Building a Technocracy in China: Semiconductors and Security

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China's capacity to surprise is great, and so too is the necessity for reasoned assessments of its economic, social, and political trajectory. This chapter focuses on one important aspect of China's rise and future capacity to provide regional and international leadership. The country's current leaders certainly view the expansion of the indigenous semiconductor industry as a key strategic priority. They seek the capability to design and manufacture state-of-the-art semiconductors, the microchips at the core of computers, electronics, telecommunications, weapons systems and much more.[1] In this light, our research concentrates on the growth of the base for <u>applied research</u> in this sector.[2] The building of such a base is a crucial step in the value-added innovation-production chain. In its absence, only lower level assembly and manufacturing operations are possible; in its presence, we may catch an early glimpse of an emerging innovation system capable someday of shifting global structures of industrial power.

Larger issues of inter-state policy interaction inform our research. Standard theories of systemic power balancing and power transition are ill-equipped to deal with the mutually constructed perceptions of industrial leaders and official policymakers in sectors like this one.[3] The empirical evidence we present in this chapter may be interpreted in diverse ways. To be specific, as long as U.S.-China relations remain on a reasonably even keel, the building up of internal strategic resources in China can be suggestive of either a long-run strategy of balancing the power of others <u>or</u> of promoting the peaceful global integration of a transformed Chinese economy. In the language of international relations, our evidence cannot unambiguously suggest whether or not China is becoming a 'status quo power.' It cannot do so because it cannot separate capabilities from intentions, and it cannot make any less thorny the intersubjective character of the intentions of China and its industrial partners and competitors. Whether China's high-technology performance contributes positively to the interdependent international economy established so painstakingly during the past half century, or whether it tips in the direction of an economic nationalism destructive of the global system, depends both on the clarification of China's intent and on official and corporate reactions abroad. What we can do in this chapter, nevertheless, is lay out the facts as they are developing in this important case, cast them in an historical and comparative light, and draw out some concluding speculations in dialogue with the other chapters of this book.

Why Study the Semiconductor Industry in China?

China's rise is transforming the regional and global foundations of the semiconductor industry. Biotechnology may be the key industry of the future, but micro-electronics is arguably the key industry of the present. Certainly Chinese industrial planners see it this way, for they have assigned it their leading strategic designation. The development within China not only of a competitive manufacturing base for integrated circuits (ICs), but eventually also of a serious national system for related research and development poses new challenges for the industry globally. The evolution of an *applied research base* linked to now-burgeoning manufacturing operations, would be an essential early step suggestive of larger national objectives. Such a base is typically contrasted with laboratories for basic research; essentially, it refers to expertise and technology most often located in or near production facilities and centered on innovative engineering at the pre-commercial phase of product development. A country intent on moving ahead quickly in a particular industry may be expected to concentrate efforts here, since it can generate in the near term the resources required for rapid development.

The most important factor underlying the development of China's applied research base in semiconductors is the expansion of a vast pool of engineering and, eventually, scientific talent throughout the country. Over the past decade, internally generated skills have been augmented by the migration to China of highly educated engineers, many of Chinese origin and returning with industry experience, mainly from the United States and Taiwan. Indeed, relevant expertise has flooded into China, both as Chinese firms expanded their recruiting abroad, and as large-scale foreign direct investment bolstered a semiconductor industry developing to serve global and, increasingly, internal markets. Key elements of an internationally competitive semiconductor manufacturing industry in China are in place. Foreign investment in assembly operations and low-cost labor with improving skill-sets have played a significant role. In the medium term, despite impediments all too obvious within China today, this will be followed by a globally competitive applied research base. Before we examine evidence suggestive of such a conclusion, some context is required.

Technology and China's Rise

After a long period of backward movement, in 1978 Deng Xiaoping reopened the book on China's industrial modernization. Western technology, embedded in both tools and minds, was critical. In contrast to analogous efforts preceding 1949, dependence on foreign loans would be minimized. Direct foreign investments would be conditioned on tangible technology transfers, and foreign majority control of Chinese enterprises would be carefully limited. A new resource, however, would be tapped to the fullest extent possible. Chinese business networks flourished in the diasporas that followed the collapse of imperial China. Their nodes spread from Hong Kong and Taiwan to Southeast Asia, Europe, and the United States. Re-linking old China directly into them had both supply-push and demand-pull logic. In this light, it hardly appears surprising that overseas Chinese networks and foreign joint venture partners would form the key building blocks for success in the top priority sectors for industrial development in the new opening semiconductors and information technology.

China possessed hardly any integrated circuit industry at the time of Deng's policy reform. By 1985, it had imported some two dozen 3-inch wafer semiconductor lines, the first from Japan's Toshiba in 1982. Ten years later, Huajing Electronics, the pioneering state-owned enterprise in this sector, followed with 5-inch manufacturing-on-silicon (MOS) lines from Siemens and Lucent. In 1998, Huajing bought a 6-inch line from Lucent. With technology and joint-venture capital from Motorola, NEC, STMicroelectronics, Mitsubishi, Philips, Siemens, and Toshiba, five other Chinese firms—Huawei, Shanghai Belling, Advanced Semiconductor Manufacturing Corporation, Shougang, and Huahong—did the same.[4] Given the recent pace of change in this dynamic and still-high priority sector, these relatively recent innovations seem like ancient history.[5]

By 2005, the domestic Chinese market for semiconductors had become the fastest growing in the world. On current trend, it will soon be the second largest after the United States. With the vast majority of China's electronics production still based on imported chips, however, the government remains committed to ambitious goals for domestic substitution. The central government's Ninth Five-Year Plan targeted large-scale indigenous chip production on 6-inch wafers using an 800 nanometer (nm) design rule. Eight-inch wafers with design rules as low as 300nm and advanced packaging technology were targeted for prototyping under the government's Project 909. In 2000, Huahong-NEC produced 350nm chips on 8-inch wafers and exported 10,000 wafers (primarily memory chips) per month to Japan. By 2004, the world's leading semiconductor manufacturers were capable of mass producing chips with a design rule of 90 nm. Chinese manufacturers hoped to match and surpass this performance in a short period of time.

