we must therefore conclude that lead firms in the electronics industry have either failed to do so or have chosen not to (personal communication, Professor Donald Lessard, May 3, 2002). Another explanation might be the complexity of the products where modular value chains are important; the complexity of deploying in-house assets globally go up with the number of inputs required, as do the challenges for logistics and materials management.

At the very least, it is clear that the establishment of spatially dispersed operations has pushed global suppliers to develop new sets of competencies in areas related to global integration. Operating in a wide variety of national contexts is a difficult challenge, especially since a high degree of inter-plant compatibility and an ability to collect data and control inventory across diverse and distant facilities has become a crucial part of global integration. It was repeatedly stated during our interviews with lead firm managers that the largest contract manufacturers were struggling with their new role as global suppliers. As one manager put it during an interview, “Contrary to the picture they’ve painted of themselves, contract manufacturers are not very good at forecasting, materials management, or logistics. They are only good at manufacturing.” Another stated, “Engineering and materials management teams at contract manufacturers are less capable than those at lead firms. Personnel are paid less, and there is less time and money to work out difficult problems.”

While there are clearly problems that remain to be solved, I do argue that modular production networks offer theoretical performance advantages over more relational networks where close ties between lead firms and suppliers inhibit capacity pooling. Still, there is a big difference between the theoretical performance characteristics of conceptual models and real-world performance. Firms and their specific value chains can be observed with an almost infinite variety of characteristics, and the definition of any value chain “type” is at best an approximation of what might be observed in the field. The standards that enable the codification of product and process specifications are different in different industries and are constantly evolving. Some sectors use technologies that are more easily codified than others. The tight tolerances required for the assembly of hard disk drive heads, for example, appear to be an important part of the reason that this process has been retained in-house by the firms that develop and market disk drives (personal communication with David McKendrick, February 24, 2001). Standards for codifying product and process specifications can become obsolete as technologies change or when there is a drive to bundle value chain activities in new ways. As Michael Storper has pointed out, new technologies can restart the clock on the process of codification (Storper, 1995, p 207). Even when the underlying conditions for value chain modularity are well established, as in the Japanese personal computer industry, large scale outsourcing might be antithetical to long-standing corporate strategies and societal expectations, such as "life time" employment. Finally, capturing the theoretical advantages of value chain modularity requires that lead firms and suppliers alike perform well in their respective areas of responsibility. Our field interviews have shown that this does not always occur, even when both parties fully embrace the model. So, conceptual models provide only limited utility in the field and we should expect empirical outcomes to be highly variable. The evolution of value chain structure can be extremely rapid, and generalizations, however true they may ring in the moment, may become outmoded as time goes on.

However, I do maintain that some value chains have characteristics that are more "modular" than others, and that the broad historical trend appears to be toward value chain modularity. Global integration, the emergence of better product and process standards, and the increasing competence and geographic reach of suppliers are all long-term trends that might support the growth of modular production networks over time. This is not to say that the shifts that have led to value chain modularity have gone uncontested or that modular production networks have not created new problems as they have solved others. To the extent that the modular system exists in the real world, it is by definition new, untested, and unrefined. In the following section I explore four risks raised by value chain modularity in the electronics industry.

Four Risks Raised by Value Chain Modularity in the Electronics Industry

Along with the (theoretical) advantages outlines above, value chain modularity has also introduced a set of (theoretical) risks to the American-led electronics industry. As with the advantages, if and how such risks affect firm and industry performance depends on how well strategies are crafted and executed, how competing and cooperating firms behave, as well as on the institutions in which firms are situated. This section briefly discusses four risks raised by value chain modularity, and discusses the recent responses of North American electronics contract manufacturers and their customers to these risks.

Intellectual Property Risk

Until very recently, most North American contract manufacturers were almost exclusively focused on the manufacturing process, which contains little critical information about product strategy, product design, or customers. Since most of the key intellectual property (IP) has resided in software and component-level hardware, especially application-specific integrated circuits (ASICs), firms that did not consider product-level manufacturing as a source of innovation—and most North American lead firms have not—had little concern with IP leakage through contract manufacturers. Today, as contracts are becoming more deeply embedded in the day-to-day operations of their customers, the potential for "leakage" of key information to competitors is heightened, especially when suppliers are involved in the design process and provide services, such as build-to-order, fulfillment, and distribution, that are close to the end user. Outsourcing of design processes is perhaps the most risky.

Recent interviews show that some important North American lead firms are currently driving their contractors to take on additional functions such as detailed product design, build-to-order, and distribution. In the context of the industry down-cycle, lead firms are seeking to cut costs and hope that the pooling mechanism that contractors have provided in the realm of manufacturing can be extended to detailed design and distribution. As this trend has gathered momentum, the issue of knowledge management has become more problematic. As contractors take on more design work, begin to select more components, manage the entire global production system for their customers, and move closer to the end customers of lead firms, they are gaining strategic insights into their customers' business that could be quite damaging if leaked other lead firms, who are often direct competitors but share the same contractors.

