Title

Impacts of Globalization and Offshoring on Engineering Employment in the Personal Computing Industry

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EXECUTIVE SUMMARY

Globalization has changed the nature, organization, and location of engineering work in the personal computing industry. As a consequence, lower skill and lower paid engineering jobs that might have been created in the U.S. are instead being created overseas, while higher skill and higher paid jobs remain in the U.S. The engineering work that remains in the U.S. requires skill in traditional engineering disciplines, as well as in the intersection of engineering and computer science, and in new specialties such as small form factor design, communications and networking, software engineering, and the interfaces between these. Software engineering in particular is becoming a greater part of engineering work in innovative new products such as smart phones and handheld devices which add functionality through tightly integrated hardware and software. For PCs and components, embedded software enables large scale, low cost production of standard physical products that can be provided with different features, tailored to particular markets, and continually updated to extend product life.

The nature of work done by branded PC makers has changed from physical engineering concerned with building, testing and mass production, to conceptual design, planning and product management, with physical engineering largely done outside the branded firms. The PC firms initially did all phases of new product development in-house, but subsequently outsourced manufacturing of desktops to contract manufacturers (CMs) in the major world regions and outsourced development <u>and</u> manufacturing of notebooks to original design manufacturers (ODMs), mainly in Taiwan. Today, much desktop development is also being handed off to ODMs.

As production and development was outsourced, the location of engineering jobs also shifted. For instance, notebook development and manufacturing was originally done mostly in Japan and in some cases in the U.S., but these activities steadily moved to Taiwan, which developed the required skills and had lower costs. More recently, Taiwanese ODMs have moved engineering work to mainland China for even lower costs and proximity to manufacturing.

Interviews with executives in charge of new product development in branded PC firms indicate that the jobs that remain in the U.S. are relatively small in number, and require highly skilled, innovative people with considerable experience. Accordingly, U.S. engineers earn high salaries, which have grown steadily in recent years, that commensurate with their skill, experience and productivity.

Historical data and national statistics on the entire computer industry show no significant change in the number of engineers since 2002. There is no comparable job data for the personal computing industry, per se. However, while the personal computing industry has continued to grow in scale and complexity, increasing the need for engineering work, it appears that there is little or no growth in engineering jobs in the U.S. This can partly be explained by the greater productivity of engineers, but also has been accompanied by a large increase in engineering jobs in the CMs and ODMs, especially in Taiwan and China.

Within this context, the nature of engineering work that remains in the U.S. is being shaped by the newer, smaller personal computing products such as wireless notebooks, tablet notebooks, PDAs, MP3 players, and smart phones. Such work requires not only knowledge about engineering design for small form factor, but also requires new engineering specialties related to communications, networking, embedded software, and particularly the interfaces between these and hardware engineering.

Interviewees in PC companies said that there was generally a good balance of supply and demand of engineers in the U.S., but pointed to shortages in experienced managers (product managers, engineering discipline managers, project managers, high level design mangers) and in particular, engineering sub-disciplines mentioned in the body of this report. While a few firms carefully develop engineers through sourcing from elite engineering schools, most of the PC firms source "experienced engineers" from other firms.

All firms interviewed source at least some engineers outside of the U.S., some primarily for cost, others for specialized knowledge. In some cases they hire engineers in offshore facilities, but more commonly they hire foreign-born engineers to work in the U.S., often from U.S. universities. All the executives considered U.S. immigration policies flawed in substance (failing to consider industry need, treating all engineering jobs/levels alike, making it difficult for graduates to stay in the U.S.) and in limits on the number of visas. On the other hand, most executives felt that the offshoring of lower skill engineering jobs was inevitable and that the U.S. should concentrate on maximizing its strengths in more dynamic and analytical skills to continue to lead in development and commercialization of innovation.

INTRODUCTION

The personal computing industry includes desktop and notebook PCs, PC-based servers, and various handheld computing devices such as PDAs, personal music players, and smart phones. Worldwide revenues for the PC industry totaled $213 billion in 2004, including $170 billion in desktop and notebook PCs, $27 billion in PC servers, and $16 billion in smart handheld devices (IDC, 2004). In addition, the PC industry accounts for a large share of the packaged software industry, whose sales were $214 billion, and also drives sales of IT services and of other hardware such as storage, peripherals, and network equipment.

In 2005, over 200 million PCs were shipped worldwide, including 135 million desktops and 65 million notebooks (IDC 2006). The largest market is the U.S., with 61 million units shipped, followed by Western Europe at 47 million, Asia-Pacific at 40 million and Japan at 14 million, with the rest of the world at 38 million. The U.S. is not only the leading market, but is home to the top two PC vendors, Dell and HP, and to Microsoft and Intel, who continue to set the key technology standards for the global industry. On the other hand, competition is increasingly global, with non-U.S. firms holding the next five spots (Table 1) since IBM's PC division was acquired by China's Lenovo in 2004.

TABLE 1. Worldwide PC Market Share, 2005

Company	Market share (%)
Dell*	18.2
HP*	15.7
Lenovo	6.3
Acer	4.7
Fujitsu/Fujitsu Siemens	4.1
Toshiba	3.5
NEC	2.9
Apple*	2.3
Gateway*	2.2
Sony	1.6

*U.S. companies; Source: IDC 2006

The fastest growing product categories are notebooks and various handheld devices, as the cost of key technologies such as displays has fallen and customers desire more mobile products. Such products as less standardized than desktop PCs and require more engineering effort in the new product development process. In addition, there has been a proliferation of PC models and form factors as vendors try to offer more choices to customers, which also increases the engineering requirements of the industry. Finally, PC-based servers account for the largest and fastest growing share of the server market, driving more engineering effort into getting cheaper hardware to handle the work formerly done by expensive proprietary systems.

