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Authors

Dedrick, Jason
Kraemer, Kenneth L
Linden, Greg
et al.

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PCIC Personal Computing Industry Center
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Organizing Global Knowledge Networks in the Electronics Industry[1]

Jason Dedrick, Kenneth L. Kraemer
Personal Computing Industry Center
University of California, Irvine
Suite 3200, Berkeley Place North
Irvine, California 92697
jdedrick@uci.edu

Greg Linden, Clair Brown
University of California, Berkeley

Tom Murtha
University of Illinois, Chicago

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1. Introduction

This paper illustrates the dynamics of global knowledge networks using studies from the electronics industry. We examine the nature of knowledge inputs, the innovation process, and the need for human interaction, and how these shape global knowledge networks for various electronic products. These include personal computers, ink-jet printers, semiconductors, and flat panel displays. We also examine the evolution of knowledge networks as products and processes mature and stabilize, or face disruptive change at various times. We do so by looking at product innovation in each industry segment, using a general framework which distinguishes R&D, design, development and production-related knowledge work.

This framework enables us to compare and contrast the different industry segments in terms of the mix of vertical, relational, modular and market-based interactions seen at different phases of product innovation. Each case study raises specific issues in terms of the factors that shape these knowledge networks and the types of coordination mechanisms employed. We then shift the level of analysis to the overall electronics industry to illustrate the concept of massive coordination as a mechanism to manage the complexity of global knowledge networks.

The paper illustrates the following key ideas:

- Knowledge networks can be characterized as having one of four types of organization: vertically integrated, relational, modular, or market. The organization of particular knowledge networks is shaped by the nature of knowledge inputs, interdependencies in the innovation process, and the need for human interaction, as well as by firm strategies.

- Although individual interfirm linkages can be characterized as one of these types, firms are involved in a network of relationships that usually include more than one type. Moreover, these networks will change over time with the modularity and maturity of product and process technology.

- The complexity and changing nature of these knowledge networks creates the need for massive coordination, which has become a requirement for firm survival and a potential source of competitive advantage.

2. Industry evolution and the need for collaboration

Interfirm collaboration for knowledge creation and capture is not new, but in recent years has been widely expanded as industries have globalized and vertical integration has been replaced by virtual integration and specialization. The result has been referred to as “massive coordination” of global knowledge networks (Murtha and Sturgeon, forthcoming). These trends can be seen in the evolution of firm interfaces related to new product innovation in the electronics industry. The interfaces might be related to R&D, design, development and/or manufacturing depending on the industry segment.

The U.S. electronics industry has been restructuring since the 1990s, with leading firms outsourcing manufacturing and eventually knowledge activities as well (Dedrick and Kraemer, 2006; Sturgeon, 2002; Curry and Kenney, 1999). For instance, PC makers first outsourced production of subassemblies and then complete systems to outside contract manufacturers (CMs). As these suppliers expanded their own capabilities, the PC makers began to outsource knowledge-intensive activities such as product development to so-called original design manufacturers, or ODMs, who had product development as well as manufacturing expertise. Logistics, repair and some aspects of customer support were also outsourced later to CMs and other specialists. As more activities were outsourced, the need for collaboration at the interface of these activities grew between (See box for distinction among these various terms).

While PC makers were early movers, the outsourcing trend spread in the 1990s to other electronics industries such as network devices, telecommunications equipment, mobile phones and consumer electronics. Brand name companies sold many of their assembly plants to contract manufacturers and turned over entire production processes. CMs also took over knowledge activities such as logistics, new product introduction, process engineering and procurement. With CMs offering a variety of product development services, as well as providing other support services in the physical supply chain, an increasing share of knowledge work is being outsourced. However, the brand name companies still keep R&D and high-end design work in-house, often collaborating with key component suppliers, requiring extensive coordination among all participants in this knowledge network.

The major exception to this pattern are the large vertically integrated Japanese and Korean manufacturers, such as Sony, Toshiba, Matsushita and Samsung, who still design, develop and manufacture most of their own products, often with many internally-produced components. They do, however, outsource development and manufacturing of an increasing number of mature or less valuable products, again creating a need for collaboration.

In the semiconductor industry, which produces the core technology for the electronics industry, there also has been a reorganization of knowledge work, with the rise of foundries who manufacture integrated circuits (ICs) for others. Taking advantage of the ability to outsource fabrication, a new generation of “fabless” semiconductor companies has grown up entirely focused on design. These include firms such as Nvidia, Qualcomm, Broadcom and ATI Technologies. This combination of fabless design firms and foundries has proven to be an effective structure for designing and manufacturing new products using proven process technologies. Also, some established IC makers, such as Freescale (formerly Motorola) and LSI Logic are pursuing a "fab-lite" strategy that places more production at foundries while scaling back, and possibly eliminating, their own future investments in fabrication capacity.

Foundries such as Taiwan’s TSMC and UMC have gone from being several years behind the leading edge of process technology to now being able to implement new fabrication processes within months of large integrated firms such as Texas Instruments or Intel.

Foundries have also invested in supply chain partners for assembly, test and design services to be able to offer complete technical and logistical support to their fabless customers.

These new types of knowledge networks in semiconductors may be contrasted with sectors in which major players remain large vertically integrated firms who conduct R&D and design, develop and manufacture their own products. For instance, firms such as Intel, TI, Infineon, Toshiba, and Samsung continue to invest in massive internal fabrication capacity, although most of these firms also use some foundry services for strategic reasons. Even for these firms, however, there are limits to vertical integration, as they must work closely with equipment and materials suppliers such as Applied Materials, Nikon and Tokyo Electron to keep chip technology advancing at a rapid pace.

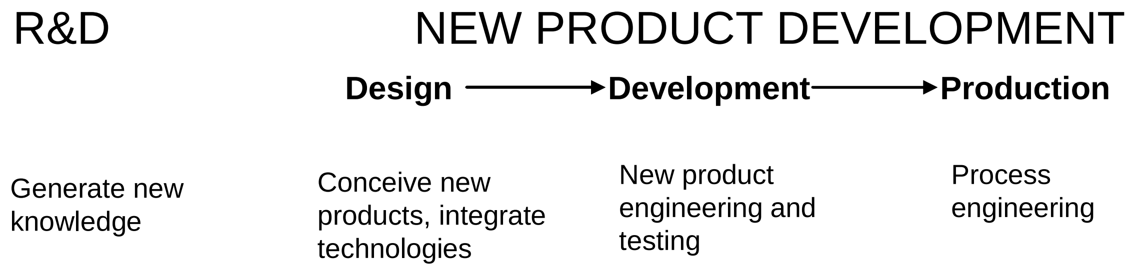
Likewise, in flat-panel displays (FPD), the major producers remain large integrated firms who conduct basic R&D, design new products and manufacture those products. This integration of knowledge work inside the company is partly due to the integrated nature of the technology, but also to the fact that the industry leaders are Japanese, Korean and Taiwanese companies, who have a tradition of vertical integration. There are no U.S. FPD manufacturers of any significance, and the separation of R&D, design and manufacturing spurred by U.S. companies in other industries has not happened in flat panels. However, even the integrated Asian manufacturers are not immune from the need to collaborate across firm and national borders to gain access to required knowledge. In order to bring new generations of displays into production, FPD makers work very closely with key material suppliers such as Corning, and with equipment suppliers such as AKT, whose engineers may take up residence in the FPD maker's labs for months at a time until production yields reach a determined level (Murtha, Lenway and Hart, 2001).

As the foregoing illustrates, the trend of de-verticalization and the consequent need for collaboration between lead firms and their partners is common throughout much of the electronics industry. The purpose of this paper is to understand how some segments in the industry's global knowledge network are organized for inter-firm collaboration. In section 3, we introduce a common framework for comparison of activities in new product innovation, including the phases of R&D, design, development and production (manufacturing). In section 4 we systematically review the organization of knowledge networks for product innovation in the PC, printer, semiconductor and FPD segments. In section 5, we take a broader view of the electronics industry and discuss the mix of firms and relationships in the industry's massively coordinated global knowledge network. In section 6 we summarize and further analyze the findings from the different industry segments and discuss the implications of massive coordination for firm strategy.

