National Innovation Systems for Rapid Technological Catch-up: An analytical framework and a comparative analysis of Korea, Taiwan and Singapore

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Abstract

Among small, late-industrializing economies in the developing world, three – Korea, Taiwan and Singapore – have achieved remarkably rapid industrial and technological catch-up. More interestingly, they have done so by evolving distinctly different models of national innovation system. This paper presents an analytical framework for characterizing the generic evolutionary paths for rapid technological catch-up by late-industrializing countries. The framework seeks to integrate three theoretical perspectives: the resource-based view of the firm, the network interaction perspective on the technological learning process, and the institutional economics perspective on the contexts of late-industrialization. The framework is found to be useful in explaining the divergent evolutionary patterns among these three distinct national innovation systems. The framework also highlights potential limits of the respective innovation systems as the catch-up process reaches an advanced stage, and suggests new directions for change. Implications for future research on national innovation system for late-industrializing countries are explored.

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Introduction

Historically, the Asian Newly Industrialized Economies (NIEs) shared a common characteristics with many other developing countries in that they were all rather late-industrializing countries in the global economy (Hikino and Amsden,1994). Indigenous firms from these countries face two common problems in terms of developing high-tech industrial capability: firstly, they were typically distant from the lead user markets in North America, Europe and Japan; secondly, they were also far away from and disconnected to the leading sources of technological innovation in advanced countries. Despite these disadvantages, however, three of the Asian NIEs – Taiwan, Korea and Singapore -- have managed to achieve significantly faster high-tech industrial growth over the last three decades than all other developing countries (see e.g. Wong(1999b) for a recent review of the empirical evidence). By the late-1990s, many indigenous firms from these three countries have achieved remarkable technological "catch-up", and in some cases, have even pulled ahead of market leaders from the advanced OECD countries. How did these firms from the Asian NIEs manage to become competitive in a wide range of high-tech industries? More importantly, how much of their success has been due to the specific national innovation system characteristics of their home countries, including in particular the influence of state innovation policies and institutions in their respective countries?

There is by now a large literature on the common factors contributing to the rapid industrialization of East Asia in general and the three Asian NIEs in particular. Among the most influential of these literature, the "East Asian Miracles" by the World Bank, put much emphasis on such common factors as political stability, prudent macroeconomic policies, export-orientation, and public policies leading to high savings rate and heavy investment in human resource development (World Bank(1993)). However, their largely neoclassical explanation stressing "market friendly" state interventions and "getting prices right" has been rightly criticised as ignoring the substantial state intervention role in these countries (see e.g. Amsden(1995), Wade et.al.(1994), Wong(1999b)). Moreover, even a cursory review of the recent research findings focusing on the industrial and technological development patterns of the three individual Asian NIEs will show that they in fact manifest quite different strategic approaches to industrial technological capability development (see e.g. Amsden(1989) and Kim(1997) for Korea, Dahlman and Sananikone(1993) and Hou and Gee(1993) for Taiwan, and Wong(1995a,1999) for Singapore). In effect, from the perspective of technological capability development, there is not one East Asian miracle, but **three** different ones.

Unfortunately, in the search for a unified explanation of the rapid industrialization of East Asia, there has been a tendency in much of the recent development economics literature on East Asia to emphasize the common characteristics among these economies while downplaying their differences. This led to much attention being focused on such common fundamentals as export-orientation and openness (see e.g. Leipziger 1997, World Bank 1993), relatively equitable initial distribution of assets and income (see e.g. Campos and Root 1996), high investment in education and high savings (see e.g. World Bank 1993, Stiglitz 1996, ADB 1997) or institutional capability and governance (Root 1996, Rowen(ed.) 1998). In so doing, however, significant differences in their technological innovation patterns tend to be over-looked.

The few studies that focus more specifically on the innovation systems of Asian NIEs (see e.g., Hobday 1995, Mathews 1996, Dedrik and Kraemer 1998) do acknowledge significant differences among them, but these studies tend to focus primarily on the innovation performance of the NIEs in one specific industry cluster – the electronics/IT industry cluster. Possibly because of this sector specific focus, there is a tendency to either prescribe more commonality than exists (e.g. Hobday(1995)'s emphasis on the "OEM-ODM-OBM migration route" as a common route for most Asian firms) or to generalize too broadly across countries that have distinctly different innovation performance (e.g. Mathews(1996)'s attempted generalization of the "development resource leverage" concept from the semiconductor industry development experience of Korea and Taiwan to other countries like Malaysia).