Unlike the mainframe computer industry which consisted of vertically integrated firms, the structure of the PC industry is based on specialization, with most firms concentrating on one segment such as components, systems, software, distribution or services. Most PC makers have focused even further by outsourcing manufacturing, logistics, and other functions, while concentrating their own efforts on high-level design, marketing, and branding. Subassembly and then final assembly was outsourced to contract manufacturers starting in the early 1990s. For notebook PCs, some parts of the product development process were outsourced to Taiwanese companies that came to be referred to as “original design manufacturers” (ODMs).

PC makers that produce industry standard, or “Wintel” PCs, based on the Windows operating systems and Intel-compatible microprocessors have a limited scope of innovation. These products are based on hardware and software interface standards set by Microsoft and Intel, with all of the necessary components available from outside suppliers. Most of the R&D in the industry is done by component makers, including semiconductors, displays, hard drives and other storage, and software.

Yet while they do not generally create new technologies, PC makers play a critical role in their integration and adoption. PC makers decide which technologies are brought to market, in which combinations, and at what price. Although they have little choice in cases such as operating systems, where Microsoft drives adoption, PC makers have a critical role in choosing when to integrate and which standard to support (when multiple standards are being promoted, as is often the case). These choices about which innovations to integrate involve a combination of technical and market knowledge which PC companies must nurture in order to develop and produce successful products.

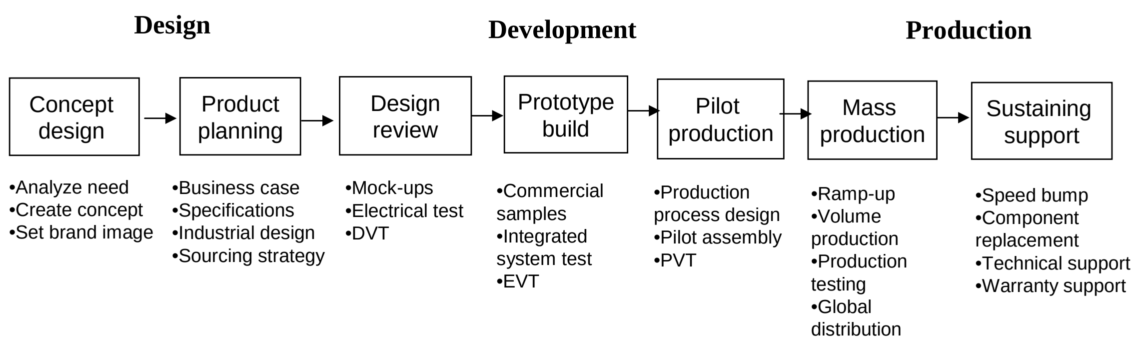
ENGINEERING WORK IN THE PC INDUSTRY

In the PC industry, most engineering work consists of new product development rather than R&D. Spending on R&D is just 0.9% of revenues for the leading PC maker, Dell. Number two ranked HP spends more as a company, but much of its R&D is concentrated on its printing business. Even companies such as Apple or Palm, who spend proportionately more on R&D, engage in more product development and integration of new technologies than research. Most core innovation in the industry is now at the component level, in semiconductors, displays, and hard drives. R&D efforts in the industry focus more on system engineering, power management, heat dissipation, software tools, and security and data protection (e.g., turning off the hard drive if a notebook PC is dropped).

There has been a shift in emphasis of engineering effort over the past decade as outside suppliers have provided standardized chipsets, integrated more functionality in the microprocessor, and developed standard motherboard designs. In the past, some PC companies were involved in the design of application specific integrated circuits (ASICs) but today these firms either use standard chip sets or work with chip design companies to customize ASICs for their products. Likewise, PC companies used to do their own board layout, but now they mostly use standard motherboards for desktops and outsource board layout for notebooks. Today, most engineering work in the industry involves new product development for desktop and notebook PCs, with a growing effort devoted to new products such as tablet PCs, blade servers, and smart handheld devices.

The product development process is quite standardized across the industry. As outlined by Wheelwright and Clark (1992), product development consists broadly of three phases: design, development, and production. The design, development, and production processes are further divided into specific activities, with outputs and gates to pass before proceeding to the next phase. Design refers to the process of envisioning and defining a new product based on those innovations and on customer needs. Development is the process of making and testing a working product based on the design. Production is building and shipping the product, which involves knowledge work in the form of process engineering, cost reduction, logistics, and other activities. Figure 1 illustrates the new product development process for notebook PCs.

FIGURE 1. Product Development Cycle for Notebook PCs



While the process has been standardized in the industry, the nature of the engineering effort varies significantly by product category. Developing a desktop product is primarily a problem of system integration, i.e., incorporating new technologies into products and ensuring that they work together. In terms of physical design, most desktop models are still based on industry standard form factors, such as the bulky but flexible mid-tower chassis. Also, there are standard motherboard designs available from Intel and various third-party manufacturers, and other components such as drives and add-on cards that are built to fit into standard enclosures. For desktops, the emphasis is on developing a new chassis upon which multiple models or stock keeping units (SKUs) can be designed for different markets and with different configurations. A PC company executive said that while the design of a new chassis takes around nine months, a new model based on an existing chassis could be built and tested in as little as two weeks. For instance, one vendor introduces as many as 1,000 different consumer desktop SKUs in one year globally. The relative ease of developing a new model of desktop makes this possible.

