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The Personal Computing Industry

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I. Introduction[1]

August 2006 marked the 25th anniversary of the release of the original IBM 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, 1996; 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. This 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 except Apple 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 ultramobile PCs, 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 not counted 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.

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Worldwide revenues for the core PC industry totaled $235 billion in 2005, including $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 IT services and of other hardware such as storage, peripherals, and networking equipment (IDC, 2006c).

The PC has undergone considerable innovation and change since 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" (*The Economist*, 2006). Communications devices (phones, PDAs) are gaining computing capabilities so 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. While the traditional desktop and laptop PC is becoming less central to all computing activities, over 200 millionPCs were sold in 2005 and the PC is often the first place for innovations to appear 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%-30% cheaper than it otherwise would be (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.

While globalization has been a major factor in the PC industry's growth and innovation, 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, anti-trust, 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 optomistic 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 U.S. A more pessimistic view is that innovation will follow manufacturing offshore, leaving U.S. firms uncompetitive and draining the U.S. of the innovation that drives growth and employment (Kotkin and Friedman, 2004).

While macro-level data can be useful in analyzing these impacts of globalization, it can be easier to spot trends and impacts at the industry level, especially by 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.

The chapter is a fact-based analysis grounded in over 200 personal interviews with industry executives in the U.S. and Asia, data from the International Data Corporation (IDC), The Market Intelligence Center, Reed Electronics Research and Juliussen, published empirical research, and our study of the industry for over twenty years.

We find that the global division of innovation-related activities can be characterized as follows: component-level R&D, concept design and product planning are performed 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, while 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 U.S. Finally, from the consumer perspective, consumers in the U.S. 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. Section II analyzes the nature of innovation and how production and innovation are organized across the value network. Section III describes international trends in PC demand and production. Section IV reviews the global structure of innovation in the PC industry and the factors driving globalization. Section V considers the implications of the foregoing trends for firm strategy and U.S. national policy.

II. 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 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 as 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 non-standard technology. Another is to license the technology broadly, which might bring in license fees and even establish the technology as an industry standard, but will eliminate product differentiation. One current example is 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 radical innovation, PC makers are pushed to incremental innovation by component makers 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 such as semiconductors, storage or power supply. PC makers feel they have to adopt these changes rather than risk being left behind by a competitor that does adopt. One PC maker expressed the view that it would be better for everyone if the pace of innovation were slower, but no one is willing to take the risk of such a slowdown. Thus, competition and innovation in the supply chain tends to push PC makers into incremental changes that do little to differentiate products.

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 ultra-light notebooks, rather than more distinctively innovative products.[2] 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 outsourcing, 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 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 build to order processes that is optimal for their targeted markets. The result is greater efficiency in the industry as a whole, but the benefit 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.[3]

In order 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 between innovation processes, products, and the structure of the network.

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[2] 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% 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.

[3] Even these duopolists 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).[4]

The industry can be characterized as horizontally specialized with the branded firms being "system integrators" doing design and outsourcing development and production to CMs or ODMs. There are about a dozen globally competitive PC makers and many small 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, batteries. Further upstream in the supply chain, there are several thousand suppliers of parts and components, most of which are small and medium-sized firms; a few very large firms also exist in each category. 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 U.S. (microprocessors, graphics, memory, hard drives, networking, software), Japan (LCDs, memory, hard drives, batteries), Korea (LCDs, memory), and Taiwan (LCDs, memory, optical drives, power supply, various peripherals). However, while some companies have set up R&D labs around the world, most R&D is still done in the home country. Some PC makers also make components and peripherals, such as HP, Toshiba, Sony, and Samsung, but these are generally done in separate business units who sell to competing PC makers as well as their internal PC units.