From the perspective of lead firms, there are two negative outcomes associated with IP risk. The first is the possibility that contract manufacturers will develop their own products and compete with their customers. A recent announcement by Flextronics that they plan to design a generic cell phone to sell to carriers has created a considerable amount of consternation in the industry. The second is that critical information will leak to competitors.

To ameliorate some of these risks, contract manufacturers have put up partition walls in high volume production facilities to separate production lines that are "dedicated" to particular customers. This assures customers that competitors will not be walking along the lines where their products are being assembled. But in high mix facilities, and these are the facilities where the most technologically dynamic products are typically produced, there are rarely dedicated lines. Another solution is for customers to demand that their contractors work only for customers in unrelated business lines. While this is possible because of the generic nature of the production process, it still decreases the flexibility of the network, which would move closer to the "captive" model. And, as consolidation provides the largest contractors with size and power, fewer customers have the influence required to make such demands.

Market Entry Risk

With widespread outsourcing to turn-key suppliers, crucial value chain functions become commodified. According to the asset-based view of the firm, how and if firms can capture value depends in part on the generation and retention of competencies that are difficult for competitors to replicate (Penrose, 1959). In modular production networks lead firms strive to outsource all activities that are not perceived as "core." Removing layers of activities surrounding the core, however, might also remove barriers to entry for competitors because many of the essential—but not core—activities of the firm, manufacturing for example, exist as services that can be easily purchased by competitors (Sturgeon, 2000). While this is an advantage for start-ups, it can prove disruptive for existing firms.

Witness the low barriers to entry for "fabless" semiconductor firms and "virtual" start-ups in the various product-level electronics markets like communications. The manufacturing strategy of a small California communications start-up interviewed in 2001 provides a telling example. The founders had experienced great success with a previous start-up in the mid-1990s when the sudden and widespread acceptance of their product led to the acquisition of their firm by an established communications firm for a huge sum. This time round, the founders wanted to see their product succeed without selling the firm. To meet this goal, an anticipatory high-volume manufacturing strategy was developed from the very beginning that would allow production to increase from the pilot phase to high volume production in short order. To do this, the firm sought a close relationship with a large contract manufacturing firm as part of their basic business plan, and co-developed the manufacturing process alongside its product development efforts. To be ready to meet an initial spike in demand, pilot runs were established, not in a local "job-shop" or in an in-house pilot manufacturing facility as is the typical practice, but in the high volume facilities of their contract manufacturing partner. To do this, the start-up had to convince the contract manufacturer of the potential of its product, just as it would a venture capitalist.

The reasons for making this kind of effort from the contract manufacturer's perspective was clearly spelled out during a recent interview with a manager at a large contractor.

> We do not partner with every start-up; we must choose carefully. Cisco is only 12 years old. No one wants to miss out on that kind of opportunity. We manage a portfolio of start-ups, as venture capitalists do, which also keeps us abreast of technology. Venture capitalists tell start-ups, 'we'll fund you, but you must use [a specific contract manufacturer.' Start-ups may only have a schematic [circuit design] and so there is a lot of value added that we can provide [e.g. with layout or industrial design services]. Start-ups comprise 5-10% of our business.

From an industry-wide perspective, the ability of start-ups to leverage the global production capacity of contract manufacturers to quickly establish a large market presence in the face of sudden demand represents a significant lowering of entry barriers for new players relative to an industry structure dominated by in-house manufacturing or small, regional contractors. The global contract manufacturing infrastructure that lead firms have helped to create through their outsourcing activities has effectively lowered the barriers to market entry for their future competitors.

A second category of market entry risk, and one which overlaps with the above discussion of IP risk, comes from the contract manufacturers themselves. To perceive the risk involved we need only think of RCA sewing the seeds of its own demise in the 1960s and 1970s by outsourcing production, and finally design, to Japanese consumer electronics firms. Concerns over IP leakage has contributed to the rapid growth of North-American-based contract manufacturers over another set of contract manufacturers, the original design manufacturers (ODMs) based in Taiwan. The ODMs have long provided product design services for lead firms in the personal computer industry. Personal computers are unusual, however, in that the bulk of product functionality is located in two *de facto* industry standard components, Intel's "x86" series of microprocessors and Microsoft's "Windows" operating system. This makes the product design process unusually routine. The ODMs have been trying to expand into other product areas such as computer servers and telecommunications, but as yet have only had success with another relatively standardized product, the mobile phone. Historically, many ODMs have tried to leverage their design and manufacturing competencies to develop their own line of branded products, although only Acer has met with limited success. The notion that ODMs were striving to become direct competitors to their customers has made lead firm managers extremely worried about sharing key IP with them. In an interview, one lead firm managers stated the "[ODMs] scare the hell out of us. These guys are thieves." A manager at a leading contract manufacturer stated that "[we] will never compete with our customers. We have not created the brand equity that would allow us to add value by branding. The ODMs have more power than the PC firms; they are now doing cell phones and are encroaching on networking equipment. The lead firms know that the [North American contract manufacturers] will not compete with them, but ODMs will take their designs and sell them to others." This perception may help to explain why, during the surge in electronics outsourcing in the 1990s, the bulk of new business went to North American contract manufacturers and not to established contractors based in East Asia (Sturgeon and Lee, 2001).