3. Knowledge activities in product innovation

We use a general categorization of knowledge activities in product innovation that can be applied to any industry (Figure 1). Product innovation occurs through two broad processes--R&D and new product development (NPD). R&D is an ongoing activity that generates new knowledge and technical innovations that can be applied to new products, while NPD involves design and development of a particular product. In reality, there is often a close interaction between the two, as NPD integrates knowledge developed by R&D, and R&D is often called on to solve a problem in product development.

Figure 1. Knowledge activities in product innovation



Source: Adapted from Wheelwright and Clark, 1992.

As outlined by Wheelwright and Clark (1992), new product development is a multi-stage process of design, development and production that creates physical products for target markets. Design refers to the process of envisioning and defining a new product based on innovations from R&D and on customer needs. Development is the process of making and testing a working product based on the design. Production is building and shipping the product, which involves knowledge work in the form of process engineering, cost reduction, logistics and other activities. In many cases design, development and production processes are further divided into sequential activities, with outputs and gates to pass before proceeding to the next stage (Dedrick and Kraemer, 2005). In other cases, activities are carried out in parallel or iterative processes.

Within this context of product innovation, we analyze the way that knowledge work is structured within and among firms in terms of (1) the nature of the knowledge inputs and the innovation process; (2) the degree of human interaction needed to capture the full value of an input; and (3) the types of relationships that exist among the network members. For instance, is the knowledge embodied within a product or codified in a blueprint or software code, or is it so tacit that it must be exchanged via direct face-to-face discussions? How strong is the link between design and manufacturing? Is the input modular, in that the hand-off of specifications follows a set of predetermined rules, or is it market-based and its use self-explanatory, or does its use require extensive customization? Are inter-firm ties primarily market-based, modular or relational? These concepts enable us to compare and contrast the organization of global knowledge networks within and across firms in different segments of the electronic industry in the next section.

While our analysis is mostly at the industry and sectoral level, and focuses on these issues, we acknowledge that decisions about which activities to keep within the firm and which to outsource are firm level decisions. Moreover, they are often considered strategic in the sense of choosing where a firm can provide value or differentiate its products or services in the market. This depends in part on where it has distinct resources that cannot be imitated easily by competitors, in particular the ability to create or deploy knowledge in ways that competitors cannot (Penrose, 1959; Barney, 1991; Kogut and Zander, 1992). For this reason, different firms in the same industry sector often make different choices about how to organize their knowledge activities.

4. Knowledge networks in four industry sectors

In this section, we utilize industry sector studies to illustrate different types of interfaces and organizational forms found in global knowledge networks, as well as showing the challenges for coordination that arise in these different forms. We look first at desktop and notebook PCs to distinguish between products that are highly modular versus more tightly integrated. We then examine the other cases that are increasingly integrated in nature -- ink-jet printers, semiconductors, and finally flat panel displays (Table 1). Each of these industries has its own set of knowledge inputs, requirements for human interaction and organizational outcomes, determined by the characteristics of the technology, markets, firm strategies and other factors.

To summarize briefly, the PC industry illustrates the impacts of a nearly universal set of product platform standards (the "Wintel" standards) with an associated high level of product modularity. This leads to standardized knowledge inputs, limits the requirements for human interface in the knowledge network, and has led to mostly modular relationships among specialized firms, although the outsourced development of notebook PCs involves more relational interactions due to the more integrated nature of the product. The ink-jet printer industry is marked by more integrated proprietary products and lack of standardization of key components, so printer makers mostly keep R&D and product development in-house while outsourcing production. The fabless semiconductor industry involves complex knowledge inputs in the design and manufacturing processes, but has developed the means for a codified hand-off between the two with limited human interaction. However, as this segment of the chip industry moves toward the leading edge of product and process innovation, there is greater need for human interaction and relational interfaces are becoming more prevalent. Finally, the development of next generation flat-panel displays involves the highest level of tacit knowledge inputs and greatest need for human interaction to solve emerging problems. The result is a combination of vertical integration and extensive inter-firm penetration between FPD makers and key equipment suppliers.

Table 1. Form of knowledge networks prevalent in different industry sectors

Product/ industry sector	Factors in the organization of knowledge networks		
	Knowledge inputs	Need for human interface	Types of interaction (modular, relational, market)
Personal computers	Innovation mostly external; done by component makers (Wintel standard). Desktops: product is highly modular with codified, standard inputs.	Product specifications can be handed off with only monitoring interfaces needed.	Design and development kept in-house, manufacturing outsourced (modular).

	Notebooks: product is highly integrated with custom, tacit knowledge inputs, but still based on codified interface standards	Close interaction needed for handoff and for joint problem solving in development. Design for manufacturing requires close interaction.	Development and manufacturing outsourced together. Deep relational interface between lead firm and contractor.
Ink-jet printers	Innovation is internal. Non-standard, proprietary inputs by lead firms. Each firm develops its own core technology in printers, ink cartridges and firmware. Printer heads and cartridges are strategic IP.	Complex electro-mechanical aspects of printers require close interaction between design and development. Complexity of manufacturing requires contractor to locate close to branded firm during development; also requires branded firm to locate engineers at contractor sites during production.	Design and development of printers kept in-house, but manufacturing outsourced. Design, development and manufacturing of printer heads and ink cartridges kept in-house.
Fabless semiconductors	Product innovation is internal. Process innovation is outsourced to foundries Single technology ASICs use standard inputs. Systems on a chip (SOC) embody non-standard, proprietary inputs.	Modular relationships in more mature process technologies. Closer interaction for leading edge processes. Use of standard design tools and process guidelines facilitates knowledge transfer.	Design done in-house by design firms. Fabrication outsourced to foundries.
Flat panel displays	Innovation is both internal and external. Knowledge is developed in the course of doing; non-codified.	Strong relational interactions with component and equipment suppliers.	Design, development and manufacturing in-house.

4.1. The PC industry

Although the personal computing industry[2] includes many devices such as PC-based servers, and various handheld computing devices, we focus on desktop and notebook PCs. Driven by innovation in major components (microprocessors, memory, and other semiconductors, software, and storage), and by its own constant effort to increase efficiency, the industry has produced more powerful systems with faster product cycles and cheaper prices for over thirty years. The industry is also highly global, with production, markets and innovation around the world. The top two PC makers, HP and Dell, control about one-third of the world market, but six of the top ten vendors are from outside the U.S. The industry also has undergone significant shifts in organization in the past decade, with PC makers concentrating mostly on sales, marketing, branding and product management, while outsourcing most manufacturing, some product development, and many support services.

Knowledge inputs and innovation processes

In the PC industry, the generation of new knowledge through R&D occurs largely outside of the branded PC vendors. R&D is performed by Intel and Microsoft who control key industry standards or by component and subsystem suppliers who are upstream in the industry value chain. Since its early years, the PC industry has been dominated by a single technology standard, the IBM-compatible, later "Wintel" platform, meaning that most components can be designed and produced by independent suppliers as long as they follow interface rules set mostly by Microsoft and Intel. This allows standard components such as hard drives, optical drives, add-on cards, keyboards, and displays, as well as software, to be developed with only limited interaction between the PC maker and the outside supplier. Most PC makers concentrate on NPD, integrating those components into new products, while leaving more fundamental R&D to the component and software makers.[3]

While both desktop and notebook PCs are based on the Wintel standard, there are important differences between these two form factors (Table 2) that affect the nature of knowledge inputs, the need for human interaction in new product development and the form of organizational interactions.

Because they are highly modular, the knowledge inputs for desktops are well codified. Developing a desktop product is primarily a problem of industrial design and system integration, i.e., deciding on the physical design of the product and incorporating new technologies into products and ensuring that they work together. The challenges are greater when developing new product platforms based on new chipsets, or especially for

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[2] Worldwide revenues for the PC industry totaled about $215 billion in 2004 (IDC Worldwide Black Book, 2004).

[3] To illustrate, among pure PC companies, R&D spending as a percent of revenue was only 0.9% for Dell, 1.7% for Lenovo and 0.1% for Acer in 2005. By comparison, among software and component makers, R&D spending equaled 15.5% of revenues for Microsoft, 13.5% for Intel, 8.5% for Seagate and 12.4% for Micron Technology (Electronic Business, 2006).

a major technological change such as a new generation of processors or a new operating system. Most desktop models are still based on industry standard form factors, such as the full-tower and mid-tower chassis. Also, there are standard motherboard layouts available from Intel and various third-party manufacturers that are designed for these chassis. Within the standard enclosure, desktop makers make decisions about how to organize components, the location and function of screws, hooks and hinges, and the color and shape of external plastic parts.