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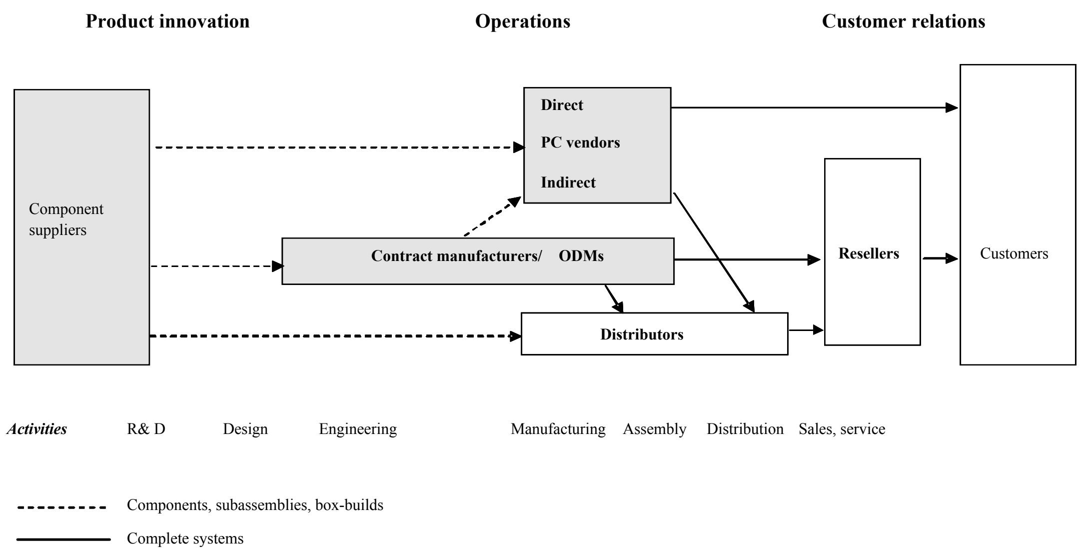
[4] The terms contract manufacturer (CM) and original design manufacturer (ODM) are use commonly, but not always consistently in the electronics industry. *Contract manufacturers* provide a range of manufacturing services, including subassembly, final assembly, logistics and even customer service. *Original 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.

Figure 1. The PC Industry Innovation Network



Adapted from Curry and Kenney (1999).

The pace of this upstream innovation is a major factor shaping innovation by branded PC vendors who innovate through "systems integration." The PC vendors innovate by identifying new product markets and designing 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 in to 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 importantly, they had to introduce a new technology at a time when the infrastructure to support wireless networking was nearly non-existent, 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 by taking the risk helped to create the market for them.

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/performance of components needed to succeed. Buy 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 road maps, which are different from those provided by Intel 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 new knowledge that can be applied to new products. *New product development* is a multi-stage process of design, development and production that creates physical products for target markets.[5] 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 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

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[5] A detailed discussion of these phases and the activities within each is provided in Dedrick and Kraemer (2006b).

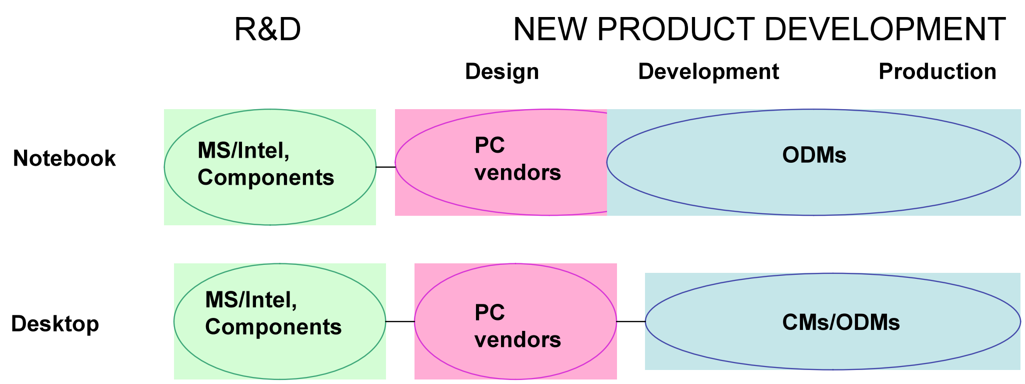
and ensuring that they work together. The system is largely standardized with respect to components, parts, and interfaces according to standards set by Microsoft and Intel. So, innovation involves the selection of components to be included for different target markets (e.g., home, office, game, "value" or "power" user). Most use a standard full tower or mid-tower 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. 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 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, in order 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



