## Contents

INTRODUCTION  
*Jeffrey T. Macher and David C. Mowery*  
1

1 PERSONAL COMPUTING  
*Jason Dedrick and Kenneth L. Kraemer*  
19

2 SOFTWARE  
*Ashish Arora, Chris Forman, and JiWoong Yoon*  
53

3 SEMICONDUCTORS  
*Jeffrey T. Macher, David C. Mowery, and Alberto Di Minin*  
101

4 FLAT PANEL DISPLAYS  
*Jeffrey A. Hart*  
141

5 LIGHTING  
*Susan W. Sanderson, Kenneth L. Simons, Judith L. Walls, and Yin-Yi Lai,*  
163

6 PHARMACEUTICALS  
*Iain M. Cockburn*  
207

7 BIOTECHNOLOGY  
*Raine Hermans, Alicia Löfler, and Scott Stern*  
231
1

Personal Computing

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INTRODUCTION

August 2006 marked the 25th anniversary of the release of the original IBM personal computer (PC), the product that defined the standards around which a vast new industry formed. Unlike the vertically integrated mainframe industry, the PC industry consisted of a global network of independent suppliers of systems, components, peripherals, and software (Grove, 1999; Dedrick and Kraemer, 1998). The key factor shaping the industry's structure was the design of the IBM PC as a modular, open system with standard interfaces, which allowed many newcomers to enter the market by specializing in one industry segment and developing innovations that could be integrated into any IBM-compatible system. It also permitted producers of parts, components, and systems to achieve global economies of scale as most of the world adopted the IBM standard. In time, desktop PCs were joined by portable laptop/notebook PCs and PC servers as the industry innovated on this common standard.

Today, the core personal computing industry includes not only traditional desktop and laptop PCs and PC servers but also smart handheld devices such as personal digital assistants (PDAs) and smart phones. This core industry is supported by a large number of component suppliers, manufacturing services and logistics providers, distributors, retailers, service specialists, and others. These companies also support other segments of the electronics industry, and so are counted here not as part of the PC industry but as part of its overall production and innovation network. This network not only supports innovation in the core industry segments but also provides the necessary infrastructure for innovations
in newer product categories such as ultramobile PCs, MP3 players (e.g., the iPod), and smart phones.

 Worldwide revenues for the core PC industry totaled $235 billion in 2005: $191 billion in desktop and portable PCs, $28 billion in PC servers, and $16 billion in smart handheld devices (IDC, 2006a). In addition, PC software accounts for about half of the packaged software industry, whose 2006 sales were $225 billion, and PC use also drives sales of information technology (IT) services and of other hardware such as storage, peripherals, and networking equipment (IDC, 2006c).

 The PC has undergone considerable innovation and change since it was first introduced. The traditional PC is no longer expected to be the sole locus of innovation in the future, but simply one of many devices "orbiting the user" (Economist, 2006). Communications devices (phones, PDAs) have acquired computing capabilities and people now send e-mail with a BlackBerry or download music on a mobile phone. Digital photos can be transferred from a camera to a PC and uploaded to a website, transferred directly to a printer, or shot and e-mailed with a mobile phone. And although the traditional desktop and laptop PC is becoming less central to all computing activities, over 225 million PCs were sold in 2006 and the PC is often the first place to find innovations that may migrate later to other devices.

 As important as product innovation has been, equally important is the steady price declines in recent years, which have brought PCs within the reach of more of the world's population. Emerging markets such as China and India are growing much faster than the more mature developed markets, and PC makers have begun to focus on innovation that addresses the needs of those markets at low prices. Globalization of production has been credited for making computer hardware 10 to 30 percent cheaper than it would be otherwise (Mann, 2003). The availability of ever cheaper, smaller, and more powerful hardware has continued to expand the market and has stimulated ongoing innovation in hardware, software, and services.

 Although globalization has been a major factor in the growth and innovation of the PC industry, it raises issues for U.S. companies, government and other institutions, and workers. U.S. PC makers are struggling to eke out a profit in an environment of falling prices and intense international competition. Government policy issues include tax incentives, antitrust, immigration, and market access. Universities must ensure that they are training people with the skills that industry needs, and workers must invest their own time and money to acquire those skills even as more highly skilled knowledge work is moved offshore.

 The impacts of globalization have been debated extensively. An optimistic view is that U.S. firms are outsourcing and offshoring lower-end manufacturing and routine engineering work, freeing resources to focus on more dynamic innovation that will sustain profitability and create new jobs in the United States.

 A more pessimistic view is that innovation is leaving U.S. firms uncompetitive and driving growth and employment (Ko, 2002). While macro-level data can be useful when looking at more dynamic industries, personal computing is one such industry. Globalization of innovation in the PC industry and policy implications. The focus is on U.S.-branded PC companies set in the context of PC companies in other economies such as those in emerging markets that bring them in as part of the global supply chain.

 This chapter is a fact-based analysis of views with industry executives in the United States, International Data Corporation (IDC), Taiwan Electronics Research and other sources of study of the industry for over 20 years. We find that the global division of innovation and policy can be characterized as follows: component-level research, design, and product planning are performed in Japan; applied R&D and development in Taiwan; and product development for manufacturing and sustaining engineering are performed in U.S. PC firms have benefited from this approach, which has supported rapid innovation and quick entry of new versions of their products. The growing demand for U.S. firms' strengths in product architecture is a bigger problem is earning profits from Microsoft and Intel, who capture very high profits of key standards. From the perspective of the United States, the strategy is more mixed. The shift in production including many new product development jobs to locations with lower labor costs has continued and innovation in demand has created large new demands that have helped new jobs. The remaining structure that globalization has produced in the United States has been reduced continually.

 Following this Introduction, the structure of the chapter is as follows. Section "Innovation in the Industry" analyzes how production and innovation are organized in PC demand and production. The fourth section "Personal Computing" characterizes the structure of demand and production in the PC industry and assesses the implications of globalization of innovation on innovation and policy in the industry. The final section "Conclusion and Policy Implications" synthesizes the findings and offers recommendations for policy makers, industry executives, and workers.
A more pessimistic view is that innovation will follow manufacturing offshore, leaving U.S. firms uncompetitive and draining the United States of the innovation that drives growth and employment (Kotkin and Friedman, 2004).

While macro-level data can be useful in analyzing the impacts of globalization, trends and impacts can be easier to spot at the industry level, especially when looking at more dynamic industries where change is happening faster. Personal computing is one such industry. Therefore, this chapter examines the globalization of innovation in the PC industry, its causes, its impacts, and its strategy and policy implications. The focus is mainly on innovation-related activities in U.S.-branded PC companies set in their global context; it is not an analysis of PC companies in other economies such as Japan, Taiwan, or China, although it brings them in as part of the global supply chain and the competitive context.

This chapter is a fact-based analysis grounded in over 200 personal interviews with industry executives in the United States and Asia, data from the International Data Corporation (IDC), Taiwan’s Market Intelligence Center, Reed Electronics Research and other sources, published empirical research, and our study of the industry for over 20 years.

We find that the global division of innovation-related activities can be characterized as follows: component-level research and development (R&D), concept design, and product planning are performed mostly in the United States and Japan; applied R&D and development of new platforms mostly take place in Taiwan; and product development for mature products and a majority of production and sustaining engineering are performed in China.

U.S. PC firms have benefited from this international division of labor, which has supported rapid innovation and quicker integration of new technologies into their products. The growing demand for smaller, more mobile products plays to U.S. firms’ strengths in product architecture and early-stage development. Their bigger problem is earning profits from innovation in an industry dominated by Microsoft and Intel, who capture very high profit margins thanks to their control of key standards. From the perspective of U.S. knowledge workers, the situation is more mixed. The shift in production away from the United States has pulled many new product development jobs to Asia, whereas design and early-stage development work has remained largely in the United States. Still, the new jobs created by the industry’s growth are largely outside of the United States. Finally, consumers in the United States have been clear beneficiaries of the very low cost structure that globalization has produced in PCs as average selling prices have been reduced continually.

Following this Introduction, the structure of this chapter is as follows. The section “Innovation in the Industry” analyzes the nature of innovation in PCs and how production and innovation are organized across the value network. “Changing International Structure of Demand and Supply” describes international trends in PC demand and production. The fourth section, “Globalization of Innovation,”
reviews the global structure of innovation in the PC industry and the factors driving globalization. "Implications of Globalization of Innovation" considers the implications of the foregoing trends for firm strategy and U.S. national policy.

INNOVATION IN THE INDUSTRY

The PC industry has introduced many innovations in its 25-year history. Product innovation includes the creation of new product categories such as notebook PCs and PDAs, as well as the creation of new product platforms such as multimedia PCs and wireless "mobility" notebooks. The scope and outcome of product innovation in PCs is shaped by the presence of global architectural standards set originally by IBM and now largely controlled by Microsoft and Intel. Common interface standards enable innovators to reach a global market with standard product lines; thus, economies of scale can be achieved to support investments in product development and manufacturing capacity. This is different from other industries, such as mobile phones or video games, in which multiple incompatible standards exist. An example of the benefits of standardization is the acceptance of 802.11 as a common standard, which spurred the introduction of wireless networking as a standard feature on notebook PCs. On the other hand, standardization battles can constrain innovation because PC makers are reluctant to incorporate technologies before a standard is set, as is the case with second-generation DVD technology.

When PC makers do innovate, they face hard choices in trying to capture profits from their innovations. One alternative is to incorporate the innovation only in their own products to differentiate their PCs from those of competitors, but there is a question of whether they can convince customers to pay for the differentiation and also whether customers will want to adopt a nonstandard technology. Another is to license the technology broadly, which might bring in license fees and even establish the technology as an industry standard, but which will eliminate product differentiation. One current example is Hewlett-Packard’s (HP’s) Personal Media Drive (PMD), a portable hard drive that slides into a special slot in HP Media Center PCs. HP incorporated the special slot into some of its own products, while letting customers connect the PMD to competitors’ PCs using a slower USB connection, thus differentiating HP’s PCs. By contrast, HP has licensed its LightScribe technology, for labeling DVDs and CDs, to other PC makers. In either case, it can be difficult to translate innovation into profits sufficient to justify the R&D effort.