In this paper, we argue that the remarkable technological capability development performance of Taiwan, Korea and Singapore can be best understood not by focusing on their commonality, but by highlighting their differences. In particular, we present an analytical framework that highlights the alternative generic evolutionary paths for rapid technological catch-up by late-industrializing countries in general. The framework is synthesized from integrating three theoretical perspectives: The resource-based view of the firm, the innovation network perspective on technological learning process, and the institutional economics perspective on the contexts of late-industrialization. Using this framework, we then show how the Korean, Taiwanese and Singaporean development experience can be understood as representing three different national innovation system models that involve a different mix of firm strategies, innovation network structure, and state intervention roles. We further suggest that our analytical framework is applicable to explaining the technological development experience of other late-industrializing countries, including the experience of industrialized countries in their earlier industrial catch up phase (e.g. Finland in the 1970s).

The organization of the paper is as follows. In the next section, I present a basic analytical framework for examining the strategic options for rapid industrial and technological catch-up by late-industrializing countries. In Section 3, I use the framework to highlight the key differences in the technological capability development approaches of Taiwan, Korea and Singapore. Section 4 concludes by summarizing the main contributions of the paper to the existing literature and providing some tentative suggestions on the implications for future research on national innovation system for late-industrializing countries.

2. Generic Routes for Rapid Technological Development of Late-Industrializing Countries – Towards a Conceptual Framework

As pointed out by others (see e.g. Hobday1995, Hikino and Amsden1994, Kim 1997 and Mathews 1996), the initial conditions that firms from late-industrializing countries faced were very different from those of firms in the advanced countries. Consequently, the design of industrial organizations and national innovation systems for rapid technological catch up by late-industrializing countries ought to be very different from those for sustaining technological competitiveness in the advanced countries. However, there appears to be little agreement as to what elements are necessary for such rapid technological catch-up. Hikino and Amsden(1989), for example, argue that late-industrializing countries should evolve large conglomerated firms as a means to rapidly transfer management know-how across many production units due to the scarcity of such management know-how in late-industrializing countires. Based on the experience of Korea, Kim(1997) argued that large conglomeration indeed provided the “deep-pocket” investments necessary for rapid technological catch up with more advanced countries. However, this emphasis on large firms for rapid technological catch up is contested by supporters of the Taiwanese development model (see e.g. Hou and Gee(1993), Shieh(1992)). These authors suggested that it is the existence of many small and medium sized enterprises (SMEs) that contributed to the rapid pace of industrial and technological learning in Taiwan. Still others like Wong(1992) and Hobday(1995) suggested that the presence of foreign multinational corporations (MNCs) significantly stimulated the industrial technological development of local firms in countries like Singapore (and to a smaller extent, Malaysia).

Rather than attempting to generalize from the experience of any single NIE’s technological development model, we believe that the different approaches of Taiwan, Korea and Singapore strongly suggest that there are **multiple** generic evolutionary paths for rapid technological catch-up. Consequently, any theoretical framework for understanding rapid technological catch up by latecomer firms from late-industrializing countries must allow, indeed explain, this diversity of catch-up models. In addition, of course, it must also explain why rapid technological catch up has NOT been a general phenomenon among all late-industrializing countries.

Taking the resource-based view of the firm and building upon the argument of Cho, Kim and Rhee(1988), we believe that the starting point for new insights on how latecomer firms can achieve rapid technological catch up must be based on a deeper understanding of the **specific contexts of late-industrialization**, and how these consequently shape the **strategic choices** of firms from these countries. In essence, we argue that latecomer firms from late-industrializing countries need to evolve technology strategies that are distinctly different from those for firms in the advanced countries in order to best exploit their unique resources in the contexts of late-industrialization.

The Resource-Based View of the Latecomer Firm

The resource-based view of the firm (see e.g. Barney 1991) suggests that the superior performance of a firm derives from its pursuing a strategy that best exploits its unique resource positions. To understand why certain latecomer firms were able to achieve rapid technological catch up performance, therefore, we need to be able to delineate the unique resource positions of these firms.

Following Cho and Mathews(forthcoming), we distinguish latecomer firms in the late-industrializing countries from late-entrant or late-mover firms in advanced countries, which may be large, established firms with well-known brand/market positions in other high tech industries. While the latter firms may have adopted late-entry to a particular industry or technology area as a deliberate strategy, the former started as late-movers not by choice, but by historical necessity. Indeed, much of the literature on latecomer firms dwell on the inherent disadvantages that they suffer from being late-entrants. However, it is also true that latecomer firms do enjoy certain advantages compared to the earlier entrants. It is therefore through a careful analysis of the specific disadvantages and advantages of the latecomer context that we can begin to understand the unique resource positions of these firms.