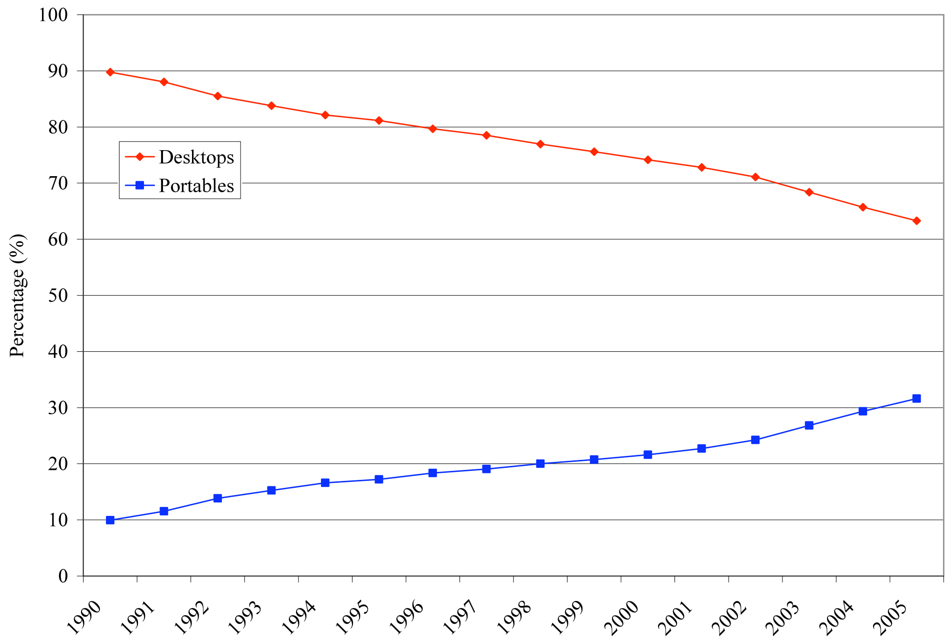
As a result of the interdependencies in notebook PC development, leading PC makers HP and Dell have set up design centers in Taiwan to work closely with ODMs, while others frequently send staff from the U.S. The ODMs may divide product development and manufacturing between Taiwan and China, but with very close interaction between the two locations. For desktops, it is easier to separate development and manufacturing geographically as well as across firm boundaries.

III. Changing International Structure of Demand and Supply

Trends in Demand

PC demand has been shifting steadily for over a decade towards smaller, more integrated and more communications-oriented products. The global demand for PCs is changing in terms of form factor, commercial vs. consumer markets and regional consumption. Portable devices (laptops and notebooks) are the fastest growing form factor, totaling 32% of unit demand in 2005, compared to just 10% in 1990 (Figure 3), and expected to exceed desktops in the next five 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 in the future and that coordination among these stages will have to become much closer.

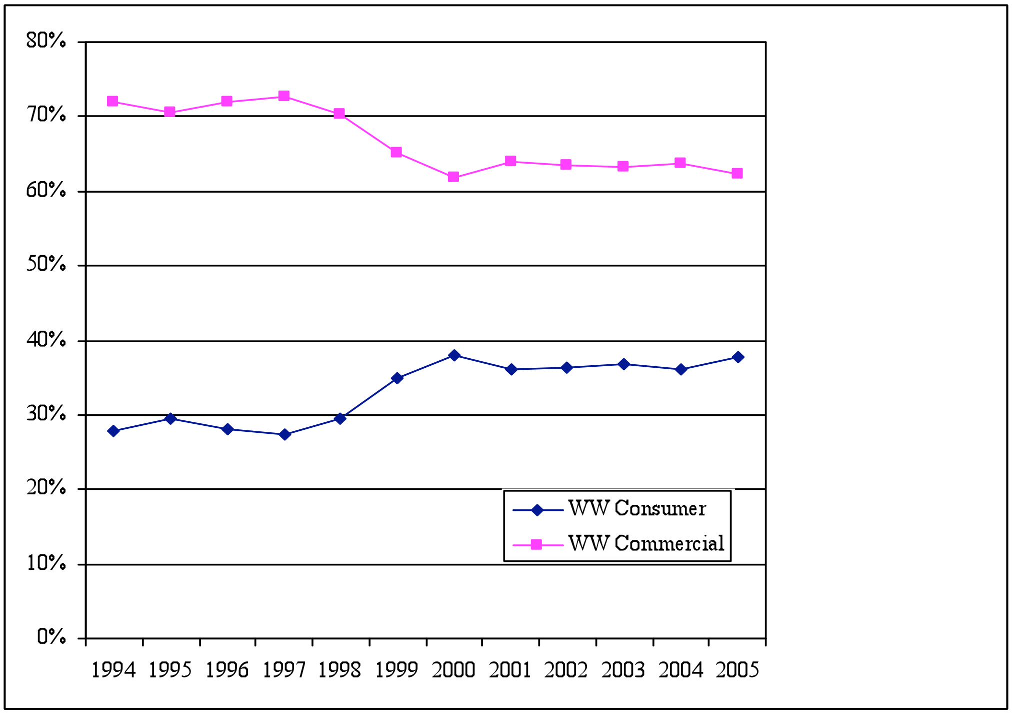
Figure 3. Global Demand for Desktops and Portables, 1990-2005 (units)



Source: Juliussen, 2006.