Despite these challenges, which may discourage more fundamental product innovation, PC makers are pushed to incremental innovation by component makers (such as for semiconductors, storage, or power supply) who introduce frequent changes in their products (faster speed, greater capacity, smaller form factor, longer life) in efforts to gain greater market share within their industry sector. They also are pushed by consumers who want the latest technologies. PC makers feel they have to adopt these or being left behind by a competitor that does.

As a result, PC makers have tended to focus on marketing, and distribution rather than production as the primary source of sustainable competitive advantage within the industry. At the system level tends to be increased emphasis on different products for narrowly defined segments rather than on more distinctly innovative products that are typically upstream in components and systems rather than downstream in products such as PCs.

Consistent with the emphasis on efficiency, component makers have introduced business process innovations such as using the Internet as a direct sales channel, virtualizing logistics, and build-to-order (BTO) products. Component makers have replaced assembly lines with small product lines and have adopted process improvements and improving quality in final assembly. Information technologies such as shop floor control, automated software downloads to improve facilities, and desktop computing applications such as desktop publishing and e-mail have all been important in reducing time to market for new products. Today, most companies use a mix of building processes that are optimal for their targeted markets. The result is that the PC industry as a whole, but the biggest benefits have been as software and microprocessors accounted for 80% of the cost of a PC.

To understand innovation in the industry, one needs to consider the nature of the innovation network, the innovation in computing products, and interdependencies in the system and the structure of the network.

\textsuperscript{1}An exception is Apple, which emphasizes proprietary software in its products. While this helps to reduce costs, Apple has under 4 percent market share in PCs worldwide, so rather than satisfy a small core of Mac users who are willing to pay Intel processors for all of its products, Apple has been able to capture some of the benefits of global economies of scale and greater competition.

\textsuperscript{2}Even these two face challenges: Intel from Apple in the server category (servers).
makers feel they have to adopt these often-incremental changes rather than risk being left behind by a competitor that does adopt.

As a result, PC makers have tended to concentrate on operational efficiency, marketing, and distribution rather than trying to use product differentiation as a source of sustainable competitive advantage (Porter, 1996). Product innovation at the system level tends to be incremental and emphasizes developing slightly different products for narrowly defined market niches, such as PC gamers who demand high performance or business travelers who desire ultralight notebooks, rather than more distinctively innovative products. Instead, most product innovation occurs upstream in components and software, which are then incorporated by PC makers.

Consistent with the emphasis on efficiency and distribution, the industry has introduced business process innovations such as outsourced manufacturing, using the Internet as a direct sales channel, vendor-managed inventory, third-party logistics, and build-to-order (BTO) production. At the plant level, some firms have replaced assembly lines with small production cells to facilitate BTO production and have adopted process improvements such as reducing the number of steps and improving quality in final assembly. They also have employed a range of information technologies such as shop floor management systems, bar coding, and automated software downloads to improve manufacturing performance (Kraemer et al., 2000). However, while early adoption of these innovations benefited some companies, particularly Dell Inc., competing PC makers have since adopted these and other process innovations and closed the gap on key measures such as inventory turnover and time to market for new products (Dedrick and Kraemer, 2005). Today, most companies use a mix of build-to-forecast and BTO processes that is optimal for their targeted markets. The result is greater efficiency in the industry as a whole, but the biggest benefits have not gone to the PC makers. They have mostly gone to consumers in the form of lower prices, and to Microsoft and Intel, as software and microprocessors account for an ever greater share of the total cost of a PC.

To understand innovation in the industry, it is important to look at the structure of the innovation network, the innovation processes, the key personal computing products, and interdependencies among innovation processes, products, and the structure of the network.

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1 An exception is Apple, which emphasizes attractive design and close integration of hardware and proprietary software in its products. While this has been very successful in its iPod line, Apple's market share in PCs is under 4 percent worldwide, so it is unclear that its innovative PCs have done more than satisfy a small core of Mac users who are willing to pay a premium for its products. By adopting Intel processors for all of its products, Apple has abandoned its proprietary hardware platform in favor of global economies of scale and greater compatibility with Windows PCs.

2 Even these two face challenges: Intel from AMD and Microsoft from Linux in one product category (servers).
The Innovation Network

The PC industry’s innovation network consists of component makers, contract manufacturers (CMs) and original design manufacturers (ODMs), branded PC firms, distributors, and resellers (Figure 1).\(^3\)

The industry can be characterized as horizontally specialized, with the branded firms as the “system integrators” doing design and outsourcing development and production to CMs or ODMs. There are less than a dozen globally competitive PC makers and many smaller local assemblers, supported by another dozen major CMs and ODMs. There are several major suppliers of most key components (e.g., motherboards, hard drives, displays, optical drives, memory, and batteries). Farther upstream in the supply chain, there are several thousand suppliers of less expensive parts and components, most of which are small- and medium-sized firms. Distribution is mostly decentralized and local, although there are a few large distributors who operate internationally such as Ingram Micro, Tech Data, and Arrow Electronics. Our main focus in this chapter is on the branded PC vendors and ODMs who collaborate to bring new products to market using components from upstream suppliers.

Most R&D is done upstream in the industry—by the suppliers of microprocessors, software, peripherals, and components. This innovation is global in the sense that there are major component makers in the United States (microprocessors, graphics, memory, hard drives, networking, software), Japan (liquid crystal displays [LCDs], memory, hard drives, batteries), Korea (LCDs, memory), and Taiwan (LCDs, memory, optical drives, power supply, various peripherals). However, although some companies have set up R&D labs around the world, most R&D is still done in the home country. Some PC makers such as HP, Toshiba, Sony, and Samsung also make components and peripherals, but these are generally done in separate business units who sell to competing PC makers as well as their internal PC units.

The pace of this upstream innovation is a major factor shaping innovation by branded PC vendors who innovate through “systems integration.” The PC vendors identify new product markets and design systems that incorporate new technologies to serve those markets. For instance, PC makers identified mobile PC users who want network access without having to plug into a phone line or local area network. This capability was made possible when wireless networking technologies such as WiFi were introduced by component makers. It was then up to PC makers to incorporate the technology into their products. More important, they had to introduce a new technology to support wireless networking was nearly create the impetus for firms and consumers initially jumped in by incorporating 802.11b books, and was soon followed by other PC available in offices, homes, schools, airports. Apple’s early decision was very risky, as taking the risk helped to create the market.

The creation of new markets by PC firms of upstream innovation in components. Firms need to decide which networking standard(s) to support with low power consumption, longer battery life, components seldom meet all these needs, so their own product roadmaps, which signal what the firm is headed, the target markets and expected performance of components needed to succeed. Some knowledge to the upstream suppliers who aggregate demand across PC vendors, plan their own suppliers. These PC maker roadmaps

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\(^3\)The terms contract manufacturer and original design manufacturer are used commonly, but not always consistently, in the electronics industry. Contract manufacturers provide a range of manufacturing services, including subassembly, final assembly, logistics, and even customer service. Original design manufacturer is a term coined in Taiwan when its contract manufacturers began to offer product design and engineering as well as manufacturing of notebooks, motherboards, and other products.
tant, they had to introduce a new technology at a time when the infrastructure to support wireless networking was nearly nonexistent, hoping that this would create the impetus for firms and consumers to invest in wireless networks. Apple initially jumped in by incorporating 802.11 wireless technology in all of its notebooks, and was soon followed by other PC makers. Soon, wireless networks were available in offices, homes, schools, airports, and coffee shops around the world. Apple’s early decision was very risky, as there were few networks available, but taking the risk helped to create the market for them.

The creation of new markets by PC makers, in turn, can shape the direction of upstream innovation in components. For wireless notebooks, PC vendors had to decide which networking standard(s) to incorporate as well as find components with low power consumption, longer battery life, and light weight. Available components seldom meet all these needs, so the lead PC vendors each developed their own product roadmaps, which signal to the component suppliers where the firm is headed, the target markets and expected volumes, and the price and performance of components needed to succeed. By doing so, they provided advance knowledge to the upstream suppliers who could respond in terms of feasibility, aggregate demand across PC vendors, plan for the coming changes, and inform their own suppliers. These PC maker roadmaps, which are different from those
provided by Intel and Microsoft to the PC makers, are essential to knowledge integration along the supply chain.

Innovation Processes

Product innovation in the industry occurs through two broad processes—R&D and new product development. R&D is an ongoing activity that generates knowledge that can be applied to multiple products. New product development is a multistage process of design, development, and production that creates physical products for target markets. Although conceptually distinct, there is often a close interaction between the two in practice. New product development integrates knowledge developed by R&D, and R&D is often called on to solve a specific problem in product development. Given that most R&D is done upstream by the component suppliers, the process of knowledge integration occurs between the supplier and the PC maker. The focus is on knowledge needed to integrate a standard component, but occasionally it involves customization or even more intensive joint development. This is especially the case when an entirely new product is being created, such as the wireless notebook that requires integration of communication technologies, or in the case of a new product category such as the Apple iPod.

Products and Innovation Activities

Although new form factors are emerging, desktops and notebooks remain the leading products in the industry, with important differences between them that affect innovation activities. For desktops, product innovation mainly centers on conventional systems integration—incorporating new parts, components, and software into a system and ensuring that they work together. The system is largely standardized with respect to components, parts, and interfaces. So innovation involves the selection of components to be included for different target markets (e.g., home, office, game, “value” or “power” user). Most use a standard full tower or midtower chassis with industrial design applied mainly to the bezel (face) to reflect a certain brand image. A few newer models aimed at consumers’ living rooms have moved away from the “beige box” to smaller and more stylish designs with unique chassis and industrial designs. PC vendors generally keep concept design and product planning in-house for close control over brand image, user interface, features, cost, and quality. Outsourcing of physical development has occurred in a series of steps since the mid-1990s—first motherboard design, then mechanical design, system test, and finally software build and validation.

For notebooks, innovation involves complex mechanical, electrical, and software design factors presents special challenges with respect to electromagnetic interference, and power consumption (less than one watt, with greater ruggedness. Although components are mostly standardized, notebooks involve integration of the modular components within the notebook itself. In addition, the battery pack may have to be customized for specific needs, and other mechanical parts require custom tools.

PC vendors usually keep notebook development jointly with the ODM because the physical product development and product development take manufactureable form only when the product is developed and tested in a particular assembly plant with specific manufacturing requirements. As a result, product development and final assembly are done by one company. In some cases, this means that a product model is outsourced to a CM for manufacturing. However, because of the high degree of customization, notebooks tend to be designed by PC vendors and ODMs.