The Tenth Five-Year Plan ending in 2005 specified a production goal of 20 billion integrated circuits (ICs) per year, and an import substitution goal of 30 percent of local demand growing to 50 percent by 2010. It envisaged up to four new 6-inch production lines, five 8-inch 350-180nm lines, and two 12-inch 180-130nm lines. It also targeted an array of national R&D centers focusing on high volume production technology and system-level semiconductors, as well as a sufficient number of IC design and computer-assisted design (CAD) companies to generate annual revenues exceeding $10 million. Finally, it promised significant assistance for selected Chinese packaging, testing, equipment, and materials companies.[6] More directly, restrictions were reinforced on foreign investors and vendors. Although the desire for rapid technology transfer and the simultaneous acceptance of WTO obligations suggested some eventual loosening of those restrictions—especially those specifying less than 51 percent foreign control of joint ventures—industrial planners kept an eye trained on the country's historical experience of excessive reliance on foreign vendors for related cutting-edge technologies..

Rapid economic development in China continues to depend on technology transfer from abroad, as it did in the early twentieth century. But this time a basic commitment to national control in strategic industrial sectors seems firm, and semiconductors is certainly one of those sectors. The delicate task of accelerating the inward transfer of technology without recapitulating the historical experience of excessive dependence on foreigners now lies at the core of a novel political experiment. That experiment combines capitalism with centralized national planning and decentralized industrial governance. It poses stark challenges for an industry that well exemplifies both the conflictual and the cooperative faces of economic globalization.

Building a Technocracy in China

A range of policy debates—in the world's major semiconductor manufacturing firms, in universities, and in governments—now swirl around early evidence of China's rise in this sector. The question of when China's base for applied semiconductor research will reach internationally competitive levels is important, but virtually all close observers consider such a development to be inevitable. The more important question has to do with the character of that base when it does mature. Will it remain a net taker of technology from world markets, or will it become a more open and steady contributor?

From its earliest days, China's integrated circuit industry aimed in general at self-reliance. Korea and Japan provided the classic models for an industry organized around integrated device manufacturers (IDMs), firms that combined production capabilities from the design of micro-chips to the manufacture of devices for end-users. This was the model for pioneering Chinese firms like Huajing and Shanghai Belling. By 2000, however, the more-specialized *foundry* model perfected by Taiwan had clearly become dominant on the mainland, even if IDMs remained a strategic objective for the long term. (Foundries can produce chips nearer to the cutting edge, typically under contract to end-use device makers.) Burgeoning local and foreign demand for semiconductors and the promise of more rapid technology transfer provide significant reasons for the switch in near-term preferences. Even low-end Chinese chips simply could not be produced fast enough. The promise of relatively quick profits was also at work, and this certainly helped attract foreign foundries, especially from Taiwan. Table 3.1 gives an indication of China's demand for integrated circuits as well as of local production capacities.

(TABLE 3.1)

During the past decade, business networks established after 1949 by overseas Chinese clearly sought opportunities to establish critical industrial nodes back in China. Taiwan's foundries—and the entrepreneurs with experience inside them—are the best example; their role in helping to build China's newest semiconductor fabrication facilities (fabs) is obvious. Of all fabs being built around the world by 2004, 33 percent were in China and 14 percent in Taiwan. Such developments were welcomed, and even endorsed by official and unofficial patronage—and for many reasons. Foundries promised municipal and provincial governments in China rapid economic growth and an expanding array of skilled jobs. They also translate into wealth for local and national elites who investe in them. Over the next decade, massive growth is forecast for China's computer components market; in 2002, a leading foundry, the Semiconductor Manufacturing International Corporation (SMIC), forecast a 21 percent compound annual growth rate.[7] In addition, China is already the world's largest market for mobile phones, and on its way to becoming the largest market for other consumer electronic products. Import substitution alone could justify the foundry strategy, even in the absence of financial incentives provided by various levels of government. (The contention that the manufacture of advanced chips in China is purely a function of VAT rebates and other trade-distorting measures is therefore quite doubtful.[8]) In addition to obvious strategic factors pulling local and foreign investment into Chinese foundries, the most important long-run implication is that foundries have opened a critical avenue for the import of leading-edge manufacturing technology. This is exactly what is required to implement the stated intention of national leaders to ‘catch up’ with the West and even to ‘leapfrog’ into next-generation electronics.

Semiconductors and Talent Migration

China is now drawing heavily upon an intellectual reserve built up over the past twenty years in the Chinese diaspora. U.S. National Science Foundation data indicates that fifty percent of all science and engineering (S&E) doctorates awarded to foreign students in the United States are accounted for by Chinese, Taiwanese, South Korean and Indian citizens (68,500 of 138,000 in 2004). Chinese students comprise the largest group: engineering and biology are the two largest fields.[9]

Since 1985, approximately 70 percent of Chinese citizens who earned their S&E doctorates from U.S. universities stayed in the United States for employment in post-doctoral programs.[10] If the pattern for Taiwanese who earned S&E doctorates from U.S. universities holds, this will soon begin to fall. During the 1990s, these highly educated Taiwanese were lured home by a variety of enticements now commonly offered by semiconductor companies operating out of Beijing and Shanghai. Certainly official Chinese government programs are designed to reduce this ‘brain drain.’ Anecdotal evidence strongly suggests that burgeoning new opportunities in Chinese electronics and other industries are beginning to work in the same direction. At the same time, as will be described and analyzed below, such efforts are complemented by a national commitment to expanding rapidly, in both absolute and relative terms, the size of the national talent pool in the sciences and, especially, engineering.

The Development of Manufacturing Technologies

The success of the foundry model in Taiwan continues to depend on a highly trained workforce. As important, however, has been the ability of the foundries to convince their customers that the intellectual property they hand over for low-cost batch-manufacturing is sacrosanct. Replicating similar assurances in China-based foundries has been challenging. Given the recent troubled history of Chinese intellectual property protection regimes, concerns among foreign customers remain, even as World Trade Organization (WTO) disciplines kick in. Nevertheless, internally generated competitive pressures among foreign chip producers—who worry about gaining a position in future Chinese electronics markets—push in the opposite direction. Here is where policy debates in the United States and elsewhere about offshoring, and especially about Chinese strategic intentionality, gain relevancy.

