

**Beyond the “Global Factory” Model:
Innovative Capabilities for Upgrading China’s IT
Industry¹**

**Dieter Ernst,
East-West Center, Honolulu, Hawaii
ernstd@EastWestCenter.org**

1. Introduction

China's information technology (IT) industry may be a relative newcomer on the world scene but it is doing something right, and in a big way. China is now the largest exporter of IT goods, surpassing the United States, up from a world ranking of tenth in the year 2000. And China's booming market for electronics products and services reshapes the global IT market and defines innovation roadmaps². As the second largest IT importer (up from the seventh place in 2000), China has accumulated bargaining power, especially for telecommunications equipment (both fixed-line and wireless), computers, software and semiconductors³.

China's success is due to a unique combination of competitive advantages (Ernst, 2006b; Ernst and Naughton, 2007). The rapid growth of the China market encompasses both high-end 'lead customers' (Beise, 2004) in Shanghai, Beijing and Shenzhen, as well as 'bottom-of the pyramid' customers in lower-tier cities and rural areas (Pralhad and Lieberthal, 1998) that require ultra-low-cost products and services. China also has the world's largest pool of low-cost and easily re-trainable knowledge workers⁴. This has attracted foreign direct investment (FDI) on an unprecedented scale. For China, inward FDI is more than ten times as important as during Japan's and Korea's high growth periods - and nowhere more so than in high technology exporting. This has given rise to a deep integration into global production networks (GPNs), exposing Chinese firms to leading-edge technology and best-practice management approaches⁵. This, in turn, has created new opportunities, pressures, and incentives for Chinese firms to upgrade their technological and management capabilities and the skill levels of workers.

Equally important for China's success are aggressive, yet selective and continuously adjusted support policies that have enabled domestic firms to exploit those opportunities and to improve their positions in these networks. Of particular importance are concerted policy efforts (both at the national and regional level) to strengthen China's innovation system and to foster the emergence of sophisticated lead users and test-bed markets (especially in wireless telecommunications).

But this "global high tech factory" model is now confronted with new competitive challenges, both from below and from above. From below, the rise of lower-cost manufacturing sites in Vietnam, India, Bangladesh, Pakistan or Sri Lanka implies that simply creating cheap-labor manufacturing jobs is not a viable development strategy. And from above, China is now confronted with a more hostile international environment, where established industrialized economies in the US, the EU and Japan are seeking for new ways to protect their industries, and to recreate their competitive edge through R&D.

In addition, the "global factory" model is also facing new challenges that arise from shifts in the global innovation system, as globalization transforms markets for technology and knowledge workers. These challenges include the intensifying competition for a limited global talent pool and profound changes in the innovation management of global corporations that give rise to the geographic dispersion of research, development and engineering jobs through global innovation networks ("innovation offshoring") (Ernst, 2006a).

This has forced China's policy makers and corporate strategists to seek for new ways to move beyond the "global factory" model. Much of the debate has focused on a strategy of industrial upgrading through innovation. But most firms and policy-makers are still groping in the dark what precisely that strategy requires, for the

time being content with adopting a pragmatic trial-and-error approach until they find something that works.

This paper seeks to establish what is necessary and feasible, using illustrative examples from China's IT industry. I start out with a brief review of China's "global high tech factory" model, highlighting its integration into diverse global network arrangements, as well as achievements and weaknesses of the model. In part two, I introduce a concept of "industrial upgrading" that links specialization with firm-level and industry-level upgrading.

Finally, in part three of the paper, I explore what specific innovative capabilities are required to upgrade China's IT industry. I emphasize that "soft" entrepreneurial, management and system integration capabilities need to complement "hard" R&D in order to create products and services that customers are willing to pay for. I argue that "technology leadership strategies" that focus on 'radical' innovations are not the only option. "Technology diversification" can serve as a complementary, and arguably less costly option.

2 China's "Global Factory" Model

A defining characteristic of China's "global factory" model is its integration into multiple corporate and informal global networks of production and innovation. China is far more integrated into global knowledge networks than were Japan and Korea at a similar stage of their development.

Formal corporate networks link Chinese firms to global customers, investors, technology suppliers and strategic partners through foreign direct investment (FDI) as well as through venture capital, private equity investment and contract-based alliances.⁶ And *informal global social networks* link China to more developed overseas innovation systems, primarily in the US, through the international circulation of students and knowledge workers.

2.1. *Formal corporate networks through foreign direct investment*

China's rise as the primary global electronics factory reflects its integration into global production, sales and R&D networks that industry leaders (primarily from the US) and their Taiwanese junior partners have established through *foreign direct investment* (FDI). This has generated deep integration with global customers, technology suppliers and strategic partners.

Since 2003, China is the world's largest recipient of FDI, overtaking the US, traditionally the largest recipient. Incoming FDI has averaged 5% of GDP in China over the past decade; during Japan's and Korea's high growth periods, incoming FDI was never as much as one half of one percent of GDP. FDI is more than ten times as important in China as in these earlier latecomers, and nowhere more so than in high technology exporting. In 2005, foreign-invested enterprises (FIEs) produced 58% of China's total exports, but 88 % of high-technology exports. And Taiwan-owned FIEs produced 60% of China's exports of computers and handsets.

In addition, practically all global IT industry leaders have begun to conduct R&D in China, as part of aggressive innovation offshoring strategies (Ernst, 2006a). A recent survey of the world's largest R&D spenders showed that by 2004 China had become the third most important offshore R&D location after the United States and the United Kingdom, followed by India (sixth) and Singapore (ninth) (UNCTAD

2005).⁷ Much of the R&D offshoring to Asia is concentrated in the electronics industry, with China dominating hardware R&D for hardware.

As for non-equity forms of R&D internationalization (“offshore outsourcing”), China is now the third most important location behind the United States and the United Kingdom, but ahead of Germany and France. The same survey projects that China will be a more attractive location for future foreign R&D than even the United States.

2.2. *Venture capital and private equity investment*

More recently, *venture capital* and *private equity investment* have added a new and critically important dimension to China’s integration into formal corporate knowledge networks.⁸ Venture capitalists in Silicon Valley now require start-ups to present an “offshore outsourcing” plan as a precondition for funding. The emerging business model is to keep strategic management functions like customer relations and marketing, finance, and business development in Silicon Valley, while increasingly moving product development and research work to offshore locations (Ernst, 2006a).