Intel facilitated this trend by providing solutions for suppliers who develop motherboards and full system designs. For desktops, the PC makers often develop motherboard designs and work with ODMs for mechanical design, system test, and final assembly. However, for notebooks, the process is more complex because the notebook involves both mechanical and software design.

A detailed discussion of these phases and the activities within each is provided by Dedrick and Kraemer (2006b).
Intel facilitated this trend by providing support and reference designs to ODMs who develop motherboards and full systems.

For notebooks, innovation involves high-level system integration with complex mechanical, electrical, and software challenges. Design of such a small form factor presents special challenges with respect to heat dissipation, electromagnetic interference, and power consumption, while the need for portability requires greater ruggedness. Although components such as disk drives and flat panels are mostly standardized, notebooks involve many custom parts. For example, to fit the modular components within the notebook chassis, the motherboard and battery pack may have to be customized for each notebook model. The chassis and other mechanical parts require custom tooling.

PC vendors usually keep notebook design in-house but coordinate physical development jointly with the ODM because there is a strong interdependency between the physical product development and manufacturing. It is critical that product 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. Most notebook PCs are designed to be built in a particular assembly plant with specific manufacturing process requirements. As a result, product development and final assembly are almost always handled by one company. In some cases, this means the PC maker keeps both in-house. In most cases it means outsourcing both development and manufacturing of each model to a single ODM.

Thus, the interdependencies of PC form factors and new product development (NPD) activities have led to different organizational arrangements for desktops and notebooks (Figure 2). Because desktops are less complex and more standardized, a complete product specification can be handed off for development and production to ODMs, or a fully developed product can be turned over to a CM for manufacturing. However, because of their greater complexity and customization, notebooks tend to be designed and developed jointly by the PC vendors and ODMs.

![Figure 2: Organization of innovation for desktops and notebooks.](image-url)
As a result of the interdependencies in notebook PC development, leading PC makers HP and Dell have set up design centers in Taiwan to work closely with ODMs, whereas others frequently send staff from the United States. The ODMs may divide product development and manufacturing between Taiwan and China but keep very close interaction between the two locations. For desktops, it is easier to separate development and manufacturing geographically as well as across firm boundaries.

CHANGING INTERNATIONAL STRUCTURE
OF DEMAND AND SUPPLY

Trends in Demand

PC demand has been shifting steadily for over a decade toward smaller, more integrated, and more communications-oriented products. The global demand for PCs is changing in terms of form factor, commercial versus consumer markets, and regional consumption. Portable devices (laptops and notebooks) are the fastest growing form factor, totaling 32 percent of unit demand in 2005 compared to just 10 percent in 1990 (Figure 3), and are expected to exceed desktops in the next 5 years (IDC, 2006b). Other portable devices such as smart phones have seen rapid growth as well. This means that there will be more demand for complex innovation in concept, design, and engineering among these stages will have to become cheaper.

Continued price and performance gains shift of production to lower-cost locations overall demand for PCs. One impact is in total market increased from 28 to 38 percent (Figure 4). Another impact is in emerging countries providing the income to afford these expensive. South America are still the biggest markets. Middle East, and Africa (EMEA), the Asia market (Figure 5). The United States is the biggest market.


innovation in concept, design, and engineering in the future and that coordination among these stages will have to become closer.

Continued price and performance gains in key components as well as the shift of production to lower-cost locations have driven prices lower, expanding overall demand for PCs. One impact is in consumer markets, whose share of the total market increased from 28 to 38 percent between 1994 and 2005 (Figure 4). Another impact is in emerging country markets where economic growth is providing the income to afford these ever-cheaper PCs. Although North and South America are still the biggest market in the world, followed by Europe, the Middle East, and Africa (EMEA), the Asia-Pacific region is the fastest-growing market (Figure 5). The United States is the single largest market, with 61 million units shipped in 2005, but fast-growing China has surpassed Japan as the second biggest market.

**FIGURE 4** Global PC consumption by commercial/consumer markets (percent of units sold). SOURCE: IDC (2006d).
Geographic Location of Production

With desktop PCs, final assembly by the branded vendors historically was located close to end-user demand because of logistics (they are too heavy to ship affordably by air) and greater customization for national or regional markets. Major PC vendors such as IBM, Compaq, HP, Apple, and Gateway initially had their own production facilities in each world region, but they later outsourced production to CMs such as SCI, Flextronics, Solectron, Mitac, and Foxconn (the registered trade name of Hon Hai Precision Industry Co.), starting in the late 1990s. Dell kept final assembly in-house, but it outsourced base unit production, including chassis with cables, connectors, drive bays, fans, and power supplies. Japanese and Asian vendors generally kept production in-house.

As the branded PC vendors moved offshore and then outsourced, there was a shift in the location of production from the Americas and EMEA to the Asia-Pacific region (Figure 6). Initially, production was spread throughout East Asia in Japan, Malaysia, Singapore, Taiwan, and Korea. Production of desktop base units and various components and subassemblies by Taiwanese companies shifted to the Pearl River Delta in Southern China, but final assembly was usually done regionally: in the United States and Mexico for the Americas, in Ireland and Scotland for EMEA and Malaysia, and in the Asia-Pacific region.5

Some U.S. companies outsourced notebook production to Taiwanese and Korean manufacturers but even early to ODMs. In 2001, the Taiwanese government bundled Taiwanese firms and the notebook industry into the Pearl River Delta near Shanghai.6 Japanese firms such as Sharp and Fujitsu outsourced much of their production to the region to take advantage of low-cost suppliers to Poland for EMEA; both Dell and HP are setting up final assembly in the Asia region; and Dell is setting up final assembly in Poland.7

5These locations are now changing once again. For example, Dell has moved its notebook supply base when most of the industry moved. For example, 45,000 by 2005 (Einhorn, 2005).
6Some notebook ODMs and suppliers moved to the Pearl River Delta when most of the industry moved. For example, in 1999 and 2000, 45,000 by 2005 (Einhorn, 2005).
7This was the case with the IBM PC Computer Challenge, for example.
and Scotland for EMEA and Malaysia, and in Taiwan and China for the Asia-Pacific region.\textsuperscript{5}

Some U.S. companies outsourced notebook production to Japanese, Taiwanese, and Korean manufacturers but eventually shifted mostly to Taiwanese ODMs. In 2001, the Taiwanese government changed investment limitations for Taiwanese firms and the notebook industry moved en masse to the Yangtze River Delta near Shanghai.\textsuperscript{6} Japanese firms such as Toshiba moved their own notebook production to the region to take advantage of the supply base, but they also outsourced much of their production. Chinese firms such as Lenovo used these same supply bases for their own production and outsourced some as well.\textsuperscript{7}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{image1}
\caption{Computer hardware production by region, 1985-2004. 2004 data are a forecast. The graph includes parts and subassemblies such as base units that are specifically produced for use in computer equipment. SOURCE: Reed Electronics Research (2005).}
\end{figure}

\footnotesize
\textsuperscript{5}These locations are now changing once again. For example, Dell is moving final assembly and suppliers to Poland for EMEA; both Dell and HP are encouraging their CMs to move to India for the Asia region; and Dell is setting up final assembly in India.

\textsuperscript{6}Some notebook ODMs and suppliers moved to the area as early as 1998 so there was already a supply base when most of the industry moved. For example, Asustek had 300 employees in China in 1999 and 45,000 by 2005 (Einhorn, 2005).

\textsuperscript{7}This was the case with the IBM PC Company and Lenovo both before and after their integration.
By 2005 China was the single largest producer of PCs and computer equipment in the world. Although the production facilities were located in China, they were mostly owned and managed by Taiwanese firms, such as HonHai/Foxconn and Mitac for desktops, and Quanta, Compal, Wistron, and Inventec for notebooks. The supply chain was also composed largely of Taiwanese firms. Foxconn has a huge facility in Shenzhen that employs over 100,000 workers and produces base units and complete systems for nearly every branded PC vendor, while also assembling products such as game consoles and iPods and making components such as cables, connectors, chassis, and motherboards. Taiwanese ODMs produced 85 percent of all notebooks in the world in 2005 (Table 1), mostly in the Shanghai/Suzhou region of China.

In the past, the location of final assembly was driven by the need for proximity to demand in the United States and Europe but now appears to be driven by growing demand in Asia as well as by the growing capability of firms to exploit lower costs for labor, land, and facilities, the availability of cost-effective skilled labor, and government incentives in China. For instance, low-cost sea shipment of standard (not BTO) desktop PCs from China to the United States, supported by more sophisticated demand forecasting and planning tools, allows PC makers to build a 3-week shipment time into the new product introduction cycle. Notebooks can be economically shipped by air, so even BTO production can be centralized in Asia. Also, with most of the supply chain in Asia, it can be cheaper to assemble there and minimize shipment time for components because the supply base is concentrated there.

GLOBALIZATION OF INNOVATION

The location of NPD activities by the branded PC firms is driven by the product and process interdependencies discussed earlier, the capabilities and relative costs of different locations, and relational factors that tend to “pull” innovation outside the PC vendor or offshore. The relative capabilities and costs of U.S. firms and those in other countries have resulted in a new global division of labor: higher-value architectural design and business management, along with associated “dynamic” and analytical engineering work, is done in the United States, whereas the development and manufacturing of the physical product, along with the more routine, “transactional” product and process engineering, is done in Taiwan and increasingly in China. The result is that both component and system innovation is increasingly global, but U.S. firms continue to play leading roles in both.

The design of desktops and notebooks reflects the interaction of customer demand, as well as technology trends, with innovation in high-level architectural design, with the needs of industrial design, and business and product development, it is important to be located in leading developed and adopted first.

Development for desktops or notebooks includes product and process engineering. Therefore, electrical, and software engineering skills are important. In addition, notebook development involves design and electromagnetic interference, shock, materials, radiofrequency, and software. Training and experience working in a particular region working on the specific product type.

Such knowledge and skill levels vary according to at least three factors: (1) historical institutional and specialized skills, (2) output of educational institutions, including market scale and the extent to which these skills may be described as cutting edge, with developed industries.