A 2002 study of the U.S. General Accounting Office found that after ten years of explosive growth, China was only two generations behind in semiconductor manufacturing technology, and one generation behind "the commercial state-of-the-art."[11] This was somewhat exaggerated, since it gave too much weight to innovations in the most advanced foundries, which were unlikely in the near term to outclass well-established foundries in Taiwan and elsewhere. China's foundries remain focused on export markets, even for lower-end chips. Nevertheless, it is increasingly clear that leading-edge Chinese foundries intend to compete directly with the best in the world. They also intend eventually to focus more of their sales efforts on internal Chinese markets.

Security Complications and Export Controls

The near-term prospects for open, mutual collaboration are complicated, however, by signals on the national security front emanating from China's central government and from the Peoples Liberation Army (PLA). Even though Jiang Zemin finally abdicated formal political control over the military, policies he championed to compensate for China's conventional military weakness by encouraging the rapid import and absorption of microelectronics technology are likely to persist. Certainly the PLA would like to jump to next-generation innovations and enhance its electronic warfare capabilities. Few western military observers would bet on success in this regard, but the rhetoric of China's leaders is being taken seriously in defense policy circles in the United States and in Congress.[12] For their part, senior Pentagon officials assert that the PLA is already supported by a 'cutting-edge' domestic semiconductor industry focused on 'pockets of excellence.' The claim is that sophisticated chips are already being produced to fit military requirements for long-range precision strike capabilities, information dominance, command and control, and integrated air defense. Pockets now being developed are said to include advanced phased-array radar, anti-satellite technology, and electromagnetic pulse weapons.[13] At the same time, expert observers are aware that the hierarchical structure and risk aversion of China's military industry continue to make it difficult for the PLA to integrate sophisticated weapons systems effectively.[14] Acquiring the tools to innovate is also a serious challenge.

Export controls designed to slow the pace of semiconductor tool acquisition and/or development are fraught with complexities. The loose Wassenaar Arrangement on Export Controls for Conventional Weapons and Dual-Use Goods and Technologies confronts the reality that only the United States considers the acquisition of semiconductor manufacturing equipment by China problematic. In 2002, the GAO found that under competitive pressure, European, Japanese, and even U.S. authorities were licensing the sale of tools at least two generations more advanced than specified Wassenaar thresholds.[15]

From the point of view of foreign semiconductor firms operating in China, the concerns of the U.S. military tend to be overwhelmed by now-obvious opportunities and competitive forces. If there is a long-term threat on the horizon as they see it, it is a threat to future profitability, given the possible future development of a more autonomous and less open semiconductor industry emerging in China across the whole value-chain. But such a threat is ultimately a function of the development of local design capabilities.

Innovation in the Chinese Semiconductor Industry

Despite early efforts by government at various levels to stimulate design centers, design industry revenues in China do not yet exceed $250 million per year. Most indigenous chips are application-specific (ASIC) or customized for relatively inexpensive and easy to produce local power-management products. Few Chinese designers at this stage are able to work on sophisticated system-on-a-chip designs. Until 1995, there was little capability in either the design or test areas outside of Fudan, Tsinghua, and Peking universities.[16]

By 1999, however, the state-owned IC Design Center in Beijing had produced an 8-bit central processing unit (CPU) for smart cards (using 800nm technology) and an MP3 decoder, with China's first complete large-scale computer-assisted design (CAD) system. Within five years, the Center was reported to be capable of prototype and even production testing on a small scale, and was also reported to be sharing its expertise with more recently established design centers in seven locations around the country. A similar pattern is observable in the National Engineering Center for ASIC Design, which grew out of the Microelectronics Institute of the Chinese Academy of Sciences, which concentrates on IC analysis tools. Fabless design houses are also springing up, and by 2004, over 150 companies employing 3,000 engineers were estimated to exist. Most were located in government sponsored centers in Shanghai, Beijing, Shenzhen, Wuxi, Chengdu, and Xi'an.[17]

Interviews—as well as personal observation at showcase design centers in Beijing, Shanghai, and Xi'an—suggest that the industry is off to a modest start. It is important to note, however, that its future potential is already sufficient to have generated keen interest from global semiconductor tool manufacturers. Although leading-edge tool manufacturing in China on any serious scale remains a distant goal, Huawei in Shenzhen and others have reportedly developed a variety of relatively advanced tools.[18] And universities other than the Big Three have demonstrated the existence of a serious new market for tool makers.

As has been the case in other countries, there is in China an evolutionary movement in the indigenization of semiconductor production, from tools to finished micro-chips. Reverse engineering and process emulation lead to learning and gradual innovation. A generation ago, Japan was not expected to be in a position to support a high-level industry, and especially not an advanced tool industry. Expectations changed swiftly once Japan’s national innovation system began to focus on specific targets.

China is still basically in the emulation phase of industrial development in semiconductors, but signal advances are already being made. National Jiaotung University, for example, recently developed China’s first digital signal processing (DSP) chip, a 16-bit chip produced by SMIC using a 180nm design rule, packaged and tested by local firms in Shanghai. Even though it can only compare with low-end chips sold by companies like Texas Instruments, its development in China surprised many industry observers. Recent innovations in closely related sectors, like telecommunications, also suggest that Chinese industrial planners are aggressively seeking to use the scale and scope of local markets to establish new standards.[19] Mobile telephones provided only the most obvious of targets in this regard. Even at less advanced levels of technology, associated national strategies will help local manufacturers build up the financial resources necessary to invest much more heavily in applied research and, eventually, in basic research.

Electronics Research in China

China’s electronics research base was hobbled by the legacy of a Soviet-style science and technology system. During the 1980s and 1990s, rapid moves were made to jettison this legacy at the national level by following best practices in the United States and Western Europe. The Ministry of Science and Technology, the Chinese Academy of Sciences (CAS), the Chinese Academy of Engineering (CAE), a new Ministry of Information Industries, and a new National Science Foundation—together with the Ministry of Education which funds universities—lie at the core of official reform efforts. Between the mid-1990s and the present, aggregate national R&D expenditures have risen from about .5 percent of GDP to over 1 percent.[20] Although still much lower than the 2 to 2.5 percent registered in the most advanced industrial countries, the rate of change is staggering, particularly when China has confronted so many other pressing needs. The National Science Foundation of China (NSFC) budget doubled between 1996 and 2000, and again between 2000 and 2003. Meanwhile, undergraduate and graduate enrollments in science and engineering programs at Chinese universities and institutes increased by more than 25 percent per year in the early years of the 21st century.