Table 2. Desktop versus notebook new product development

Desktop	Notebook
▪ Highly modular design ▪ Development = system integration of new parts and software ▪ Mostly standardized parts, e.g., motherboards, drives, chips ▪ Design for easy assembly, repair ▪ Shorter product cycles, more models ▪ Mature product	▪ Highly integrated design ▪ Development = complex mechanical and electrical engineering challenges due to size, heat, ruggedness requirements ▪ Mix of standard and customized parts ▪ Design for manufacturability critical ▪ Longer product cycles, fewer models ▪ Newer, still evolving product

For desktops, the emphasis is on developing a few chassis upon which multiple models or SKUs can be designed for different markets and with different configurations. While the design of a new chassis takes around nine months, a new model based on an existing chassis can be built and tested in as little as two weeks. With a configure-to-order model, Dell and others might have thousands of potential hardware and software permutations on a single platform. This complexity creates many opportunities for conflicts and incompatibilities, so testing all of these combinations becomes a major part of the new product development process.

Notebook PCs have characteristics that create challenges in product development as they must run on batteries, they incorporate the display as part of the unit, , plus they are more visible so users care about style as well as function. Components must be packaged very tightly into a product that is small, thin, light, portable, durable and energy efficient, and which doesn't become too hot to handle from the heat generated in its operation (combustible Sony batteries led PC makers to recall millions of laptops in 2006). Manufacturability is a major issue, as the product must be built in high volumes and at low cost, so final assembly must be a relatively simple process that allows packing components and subassemblies into a very tight space quickly and with a high level of reliability. As a result of these characteristics, notebooks have a longer and more expensive product development process. Even an upgrade of a model based on an existing platform can take 3-6 months to develop, and a new chassis takes 12-15 months.

There are strong interdependencies among certain activities in new product development for notebooks that make codification difficult and instead call for deep human interaction. For instance concept design and product planning in the design phase require monitoring both technology and market trends and developing specifications for products that can be developed and delivered with combination of form, function and price that will be attractive to customers. PC makers have kept concept design, product planning, marketing and product management in-house, run by product teams that can include members from marketing, planning, finance, manufacturing, cost engineering, software and service/support, reflecting the interdependencies of the these activities.

Another interdependency in the notebook PC development process is between physical product development and manufacturing. It is critical that physical development take manufacturability into account from the beginning; otherwise a product may be developed that cannot be produced at the necessary volume, cost or quality. To achieve design for manufacturability, most notebook PCs are designed to be built in a particular assembly plant, with specific manufacturing process requirements. As a result, development and final assembly activities are almost always handled by the same company. In some cases (e.g., Toshiba and Lenovo), this means keeping both activities in-house. In most cases it means outsourcing both development and manufacturing of each model to a single ODM.[4] By contrast, for desktop PCs, there is less interdependency between the development and manufacturing phases, and it is easier to come up with a more fully specified product that can be handed off to a contract manufacturer for production. The process, and the product, are more modular.

For notebooks, the point at which there is less interdependency and more opportunity for an inter-organizational hand-off is between the design and development stages. At this point a number of documents are generated that codify the product design as well as specifying the development process to be followed. Formal transfer from PC maker to the contract manufacturer occurs when the contractor is given the final design specification and bill of materials to work from. The stages and gates process enables teams to set up entry and exit criteria for each phase and processes for collecting performance data. The formal gates at the end of stages in the design and development cycle facilitate coordination and information sharing because they document key outcomes of the preceding stage.

Need for human interface

When there are limits to the codification of a final product specification, such as in a notebook PC, many details of how to put together components to be functional and manufacturable must be worked out in the development stage. Also, while the formal contract and transfer of product specifications looks like a clean hand-off from PC maker to a contractor, there is much iterative coordination between the two in the development stage. For instance, PC vendors and contract manufacturers typically have formal meetings only 4-5 times over an 8-12 month design/development cycle. However, there are often more face-to-face meetings between individual designers or engineers to work out specific issues or problems. As said by one ODM, “there is somebody (from the PC maker) here about every two weeks throughout development. The engineers usually stay a week and work closely with our engineers. They want to be sure things are going ok

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[4] Apple is an exception, preferring to keep development in-house until manufacturing is turned over to a CM. This is strategic, because Apple feels it has greater design and development competency and for secrecy, in order to exploit first mover advantage on its often-dramatic new innovations.

and they want to see how things are being done in detail." A PC company executive said that engineers from his company had spent months in Korea working with the company that manufactured a new, non-standard PC that was a major departure from its existing products.

This kind of deep interaction contrasts with NPD for desktops, in which it is more common for PC makers to outsource development and/or manufacturing to CMs in a more modular interaction. Because subassemblies and components are standardized and usually purchased from third party suppliers, the role of contract manufacturers is usually final assembly, although a few such as Foxconn and Quanta also make subassemblies (motherboards). Given that most parts are standardized, most CM effort goes to building and testing various configurations and to ramping up production to take out cost and ensure quality. PC makers often do testing in parallel with CMs, and work with them to solve technical issues that arise.

Nature of relationships in the PC industry

To summarize, most PC companies have turned over development and manufacturing of notebook PCs to ODMs who have those specialized engineering capabilities in disciplines such as heat dispersion, electromagnetic interference, power management and circuit board layout as well as high volume manufacturing facilities in China. The firms are all based in Taiwan, with the largest being Quanta, Compal, Wistron and Inventec; overall there are about a dozen Taiwanese ODMs specializing in notebooks. The only major PC makers that still have internal development and manufacturing resources are Toshiba, Fujitsu, Lenovo, and Sony, and even these firms outsource an increasing share of their models, especially at the low end. For desktops, PC makers usually do design in-house and outsource manufacturing to diversified contract manufacturers such as Foxconn and Sanmina-SCI or to Taiwanese and Korean companies who specialize in PC production, such as Mitac, FIC and Trigem.[5]

Figure 2 illustrates the difference in the organization of new product development between notebooks and desktops. The overlap between PC vendors and ODMs in notebooks shows the degree of organizational interpenetration in the development phase of notebooks, while the separation of PC vendors from CMs shows a modular relationship with less intensive interaction. This difference is a result of differences in the types of knowledge exchanged and the nature of the innovation process for each product, which leads to a greater need for human interaction in notebooks than in desktops.

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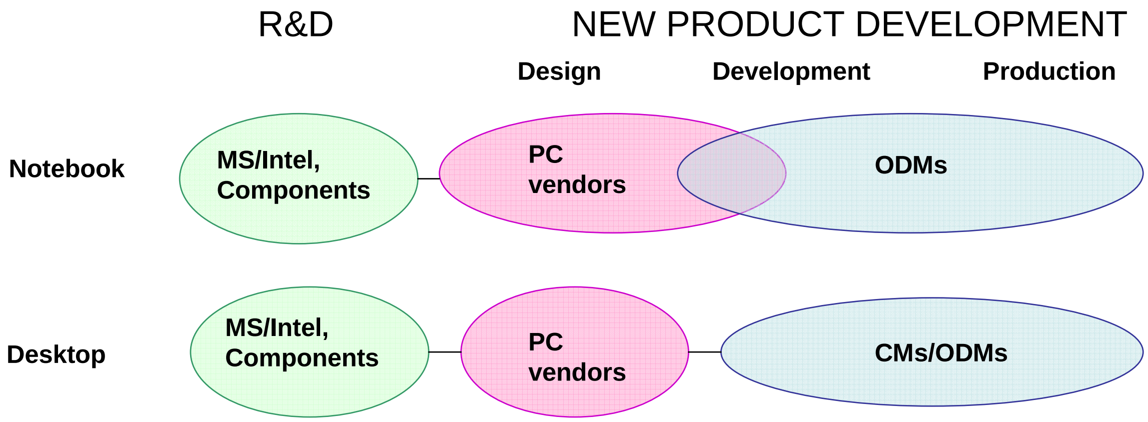
[5] An exception is build-to-order assembly, which Dell and most others keep in-house in order to directly control this complex order fulfillment process; however, they usually buy partially assembled "base units" from CMs or ODMs and just do final configuration at their own facilities.