A typical example is a start-up company in Shangdi Information Industrial Base in Beijing’s Haidian District that specializes in mixed-signal chip design (Interview CA 092105). Chinese engineers who hold Ph.D. degrees from leading U.S. universities and have worked as senior project managers in leading U.S. semiconductor companies founded the company. The company has received venture capital funding for developing chip designs in both China and Silicon Valley. A fully integrated design team in Beijing develops decoder chips customized for the new Chinese AVS (audio-video signal) standard. Of the more than 60 engineers at the Beijing facility, 90 percent hold at least Masters Degrees. Five senior managers based in Santa Clara handle customer relations and provide design building blocks (the co-called SIPs) and tool vendors for design automation, testing and verification.

Since the turn of the century, fund raising in private equity has rapidly increased, and is now also targeting China’s high-tech industries. Much of these new forms of network integration take place behind the scenes, and hence are difficult to document⁹. A recent survey estimates that \$ 1,300 billion have been invested in global private equity, a figure set to rise significantly.¹⁰

Private equity investors are now firmly established as major global economic players. Take Texas Pacific Group (TPG), one of the industry leaders that has played a key role in Lenovo’s acquisition of IBM’s PC division (Ernst, 2006b). Its portfolio companies employ around 300,000 people and generate annual revenues of \$ 65 billion. Aggregating these companies would create a business in the top 20 of the Fortune 500. In addition, TPG has established a strong presence in Asia through its Hong Kong-based Newbridge affiliate, well ahead of other leading players.

Viewed from the broader perspective of China’s economic development, the expansion of VC and private equity investment is a double-edged sword. There is concern that, as long as it remains unregulated, the expansion of private equity funding may endanger the stability of financial systems. As they obtain important management information in advance, private equity firms can use such information to avoid losses or to unfairly take profits through insider stock trading, transferring losses to ordinary shareholders.¹¹ Yet, as shown in Ernst (2006b), both venture capital and private equity investment may act, under certain conditions, as carriers of knowledge on markets, technology and best practice management approaches.

2.3. *Informal social networks*

Equally important is China's growing integration into *informal* global knowledge networks through the international circulation of students and knowledge workers. Since the opening of its economy, China has become intricately linked to more developed overseas innovation systems, first through a massive brain drain of its students and, more recently, through a reverse brain drain that brings returnees and overseas Chinese knowledge workers back to China.

The primary link of course has been with the US, and its universities, its high-tech industries and its financial sector. In 2005, for instance, China had more than 61,000 students in American universities, more than any other country except India.¹² Associations of U.S.-based Chinese engineers and managers such as Mount Jade, CASPA and NACSA, play an important role in channeling back and forth information flows and knowledge exchange between the US and China. China is also deeply integrated with US-centered professional peer group networks. In the IT industry, this includes IEEE and its many specialized working groups, but also industry segment-specific associations like for instance the Electronic Design Automation Consortium (EDAC)¹³.

China's integration into these informal global knowledge networks provides an important enabling factor for the development of its innovative capabilities. Exposure to professional peer group networks, China's large *diaspora* of skilled migrants, and "IT mercenaries" (from Taiwan, Hong Kong, Singapore, Malaysia, the Philippines, as well as Japan, the US and Europe) can all help to diffuse complex and often tacit knowledge about technology and management. In addition, these informal social networks can provide much needed experience and links with markets and financial institutions, and they can become an important source of reverse brain drain.

2.4. *Structural weaknesses*

There is no doubt that the "global factory" model will continue to be an important source for China's economic growth and capability development. However, both the 1997 financial crisis and the downturn in the global electronics industry in 2000 have brutally exposed the downside of that model. A country is more vulnerable to external disturbances, the higher the share of electronics in its exports, the greater its integration into GPNs, and the more it depends on exports to the United States (Ernst, 2001).

China's "global high tech factory" model is now experiencing decreasing returns, in terms of value added, profit margins and job creation. This limits funds available for R&D and makes it difficult to sustain wage increases. These decreasing returns reflect fundamental structural weaknesses that result from China's unequal integration into fragmented and hierarchical global production networks.

Furthermore, China firms heavily rely on American, Japanese and European firms as the dominant sources of new technology. This reflects the heavy concentration of R&D, innovative capabilities and intellectual property rights (IPR), much of it centered on the United States.¹⁴ For Chinese firms, this has resulted in razor-thin profit margins owing to the hefty licensing fees charged by the global brand firms. Hence, their capacity to develop new product markets and to shape technology

road maps and standards remains heavily constrained, and they struggle to improve their branding capabilities.

In response to these weaknesses of the “global factory” model, a broad consensus has emerged that China’s IT industry needs to upgrade to higher value-added and technologically more demanding products, services and production stages, and that this requires the development of strong innovative capabilities. To achieve this goal, China’s government and IT companies are seeking to develop and improve the skills, knowledge, and management techniques needed to create and commercialize successfully new products, services, equipment, processes and business models.

3. Industrial Upgrading - An Operational Concept

The concept of “industrial upgrading” (IU) can serve as a focusing device for China’s attempts to move beyond the “global factory” model and to unlock new sources of economic growth. The main objective is to exploit the productivity-enhancing potential of innovation, in order to avoid a race to the bottom that is driven solely by cost competition.

Hence, in general terms, industrial upgrading must focus on improvements in specialization, local value-added, productivity, and forward and backward linkages, all of which necessitate a broad base of knowledge and innovation (Ernst and Lundvall, 2004).

I distinguish two aspects of industrial upgrading that are of greatest policy relevance: “firm-level upgrading” from low-end to higher-end products and value chain stages, and “industry-level linkages” with support industries, universities and research institutes.¹⁵

“Firm-level upgrading” is the key dimension - without it, there is little hope that China can sustain and reinvent the success of its IT industry. In other words, Chinese firms must develop the capabilities, tools and business models that will allow them to address the weaknesses of the “global factory” model. And it is the strength of such firm-level upgrading that will decide whether Taiwan can cope with the new challenges from shifts in the global innovation system.

But for firm-level upgrading to succeed, upgrading must take place simultaneously at the level of “industry linkages”. To broaden the pool of firms that are fit for sustained firm-level upgrading, strong support industries are required and dense linkages with universities and research institutes. The challenge is to enable firm-level and industry-level upgrading to interact in a mutually reinforcing way, so that both types of upgrading will give rise to a ‘virtuous circle’.