Inventory Risk

Inventory risk comes from the forecasting distortions caused by the insertion of new actors into the value chain. Before value chain modularity, electronics products, including the components they were comprised of, were developed and produced entirely in-house. Then, as a "merchant" electronic components industry came into being, lead firms began to source their components from suppliers and distributors. Today, new value chain actors are in the mix. Lead firms might use a fabless semiconductor firm for the design of specialized devices, a semiconductor foundry to manufacture the device, and a contract manufacturer to buy standardized components, manufacture sub-assemblies, and build final products. In the past, vertically integrated lead firms would create their production forecasts based on their own sales projections and transfer this information to their key component suppliers. Component suppliers then based their own production forecasts on the forecasts from customers. Because of the dynamic and volatile nature of the industry, inventory gluts and component shortages, sometimes coming in quick succession, were commonplace. Today, the situation has become more extreme because lead firms now provide forecasts to *both* their contract manufacturers and key component suppliers, and contract manufacturers in turn pool their orders and provide yet another set of imperfect forecasts to components suppliers, who then must reconcile the two to construct their own forecasts. Because of this "forecast layering," contract manufacturers have introduced additional "noise" into an already imperfect system of production forecasting in the electronics industry. In addition, the function of materials management is a relatively new one for contract manufacturers, especially at the global scale that it must now be practiced, and by most accounts they are not yet very proficient at it.

The end of the boom period of 1992-1999 exposed some spectacular instances of poor inventory planning. Cisco alone wrote down nearly $2B in excess inventory. As late as the first half of 1999, the problem for companies supplying the hardware to power the "dot.com revolution" was in keeping up with demand. Cisco purchasers ordered twice, and in some cases <u>three times</u> the volume of components and finished products that they needed to fill current orders from customers. The company knew the lesson, learned the hard way by other Silicon Valley firms such as Apple Computer, that the worst blunder they could make in selling to highly dynamic markets was to be unable to meet sudden spikes in demand for their most advanced products. In new markets, where buying patterns and customer loyalty is yet to be established, being unable to ship finished products to customers means losing the chance to dominate new market niches. During the boom this strategy worked well for Cisco, the were able to keep up with the radical growth in demand for internet switching gear and accumulated an 80% market share, which in turn drove the company's share price into the stratosphere. When the market collapsed suddenly in the fall of 1999, Cisco, and its suppliers, found themselves with huge volumes of excess inventory.

Still, while the Cisco case was widely noted and certainly emblematic of a wider problem, it is important to note that other lead firms in the electronics industry practiced much better inventory control during the boom period than Cisco. Many lead firms generally do not ask their contract manufacturers to buy parts in advance. A conservative approach described by a lead firm manager interviewed for the study provided contractors with two forecasts, build forecasts and inventory/capacity assignment forecasts. The capacity assignment forecasts mean: "go buy this stuff and plan to build it." Build forecasts are what the lead firms believes the up-side or down-side potential is. This was described as more of a "heads-up."

Who owns excess inventory, lead firms, contract manufacturers, or component suppliers? Nominally, and legally, this question is easy to answer. As a manager at a large contract manufacturer put it during an interview: "Lead firms use contractors to 'hide' inventory and improve their return on investment numbers. They can keep contractor-purchased components off their books, but only to a point. If markets are not growing, or if they collapse, then inventory ordered by the lead firm must be paid for, which transfers inventory cost onto the lead firm's books. When things were growing, lead firms were unabashed about telling the contractors to order inventory, and this backfired."

So, components, in-process inventory, and finished products that have been ordered by lead firms ultimately belong to lead firms, even if contract manufacturers have paid for components out-of-pocket under "turn-key" contracts. In practice, however, no firm wants to pay for excess inventory and so there is a great of pressure put on upstream partners to pass unused inventory back up the value chain. In this regard, is useful to consider two classes of inventory: 1) generic parts and 2) custom parts and finished goods. Generic parts, because the are relatively standard, can be taken back by component suppliers or reused by contract manufacturers, with permission, in the manufacture of products for other customers. Component suppliers can also be pressured to take back unused standard parts from contractors. Custom parts and finished good, however, are only useful for specific products and therefore must be written off by someone if they go unused.