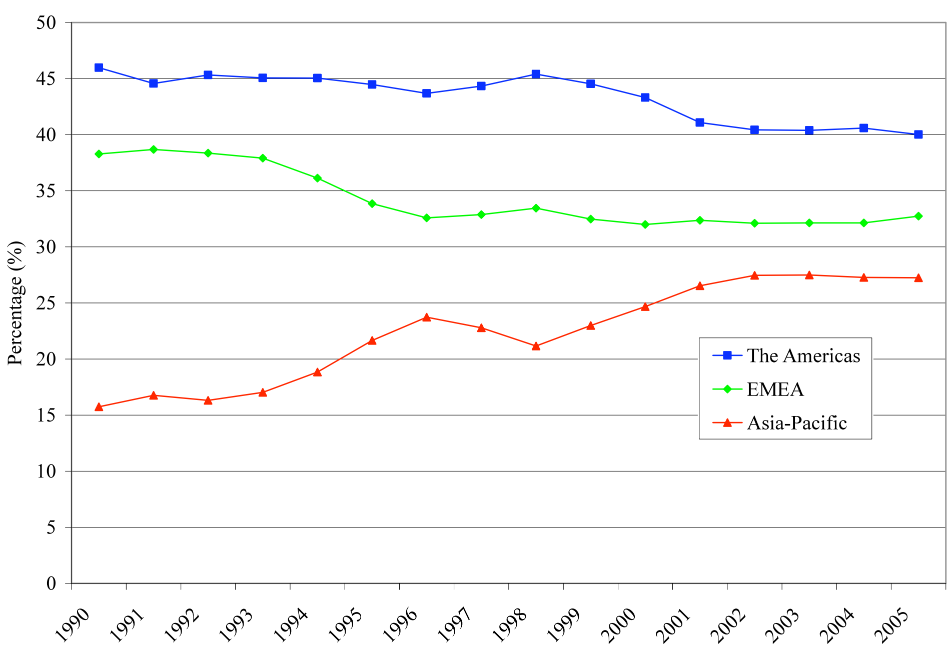
Continued price/performance gains in key components as well as the shift of production to lower cost locations have driven prices lower, expanding overall demand for PCs. One impact is in consumer markets whose share of the total market has increased from 28% to 38% between 1994-2005 (Figure 4). Another impact is in emerging markets where economic growth is providing the income to afford these ever cheaper PCs. Although The Americas 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 U.S. 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 (% of units sold)



Source: IDC, 2006d

Figure 5. Global PC Consumption by Region, 1990-2005 (% of units sold)



Source: Juliussen, 2006.

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 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 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 U.S. and Mexico for The Americas; Ireland and Scotland for EMEA and Malaysia; Taiwan and China for the Asia-Pacific.[6]

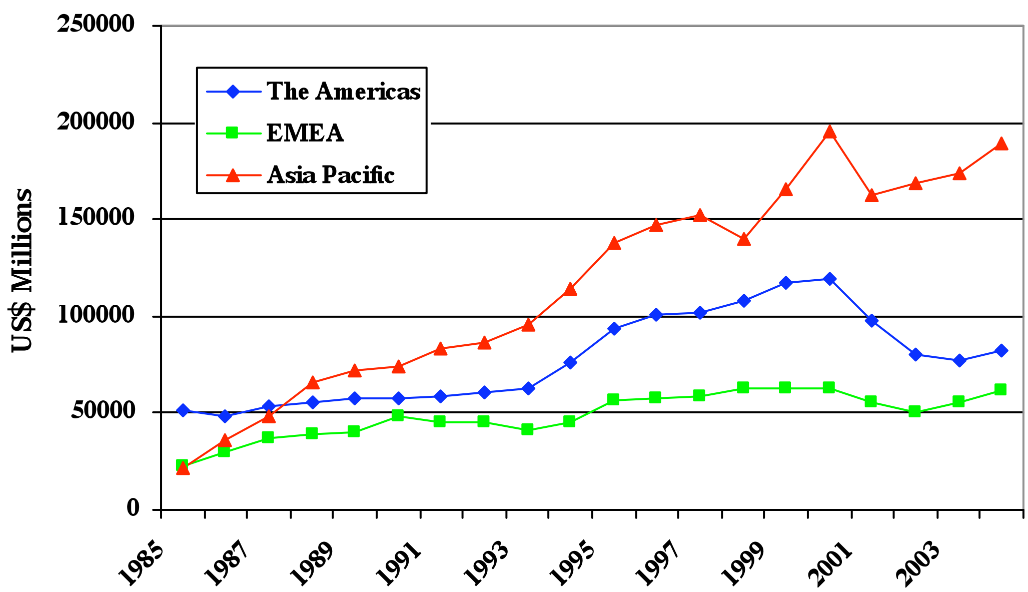
Some U.S. companies outsourced notebook production to Japanese, Taiwanese, and Korean manufacturers, but eventually shifted mostly to Taiwanese ODMs. In 2001, the Taiwanese government changed investment limitations for Taiwanese firms and the notebook industry moved *en masse* to the Yangtze River Delta near Shanghai.[7] Japanese firms such as Toshiba moved their own notebook production to the region to take advantage of the supply base, but also outsourced much of their production as well.