Industrial upgrading in China also faces a second challenge. As its companies are integrated into multiple global networks of corporate production and innovation and informal knowledge communities, it is obvious that international linkages are critical for industrial upgrading. Hence, we need to distinguish domestic (‘local’) and international (‘global’) elements.

Finding the right balance between firm-level and industry-level upgrading, and between domestic and international elements poses a continuous challenge for policy makers and corporate planners - the “right balance” is a moving target, it is context-specific and requires permanent adjustments to changes in markets and technology. I argue that all four elements hang together - a strategy that neglects one element at the detriment of the others is unlikely to create sustainable gains. The stronger the links

between those four elements, and the better they interact, the greater are the chances that Chinese firms can shape markets, prices and technology road maps.

The international dimension of industrial upgrading will be addressed in a separate paper. Our focus here is on the domestic elements. We know from the study of 'national innovation systems' (e.g. Freeman, 1987; Nelson, 1993, Lundvall, 1992) that peculiar features of economic structures and institutions offer quite distinct possibilities for learning and innovation, and hence shape the technological (or economic) performance of a country/region. The economic structure determines specialization (i.e. the product mix and the production process) and learning requirements (the breadth and depth of the knowledge base, tools and capabilities). Institutions, on the other hand, shape learning efficiency: they define how things are done and how learning takes place. An important concern is the "congruence" (Freeman, 1997:13) of different subsystems, which is necessary to create a *virtuous* rather than a *vicious* circle.

This indicates that, on the domestic front, an essential prerequisite for industrial upgrading are institutions and incentives that facilitate innovation and the development of support industries, and that provide a sufficiently large pool of experienced and re-trainable knowledge workers with specialized skills. The role of institutions and incentives is well covered in the literature (e.g., Naughton and Segal, 2001). But we know less about the second equally important domestic element - how specialization in products and types of production may enhance the potential for industrial upgrading.

3.1. *Specialization and upgrading potential*

Specialization is an important indicator of the degree of industrial upgrading that a country or region can realistically expect to achieve. Specialization patterns reflect differences in product mix (e.g., homogeneous versus differentiated products), and in types of production (where I suggest to distinguish between 'routine' and 'complex' production, and between 'modular' and 'integrated' production). These differences in specialization, in turn, give rise to divergence in the complexity of technology, demand patterns and market structures. Most importantly, differences in specialization shape a country's (a region's) upgrading potential, in terms of learning opportunities, capability requirements, value-added and linkages.

For our purposes, a critical policy issue is to identify conditions under which specialization and upgrading potential are linked by a *virtuous* rather than a *vicious* circle. In fact, a narrow specialization on homogenous products or on 'modular' production may well make sense at an earlier stage of development, as it matches with the then prevailing competitive advantages. Yet, this very same specialization may later on hinder a transition to differentiated products or 'integrated' production.

3.2. *Product specialization*

Table 1 shows how the link between product specialization and upgrading potential works. Homogenous products ("commodities") have only a limited upgrading potential, in terms of learning opportunities, capability requirements, value-added and linkages. The opposite is true for differentiated products.

For our purposes, it is useful to establish a link with the product life cycle (PLC) theory. Following Vernon (1966), differentiated products are typically

associated with the early stage of the PLC, while homogenous products most likely to prevail during the late stage. Take the PC industry, a typical example of a 'late-stage' industry, which is an important sector of China's IT industry. As a "commodity", the PC has very limited upgrading potential. The root cause is that Intel and Microsoft are in almost complete control of the standards and technologies, with the result that return on innovation for PC vendors is low, while the cost of innovation is high.

**Table 1. Product Specialization and Upgrading Potential
(about here)**

By contrast, the scope for differentiation is broader for high-end handsets (especially smart phones) and for the mobile network industry. Both are examples of 'early PLC stage' industries. While entry barriers are high in both industries, in terms of investment and technology, there are ample opportunities for new entrants to upgrade through innovation.

High entry barriers are accompanied by qualitative competition. This requires complex capabilities to understand customer needs and to provide integrated solutions. Without policy support in "industry-level" upgrading, Chinese firms would be hard-pressed to cope with these demanding requirements.

At the same time, this is an industry where premium pricing is possible, at least in some market segments. To the degree that this translates into high profit margins, this facilitates investment in R&D. As system architectures and interface standards remain fluid and are evolving rapidly, there are many learning opportunities and Chinese firms are under considerable pressure to develop their capabilities. Furthermore, the mobile network industry provides ample opportunities for creating value-added and for developing linkages (both domestic and international) with customers, suppliers of core components and technology, and private and public R&D partners.

3.3. Types of production

The potential for industrial upgrading also differs for different types of production. I suggest distinguishing between 'routine' and 'complex' production, and between 'modular' and 'integrated' production¹⁶.

'Routine' versus 'complex' production

For "routine" production, the upgrading potential is obviously lower than for "complex" production that needs to combine diverse technologies and that may require customization, quick responses to changes in market and technology, and the provision of integrated solutions. The rewards for a transition to "complex" production can be high - if a firm successfully implements complex processes, it may benefit from premium pricing and significant profit margins, which in turn could provide sufficient funding for R&D. The downside, of course, is the substantially higher up front preparatory efforts that are necessary for successful entry into the more knowledge-intensive complex production.

Take chip design, where "routine" functions ('design implementation') are distinguished from "complex" stages of design that center on conceptualization, circuit architecture and system specification. The requirements for making the transition from design implementation to conceptualization are quite demanding.

Entry barriers are extremely high, as design costs at the 90 nano-meter technology (the current best-practice) can be as high as \$ 20 to 30 million (Ernst, 2005 a). Intensifying pressures to improve design productivity, combined with increasingly demanding performance requirements for electronic systems have produced an upheaval in chip design methodology.¹⁷ “System-on-chip“(SoC) design has moved design from the individual component on a printed circuit board closer to “system-level integration” on a chip.

These new challenges are likely to impose quite far-reaching changes on industry structure, business models and firm organization, illustrating again how closely inter-related are firm-level and industry-level upgrading.