In the United States, there are business and product management that are hard to find industrial design firms that specialize in notebooks and cell phones, and strong software skills. These skills are taught in universities, inveterate the industry, and honed through proximity.

In Japan, there are industrial design firms that are primarily for the Japanese market, but who also have experience. Japanese engineering teams have deep specialties such as miniaturization that have been developed for small, lightweight products. Japan also has a strong manufacturing operations, thanks to immersions in manufacturing.

In Taiwan, mechanical and electrical engineers have at least 4-year degrees in engineering, and are usually more experienced than their US counterparts. They usually have less than 4-year degrees and are not as highly trained in software engineering. The design of desktops and notebooks reflects the interaction of customer demand, as well as technology trends, with innovation in high-level architectural design, with the needs of industrial design, and business and product development, it is important to be located in leading developed and adopted first.

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In Taiwan, mechanical and electrical engineers have at least 4-year degrees in engineering, and are usually more experienced than their US counterparts. They usually have less than 4-year degrees and are not as highly trained in software engineering.
Capabilities and Cost

The design of desktops and notebooks involves understanding markets and customer demand, as well as technology trends, anticipating how customer demand and technology trends are converging, and coordinating mixed teams of marketing people and technologists. It requires people with skills and experience in high-level architectural design, with the associated dynamic engineering skills, industrial design, and business and product management. In terms of proximity, it is important to be located in leading markets where new technologies are developed and adopted first.

Development for desktops or notebooks involves more routine, transactional product and process engineering. Therefore, it requires people with mechanical, electrical, and software engineering skills and technical project management experience. In addition, notebook development requires specialized skills in thermal and electromagnetic interference, shock and vibration, power management, materials, radiofrequency, and software. These require a combination of formal training and experience working in a particular engineering specialty, as well as working on the specific product type.

Such knowledge and skill levels vary significantly in different locations due to at least three factors: (1) historical industrial development leading to creation of specialized skills, (2) output of educational systems, and (3) the nature of demand, including market scale and the extent to which the local or regional market may be described as cutting edge, with demanding and innovative customers.

In the United States, there are business skills such as market intelligence and product management that are hard to find elsewhere. There are also leading industrial design firms that specialize in small electronic products such as notebooks and cell phones, and strong software and high-level engineering skills. These skills are taught in universities, invested in by leading domestic firms in the industry, and honed through proximity to leading-edge users.

In Japan, there are industrial designers that are very good at designing for the Japanese market, but who also have experience designing for global markets. Japanese engineering teams have deep skills in design and development, with specialties such as miniaturization that have developed to meet Japanese demand for small, lightweight products. Japan also is very strong in process engineering and manufacturing operations, thanks to its historical and continued emphasis on manufacturing.

In Taiwan, mechanical and electrical engineers are available with strong...
practical experience as well as formal training. Taiwan's historical specialization in the PC industry, and with notebooks in particular, has created a pool of engineers with a great depth of knowledge of these products. Taiwan also has strong process and manufacturing skills. These have developed over time as Taiwanese firms have taken on greater responsibilities in PC development and manufacturing. Taiwan mostly lacks marketing skills and industrial design skills that would allow it to take over the concept and product planning stages, because of its focus on original equipment manufacturer/ODM production rather than development of branded products.

China has many well-trained mechanical and electrical engineers, but most lack the hands-on skills that come with experience. Industrial design is weak, and marketing and business skills are very underdeveloped. A large number of engineers are produced each year, but quality varies greatly by university. According to one interviewee, China's engineers “work perfectly at doing what they have been told, but cannot think about what needs to be done; they lack both creativity and motivation. They are good at legacy systems, but not new things; they can’t handle ‘what if’ situations.”

In comparing cost across countries, the average salary for electronics engineers in all industries in the United States is about $80,000, compared to $60,000 in Japan, $20,000 in Taiwan, and under $10,000 in China (Dedrick and Kraemer, 2006b). Obviously there are cost advantages to moving engineering to China, but differences in productivity related to education and experience can negate the direct cost differences. Also, it is reported that engineering salaries are rising quickly in China, especially in industry clusters such as the Shanghai/Suzhou area, as multinationals and Taiwanese firms compete with domestic companies for talent. The willingness of multinationals to pay higher salaries gives them access to more experienced engineers and graduates of top universities, but turnover rates are high.

Based on a survey of Taiwanese PC and electronics firms, Lu and Liu (2004) found that the main reason these companies were moving R&D (primarily development) to China was the availability of well-educated and cost-effective local engineers. This finding is supported by our own interviews with Taiwanese companies. As Taiwan’s supply of engineers has failed to keep up with demand, the attraction of a large pool of engineers with both linguistic and geographical proximity has been strong. This has enabled Taiwanese engineers to concentrate on more advanced development activities while lower-value activities such as board layout and software testing have moved to China.

The New Global Division of Labor

This confluence of product and process interdependencies with changing capabilities and costs in different locations has led to a new global division of labor (Figure 7). In 1990, the entire NPD process was located in the United States (and Japan) in large vertically integrated companies such as IBM Corporation, and Toshiba, or PC specialists such as Apple handled virtually all elements of system-level design. In 2000, only design remained in the United States, and the production of notebooks was outsourced mainly to Taiwan. Development was outsourced to major world regions. Japan’s strength was in the production of desktops and many computer peripherals (usually more mature product lines). Location-specific coordination with CMs and ODMs and product planning led to better quality control and problem resolution. Knowledge transfer to the ODMs and Taiwan’s software engineers to take on more project management activities. This division of labor is similar to some U.S. companies keep desktop development local and outsource manufacturing to Asia. However, many Taiwanese ODMs in many cases.

The next critical development was the move of R&D to China. Encouraged by U.S. PC vendors, Taiwanese firms moved R&D centers to China to attract the best engineers in the region. As R&D moved to China, R&D activities moved to Taiwan. Taiwanese firms began to provide project management to ODMs. This move of R&D to China has led to a new global division of labor where Taiwan focuses on R&D, while China focuses on manufacturing.
Japan) in large vertically integrated companies like IBM, HP, Digital Equipment Corporation, and Toshiba, or PC specialists like Apple, Compaq, and Dell, which handled virtually all elements of system-level design and integration. By 2000, only design remained in the United States, while development and manufacturing of notebooks was outsourced mainly to Taiwan and manufacturing of desktops outsourced to major world regions. Japanese PC firms still kept NPD in-house, at least for higher-value products.

In 2006, the U.S. position was unchanged. However, PC vendors like HP and Dell had set up design centers in Taiwan to manage NPD for some products (usually more mature product lines). Locating design in Taiwan allows closer coordination with CMs and ODMs and potentially speeds up NPD, allowing better quality control and problem resolution. They also use these design centers to transfer knowledge to the ODMs and to train locally hired hardware and software engineers to take on more project management and advanced development activities. This division of labor is similar for notebooks and desktops, although some U.S. companies keep desktop development in the United States and then outsource manufacturing to Asia. However, desktop development is being shifted to Taiwanese ODMs in many cases.

The next critical development was the rapid shift of production to mainland China. Encouraged by U.S. PC vendors, Taiwanese manufacturers had moved the production of desktops and many components and subassemblies to the Pearl

![Figure 7 - New global division of labor in the PC industry.](image-url)
River Delta near Hong Kong in the 1990s. Even more dramatic was the shift of notebook production to the Shanghai/Suzhou area after 2000. Many Taiwanese suppliers to the notebook industry had moved to China before 2001. When the Taiwanese government lifted its restrictions on notebook production in China, the ODMs and the rest of their local suppliers moved nearly all of their production to the mainland (Dedrick and Kraemer, 2006a).

In response to U.S. PC makers outsourcing production to Taiwanese ODMs in China, the Japanese PC makers also shifted significant production to China, both through their own subsidiaries and through outsourcing to the Taiwanese ODMs. This further illustrates the compelling economies of the production bases in China as Japanese firms have previously tended to keep production in-house, either in Japan or in Southeast Asia.

**China’s Expanding Role as a Locus of Innovation**

As a result of “production pull” as well as the large pool of lower-cost engineering skills, there is an ongoing shift of product development activities from Taiwan to China. During our interviews with notebook makers in Taiwan and China, one major ODM told us that they did all of their board layout and most packaging design in China, while doing mechanical engineering and software engineering in Taiwan. They were in the process of training people in their electronic engineering methods in China in order to move more development there. As one manager said, “China is a gold mine of human resources, but if you don’t get in and train them you won’t be able to take advantage of it.”

It is expected that more of the NPD process and the associated engineering tests will be conducted in China by many notebook makers (Dedrick and Kraemer, 2006a). These will be relocated from Taiwan and, in some cases, Japan. The shift of product development to China is distinguished not only by which activities have moved or are moving, but also by the type of products that are being developed. Some ODMs are moving product updates to China. However, the development of completely new products and platforms is still done by the ODMs in Taiwan, or by PC makers such as Lenovo (for Thinkpad notebooks) and Toshiba in Japan. More recent interviews with Taiwanese companies suggest that they are hesitant to move these activities to China. This is due in part to the high turnover rate of engineers in China, which makes it hard to create cohesive development teams and also raises the risk of intellectual property loss. Also, unless intellectual property protections are strengthened, China is not likely to become a center for advanced component-level R&D (e.g., in microprocessors, LCDs, or wireless technologies).

A near-term division of labor for product development is likely to be as follows: component-level R&D, concept design, and product planning in the United States and Japan; applied R&D and development of new platforms in Taiwan; and product development for mature products, and nearly all production and sustaining engineering, in China. It is likely this division of labor will last. A recent study by Li shows that the rapid growth of low-margin Taiwanese multinational corporations has provided Taiwan with the motivation to invest more in R&D to develop new products, and capture more high-value design work. As a result, multinational corporations have shown a greater incentive to pursue further lower costs. Li also shows that Taiwan’s continued growth in intellectual property from its innovation efforts by filling out its patent applications in the United States. As Taiwan to China may be slowing but the shift of innovation to China could continue.

In addition, Taiwanese manufacturers such as Acer and Lite-on have developed their own brands of networking equipment, smart phones, and industrial software. Acer has captured 14.1 percent of the world market share in the industrial market, whereas D-Link has become the top seller of networking equipment in the United States. As these companies enhance their design capabilities, U.S. companies may find Taiwan to be a logical source for new innovation.

