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Late Innovation Strategies in Asian Electronics Industries: A Conceptual Framework and Illustrative Evidence

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LATE INNOVATION STRATEGIES IN ASIAN ELECTRONICS INDUSTRIES - A CONCEPTUAL FRAMEWORK AND ILLUSTRATIVE EVIDENCE[1]

by

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prepared for the special issue of Oxford Development Studies in honor of Linsu Kim

[1] This article draws on discussions with the late Linsu Kim. We were planning to write a follow-up piece to our contribution to *Research Policy* (2002) that was to explore how Asian firms can use integration into global production and design networks to proceed from *sequential* innovation strategies (as introduced in Kim, 1980) to *concurrent* innovation strategies that would combine learning from foreign technology and innovation in system-level chip design.

Introduction

The emergence of Asia (outside Japan) as a global export platform base in the electronics industry is one of the few success stories of Third World economic development. The primary goal has been to catch up with operational, mostly production-related capabilities of advanced nations and to out-fox them by becoming faster and lower-cost followers (Kim, 1980, 1997; Westphal, Kim and Dahlman, 1985; Ernst and O'Connor, 1992; Hobday, 1995; Lall, 2000; Ernst, Mytelka, Ganiatsos, 1998; Mathews and Cho, 2000; Ernst, 2000). By reversing the sequence of technological development in advanced countries (Dahlman, Ross-Larson and Westphal, 1987), Asian firms have used production capabilities as the foundation for developing capabilities in investment and adaptive engineering, while product and market development and process innovation were postponed to a later stage of development.

These strategies have produced impressive results. In electronics manufacturing for instance, five Asian countries (China, Korea, Taiwan, Singapore and Malaysia) account for over one quarter of world production. Furthermore, while India has failed to excel as a global manufacturing exporter, the country has firmly established itself as a global export production base for software and information services. These achievements are now history. Today, Asia's leading electronics exporting countries are aggressively pursuing strategies to establish themselves as new sources of innovation and global standards in industries like electronic components (especially semiconductors and chip design), digital consumer devices, wireless telecommunication systems, and business process software. In addition to design implementation, this includes innovations in process technology for electronic components and in the design of complex system architectures.

A defining characteristic of these "late innovation strategies" is a heavy reliance on international knowledge sourcing from global industry leaders, for instance for critical component and process technologies. But how is it possible that Asian firms can innovate in industries that involve highly complex technological knowledge, while they continue to lag substantially behind advanced nations in the development of their R&D and innovative capabilities?

That new actors from Asia are entering the "global innovation race" (Baumol, 2002) raises two important puzzles for the study of innovation. First, it runs counter to a widespread assumption in innovation theory that innovations and global standards necessarily emerge first in a few global "centers of excellence", especially in the US. Underlying this assumption is the well-established notion that innovation requires dense interactions within co-located specialized knowledge communities in order to reduce the dual challenges of cognitive and organizational complexity (Pavitt, 1999: XI). One would thus expect innovative activities that involve highly complex technological knowledge to remain spatially concentrated, much less prone than manufacturing to geographic relocation to Asia.

A second puzzle results from the equally well established notion that, as industrial latecomers, Asian economies had to proceed *sequentially* from imitation to innovation (Kim, 1997). The cumulative character of technological learning, from acquisition to assimilation and on to improvement of foreign technology, would thus seem to impose fundamental barriers to a strategy of combining international knowledge sourcing from industry leaders with the *concurrent* development of engineering, development and research capabilities.

Unfortunately, recent attempts in Asia to develop "late innovation strategies" are poorly understood and under-researched. We thus need to take stock of what is really happening. As a first step, I conducted interviews during 2002 and 2003 with a sample of 50 companies that are involved in electronic design (for integrated circuits as well as systems) in the US, Taiwan, Korea, China and Malaysia[2]. Using illustrative evidence from this research, this paper develops a conceptual framework to explore the international and domestic forces that drive "late innovation strategies" in Asian electronics industries. Part one highlights challenges that have induced Asia's leading electronics exporting countries to explore and implement "late innovation strategies". Part 2 reviews evidence on the evolution of electronics design in Asia's leading electronics exporting countries, to establish what capabilities have been developed, and to shed light on the forces that are driving these "late innovation" strategies. The rest of the paper introduces a few conceptual building-blocks that we need to capture peculiar features of these strategies. Part 3 introduces key hypotheses and identifies intellectual sources that can be used to theoretically ground these hypotheses. Finally, in part 4, I argue that transformations in global markets, production and innovation systems are providing new opportunities for Asian "late innovation strategies" to proceed with the *concurrent* development of engineering, development and research capabilities.

1. New Challenges

There is a dearth of research on the recent attempts in Asia to develop "late innovation strategies" in the electronics industry. I argue that these strategies are a response to the daunting challenges facing Asian electronics firms as they seek to grow and remain profitable in the context of rapidly changing technologies and markets. First, *decreasing returns* to export-led industrialization have demanded that firms and states seek to upgrade to higher value-added and knowledge-intensive products and services in order to sustain profits and growth potential. A number of factors are responsible for the trend, including: declining employment generation capabilities (especially when laid off workers are not rehired, as was more commonly the case through the mid-1990s); a general slowdown of productivity growth (e.g., Yusuf, 2003); cyclical factory closures as global brand leaders and their contractors move to lower labor-cost regions when wages rise; and truncated local spill-over effects as highly mobile production facilities reduce local investments and relationship- building efforts of the sort that generate long-term payoffs for local economies.

Second, successive waves of *external shocks*-- economic, political, and health-related-- have introduced periodic disruptions and uncertainty into markets. Innovation is widely perceived as an important weapon to shield Asian economies against external shocks that now appear as all but permanent features of a fluid and volatile global marketplace.

[2] The sample includes eight strategic groups: global system companies, global integrated device manufacturers (IDMs), global providers of electronic manufacturing services (EMSs) and design services (the so-called ODMs, or "original-design-manufacturers), global "fabless" chip design houses, global vendors of electronic design automation (EDA) tools, Asian system companies, Asian fabless design houses, and Asian design implementation service providers (both private and public). In China, the sample includes state-owned enterprises (SOEs), collective enterprises, and private technology firms.

“Globalization”, in essence, increases the integration, across borders, of markets for capital, goods, services, knowledge, and labor (Ernst, 2003a). Barriers to integration continue to exist, of course, especially for low-wage labor. But there is no doubt that a massive integration has taken place across borders that, only a short while ago, seemed to be impenetrable. This has increased the synchronization of economic activities, including financial crises and recessions (Eichengreen and Rose, 1998).