‘Modular’ versus ‘integrated’ production

‘Modular’ production has played an important role for China’s “global factory” model. The PC industry has been an important breeding ground for this industrial organization model since the mid-1980s. Based on standard interchangeable components as well as the widely shared Wintel architecture, modular design has rapidly eroded the economic rationale for vertical integration (Baldwin and Clark, 2000).

Market-led standardization (through technical standards and design rules) of the interfaces between organizationally separate stages of production has made it possible to transform PCs and related products into fully “modular” or decomposable building-blocks, enabling firms to focus on those activities (‘core competencies’) that generate the highest margins and which are critical for sustaining the company’s competitive advantage (e.g., Sanchez and Collins, 2001). This has created ample opportunities for vertical specialization (‘fragmentation’) of the PC value chain, giving rise to the OEM/ODM arrangements discussed in this paper.

But modular production has been extended well beyond the PC industry. In the semiconductor industry, this gave rise to the decoupling of design and fabrication that culminated in the well-known symbiotic fabless/foundry relationship, a relatively simple structure. As with earlier forms of modular production in the PC industry, decoupling between IC design and fabrication was based on shared interface standards and well documented and automatically checkable “design rules”.

Yet, ‘modular’ production now seems to give way to more integrated forms of IC production (Ernst, 2005b). In fact, decoupling of design and fabrication became impractical once large, complex SoC designs had to be fabricated with 90 nanometer process technology. This required a re-coupling of design and fabrication, giving rise to much closer interaction between chip designers, design service providers, mask makers, foundries, EDA tool providers and IP providers.

The important point for our purposes is that the shift to more integrated forms of production may well enhance the upgrading potential of China’s IC industry. For design teams, the recoupling of IC design and fabrication implies that they now have to “design-for-yield-enhancement.” In other words, designers must now take into account the effects of fabrication process variations, which make design even more complex. The greatest upgrading pressures are on EDA tool providers which are forced to come up with new integrated solutions under the heading of “design for manufacturing” that would facilitate close interaction. And there will be a huge demand for design service firms that have to fill the gaps left by global EDA tool providers.

As the established “fabless/foundry” model is being eroded, it is not yet clear which new model is likely to take its place (Ernst, 2006c). As a late-latecomer, China can watch how IC firms at different levels of the global IC value chain are experimenting with diverse upgrading approaches. Such an approach, which requires a bit of patience, provides priceless learning opportunities about what is necessary and feasible.

4. Implications for Innovative Capabilities

What specific innovative capabilities are required to upgrade China’s IT industry? To answer that question, we can draw on the concept of “industrial upgrading”, developed in this paper. In addition, however, we need to open the black box of “innovation”.

4.1. Conceptual building-blocks

To determine more precisely the nature of ‘innovative capabilities’, we can draw on some building blocks provided in the literature.

The study of R&D expenditures has focused on econometric studies of panel data that convey some useful “broad brush” indicators, but provide only limited guidance on firm-level innovative capabilities. However, the increasing sophistication of patent data analysis (e.g., Jaffe and Trajtenberg, 2002 and Granstrand, 1999) now makes it possible to extend that analysis to the level of the firm.

In addition, patent data analysis can now be used as a proxy indicator for measuring progress in Asia’s innovative capabilities, as “patenting activities in the region appear to have grown to sufficiently high levels” (Wong, 2006: 11). This is true at least for the NIEs-4, China and India. Specifically, the analysis of patents filed at the USPTO can help to identify the location of an invention (address of first-named inventor) and the nationality of the patent owner (location of assignee). U.S. patent data analysis can also help to determine the quality and impact of patents (patent citations) and their complexity (science-intensity); the clustering/geographic dispersion of patenting activities (by measuring “hot spots”); and the knowledge exchange between inventors at different locations.

Especially useful for our purposes is research that, based on questionnaire surveys and structured firm interviews, has developed operational data sets for measuring firm-level innovative and R&D capabilities¹⁸. For instance, a comprehensive taxonomy of firm-level capabilities was developed in a study, prepared for the United Nations Conference on Trade and Development (UNCTAD), that distinguishes capabilities required for production, investment, minor change, strategic marketing, establishing inter-firm linkages, and major change (Ernst, Ganiatsos, Mytelka, 1998). This taxonomy, which suggested a sequential ordering of priorities for capability formation, was largely confirmed in that study’s comparative analysis of how electronics and textile firms have developed their capabilities in Taiwan, Korea, Thailand, Indonesia and Vietnam.

4.2. A broad definition of “innovative capabilities”

Building on this literature, I suggest to use a broad definition of “innovative capabilities” to emphasize that, in addition to R&D and patents, complementary “soft” entrepreneurial, management and system integration capabilities are of critical

importance. I define “innovative capabilities” to include the skills, knowledge and management techniques needed to create, change, improve and commercialize successfully “artifacts”, such as products, services, equipment, processes and business models (Ernst, forthcoming).¹⁹

Innovations in the IT industry require R&D capabilities. Amsden and Tschang (2003) provide a useful classification of technological complexity of different categories of R&D. They distinguish “process development” (to reduce costs, uncertainties and time-to-market of manufacturing, and to improve flexibility); “prototype development” (to implement a product or system design as an engineered system through detailed product design and engineering samples); “applied research” (to transform, modify and recombine known technologies so that they fit new applications); “basic research” (to apply new knowledge for radically new marketable products); and “pure science” (to uncover new scientific principles).

While R&D is essential, it is important to emphasize that equally important are complementary “soft” capabilities beyond the fields of science and engineering. Research on successful innovations demonstrates that “the technology is the easy part to change. The difficult aspects are social, organizational, and cultural” (Norman, 1998).

Specifically, I emphasize the following “soft” innovative capabilities that need to complement “hard” R&D, in order to create products and services that customers are willing to pay for:

- sense and respond to market trends before others take note (“entrepreneurship”);
- recruit and retain educated and experienced knowledge workers who are the carriers of new ideas;
- global knowledge sourcing for core components, reference designs, tools, inventions and discoveries;
- raise money required to bring an idea quickly to the market (the litmus test of innovation);
- deliver unique and user-friendly industrial designs (which is of critical importance especially for fashion-intensive consumer devices, like mobile handsets);
- develop and adjust innovation process management (methodologies, organization and routines) in order to improve efficiency and time-to-market;
- manage knowledge exchange within multidisciplinary and cross-cultural innovation projects;
- participate in and shape global standard-setting;
- combine protection and development of intellectual property rights; and
- develop credible and sustainable branding strategies.