As China gains experience, it is still possible that the development of the development process and newer product platforms will remain key final market for PCs, it is not likely to remain a key final market for PC innovation. As China’s PC market continues to grow and become more demanding, it may become the leading design region, and definition and planning of products will be done there. Finally, while Chinese brands remain a key factor in the international personal computer market, Huawei, and Haier are already leading brands in international markets for PCs, network equipment, and sustaining engineering.

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1. Sustaining engineering is the second of two phases of product development.

Mass production involves the physical manufacturing of products and requires manufacturing engineers to manage and plan the production process. Mass production engineers to continually improve product and process designs so that they will know the product extremely well and are best positioned to know what changes the product will need to make during the warranty period when problems occur.
and sustaining engineering.\textsuperscript{11} in China. It is difficult to estimate how long this division of labor will last. A recent study of Taiwanese manufacturers (Li, 2006) shows that the rapid growth of low-margin outsourcing business from foreign multinational corporations has provided Taiwanese firms with the resources and motivation to invest more in R&D to develop greater technology expertise and capture more high-value design work. As the ODMs’ expertise grows, multinational corporations have greater incentive to outsource more design activities to further lower costs. Li also shows that Taiwanese firms are attempting to capture value from their innovation efforts by filing for more patents. So the shift from Taiwan to China may be slowing but the shift from the United States to Taiwan could continue.

In addition, Taiwanese manufacturers such as Acer, Asus, BenQ, D-Link, and Lite-on have developed their own brand-name PCs, motherboards, monitors, networking equipment, smart phones, and other products. Acer and Asus brands have captured 14.1 percent of the world market for notebooks (Digitimes, 2006), whereas D-Link has become the top seller of wireless routers for the consumer market. As these companies enhance their R&D, design, and marketing capabilities, U.S. companies may find Taiwan to be a source of competition as well as cooperation.

As China gains experience, it is still possible that the ODMs will shift more of the development process and newer products there, but, unless it becomes a key final market for PCs, it is not likely to capture the market-driven functions of concept design and product planning. As of now, China’s PC market is still only about one-third the size of the U.S. market and does not have leading-edge users who are defining what features and standards are developed for the global market. However, as China’s PC market continues to grow, and its users become more demanding, it may become the leading market at least for the Asia-Pacific region, and definition and planning of products suitable for the region may be done there. Finally, while Chinese brands remain minor players in the global PC industry for the most part, this may change. Chinese companies such as Lenovo, Huawei, and Haier are already leading brands at home and are expanding to international markets for PCs, network equipment, and other electronics products.

\textsuperscript{11}Sustaining engineering is the second of two phases in production; the first is mass production. Mass production involves the physical manufacturing of a product in large volumes. It requires manufacturing engineers to manage and plan the production process and test facilities and quality engineers to continually improve product and process quality. Over time, these engineers come to know the product extremely well and are best positioned to provide sustaining engineering support that was previously provided by the original product development teams. Sustaining engineering deals with changes that occur because of new chips, failing or end-of-life components, or improved components. Each change must be evaluated in terms of its implications for system performance and assembly, and incorporated into the production process. The sustaining engineers also provide the highest level of technical support when problems occur during use during a product’s 2- to 3-year warranty period.
Lenovo's acquisition of IBM's PC business has put it directly in competition with HP and Dell around the world, while Huawei uses its relationship with 3Com to access technology and markets and compete with Cisco and others. These companies can use the supply base of Taiwanese and foreign companies in China to match the multinationals on cost, develop products that fit the local market, and then target other emerging markets where innovations developed for the Chinese market are likely to be attractive.

Measurement of the Globalization of Innovation

Measuring the globalization of innovation is more difficult than measuring globalization of manufacturing, which can be captured in national production, trade, and foreign investment accounts. Innovation might be indirectly measured by R&D spending and employees, patents, and new product introductions. While some public data on these measures are available, often the data are not sufficiently disaggregated at the firm level so that they can be tied to a product line such as PCs. This is especially true of multidivision firms such as HP, Fujitsu, Toshiba, Hitachi, Samsung, and Sony. Also, firm-level data do not show the extent to which R&D or other innovative activity is carried out in the home country or other locations.

Given these difficulties, an alternative approach is to measure the innovation effort by the CMs and ODMs who are doing much of the manufacturing in the industry. The share of global notebook shipments produced by Taiwanese ODMs rose from 40 percent in 1998 to 85 percent in 2005 (Table 1). Since manufacturing and development are usually outsourced together, this suggests that the share of offshore product development activity has increased proportionately. This trend is supported by data showing that R&D spending by Taiwanese ODMs and CMs increased significantly from 2000 to 2005 (Table 2), as did the proportion of employees with Ph.D. and master’s degrees in these firms. However, most of this R&D spending is on the development side rather than the research side.

Also, reiterating a point made earlier that most innovation is done by upstream component makers, the R&D spending by the ODMs and CMs, as well as nearly all of the PC makers, is minor in comparison to that of upstream suppliers. For example, Table 3 shows that in 2005 some of the lead PC makers\(^{12}\) spent 1.4 percent of revenues on R&D on average (weighted), the leading ODMs and CMs spent 1.3 percent, and the upstream suppliers, which is where innovation occurs in the PC industry, spent an average of 11.8 percent, or nearly nine times greater than the PC makers, ODMs, and CMs.

\(^{12}\)We could not get public estimates of R&D investment for the PC divisions of large multidivision companies such as HP, Fujitsu, Toshiba, Sony, and NEC, so they are excluded from the table.
TABLE 1 Taiwanese Notebook Industry Share of Global Shipments, 1998-2005

<table>
<thead>
<tr>
<th></th>
<th>1998</th>
<th>1999</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shipments volume (thousands)°</td>
<td>6,088</td>
<td>9,703</td>
<td>12,708</td>
<td>14,161</td>
<td>18,380</td>
<td>25,238</td>
<td>33,340</td>
<td>50,500</td>
</tr>
<tr>
<td>Global market by volume (thousands)</td>
<td>15,610</td>
<td>19,816</td>
<td>24,437</td>
<td>25,747</td>
<td>30,033</td>
<td>37,857</td>
<td>46,110</td>
<td>59,411</td>
</tr>
<tr>
<td>Taiwan’s share of global market volume</td>
<td>40%</td>
<td>49%</td>
<td>52%</td>
<td>55%</td>
<td>61%</td>
<td>66%</td>
<td>72%</td>
<td>85%</td>
</tr>
</tbody>
</table>

°Shipments by Taiwan-based firms, regardless of location of production.


Industry-Level Drivers of Globalization of Innovation

The globalization of innovation in the PC industry has been driven primarily by economic factors and secondarily by relational factors that involve interdependencies of activities, as well as social networks that often influence the choice of suppliers or location. Examples of relational factors include the close interdependence between development and manufacturing of notebook PCs, and the “guanxi” social networks that link Taiwanese firms and managers.

TABLE 2 R&D Investment by Taiwanese ODMs and CMs (million U.S. dollars)

<table>
<thead>
<tr>
<th>Company Name</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quanta</td>
<td>27.13</td>
<td>38.36</td>
<td>54.55</td>
<td>74.31</td>
<td>92.56</td>
<td>102.36</td>
</tr>
<tr>
<td>Compal</td>
<td>24.77</td>
<td>44.69</td>
<td>62.11</td>
<td>70.21</td>
<td>78.78</td>
<td></td>
</tr>
<tr>
<td>Wistron</td>
<td></td>
<td>61.12</td>
<td>55.06</td>
<td>68.94</td>
<td>72.49</td>
<td></td>
</tr>
<tr>
<td>Asustek Computer</td>
<td>31.97</td>
<td>40.57</td>
<td>53.14</td>
<td>65.87</td>
<td>97.38</td>
<td>128.57</td>
</tr>
<tr>
<td>Medac</td>
<td>24.37</td>
<td>24.70</td>
<td>25.28</td>
<td>32.66</td>
<td>36.90</td>
<td>46.62</td>
</tr>
<tr>
<td>Inventec</td>
<td>30.75</td>
<td>25.14</td>
<td>27.38</td>
<td>39.42</td>
<td>48.56</td>
<td></td>
</tr>
<tr>
<td>Aroma</td>
<td>13.42</td>
<td>12.74</td>
<td>14.85</td>
<td>15.00</td>
<td>19.60</td>
<td>16.71</td>
</tr>
<tr>
<td>ECS</td>
<td>3.58</td>
<td>7.20</td>
<td>21.03</td>
<td>14.98</td>
<td>12.74</td>
<td>11.00</td>
</tr>
<tr>
<td>First Internatioonal Computer (FIC)</td>
<td>28.21</td>
<td>10.91</td>
<td>46.72</td>
<td>44.58</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clevo</td>
<td>8.71</td>
<td>8.10</td>
<td>8.97</td>
<td>9.28</td>
<td>10.28</td>
<td>10.05</td>
</tr>
<tr>
<td>Twinhead</td>
<td>7.24</td>
<td>5.31</td>
<td>1.10</td>
<td>0.31</td>
<td>0.43</td>
<td>0.47</td>
</tr>
<tr>
<td>Unwill</td>
<td>7.27</td>
<td>8.20</td>
<td>9.89</td>
<td>11.15</td>
<td>11.55</td>
<td>12.48</td>
</tr>
<tr>
<td>Foxconn (HonHai)</td>
<td>32.43</td>
<td>58.14</td>
<td>64.45</td>
<td>66.69</td>
<td>128.78</td>
<td>132.86</td>
</tr>
<tr>
<td>Subtotals</td>
<td>239.85</td>
<td>239.37</td>
<td>433.17</td>
<td>491.42</td>
<td>549.37</td>
<td>660.95</td>
</tr>
</tbody>
</table>

NOTE: Blank cells occur where data was not available in annual reports or elsewhere.