Figure 2. Organization of knowledge activities in the PC industry



Looking to the left of the PC vendor in Figure 2, we see that the interaction between PC makers and component and software makers is primarily market-based or modular. This is explained largely by the standard "plug and play" technical interfaces of the Wintel architecture. Yet even here, there is a surprising amount of interaction. For instance, even "standard" hard drives and memory modules are often customized for different PC makers, and significant customization of software, power supplies and other parts is done for different national markets. For notebooks in particular, many parts are customized, from motherboards to chassis, keyboards and hinges. This means bringing in the supplier early in the development stage to make sample parts for prototypes and make changes as necessary.

These relationships are dynamic and may move towards greater or lesser organizational integration and human interaction over time. When a product is entirely new, there is a greater need for human interaction than when it is the later phase (derivative products, refresh cycle, or mature product). For example, PC makers and ODMs reported that when a new platform is introduced, there will be close interaction with only one contractor, but as derivative models are produced from that platform, each one may be contracted out to a different ODM to take advantage of market-based price competition.

By the same token, the amount of interaction has increased in the desktop segment due to the many models that are brought to market in ever shorter cycles each year. As a former executive put it, "To do all the testing and fix the problems really involves three parties: us, the contractor and whoever made the component or software that's causing the problem." In this case it is not so much a design for manufacturability issue that brings the parties together as design for compatibility of thousands of potential configurations.

Finally, when the PC maker and contractor have little experience with one another, there is greater need for human interaction, while after working together on a number of development projects, the need for human interaction can fall significantly. Experience also can lead to greater trust among individuals in the relationship, inspiring greater effort and innovation by the contractor. As one PC manager said, "If you build a relationship, the person at the contractor will do 10 iterations to try to fix a problem and will have a solution the next day. If not, they'll try one thing and if it doesn't work, will wait for the next instructions."

4.2. Inkjet printers[6]

Inkjet printers have become nearly ubiquitous accessories for home and small business PC users. Shipments of these printers were estimated at 45 million units accounting for $4.8 billion in revenues worldwide in 2005. These figures represent a decline from 55 million units and $6.3 billion in 2003 (IDC, 2006). The inkjet printer industry is oligopolistic, dominated by HP, Canon, and Epson which together captured 88% of inkjet revenues, while Lexmark and Dell accounted for another 10% (IDC, 2006). There is little standardization in the industry as each firm has its own proprietary components such as chips, printer heads, firmware, ink cartridges, and photo paper.

Knowledge inputs and innovation process

Even though one can buy a good ink jet printer for under $100, the engineering behind them is extensive. It involves mechanical tolerances measured in nanometers, extreme speeds and temperatures, constant experimentation with combinations of ink and paper, fluid dynamics, photo spectroscopy, and software engineering along with skill in precision manufacturing (Hannaford, 2004). As a result, and in contrast to the PC industry, the generation of new knowledge in printers occurs largely inside the branded firms who conduct their own R&D and new product development. Manufacturing of the final product and most components and subassemblies is usually outsourced (at least by U.S. companies) whereas ink cartridges, print heads and papers are produced in-house and carefully guarded to prevent cloning of the most profitable part of the printer business.

New printers are centrally designed and developed, but they are designed as "platforms" that can be configured differently at distribution points in order to meet the varying language and other requirements of individual countries, or even to provide different models for different retail outlets. Ink-jet printers involve complex electro-mechanical subsystems as well as firmware that directs the printer functions and enables the printer to interface with other devices such as computers and digital cameras. The electro-mechanical aspects of printers are very difficult to codify. This limits the potential contractors that printer companies can work with and slows the hand-off from development to manufacturing significantly. This complexity has implications for the choice of contract manufacturer, the human interfaces and the nature of relationships with the lead firm. The contract manufacturers tend to be large firms, with sophisticated engineering and manufacturing staffs capable of highly automated production and testing. Relationships tend to be long term and limited to a few firms. For example, Hewlett-Packard outsources most of its inkjet printer manufacturing to one contractor, Flextronics. Other lead firms also use the same contractor.

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[6] This section is based in part on contributions from Tim Sturgeon.

Need for human interface

Getting high-quality long-lasting photo prints from an ink jet printer involves an interdependence of printer, ink and paper. Consequently, the lead firms keep R&D and new product development internal, using the same R&D resources to support multiple product platforms such as standalone and all-in-one printers. Because of their tight tolerances and operating speeds, multiple prototypes are developed and tested internally in order to achieve designs that can be manufactured externally. Newer products need much more prototyping than derivatives or mature ones. When products are handed off for manufacturing, their mechanical tolerances and electro-mechanical complexity requires close interface between the development organization and the manufacturer in set-up and ramp-up in preparation for volume production, and monitoring and testing to ensure quality during production. To handle this collaboration, the contractors build test-production lines near the lead company's development organization where the manufacturing process can be tested and refined.

Nature of relationships

Manufacturing of ink jet printers is outsourced to CMs based on fully developed and tested prototypes and the bill of materials for each printer. However, the tooling required to build prototypes is not the same industrial strength as required for volume manufacturing and complex monitoring and testing equipment has to be installed on production lines. This complexity of the manufacturing and test processes requires that a team of engineers from the development team of the branded firm work at each contractor's factory for the life of the product. This is to transfer tacit knowledge about the product and the manufacturing process, to ensure quality production early on, and to ensure continuous cost improvement over the product's life cycle.

In summary, the nature of relationships in the industry stems largely from the profit model for ink jet printers and the electro-mechanical nature of the product. The industry profit model eschews standardization of components, keeping barriers to entry high and resulting in exclusive relationships with manufacturers for economies of scale and to prevent imitation. Printers are sold cheaply to gain customers; the lack of standards creates lock-in; and vendors profit mainly from aftermarket sale of ink cartridges, related products such as digital cameras, and high quality printing and photo paper. The complex electro-mechanical nature of the product makes it hard to codify and hand off cleanly to a CM. Consequently, lead vendors tend to work in highly collaborative relationships with one or two CMs over a long period.

4.3. Fabless semiconductor

Global knowledge networks in the semiconductor industry have evolved over time. An important subset of the $200 billion industry now uses a combination of modular and relational interfaces to develop new products that would have developed internally in a previous era. Over the last ten years, the linkages, especially among industry leaders, have tended toward the relational as technology has become more complex.

Through the 1970s, the semiconductor (“chip”) industry relied on full vertical integration, meaning that firms both designed and manufactured the general-purpose chips they sold. Their advantage in the market lay primarily in their process knowledge, but the importance of design grew as continued miniaturization permitted the placement of ever more dense and complex functions on a single chip.

New technologies facilitated the emergence in the mid-1980s of design-only (“fabless”) chip companies that outsourced the design of their chips for manufacturing by a chip company with spare capacity. In the late 1970s, the industry adopted the GDS II data format – still in use in 2006 – as a de facto standard for conveying a design to the manufacturing side. During the 1980s, the gradual acceptance of scalable metal-oxide semiconductor (MOS) manufacturing as the dominant semiconductor process technology provided a predictable technology trajectory for designers to target. Around the same time, the Berkeley transistor simulation model, BSIM, appeared and was formally adopted in 1994 over competing models as an industry standard for conveying manufacturing information from the factory to design automation software.

In the late 1980s, new manufacturing-only (“foundry”) firms that sold no products of their own appeared, primarily in Taiwan, to solve the intellectual property and capacity commitment issues that arose when fabless companies used potential competitors for their manufacturing. The oldest and largest two foundries are TSMC and UMC, which eventually developed process know-how comparable to that of the leading integrated chip companies and together accounted for 60% of foundry revenue in 2005. Fabless firms have little incentive to invest in their own manufacturing since the cost of an efficient semiconductor factory has risen steadily by an order of magnitude to about $3 billion in 2005, and losses mount quickly if capacity is underutilized.

Knowledge inputs and innovation process

The interface between the design and manufacturing firms evolved to encompass two primary elements: *technical models* like BSIM detailing the precise characteristics of each type of micro component, such as a transistor, that the manufacturer offers (subtle variations can occur even in different factories of a single company); and a set of *design rules* for physically arranging these devices in a chip layout (designs must follow the rules to be manufacturable, although designs will still vary in their yields).