[6] 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; Dell is setting up final assembly in India.

[7] 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).

Chinese firms such as Lenovo used these same supply bases for their own production and outsourced some as well.[8]

Figure 6. Computer Hardware Production by Region, 1985-2004



Source: Reed Electronics Research (2005). 2004 data is a forecast. Includes parts and subassemblies such as base units that are specifically produced for use in computer equipment.

By 2005 China was the single largest producer of PCs and computer equipment overall 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.[9] 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/or 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% of all notebooks in the world in 2005 (Table 1), mostly in the Shanghai/Suzhou region of China.

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[8] This was the case with the IBM PC Company and Lenovo both before and after their integration.
[9] After IBM sold its PC Division to Lenovo, only Dell (among the U.S. PC companies) had its own final assembly plant in China. Dell's largest assembly site in Asia is still in Penang, Malaysia.

In the past the location of final assembly was driven by the need for in the U.S. 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.[10] For instance, low cost sea shipment of standard (not build-to-order) desktop PCs from China to the U.S., supported by more sophisticated demand forecasting and planning tools, allows PC makers to build a three-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 as the supply base is concentrated there.

IV. Globalization of Innovation

The location of NPD activities by the branded PC firms is driven by the product and process interdependencies discussed in Section II, the capabilities and relative costs of different locations, and relational factors that tend to "pull" innovation outside the PC vendor and/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"/analytical engineering work is done in the U.S., 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.

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

[10] Dell is the only U.S. PC maker who still assembles desktop PCs in the U.S.; most final assembly of notebooks is centralized in Malaysia. The subassemblies come from the Pearl River Valley (desktops) and the Yangtze River Delta (notebooks) in China. Dell also does final assembly in China and other major markets.

design, with the associated dynamic engineering skills, industrial design, and business/product management.[11] In terms of proximity, it is important to be located in leading markets where new technologies are developed and adopted first.

*Development f*or 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, electromagnetic interference, shock and vibration, power management, materials, radio frequency, 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. These are: (1) historical industrial development leading to creation of specialized skills, (2) output of educational systems, (3) 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 U.S., 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 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.

[11] Gereffi and Wadhwa (2006) distinguish between dynamic and transactional engineers, a classification that we find useful in characterizing the engineering work forces in different countries based on our interviews. Dynamic engineers are capable of abstract thinking and high-level problem solving using scientific knowledge, able to work in teams and work across international borders. These engineers have at least four-year degrees in engineering and are leaders in innovation. Transactional engineers have engineering fundamentals but not the skill to apply this knowledge to larger problems. They usually have less than four year degrees and are responsible for rote engineering tasks.

In Taiwan, mechanical and electrical engineers are available with strong practical experience as well as theoretical knowledge. 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 in 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 OEM/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 U.S. 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.