Each and every of these “soft” capabilities is important in its own right. But they are also inseparable. For instance, a narrow focus on brand marketing is insufficient. Branding efforts need to be supported by a broad mix of “soft” and “hard” innovative capabilities. This implies that a capacity to provide “integrated solutions” is arguably one of the most important prerequisites for industrial upgrading based on innovation.

According to Davies et al (2001:5), “integrated solutions” encompass four sets of capabilities: (1) system integration: to design and integrate components and subsystems into a system; (2) operational services: to maintain, finance, renovate and operate systems through the life cycle; (3) business consulting: to understand a

customer's business and to offer advice and solutions that address a customer's specific needs; and (4) finance: to provide a customer with help in purchasing new capital-intensive systems and in managing a customer's installed base of capital assets. By and large, US, Japanese and European electronics firms have sophisticated and proven strategies in place that can provide simultaneously these four complex "integrated solutions" services.

A few large Chinese IT firms (like Lenovo, Huawei, ZTE and Haier) are now making serious efforts to catch up in the mastery of these most critical innovative capabilities. They seek to develop less over-engineered and expensive products that address effective customer needs that market leaders have neglected. Two examples are Huawei's integrated IP phone services platform ME60 (discussed below) and Lenovo's Tianxi laptop, a decisively low-tech model introduced in the mid-1990s that single-handedly created the Chinese PC market for private consumers and small businesses²⁰.

In addition, a few Chinese chip design start-up companies (such as Verisilicon, Chipnuts, Vimicro, RDA, Jade) have made an effort to build a broad portfolio of 'soft' innovative capabilities and to provide unique and lower-cost integrated solutions (Ernst, 2006e). But these efforts still have a long way to go. This requires conscious efforts of industry-level upgrading. The challenge for policy-making is to foster "integrated solutions" capabilities on an industry-wide level so that individual firms can access these capabilities without encountering the extremely high cost burden of developing them in-house.

4.3. Technology leadership is not the only option

There is no doubt that, despite its impressive achievements, China continues to lag behind advanced nations in the development of a broad-based science and technology system. Structural weaknesses of the "global factory" model add an additional important constraint. These constraints are hardly surprising - they reflect China's status as a late-latecomer to industrialization.

At the same time, however, being a late-latecomer also conveys important advantages. Not only can China learn from the experience of earlier latecomers, but it can also seek to benefit from recent shifts in the international technology system, especially deeper integration into global innovation networks.

The "global factory" model has helped Chinese firms to perfect "fast-follower" strategies that aim at entering a product market right at the beginning of its high-growth stage (e.g., Mathews and Cho, 2000). But which model should follow next?

Research on innovation strategies in industrialized countries (e.g., OECD, 2000) points to "technology leadership" strategies that focus on 'radical' innovations that involve both the use of new component technology and changes in architectural design (Henderson and Clark, 1990). The objective is to become a prime mover of knowledge creation, by setting global standards during product introduction. Radical innovations challenge established market leaders, since they destroy the usefulness of the leaders' capabilities. This requires the creation of new "intellectual property rights", especially a broad portfolio of frequently cited "pioneer" patents connected with important inventions and discoveries.

In the literature on China, there is a tendency to discard 'technology leadership strategies' out of hand as a retreat to old-fashioned 'techno-nationalism'. This neglects

the needs of a large quasi-continental economy and its growing role within Asia and the global economy. Whether one likes it or not, there is no doubt that China will seek access to best-practice technologies that provide solutions to its military and space programs. Given the restricted nature of these technology markets, the Chinese government believes that it has to develop its own technologies, simply to develop sufficient leverage for international technology cooperation²¹. Similar pressures to develop a critical mass of own technologies exist for complex technology systems in energy, environment, climate prediction, although the scope for international collaboration is certainly larger, once China has established itself as a serious player.

“Technology leadership” strategies however come at a horrendous cost. It is important to emphasize that attempts to compete head-on with global technology leaders necessitate a massive upgrading of innovative capabilities. To become a “technology leader”, a firm needs to have access to a broad set of capabilities in applied research, basic research, as well as in “pure science”. To develop such a portfolio of demanding capabilities needs time. It also needs very deep pockets to finance the massive increase of R&D. This in turn necessitates high profit margins based on premium pricing.

Most importantly, “technology leadership” strategies are extremely risky and market prospects are highly uncertain. The new products may reflect ingenious radical innovations. Yet, this does not guarantee that customers are willing to pay for these innovations. In fact, the more complex the technology, the more difficult to use are the resultant products, and the more they are prone to breakdowns due to unproved technology. The IT industry is full of examples that show that only very large, cash-rich firms can cope with such high risks²².

In China’s IT industry, only very few companies can master this game. But even they are sometimes forced to stretch their resources to the limits. An example are super computers. China’s decision to develop by herself high performance computing technology, as well as some other key technologies such as those in telecom equipment, was largely due to the technology export control imposed by organizations of the most developed countries, such as the Coordinating Committee for Multilateral Export Control (COCOM). In a way, China was forced to choose the “technology leadership” option.

That strategy did produce some tangible results. China’s most powerful supercomputer, Dawning’s 4000A, was ranked as 10th in the world as early as in 2004. Its grid-oriented AMD 64 PC-Cluster design uses some unique features, which allows for a theoretical peak performance of 22 T Flops. This is quite an achievement for a company that pales in size relative to global industry leaders and that has only limited financial and human resources. Of critical importance were close links with the Institute of Computing Technology of the Chinese Academy of Sciences (CAS), whose president chairs the board of Dawning. But to keep up with the accelerating pace of high-end computing technology will require increasingly large resources.

A similar story of impressive, yet costly achievements emerges from Lenovo’s super computer projects (Ernst, 2006b). The first project was the *DeepComp 1800 supercomputer*, introduced in 2001, which, based on 526 Intel Xeon processors, was ranked 51st by 2002. This was followed, in November 2003, by the *DeepComp 6800* model that was ranked 14th worldwide, and was jointly funded by the Ministry of Science and Technology and the Chinese Academy of Sciences. There were expectations that a commercialized version of this machine could be used during the 2008 Beijing Olympic Games for a precise 36-hour weather forecast on a specific area

within just 30 minutes of computing work (which now requires 40 hours). Markets were also expected to exist for computing data from oil fields, in disease control centers and physics labs. It is unclear however to what degree these expectations will materialize.