Under this fabless-foundry business model, the fabless firms are able to compete based on their intellectual property, such as algorithms for compressing video, without having to master the complex process technology, or bear the heavy investment of chip manufacturing. This division of labor proved very successful and the fabless sector has grown much faster than the chip industry as a whole. Some medium-size integrated producers, such as LSI Logic, have gone fabless because of the attractive economics of the business model. Although there are hundreds of fabless companies worldwide, with concentrations of mostly small companies in Taiwan, South Korea, Israel, and China, U.S. fabless companies accounted for more than two-thirds of the fabless sector’s $35 billion in 2005 revenue. As a result, the U.S. fabless-Taiwan foundry linkage is one of the chip industry's most critical.

For more than ten years, the fabless-foundry model worked mostly by the book. The foundry would issue design rules, the fabless company would provide a design file that complied with the rules, and the foundry would send back samples for evaluation prior to volume production.

Need for human interface

Within this modular system, there are occasions requiring engineer-to-engineer contact. Prototype problems with non-obvious causes sometimes require face-to-face troubleshooting. Even when the fault could be shown to be specifically design- or manufacturing-related, it might make sense, after due consultation, to adjust a manufacturing process rather than redo the design, which would require an expensive new "mask" (the template used by the factory to transfer the design to silicon). Once volume production had begun, collaboration usually occurs around improving a chip's manufacturing yield, which is crucial for lowering the chip's cost and often necessitates adjustments on both sides of the fabless-foundry interface.

Fabless-foundry relationships have tended to be long-term, with shifts of allegiance by large fabless companies making headlines in the industry press. There are many reasons that draw the companies close together, including the familiarity of the fabless company's physical design team with the peculiarities of a foundry's process models and rules, the compatibility of formats for non-standardized data such as production yield, and a thick relationship across a large number of designs with foundry prices being renegotiated quarterly or more often.

In recent years, the fabless-foundry linkage has become more complex because the steady improvements in process technology have pushed chip manufacturing to the limits of physics, with the smallest features ("linewidths") on a chip approaching a few dozen molecules in width. As a result, the model has evolved toward closer collaboration between design houses and foundries.

One complication is that the once compact set of "design rules" have given way to a voluminous set of "design guidelines" with frequent updates, and it is no longer certain that a conforming design file will lead to a working chip since the outcomes are more probabilistic rather than deterministic at the smallest linewidths. Foundries now need to be told which details on a chip are the most important to monitor and adjust during production, and fabless companies need to run more types of tests on a foundry process in order to achieve the desired specifications. The foundries also need to give more data—for which there are not yet standard formats—to the fabless companies for inclusion in the design process. Moreover, some of the data, such as yield models, reveal proprietary information that the foundries regard as critical trade secrets. The fabless companies also want to limit the amount of information they give to the foundry about the product for which the chip is designed and its exact functionality.

While much of this increased data exchange still occurs at a distance, the movement of people back and forth to prevent or address problems has steadily increased. The greatest increase in face-to-face interaction has been in the area of process definition, particularly for customers needing an early-stage or specialized process. This includes the foundry's lead fabless users as well as vertically integrated companies that use the foundry for buffer capacity. The buffer capacity model requires the foundry to duplicate the characteristics of the customer's in-house process. Nearly half of foundry revenue in recent years has come from chip companies with in-house production.

Nature of relationships

For customers using leading-edge technology—a small but vital group of users who are critical to the foundry's technology development process—the engagement with the foundry begins long before the design is complete, and requires several engineers with production experience to be dispatched from the fabless company to the foundry for extended periods of time.[7] The interaction begins when the design team describes what process characteristics it wants. The foundry responds with test devices from a proposed process that probably misses some of the targets, which the design team evaluates. This leads to successive rounds of interaction—what one fabless executive described as "an ongoing exchange of ideas"—until the customer requirements and the foundry process converge, at which point the foundry issues design rules and device models that lead to a more or less ordinary customer-foundry engagement from that point on. These pre-production engagements are expanding in length, from one year in the late 1990s to two years or more currently.

As this example demonstrates, chip companies that use foundries, especially those that use leading-edge processes, have needed to get better at understanding production issues. At the same time, foundries have been getting deeper into design. For example, chip designers rely on libraries of standard elements that they use as building blocks for the design. In order to make sure that customers will be able to design using the foundry's most advanced process, leading foundries like TSMC and UMC have begun developing these design libraries in-house or through an affiliated design services partner, rather then relying upon third-party providers of design libraries with little incentive to be ahead of the market for leading-edge linewidths. The use of foundry-generated libraries has the added advantage of improving the chances that the final design will obey the foundry's design guidelines and produce a satisfactory prototype.

Other interfaces in the fabless-foundry global knowledge network are also becoming more relational. Foundries, for example, are collaborating more with *EDA companies*, who produce the design automation software used by designers, to develop recommended design methodologies for their customers; with *IP design companies*, who produce the

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[7] In addition to field interviews by Greg Linden and Clair Brown, this paragraph draws on Yea-Huey Su, Ruey-Shan Guo, and Shi-Chung Chang (2004) "Inter-firm Collaboration Mechanism in Process Development and Product Design between Foundry and Fabless Design House," in Semiconductor Manufacturing Technology Workshop Proceedings, 2004, IEEE, p.47-50.

cores or modular elements that are incorporated into a design, to pre-verify their functionality using the foundry's process; and with their *equipment suppliers* during the process definition phase to address increasingly complicated materials and process issues.

4.4. Flat-panel displays

Since the first high volume, large-format thin-film-transistor liquid crystal display (TFT LCD) fabs opened in 1990, total FPD sales, including rival technologies, such as Plasma (PDP) have grown from $3.17 billion to a projected $93 billion in 2006. The market research firm, DisplaySearch, forecasts sales of $120 billion in 2010. TFT LCDs continued to capture increasing proportions of market share over rival technologies for all products, from 75% in 2006 to 83% by 2010. In order to understand the organization of global knowledge networks in this sector, we review the industry in general, and focus on a critical equipment supplier, AKT.

Nature of knowledge inputs

The innovation path for thin-film-transistor liquid crystal displays (TFT LCDs) can be traced over at least ten distinct generations of equipment and materials. Each represented solutions to technology challenges associated with using larger and larger glass substrates in the manufacturing process. Substrates have increased in size from generation to generation because new product applications continue to emerge that require larger and larger panels, and larger substrate sizes have continued to result in manufacturing efficiencies. The earliest high-volume, large-format TFT LCD fabs enabled the notebook computer to emerge, followed by flat desktop monitors. By the early 2000s, FPD technology enabled the most significant innovation in home television since the introduction of color, as consumer preferences swung rapidly toward new, large flat panel TVs.

In order to accommodate this technological evolution, the equipment used to manufacture FPDs has needed to grow in size as well. Buildings erected in 2004 to house 7th generation fab lines rank among the largest ever built. Core components for some tools, such as CVD equipment, have grown so large that they can no longer fit in the cargo bay of the largest jet transport aircraft, unless cut into several pieces. Current estimates of the cost of a new Generation 8 manufacturing facility processing 60,000 substrates per year exceed $3.3 billion.

Need for human interface

Significant technological challenges accompany transitions from one generation's manufacturing equipment to the next. Each firm's success in managing these transitions relies on the availability of sufficient numbers of experienced people to transfer forward to new generations, while at the same time maintaining the necessary experience ratio on existing lines. As generations continue to succeed one another, human capital has been spread thin, particularly in Japan. Automation and reliance on experienced suppliers have both played vital roles in leveraging producers' in-house workforces to sustain continuous innovation.

Several factors tie new knowledge about starting up new generation facilities strongly to people and place. The importance of experience derives from the critical nature of tacit knowledge embedded in individuals and teams. The pace of change contributes to a knowledge codification backlog as scientists, engineers and operators work to invent the manufacturing processes associated with new generation equipment. The sheer scale of plant and equipment, as well as the quantities and physical dimensions of input materials needed for manufacturing cause TFT LCD producers as well as their suppliers to thrust deep roots into the soils of their locations. Sharp calls its Generation 6 facility "Mie Kanagawa Display City." LG Philips has built 6 successive generations of facilities in Gumi, Korea, moving on to a new location only after running out of buildable land in this mountain valley.