Our field interviews strongly suggest that lead firms ultimately did pay for the bulk of excess inventory during the downturn. This is because most lead firms, when the scope of the downturn became clear, did pay contractors and component suppliers for excess custom parts and finished inventory. Although their numbers a fewer, the value of custom components in any given electronics product is much higher than standard components. Custom components include specialized semiconductors as well product-specific parts like wire harnesses and enclosures. Together, these parts make up 80-90%

of the materials bill, but only 10-15% of parts list. Finished inventory, or course, can only be adapted to new uses is rare cases. To avoid a glut of it's own finished products Cisco is reported to have destroyed hundreds of tractor trailers full of finished Internet switching gear. According to one of our interview respondents major contract manufacturers, as a group, wrote off only about $200M in excess inventory in 2000. [17]

Today, there are serious efforts underway to improve materials management across the value chain. First, lead firms have cut back on double ordering and are sharing more accurate forecasts with a smaller pool of suppliers. Second, the largest contract manufacturers are taking full responsibility for ordering standard parts. Components used to be "drawn off" contracts between lead firms and component suppliers, but contract manufacturers are increasingly dealing with component suppliers directly. Thus, it is becoming the contractor's responsibility to "pull the plug" on open contracts and cancel orders for standard components when the need arises. A purchasing manager at a top contract manufacturer stated that his firm spent $10B on components in 2000. Another stated that his firm spent $14-15B and was Texas Instruments' third or fourth largest customer in 2000. Pooling orders for standard parts allows contractors to get excellent pricing from component suppliers but also to attain better control over global inventory.

A third response is to build better inventory control into information technology systems. An IT manager at a major contractor described the implementation of a global "data warehouse" at his firm that will aggregate global purchases and allow personnel in all locations to locate and use excess inventory anywhere in the system. This system is

[17] Because notebook PC designs are so similar and share so many common parts, contract manufacturers making them can reuse inventory in other lead firm's products if a lead firms gets its forecast wrong. This is not the case with the largest contractors because they do not specialize in any one product set. So, there is less inventory risk when using the Taiwanese "ODMs'"

combined with enterprise resource planning (ERP) systems that will not allow purchasers to order parts if there is excess inventory in the system. Finally, contractors are setting up "supplier-owned inventory" schemes that provide component distributors with warehouse space, either within a factory or in an industrial park setting, which allows them to pay for parts only as they are used on the production line.

While the emergence of the contract manufacturing layer of the value chain may well have introduced additional "noise," it is just this noise that increases system flexibility. Vertically integrated lead firms have long had the ability to buy and sell generic components on the "gray market," which serves the function, among others, of re-pricing and selling excess inventory for new uses. The contract manufacturers can and do buy and sell on gray markets as well, but they have an internal operational mechanism that component brokers do not. As already mentioned, generic components can be, with permission, used in the manufacture of other customer's products. In a sense, the additional value chain layer introduced by the contract manufacturers opens up additional avenues for the productive use of excess inventory, and thus could help to smooth rather than exacerbate the capacity shortages and gluts that have long plagued the electronic components sector.

Asset Specificity Risk

As the rate of outsourcing increased in the 1990s, lead firms found themselves managing an increasing number of outsourcing relationships in a growing number of locations. The combination of rapid globalization with rapid outsourcing created a Medusa's head of multiple and overlapping regional supply relationships. To simplify the management of the network, and to focus supplier competence in fewer hands as more functions were outsourced, lead firms have been aggressively reducing the number of suppliers they use. Lead firms such as IBM, Cisco, and Hewlett Packard have moved from using scores of contract manufacturers to using perhaps a dozen, and recent moves indicate that the top 3-4 contracors are set to win the bulk of the new business from nearly all of the largest lead firms. As lead firms based in Europe and Japan increase their use of contract manufacturers, the business is going almost without exception to the largest North American contract manufacturers. This kind of consolidation may work restrict the flexibility of the network by locking trading partners into their relationships through the build-up of asset specificity. When annual contracts are valued in the billions of dollars, there is incentive for both parties to invest in assets that are specific to the relationship, such as personnel, routines, and fixed assets. When such assets are in place, it becomes more difficult for either party to switch.

Information technology is an area of particular concern The drive to streamline the hand-off of product specifications, forecasting data, and order data is requiring the information systems of lead firms and contract manufacturers to become deeply embedded in one another, often through the use of proprietary, highly customized systems. This is driving asset specificity up, which creates pressure for either vertical integration (Williamson, 1975) or captive inter-firm relationships. A countervailing trend is the development of open standards for supply chain management (SCM) systems such as RosettaNet and the success of some third-party vendors of SCM software such as E-buy and ECNet. But even with open standards or third-party systems, supplier ownership and control of IT systems can raise lead firm switching costs dramatically.

As with semiconductors, time is an extremely important success factor in product-level electronics. Rapid product cycles (and the concomitant market churn and boom bust cycles) have long been driven by rapid advances in semiconductors and the functionality of other key components such as disk drives. More recent trends toward lean retailing and build-to-order final assembly have mirrored those in the apparel sector (Abernathy et al, 1999). Even as manufacturing has been outsourced, many lead firms, most notably Dell Computer, have retained final assembly to support close customer linkages, build-to-configuration, and rapid fulfillment. Time considerations have thus fed into the regional production structures because final assembly has been pushed close to end markets. Most recently, final assembly too has also begun to migrate to contract manufacturers, requiring closer collaboration than ever between lead firms and contract manufacturers.