Third, there is a widespread fear in Asia’s leading electronics exporting countries that a US-centric *concentration* of economic power and of the sources of innovation may constrain, if not foreclose attempts to move from manufacturing to innovation. There is clear evidence that the concentration of economic power has substantially increased since the late 20th century, first through mergers and acquisitions --fueled by the “New Economy” boom-- and now through consolidation imposed by recession. In the electronics industry, this has benefited primarily U.S. corporations that have consolidated leadership in semiconductors and computers (e.g., Langlois and Steinmueller, 1999; Ernst, 2002, IEBM). American firms have created new product, software and service markets, e.g. the Internet, e-business, advanced microprocessors, and operating systems for an increasing variety of digital devices. They have raced ahead in the most prized areas of technological innovation, as far as these can be measured by patent statistics. The US “innovation score” has more than doubled from 41 (in 1985) to almost 101 (in 2002), a rate far better than for any other country[3] (CHI/MIT 2003). In 2002, all 15 leading companies with the best record on patent citations were based in the US, with nine of them in the electronics industry.

Fourth, a *shift of regional economic power* from Japan to China has forced Korea, Taiwan, Singapore, Malaysia, as well as India, to ratchet up their own innovative capabilities in an effort to stay competitive. As its role as a regional economic hegemon declines, Japan is less important as a source of capital, technology, and development models (Ernst, 2004a). On the other hand, China’s new role as a major market and manufacturing base for increasingly sophisticated industrial products, and as a priority investment target for global industry leaders, has raised the bar for the above five countries.

2. Evolution of Electronics Design in Asia

2.1. Relocation

Over the last few years, Asia’s leading electronics exporting countries appear to have seized upon new opportunities in the midst of a global downturn in the electronics industry, to create commercially successful innovations in the production of hardware, software, and services. Of particular importance are attempts to enter the global market for electronics design, for integrated circuits as well as systems.

[3] The US “innovation score” measures the number of patents granted by the US Patent Office, multiplied by the so-called “citation index” that indicates the value of these patents The citation index measures the frequency of citation of a particular patent. When the US Patent Office publishes patents, each one includes a list of other patents from which it is derived. The more often a patent is cited, the more likely it is a pioneering patent, connected with important inventions and discoveries. An index of more than 1 indicates that patents are cited more often than would be expected for a specific group of technologies, while less than 1 indicates they are cited less often than expected (Narin, 2000)

All standard data sources for the global IC design industry[4] confirm that a massive relocation of electronics design is under way to the above Asian countries. Let us look at a few illustrative examples. Asia (excluding Japan) is the fastest growing market for EDA (= electronic design automation) tools. In 2000, Asia's EDA tool market grew 24%, compared with 6% growth in North America, 13 % in Europe, and 17% in Japan (iSuppli, 2001). A survey conducted in January 2003 suggests that, excluding Japan, Asia's share in the global production of chip designs has increased from practically nothing during the mid 1990s to around 30% in 2002, relative to North America's share of 60% (iSuppli, 2003: 21). Over the five years until 2008, Asia's share is projected to grow to more than 50%. Such projections are in line with a widespread consensus in the industry, confirmed in the author's interviews, that "the center of gravity of the global semiconductor industry … (is rapidly shifting, DE) …to the Asia-Pacific region "[5], primarily centered on "Greater China", Korea and India.

2.2. Stages of Design

But such broad-brush figures tell us little about what stages of design are involved, and who are the main carriers of design relocation. Based on a widely used flow chart for IC design, Chang and Tsai (2002) provide a useful classification of chip design into "system/application specification" (the three shaded boxes in the upper part of the figure) and "design implementation" (the six boxes in the middle of the figure that are un-shaded) (see **Figure 1**[6]). I use this distinction to highlight two important features of electronic design in Asia. First, it has a much longer history in this region than is generally known. And, second, while design implementation has played a dominant role, system specification has started to gain in importance over the last few years.

Figure 1: Taiwan's Competitive Advantage in Digital Circuit Design

Note however that the distinction between design implementation and system specification cannot be used to distinguish design stages by knowledge complexity. Of course, system specification provides leverage for defining global standards and for innovation rents via premium pricing. However, as demonstrated elsewhere (Ernst, 2004b), it does not necessarily require more complex knowledge than design implementation. Knowledge complexity depends on how much functionality is squeezed onto the chip, the printed circuit board, or the system. Equally important is the sophistication of the design methodology. Knowledge complexity tends to increase substantially for the six design implementation stages, the closer chip design is moving from the individual component to system-level integration, and the greater use is made of "modular design".

2.3. History: Carriers of Asian Electronic Design

[4] Data sources include: commercial consulting surveys, prepared by Gartner/Dataquest, the Electronic Engineering Times, iSuppli, and IBS; reports and data provided by public research institutes and support institutions in the US and the above Asian countries ; company reports (e.g. 10K, Datamonitor, etc); and interviews with the sample of companies described in note 1.

[5] Ray Bingham, president and CEO of Cadence Design Systems Inc, one of the leading vendors of electronic design automation (EDA) tools, quoted in Electronic Engineering Times, 28 February 2003

[6] All figures are in the appendix.

Electronic design in Asia started during the early 1980s with board-level design performed in Asian computer and consumer electronics companies (primarily in Korea and Taiwan) to provide the optimum in the circuit layout of discrete components (including ICs, capacitors, inductors, resistors) and their interconnecting 'wires' on a printed circuit board (PCB)[7] (Ernst and O'Connor, 1992, chapter IV). Note that, while design complexity is low for a simple single-layer board, it rises substantially for very complex multi-layer boards (some up to 18 or 24 layers, for notebooks). Combined with the experience in detailed product design and engineering that Asian firms have accumulated in the fabrication of high-precision components (like ICs), board-level design has given rise to a broad portfolio of design implementation capabilities. This explains why today Asian original-design manufacturers (ODMs) like HonHai, Mitac and BenQ from Taiwan, NamTai from Hong Kong, and dozens of other Asian companies are able to compete successfully with the leading US-controlled global electronic manufacturing services (EMS) providers, like Flextronics or Solectron (Ernst, 2003a).

A third carrier of Asian design capabilities are fabless IC design start-up companies, especially from Taiwan like Etron, Via, or MediaTek. When these companies first entered the market, during the late 1980s, they were focused on semi-custom or ASIC design, where the goal was to avoid the very high cost and time required to design a full-custom IC[8]. An important catalyst was the establishment of Taiwan Semiconductor Manufacturing Corporation (TSMC) in 1987 as a provider of contract IC fabrication ("silicon foundry") services for chipless IC design companies. This enabled Taiwanese IC design start-ups to gain privileged access to a low-cost, high-speed supporting manufacturing system that encompasses both assembly and test, and wafer fabrication.

An equally important enabling factor for the entry of Asian IC design houses was the emergence of global EDA (="electronic design automation") tool vendors (like Synopsys, Cadence and Mentor). ASIC design required well-defined procedures to develop and use cell libraries that contain design modules. To do this cost-effectively, a new design methodology was developed where the design requirements were implemented in a software language that described digital circuits at the so-called register-transfer level (RTL) (see again **Figure 1**). To implement this new design, access to increasingly sophisticated EDA tools was critical. As these tools were available on the market, albeit at a very high price, this provided entry opportunities for Asian design companies. And as the effective use of these tools always require substantial tweaking and adjustments, these Asian companies were able to accumulate a broad set of capabilities related to the implementation of these increasingly automated design methodologies.