Nature of relationships

Interfirm collaboration in global knowledge networks represents a *sine qua non* of the evolution of the TFT LCD sector of the Flat Panel Display industry. FPD producers have needed to engage in vertical collaboration with equipment and materials suppliers in order to create new manufacturing solutions, integrate offerings from diverse sources into functioning fab lines, and bring these lines to commercial yield. These same equipment and materials suppliers act as cross-cutting knowledge agents, as they apply the new knowledge created in their own specialties across multiple fab startups in the same generation. At the same time, producers have collaborated with each other to create or contribute to joint ventures that have maintained market leadership during different periods of the industry's history, including DTI (IBM-Toshiba), LG.Philips, and SDI (Samsung-Sony).

Equipment and materials suppliers to the TFT LCD sector have responded to this environment by putting their knowledge on the road, in the form of people. In so doing, they have transformed an assembly-line factory model of goods production and exchange into a business that consists heavily of services delivered on a customer-specific basis. Equipment suppliers provide the install teams, or in some cases, assemble experts from third companies under the leadership of their own senior engineers. Startup involves local operators who set objectives to fully staff operations with in-house personnel as rapidly as possible. Experiments return suppliers' teams to the fab, when costs seem out of line or the rate of yield improvement diminishes.

The basis for the intimate involvement of outsiders in fab operations from startup until much later in the fab's operational cycle rests on knowledge. New generation fabs create new technical challenges, and the need for new knowledge in startup, line integration, and process innovation. Suppliers gain extensive, unique knowledge by experiencing equipment and processes in multiple settings. In many circumstances, suppliers may know more about the cutting edge of line integration and yield enhancement than individual display producers. Knowledge constitutes the principal leverage through which suppliers maintain intimate customer relationships and secure a share of the rents from new generation innovation.

Tacit and verbal knowledge elements require close personal interaction on the shop floor, where the new equipment must be used and property rights eventually transferred from the supplier to the client. FPD manufacturers tolerate the presence of these service teams in the fabs until their perceived risk of losing proprietary knowledge exceeds the value of knowledge co-creation and transfer. Given the long-standing relationships between most producers and suppliers, considerable trust exists to support a calculus in favor of openness. At the same time, the combination of experience, trust and shared knowledge creates a high entry barrier for new entrants to the equipment and materials sectors of the industry.

AKT, the FPD manufacturing equipment division of Applied Materials, Inc., based in Santa Clara, California, builds a number of tools for FPD fabs. AKT has retained most of the global market for chemical vapor deposition (CVD) equipment since shortly after the high volume industry emerged in the early 1990s, with a share estimated at 85% in 2006. CVD equipment represents one of the largest investments TFT LCD manufacturers must make to establish new fabrication lines – perhaps as much as 10 percent of total costs, second only to lithographic exposure tools, in which Nikon and Canon hold leadership.

AKT's R&D contributions to early industry development played a critical role in overcoming major technological obstacles to establishing a viable TFT LCD manufacturing process. Nonetheless, cancelled orders following the Asian financial crisis of the late 1990s almost led Applied Materials to close the AKT division down. Managers within the unit proposed a business model innovation that they believed would make survival possible. Applied Materials performed as many of its activities internally as possible. The AKT managers proposed, instead, that AKT seek external contractors to manufacture any components and subassemblies that did not incorporate the firm's core intellectual property. System integration, final assembly and testing would take place in Santa Clara. At the same time, the company shifted from an "assembly line" production model that sought conformity in customer specifications to a "job shop" approach that responded to special customer requests to meet the technical requirements for each new generation of equipment.

The network strategy that AKT implemented in the late 1990s evolved in the early 2000s to accommodate the demands of increasing equipment size, as well as even closer engagement with customers. The new strategy envisioned three service "tiers" of customer engagement. Most of AKT's suppliers now ship their CVD components and subassemblies directly to customers' fab facilities while under construction. In Tier 1, AKT sends a global installation team to assemble units. In Tier 2, additional AKT team members help start up the equipment and assist customers to integrate it with other equipment on the line. Soon after this point, most customers prefer an exclusively in-house team to take over the difficult process of bringing their new fab lines up from low startup yields to commercial yields (80-90%). AKT offers additional Tier 3 services, for which engineering teams remain in customers' facilities past the startup phase, to help address particular challenges that may arise. Although clients may prefer to minimize the presence of non-employees in their fabs after the initial startup phases, many find Tier 3 services too useful to refuse.

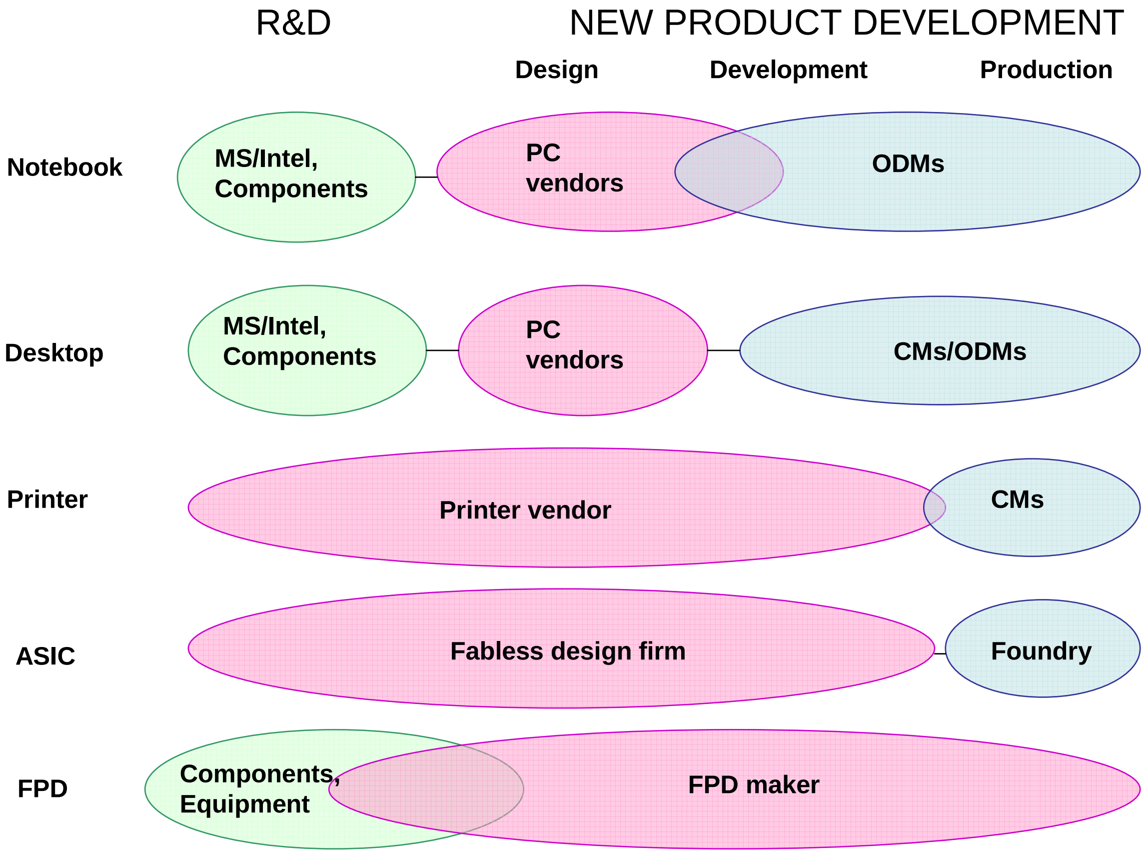
Note that the AKT business model blends an open modular knowledge network interface with organizational interpenetration in order to transfer knowledge. The components and subassemblies that it outsources, as well as the gas deposition chambers that it manufactures itself in Santa Clara, all arrive in modular form at customers' sites. But substantial human interaction with customers has gone into the design and testing of these components before they can be manufactured.