Notebook PCs have different characteristics that add complexity to the design and development process. Notebooks must be able to run on batteries, they incorporate the display as part of the unit, they must be lightweight yet very sturdy, plus they are more visible so users care about style as well as function. Components must be packaged very tightly into a product that is small, thin, light, portable, durable, and energy efficient, and which doesn't become too hot to handle from the heat generated in its operation. It also requires making choices and tradeoffs to optimize a number of factors (a bigger battery will run longer but add weight; more memory will improve performance but add cost; a faster processor increases speed but adds heat). New product development involves solving problems as new technologies are added or new form factors are introduced. Manufacturability is a major issue, as the product must be built in high volumes and at low cost, so final assembly must be a relatively simple process that allows packing components and subassemblies into a very tight space quickly and with a high level of reliability.

In non-Wintel products such as smart phones, iPods, or PDAs, there are no dominant technology architectures, and most products are unique to a particular company. More fundamental design choices must be made, such as selection of core components and operating systems, knowledge is more tacit, and collaboration across engineering disciplines is more important. This is especially true for convergence products such as smart phones or other mobile products.

Skill Requirements

The skill requirements for each stage of product development are quite different (Figure 2). The design stage requires people who know markets and customer demand, as well as engineers who understand technology trends. There is also a need for engineers who can talk to the marketing people and understand how customer demand and technology trends converge. These are usually engineers who have moved into product management. They generally have both experience and advanced degrees. The teams who develop new product concepts and manage them through to fruition often include a software engineer, cost engineer, and technical product manager, as well as a general project manager and people with business skills such as finance and marketing. Another key skill at this stage is industrial design, which is taught in universities, but is said to require a strong sense of the aesthetics of a particular market.

FIGURE 2. Engineering Skills Required in the PC Industry

Function	R&D	NEW PRODUCT DEVELOPMENT		
		Design →	**Development** →	**Production**
Engineering skills	Materials Electrical Electronic Software	Industrial design Hardware Software Product mgmt	Hardware Mechanical Electrical Electronic Software Technical mgmt	Industrial eng Quality Mfg mgmt

At the development stage, a variety of engineering skills are required, primarily in mechanical, electronic and electrical engineering, PCB layout, and software engineering. For notebook PCs, specialized skills are needed in thermal dissipation, EMC, acoustic, shock and vibration, power management, materials, and radio frequency. For communications products such as smart phones, skills in radio frequency and software control of telephonic components are more critical. These require a combination of formal training and experience working in a particular specialty.

At the production stage, the skills required are mainly industrial engineering, quality assurance, manufacturing management, and logistics. In addition, there is sustaining engineering, which

involves supporting products after they are in volume production to handle mid-life upgrades (e.g. adding a faster processor), end-of-life components, or problems that show up in the field.
In addition to technical skills, firms look for the ability to work in teams that may include engineers from different disciplines as well as marketing people, product managers and other non-engineering professionals. These are particularly important in the design stage, and throughout development of new product categories, where roadmaps are not clear and activities involve a mix of art and science, or what one company refers to as the “zen” of design. This design sense is something that is transferred by working closely in teams led by “zen masters” who have the sense of what features to include and what to leave out.

Experience Requirements
Some firms look primarily for experienced engineers in order to avoid the cost of training and to get immediate productivity. One executive said, “Over the last 15 years, the industry has become so competitive that we have to hire mostly experienced people; we can’t wait for junior engineers to learn. We still recruit at colleges but not as much as in the past. It used to be 10-15 new hires a year, now it is more like 2 per year. Nowadays, engineers get into the field and keep moving around in order to learn.”

On the other hand, an executive from a nearby competitor said that he liked to hire engineers right out of college, and had set up an internship program with six universities to give experience to students during their summer breaks. Interns are placed into core design teams right away and after a couple of years are “very self-assured.” Most of these students spend two or three summers working with the company. Over half are offered jobs after graduating, as managers have to commit to create openings, and nearly all accept unless they are going on to graduate school.

A similar view of the value of new graduates was expressed by a component maker executive who runs an R&D organization. He said that most of his new hires are new PhDs in their first jobs. He prefers to hire people without experience in manufacturing or development because they “don’t know that some things can’t be done.” If they go into manufacturing or development first, they will too often feel that things can’t be done. His company wants people who are not “burdened by experience.”

At the other end of the spectrum, there is a big need for experienced engineering managers to run projects and departments. Interviewees reported that there is a shortage of experienced engineering managers in the U.S. and that the shortage is even more acute outside the U.S. Interviewees defined two types of engineering managers. One group is engineering supervisors who manage the engineering teams. The other is technical program managers whose responsibility is to get products to market; they do not necessarily have deep technical knowledge, but are good planners and organizers. The very best are deep in the technology or in understanding the market and how a product will actually function in a market. They have to deal with the problems of getting various internal organizations (e.g., engineering, manufacturing, product managers) to work on one product plus outside firms (ODMs and component suppliers). According to one executive, “They have to be able to whip people into order.”

Changing Requirements

The firms interviewed reported that an increasing share of engineering jobs are in software engineering, a trend that is not so obvious in government employment data for the computer industry (Table 2), but is evident in the survey data from the firms (Appendix Table A). More software engineering is needed because more functionality in many products is being located in software rather than hardware, including smart phones, music players, and even hard disk drives, where drives are customized for different clients with software rather than hardware.

Another point made by interviewees was the need for people with both software and hardware skills. This is especially true for emerging products that involve close integration of software and hardware functions such as smart phones and other handheld devices with communications capabilities. For instance, a smart phone may support multiple radio frequencies (e.g., GSM, CDMA, WiFi), and a number of applications such as e-mail, instant messaging, and web browsing, and the formatting of the bit structure from the applications is different for each radio protocol. Plus, software for many products must be written to fit and run on specific integrated circuits. This is in contrast to the PC, in which software applications can run on any Intel-compatible hardware running Windows via Windows application programming interfaces, making software development largely independent of specific hardware configurations.