For formerly vertically integrated lead firms such as Ericsson, IBM, Xerox, and Hewlett Packard, the process of outsourcing has been accompanied by selling facilities to their most important contract manufacturers. These deals typically include 2-3 year contracts to continue manufacturing the lead firm's products in the plant. For lead firms, such deals are motivated by several factors. First, the selling of fixed assets to contract manufacturers removes these assets from lead firm balance sheets, for which they were richly rewarded by financial markets during the boom. Second, selling facilities to contractors mutes the political and labor resistance that might come from an outright plant closing, since most employees typically stay on as employees of the contractor. Third, keeping an existing facility running, even as its ownership is transferred, ensures a continuous supply of products. For the contractor's part, acquiring customer facilities allows them win new business and grow quickly, for which they too have been rewarded by financial markets. Once under the ownership of the contractor the divested plants can be used to manufacture for a wide range of customers, which opens the possibility of more intensive capacity utilization through capacity pooling.

As lead firms turn over more plants and award more business and more value chain functions to the largest contractors, these contractors are often designated as "strategic partners." Ercisson, for example, identified two American contract manufacturers as strategic partners in the late 1990s and began the process of turning over their worldwide manufacturing operations to them. As the process of supply-base consolidation accelerates, the questions of lock-in and network rigidity come to the fore.

The optimum number of suppliers is an important strategic question with no single answer. A key questions is: what is the optimum number of supplier needed to create capacity pooling effects and enhance supplier autonomy but which keeps the number of supplier relationship at a manageable number? There clearly is a point where the benefits of capacity pooling are outweighed by increased supplier power. The clear trend is toward smaller numbers of larger suppliers, but how few are too few? Again, the answer to this question varies. During an interview, a manager at a large lead firm put it as follows. "There is a push to 'right size' the supply base at [our firm]. How many suppliers are needed? Clearly one is too few. You need at least two, unless it is for very low-volume products. The optimum number of component suppliers also varies by component. For AVL capacitors [a standard item], we have seven suppliers; for a given ASIC, we have one supplier. The optimum number of suppliers also changes over the lifecycle of the product. At first, one or a few suppliers is needed, then, as volumes ramp up, more suppliers are needed. At the end of a product's life, fewer suppliers are needed. There is no hard and fast rule about this. The best solution varies."

Lead firms can work to keep supplier switching costs low by using standard supply chain management software, but these systems are just developing and neither open nor *de facto* standards yet exist for complex transactions. Another approach to keeping switching costs low is to monitor suppliers carefully to maintain critical knowledge in-house and to keep close tabs on engineering work, in what is known in the industry as "shadow engineering." Of course, close monitoring and shadow engineering are expensive and so can offset the cost savings of outsourcing. There is also tension within contract manufacturing firms about the degree that they want customers to become locked in. Lock in ensures future business, to be sure, but the engineering effort required to create and maintain proprietary IT systems cannot be spread across the entire customer base and so increases costs. Most attempt to provide standard systems that can be "tuned" to the needs of important customers, creating the illusion of a customized system without significant investment..

Mapping the Interface Between Tacit and Codified Information in Modular Production Networks

This section explores the interface between tacit and codified information in the context of product-level electronics outsourcing, and especially the points in the value chain where this interface overlaps with the inter-firm link between large lead firms and global turn-key contract manufacturers. This is a challenging task because there are constant efforts to codify tacit activities even as new activities emerge that cannot yet be codified. At the same time, there is a general trend in the industry to pass more tasks out-of-house to contract manufacturers, so the division of labor is also highly dynamic. This dynamism has been heightened by the industry cycle that unfolded over the past ten years; the imperative to add additional capacity during the boom was quickly followed by the imperative to cut costs during the downturn. Further, some lead firms have more aggressive approaches to the processes of codification and outsourcing than others, so generalizations are difficult to make. Finally, contract manufacturers also have different strategies and capabilities that they bring to the table. Still, an effort to map the flow of activities from lead firm to contractors as new products are brought on-stream is worthwhile. It reveals how the process of codification is unfolding in the context of value chain modularity and allows us to see the trends that might reinforce the system or cause it to break down.

Codification is the very heart of value chain modularity. When complex information can be codified and handed off between value chain actors the division of labor in an industry can grow and specialized value chain niches can emerge as viable businesses. When codification is accomplished according to widely known and widely used standards, supplier switching costs can be kept at levels that maintain the organizational and geographical fluidity of the system, allow for the build-up of large external economies of scale, and enable lead firms to reap the dynamic advantages of value chain modularity, especially the ability to quickly access new capacity in the face of demand surges. Low supplier switching costs allow lead firms to quickly shift business away from suppliers that perform poorly or raise prices unduly and likewise allow suppliers to quickly shift their attention to new customers in the face of poor treatment or sudden drops in demand for specific products. There are two areas where the activities of lead firms and contract manufacturers overlap strongly: new product introduction and distribution. In the following sub-sections I examine the evolution of the lead firm/contractor linkages in each of these areas.