Finally, the most recent project, the *1000 TFLOPS supercomputer*, which was started in 2005 and scheduled for completion before 2010, is supposed to be nearly ten times more powerful than the world's fastest supercomputer. But resource requirements are also growing. The underlying rationale was clearly more political than commercial, driven by the perception that China cannot rely on other countries to develop a supercomputer that meets its needs.

In short, for Chinese IT firms, "technology leadership" based on "radical" innovations pose a difficult challenge - investment requirements are huge and require substantial government support, while markets are likely to be limited. There may however be indirect commercial benefits, as successful completion of a radical innovation project may help to establish a company as a serious player and foster its brand image.

Nevertheless, the future of China's IT industry critically depends on quick access to radical innovations, especially in generic technologies. For instance, Chinese firms need core component technologies and insider information on interface standards, in order to compete in the mobile network industry. The same is true for in system-on-chip (SOC) design for wireless and optoelectronics systems and for embedded processors. And quick application of nano-technology research is critical for the upgrading of China's semiconductor and optoelectronics industries.

To move ahead in these areas obviously requires concerted industry-level upgrading efforts by the government and industry. Such efforts are needed to reduce the very substantial barriers that individual firms face when they try to move to technology leadership strategies. China has significant policy initiatives in each of the above areas²³. The question is how quickly these initiatives will enable firms to develop successful products.

But even then, the risks are high. This implies that an exclusive focus on technology leadership strategies is unlikely to support a broad-based upgrading through innovation strategy.

4.4. Technology diversification as a complementary option

In short, "technology leadership" strategies are not the only option for China's attempts to move beyond the "global factory" model. "Technology diversification" can serve as a complementary and arguably less costly option (Ernst, 2005c).

Defined as "the expansion of a company's or a product's technology base into a broader range of technology areas" (Granstrand, 1998:472), technology diversification focuses on products that draw "... on several... crucial technologies which do not have to be new to the world or difficult to acquire" (Granstrand and Sjoelander, 1990: p.37). It requires strong research capabilities, but it is much more focused than "technology leadership" on applied research that feeds directly into product development.

Empirical research on Japanese, U.S. and Swedish companies has demonstrated that technology diversification plays a more important role than technology substitution, as seen from the larger number of old technologies in a current product generation, compared to the number of obsolete technologies (e.g.,

Granstrand, Patel and Pavitt, 1997). Japanese firms in particular have played a pioneering role in the development of technology diversification strategies (Kodama, 1995). Japanese firms pursued this strategy to compensate for the decreasing returns of their existing manufacturing exports. They also used it to develop generic technologies that could form the base for penetrating future growth markets, and to avoid the high cost and uncertainty of “technology leadership” strategies.

For China, “technology diversification” promises several advantages. By recombining (mostly known) component and process technologies, it generates technology-related economies of scope. ‘Technology diversification’ could thus avoid the high cost and risk of a “technology leadership” strategy. Second, technology diversification can also build on China’s existing strengths in process development, “prototyping and electronic design, as well as on recent progress in the development of “integrated solutions” capabilities. Third, Chinese firms can build on their accumulated capabilities to implement, assimilate and improve foreign technologies, as technology diversification often involves the exchange of knowledge with foreign parties.

This brings us to a last, but critical advantage of ‘technology diversification’. By focusing on ‘architectural’ innovations, this strategy allows Chinese firms to extract greater benefits from deeper forms of integration into global innovation networks.

“Architectural” innovations are “innovations that change the architecture of a product without changing its components” (Henderson and Clark, 1990: 9). These innovations use existing component technology, but change the way components are designed to work together, hence *breaking new ground in product development*.

Capability requirements are demanding, but they are within reach of Chinese companies. By definition, late-latecomers like Chinese IT firms continue to lag behind industry leaders in the breadth and depth of their R&D and innovative capabilities. Their strength however is that they are familiar with peculiar characteristics of China’s markets and institutions, and that they are exposed to user requirements that global industry leaders have neglected. Having started as distributors of foreign products and services, Chinese firms have been exposed to China’s insatiable but largely untouched demand for products and services that are not over-engineered and hence are less expensive, but provide essential performance features.

Chinese firms can use this knowledge to penetrate China’s large mass markets, *not by following but by breaking new ground in product development*. Of critical importance is a capacity to develop products and services that are less over-engineered and expensive than those of global market leaders, and that address “effective customer needs”²⁴ that incumbent global market leaders have neglected. This requires a change in the architecture of a product or service.

And barriers to implement that new architecture are limited. In fact, Chinese firms do not need to develop the necessary components, nor do they have to change them. Integration into multiple global production and innovation networks enables Chinese firms to buy in the relevant component technology from specialized suppliers. As demonstrated by Iansiti (1997), global markets for technology imply that a firm’s competitive success critically depends on its ability to monitor and quickly seize external sources of knowledge. Hence, Chinese firms can leverage basic or generic technologies developed elsewhere. Chinese firms might also engage in collaborative development of some of these components.

An early example is the development of China's electronic switching system HJD04 - the innovation consists in developing a system architecture that optimizes performance features in line with the specific features of the national telecommunications network structure and the specific needs of the service providers (Shen, 1999). Other examples include: the development of Chinese-language electronics publishing systems by the Founder Group Company, a spin-off from the Institute of Computer Science and Technology of Beijing University (Lu, 2000: chapter 4); and the development of the unique Chinese video compact disk (VCD) technology and the successful transition to Chinese DVD system technology.

While these architectural innovations use existing component technology, they nevertheless introduce substantially new and distinct features to existing system architectures. Another more recent example is Huawei's development of a new integrated IP service platform ME 60. This is the first integrated multi-service platform on the market that enables telecommunications operators to substantially improve the quality of service and the security of their IP services at a reduced cost of operation.

Current IP networks do not offer the security and quality of service that operators request, while traditional networks are incapable of supporting bandwidth-hungry multimedia services such as IPTV. Operators have a number of consumer and business products in the market, such as DSL, cellular, ATM²⁵ IP VPN²⁶, and central office exchange services. To improve service quality and security, these products need to be aggregated and run over a common IP core²⁷. The ME60 is the "Swiss army knife" that enables operators to aggregate multiple services from various networks into one IP core and that improves the operators' real-time control over these services.