Examples of skills needed include software engineers who know telephony and how communication networks function, or electrical engineers who know how software controls telephony functions on a smart phone, or engineers who can program a microprocessor to communicate with the network. These skills now have to be taught on the job, as few universities have programs that combine computer science and electrical engineering training.

Productivity and Demand for Engineers

The productivity of engineers has improved steadily, so fewer engineering resources are needed per model/SKU (Number of engineers/SKU is used as a productivity measure by some PC makers). However, because of the growth of the industry and the proliferation of SKUs, demand for engineers has grown. For instance, ten years ago one PC company reported having 50 engineers shipping 50-75 SKUs per year in consumer desktops. Today they have 165 people shipping 1,000-1,200 SKUs per year; part of this productivity is due to the use of CAD tools, but it also is due to the increased outsourcing of development to ODMs. In spite of outsourcing and increased productivity, the demand for engineers in the PC companies has still grown.

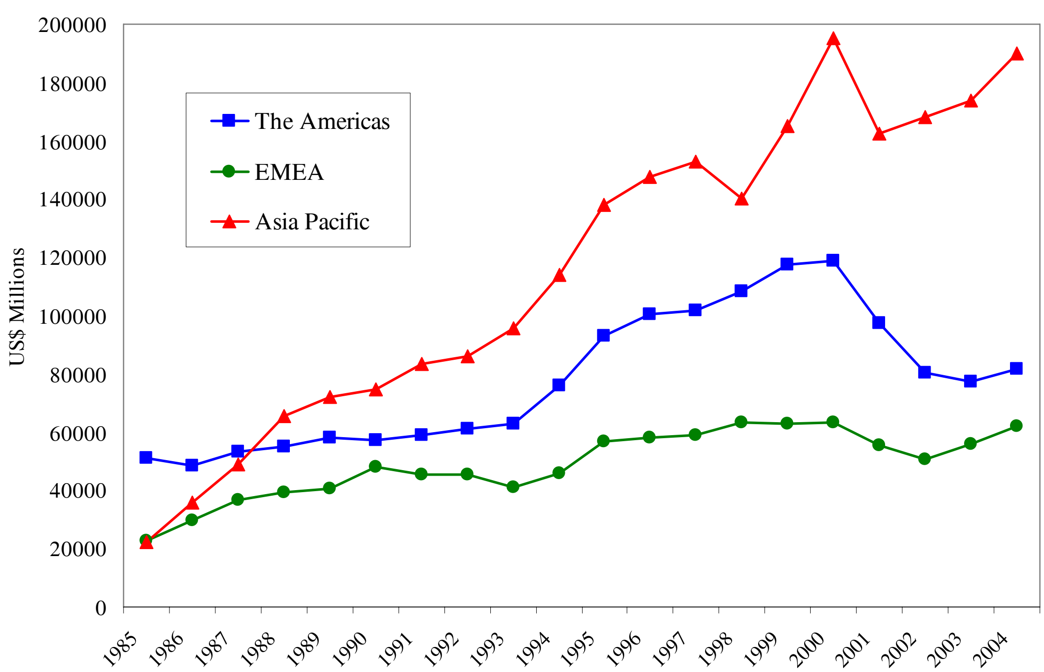
GLOBALIZATION OF THE INDUSTRY

The personal computing industry is highly globalized, with final assembly in dozens of countries, but manufacturing is increasingly concentrated in the Asia-Pacific region (Figure 3). The globalization of the industry was present almost from its inception in the late 1970s, as early PC makers sourced a number of components from Asian suppliers. Later in the 1980s, leading PC makers such as IBM, Compaq, Apple and Dell set up assembly operations for desktops and notebooks offshore, with production in each major world region (including Ireland, Scotland, and France for Europe; Malaysia and Singapore for Asia Pacific; and Mexico for the Americas).

Subassemblies such as motherboards and base units were sourced from Asian suppliers or U.S. contract manufacturers who located production near the major vendors. Final assembly also has been increasingly outsourced to CMs and ODMs, with time-critical build-to-order production located in regional markets and less time-sensitive build-to-forecast production mostly in China.

U.S. PC makers began moving notebook production offshore in the early 1990s. Taiwan developed a homegrown industry focused on notebook PC production, led by a set of ODMs such as Quanta and Compal, who developed specialized technical knowledge in issues critical to notebook performance such as battery life, heat dispersion, rugged mechanicals, and electromagnetic interference. Production was in Taiwan or Southeast Asia, but as pricing pressure increased on the ODMs, the Taiwan government removed restrictions on manufacturing notebooks in China, and the Taiwanese notebook industry moved *en masse* to the Shanghai/Suzhou area of eastern China. By 2005, over 80% of the world's notebook computers were produced by Taiwanese firms, almost entirely in China (Digitimes, 2006).

FIGURE 3. Computer Hardware Production by Region



Source: Reed Electronics Research, 2005

Offshoring and Outsourcing of New Product Development

The branded U.S. PC makers did product development in-house and onshore in the 1980s, but in the notebook market they fell behind Japanese competitors who had superior skills in miniaturizing components and developing small, light, thin products. IBM reacted to Japanese competition by moving notebook development to its IBM Japan subsidiary, which came up with the very successful Thinkpad design. Compaq worked with Japan's Citizen Watch Co. to engineer its notebooks and produce key subassemblies. Apple contracted with Sony for one of the original Powerbook models (Business Week, 1991).