SOURCE: Annual reports of the companies.
TABLE 3 R&D Investment as Percent of Firm Revenues, 2005

<table>
<thead>
<tr>
<th>PC Makers</th>
<th>R&amp;D as % of Revenue</th>
<th>Taiwan ODMs &amp; CMs</th>
<th>R&amp;D as % of Revenue</th>
<th>Component Suppliers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dell</td>
<td>0.9</td>
<td>Quanta</td>
<td>1.1</td>
<td>Microsoft</td>
</tr>
<tr>
<td>Apple</td>
<td>3.8</td>
<td>Compal</td>
<td>1.4</td>
<td>Intel</td>
</tr>
<tr>
<td>Gateway</td>
<td>n.a.</td>
<td>Wistron</td>
<td>1.6</td>
<td>AMD</td>
</tr>
<tr>
<td>Lenovo</td>
<td>1.7</td>
<td>Asustek</td>
<td>1.7</td>
<td>ATI Technology</td>
</tr>
<tr>
<td>Acer</td>
<td>0.1</td>
<td>Mitac</td>
<td>2.0</td>
<td>Seagate (HDD)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inventec</td>
<td>1.4</td>
<td>Western Digital (HDD)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Arima*</td>
<td>2.8</td>
<td>Maxtor (HDD)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ECS*</td>
<td>1.6</td>
<td>Chungwha (Displays)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FIC*</td>
<td>n.a.</td>
<td>Tatung (Displays)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Clever*</td>
<td>4.2</td>
<td>AU Optronics (Displays)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Twinhead*</td>
<td>0.2</td>
<td>Moless (Cables/ connectors)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Uniwill*</td>
<td>1.6</td>
<td>Delta (Power supply)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HonHai</td>
<td>1.0</td>
<td>Creative (Sound cards)</td>
</tr>
</tbody>
</table>

| Total firm revenues (millions) | $92,535 | $76,191 | $128,773 |
| R&D (% of revenues) for selected firms (weighted) | 1.4 | 1.3 | 11.8 |

NOTE: Large multidivision PC makers like HP, Toshiba, Sony, Fujitsu, and NEC are omitted because R&D investment is not available by division.

*Value calculated from data in company annual reports.


Regarding economic factors, the manufacturing of desktops was primarily pushed offshore to major world regions to reduce production cost, and secondarily for proximity to markets. Manufacturing was then outsourced to CMs as most PC makers looked to further cut costs and concentrate on product design, branding, sales, and marketing. These CMs are currently moving to new locations within each region (Eastern Europe for EMEA, Mexico for North America, and China for Asia-Pacific)—once again to reduce costs. As noted earlier, for standard build-to-stock desktops, production in the U.S. market, because low-cost shipping turnaround is not necessary.

Cost was also the key factor for note PC manufacturing being outsourced or offshored. When Japan, then to Taiwan, and currently to China, BPC manufacturers and manufacturing of small form factor, costs, development of strong indigenous engineering expertise to manufacturing in China for lower-cost labor, and some development activities to China as well, in R&D, design, and other high-value activities. This is through continued outsourcing and by some degree, onshore.

Regarding relational factors in the PC industry, moves to a low-cost location, it will pull. Reinforcing our findings about production practices (2004) found that the second major location (low-cost engineers) is proximity to the manufacturing. In some cases, true for notebook PCs given the importance of design, production engineering and sustainancemanufacturing, because product design, and manufacturing can be tested in production models from the assembly line, movement of pilot production to China rather than Taiwan just for this purpose. Then the question as to whether the design review and prototype processes as well.

Beyond proximity considerations in manufacturing, "pull" from the ODMs. They often bundle deals in order to win contracts. But once the ODM has incentives for the PC maker to work with the ODM in enhancements to the product. In addition, the value created in the development process that is known as a "pull." Finally, the close linkage between manufacturing and the feedback to design from manufacturing that favor continuing the ODM relationships.

The concentration of product development in China has reduced cost and accelerated new product development average unit prices, and helping to expand margins. The average unit price for a PC and monitor has decreased $1,100 and $1,400, respectively, in the United States.
standard build-to-stock desktops, production is increasingly done in China for the U.S. market, because low-cost shipping by sea is viable when fast order turnaround is not necessary.

Cost was also the key factor for notebooks, where both development and manufacturing were outsourced or offshored almost from the beginning—first to Japan, then to Taiwan, and currently to China. Japan’s capabilities with development and manufacturing of small form factors provided an initial pull, but lower costs, development of strong indigenous engineering capabilities, and the fact that Taiwanese firms were considered less likely to compete directly with U.S. firms resulted in U.S. PC vendors shifting to Taiwan. In turn, Taiwan has moved manufacturing to China for lower-cost labor, and manufacturing is now pulling some development activities to China as well. Taiwan is trying to expand its role in R&D, design, and other high-value activities, and PC vendors have facilitated this through continued outsourcing and by setting up design centers in Taiwan.

Regarding relational factors in the PC industry, it appears that once production moves to a low-cost location, it will pull some higher-level activities to it. Reinforcing our findings about production pulling knowledge work, Lu and Liu (2004) found that the second major location factor for R&D (after access to low-cost engineers) is proximity to the manufacturing site. This is particularly true for notebook PCs given the importance of design-for-manufacturability. For example, production engineering and sustaining engineering clearly benefit from proximity to manufacturing, because production problems can be addressed immediately on the factory floor and engineering changes in existing products can be tested in production models from the assembly line. It also makes sense to move pilot production to China rather than to maintain an assembly line in Taiwan just for this purpose. Then the question arises whether to move the expensive test equipment from Taiwan to China. If so, then there is more reason to relocate the design review and prototype processes as well.

Beyond proximity considerations in manufacturing, there is a relational “pull” from the ODMs. They often bundle development with manufacturing in order to win contracts. But once the ODM has a contract, the relationship creates incentives for the PC maker to work with the same ODM for future upgrades and enhancements to the product. In addition, there is a great deal of tacit knowledge created in the development process that is known only by the ODM, which creates a further pull. Finally, the close linkage of development activities to manufacturing and the feedback to design from manufacturing has created linkages that favor continuing the ODM relationships.

The concentration of product development and manufacturing in Taiwan and China has reduced cost and accelerated new product innovation, driving down average unit prices, and helping to expand markets. For example, the worldwide average unit price for a PC and monitor has declined markedly over the past 15 years (Figure 8), with desktops and notebooks selling at an average of under $1,100 and $1,400, respectively, in the United States in 2005, and many models
available for well under $1,000. Of course, when adjusted for quality improvements, the price decline is much more dramatic. Moreover, the price differences between the United States and other regions have declined so that there is now effectively one world price.

Beyond cost reduction, the globalization of innovation also has been driven by a desire to develop a better understanding of the needs of big emerging markets such as China, India, and Brazil to enable the right versioning of existing products. Some PC vendors and ODMs (as well as other suppliers like AMD, Intel, and Microsoft) are seeking new markets in less-developed economies by developing new PCs with much lower price points while also tailoring the technologies to the more extreme environments of these countries. These new product concepts include the One-Laptop-Per-Child design, Intel’s Classmate PC, and Asus’s eeePC. While previous efforts to develop very-low-cost PCs for developing countries have failed, PC makers and others continue to experiment with new designs.

IMPLICATIONS OF GLOBALIZATION OF INNOVATION

The globalization of innovation has led to a new global division of labor as described earlier. This new international structure of the PC industry has implications for firm competitiveness and strategy, firm strategy, and U.S. policy.

Implications for U.S. Firms

Overall, the changes in the industry applicability of U.S. firms. U.S. companies dominate processors, graphics and other chips, and hard disks. Apple holds nearly 40 percent of the world market in tablets, an uncontested leader in operating systems and mobile phones. On the other hand, Asian firms are leaders in displays, motherboards, optical drives, and other components, with some leading PC brands such as Lenovo, Taiwan’s CMs and ODMs increasingly common for outsourced development and manufacturing, the largest share of industry particularly Microsoft and Intel, but also to other Asian companies. The size of the Asian companies is generally lower.

Implications for Firms

For branded PC vendors, the internationalization earlier enables faster product cycles with quality increases, and supply cost-effective engineers in Taiwan and other regions, changes, and upgrades. It has increased competition, and for a long time was advantageous for it an advantage in getting those products to market. On the other hand, Asian firms are efficient in minimizing inventory costs, and for a long time was advantageous for it an advantage in getting those products to market. The most firms are efficient in minimizing inventory costs, particularly Microsoft and Intel, but also to other Asian makers such as Nvidia, TI, and Broadcom. The size of the Asian companies is generally lower.

\[13\] Acer, which has been a successful Taiwanese brand and Packard Bell in October 2007.

\[14\] As desktop PCs in particular have become common, direct sales, BTO, and just-in-time inventory have become important. They provided an initial advantage to Dell and Gateway. Gateway stumbled badly and Dell’s efficiency advantages gone to direct BTO sales. The Dell model has also been popular in direct sales are less popular than in the United States. The model innovation has been a general improvement in most firms have adopted these practices.
Implications for U.S. Firm Competitiveness

Overall, the changes in the industry appear not to have hurt the competitiveness of U.S. firms. U.S. companies dominate key components such as microprocessors, graphics and other chips, and hard drives, and PC vendors Dell, HP, and Apple hold nearly 40 percent of the world market for PCs. U.S. firms are still unquestioned leaders in operating systems and packaged applications. On the other hand, Asian firms are leaders in displays, memory, power supplies, batteries, motherboards, optical drives, and other components and peripherals. Asia has some leading PC brands such as Lenovo, Toshiba, Acer, and Sony, and Taiwan’s CMs and ODMs increasingly compete with U.S. contract manufacturers for outsourced development and manufacturing. On another measure of firm competitiveness, the largest share of industry profits flows to U.S. companies, particularly Microsoft and Intel, but also to Apple, Dell, HP, and to component makers such as Nvidia, TI, and Broadcom. The profitability of most Japanese and Asian companies is generally lower.