In technical terms, this system is quite an achievement. As a 10-Gigabit multi-service control gateway²⁸, the ME is an edge router that sits between the IP core and the access network (which may be fixed or mobile).

But equally important is the systems' capacity to provide, at reasonable cost of operations, customized solutions to problems that thus far have obstructed the progress of IP networks. A defining characteristic of the ME-60 is its ability to deliver tailor made products as a response to customers' specific needs. This is quite unusual in the network equipment industry, where incumbent industry leaders typically provide standard solutions.²⁹

Huawei's approach is very different. The key to the success of the ME60 system is Huawei's capacity to integrate multiple system components into a versatile and flexible system. A distinguishing feature of the ME 60 is its high level of integration through a single software system. This makes it possible to integrate the capabilities currently separated in different network parts (like broadband remote access server and fire walls) which until now had no common communication standards.

This capacity to provide integrated solutions does not seem to be widely shared in the network equipment industry. According to industry experts, Cisco, the industry leader, could only build such a system by teaming up with other companies like Ericsson.³⁰ While Cisco has major advantages in market reputation and product quality, its products apparently lack the integration of multiple functions that is characteristic for Huawei's ME60 system³¹.

5. Conclusions

This paper has explored what innovative capabilities are required for upgrading China's IT industry. To answer that question, I have highlighted achievements and weaknesses of China's "high tech global factory" model.

In addition, I have introduced a concept of "industrial upgrading" that links specialization with firm-level and industry-level upgrading. At the center of this concept is the need to find the right balance between firm-level and industry-level upgrading, and between domestic and international elements. This poses a continuous challenge for policy makers and corporate planners - the "right balance" is a moving target, it is context-specific and requires permanent adjustments to changes in markets and technology.

The paper culminates in a discussion of specific innovative capabilities that are required to upgrade China's IT industry. I emphasize that "soft" entrepreneurial, management and system integration capabilities need to complement "hard" R&D in order to create products and services that customers are willing to pay for. I argue that, as "technology leadership" strategies are extremely costly and risky, only few companies in China's IT industry can master this game. As the future of that industry critically depends on quick access to radical innovations, especially in generic technologies, this requires concerted industry-level upgrading efforts by the government and industry. Such efforts are needed to reduce the very substantial barriers that individual firms face when they try to move to technology leadership strategies.

Hence, "technology leadership strategies" that focus on 'radical' innovations are not the only option for China's "upgrading through innovation" strategy. "Technology diversification" can serve as a complementary, and arguably less costly option. I emphasize that the most important bottleneck to technology diversification right now are "soft" entrepreneurial, management and system integration capabilities.

This has important implications for the design and implementation of China's upgrading strategy. First, as a late-latecomer, China has to develop its own idiosyncratic approach to policies, support institutions and business strategies. The experiences of other countries, in Asia, but also in the US and Europe, can provide important insights. But, in the end, China has to come up with its own solutions, based on its own peculiar strengths and weaknesses.

Second, given the rapid pace of change in the global electronics industry structure, upgrading the country's electronics industry involves multiple moving targets, hence solutions have to be constantly adjusted. Of critical importance is the choice of appropriate sequencing patterns for developing innovative capabilities. Equally important is a sufficient degree of flexibility in policies and institutions that allow for quick response and adjustments to abrupt changes in markets and technology, and to unexpected outcomes of upgrading policies.

Third, and finally, multiple international linkages are considered to play an important catalytic role in facilitating and accelerating the upgrading of China's electronics industry. The focus however has moved away from an earlier heavy reliance on technological capabilities developed within affiliates of global flagships, and their eventual spill-overs into local firms. Also, earlier attempts (especially in the car industry) to trade market access in exchange for access to technology may not be sustainable any longer.

China needs to expand and deepen international knowledge sourcing through multiple linkages with foreign universities, research institutes, and consulting firms, and by tapping into the vast informal global peer group networks of overseas Chinese

researchers, engineers and managers. A progressive integration into these diverse global innovation networks can help Chinese IT firms to bridge existing gaps in specialized skills and innovative capabilities. Most importantly, it can catalyze changes in organization and procedures that are necessary to develop these capabilities locally.

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Table 1. Product Specialization and Upgrading Potential

Variables	Low specialization	High specialization
Product specialization	homogeneous (commodities) <ul style="list-style-type: none"> • mature technology • established design • easy to replicate • predictable changes in demand and technology • limited interactions with customers 	differentiated <ul style="list-style-type: none"> • new technology • fluid design • difficult to replicate • unpredictable changes • close interaction with customers
Market structure	<ul style="list-style-type: none"> • low entry barriers • price competition • speed-to-market • periodic over-capacity & price wars (“commodity trap”) • low profit margins 	<ul style="list-style-type: none"> • high entry barriers • qualitative competition (customer needs; integrated solutions) • premium pricing • high profit margins
Upgrading potential	<ul style="list-style-type: none"> • few learning opportunities • limited capability requirements • low value-added • limited forward & backward linkages 	<ul style="list-style-type: none"> • many learning opportunities • demanding capability requirements • high value-added • extensive forward & backward linkages

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¹ I gratefully acknowledge ideas, comments and suggestions from Calestous Juma, Greg Shea, Clark Duncan, Richard P. Suttmeier, Barry Naughton, Ron Wilson, Xielin Liu, Xudong Gao, Chintay Shih, Kane Wang, T.C.Tu, Shin-Horng Chen, Pang Eng Fong, Wong Poh Kam, Ted F. Tschang, Xiaobai Shen, Boy Luethje and Adam Segal. At the East-West Center, I am grateful to Charles Morrison and Nancy Lewis for supporting this research, and for discussions with Ray Burghardt, Carol Fox, Dick Baker and Mark Borthwick. The Volkswagen Foundation provided generous funding. Kitty Chiu, Peter Pawlicki and Rena Tomlinson provided excellent research assistance. I am grateful to Brenda Higashimoto for her constructive suggestions in editing the manuscript.

² The importance of lead users for innovation is demonstrated by von Hippel (1988 and 2005).

³ Rapid growth of mobile, internet and broadband subscribers, together with still vibrant PC sales, drive massive investments in IT infrastructure and generate a voracious demand for semiconductors. Together

with Japan, China now dominates Asia's semiconductor market, well ahead of South Korea, Taiwan and Singapore. (Hopfner, 2007)

⁴ "Knowledge workers" are defined to include science and engineering personnel, as well as managers and specialized professionals (in areas like marketing, legal services and industrial design) that provide essential support services to research, development and engineering.