As would be expected at this stage of China's development, the R&D intensity of Chinese firms is low in comparison with firms from advanced industrial countries. Still, patent applications by firms and research institutes rose from 83,000 in 1995 to over 170,000 five years later. And in response to financial incentives put in place by the government, China's rank in the global index of peer-reviewed and cited papers rose from seventh in the world to third.

Clearly, China's government is trying to compensate in part for the under-investment in R&D by local companies and to lay the groundwork for a fully functioning national innovation system. Most university researchers are forced to retire early (age 60 for men, 55 for women) to make room for new scholars. National resources devoted to scientific research are being expanded rapidly. CAS itself runs an elite graduate school, with research as its focal point. Through the Hundred Talents Program administered by the NSFC, it is trying to recruit star professors from leading foreign universities.[21] (Salaries offered are far in excess of typical academic salaries in China, a generous research allowance is provided, and a grant of RMB200,000 is made for the purchase of a home.) When the program started in 1995, seven recruits, with an average age of 34 years came from abroad. By 2001, recruiting was at the level of 130-190 per year.[22] Where Chinese universities have a difficult time differentiating between excellent and just competent performers, or among various fields of study, CAS is deliberately attempting to emulate high-level science and engineering faculties in the United States. If there is a Chinese MIT in the future, it may well be located outside conventional academic boundaries and in the elite research institutes of CAS.[23]

Two of the most prominent of those institutes are the Institute of Semiconductors and the Institute of Software. Although competition among all CAS institutes for funding is intense, these institutes and their branches across the country are flourishing. They are typically led by scholars with significant research experience overseas, and they are well known for their burgeoning links to analogous research networks in the United States. CAS scholars routinely travel abroad for conferences, although U.S. visa restrictions have begun to impede this activity. Anecdotes abound concerning recent difficulties encountered.

Related organizational innovations followed the creation of the Chinese Academy of Engineering in 1994. It has a more specific mandate to provide government and firms (often spin-offs from work done in CAS institutes) with advice on the future development of engineering S&T. Information and electronic engineering is one of the seven main divisions of the CAE. Among other things, the division seeks to organize and promote domestic and international collaborations. Another division focuses on chemical, metallurgical, and materials engineering. Unlike CAS, the modus operandi of the CAE divisions is to work through university engineering departments. Thus far, their key partner is Tsinghua University. During the last couple of years, more prominence has been given to strengthening the management skills of engineering graduates coming out of Tsinghua and other prestigious universities.

The National Science Foundation of China (NSFC) has also been more intensively promoting research of interest to China's semiconductor manufacturers, especially in life sciences and material sciences. The Foundation provides research grants on the basis of national competitions. Recently, the success rate has been approximately 16 percent of applications; a decision was taken two or three years ago to concentrate resources on larger projects with the most promising prospects for near-term results. For the five-year period beginning in 1998, government funding increased by a total of 45 percent. (The total NSFC budget increased from RMB 80 million in 1986 to RMB 2.6 billion by 2002; its average research grant now exceeds RMB 172,000, but key or major projects can be funded at the level of RMB 1-5 million, for up to five years. In recent years, grants in engineering and materials sciences exceeded RMB 100 million, the second largest category after life sciences.[24]) Even a glance at Figure 3.1 indicates the dramatic rise in Chinese government funding of science and technology.

[INSERT FIGURE 3.1 HERE]

Expanding the Human Resource Pool

A serious national commitment to building a solid foundation in the medium term for advanced industrial production and innovation in China is evident in the rapid expansion of university-level teaching programs. Human resources are, of course, the core of any applied or basic research base in the information technology industries, including semiconductors. In this regard, careful consideration must be given to the scale and scope of what China is now accomplishing.

One broad measure of the national educational commitment is an astounding and rapidly accelerating increase in the number of Chinese students over the past decade graduating from institutions of higher learning, with about half of all degrees awarded in the fields of science and engineering. Unlike data from the U.S. National Science Foundation, the Chinese data include statistics for engineers educated at China's vast network of technical institutes, many of which are two or three year programs. Nevertheless, even when the lower NSF figures are analyzed, as they are later in this chapter, the trend is the same, and its magnitude is still staggering.

Figure 3.2 shows the numbers of students who graduated with a bachelors-level degree in science or engineering in China from 1994 through 2003. These figures are remarkable in themselves. But it is the slope of the increases in *engineering* since 2001 that bears further scrutiny.

[INSERT 3.2 HERE]

Figure 3.3 indicates the number of individuals *entering* bachelors-level science and engineering programs in China during the same time period, 1994 to 2003.

[INSERT FIGURE 3.3 HERE]

After 1998, there is an obvious and dramatic acceleration of the numbers of young people entering higher education in both science and engineering. During the next five years, the number of students entering bachelors-level engineering programs increased from 412,000 in 1998 to 1,242,000—an increase of more than 300 percent. During the same time period, the number of students entering science programs rose from 121,000 to 330,000—an increase of about 273 percent.

For both categories—students entering science programs and students entering engineering programs—one would expect some attrition; this is borne out in Figure 3.4, which shows the numbers of scientists and engineers officially *enrolled* in bachelors-level programs for the period 1994-2003.

[INSERT FIGURE 3.4 HERE]

If all engineering and science students entering in 2000 through 2003 had remained in school, the expected number of enrollees would have been 4.0 million and 1.1 million respectively. Accordingly, the attrition rate is approximately seven percent in engineering programs and nine percent in science programs.

These calculations provide a rough basis for projecting the numbers of bachelors-level graduates who will be available either for entrance into the Chinese workforce or for further graduate education in science and engineering. We know the number of students entering bachelors-level science and engineering programs from 1999 through 2003. If we conservatively assume an attrition rate of 10 percent, we can make an educated guess regarding the numbers of students likely to receive such degrees for the period 2004 through 2007. Table 3.2 provides a rough projection. Barring an economic meltdown in the region, military conflict involving

China, or large-scale civil strife within the country, these numbers are very likely to be realized or exceeded.