Relying on foundries and EDA tools enabled Asian, and especially Taiwanese design companies to concentrate their limited resources on pursuing a consistent niche strategy, with a focus on design implementation and on organizational innovations that make it possible to reap as much benefits as possible from competitive strengths in speed, cost, flexibility and quality (Chang and Tsai, 2002). This has resulted in a rapid growth of

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[7] A printed circuit board (PCB) is an internally wired, typically rectangular, substrate which holds a number of electronic components. The internal wiring is accomplished through a series of photolitographic processes when the PCB is manufactured.

[8] An ASIC typically is composed of standard building blocks called "cells" that are designed to implement a specific customer application.

Taiwan's fabless IC design industry, producing a 31% compound annual growth rate between 1995 and 2001[9]. In March 2003, a survey conducted by *EETimes* identified 234 Taiwanese IC design companies (Nanda, 2003). Five of the top 20 worldwide fabless companies are from Taiwan; and two Taiwanese design houses have moved up to the number 5 and 6 spot, capturing 16% of total fabless revenues.

2.4. Upgrading of IC Design Capabilities

Three more recent developments have further accelerated the growth and expanded the scope of electronic design in Asia: i) global firms are expanding and upgrading their design centers in Asia as part of their global design networks (GDNs); ii) leading Asian firms are emerging as new sources of IC design, as part of their strategies to upgrade system development and standard-setting capabilities, especially in China (including Hong Kong) and in Korea; and iii) smaller Asian firms attempt to enter GDNs as specialized suppliers, primarily of design implementation services.

All five global strategic groups in our interview sample have invested in IC design-related activities in Asia over the last few years, and/or are planning to expand such activities. While there are no systematic data on investment outlays and type of design activities, the interviews produced three general findings. First, all global firms consider the lower cost of Asian design engineers to be an important pull factor. In light of the fact that the annual cost of employing a chip design engineer in East Asia is between 10 and 20% of the cost in Silicon Valley (**Figure 2)**, it is hardly surprising to find that global firms relocate chip design to leading electronics clusters in East Asia that provide a skilled and re-trainable workforce as well as easy access to foundry, assembly and testing services. Second, global firms also consider as equally important proximity to higher-end specialized network suppliers of components, manufacturing services and knowledge-intensive business services, especially design and engineering support services. And third, as IC design expands in Asia, this creates significant new entry possibilities for Asian specialized suppliers of a broad array of design implementation services.

Figure 2: Annual Cost of Employing a Chip Design Engineer (US-$), 2002

Specific motivations differ across sectors and strategic groups. For mobile communication systems for instance, all major global system companies are expanding their Asian IC design centers to establish their own reference or "platform" designs[10] as *de facto* standards in the region. This reflects the growing importance of Asia as a major

[9] During 2001, Taiwan's IC design industry's revenue growth was 18%, significantly outpacing the almost flat growth of the global IC design industry ("Forecast for Taiwan's SIP (Silicon Intellectual Property) Industry", 1 June 2002)

[10] The concept of "platform design" was first developed in the car industry, under the heading of "modular design" (Baldwin and Clark, 2000; Sanchez and Mahoney, 1996). To deal with increasingly demanding cost reduction pressures, car manufacturers used a common template architecture for different car models, allowing the sharing of molds and common elements, the "design modules". This design methodology was then applied to other industries, including the computer industry (Langlois and Roberston, 1992). In the semiconductor industry, platform design is an organised method to reduce the time required and risk involved in designing and verifying a complex system-on-a-chip (SoC), by heavily and systematically reusing as many design steps as possible (Chang, 2003:23).

growth market for electronics products and services. As a result, global brand leaders in the electronics industry, like Intel, Microsoft, and Cisco, attempt to push their "platform leadership" strategies into Asia[11].

An additional powerful driver behind the expansion of electronic design in Asia is that leading firms from China, India, Korea, Taiwan and Singapore are emerging as potential new sources of innovation and global standards. This includes innovations in process technology for electronic components (especially semiconductors and displays), where Korean and Taiwanese firms are among the industry leaders. But it also includes system specification (as defined in **figure 1**): Asian firms are now producing innovations in the design of complex system architectures[12] in sectors like digital consumer systems, wireless telecommunication systems, and business process software.

For instance, in consumer electronics, there are joint efforts by China and Taiwan to develop a new video-disk technology format, called EVD (enhanced versatile disk) that would allow resolution five times higher than the current de facto industry standard DVD, while helping China's consumer electronics industry to escape full royalty payments to the dominant DVD licensing groups. Beijing E-World Technology, a consortium of 10 Chinese DVD manufacturers, is conducting government-sponsored research, in collaboration with Taiwan's Industrial Technology Research Institute (ITRI), and Taiwanese disk makers and chip design houses.

In telecommunications, Korea's four leading players (Samsung, LG, SK Telecom, and KT) are all engaged in serious efforts to become major platform and contents developers for complex technology systems, especially in mobile communications. These efforts can build on considerable capabilities, accumulated in public research labs (like ETRI, the Electronics and Telecommunications Research Institute), as well as in R&D labs of the chaebol, to develop complex technology systems like TDX (a switching system) and communication systems that are based on the CDMA (= code-division multiple access) standard. Furthermore, China's attempt to develop an alternative third generation (3G) digital wireless standard, called TD-SCDMA (time-division synchronous code-division multiple access), has created a powerful motivation to expand Asian electronic design activities for all eight strategic groups in our interview sample (Ernst, 2004b). The TD-SCDMA standard was developed by Datang Telecom, a Chinese state-owned enterprise, and the Research Institute of the Ministry of Information Industry, with technical assistance from Siemens[13]. To accelerate the implementation of this strategy, Datang has

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[11] "Platform leadership" strategies are defined by decisions on the "system architecture (the degree of modularity), interfaces (the degree of openness of the interfaces to the platform), and intellectual property (how much information about the platform and its interfaces to disclose to outside firms)" (Gawer and Cusumano, 2002: 40). These strategies have two objectives: to avoid the very high costs and risks of trying to develop complex technology systems in-house; and to enhance and control patterns of innovation in an industry.

[12] Computer designers use the term "architecture" to refer to "the partitioning of the …(computer)…system into components of a given scope and related to each other functionally and physically through given interfaces. From a given architecture flows the design of components' functions and how they relate to each other (Gawer and Cusumano, 2002: 18). These authors compare a system architecture with a geographic map, where the components of the system are the countries' territories and the interfaces between components are the countries' borders (ibid.:19).