Is the new product introduction process becoming de-codified?

A key location in the electronics value chain is the point where product design data hand is handed off to manufacturing. This point may reside within a single firm, but increased outsourcing has meant that this hand-off increasingly occurs between legally distinct entities.[18] The proposition that product design can be effectively separated from manufacturing in this way may be surprising. The growing split between design and manufacturing in the electronics industry seems to contradict literature that drew on the example of the Japanese production system to argue that American firms needed to develop tighter coordination between product design and manufacturing to improve industrial performance (e.g., Dertouzos et al, 1990; Florida and Kenney, 1991, 1993). But as the electronics industry has evolved, certain kinds of knowledge has become increasingly codified. As was mentioned earlier, production equipment for circuit board assembly has come to be dominated by three firms, Fuji, Panasonic, and Siemens, making it easier to bring additional machines on-line once the process for the assembly of a particular product has been validated. Similar *de-facto* standards have come to exist for a variety of other production equipment, including electronic design software, soldering ovens, and automatic test equipment. International standard setting bodies such as the International Organization for Standardization (ISO) and the International

[18] This discussion covers product-level design and production only. As already has been mentioned, similar processes of codification and outsourcing are underway in the semiconductor industry, but the details are different.

Electrotechnical Commission (IEC) emerged early on in the electronics industry to help develop industry-wide classification and specification of components.

Today firms in the electronics industry are using information technology, increasingly deployed via the Internet, to communicate across firm boundaries using these standard classification systems as a basis. For example, firms are increasing their use of data communications technology to pass computer aided engineering (CAE) and design files (CAD) to computer controlled production equipment on the factory floor. Components with required specifications can be located and purchased with electronic purchasing systems, early versions of which were known as electronic data interchange (EDI), but which are coming to be integrated with manufacturing and enterprise resource planning (MRP and ERP) systems that track inventories and monitor component availability and pricing. Although progress has been slow and there is still much room for improvement, these systems are evolving toward full-blown supply-chain-management (SCM) systems that will tie demand forecasts to component purchasing, inventory management, and capacity planning in real time. The fact that these systems are being extended across broad swaths of the value chain means that firms in the network are sharing forecast and pricing data in ways that were unheard of only a few years ago.

The recent advent of RosettaNet, a set of Internet-delivered forms and standards developed by a broad industry consortium, is pushing level of codification in the electronics industry to a new level, offering firms a set of standardized forms and procedures to govern a wide variety of business processes, especially those that structure inter-firm linkages such as contracts and relationship roadmaps. The combination of excellent standards and heavy use of information technology in the electronics industry has enabled highly formalized links at the inter-firm boundary, relative to other industries, even as the flow of information across the link has increased.

In complex assembly industries such as electronics, hundreds, perhaps thousands of individual components must be designed into final products and then purchased and brought together at the right time in the right place before production can begin. Components are produced and distributed in a variety of locations by a variety of firms, so this requires a deal great effort, planning, and coordination. In the electronics industry, where product lifecycles run from six to eighteen months, these problems must be faced again and again, and in practice, the process of bringing new products on-stream constant and ongoing. Standardized components that might be used in many products can be stockpiled, and even “custom” components can be held in inventory, but the imperatives of “lean” production militate against large component inventories, which tie up capital and mask defects.

The central process in product-level electronics manufacturing is circuit board assembly, where individual components are placed onto non-conductive epoxy resin boards (circuit boards) impregnated with conductive wires (vias) that interconnect the components. The schematic diagrams that represent this circuitry are first created using CAD software, but before a product can be manufactured this abstract circuitry must be made concrete. This embodiment occurs at both the component-level and the circuit board level.

At the circuit board level, the process of turning abstract circuit diagrams into physical representations is called “circuit board layout.” Even as outsourcing accelerated during the 1990s, circuit board layout was largely kept in-house by lead firms. Because the size, shape, and thermal characteristics of circuit boards have much to do with ultimate characteristics of the final product, it has been difficult to separate circuit design from circuit board layout. What allowed outsourcing to catch hold in the industry was the emergence of a standard way of representing the physical characteristics of circuit boards, what is called a "Gerber file." Gerber files show exactly where the components sit on the surfaces of the circuit board and provides a "map" of the circuitry embedded in the board. Specialized firms arose, first to fabricate the bare circuit boards, and later to do the assembly, both according to the specifications in the Gerber file. Gerber files can be translated into instructions for robotic production equipment that places individual components in their correct locations on the board.

Lead firms used a wide variety of CAD systems, some proprietary and some purchased on the open market, but gradually all of these could be used to generate Gerber files as the ultimate output. It was a relatively simple thing to hand off the Gerber file to outside firms. Moreover, since much of the detailed circuitry of electronics products are contained within highly integrated semiconductors, there is little proprietary information contained in the Gerber file, which only specifies the physical location of components on the board, not the circuitry within the components, so the threat of IP leakage from sharing Gerber files is minimal.