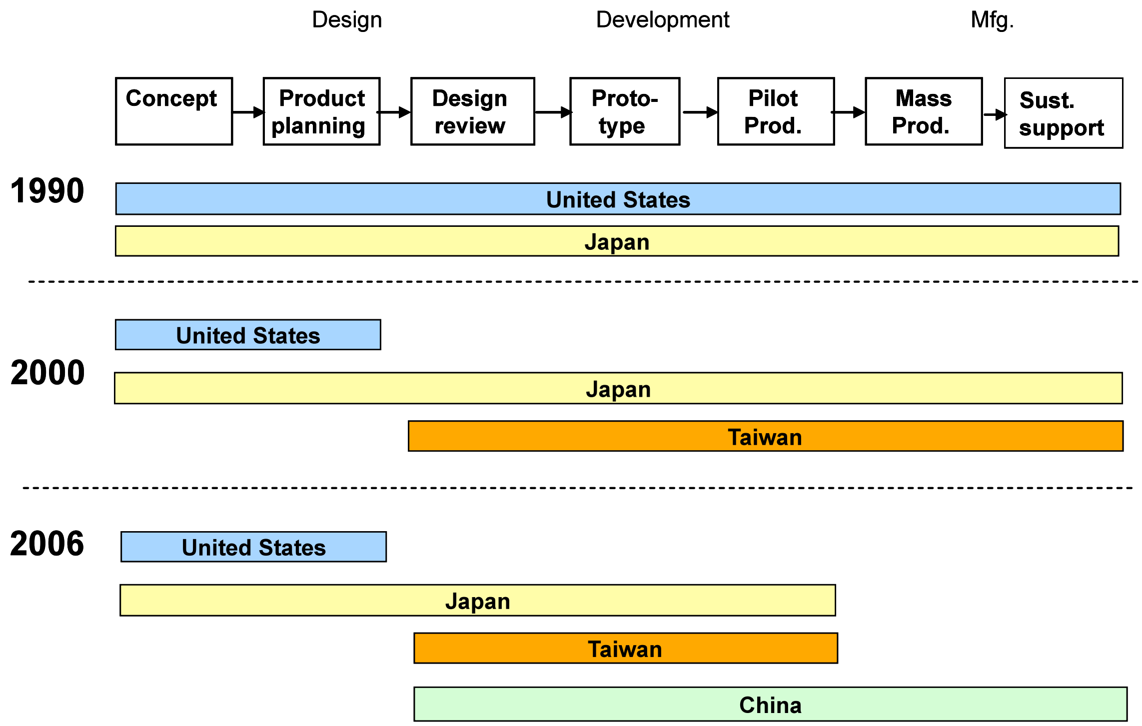
Based on a survey of Taiwanese PC and electronics firms, Lu and Liu (2004) found that the main reason these companies were moving R&D (primarily development) to China was the availability of well-educated and cost effective local engineers. This finding is supported by our own interviews with Taiwanese 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 U.S. (and Japan) in large vertically integrated companies like IBM, Hewlett-Packard, 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 U.S. 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, potentially speeding up NPD and 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 software development activities. This division of labor is similar for notebooks and desktops, although some U.S. companies keep desktop development in the U.S. and then outsource manufacturing to Asia. However, desktop development (which is much more limited, given the standardization of components and subassemblies) is being shifted to Taiwanese ODMs in many cases.

Figure7. New Global Division of Labor in PC Industry



The next critical development was the rapid shift of production to mainland China. Encouraged by U.S. PC vendors, Taiwanese manufacturers had moved production of desktops and many components and subassemblies to the Pearl 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 economics of the production bases in China as Japanese firms have previously tended to keep production in-house, either in Japan or 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 not only distinguished 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, 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 make it hard to develop 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 U.S. and Japan; applied R&D and development of new platforms in Taiwan; product development for mature products, and nearly all production and sustaining engineering[12] in China. It is difficult to estimate how long this division of labor will last. A recent study of

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[12] Sustaining engineering is the second of two phases in production: mass production and sustaining engineering. *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 2-3 year warranty period.

Taiwanese manufacturers (Li, 2006) shows that the rapid growth of low margin outsourcing business from foreign MNCs has provided Taiwanese firms with the resources and motivation to invest more in R&D in order to develop greater technology expertise and capture more high value design work. As the ODMs' expertise grows, MNCs 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 U.S. to Taiwan could continue. This is exemplified by the rapid growth of Taiwan design centers owned by HP and Dell.

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% of the world market for notebooks (Digitimes, 2006), while 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 mostly 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. 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 marekt 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 is available, often it is not sufficiently disaggregated at the firm level so that it can be tied to a product line such as PCs. This is especially true of multidivisional firms such as HP, Fujitsu, Toshiba, Hitachi, Samsung and Sony. Also, firm-level data does 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% in 1998 to 85% in 2005 (Table 1).

Table 1. Taiwanese Notebook Industry Share of Global Shipments, 1998-2005

	1998	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**
Shipments volume (thousands) [a]	6,088	9,703	12,708	14,161	18,380	25,238	33,340	50,500
Global market by volume (thousands)	15,610	19,816	24,437	25,747	30,033	37,857	46,110	59,411
Taiwan's share of global market volume	40%	49%	52%	55%	61%	66%	72%	85%

Sources: For 1998-2004, MIC (2005). For 2005, Digitimes (2006).