In time, however, most PC makers turned to Taiwanese ODMs for manufacturing, partly due to lower costs and also to avoid dependence on Japanese partners who could become competitors. The ODMs gradually developed specialized engineering skills and began to take over product development as well. Companies such as Dell and Gateway were able to enter the notebook market by working with the ODMs on design and development, taking advantage of capabilities nurtured by their competitors.

A major factor influencing the move to outsourcing development was a “pull” from the ODMs. Taiwanese ODMs often did not charge explicitly for development, but did it in order to win production contracts (interviews in Taiwan and China). In addition, once the ODM had a contract, the relationship created incentives for the PC maker to work with the same ODM for future upgrades and enhancements to the product. There was a great deal of tacit knowledge created in the development process that was known only by the ODM. In addition, the close linkage of development activities to manufacturing and the feedback to design from manufacturing and sustaining support, created linkages that favored the continual ODM relationship in order to reduce costs and improve quality.

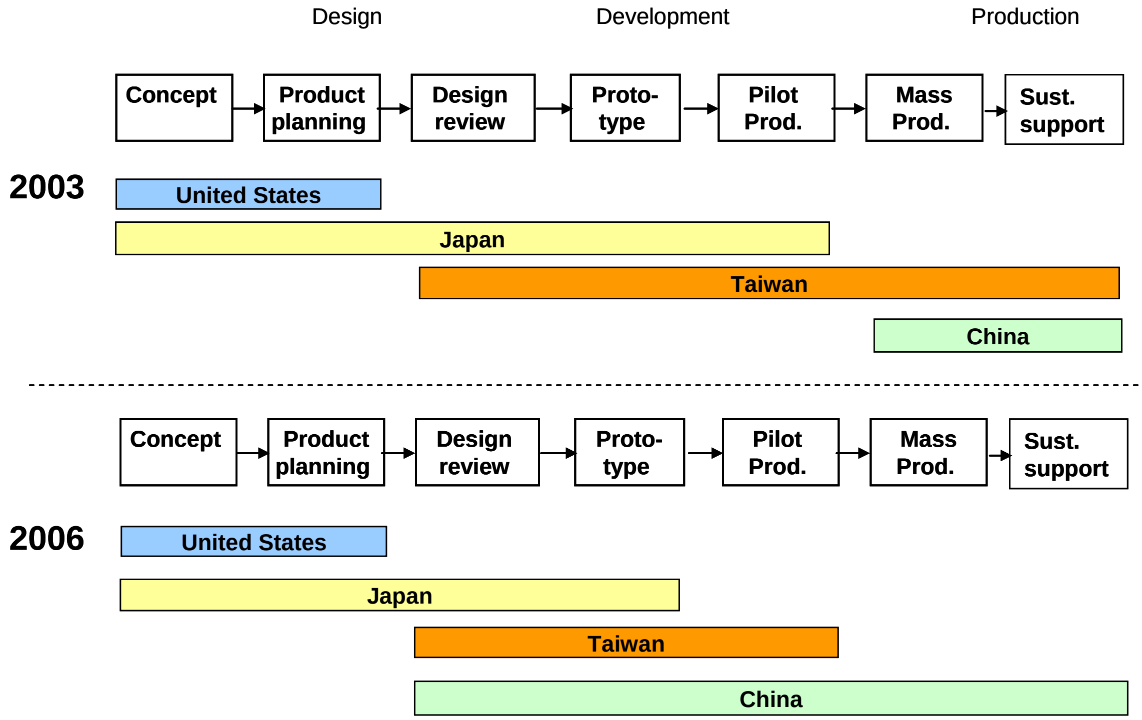
Beyond the pull from ODMs, there has been a “push” offshore by PC vendors. Some PC makers (notably Dell and HP) have set up their own design centers in Taiwan in recent years, thus offshoring some detailed system design, while keeping concept design and system architecture in-house. The motivations were multiple: lower cost engineers and programmers, faster development by having test facilities nearby, availability of experienced engineers, government tax incentives, and closeness to emerging markets in Asia. Also, by being close to the ODMs, the design center can send personnel to the ODM for problem solving and use the ODMs testing facilities. Taiwan also has a skilled and experienced pool of engineers that are less expensive than their U.S. counterparts, and the Taiwanese government provides incentives to attract design centers.

As for the ODMs, they have been moving engineering work to China along with manufacturing. Their design teams in Taiwan are still responsible for the development of advanced technologies and new products that provide competitive advantage. As these products mature, development of product variations, incremental improvement, and life cycle support has moved to China to be close to manufacturing and to take advantage of lower costs.

As Figure 4 shows, notebook PC makers and ODMs have shifted more new product development activities from Taiwan to China, a trend that is driven both by the cost of engineers in China and the value of proximity to manufacturing. Lu and Liu (2004) found that after access to engineers, the second major factor for R&D activities is proximity to the manufacturing site. For notebooks and other products where design-for-manufacturability is very important, it is valuable to be able to build and test prototype on the actual final assembly line. Also, the time frame for ramping up to mass production has been cut dramatically along with overall product cycles as firms try to introduce new technologies quickly and avoid product obsolescence. This means that critical manufacturing processes and equipment (particularly tooling equipment) must be in place at the manufacturing site to begin volume production almost immediately after the design is finalized. ODMs save both time and money by having both pilot and mass production in China. A key decision is whether to move expensive testing equipment to China; once this happens, it is cost effective to move more development as well, even if this means bringing in experienced engineers from Taiwan for a year or more to lead development teams there.