The hand off of the Gerber file, then, became the key element of codification that allowed the organizational separation of design from manufacturing and value chain modularity to flourish in the electronics industry.[19] With the standardization of

[19] At the component level, the analog of the Gerber files is the GDS2 file.

automated assembly in the late 1980s, and the rise of a few dominant production equipment suppliers, lead firms and contract manufacturers could be mixed and matched quickly and efficiently with minimal interaction. The ease of switching partners kept interdependence low and the network fluid.

Over time, the role of contract manufacturers in the new product introduction process has gradually become greater. Five to seven years ago lead firms simply handed contractors parts and a Gerber file and took back assembled circuit boards for testing. Gradually, contractors began to offer, and be asked to perform, additional services such as design-for-manufacturability (DFM), design-for-testability (DFT), and most recently, design for supply-chain availability (DFSCA). Gerber files are of limited value for these activities, since the physical layout of the board is often changed and components substituted to improve manufacturability, testability, reduce costs, ensure component availability, and increase circuit density (the latter can reduce the ultimate size of the product and improve the performance of the circuitry).

To perform these services, contract manufacturers must see the entire CAD file, not just the Gerber file, which means that lead firms must reveal critical IP to suppliers that may work directly for one or more competitors. According to our field interviews, lead firms have been extremely reluctant to share CAD files with their suppliers, but have recently shown a greater willingness. As manufacturing moves out of house, or if in-house manufacturing has never been established, then the expertise regarding how best to physically lay out a circuit board so that it can be efficiently assembled increasingly resides in contract manufacturers, so in more and more instances lead firms have little choice. In addition, contractors are increasingly buying components on behalf of lead firms, so contractors are providing more input on the bill of materials and approved component vendor lists as well. Thus, what had been a relatively clean hand off of Gerber files and components is becoming "de-codified" and the level of interaction between lead firms and their contract manufacturers is in many cases increasing quite dramatically.

Once the Gerber file for a new product has been finalized, and the bill of materials and approved vendor lists created, the new product introduction process can begin. The first step is process validation, where the details of the manufacturing process are simulated. The next step is to create a physical prototype of the product. Historically, lead firms used in-house resources or used small engineering "job shops" to create prototypes. Prototypes can reveal design defects and manufacturing problems prior to volume production and provide an opportunity to work out such problems before an expensive production line is allocated. The largest and most capable contract manufacturers have become much more involved in building prototypes in recent years. During an interview, one a manager at a large contractor reported that his company had built 16,000 different prototypes at their headquarters location in the previous year. While prototype production was considered profitable, the contractor did not offer the service as a stand-alone business and all prototypes were built with the intention of subsequent production in the contractors facilities. As our interview respondent put it, "We are not interested in getting a product ready for our competitors to manufacture."

After the prototype comes the pilot run phase, where mass production techniques are attempted at low volumes and problems are identified and worked out. Quality control and test routines are typically developed at this stage. During pilot runs contractors tend to interact less with lead firms, but problems that require changes to the board layout or bill of materials must be approved by lead firms. Once the pilot run is successful, the next stage is "ramp up" to volume production. The interface between pilot runs and ramp-up is a critical moment where designs and processes are "frozen" and manufacturing readiness is reviewed. Frozen designs and processes represent a fully codified set of instructions. Once these are complete, contractors with global operations can "clone" the manufacturing process worldwide. At this stage interaction between lead firms and contractors is vastly reduced and centering on issues such as build forecasts, component availability, and build orders.

Should suppliers be allowed to "touch" the end user?

On the other end of the value chain are activities related to finished inventory management and distribution. Although not as common as DFM, contract manufacturers are increasingly becoming involved in activities such as build-to-order and direct shipment of final products to retail outlets such as Circuit City. Lead firms are seeking to set up a "demand chain" that pulls products through based on actual, not forecast demand. In this way lead firms can, under normal conditions, completely avoid ownership of finished inventory. This can be seen as accounting trickery, since the lead firm would have to pay for most of the inventory if it were to be unused for some reason, but there are also real financial advantages and benefits in the realm of information management when contractors manage the supply chain end to end. Not only are turn-key suppliers taking on the financial burden of component purchasing and in-process inventory, but they are now beginning to retain ownership of finished inventory until the point of sale. This was not done historically because 1) lead firms wanted to "own" their customers, 2) the IT wasn't there to manage the system, and 3) lead firms wanted their control infrastructure near the customer to manage and buffer the process. During and interview a respondent from a large lead firms stated, "The latest cycle is part of the natural evolution of the industry. Everyone has been talking about supply-chain-management (SCM), but now they are taking action. OEs [lead firms] were not truly cooperating with their contractors, they were not sharing critical information. Now, we are working with [contractor A] on distribution."