Latecomer Disadvantages

Following Cho, Kim and Rhee(1998), the disadvantages of being late entrants in general can be seen as the converse of the three generic types of first mover advantages: (1) first movers may have market (consumer) advantages in the form of early capture of consumers and subsequent switching costs (brand recognition, user sunk cost, etc.); (2) first movers may have competitive advantages in the form of preemption (capture of key resources and their subsequent immobility, predatory investment in capacity, etc.; and (3) first movers may enjoy advantages in the form of learning curve effect (where cumulative R&D or learning by doing is significant) and "winner-take-all" type of races (e.g. patent race).

Over and above these general late entrant disadvantages, however, we can characterize the latecomer firms from late-industrializing countries as suffering several additional disadvantages than other late-entrant firms in the more advanced countries: (1) their distance from lead-user markets, which are typically located in the advanced countries; (2) their distance from the leading sources of technology, which typically belong either to advanced firms or universities/public research institutes located in the advanced countries; (3) their relative shortage of specialized input resources and inadequate public infrastructures, which are often induced locally in support of the leading firms' activities located in the advanced countries (Porter, 1990). Thus, not only are latecomer firms having to overcome the general disadvantages of being late-movers, they have to do so under more adverse conditions than those faced by other potential late-mover firms in the advanced countries.

Latecomer Advantages

While the latecomer disadvantages identified above certainly appear daunting, there do exist some potential latecomer advantages that, when appropriately leveraged, can be used to offset the disadvantages. Again, we can characterize these in terms of general late-mover advantages and additional factors specific to the late-industrializing contexts. Rephrasing the argument of Cho, Kim and Rhee(1998), we can identify five general categories of late-mover advantages as follows: (1) when there are significant asset specificity in serving the existing customers, late-movers may enjoy advantages when there is a significant change in consumer (market) taste, which imposes switching costs ("mobility barriers") on the part of the early movers, whereas the late-movers have no such sunk investments to protect; (2) late-movers similarly will have an advantage when there is a significant shift in technology that make obsolete or destroy the existing competencies of the early movers; (3) More generally, the late-mover advantages may amplify in the case of (1) and (2) when there are substantial organizational inertia on the part of the early movers; (4) Late-movers in the new technologies can also free-ride on the information externality generated by the early technology pioneers in terms of educating consumers, avoiding cost of trial and error, spillover of learning curve effects from the early movers and diffusion of know-how leading to lower cost of imitation by late-movers etc.; and (5) the late-mover firms may enjoy information asymmetry advantages versus the early entrants in that they are able to observe the behaviour of the existing players and the market responses in order to plan strategic attacks that leverage their other unique resources that may be less observable to the incumbents.

Besides these potential advantages accruing to latecomer firms in general, we identify several additional advantages that may accrue to latecomer firms from late-industrializing countries: (1) the late-industrializing economies provide, at least initially, lower resource costs for a wide range of factor inputs such as technical manpower and labor-intensive material inputs; (2) the late-industrializing economies may provide sheltered markets (either through government regulatory protection or specialized local market needs) that enable the local firms to hone their skills without having to face full external competition from day one, or that allow the local firms to bargain for technology transfer from advanced countries in exchange for market access/local know-how; (3) the information assymmetry advantage may be amplified as information on the leading firms and their technology partners (e.g. universities) in the advanced countries are widely available, whereas information on the challenger firms and their local sources of technology (local universities/public research institutes located in the late-industrializing countries) may be more costly to gather by outside parties.

In summary, we believe that any attempt to understand how latecomer firms from late-industrializing countries can catch up rapidly in technological capabilities must begin with a careful analysis of the specific advantageous and disadvantageous contexts that these firms face vis-à-vis firms in the advanced countries. In particular, based on the above characterizations, we are able to infer several generic technology capability development strategies that latecomer firms from late-industrializing countries can pursue to overcome their disadvantages and to exploit their advantages. To do this, we need to first examine the strategic dimensions for technological capability development by latecomer firms.

Strategic Dimensions for Technological Capability Development by Latecomer Firms

From the resource-based view of the latecomer firm, technological capability development represents only one competing use of firm resources vs. others such as investment in marketing, distribution channels, production capacities, or diversification away from their core businesses. In essence, technological capability development can be conceptualized as the allocation and leveraging of resources to use and create technologies to enhance the firm's overall competitive capabilities. The technological capabilities of a firm can be conceptualized as having two strategic dimensions: **product** technological capabilities and **process** technological capabilities. Basically, product technological capabilities cover the abilities to create, design and commercialize new products and services (including improving existing product designs and functionality). Process technological capabilities, on the other hand, cover the abilities of the firm to make multiple copies of a product or to deliver repeatedly a service once the product or service performance specifications are given.