More generally, the FPD industry represents a response to the challenges of rapid innovation in core technologies, requiring extensive problem solving both internally and across firm boundaries. The high cost of developing new technology generations and building manufacturing facilities has led to the use of joint ventures by major producers operating at the leading edge of the industry. The need for extensive interaction with suppliers to solve unpredictable problems associated with new generations has led to highly relational links between FPD makers and key equipment and materials suppliers. This has resulted in the movement of people across firm boundaries, and also across national boundaries as key suppliers from the U.S., Japan and elsewhere support FPD makers in Japan, Korea and Taiwan.

4.5. Comparing knowledge networks

Figure 3 shows the organization of knowledge activities in the different segments of the electronics industry discussed above. Especially important is the degree of organizational integration or intensity of interaction between firms, with straight lines showing more modular links while overlapping ovals shows relational ties. Several points are illustrated.

Figure 3. Organizing knowledge work in different industry segments



First, Figure 3 shows that no particular structure dominates across industry segments, but instead each segment has its own structures based on various factors that are specific to it. For PCs, the dominance of the Wintel platform has led PC vendors to concentrate on NPD and leave R&D to the component makers, with Microsoft and Intel setting most key architectural standards. By contrast, in printers, semiconductors and FPDs, the major manufacturers all conduct R&D on core technologies while also carrying out NPD for specific products. Also, in the case of FPDs (and integrated IC makers, not shown), there is often very close interaction at the R&D and early design stages between manufacturers and suppliers of critical materials and equipment, as fundamental physical design and manufacturing barriers are being addressed.

Second, the relationships between firms vary based on the relative need for human interaction. In PCs, printers and ASICs, there is a great deal of outsourcing of production to specialists such as ODMs, CMs and foundries, but the nature of the relationship with the branded vendors differs. For notebook PCs, where design for manufacturability is key and there is a great deal of product customization, PC vendors have outsourced development and production to ODMs who coordinate those processes internally. At the same time, PC makers are deeply involved in the development process, with a significant amount of organizational interpenetration. By contrast, in desktop PCs and printers, it is most common to outsource manufacturing to CMs, with a cleaner "hand-off" of codified product specifications. In the fabless semiconductor model, a relatively clean hand-off is achieved through the use of standard design software and very detailed specifications set by foundries for designs that can be fabricated at their facilities. At the other end of the spectrum are the flat-panel makers, as well as integrated device manufacturers in the IC industry (not shown here), who are vertically integrated from design through manufacturing. There is some use of outside fabrication capacity by smaller vendors, but no equivalents to the ODMs, CMs and foundries who play such a major role in other industry segments.

Clearly, these are simplified characterizations of each industry sector as there is much more complexity in the real world. For example, printer firms must work with semiconductor design firms to develop ASICs for their products. Also, firms have multiple product categories and these relationships can vary across product categories. Therefore, a given firm will often be part of multiple knowledge networks and display several patterns of organizing activities.

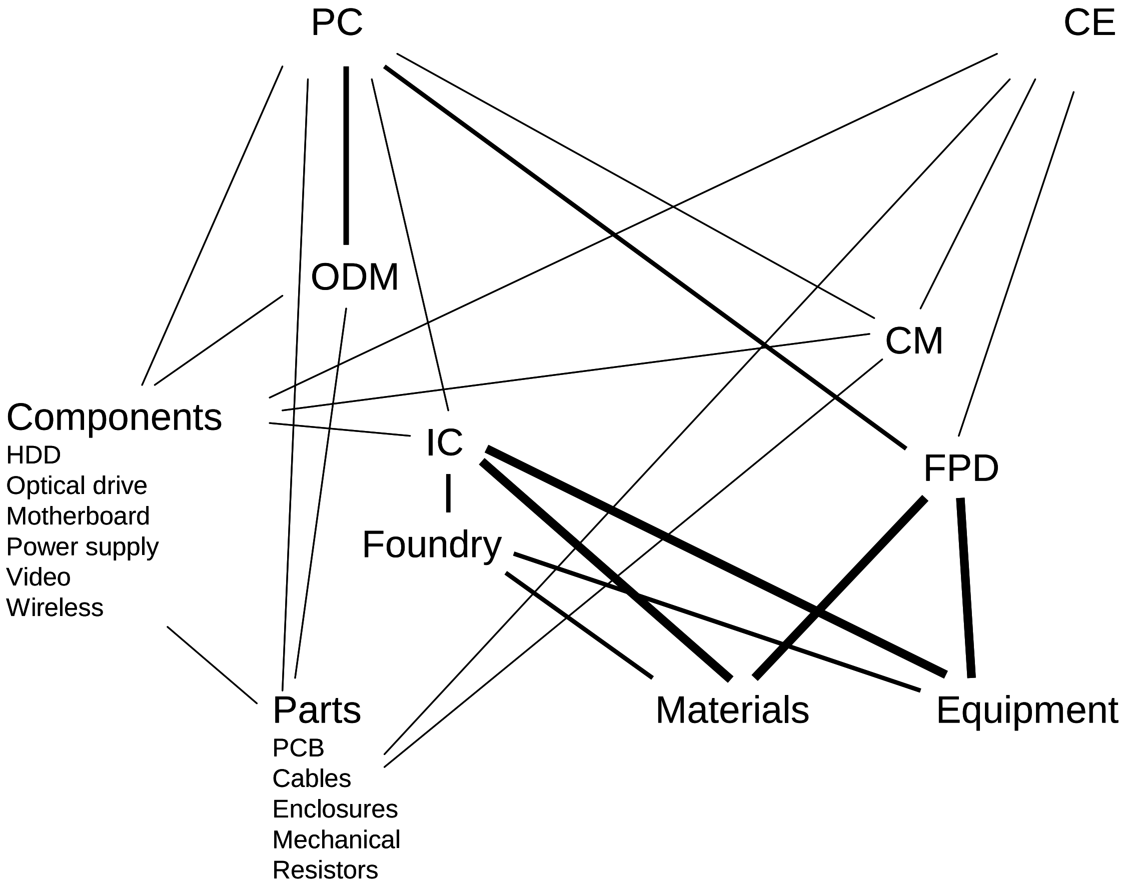
5. A broader industry view

Reviewing the foregoing descriptions of how knowledge networks are organized within and across firms and nations, we find diverse network forms at both the firm and industry level. As we have seen, firms may organize one knowledge activity internally and others in relational or modular networks.

When we step up to the industry level, we can see how the differentiated networks of individual firms are connected into a larger network with linkages among firms and industry segments. Figure 4 illustrates some points about the electronics industry's knowledge network.

First, it shows that the major industry segments that we have been discussing—PCs, printers and other product level electronics, as well as integrated circuits and flat-panel displays—are part of each other's knowledge networks and are integrated into a larger network that includes contract manufacturers, foundries, and suppliers of parts, components, materials and equipment. Many suppliers of parts and components are shared among PC makers and other final product vendors, all of whom assemble systems using various chips, circuit boards, passive parts, enclosures, displays and storage. Many contractors manufacture for a range of product level vendors, particularly large EMS companies such as Flextronics, Foxconn and Solectron that make a wide range of computing, communications, consumer, and other specialized gear.

Figure 4. Density of inter-firm relationships in the electronics industry



Note: Thickness of line represents degree of organizational integration and extent of human interface

Second, it shows that at the component level, the semiconductor, hard disk drive (HDD) and FPD industries share many of the same suppliers of materials and equipment. For instance, both flat-panel displays and hard drive heads are made in clean rooms with many of the same processes as semiconductors. As a result, they share many suppliers. However, while both HDD and FPD manufacturers are highly vertically integrated, the IC industry is different in its outsourcing of manufacturing to foundries and other manufacturing specialists (e.g., assembly and packaging), who do not have counterparts in the FPD or HDD industries.

Third, as shown by the thickness of different linkages, the interactions among these firms vary from simple market transactions such as buying commodity parts to highly relational interactions such as joint development of a new generation of flat panels by the FPD makers and their suppliers. These differences reflect the intensity of human interface and degree of organizational interpenetration involved in the different knowledge activities. For instance, FPD makers and key equipment suppliers have thick linkages because knowledge inputs are tacit and actually created anew during the R&D and NPD process for each new generation. In contrast, PC makers and component suppliers have mostly modular interactions because knowledge about components and their interfaces is well understood.

Finally, these features of the industry illustrate the importance of massive coordination. Firms in each industry segment must coordinate multiple relationships of different types, ranging from market to relational at any given time, and as noted before, these relationships can change over time. Beyond this, the broader industry network is coordinated by a mix of the invisible hand of market transactions, and the visible hand of leading firms who actively coordinate sizable knowledge networks.