[13] Approval by the International Telecommunications Union (ITU) was granted in August 2000. The two dominant competing global 3G standards are W-CDMA (compatible with existing GSM operations, and

formed a series of collaborative agreements: a joint venture with Nokia, Texas Instruments, the Korean LG group, and Taiwanese ODM (= original design manufacturing) suppliers, a joint venture with Philips and Samsung, and a licensing agreement with STMicroelectronics that will provide the Chinese company with access to critical design building blocks.

These example illustrates that the development of Asian electronic design capabilities has passed a critical minimum threshold. Of course, global R&D remains highly concentrated - 85% takes place in only seven industrialized countries, with the U.S. occupying the leading position with 37% (Dahlman and Aubert, 2001, p.34). For instance, China's total R&D spending is about $ 11billion, compared to more than $233 billion for the US.And the R&D budget of a U.S. industry leader, Microsoft, at around $ 6.2 billion (for 2003), exceeds 56% of China's total R&D budget. Nevertheless, there are clear signs that Asia's leading electronics exporting countries are *gradually* strengthening their position in the international division of knowledge creation. In a handful of emerging centers of excellence in Asia, sophisticated innovation and research capabilities appear to have followed the earlier development of electronics manufacturing capabilities. Let us now turn to possible explanations.

3. Puzzles, Hypotheses and Intellectual Sources

3.1. Puzzles

We have seen that, centered on electronic design, Asian firms have been able to innovate in industries that involve highly complex technological knowledge, despite the fact that they continue to lag substantially behind advanced nations in the development of their R&D and innovative capabilities. In addition to design implementation, this includes innovations in process technology for electronic components and in the design of complex system architectures.

This raises two important puzzles for the study of innovation. First, that new actors from Asia are entering the "global innovation race" runs counter to a widespread assumption in innovation theory that innovations and global standards necessarily emerge first in a few global "centers of excellence", especially in the US. Underlying this assumption is the well-established notion that innovation requires dense interactions within co-located specialized knowledge communities in order to reduce the dual challenges of cognitive and organizational complexity (Pavitt, 1999: XI)[14]. One would thus expect innovative activities that involve highly complex technological knowledge to remain spatially concentrated, much less prone than manufacturing to geographic relocation to Asia.

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supported by European firms), and CDMA 2000 (compatible with existing CDMA operations, and supported by US firms).

[14] As for the cognitive dimension, an artefact like a chip is "made up of numerous components and subsystems whose interactions are often non-linear and therefor impossible to predict" (Pavitt, 1999: p.X). This implies that verification and testing become a critical bottleneck; that tacit knowledge is central for interpreting the performance of a chip, and for "knowing how and where to search for improved performance" (ibid). The organizational dimension of technological complexity implies that "…a wide and increasing range of fields of specialized knowledge are being mobilized…", which necessitates "linkages with the wider knowledge communities and the capacity within the firm to experiment and learn across cognitive and functional boundaries" (Pavitt, 1999: pages X and XI).

A second puzzle results from the equally well established notion that, as industrial latecomers, Asian economies had to proceed *sequentially* from imitation to innovation (Kim, 1997). Based on his analysis of the Korean model, Linsu Kim has demonstrated that successful catching-up required a strategy that concentrated first on the acquisition, then on the assimilation and then on the improvement of "foreign technology to manufacture products whose technology and market have been tested and proved elsewhere. For this purpose, only engineering efforts are required." (ibid: 88). The cumulative character of technological learning would thus seem to impose fundamental barriers to a strategy of combining international knowledge sourcing from industry leaders with the *concurrent* development of engineering, development and research capabilities. This makes it difficult to explain how Asian firms are able to produce innovations in process technology for electronic components and in the design of system architectures.

3.2. Hypotheses

The concept of "late innovation strategies" is used to solve these puzzles. The term "innovation strategies" highlights the interactive nature of innovation (Freeman, 1987; Nelson, 1988; Kline and Rosenberg, 1986) - multiple feedback links are developed between "innovation management" and "innovation policies" (Nelson, 1993; Gibbons et al, 1994). Such interaction is particularly important for "late innovation strategies" that attempt to redress the imbalance between excellence in export-oriented production and a weak basis for knowledge creation. "Innovation management" is concerned with the development of "innovative capabilities", defined as the skills, knowledge and management approaches needed to create, change or improve products, services, equipment, and processes. "Innovation policies" include incentives that induce firms to enhance innovative capabilities, as well as the provision of "public goods" (Lundvall, 2001). In addition to infrastructure, finance, and education, "public goods" also include public institutions that, as sophisticated technology users, can catalyze innovations; databases on research, "technology roadmaps" and market trends; intellectual property rights (IPR) protection; and a consensus on the development model.

The conceptual framework of this paper explores the interplay of international and domestic forces that shape "late innovation" strategies, with a specific focus on changes in technology and business organization. To maximize analytical leverage, this framework is centered on four testable hypotheses:

Hypothesis 1

New opportunities for "late innovation" strategies result from four recent transformations in the global innovation system: (1) global production networks integrate geographically dispersed specialized production and innovation sites; (2) global firms outsource R&D to locations with lower costs of knowledge workers; (3) brain drain has produced transnational skilled migrant communities that can act as highly effective carriers of tacit knowledge; and (4) IT-based information management can improve the coordination of these diverse networks. Paradoxically, this trend towards vertical specialization within global production and innovation networks may enhance the mobility of knowledge across firm boundaries and national borders. This may enable late innovators to combine international knowledge sourcing from industry leaders with the *concurrent* development of engineering, development and research capabilities.

Hypothesis 2

International knowledge sourcing from industry leaders is critical for "late innovation" strategies. It compensates for an initially weak domestic knowledge base; it facilitates adjustment to abrupt changes in technology and markets; and it can catalyze the development and the diffusion of innovative capabilities *ahead* of what the market would provide. This may explain why Asian firms are able to innovate complex system architecture designs.

Hypothesis 3

"Strategic diversity" results from the fact that the above four global transformations have increased the variety of transmission mechanisms of international knowledge sourcing, providing choice options that did not exist previously. Hence, countries can differ in the policies, institutions, and management approaches that they use to implement "late innovation strategies".

Hypothesis 4

As a result, it may no longer be necessary (as it was arguably until the mid-1990s) to move *sequentially* up the ladder from simple to more complex technology development strategies. A shift to *concurrent* strategies reflects the growing vertical specialization in this industry. As global specialized suppliers proliferate across all stages of the value chain, including R&D&E, this opens up new opportunities for Asian firms to choose carefully realistic sequencing patterns, and to proceed in parallel with domestic efforts and with international knowledge sourcing. While local actors remain the primary agents of upgrading strategies, the essence of these *concurrent* strategies is to complement their limited resources and capabilities by establishing linkages with global as well as Asian actors.

3.3. Intellectual Sources: Shortcomings and Conceptual Building-Blocks

To theoretically ground these four hypotheses, it is possible to draw on four intellectual sources: neo-Schumpeterian innovation economics; research on Asian innovation systems, research on "modular design", "disruptive technologies", and on "complex system integration" or "integrated solutions"; and research on the impact of transformations in international business organization (especially global production networks) on the international geography of innovation. While all four approaches are highly relevant strands of research, none of them addresses head on the two main questions of this paper: How to explain the current new push into cutting-edge research and innovation in in Asian electronics industries? And what explains the diversity of "late innovation "strategies?