The shift of development to Taiwan and China depends not only on the stage of the activity but on the maturity of the product as well. The Taiwan design centers of U.S. PC makers are mostly involved in developing new models based on existing product platforms, while development of new form factors or incorporation of new technologies is still led by teams in the U.S. Taiwanese ODMs tend to keep development of new product generations in Taiwan, where they have close working relationships with key component suppliers such as Intel. They are more likely to move development of older generation products to China.

FIGURE 4. Shifting Location of Notebook PC Product Development



Source: Market Intelligence Center, Institute for Information Industry, Taiwan

The activities that are not being moved from the U.S., and do not appear likely to move in the near future are R&D, concept design, and product planning. R&D tends to be concentrated in the home country for any company, whether American, Japanese, Korean or other. Product design benefits from proximity to leading markets where new innovations are first adopted. As long as the U.S. remains the leading market for new innovations in the PC industry, and its companies remain leaders in the industry, it is likely that these functions will remain mostly in the U.S. While R&D activity is not large in the PC industry, design and product planning continue to expand with the growth in the market and rapid innovation in upstream technologies. Some of this work is moving to Taiwan, especially for notebooks, but most is still concentrated in the U.S. The story is different for foreign PC makers such as Lenovo, Acer, Fujitsu, and Toshiba, but even Lenovo has left concept design and product planning for the global Thinkpad line in North Carolina since its acquisition of IBM's PC business.

U.S. ENGINEERING WORK FORCE IN THE PC INDUSTRY

The engineering work force in the entire computer industry, for which we have data from the U.S. government, appears to be stable, holding at about 60,000 from 2002 to 2005 (Table 2). For earlier years, the Bureau of Labor Statistics employment data is based on the broader category of Computers and Office Equipment, and so is not comparable in absolute terms, but the pattern of stable employment levels is also seen from 1999 to 2001. About half of the engineers are in the two categories of computer software engineers, with applications engineering seeing the largest growth in total employment, from 10,250 to 12,800. The biggest losses have been in electrical and electronics engineers, where a combined 2,500 jobs were lost. These changes may reflect the shift in engineering effort from hardware to software reported by interviewees.

TABLE 2. Employment of Selected Engineering Occupations in the Computer Industry, 2002-2005[1]

	2002	2003	2004	2005
Computer software engineers-applications (15-1031)	10,250	9,890	12,110	12,800
Computer software engineers – systems software (15-1032)	18,809	18,148	19,430	18,240
Computer hardware engineers (17-2061)	11,140	12,030	11,880	12,940
Electrical engineers (17-2071)	4,580	4,020	3,200	2,900
Electronics engineers, except computer (17-2072)	4,360	4,030	3,490	3,710
Industrial engineers (17-2112)	3,520	3,640	3,570	3,430
Mechanical engineers (17-2140)	2,100	2,470	2,160	2,280
Engineering managers (11-9041)	5,270	5,460	5,690	5,630
Industrial designers (27-1021)	260	290	190	180
Total	60,289	59,978	61,720	62,110

[1] Computer industry is defined as NAICS 334100 (Computer and Peripheral Equipment Manufacturing). Data from years prior to 2002 is based on SIC code 357 (Computer and Office Equipment) which is incompatible.
Source: Bureau of Labor Statistics, Occupational Employment Statistics http://www.bls.gov/oes/home.htm

In the U.S., we also see that salaries in the computer industry have risen in every engineering occupation (Table 3) since 2002, a pattern also seen in the broader industry category for 1999 to 2001. In the PC industry, our interviews suggested that engineering salaries grew rapidly in the late-1990s dot.com boom, then stagnated and have recently begun to rise again. This suggests that foreign competition is not driving down salaries in the U.S. as has been feared. It also may show that U.S. engineering resources are shifting to higher value activities and that engineers are in fact becoming more productive, both of which would support higher salaries for engineers.

Compared to other major computer producing countries, U.S. engineering salaries are very high. For all engineering categories, including technicians, the average salary is $78,210 (Bureau of Labor Statistics, 2005), while the salaries for engineering professions that require four-year degrees are over $90,000 (Table 3).

TABLE 3. Mean Annual Wage of Selected Engineering Occupations in the Computer Industry, 1999-2005[1]

	1999	2000	2001	2002	2003	2004	2005
Computer software engineers-applications	$70,630	$74,350	$78,240	$81,270	$85,570	$95,180	$94,760
Computer software engineers – systems software	$70,150	$76,130	$81,180			$91,430	$92,030
Computer hardware engineers	$74,880	$78,760	$83,940	$82,820	$96,540	$96,980	$94,690
Electrical engineers	$67,030	$71,870	$73,210	$75,490	$80,180	$82,810	$84,820
Electronics engineers, except computer	$68,920	$70,940	$75,580	$76,930	$81,320	$85,270	$86,330
Industrial engineers	$61,660	$64,070	$68,910	$73,330	$76,210	$77,480	$77,710
Mechanical engineers	$59,830	$64,810	$67,310	$68,460	$73,620	$77,250	$78,740
Engineering managers	$97,380	$104,550	$107,290	$125,080	$128,470	$129,450	$130,020
Industrial designers	$59,570	$63,480	$65,180	$66,070	$80,280	$91,850	$94,800

[1] Computer industry is defined as SIC 357 (Computer and Office Equipment) for the years 1999-2001; NAICS 334100 (Computer and Peripheral Equipment Manufacturing) for 2002, November 2003 and November 2004. While industry definitions are different, occupational definitions are the same, so we include data from the entire 1999-2005 period to show trends in salaries.

To compare with other 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 (Tables 4 and 5). It is reported that engineering salaries are rising fast 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.