(TABLE 3.2)

There is an important debate as to whether or not the supply of talent creates its own demand. And the Chinese economy may or may not be able to shift quickly to higher value-added work in semiconductors and other industries. One analyst argues that only about a third of Chinese engineering graduates have been able to find technical work in the Chinese economy.[25] And a 2006 study by students at Duke University suggests that the Chinese figures are inflated, in effect that China educates only three times the number of scientists and engineers as does the United States.[26] Nevertheless, all available data sets point in the same direction: Chinese national education policy is clearly gearing up to promote a transition to a technically literate and highly capable work force. The point is reinforced by an analysis of the production of masters- and doctoral-level scientists and engineers, as documented in Figure 3.5.

[INSERT FIGURE 3.5 HERE]

Based on Chinese data, Figure 3.5 indicates the general trend. Although NSF calculations result in lower numbers, the Chinese report is quite consistent with the data presented in Figure 3.2 (above) on bachelors-level graduates in engineering and science. There is, once again, a remarkably steady increase in the numbers of students receiving advanced degrees in science and engineering between 1994 and 2003, the last year for which Chinese source statistics are available. From 1998 to 2003, the number of students graduating with masters-level degrees and above in engineering soared by 196 percent—nearly a factor of two. As with undergraduate engineering students, the spike for graduate students in 2003 is also quite pronounced.

Growth in the number of students earning graduate degrees in science was smooth and consistent from 1994 through 2003, increasing by about 217 percent over the whole period. Interestingly, the number of science degrees granted, at both undergraduate and graduate levels, spikes decidedly in the year 2003. Nevertheless, while scientific training remains important, the real emphasis—especially after 1998—has been placed on the field of engineering. Figures 3.6 and 3-7 give these trends graphical expression.

[INSERT FIGURE 3.6 HERE]

As Figure 3.6 indicates, the number of students *entering* graduate training programs in engineering began to increase precipitously after 1998, rising by 356 percent in 2003—in just six years. There was also a quite steep, if more moderate, increase in the number of science students entering graduate programs in China between 1998 and 2003, an increase of almost 309 percent—again, in only six years.

As with bachelors-level enrollments in Chinese science and engineering programs, a number of insights can be gleaned from the overall numbers of students matriculating at the masters-level and above. Figure 3.7 shows a strong upward swing in enrollments in both engineering and science graduate programs, again accelerating after 1998.

[INSERT FIGURE 3.7 HERE]

While it is more difficult to calculate attrition rates in graduate science and engineering programs, we can still get a rough idea of the numbers of post-graduate degrees likely to be awarded in the years immediately ahead. Like Table 3.2 above, Table 3.3 adapts the data and assumes an attrition rate of 10 percent.

(TABLE 3.3)

Even if an attrition rate of twenty or even thirty percent is assumed, in time the rate of growth of its science and engineering graduate schools will place China in the first rank of technologically advanced economies. The impact is already beginning to be felt in semiconductors and in associated information technology industries, both upstream and downstream.

The Prospects for High-Technology Innovation in China in Comparative Perspective

The quantity of human resources available to Chinese industry now and in the future does not necessarily translate directly into an internationally competitive labor force of high quality. One report suggests that some thirty percent of Chinese university graduates failed to find employment in 2004. It also argued that improvement in the quality of basic undergraduate engineering programs has not kept pace with rapidly expanding enrollments.[27]

Within international engineering circles, debate continues to rage on this issue. Skeptics suggest that the quantity of Chinese engineers poses little threat. They contend that Chinese data overstate the numbers of engineering graduates at all levels, especially graduates capable of competing on an even level with their peers in the United States, Europe, and Japan. Indeed, they stake their claim that advanced engineering jobs in sectors like semiconductors—at comparatively high salaries—remain secure for the foreseeable future because of the vast gap in quality now evident between Chinese engineers and their counterparts elsewhere.

On the other side of this important debate are those who remind the skeptics about similar arguments made not-so-long ago in the case of Japan. Few close observers of the electronics industry in China, moreover, doubt that large numbers of adequately trained and relatively inexpensive engineers and scientists are quite likely to compete effectively in the near future in fields where technologies are reasonably stable and most innovations are of an incremental nature. Under such conditions, advances are most likely to be made on the shop floor, so it was certainly significant that by 2005 China had become the key global producer of consumer electronics and the world’s largest market for semiconductors—even if many are still imported. As the Chinese economy continues to expand, far more robust resources are likely to be made available to Chinese universities for the development of higher quality students. This would translate in the near-term into serious advances in local and national systems of innovation. Because so much has already been accomplished in the establishment of nation-wide production facilities for semiconductors, it had long been likely that one of the first such systems—for applied research—would appear in this industry. Its foundations are already apparent in key municipalities where significant semiconductor production is now being scaled up. They are sure to be enhanced as that production is targeted less on export markets and more on a rapidly growing internal market, where indigenous firms are likely to retain a marketing advantage over foreign competitors.

It is important to keep this development in perspective. Not so many years ago, applied research in the United States was considered to be far less important than it is today. The lag time for comprehending its importance was even greater in Europe and Japan. It would be folly to assume that Chinese industrialists are not seeking to replicate the success of the semiconductor industry in the world's most advanced economies, partly by emulating their move up the research ladder from product development to applied research, and eventually to basic science.

Many observers were caught off guard by the rapid rise of a competitive Japanese semiconductor industry in the 1980s; others watched with incredulity as the Korean IDM and Taiwanese foundry models later gained significant global traction and competitiveness. The difference between these three cases and the Chinese case does not lie in relative work ethics; Chinese students are among the most able and most motivated in the world. It does not lie in ambition, for there is no doubt that China's leadership aims to return China to the global prominence it historically enjoyed. China is simply a late mover in the industry, and the key to catching up lies in the sheer volume and improving quality of the manpower available to strategic industries like semiconductors.