An additional shortcoming is a lack of communication between the four types of literature. With but a few exceptions that I will highlight in a moment, interaction between neo-Schumpeterian innovation economics and research on Asian innovation systems typically is a one-way street where theoretical frameworks in the first draw on empirical research in advanced economies, and then are applied in research on Asian innovation systems. Even more glaring is the lack of communication between innovation research and research on the impact of transformations in international business organization[15]. Nevertheless, once brought together, these four strands of research provide important building-blocks that can be used, with some adjustments, to construct a framework for analyzing the drivers and diversity of "late innovation" strategies.

3.4. Generic Principles of Innovation Strategies

Research by neo-Schumpeterian innovation economists is typically focused on the leading industrialized economies and their most dynamic innovation clusters (e.g. Antonelli, 1998 and 2003; Pavitt, 1999; Mowery and Nelson, 1999; Steil, Victor and Nelson, 2002). There are however some pioneering contributions that have established bridgeheads for research on Asian latecomer innovation strategies (Freeman, 1995; Perez and Soete, 1988; Nelson, 1990 and 1993; Antonelli, 1991; Bell and Pavitt, 1993; Nelson and Pack, 1999; Teece, 2000; Freeman and Louca, 2001). The concept of "late innovation strategies" can build on three important generic principles.

First, in addition to monetary and macro-economic stability, policies are required to compensate for "market imperfections" due to the inherent uncertainty of innovation (Arrow, 1962), and to provide incentives for knowledge diffusion and for high-risk investment in innovation. Competition policy is critical to make such incentives work: firms will only invest in productivity-enhancing technology, learning and innovation if competition and regulatory reform force them to do so (Mowery and Nelson, 1999: 379). Second, innovation policies can play an important role in the provision of a broad array of "public goods" that provide tangible and intangible inputs to knowledge creation from outside the firm. And third, a coherent broad-based innovation strategy must be in place to ensure that policies produce the expected impact on innovation management in firms and research institutions. A critical concern of innovation strategy is the "congruence" (Freeman, 1997:13) of different subsystems, which is necessary to create a *virtuous* rather than a *vicious* circle.

3.5. Innovative Capabilities - Internal and External Sources

Research on Asian innovation systems (e.g., Kim Linsu, 1993 and 1997; Lall, 2000; Hobday, 1995; Ernst, Mytelka and Ganiatsos, 1998; Lu, 2000; Mathews and Cho, 2000; Naughton and Segal, 2002; Liu and White, 2001; Yusuf, 2003; Amsden and Chu, 2003; Segal, 2003; Lazonick, 2003; Lu Feng and Mu Ling, 2003) has emphasized that peculiar features of economic structures and institutions offer quite distinct possibilities for learning and innovation, and hence should be reflected in the design of innovation strategies. Asia's electronics exporting countries thus have to develop their own idiosyncratic approaches to innovation strategies, policies and innovation management. As latecomers to innovation, they are confronted with substantial barriers. At the same time, being a latecomer also conveys important advantages, as it is possible to learn from the mistakes of incumbents and from the problems faced by earlier latecomers to innovation.

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[15] According to Dunning (1998:291), "most of the work of scholars from these disciplines…(i.e. economic theories of innovation and the firm, DE) …has not generally embraced an international dimension and, as a result, our understanding of the way resources are organized and distributed across national boundaries has been constricted."

More specifically, our framework can build on research that has moved the analysis beyond generic principles, to get down to the tedious task of developing operational data sets for measuring firm-level innovative and R&D capabilities. Important contributions include Lall (1992), Rasiah (1995), Bell and Pavitt (1995), Hobday (1995) and Ariffin (2000). Ernst, Ganiatsos, Mytelka (1998), a major study for the United Nations Conference on Trade and Development (UNCTAD), presented arguably the first comprehensive taxonomy of firm-level capabilities required for production, investment, minor change, strategic marketing, establishing inter-firm linkages, and major change. 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.

More recently, Amsden and Tschang (2003) have developed a classification of technological complexity of different categories of R&D, which can inform our analysis of current "late innovation" strategies. Two recent studies provide an additional missing link: the analysis of capabilities needs to move beyond the boundaries of the firm which increasingly depends on tangible and intangible inputs from outside. Jefferson and Kaifeng (forthcoming) identify 23 indicators ("attributes") that potentially enhance the productivity and profitability of firm-level R&D operations, under four headings: openess/competition, human capital, feedback links of R&D networks, and peculiar features of institutions. This excellent study however is constrained by a lack of disaggregation of data; nor does it attempt to get to the specifics of particular sectors. And Rasiah (2003) attempts to extend the concept of capabilities to include what he calls "systemic and institutional dimensions", i.e. the role of "intermediary organizations" such as chambers of commerce and government-business councils in generating feedback links between innovation agents.

3.6. Taxonomy of Innovation

We also need to open the black box of "innovation" to establish what are realistic options for "late innovation strategies". We have seen that Asian firms in the electronics industry no longer stick to a sequential strategy of moving from acquisition to assimilation and on to improvement of foreign technology, before venturing into innovation. Instead, there are attempts to combine international knowledge sourcing from industry leaders with the *concurrent* development of engineering, development and research capabilities. To address this puzzling feature of "late innovation strategies", I suggest to draw on three intellectual sources: a useful taxonomy of innovation provided by Henderson and Clark (1990); the concept of "disruptive technologies, as developed by Christensen (1993 and 1997); and the concept of "complex system integration" (e.g., Pavitt, 2003; Brusoni, 2003) or "integrated solutions"(Davies et al, 2001).

Henderson and Clark (1990) classify innovations by the degree to which they reinforce or render obsolete the expertise of established firms along two dimensions - components and architecture, where the latter determines what components are part of the system (for instance a computer) and how they interact with each other (Baldwin and Clark, 2000: 77). Their taxonomy distinguishes incremental, modular, architectural and radical innovations. "Incremental" innovations build on a firm's expertise in component technology, and refer to improvements in component technology. With "modular" innovation, new component technology is plugged into a fundamentally unchanged system architecture. "Architectural" innovations use existing component technology, but change the way components are designed to work together. Finally, "radical" innovations involve both the use of new component technology and changes in architectural design.

Using this taxonomy, it is possible to argue that late innovators may have realistic chances to engage in incremental innovations as well as in architectural innovations. Incremental innovations take the dominant component design for granted, but improve on cost, time-to-market and performance. Typical examples are improvements in computer memories (especially DRAMs) and displays by Korean and Taiwanese firms (e.g., Ernst, 1998 and 2000). And architectural innovations build on a company's familiarity with market trends and user requirements to specify an electronic system, but use existing component technology that is available on the market to implement this design. An important example is the commercialization government-sponsored large-scale R&D projects in Korea's telecommunications sector, especially the time division exchange (TDX) project that lasted over more than 15 years (e.g., Chung et al, 1998; Choung et al, 2003). And China provides various examples of successful architectural innovations: 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 (Lu Feng and Mu Ling, 2003).