Notes: [a] Shipments by Taiwan-based firms, regardless of location of production

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 has increased significantly from 2000 to 2005 (Table 2), as has the proportion of employees with PhD and masters degrees in these firms. However, most of this R&D spending is on the development side rather than the research side.

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

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

Source: Annual reports of the companies.

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

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[13] spent 1.4% of revenues on R&D on average (weighted), the leading ODMs and CMs spent 1.3%, and the upstream suppliers,

[13] We could not get public estimates of R&D investment for the PC divisions of large multidivisional companies such as HP, Fujitsu, Toshiba, Sony and NEC so they are excluded from the table.

which is where innovation occurs in the PC industry, spent 11.8% on average or nearly nine times greater than the PC makers, ODMs and CMs.

Table 3. R&D Investment as Percent of Firm Revenues, 2005

PC Makers		**Taiwan ODMs & CMs**		**Component suppliers**	
	R&D as % of Revenue		**R&D as % of Revenue**		**R&D as % of Revenue**
Dell	0.9	Quanta	1.1	Microsoft	15.5
Apple	3.8	Compal	1.4	Intel	13.3
Gateway	n.a.	Wistron	1.6	AMD	19.6
Lenovo	1.7	Asustek	1.7	ATI Technology	14.7
Acer	0.1	Mitac	2.0	Seagate (HDD)	8.5
		Inventec	1.4	Western Digital (HDD)	6.6
		Arima*	2.8	Maxtor (HDD)	7.5
		ECS*	1.6	Chunghwa (Displays)	3.4
		FIC*	n.a.	Tatung (Displays)	2.6
		Clevo*	4.2	AU Optronics (Displays)	2.2
		Twinhead*	0.2	Molex (Cables/connectors)	5.2
		Uniwill*	1.6	Delta (Power supply)	4.8
		HonHai	1.0	Creative (Sound cards)	6.7
Total firm revenues (millions)	$92,535		$76,191		$128,773
R&D (% of revenues) for selected firms (weighted)	1.4		1.3		11.8

Source: Electronic Business Top 300 (2006), unless otherwise indicated. *Value calculated from data in company annual reports.

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

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.

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 above, for standard build-to-stock desktops, production is increasingly done in China for the U.S. market, as low cost shipping by sea is viable when fast order turnaround is not necessary.

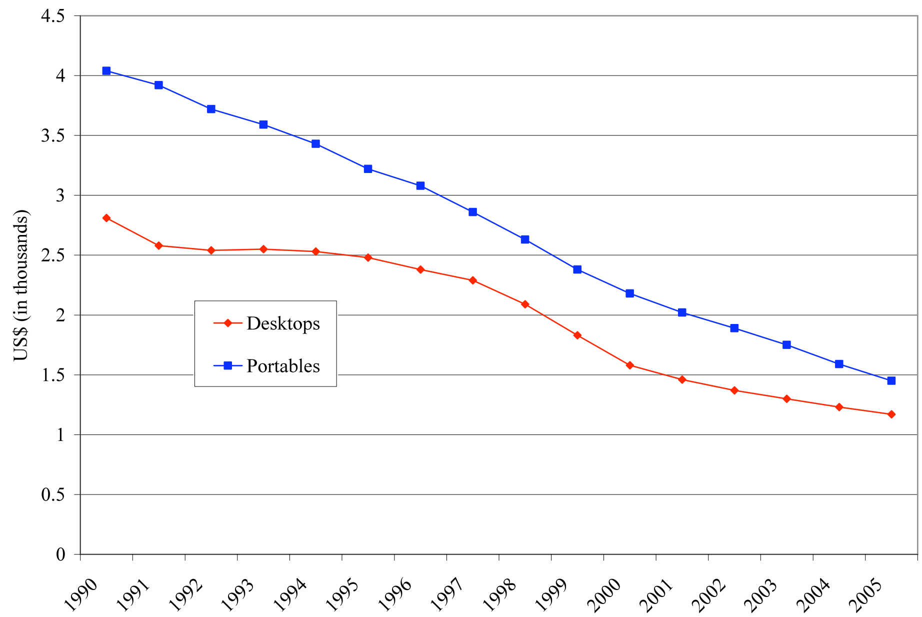
Cost was also the key factor for notebooks, where both development and manufacturing were outsourced or offshored almost from the beginning—first to Japan, then to Taiwan, and currently to China. Japan's capabilities with development and manufacturing of small form factors provided an initial pull, but 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 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, as 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 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 favoring 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 (AUP), and helping to expand markets. For example, the worldwide average unit price for a PC and monitor has declined markedly over the last fifteen years (Figure 8), with desktops and notebooks selling at an average of under $1,100 and $1,400, respectively in the U.S. 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 U.S. and other regions has declined so that there is now effectively one world price.