Implications for Firm Strategy

For branded PC vendors, the international innovation network described earlier enables faster product cycles with quicker integration of new technologies because the Taiwanese companies are good at fast turnaround and there is a good supply of cost-effective engineers in Taiwan and China to handle more models, changes, and upgrades. It has increased consumer choice, helped grow the market, and for a long time was advantageous for Dell because its direct model gave it an advantage in getting those products to the business customer. But now that most firms are efficient in minimizing inventory and getting new products into the market, the fast product cycles could be seen as an expensive race to the bottom that no PC vendor or component supplier really wins (except Intel and Microsoft). Some PC vendors complain that component innovation is too fast, 

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13 Acer, which has been a successful Taiwanese branded company, purchased Gateway Computer and Packard Bell in October 2007.
14 As desktop PCs in particular have become commoditized, business model innovations such as direct sales, BTO, and just-in-time inventory have provided temporary advantage in the industry. They provided an initial advantage to Dell and Gateway, who were the first to adopt direct sales, but Gateway stumbled badly and Dell's efficiency advantage has been reduced as other PC vendors have gone to direct BTO sales. The Dell model also has proved less successful in overseas markets where direct sales are less popular than in the United States. The most important impact of past business model innovation has been a general improvement in the efficiency of the industry as a whole, as most vendors have adopted these practices.
and they feel pressured to introduce too many products for too small markets. For example, one major PC vendor introduces around 1,000 different consumer desktop SKUs (stock-keeping units) in one year globally (Dedrick and Kraemer, 2006b). A question raised by more than one company that we have interviewed is whether the cost of managing so many products might outweigh the benefits of being able to offer products that more closely match the needs of customers.

Beyond desktop and notebook PCs, the growing demand for new products that are smaller, are more mobile, and integrate new functions is bringing new innovation and new players into the personal computing industry. Hit products such as RIM’s BlackBerry and Palm’s Treo have been developed by firms with no traditional PC business, while Apple’s iPod was developed on an entirely different platform from the Macintosh computer line. Such radical or architectural product innovation (Henderson and Clark, 1990; Utterback, 1990) has important differences from the incremental model of development as illustrated in Table 4. The scale and scope of global collaboration is often greater for radical innovation, as existing technologies are adapted to new uses and new technologies are developed. As a result, there is greater need for joint development with partners, while key technologies (particularly software) are developed internally and the entire process is shaped by strong central vision, integration, and control.

An example of the nature of radical innovation is the iPod, which was developed by Apple in collaboration with many external partners in multiple geographic locations. Apple used its internal capabilities to create a closely integrated hardware and software design, while relying on outside partners for both standard and custom components, and for manufacturing. For instance, Apple used a reference design and worked jointly with PortalPlayer to develop the microchip that controlled the iPod’s basic functionality. It worked with others for additional chips (e.g., United Kingdom’s Wolfson Microelectronics for the digital-to-analog sound chip; New York-based Linear Technology for power management chips; California-based Broadcom for a video decoder chip) with Toshiba for the 1.8-inch hard drive; and with Taiwan’s Inventec for manufacturing (Murtha et al., forthcoming).

Apple designed the system architecture that affected critical features such as sound quality and power consumption and developed the distinctive industrial design of the iPod; it developed most of the iPod and iTunes software in-house or adapted others’ software. Apple tightly managed the whole process, coordinating closely with outside partners so that it could design the iPod, and its manufacturer and suppliers could concurrently prepare the tooling and supply chain for large-volume manufacturing, and bring it to market in 8 months. As put by the iPod’s lead engineer, “Today, there is too much complexity in products for one person or organization to understand. You need a team of internal and external resources working with you to conceive, design, and implement new products” (Murtha et al., forthcoming). The resulting design process is much different from that in PCs, with more internal development and fewer key component suppliers.

Finally, for the iPod to be successful, Apple needed a business model that integrated hardware, software, and content. It developed iTunes software to collect and easily transfer that content to the iPod. It acquired the classic music store and integrated a content distribution system with the digital music and movie, and television industries, and established business models that were attractive to consumers. The result is a 14 percent in both the personal music player and digital music industry.

Table 4: Features of Incremental and Radical Innovation

<table>
<thead>
<tr>
<th>Design</th>
<th>Radical innovation (iPod, iPhone, Treo)</th>
<th>Incremental innovation (desktops, notebooks)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>— Set system architecture, sometimes building on external reference design</td>
<td>— Innovate on WinTel architecture</td>
</tr>
<tr>
<td></td>
<td>— Strong central vision and industrial design</td>
<td>— Control product planning, brand image, marketing, concept design internally</td>
</tr>
<tr>
<td></td>
<td>— Tightly control all aspects of NP</td>
<td>— Internal or outsourced industrial design</td>
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<tr>
<td></td>
<td>— Develop key software internally</td>
<td>— HW and SW are modular</td>
</tr>
<tr>
<td></td>
<td>— Integrate hardware, software, even services (e.g., iTunes, iTMS)</td>
<td>— Leverage existing complementary resources and distribution</td>
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<td></td>
<td>— Design or license complementary assets (SW, content) and distribution system</td>
<td>— Design or license complementary assets (SW, content) and distribution system</td>
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<td>— Collaborate closely with a few key partners for core components</td>
<td>— Collaborate closely with a few key partners for core components</td>
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that in PCs, with more internal development and much closer interaction with key component suppliers.

Finally, for the iPod to be successful in the market, Apple created a new business model that integrated hardware, software, and online content delivery. It developed iTunes software to collect and manage content on a PC or Mac and easily transfer that content to the iPod. It also developed the online iTunes Music Store and tightly integrated that with the iTunes application. Apple licensed content from all the major music labels and subsequently from the audio book, movie, and television industries, and established pricing and digital rights models that were attractive to consumers. The result was a U.S. market share of over 70 percent in both the personal music player and the music download markets.
Given that such design innovation has the potential for creating differentiation in products and gaining competitive advantage, the strategies of at least some branded PC firms are likely to focus more on creating new product platforms. However, examples such as the iPod, Treo, and BlackBerry suggest that radical innovation requires a different process of new product development. As illustrated by our earlier discussion of these innovations, elements of the process include leveraging a firm's unique internal capabilities with those of external partners; working closely with external partners in multiple geographies; engaging in a global search for technologies that can be adapted and integrated into new products; maintaining tight architectural and managerial control over the process; and possibly introducing new business models to provide complementary content and services.

This kind of process is far removed from the incremental innovation within a well-established product architecture and the mature market of the Wintel PC world. As a result, it has been more diversified companies such as Samsung and Sony, wireless specialists such as Nokia, as well as many startups that are trying to innovate with new product platforms that mix communications, entertainment, and computing capabilities in smaller form factors. In these cases, firms have worked with outside partners to exploit external sources of knowledge while keeping their own innovative activities mostly in-house and close to their home base.

Increasingly, hardware-software integration is becoming important as a means of tailoring products to different market requirements such as communications standards, power consumption, language, and customer tastes. Such integration also helps to reduce product costs by enabling standard physical platforms to be produced in large volumes for global sales. More important, it enables greater product differentiation for ever-finer market segments by customizing through changes in software, rather than through costly physical changes in hardware.

**Location of Innovation**

Innovation at the national level is closely tied to the presence of both technically skilled and entrepreneurial individuals, the quality of infrastructure, and the presence of advanced users who drive firms to innovate. Rapid diffusion of Internet infrastructure in the United States led to ongoing innovation in hardware (e.g., routers, switches), software (e.g., browsers, search engines), and services (e.g., online retailing, banking, stock trading, travel services). The United States has seen strong user-driven innovation (Von Hippel, 1998) such as IT-enabled business process redesign and e-commerce in the corporate world and user-created content in the consumer world. From Cisco and Amazon, to Dell and Wal-Mart to Google and MySpace, innovation on the web has largely occurred in the United States.

By contrast, the relatively slow adoption of broadband and advanced mobile technologies in the United States has left the market open for other countries of innovation. For instance, South Korea is a leader in mobile Internet thanks in part to its widespread deployment of South Korea's iMode system for mobile Internet access, Japan's iMode system for mobile Internet access, and South Korea's iMode system for mobile Internet access. In short, the lack of innovation in the United States has been less diversified and innovative than its counterparts in Japan and South Korea. The United States has seen strong user-led innovation and drive demand for new products.

Our field interviews indicate that design and product planning, is likely to remain the purview for the major U.S. firms in the personal computer markets. It is likely to focus on be increasing use of offshore R&D and development, with a focus on specialized and cost-effective talent, that lead to a reduction in the overall cost of the device. It is also likely to underpinning the large and otherwise highly fragmented and unprofitable market for mobile services. In short, it is likely to remain behind in providing high-quality user-led innovation and drive demand for new products.

Other product development activities are increasingly being performed with manufacturing process engineers in China, and managers to perform activities previously performed in the United States or in a foreign subsidiary. In this regard, the United States is increasingly becoming a location for innovation, as these locations gain capabilities or as locations with lower labor costs are developed.

Impacts on Jobs and Wages

With respect to U.S. workers, much of the offshoring of manufacturing activity has already taken place with the offshoring of manufacturing activity from the United States to locations such as China, India, and Mexico. With the offshoring of manufacturing activity from the United States to locations such as China, India, and Mexico, there has also been a shift in the types of jobs performed in the United States. As this takes place, there will be further movement of jobs out of the United States, with the creation of new jobs in China, India, and Mexico.
technologies in the United States has left the country falling behind in new areas of innovation. For instance, South Korea is a leader in online computer gaming, thanks in part to its widespread deployment of cheap broadband Internet service. Japan’s iMode system for mobile Internet was years ahead of similar services in the United States. High rates of wireless adoption have benefited firms from South Korea, Japan, and Northern Europe, while China’s large mobile phone market has attracted firms such as Motorola, Nokia, and Siemens to do product development there. In short, the lack of innovation in industries that are providers of complementary assets (which in turn may reflect the outmoded infrastructure underpinning the large and otherwise highly sophisticated U.S. domestic market) is a major factor hampering innovation in the PC industry. If the United States is to retain its position as a leading market for computing innovation, it cannot afford to remain behind in providing high-quality, low-cost infrastructure to support user-led innovation and drive demand for new personal computing products.

Our field interviews indicate that design innovation, especially concept design and product planning, is likely to remain concentrated in the United States for the major U.S. firms in the personal computing industry. However, there will be increasing use of offshore R&D and design centers in locations that have specialized and cost-effective talent, that lead in particular technical innovations, or that represent important markets in terms of growth potential, special market opportunities (fewer regulatory requirements, government incentives), or challenges (need for cheaper or environmentally friendly PCs), or that may influence technical standards (as China is trying to do in a number of technologies). Private interviews with industry executives indicate that the primary motivation for such offshore outposts is cost reduction, through hiring less costly engineers, programmers, and managers to perform activities previously performed in-house in the United States or in a foreign subsidiary. In time, secondary benefits may also arise as these locations gain capabilities or as local markets develop.