Christensen (1993) helps us to move the analysis one step further. He has used the Henderson-Clark taxonomy to demonstrate that established, vertically integrated market leaders typically lead in the adoption of new component technology, while successful new entrants rely on architectural innovations. Christensen identifies two possible explanations. First, while technological complexity (and hence risk, time, and investment expense) are much lower for architectural design than for the development of new key components, architectural innovations tend to have much more far-reaching implications for market shares and profitability of innovating firms. Second, the key to successful innovation is whether there are enough customers who are willing to pay for these new technologies and who can profit from using them.

The concept of "disruptive technologies" (Christensen, 1997) deepens our understanding of the market constraint. "Disruptive technologies" underperform relative to established products in mainstream markets today, but may be fully performance-competitive in the same market tomorrow. Disruptive technologies differ from "sustaining technologies" which improve the performance of *established* products that mainstream customers in mainstream markets have traditionally valued. *Disruptive technologies* bring to a market very different products: they have features that initially only a few fringe (and generally new) customers value. Products based on disruptive technologies are typically cheaper, simpler, smaller, and, frequently, more convenient to use.

The existence of "disruptive technologies" can help to explain why Asian late innovators who lag substantially behind industry leaders in their innovative capabilities, can nevertheless attack incumbents. The explanation derives from the puzzling fact that incumbents apparently face more severe barriers to invest in disruptive technologies than new entrants. This is so for four reasons: i) These technologies are simpler and cheaper, and thus promise lower margins, not greater profits: "It is very difficult for a company whose cost structure is tailored to compete in high-end markets to be profitable in low-end markets as well" (Christensen, 1997, p.XX). ii) Disruptive technologies are first commercialized in emerging and insignificant markets that large companies have great difficulties to address. iii) The incumbents' most profitable customers generally do not want, and initially cannot use products based on disruptive technologies. And iv) a break of routine requires a different organizational design from sustaining technologies that can rely on customary routines.

In short, disruptive technologies provide a constant threat to the excessive product differentiation pursued by incumbents to reap the benefits of premium pricing. New entrants however face relatively low entry barriers for such technologies, compared to the entry barriers that characterize sustaining technologies. The reason is that late innovators can focus on architectural innovations, using widely available existing component technology, for instance in the form of platform designs.

However, "architectural innovations" for disruptive technologies may not be sufficient to sustain "late innovation" strategies over a longer period. The concept of "complex system integration" (e.g., Pavitt, 2003; Brusoni, 2003) or "integrated solutions"(Davies et al, 2001) can provide the missing link.

To succeed in the "global innovation race", Asian companies must accumulate experience in managing "complex technology systems" (Windrum, 1999). 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 system integration services. But for obvious reasons, Asian firms may still lag well behind in the mastery of these most critical innovative capabilities.

3.7. International Knowledge Sourcing

A central proposition of this paper is that "late innovation" strategies need to complement domestic efforts with conscious efforts to learn from multiple international knowledge sources (**H2**). On this aspect of our framework, it is possible to draw on a growing body of studies that argue that Asian innovation strategies are shaped by their integration into international trade, investment and technology flows (e.g., Wong, 1991; Hobday, 1995; Lall, 2000; Ernst and O´Connor, 1989; Ernst and Guerrieri, 1998; Mathews and Cho, 2000; Borrus, Ernst and Haggard, 2000; Hobday, 2001**;** Ernst, 2000**;** Ernst and Kim, 2002). These studies provide empirical evidence that, as Asian countries progress in their industrial transformation, their reliance on international knowledge sourcing has substantially increased. Much of this literature is based on the notion that Asian countries can overcome their initial disadvantages through strategies "…to leverage knowledge and technologies from their more advanced competitors … (that) utilize the existing and latent inter-firm connections of the global economy" (Mathews, 2002: p.VIII). But international knowledge sourcing not only compensates for initial weaknesses. It also facilitates adjustment to abrupt changes in technology and markets, and it can catalyze the development and the diffusion of innovative capabilities *ahead* of what the market would provide (**H2**).

While the role of foreign direct investment as an agent of "technology transfer" still dominates the economic literature (e.g., Blomstroem, Globerman and Koko, 2000), the above research on Asia has highlighted the critical role played by more indirect informal transmission mechanisms for international knowledge sourcing. This includes for instance exposure to best-practice management techniques for R&D through interaction with foreign suppliers and customers, especially in areas like product design specification, performance and quality control measurements, involvement in prototype development, certification through standardization bodies like ISO (the International Standard Organization), and sharing of (mostly tacit) knowledge with foreign technical and marketing personnel.

4. Global Transformations and the Mobility of Knowledge

Asia's new push into cutting-edge research and innovation may actually be less surprising than it may look at first sight. It reflects the new mobility of knowledge through vertical specialization within global production and innovation networks, which in turn may provide new opportunities for "late innovation" strategies (H1). **Figure 3** provides a stylized model of how *vertical specialization* (i.e. the dis-integration of firm organization and the geographic dispersion across national boundaries) and *re-integration* of dispersed production, distribution and innovation bases into hierarchical *global flagship networks* facilitate *knowledge diffusion*. **Figure 3** also demonstrates the role played by two complementary enabling forces in enhancing both codified and tacit knowledge exchange: *ICT-enhanced information management* and *transnational knowledge communities*.

Let us first look at the latter two enabling factors. In all Asian countries, but especially in China, earlier "brain drain" has produced *overseas* communities of engineers, scholars, and managers who are familiar with cutting-edge technology and best-practice management approaches and who understand the dynamics of international product and financial markets. These *transnational knowledge communities* can play an important catalytic role in the development of domestic innovative capabilities (Saxenian, 2002).

The use of ICT as a management tool can enhance the scope for knowledge sharing among multiple network participants at distant locations (Ernst, 2003a). But these changes will occur only gradually, as a long-term, iterative learning process, based on search and experimentation. The digitization of knowledge implies that it can be delivered as a service and built around open standards. This has fostered the specialization of knowledge creation, giving rise to a process of modularization, very much like earlier modularization processes in hardware manufacturing.

Under the heading of "e-business", a new generation of networking software provides a greater variety of tools for representing knowledge, including low-cost audio-visual representations (Foray and Steinmueller, 2001). Those programs also provide flexible information systems that support not only information exchange among dispersed network nodes, but also the sharing, utilization, and creation of knowledge among multiple network participants at remote locations (Jørgensen and Kogstie, 2000). New forms of remote control are emerging for manufacturing processes, quality, supply chains, and customer relations. Equally important are new opportunities for the joint production across distant locations of knowledge support services (e.g., software engineering and development, business process outsourcing, maintenance and support of information systems, as well as skill transfer and training). While much of this is still at an early stage of "trial-and-error", global leaders in the electronics industry now face a huge potential for extending knowledge exchange across organizational and national boundaries. However, the uncertainties and complexities of operating in global markets means that there are agglomeration economies to be derived from dense spatial concentrations of specialized network suppliers. Hence, new opportunities emerge for "late innovation" strategies in Asian electronics industries.