Figure 8. Average Unit Price, Desktops and Notebooks, 1990-2005



Source: Juliussen, 2006.

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.

V. Implications of Globalization of Innovation

The globalization of innovation has led to a new global division of labor, with higher value architectural design and business management, along with associated dynamic engineering work done in the U.S. and Japan, whereas much of the development and manufacturing of the physical product, along with related product and process engineering is done in Taiwan and increasingly in China. This new international structure of the PC industry has implications for firm competitiveness and strategy, location of innovation, employment, and U.S. policy.

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, they are leaders in hard drives, and PC vendors Dell, HP and Apple hold nearly 40% 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 [14]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 flow 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 above 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).[15] Some PC vendors complain that component innovation is

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[14] Acer, which has been a successful Taiwanese branded company, purchased Gateway Computer and Packard Bell in October 2007..

[15] As desktop PCs in particular have become commoditized, business model innovations such as direct sales, build-to-order and just in time inventory have provided temporary advantage in the industry. They

too fast, 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, 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 (Utterback, 1990; Henderson and Clark, 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., UK'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

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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 U.S. 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.

for the 1.8 inch hard drive; and with Taiwan's Inventec for manufacturing (Murtha, et al., forthcoming).

Table 4. Features of Incremental and Radical Innovation

	Design	**Development**	**Production**
Radical Innovation (iPod, iPhone, Treo)	-Set system architecture, sometimes building on external reference design -Strong central vision & industrial design -Tightly control all aspects of NPD -Develop key software internally -Integrate hardware, software, even services (e.g., iTunes, iTMS) -Design or license complementary assets (SW, content) and distribution system -Collaborate closely with a few key partners for core components	-Collaborate with many partners in multiple geographies. -Collaborate with partners of partners -Get partners to adapt existing technologies to proprietary architecture	Outsourced to CM or ODM
Incremental innovation (desktops, notebooks)	-Innovate on Wintel architecture -Control product planning, brand image, marketing, concept design internally -Internal or outsourced industrial design -HW and SW are modular -Leverage existing complementary resources and distribution	-Collaborate with one established ODM in one geography -Outsource detailed physical design, test and software built within standard architecture	Outsourced to ODM

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 eight 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 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% in both the personal music player and 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 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 start-ups 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 importantly, 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 U.S. 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 U.S. 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 WalMart to Google and MySpace, innovation on the web has largely occurred in the U.S.

By contrast, the relatively slow adoption of broadband and advanced mobile technologies in the U.S. 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 U.S. 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 U.S. 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 centralized in the U.S. 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, lead in particular technical innovations, or 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 U.S. or in a foreign subsidiary. In time, secondary benefits may also arise as these locations gain capabilities or local markets develop.

Other product development activities tend to be pulled by production, beginning with manufacturing process engineering and 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 newest generation 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 1990-2005. 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 in the future in order 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 U.S. 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 U.S. 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 2000-2005, 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% of the 1,000 employees are engineers and 80% of these are software engineers. These jobs are currently in the U.S., 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 U.S., the fact that growth and innovation in the industry is not creating new knowledge jobs (engineering, software, design) in the U.S. while 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 U.S. are that individuals, firms or related industries will lose technological advantage and ability to innovate. A recent 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, 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 U.S., 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 U.S., as long as the U.S. 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 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 U.S. and therefore consideration needs to be given to developing people with these skills if such innovation is to remain in the U.S. (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 U.S. (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 them 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 H1B visas, and/or for reform of the visa process. One issue involves procedures for keeping people who have been educated in the U.S. and perhaps interned with the firm. Another involves recruiting from abroad for skills where the U.S. supply of talent is limited, but other countries are noted for having people with the needed skills. For example, it appears that the supply of engineers in analog fields such as radio frequency in the U.S. 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, PhD) and there is no way to identify and respond to shortages of very specific skills or levels (e.g., bachelor vs. PhD).

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 U.S. 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 U.S. However, the U.S. 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 the U.S.

While specific policy issues with regard to telecommunications, Internet regulation, content and pricing are beyond the scope of this paper, those decisions 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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