⁵ For the concept of global production networks, see Ernst (1997, 2002a), and Ernst and Kim (2002). For case studies, see Borrus, Ernst and Haggard (2000), and Ernst (2003, 2004 and 2006f).

⁶ An additional important development, not addressed in the paper, is the integration of Chinese IT firms into international standard-setting alliances.

⁷ The UNCTAD sample consists of the first 300 firms of the R&D scoreboard of the 700 top worldwide R&D spenders, published by the UK Department of Trade and Industry (DTI).

⁸ Private equity investment is medium- to long-term finance provided in return for an equity stake in potentially high-growth companies that are not listed on a major public stock exchange. According to the British Venture Capital Association, it encompasses both "venture capital" (from the seed to the expansion stages of investment) and management buy-outs and buy-ins.

⁹ Sources include the US and the UK National Venture Capital Associations and consulting firms like Greenwich Associates, Private Equity Intelligence (PEI) and Shanghai-based Zero2IPO for China.

¹⁰ Courtesy of Private Equity Intelligence (PEI), a London-based specialized consulting firm (July 6, 2006)

¹¹ An example is the recent indictment of Warburg Pincus's Korean office on charges of insider trading ("Warburg Pincus faces Won 26 bn fine", FT, 19 April 2006, p.16).

¹² Data, courtesy of the U.S. Council of Graduate Schools, March 2006

¹³ China apparently now also relies on a growing circulation of students and knowledge workers with other Asian countries (especially Taiwan, Japan and Singapore), as well as with the EU, Russia and Eastern Europe (Interviews Beijing 05 24 06).

¹⁴ In 2000, 85 percent of global R&D expenditures were concentrated in only seven industrialized countries. The United States occupied the leading position with 37 percent (Dahlman and Aubert 2001, p.34).

¹⁵ The other three forms of "industrial upgrading" discussed in the literature are: (i) inter-industry upgrading proceeding from low value-added industries (e.g. light industries) to higher value-added industries (e.g. heavy and higher-tech industries); (ii) inter-factor upgrading proceeding from endowed assets (i.e., natural resources and unskilled labor) to created assets (physical capital, skilled labor, social capital); and (iii) upgrading of demand within a hierarchy of consumption, proceeding from necessities to conveniences to luxury goods. See Ozawa (2000) for discussion of upgrading taxonomies. Most research has focused on a combination of the first two forms of IU, based on a distinction between low-wage, low-skill "sun-set" industries and high-wage, high-skill "sunrise" industries. Such simple dichotomies however have failed to produce convincing results, for two reasons (Ernst, 2001b): First, there are low-wage, low-skill value stages in even the most high-tech industry, and high-wage, high-skill activities exist even in so-called traditional industries like textiles. And second, both the capability requirements and the boundaries of a particular "industry" keep changing over time. An example is the transformation of the personal computer industry from an R&D-intensive high tech industry to a commodity producer that depends on the optimization of supply chain management.

¹⁶ I use these distinctions to move the research agenda beyond the popular, but somewhat schematic dichotomy of 'Fordist mass production' versus the 'Post-Fordism Flexible Specialization'. For a detailed theoretical discussion, based on evidence from chip design, see Ernst (2005b).

¹⁷ "Design methodology" is the sequence of steps by which a design process will reliably produce a design "as close as possible" to the design target, while maintaining feasibility with respect to constraints.

¹⁸ Important contributions include Lall (1992), Ernst and O'Connor (1992), Hobday (1995), Ernst, Ganiatsos, and Mytelka (1998), Amsden and Tschang (2003), and Jefferson and Kaifeng, 2004.

¹⁹ This broad definition is in line with Peter Drucker's classic statement: "The test of an innovation, after all, lies not in its novelty, its scientific content, or its cleverness. It lies in its success in the marketplace." (Drucker, 1985, p.VIII).

²⁰ For case studies on Lenovo and Huawei, see Ernst, 2006 b and 2006d, and Ernst and Naughton, 2007.

²¹ Presentation by Ltd. General Wen Xisen, president of China's National University of Defense Technology (NUDT), at the Asia-Pacific Center for Security Studies, Honolulu, 18 June, 2007.

²² A telling example is Sony's third-generation PlayStation that is based on radical, but still unstable Bluetooth technology which causes lengthy delays in its market introduction.

²³ For IC design, the government has established two national multi-project wafer (MPW) service centers (one in Beijing, and one in Shanghai) that provide access to foundries and assembly companies, both from Taiwan (for sophisticated design rules) and from China. And seven government-supported Research Centers for Integrated Circuit Design (in Shanghai, Beijing, Suzhou, Wuxi, Hangzhou, Xi'an, and Chendu) provide a variety of knowledge-intensive services, including subsidized access to leading-edge EDA tools, that help to overcome constraints that individual Chinese design houses face when trying to transform their designs into silicon. Equally important are attempts to develop standards that could leverage China's large market and its peculiar characteristics, such as TD-SCDMA, a third generation (3G) digital wireless standard.

²⁴ I define "effective customer needs" as those customers are willing to pay for.

²⁵ Asynchronous Transfer Mode

²⁶ Virtual Private Network – allows secure remote connection within an organization's network over the Internet.

²⁷ The IP core, also sometimes called backbone, is the primary path of an IP network traffic. It connects smaller segments of a network and has a high concentration of traffic.

²⁸ A gateway is the entrance to another network. The gateway allows equipment with different protocols to communicate.

²⁹ The main explanation for the incumbents' focus on standard solutions is their very high development costs. This reflects the fact that global industry leaders have their major R&D operations located in high-cost industrialized countries. In addition, many of their products are over-engineered – they provide leading edge technology that exceeds by far the needs of most users. These high R&D costs necessitate a business model that seeks to reap economies of scale through "mass-manufacturing" of standard and fairly inflexible solutions.

³⁰ Huawei unveils god box, *Unstrung*, 21.06.2005,

http://www.lightreading.com/document.asp?doc_id=76055

³¹ According to the same source, Alcatel, another global industry leader, may only be able to build a similar system if it had the capacity to develop broadband remote access servers.