"Vertical specialization" (or "outsourcing" in common parlance) is no longer restricted to the production of goods and services but now extends to all stages of the value chain, including research and new product development. This may facilitate the implementation of "late innovation" strategies in leading Asian electronics exporting countries. Take chip design (Ernst, 2004b). Until the mid-1980s, captive semiconductor producers (like IBM) and merchant firms (like Intel) did almost all their chip design in-house. The first step of vertical specialization was the separation of fabrication and design. The emergence of independent providers of pure-play "silicon foundry" services gave rise to a proliferation of "fabless" design houses (like Altera) that focused on specific niche markets for integrated circuits.

Over time, a second stage of vertical specialization has occurred *within* the process of chip design itself. A primary driver has been a widening design productivity gap between design and fabrication. While the productivity of semiconductor fabrication over the last twenty years has seen a 58% compounded annual growth, the productivity of chip design has lagged behind, with only a 21% compounded annual rate (**Figure 4**). Given this design productivity gap, differences in the cost of employing a chip design engineer have become an important determinant for decisions to locate chip design in Asia.

In addition, radical changes in the methodology of chip design through the so-called system-on-chip (SOC) design have arguably further enhanced the scope of vertical specialization within the process of design (Ernst, 2004b). Due to the growing complexity of the design process, a single company is no longer exclusively handling the design for a specific chip. Instead, many companies are contributing, based upon their specific areas of expertise. This leads to the development of "global electronic design networks" that link together design houses, the licensors of specific design building blocks, design service providers, foundries, design tool vendors, design departments of large electronics systems, and brand name companies that are all contributing to the complete chip design solution.

This vertical specialization within global design networks facilitates "late innovation" strategies in electronic design. As global specialized suppliers proliferate across all stages of the semiconductor value chain, from assembly and test, to wafer fabrication, design tools, and different stages of electronic design, this opens up new opportunities for Asian countries to combine international knowledge sourcing from industry leaders with the *concurrent* development of engineering, development and research capabilities. Electronic design houses in country A can now rely on access to specialized silicon foundry suppliers in countries B and C, as well as on specialized suppliers of assembly & testing services in countries B, C, D, and E. Equally important, it is now possible for design houses in country A to gain "design-ins" with system companies that are located in large markets.

But vertical specialization does not imply that the "Visible Hand" of large manufacturing firms will become invisible (as argued, for instance, in Langlois, 2001), giving rise to a resurgence of market forces. "Integration" is the necessary complement to vertical specialization, and the resultant geographic dispersion: large global corporations (the network flagships) can act as system integrators for the diverse, multi-layered production and innovation networks that have evolved as a result of vertical specialization (Borrus, Ernst, Haggard, 2000; Ernst, 2002b; Pavitt, 2003, Brusoni, 2003; Tomumaru, 2004).

Trade economists have recently discovered the importance of changes in the organization of international production as a determinant of trade patterns (for example, Feenstra, 1998; Jones and Kierzskowski, 2000; Cheng and Kierzkowski, 2001). Their work demonstrates that (i) production is increasingly 'fragmented', with parts of the production process being scattered across a number of countries, hence increasing the share of trade in parts and components; (ii) that there is reintegration through global production networks; and (iii) that countries and regions which have been able to become a part of these network are the ones which have industrialized the fastest.

The model of global flagship networks (GFNs) builds on this work, but uses a broader concept that emphasizes three essential characteristics (Ernst, 2002a, 2002b, 2003 b): i) *scope*: GFNs encompass all stages of the value chain, not just production; ii) *asymmetry*: flagships dominate control over network resources and decision-making; and iii) *knowledge diffusion*: global corporations (the "network flagships") construct these networks to gain quick access to skills and capabilities at lower-cost overseas locations that complement their core competencies. Knowledge-sharing is the glue that keeps these networks growing. Flagships need to transfer technical and managerial knowledge to local suppliers to ensure that they meet the technical specifications mandated by the flagships. Originally this involved primarily operational skills and routine procedures required for sales and distribution, manufacturing and logistics. Over time, knowledge sharing also incorporates higher-level, mostly tacit forms of "organizational knowledge" required for control, coordination, planning and decision-making, as well as for learning and innovation (Ernst and Kim, 2002).

In short, the reintegration of geographically dispersed specialized production and innovation sites into multi-layered GFNs and the increasing use of IT-based information systems to manage these networks are *gradually* reducing constraints to international knowledge diffusion. GFNs expand inter-firm linkages across national boundaries, increasing the need for knowledge diffusion, while information systems enhance not only information exchange, but also the sharing and joint creation of knowledge. It is this new mobility of knowledge that acts as an important enabling factor for Asian "late innovation" strategies. But to reap these opportunities, considerable changes are required in Asia's innovation strategies, policies and management approaches. The key to success are attempts to combine international knowledge sourcing from industry leaders with the *concurrent* development of engineering, development and research capabilities[16].

Conclusions

This paper has developed some important conceptual building-blocks that we need to capture peculiar features of Asia's "late innovation" strategies in the electronics industry. Our starting-point was the finding that Asian firms recently have been able to innovate in industries that involve highly complex technological knowledge, despite the fact that they continue to lag substantially behind advanced nations in the development of their R&D and innovative capabilities. In addition to design implementation, this includes innovations in process technology for electronic components and in the design of complex system architectures. This arguably indicates that it is no longer possible to assume that innovations and global standards necessarily emerge first in a few global "centers of excellence", especially in the US. Second, it may no longer be necessary for leading Asian electronics exporting countries to proceed *sequentially* from imitation to innovation.

To solve these two puzzles, the paper explores the interplay of international and domestic forces that shape "late innovation" strategies, with a specific focus on changes in technology and business organization. This framework is centered on four hypotheses: First, vertical specialization within global production and innovation networks may enhance the mobility of knowledge across firm boundaries and national borders. This new mobility of knowledge may enable late innovators to combine international knowledge sourcing from industry leaders with the *concurrent* development of engineering, development and research capabilities. Second, international knowledge sourcing from industry leaders is critical for "late innovation" strategies. Not only does it help to compensate for an initially weak domestic knowledge base, but it facilitates adjustment to abrupt changes in technology and markets. In addition, international knowledge sourcing can catalyze the development and the diffusion of innovative capabilities *ahead* of what the market would provide. This may explain why Asian firms are able to innovate complex system architecture designs.
Third, there are no fixed formula for what works best. "Strategic diversity" results from the fact that vertical specialization within global production and innovation networks has increased the variety of transmission mechanisms of international knowledge sourcing, providing choice options that did not exist previously. Hence, countries can differ in the policies, institutions, and management approaches that they use to implement "late innovation strategies". And, fourth, as global specialized suppliers proliferate across all stages of the value chain, including R&D&E, this opens up new opportunities for Asian firms to proceed in parallel with domestic efforts and with international knowledge sourcing, and to develop *concurrently* engineering, development and research capabilities.