Semiconductor designers and manufacturers in the United States and other advanced economies cannot assume that they will be able in the near and medium term consistently to come up with leapfrog technologies that will keep leadership positions within the industry beyond the reach of China. In any event, recent history has amply demonstrated that the inventors of breakthrough technologies are not always the ones to reap the rewards. Smart 'follower strategies' have long been evident within the industry. Comparative educational data complements the statistics arrayed above and suggests the scope for a regional and global redistribution in the human resources available in the medium-term for innovation in semiconductors and cognate sectors.

In comparative data on bachelors degrees awarded in Asia in 2002, it is easy to find discrepancies with Chinese source data. Some of the differences are accounted for by the fact that agricultural sciences and social/behavioral sciences data are excluded from the NSF data sets; there are many more agricultural science and engineering degrees awarded in China than in other countries. Chinese data also encompasses a wider set of institutions of higher learning. Nevertheless, the latest NSF data reinforce the same broad trends highlighted above.

As Figure 3.8 clearly indicates, in 2002 China had already far surpassed its East Asian neighbors in terms of the number of bachelors degrees awarded in science and engineering.

[INSERT FIGURE 3.8 HERE]

By 2001, China had attained number one leadership status in the combined production of undergraduate science and engineering degrees, surpassing even the United States. As Figure 3.9 illustrates, the United States still leads the world in the number of undergraduate science degrees conferred, but China dwarfs even the closest competitor in the sheer volume of engineering degrees awarded. Moreover, when U.S. undergraduate science training is excluded, China is number one on all measures, overpowering even Germany by a factor of seven to one. This likely foreshadows even more dramatic developments to come.

[INSERT FIGURE 3.9 HERE]

In light of concerns about outsourcing in the United States, it is worth underlining the magnitude of the differential in engineering training between China and the United States, which in recent years produced approximately 200,000 and 60,000 undergraduate engineers respectively. Estimates vary, but one oft-cited figure indicates that hiring a ‘fully loaded’ U.S. engineer costs between four and six times as much as his or her Chinese counterpart. It is true that persistent productivity and creativity differentials can withstand such competition, especially at the highly-skilled end of the engineering labor pool.[28] But as more and better Chinese engineers come on line, and the infrastructure for data transmission matures, it seems only a matter of time before even highly-skilled engineering jobs move to where the labor is abundant and relatively inexpensive.

It is also significant that as many as half of the engineers currently graduating every year from U.S. universities are not American citizens. Many of these graduates are now opting or being forced by U.S. visa and immigration policies to return to their countries of origin. This is, in part, an unintended consequence of security measures taken to protect the United States in the aftermath of the 9/11 terrorist attacks. It seems very likely, however, that tighter visa policies for visiting Chinese business-people and students also reflect heightened concerns in the United States over industrial espionage.[29]   In any event, one effect is to enhance opportunities back in China for Chinese engineers already trained in the United States.

Innovation in China’s Semiconductor Industry and Policy Responses

Significant adjustments lie ahead for the world-wide semiconductor industry. Initially, China’s rise as a key manufacturing center will have dramatic consequences on both the demand

and supply sides of global markets. Based on experience elsewhere, however, the longer term consequences are likely to be the more profound. Manufacturing still matters, and human capital is the main input in technology innovation systems. With its growing manufacturing base in semiconductors and with a rapidly expanding pool of engineers and scientists, much process innovation and applied research seems certain to migrate to China in the near to medium term.

Eventually, as Chinese research institutes and universities improve through the efforts of a burgeoning population of trained engineers and scientists, pre-competitive and eventually even basic research is likely to expand as well. In related sectors, we have already seen a willingness on the part of Chinese authorities to leverage the promise and scope of national markets to establish the kinds of technical standards that allowed leading enterprises to flourish globally.[30] Similar efforts will shape the future of a globally competitive semiconductor industry.

In line with the framework set out in Chapter 1, this conclusion must be interpreted and assessed in a wider strategic and historical context.   The question debated in foreign policy circles just a few years ago focused on whether China should be viewed as a future rival or future partner of the United States has now become much more subtle. There is a deeper appreciation of the complexity of China's governing structure and of the social foundations of national political authority in the country. There is also a growing awareness of tensions among reformist economic elites, a traditional military establishment, and relatively autonomous provincial and local officials.

Techno-nationalists in China invoke memories of the experience of the early twentieth century to underpin policies designed to accelerate technology transfer without compromising future national autonomy. This has led many observers to the conclusion that China will eventually seek to consolidate its power regionally, strive to offset or balance U.S. power within its borders, and to compete more directly with the United States and other advanced countries in areas where strategic resources like petroleum are at stake.

Such a view does not necessarily portend future security conflicts, but there is certainly room for deep divisions regarding advisable foreign policy reactions by the United States and others. It is entirely plausible that a China intent on balancing U.S. power in the long run would in the short and medium term seek to deepen and strengthen bilateral relations with the United States. Strategic realists in the United States therefore advocate a response to China characterized by caution and careful cost-benefit calculations. Although they begin with a different perspective, advocates of assertive policies aimed at promoting human rights actually come to similar conclusions. Conversely, those with a more optimistic cast of mind believe that short-term calculations are unnecessary and even counter-productive, since deeper bilateral involvement will inevitably lock China into global webs of interdependence, especially in strategic industries--like semiconductors.

Hard-liners in the United States have found it difficult to build a consensus in support of containing or undercutting expanding Chinese power. They confront demands on the part of both prominent businesses and leading American allies for consistent policies designed to engage China economically, to compete with European and Japanese purveyors of advanced technology, to promote gradual change in its internal governance practices, and even to acquiesce when such change is not forthcoming. In particular, American businesses directly linked to the U.S. national defense base find themselves facing the reality that they cannot achieve necessary economies of scale in new technologies if they and only they bear the brunt of export controls aimed at keeping China a generation or two behind the United States. China's current and potential human capital, together with the gradual development of its low-cost manufacturing and research base, above all in the semiconductor industry, is now building enormous pressures in the same direction. In such a context, the global movement of human and financial capital into China's semiconductor and related industries looks like a phenomenon that has only just begun.