6. Summary and conclusions

What determines the ways that firms organize global knowledge networks and, in particular, the extent to which activities are coordinated in relational, modular, market-based or internal interactions? In this paper, we have identified the key factors as the type of knowledge inputs and innovation activities and the degree of human interaction needed to capture the full value of a knowledge input. Together, these shape the types of relationships that exist among the network members.

Nature of knowledge inputs and innovation processes

One important factor is the extent to which knowledge can be codified in detailed specifications, software code, or within a physical product such as an integrated circuit. When this is the case, modular links between firms are more likely. For example, chip designs are laid out in electronic design automation software, which can be understood and implemented at a fabrication facility. When fabrication is outsourced to a foundry, a great deal of knowledge can be transferred in codified form, so that the interaction between the chip designer and the foundry can be quite modular. A closely related factor is the degree of product and process standardization. Returning to the chip example, major foundries have standardized fabrication processes and provide process design kits to fabless companies to ensure that their designs can be manufactured using the standard processes of the foundry. This reduces the amount of process engineering required for each new chip design and provides a standard format for codifying design information so that it can be fed directly into the foundry's design automation software.

Looking at the PC industry, much of the knowledge transferred between component makers and PC vendors is codified in the component itself or captured in the product specifications. The standardization of interfaces in the Wintel platform is critical in supporting the modular, and sometimes even market-based relationships between component makers and PC vendors. By contrast, key printer components such as the ink-jet head and cartridge are specific to a model or product line, as anyone knows who has replaced those cartridges. By keeping those cartridges proprietary and non-standard, printer vendors earn enormous profits on the replacement business. This lack of standardization also means that each vendor does its own R&D and manufactures key components in-house.

Another important characteristic of a knowledge activity is the degree of interdependence with other activities. For instance, the importance of manufacturability for products such as notebook PCs has led to keeping development and production linked, with both either kept in-house or outsourced together to a single ODM. In a different example, there is a close interdependence in developing new generations of flat-panel displays between product design and manufacturing process. As a result, design and manufacturing are kept together via vertical integration. Further, there is a strong interdependence between the design of key manufacturing equipment and the design of a production line, so that FPD makers and equipment suppliers work very closely to develop both the production processes and the tools needed to support those processes.

A final characteristic of the activity is the maturity of the product and the processes used to make it. The knowledge to design and manufacture mature products such as most PCs or older generation chips or displays is well established. It may be codified or may be tacitly understood in such a way that the relevant individuals or groups know what is needed to bring the next product to market. In this case, more modular interactions are likely.

For new products or processes, however, knowledge must be created either through formal R&D or through informal learning-by-doing. Product and process design problems may need to be solved together, as in the case of new generation FPDs or ICs. Solving problems is likely to require input from more than one quarter, such as engineers from equipment makers, component suppliers and product designers. In some cases, the solution chosen is vertical integration. Yet, recent experience with the move to 65nm IC fabrication processes has shown that this is not inevitable. Rather than requiring reintegration of design and fabrication in one firm, as some expected, the problem was solved by foundries and fabless designers at about the same time as it was by integrated device manufacturers such as Intel, IBM and TI. It appears that close relational integration across firms is a viable alternative to vertical integration at least for some major new technological challenges.

Degree of human interaction needed to capture the full value of an input

Capturing the full value of a knowledge input requires understanding the potential usefulness of that knowledge and how it can be integrated with other knowledge to create valuable products or services. For instance, Toshiba had developed a 1.8 inch hard drive, but it was too expensive relative to its capacity to be used in notebook PCs. Apple and others saw the potential of incorporating these drives into a very small portable music player to hold a large number of songs. But Apple had to integrate the drive technology with other hardware and software in a successful design in order to capture the value of that technology.

The extent to which human interaction is required to capture the value of a knowledge input depends largely on the nature of the knowledge inputs and the nature of the activity. The more codified the knowledge and the more there are standardized interfaces to integrate the knowledge, the less human interaction is usually required. Much of the knowledge of how to store and retrieve data on a magnetic device is codified and embedded in the device, and for PCs there are interface standards to integrate a hard drive with the rest of the hardware and software. So, limited human interface is needed between PC makers and hard drive makers to capture the value of that knowledge. For the iPod, interfaces had to be designed and more customization of the drive was required, so the interaction was more relational.

Likewise, when new problems are being solved, such as the introduction of a new generation FPD, a lot of human interaction is required. People need to work on problems together, brainstorm for solutions, try those solutions out, make adjustments, and then go back and brainstorm some more. This requires working in close proximity as well as a great deal of trust and learning how to work together. When such interaction is required, firms tend to do the work in-house, or to have deep interorganizational integration, often with engineers from one firm working in the same location as their partners from other firms.

The importance of human interface has implications for the nature of inter-firm links, and for the geographic location of activities. The greater the degree of human interaction required to capture value, the more likely the knowledge will be integrated via vertical integration or close relational links between firms. And the greater the need for human interaction, the more likely work will be concentrated in one place rather than distributed in multiple locations.

Massive coordination and firm strategy

The complexity of the electronic industry’s global knowledge networks, and the critical importance of participating in these networks in order to be competitive, makes it clear that firms need to engage in massive coordination whatever their strategy and location in the industry. Going it alone is not an option in an industry marked by rapid technological change across all sectors, as firms simply cannot keep up in all or most of the relevant technologies. They need access to outside knowledge to compete.

On the other hand, it is not feasible to rely only on market transactions to tap these sources of knowledge either. Knowledge inputs must often be customized to a specific use, and it is typically impossible to transfer all the relevant knowledge in codified form; therefore, more intense modular and relational ties are required. To succeed in this environment, firms need to understand the nature of the knowledge involved, their own capabilities and those of external partners, and develop an appropriate mix of market, modular and relational coordination mechanisms. They also need to understand what knowledge is strategic to their own business and keep the development and use of that knowledge internal when necessary to retain strategic advantage.

In addition to the variables discussed here, another obvious factor in determining the structure and management of inter-firm linkages is individual firm strategy. To a large extent this can be idiosyncratic to each firm, based on its history or top management preferences. On the other hand, we can generalize to some extent. For instance, firms whose strategic focus is product differentiation (Porter, 1996) may be more likely to develop products in-house, or to pursue exclusive relationships with some suppliers to avoid imitation. By contrast, a firm whose strategic focus is low cost might care less about exclusive relationships and instead want to have multiple suppliers competing with one another to drive down cost. In that case, relationships are likely to be more modular or even market based.

The ability to understand the firm's capabilities and define an appropriate strategic position is considered the key to achieving and maintaining competitive advantage. But beyond a firm's idiosyncratic strategic positioning, this book argues that massive coordination itself is a critical capability and potential source of competitive advantage for firms. This paper illustrates how important this capability can be in a complex global industry such as electronics.

Box 1. A note on terminology

The terms contract manufacturer (CM), electronic manufacturing service (EMS) and original design manufacturer (ODM) are used commonly, and not always consistently, in the electronics industry and the various publications that report on the industry. *Contract manufacturer* is an older term in use when many small firms provided PCB assembly services. *EMS* came into use in recent years as a few of these companies grew to a global scale and gained the ability to provide a range of manufacturing services, including subassembly, final assembly, logistics and even customer service. *ODM* is a term coined in Taiwan when its contract manufacturers, then known as OEMs, began to offer product engineering as well as manufacturing of notebooks, motherboards and other products. The use of *OEM*, or original equipment manufacturer, is perhaps most confusing. In most industries, OEMs are the brand name manufacturers, such as GM or Toyota in cars. In electronics, brand name vendors such as IBM or HP are sometimes known as OEMs, but contract manufacturers in Taiwan were often called OEMs, while brand name vendors such as Acer were called OBMs (own brand manufacturers).

In this chapter, we use the terms EMS, CM and ODM as they are commonly used to identify firms in the industry, but do not classify them as conceptual categories. Instead, we use terminology from Chapter 1 to classify inter-firm relationships (vertical, modular, relational, market) and use examples of different industry sub-sectors such as PCs and printers to illustrate some prototypical forms of knowledge networks. We avoid the term OEM altogether.

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