To theoretically ground these four hypotheses, the paper draws on four intellectual sources: First, generic principles of innovation strategies are derived from neo-Schumpeterian innovation economics. Second, attempts to provide operational

[16] To highlight the complex challenges that lie ahead, Ernst (forthcoming) examines key features of China's "late innovation" strategies in the electronics industry.

definitions of innovative capabilities are derived from research on Asian innovation systems. Third, a taxonomy of innovation is derived from research on "modular design", "disruptive technologies", and on "complex system integration" or "integrated solutions". Fourth, and finally, the paper draws on research that explores the impact of transformations in international business organization (especially global production and innovation networks) on the international geography of innovation.

While all four approaches are highly relevant strands of research, none of them addresses head on the two main questions of this paper: How to explain the current new push into cutting-edge research and innovation in Asian electronics industries? And what explains the diversity of "late innovation "strategies? An additional shortcoming is a lack of communication between the four types of literature. Nevertheless, once brought together, these four strands of research provides important building-blocks that can be used, with some adjustments, to construct a framework for analyzing the drivers and diversity of "late innovation" strategies.

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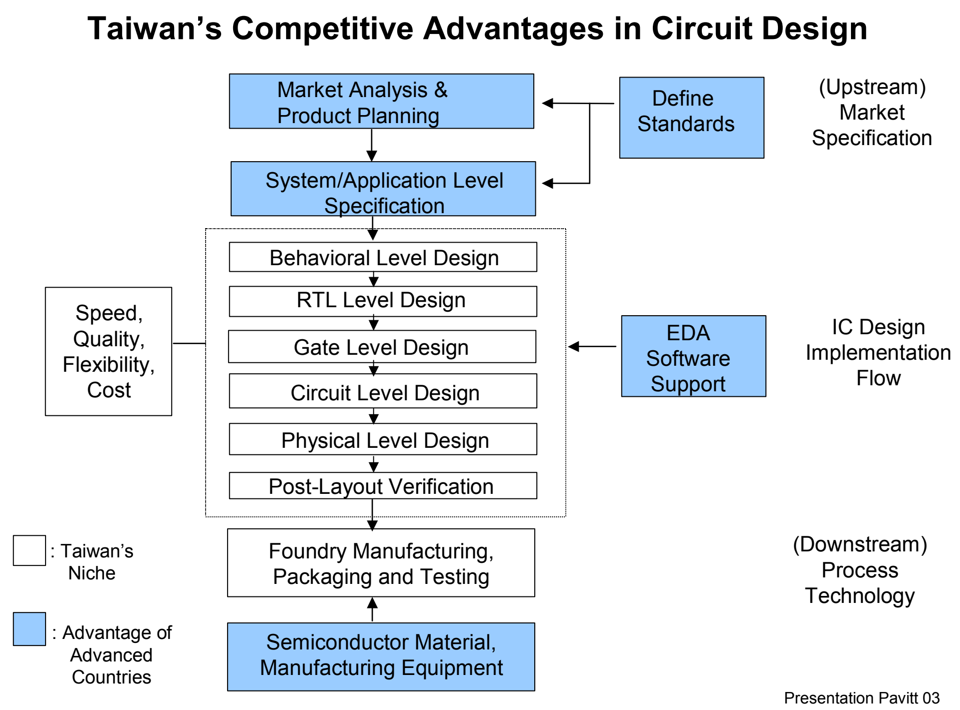
Figure 1.



Source: Chang and Tsai, 2002

Figure 2.

Annual Cost of Employing a Chip Design Engineer* (US-$), 2002

Location	Annual Cost
Silicon Valley	300,000
Canada	150,000
Ireland	75,000
Taiwan	<60,000
South Korea	<65,000
China	28,000 (Shanghai) 24,000 (Suzhou)
India	30,000

*= including salary, benefits, equipment, office space and other infrastructure.
Sources: PMC-Sierra Inc, Burnaby, Canada (for Silicon Valley, Canada, Ireland, India); plus interviews (Taiwan, South Korea, China)

Figure 3. Vertical Specialization, GFNs, and Knowledge Diffusion

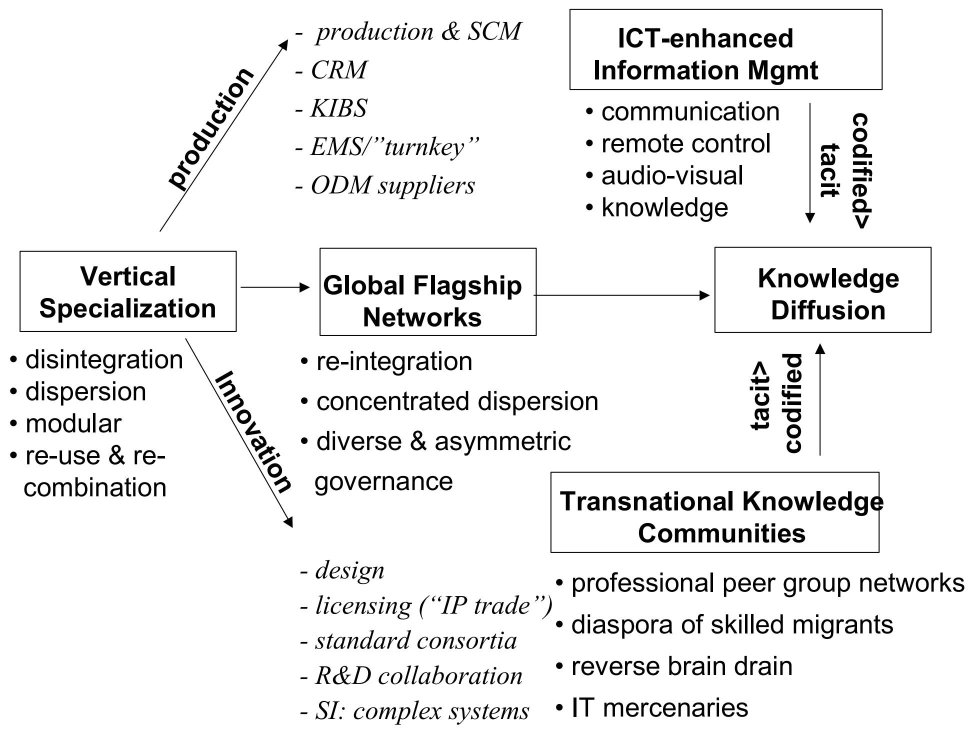


Figure 4.