It is still possible that nationalist impulses in both the United States and China could feed off one another and make coherent policies more difficult to craft. Mutually reinforcing perceptions of intentions, more than capabilities, are key.[31] The challenge is to find practical steps to accommodate China's rise without falling into either Panglossian dreams of inexorable harmony or pessimistic self-fulfilling prophecies of future disaster. It does not take much work to find indications of a classic strategic rivalry between the United States and China. But there is no self-evident reason why competitive impulses cannot be significantly displaced to the mixed conflictual/cooperative arena of global capitalism. Since 1945 this has happened in most other parts of the world. Why not here? Developments in the semiconductor industry suggest just such a scenario.

Implications of China's Ascendance

Given the potential size of its internal market and the vast scale of the human and financial human resources currently building up its national engineering base, China will fairly soon become a major force in process innovation and applied research in this field. But no country has been able to insulate comparable national systems; even if they remain rooted in national and regional foundations, they are in fact becoming ever more deeply integrated. Especially because the scale of investment required even for incremental breakthroughs is so high, this is particularly evident at the pre-competitive level of research, where collaborative, cross-national research is a fact of life. How can China resist such a tendency, especially if the manufacturing base it is now building can only stay competitive if it learns to innovate? Can the sheer size of the rapidly developing internal market shield Chinese national champions from this necessity? Experience elsewhere would suggest not, as would the decision taken in 2006 by China's Semiconductor Industry Association to join the World Semiconductor Council, an established vehicle encouraging inter-firm cooperation in the global industry.

Strategic puzzles nevertheless abound. Imagine a country where one million citizens of an 'enemy' armed to the teeth currently live inside its territory and work hard to build up its companies, companies that will compete directly with companies based in their own homeland. That's the present situation in the semiconductor industry in China and Taiwan. Now imagine some U.S. companies claiming to be recentering future corporate operations on Asia and specifically in China, while others hesitate to send or develop there any intellectual property they could not afford to lose. Which specific interests should U.S. strategists seek to defend?

It remains the case today that *basic research* in the semiconductor and other information technology sectors is dominated by the United States. Since 1945, a strong information technology sector has clearly remained a national strategic priority for the country, arguably a core pillar of its enduring hegemonic position within the international system.[32] As the comparative data above suggest, there evidently remains a consensus inside the United States that substantial human and financial resources should continue to be invested in the highest level of scientific research in the universities and laboratories currently at the cutting edge of semiconductor-related innovation. Given the physical limits now coming into view in the development of current technologies, this means that substantially more investment is flowing into advanced materials and biochemistry for the post-silicon era. No other country, including China, is yet behaving in a similar manner. Like China, the more typical country focuses national investments in engineering and science education clearly on the engineering side, where payoffs seem certain in the more immediate future.

Certainly from the point of view of balance-of-power theories, it remains surprising that American dominance in the natural sciences has not yet stimulated serious strategic responses. Perhaps it will someday, but something else could already be starting to temper that reality. Leading edge science in the United States has depended not only upon substantial public and private financial investment, but also on exceptional intellectual openness to and from the rest of the world. It has sought and attracted the best brains from around the world, but it has also not strenuously impeded those brains from leaving the territorial domain of the United States. On the basis of new science, it spawns new technologies, creates new industries, and primes the pump for pre-competitive collaboration by rival firms. But Americans could begin moving in the opposite direction by diverting long-term investment from human capital, or by moving to constrict the global flow of human resources in the sciences. Certainly the American semiconductor industry itself is worried that just such reversals are now underway, as mounting federal budget deficits threaten to constrain future investments and security hysteria impedes the flow of scientific brains to the United States. At the same time, China could seriously attempt to import and adapt foreign science and technology without allowing foreigners to benefit in any immediate sense and without reciprocating in the fullness of time.

What remains extremely difficult to imagine, however, is self-conscious acquiescence on the part of the American government, and American society more generally, to a secondary position in key industrial sectors like microelectronics. An American strategy of engagement with China, the only sensible strategy at the moment, could have the effect not only of forestalling overt balancing behavior by China but also by the United States itself. Serious engagement, however, does not mean simple acceptance of market facts. To the extent it really is possible to create images of ‘us’ and ‘them’ that do construct the world in which we ultimately live, then serious engagement means crafting policies that both steer toward desirable outcomes and away from undesirable ones. Some political scientists use the metaphor of carrots and sticks, while others highlight the dichotomy of deterrence and reassurance. Economists speak of incentives and disincentives. But is China not inherently too big, too complex, and potentially too powerful seriously to be steered by other countries?[33]

The ultimate objective must surely be to bring China fully into the system the United States and its key allies have built since 1945. At its core is a military alliance. Its economy rests on competing (and still mainly national or, at most, regional) markets that were rendered interdependent by design. The leading states cooperating with the United States in maintaining such a system certainly still compete with one another in the economic realm, but they are now structurally inclined to favor cooperative solutions to difficult systemic problems. China should one day be recognized as a leading state and optimists must surely cling to the belief that the system remains flexible enough to accommodate its key interests until that time. They must just as surely hope that deeper engagement will transform or marginalize those interests in China that are today threatened by the winds of change. Without naiveté concerning the forces of techno-nationalism at work on all sides, outside of China in sectors like semiconductors this should translate into policies that lean toward market-based competition and against market closure.

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[2] This chapter follows earlier work on the semiconductor industry in Japan, Taiwan, and South Korea. See William W. Keller and Louis W. Pauly, "Crisis and Adaptation in Taiwan and Korea: The Political Economy of Semiconductors," in *Crisis and Innovation in Asian Technology*, edited by William W. Keller and Richard J. Samuels, Cambridge: Cambridge

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University Press, 2003, pp. 137-159; and “Crisis and Adaptation in East Asian Innovation Systems: The Case of the Semiconductor Industry in Taiwan and South Korea,” *Business and Politics*, vol. 2, no. 3, November 2000, pp. 327-352. In the latter two country cases, we documented both the rapidly developing success of university systems in training engineers and the ability of local industry to absorb and conduct high-quality applied research. On the Japanese case in closely related industries, see Paul N. Doremus, William W. Keller, Louis W. Pauly, and Simon Reich, *The Myth of the Global Corporation*, Princeton: Princeton University Press, 1998.

[3] Mark R. Brawley, “The Political Economy of Balance of Power Theory,” in *Balance of Power: theory and Practice in the 21st Century,* edited by T.V. Paul, Jim Wirtz, and Michel Fortmann, Stanford University Press, 2004, p. 94.