When contractors begin to know about of the day-to-day demand for their customers' products, including the details of what customers are ordering (because the products are built-to-order) they are accumulating critical information that could be very damaging if leaked to competitors. In addition, errors, either in the configuration of a product or in its delivery directly impacts a customer's experience and thus impacts critical competitive factors such as brand reputation and customer loyalty. Furthermore, the information systems governing ordering and manufacturing in supplier managed inventory systems must become tightly linked. Though lead firms would prefer to retain control over supply chain management systems that perform these functions, doing so undermines the cost advantages of outsourcing that accrue from externalizing and pooling these capabilities in the supply-base. As a result, some lead firms are reluctantly relying on systems owned and operated by their suppliers to management their finished inventory. When these systems come under a supplier's control, however, the supplier gains even greater access to strategically vital information about customers and customer buying habits. A respondent at a large lead firm stated, "Open standards around supply chain management are key but it is also important who owns the IT system…RosettaNet is important as a standard, but this doesn't dictate who owns the system. If [Contractor A] owns the IT, it is difficult to switch. We have a third party distribution company, and as we have used them the software has become increasingly customized, and now it's hard to switch. We calculated that it will take one year and 150 man-months of programming to enable us to switch. It's a slippery slope, one off decisions and lead to lock in. We have given up the physical stuff, and we are now worrying about the intellectual stuff."

Conclusions

In this paper I have discussed the rise of value chain modularity in product-level electronics, the theoretical benefits of the system in terms of industrial performance, as well as four risks that can be seen as potentially undermining the modularity of the system. Our research suggests that some of these risks appear to be more potent than others. For lead firms, the risk of losing control over key intellectual property and creating new competitors through outsourcing is real, especially as suppliers gain access to fully blown CAD files that contain many of the details of a product's functioning. Inventory distortions caused by the insertion of large contract manufacturers into the value chain seem to be less of a problem since the excesses of the boom appear to have been isolated to a few extreme cases. Most excess inventory, ultimately, must be paid for by the very lead firms that place excess orders in the first place, and the existence of large contractors may actually provide a cushioning effect because they represent an additional route for redeploying unused inventory.

Lead firms are managing many of these risks by working with a smaller set of "pure play" contractors that have clearly have no intention of competing with their customers in final product markets, and with whom they can work intensively to develop and deploy better systems for inventory management. Geographic and social propinquity, at least at the level of management, also seems to be important, and many North American lead firms have given new business almost exclusively to a small set of global contract manufacturers with top management that is also based in North America. The recent concentration of contract manufacturing management functions in Silicon Valley, where many key lead firms are headquartered, is particularly striking.

Still, the very supply-base consolidation that reduces the risk of IP leakage, excludes suppliers with brand name aspirations, and allows the development of elaborate SCM systems to better control inventory also raises the risks associated with asset specificity and buyer-supplier lock-in. Product-level outsourcing in electronics is increasingly a game of small numbers, and large deals continue to be awarded to the very largest contractors. As the creation of new product and process knowledge becomes more of a joint effort, future research should be designed to ferret out tension over which actor in the chain controls and reaps value from innovations. What our research has clearly shown is that the largest lead firms and contract manufacturers in the electronics industry are become increasingly indispensable to one another. The combination of unmatched manufacturing prowess with new design skills and a wealth of knowledge about the preferences of end customers have put contract manufacturers in a much more powerful position than they have been in the past. At the same time, important customers are spending billions of dollars each year with their largest contractors, and the sudden loss of this volume of business would be devastating. During a recent interview with a top manager at a Fortune 500 lead firm in the electronics industry, this dual hostage situation was described as "mutually assured destruction." While such a balance might prove stable for the time being, it is doubtful that any one in this industry is getting a good night's sleep.

While the conclusions of this paper are still tentative, in part because of the dynamic nature of lead firm/contractor relationships in product-level electronics, they clearly point to the importance of understanding the interface between tacit and codified information. If the conclusions not entirely clear, the research agenda is abundantly so. Are the ongoing organizational changes in the electronics industry increasing lock-in between trading partners that is undermining the advantages of value chain modularity, or will novel ways to retain network flexibility be found?

Information technology, a set of assets critical to value chain modularity, is evolving in two directions simultaneously, toward proprietary systems that increase asset specificity and lock in, but better protect key intellectual property, and toward open and/or third party systems that better support value chain modularity but which leave the door open for IP leakage. The management of deverticalized global-scale production systems requires the deployment of new and better software to support product design, forecasting, and supply-chain, materials, and inventory management. Many of these systems are relatively new, untested, and are constantly evolving. The question of which direction the industry take, toward proprietary systems or toward common standards is still open, and its answer will help to determine the future shape of the electronics industry. Clearly, an ongoing research effort in this area is crucial.[20]

[20] It is important to note that the study of information technology does not privilege codified information over tacit. In fact, the creation and management of tacit knowledge remains the most critical success factor in product level electronics. Rather, the study of how information technology is evolving points us toward

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the dynamic interface between what can be codified and what cannot, and what firms see as their core competencies and what they deem to be less important.

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