Other product development activities tend to be pulled by production, beginning with manufacturing process engineering, then moving up to prototyping and testing and eventually electrical, mechanical, and software engineering. These are in the process of shifting to China from Taiwan and Japan, although R&D, design, and development of the newest generation of products is still likely to be concentrated in the home countries of the manufacturers (Dedrick and Kraemer, 2006a).

**Impacts on Jobs and Employment**

With respect to U.S. workers, much of the potential shift of jobs offshore has already taken place with the offshoring and outsourcing of production from 1990 to 2005. There has also been a shift in innovation-related jobs after 2000, as production has pulled development and some design activities to Asia (Dedrick and Kraemer, 2006a). Further movement of jobs offshore is likely to occur in
the future to meet competitive pressure for continuous cost reduction. The jobs will be in engineering, software, industrial design, engineering management, and project management at all levels. As one PC industry executive told us in interviews, he has to “push” more physical design and project management jobs overseas in order to keep concept design jobs at home.

The number of jobs directly moved offshore is not large and occurs incrementally. However, another indicator of the impact of offshoring is the number of new jobs that are created offshore rather than in the United States to support the industry’s continued growth and proliferation of products. One indicator of this impact is the growth of knowledge jobs in the notebook industry in Taiwan as these firms take on more design and development activities for the United States and other firms. Interviews and company data on the top ODMs in the notebook industry indicate that they hired thousands of new R&D personnel and product engineers in Taiwan between 2000 and 2005, while also hiring thousands more for product and process engineering, testing, and production in China. For example, Quanta, which is the largest notebook ODM, has increased the number of R&D engineers from 750 in 2001 to around 7,000 in 2005 (company annual reports).

As software becomes an increasingly important part of new PC products, there will be a proportionately greater increase in software jobs being moved offshore. In one company we interviewed, 50 percent of the 1,000 employees are engineers and 80 percent of these are software engineers. These jobs are currently in the United States, but the firm is experimenting with offshore teams. While there is broad awareness of the shift of jobs to India and elsewhere by software and IT services companies, there is less awareness of the number of software jobs within the computer hardware industry—jobs that are likewise vulnerable to offshoring.

For the United States, the fact that growth and innovation in the industry are not creating new knowledge jobs (engineering, software, design) in the United States but are creating them in Taiwan and China appears to be a negative. But the number of U.S. engineering jobs in the broader computer industry is fairly stable at about 60,000 between 2002 and 2005 (Dedrick and Kraemer, 2006b), and without globalization there may not be as much growth and innovation. The risks of globalization for the United States are that individuals, firms, or related industries will lose technological advantage and the ability to innovate. A Korn/Ferry International report posed the issue for industry executives as follows:

North American industrial executives must choose between two fundamental responses to their current competitive environment. One approach is to simply accept that their companies need to focus exclusively on marketing, finance and the design and development functions, while offloading their manufacturing needs and technologies to more accommodating locations, usually overseas. While this strategy can generate short-term profits, it almost inevitably guarantees that a company will lose control of its design and production capabilities.

Eventually, if history is a reliable guide, everything will cease to exist. (Kotkin and Fried)

However, earlier industry innovations such as the iPod, the Treo, and the Microsoft Xbox were largely developed in the United States, even though some component innovation and all the manufacturing was done offshore. It is thus far that these firms have “lost control” of their products. Such innovation is less likely to support engineering and other knowledge jobs, as the United States retains the capabilities needed.

Implications for Policy: Sustaining Innovation

Although U.S. PC vendors still lead innovation, moving more innovation activities offshore both through outsourcing design and development and through outsourcing design and development suppliers of key components such as microprocessors, it is also setting up R&D and design centers overseas with specialized skills such as Israel or Japan, and even with low-cost engineering talent such as in China.

The engineering, software development and related activities are key to the innovation that is key to the industry. Therefore consideration needs to be given to how such innovation is to remain in the United States. The National Academy of Engineering, 2020, indicate there is a growing need across the country for people specifically trained to work at the interface of engineering, communications, and computer science. The existing engineering schools produce specialists in a wide range of fields, but schools also need to produce people who can work at the interface of these fields as well. In particular, there is a need, for example, for hardware engineers who also understand software, and both who understand the hardware design standards, and software engineers who design systems that enable customization of products for market niches. People with such talent, firms may rely on on-the-job training of low-cost specialists.

It is also likely that U.S. firms need to find these people and develop them. Several of the companies are finding that they need experienced engineers rather than beginners, in Silicon Valley or elsewhere. They simply hire or bring in engineers from foreign countries, but hire in India, China, and other countries. However, one highly innovative company...

PERSONAL COMPUTING
Eventually, if history is a reliable guide, even home office and corporate functions will cease to exist. (Kotkin and Friedman, 2004)

However, earlier industry innovations as well as recent innovations like the iPod, the Treo, and the Microsoft Xbox were developed mostly in the United States, even though some component innovations came from offshore suppliers and all the manufacturing was done offshore. Moreover, there is little evidence thus far that these firms have “lost control” of the designs or technology for these products. Such innovation is less likely to move offshore and should continue to support engineering and other knowledge jobs in the United States, as long as the United States retains the capabilities needed for such innovation.

Implications for Policy: Sustaining U.S. Innovation Leadership

Although U.S. PC vendors still lead innovation in the industry, they are moving more innovation activities offshore both through setting up design centers and through outsourcing design and development activities to ODMs. The U.S. suppliers of key components such as microprocessors, storage, and software are also setting up R&D and design centers offshore, sometimes in locations with specialized skills such as Israel or Japan, and sometimes in big emerging markets with low-cost engineering talent such as India and China.

The engineering, software development, and management skills associated with these activities are key to the innovation capabilities of the United States and therefore consideration needs to be given to developing people with these skills if such innovation is to remain in the United States (Committee on the Engineer of 2020, National Academy of Engineering, 2005). Our interviews with executives indicate there is a growing need across the PC industry for engineers who are specifically trained to work at the interface between hardware engineering, communications, and computer science. The executives also indicate that many U.S. engineering schools produce specialists in a single engineering discipline, but few schools produce people who can work at the interfaces of these disciplines. There is a need, for example, for hardware engineers who can work with communications standards, and software engineers who can produce embedded software that enables customization of products for markets. When universities fail to develop such talent, firms may rely on on-the-job training, look offshore for experienced people with the needed skills, or develop the skills offshore through on-the-job training of low-cost specialists.

It is also likely that U.S. firms need to make greater efforts to hire rookies and develop them. Several of the companies we interviewed prefer to hire fairly experienced engineers rather than beginners and report no problems in doing so in Silicon Valley or elsewhere. They simply hire people away from other companies, or bring in engineers from foreign countries under immigration policy. However, one highly innovative company we interviewed hired engineers as
interns from the best engineering schools in the United States (e.g., Cornell, MIT, UC Berkeley, Carnegie-Mellon) and, if they worked out, made commitments to hire them even before they graduated. Starting as interns, they worked as part of project teams with operational roles and real challenges to overcome. Such on-the-job training can help sustain a career ladder for new engineers as firms offshore more lower-level jobs that would normally be filled by entry-level engineers. An executive for the firm argued that this process benefits the firm as well, by giving it access to the best talent available and the chance to incorporate that talent into product development teams and learn how the company works before the engineers develop bad habits elsewhere.

From a policy perspective, the U.S. government can encourage cross-disciplinary education and more university-industry cooperation through its funding choices, and by documenting and publicizing the need for such changes. While universities are responsive to employer needs, there can be significant inertia in academic departments and university bureaucracies, and external resources and pressure can encourage greater responsiveness and flexibility.

All of the firms we interviewed indicated a need for more H-1B visas, or for reform of the visa process. One issue involves procedures for keeping people who have been educated in the United States and perhaps interned with the firm. Another involves recruiting from abroad for skills for which the U.S. supply of talent is limited, but for which other countries are noted for having people with the needed skills. For example, it appears that the supply of engineers in analog fields in the United States such as radiofrequency is limited, whereas there is a good supply in some European countries. A reported problem with the current immigration process is that the nature of U.S. supply of talent is not considered. From an immigration standpoint, an engineer is an engineer regardless of education level (bachelor, master's, Ph.D.) and there is no way to identify and respond to shortages of very specific skills or levels (e.g., bachelor vs. Ph.D.).

In addition to such human resource issues, another key concern is sustaining the demand for innovation. PC demand, and associated innovation, has been driven in the past decade largely by the Internet and networking in general. With the United States leading in Internet adoption, the PC industry was quick to adopt networking technologies such as Ethernet and wireless networking, and new products such as the BlackBerry and Treo were developed in the United States. However, the United States has fallen behind a number of countries in both wireless and broadband adoption and is not the lead market for products and services such as mobile phones and online gaming. As a result, innovations in new personal computing devices such as smart phones, video game consoles, and other network devices are likely to target foreign markets initially, making it more likely that innovation will occur in those markets rather than in the United States.

While specific policy issues with regard to telecommunications, Internet regulation, content, and pricing are beyond the scope of this chapter, those decisions should be made with an awareness of innovation in industries such as personal computing and cooperation by providers of complementary infrastructure. Government policies should consider the speed of diffusion of infrastructure like networks. Similarly, government policies should be debated in terms of impacts on competition, consumer choice, policy makers also should look in high-technology industries.

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sions should be made with an awareness of their potential impact on U.S. innovation in industries such as personal computing. Innovation in PCs can require cooperation by providers of complementary assets, such as content or communication infrastructure. Government policies on telecommunications can influence the speed of diffusion of infrastructure like broadband, 3G, or municipal WiFi networks. Similarly, government policies on copyright can influence the terms under which content can be distributed. While these policy issues are usually debated in terms of impacts on competition, intellectual property rights, or even consumer choice, policy makers also should consider their impact on innovation in high-technology industries.

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The global movement of software engineering services and research and development of software products to locations important and growing phenomenon that has received attention within the United States and has been a source of American technological leadership. However, despite these changes in the structure of the industry, there is relatively little evidence of global clusters of software product development. U.S. companies have been the leading exporters of software products, and the number of patents suggests that inventive activity in software continues to be significant lead over other countries in the United States. In the short run, the U.S. companies have a significant advantage. Moreover, proximity to potential agglomeration economies arising from the presence of software product complementors provide software product companies with a significant advantage.