[4] Weifeng Liu, Michael Pecht, and Zhenya Huang, “China’s Semiconductor Industry,” in Michael Pecht and Y.C. Chan, eds. *China’s Electronics Industries*, College Park, MD: CALCE EPSC Press, 2004, p. 79.

[5] For an overview of the challenges China faces in its regional context, see Douglas B. Fuller, “Moving Along the Electronics Value Chain: Taiwan in a Global Economy,” in Suzanne Berger and Richard K. Lester, eds., *Global Taiwan*, Armonk, NY: M.E. Sharpe, 2005, pp. 137-165; Dieter Ernst, “Pathways to Innovation in the Global Network Economy,” *East-West Center Economics Working Papers Series*, no. 58, June 2003., especially pp. 29-33; Dieter Ernst, “Late Innovation Strategies in Asian Electronics Industries,” *East-West Center Economics Working Papers Series*, no. 66, March 2004; and Dieter Ernst, “Internationalization of Innovation: Why is Chip Design Moving to Asia?” *East-West Center Economics Working Papers Series*, no. 64, March 2004.

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[6] Ibid.

[7] *China's Electronics Industry 2004*, p. 84-85.

[8] For a thorough treatment of this issue, still relevant even after China agreed in 2004 to remove the VAT rebate system, see Dewey Ballantine LLP, *China's Emerging Semiconductor Industry*, Washington, DC, October 2003.

[9] National Science Board, Science and Engineering Indicators 2004, Table 2-9, p. 2-31.

[10] Ibid., p. 2-33.

[11] GAO 02-620, cited on page 109 of Walsh/Stimson Study.

[12] See U.S.-China Economic and Security Review Commission on China, *2004 Report to Congress*, Washington, DC, June 2004.

[13] Michael Pillsbury, "China's Military Strategy Toward the U.S.: A View From Open Sources," background paper prepared for the U.S.-China Economic and Security Review Commission on China, *2004 Report to Congress.*

[14] GAO-02-620, pp. 16-17.

[15] Ibid., p. 17-18. Competitive pressures have increased ever since a famous case in 1998, where Emcore of the USA was denied permission to sell an advanced metal organic vapor deposition machine to Hebei Semiconductor Research Institute. The German tool maker, Aixtron GmbH immediately scooped up the contract and supplied a comparable machine. Strong diplomatic protests in this and subsequent cases have accomplished little.

[16] *China's Electronics Industry 2004*, p. 85, and interviews.

[17] Ibid., p. 86.

[18] Ibid., p. 87.

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[19] See Richard P. Suttmeier and Yao Xiangkui, “China’s Post-WTO Technology Policy: Standards, Software, and the Changing Nature of Technonationalism,” NBR Special Report No. 7, Seattle, WA: The National Bureau of Asian Research, May 2004. The authors see Chinese standards policy as motivated by “neo-technonationalism,” in which technological development in support of national economic and security interests is pursued through leveraging the opportunities presented by globalization for national advantage. They depict a China that to this point in time has benefited in absolute terms from technology transfer into the country but still losing out in relative terms. Paying substantial royalties to foreign corporations leaves it in a “patent trap” that it fully intends to escape, partly by designing its own technology standards.

[20] For an excellent overview, see Deh-I Hsiung, “An Evaluation of China’s Science & Technology System and its Impact on the Research Community,” *Special Report for the Environment, Science & Technology Section*, U.S. Embassy, Beijing, Summer 2002.

[21] For relevant background, see Cong Cao and Richard P. Suttmeier, “ China’s New Scientific Elite: Distinguished Young Scientists, the Research Environment and the Hopes for Chinese Science,” *The China Quarterly*, no. 4, 2001, pp. 960-984.

[22] Hsiung, p. 26.

[23] China moved along this specialized lab route during the same era that the United States was burying the remains of its famous Bell Labs. It is, perhaps, no coincidence that President Bush’s Council of Advisors on Science and Technology has recently raised the issue once more and called for the development of a substitute national organ. See The President’s Council of Advisors on Science and Technology, *Sustaining the Nation’s Innovation Ecosystems: Report on Information Technology Manufacturing and Competitiveness*, Washington, DC, January 2004, p. 25.

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[24] Hsiung., p. 29-30.

[25] [[[Need reference to CAO et al.]]]

[26] Gary Gereffi et al, "Framing the Outsourcing Engineering Debate: Placing the United States on a level playing field with China and India," pp. 5-6. http://memp.pratt.duke.edu/downloads/duke_outsourcing_2005.pdf (Accessed on September 11, 2006.)

[27] *China Electronics Report*, February 21, 2005.

[28] For relevant analysis of key dependencies that complicate the closing of such gaps, see Cong Cao, "Challenges for Technological Development in China's Industry," *China Perspectives*, 54, July-August 2004, pp. 4-24.

[29] Some 3,000 U.S companies are currently being watched by the FBI, which suspects they are collecting information for China. See Brian Bennett, "China's Big Export," *Time*, February 21, 2005.

[30] See Alberto Gabriele, "S & T Policies and Technical Progress in China's Industry," *Review of International Political Economy*, vol. 9, no. 2, Summer 2002, pp. 333-373.

[31] On this theme, see Peter Hays Gries, *China's New Nationalism*, Berkeley: University of California Press, 2004, p. 137. For an opposing view, emphasizing the dynamics of structural competition, see John Mearsheimer, *The Tragedy of Great Power Politics*, New York: W.W. Norton, 2003, p. 4.

[32] Robert L. Paarlberg, "Knowledge as Power: Science, Military Dominance, and U.S. Security," *International Security*, vol. 29, no. 1, Summer 2004, pp. 122-151.

[33] See Alastair Iaian Johnston, "Is China a Status Quo Power?" *International Security*, vol. 27, no. 4, Spring 2003, pp. 5-56; Thomas J. Christensen, "Posing Problems without Catching Up:

China's Rise and Challenges for U.S. Security Policy," *International Security*, vol. 25, no. 4, Spring 2001, pp. 5-40; and Peter Hays Gries and Thomas J. Christensen, "Correspondence: Power and Resolve in U.S. China Policy," *International Security*, vol. 26, no. 2, Fall 2001, pp. 155-165.