TABLE 4. Comparative Costs of Electronic Engineers by Location

	Average base salary
United States	$78,000
Japan	$63,000
Taiwan	$20,000
China	$10,000

Source: For U.S., Bureau of Labor Statistics Occupational Employment Statistics. For Japan, Quan (2002). For Taiwan, EE Times (2003) and interviews with ODMs in Taiwan. For China, PR Newswire (2004) and interviews with PC makers and ODMs in Taiwan and China.

TABLE 5. Engineering Salaries in China by Home Base of Notebook PC Company

Company home base	Base salaries paid in China
U.S.	$15,000 (6-7 years experience) $7500 (new graduates)
Japan or Europe	Similar to U.S. companies
Taiwan	$5,000 (new graduates)
China	$5,000 (new graduates)

Source: Interviews with PC makers and ODMs in China, Taiwan and Japan

SKILL AVAILABILITY IN THE U.S. AND OTHER COUNTRIES

There is limited national data on production and availability of engineers in different countries, and there are problems with compatibility of definitions, as a Duke University study (Gereffi and Wadhwa, 2006) of engineering graduates in the U.S., China and India showed. There is no national data we are aware of on availability of engineers with skills in specific specialties such as electrical, mechanical, industrial, or software, so we must rely on interviews, the small survey of companies we interviewed, and other qualitative information.

Gereffi and Wadhwa 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.

United States

In our interviews, engineering managers and executives of U.S. companies have described engineers in the U.S. and elsewhere using expressions very much like Gereffi and Wadhwa, with some additional distinctions at the country level. In general, U.S. engineers are more dynamic, analytical, and able to lead the innovation process.

The team culture in most firms means that most engineers understand practices such as working in cross-functional teams and project management. Even new graduates have been trained to work in teams during their university education. Also, outsourcing offshore has meant that many engineers have gained some international experience, as U.S. firms often send engineering teams to Asia to work with local development teams, sometimes for weeks or months at a time.

In addition, there are a large number of immigrants who have earned degrees in the U.S. and stayed in the country to work for U.S. firms. These individuals have knowledge of their home countries and are often chosen to work with engineering teams in those countries. The entrepreneurial culture of the U.S. means that many engineers have gained business experience by working in product development teams or by being involved in start-up companies. These skills are critical in the early design process when matching technology roadmaps with market demand to develop new products is done, and they are skills that are not easily replicated in less entrepreneurial environments, or farther from leading markets.

Taiwan

In Taiwan there is a mix of dynamic and transactional engineers, including many mechanical and electrical engineers with strong hands-on experience. In particular, Taiwan has the deepest pool of notebook PC developers in the world. Taiwan also has extensive experience developing other products such as PC motherboards, optical drives, low-end network devices, and add-on cards, and its ODMs are moving into the mobile phone business in large volumes.

Taiwan's engineers learn mostly on the job, and develop great depth in specific disciplines such as EMI, board layout, thermal, and power management. Engineers coming out of Taiwanese universities are said to lack the analytical skills of their U.S. counterparts—skills that are important for working with key component suppliers to define new product architectures. They also have poor understanding of international markets and generally lack the ability to design successful products on their own. On the other hand, there are strong managers and team leaders able to manage their own parts of a project and to work effectively with different PC makers.

China

Chinese engineers mostly fit the Duke study's category of transactional engineers, even if they have four-year degrees. 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."

Chinese mechanical and electronic design engineers are well-trained, but lack the hands-on skills that come with experience. They are gaining this experience and are also receiving significant training on the job from both multinational and Taiwanese employers. One major ODM offers free training courses to engineers and brings in Taiwanese engineers to teach. They also work with local universities to develop courses in skills that they need. In the words of an ODM manager, "China is a gold mine of human resources, but if you don't train them, you won't be able to take advantage of it." An American executive was equally enthusiastic, "The average might not be high, but there are so many that the cream of the crop must be very good. Chinese engineers feel ownership of the product, pride in it. American engineers will work their tails off on a project if they believe in it passionately, then will want to take off to go skiing or something. The Chinese will just move on to next project."

China lacks strong design skills and marketing knowledge, especially for foreign markets, but its domestic companies are trying to develop those skills to create products for the fast-growing China market. Also, one interviewee noted that Taiwanese companies are making long-term investments in training Chinese engineers and other professionals, and he expected that his U.S. company would move some of its own development to China as those skills were developed.

Japan

In Japan, there are industrial designers that are very good at designing for the Japanese market, but also can create products for the U.S. market if they interact with U.S. design and marketing people. Good examples are the IBM Thinkpad line and the successful Toshiba and Sony notebook products. Japan's PC market is over 50% notebooks, and many products are developed specifically for that demanding market; as a result Japanese design and development teams have great depth of skills in all design and development areas. They also are very strong in design-for-manufacturability, as most Japanese firms do their own design, development and manufacturing (although an increasing amount of lower value PCs and other products are being outsourced to Taiwanese companies).

IMPACTS OF OFFSHORING ON U.S. ENGINEERING EMPLOYMENT

Engineering employment in the U.S. computer industry has remained stable in recent years (Table 2) in spite of the offshoring of new product development. One interpretation is that the offshoring process may have been well established by the late 1990s and has not greatly affected U.S. engineering employment since then. By 2000, U.S. PC makers had either outsourced development and manufacturing to ODMs, or in the case of IBM, had assigned development to teams in Japan and had manufacturing outside the U.S. As a result, much of the hardware engineering, mechanical, electrical and electronic engineering required for product development was already offshore, as was the industrial engineering associated with manufacturing. What was left in the U.S. was software engineering, engineering management, and relatively small numbers of jobs in the various hardware, mechanical, and electrical disciplines needed to support product design and management.

One result of the offshoring of notebook PC development is that capabilities have been created in Taiwan such as design for manufacturability and designing for small form factors that can be applied to new product categories such as handheld devices, smart phones, and digital music players. The fact that engineering employment is not growing in the computer industry during a time of rapid growth in demand and a proliferation of products and models likely means that more engineering is being done outside the U.S. The ODMs that gained capabilities in the PC industry are now also becoming major suppliers of mobile phones and are likely to become involved in more mobile consumer devices.

What is Moving Offshore?

Reports and data from our interviews show that the Taiwanese CMs and ODMs are rapidly expanding their engineering capabilities. According to our interviews, the largest notebook ODM, Quanta, employed about 7,000 engineers in Taiwan and 3,000 in China as of 2004. It since has opened a large new R&D facility outside Taipei which is expected to eventually house

6,000 engineers. Other ODMs also have increased their engineering resources as they take over most of the development and production of the world's notebook industry. Other ODMs have several hundred engineers apiece in China and are increasing their scope of activities there. One interviewee at a U.S. PC maker estimated that the ratio of in-house to ODM engineers on its development projects is about 1:3 for consumer desktops, but closer to 1:1 for notebooks and commercial desktops. A smaller PC maker, by contrast, had only 20 engineers overseeing the ODMs who develop all of its products.

What has mostly moved offshore is "transactional" engineering work, including board layout, tooling, electrical and mechanical engineering, and software testing. These require engineering skills and experience in specific areas such as power management, EMC, and heat dispersion. Also, engineering work related to manufacturing is mostly offshore, with just some high-level industrial and process engineers in the U.S. to oversee manufacturing and travel to Asia to help solve problems when necessary. These jobs do not require great analytical skills or "dynamic" individuals, but a large share of the engineering work required for new product development is in these categories, so numbers of engineers offshore can be very high.

For instance, the world's largest EMS, Foxconn, is said to have 10,000 tooling engineers, including 2,000 designers (Datamonitor, 2005). Many of these may be technicians with less than a four-year degree, but it shows how a Taiwanese company can employ large numbers of low-cost engineers for more routine work which needs to be done very quickly to bring high volume production online. As one U.S. executive stated, "We don't do much PCB layout, tooling or testing any more. You can't compete with the large numbers of Asian engineers for that kind of work. The U.S. can't compete on numbers of engineers. We have to take what we're great at in the U.S. and leverage the rest of the world's skills."

What is Not Moving Offshore?

More advanced engineering work is less vulnerable to offshoring. Taiwanese and Chinese engineers and companies are considered weaker in system level design and in software. In addition, they lack the ability to develop an entirely new product that is likely to appeal to the U.S. market. Every notebook vendor we have interviewed agreed that they cannot turn over concept design, product management or product architecture to an ODM, and that they only buy an off-the-shelf design from an ODM for low end products or when they need something to fill out a product line very quickly. On the other hand, one PC maker said that they only need a relatively small number of engineers for these tasks; even though they are critical activities, they are not necessarily where the bulk of the engineering work is. This is captured in the comments of two top engineering executives at U.S. PC companies.

"The jobs that are really important and are in the U.S. involve product architecture where you need senior engineers; hardware and software engineers generally; and mechanical engineers and industrial design people."

"The core of the design process is in the US. We define the product--how it looks, how it will be assembled, materials used, features and technologies to incorporate. We determine the mechanical and electrical architecture."

Also less vulnerable to offshoring is R&D. R&D depends on high level researchers with advanced degrees, often PhDs, and is kept in the U.S. because of strategic importance and the need to protect intellectual property. Unlike product development, there is little interdependence between R&D and manufacturing, so R&D jobs do not feel an offshore "pull" from manufacturing. R&D requires highly specific skills, so the key is finding those people. If they happen to be offshore, it is more likely that firms will bring them to the U.S., or will hire foreign graduates of U.S. universities. For instance, one component maker has 150 researchers at its R&D lab in the U.S., about half of which are from outside the U.S. While companies in other industry segments, such as Intel and IBM, have R&D labs outside the U.S., this is not the case in the U.S. PC industry.

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APPENDIX TABLE A. Survey Results for Different Job Categories (5 companies interviewed)

Engineering job category	**Major activity where this skill is used**	**Demand for engineers**	**Availability in U.S.**	**Availability in other locations where you do this activity***	**Cost and quality relative to U.S.***
Engineering managers	R&D, design, development	Stable or growing	Tight	Tight or enough	Lower cost, lower quality
Engineering product managers	Design, development	Stable	Tight or enough	Tight or enough	Lower cost, same quality
Hardware engineers	Design, development	Stable	Tight or enough	Enough	Lower cost, same or lower quality
Electrical engineers	R&D, design, development	Falling or growing	Tight or enough	Enough	Lower cost, same or lower quality
Electronic engineers	Development	Falling	Tight or enough	Enough	Lower cost, same or lower quality
Mechanical engineers	R&D, design, development	Stable or growing	Tight or enough	Enough	Lower cost, same or lower quality
Software Engineers	R&D, design, development	Growing	Tight	Tight or enough	Lower cost, same or lower quality
Industrial engineers	Manufacturing	N/A**	N/A**	Enough	Lower cost, same quality
Industrial designers	Design	Stable	Enough	Enough	Lower cost, lower quality

* Responses regarding availability, cost and quality of some skills in other locations vary by firm, depending on where they are doing these activities. We report one response when there was general consensus, more than one if there are different responses. Other locations included Singapore, Taiwan, Malaysia, Ireland.

** Firms interviewed had no manufacturing in the U.S., so demand and availability of industrial engineers was not relevant.

Note: Names of firms are confidential. Four were personal computing companies and one a component supplier.