While technological learning efforts often do involve knowing more about both product and process technologies, from the perspective of strategic choice, we suggest that firms can deliberately choose to focus their technological capability development efforts primarily on either the product or process side, although some may emphasize both simultaneously. Moreover, the sequencing of strategic emphasis may change over time, i.e. the focus of technological capability development may shift from one strategic dimension to another over time (e.g. from process capabilities to product capabilities, or vice versa).

While our analytical focus on the distinction between product vs. process technological capabilities as strategic dimensions for a firm's technology choice is not new, we believe that it goes beyond existing attempts in the literature in two important ways. First, while others treat the distinction as of secondary importance, we believe the distinction is of primary importance in analyzing the strategic choices of latecomer firms from late-industrializing economies. For example, in discussing the technology strategy of firms, Porter(1985) did introduce the product vs. process technology distinction, but because of his over-riding concern with characterizing all strategic choices in terms of either improving cost competitiveness vs. achieving differentiation, the product vs. process technology distinction somehow became a secondary, rather than primary, issue. Similarly, while most attempts at classifying levels of technological capability acknowledge operations capability (ability to use technology within one's operational processes) as an analytical construct (see e.g. Dahlman, Ross-Larson and Westphal(1987)), they fail to distinguish product vs. process technology in their analytical construct for adaptation and innovation capabilities. As will be discussed below, such a distinction is vital for analyzing technological catch up strategies of latecomer firms from the late industrializing countries as the learning processes involved are distinctly different (see further discussion below). Moreover, because many latecomer firms initially started as manufacturing firms, they tended to have accumulated at least some initial process technological capabilities. In contrast, few of these latecomer firms had prior experience in developing and commercializing products.

Secondly, we believe that our focus on the possible shift of strategic focus between product and process technological capabilities over time provides a more dynamic and complex view of the technological catch up process: rather than the static view of technology choice as serving a particular chosen generic competitive strategy as defined by Porter, the shifting of strategic focus between process and product technological capabilities over time represents a fundamental route for technological catch-up by latecomer firms.

In this regard, we find it useful to link the strategic dimensions of technological capability development of firms with the resource-based view of strategy (Barney,1991). Using the concept of core competence (Hamel and Prahalad,1994), we can conceptualize the strategic focus of technological capability development as either enhancing an existing core competence, or an attempt to build new core competence. We believe that this dynamic interpretation of the locus of technological capability development is particularly important in the context of latecomer firms from late-industrializing countries, where many firms may have started from a relatively inferior resource position. Technological catch up is thus a dynamic process whereby new competencies are being developed even while existing competencies are being strengthened. Moreover, this catch up process needs not be smooth, and may take the form of a series of "punctuated equilibria" of consolidating particular core competencies vs. significant leaps into new competencies. In particular, the switching of focus between product and process capabilities represents transition from one punctuated equilibria to another.

Generic Technological Capability Development Routes of Latecomer Firms

Based on the above conceptualization of the strategic dimensions for technological catch up, we are now in a position to identify five generic routes for rapid technological catch up by latecomer firms from late-industrializing countries. Figure 1 graphically illustrates the five generic routes identified while Table 1 compares and contrasts the technological learning processes and innovation network requirements implied by each of these routes. We elaborate on each of these identified routes below.

a) "Reverse Value Chain" Strategy (from OEM to ODM to OIM or OBM)

In this generic approach, the latecomer firms start by first mastering simple component subcontracting or contract assembly operations, typically on an OEM (Original Equipment Manufacturing)-subcontract basis where the end buyers provide the detailed product design specifications. They then move upstream to acquire product design capabilities to become Original Design Manufacturers (ODM) to end buyers, who now only need to provide the broad product requirements, leaving the design details to the ODMs. While many ODM firms may stay as such, some will further attempt to enter into developing own product ideas (Original Idea Manufacturing or OIM) and/or selling under their own brand (Own Brand Manufacturing (OBM)). The difference between OIM and OBM is that, while the former will still be sold under the brands of other established firms, the latter sought to develop their own distinctive brands and often their own distribution channels as well.

In essence, this technological capability development strategy involves starting with first developing process capabilities, followed by later extension into product design capabilities and finally new product creation/branding activities. This is a reversal of the normal sequence of value chain activities pursued by large, established high-tech firms in advanced countries. As suggested by Abernathy and Utterbeck(1970), the normal sequence of technological innovation starts with a radical product innovation, followed by rapid incremental product innovation activities until a dominant design emerge, after which process innovation becomes more important as competition in product features is replaced by competition in production cost and efficiency.

This OEM-ODM-OBM migration strategy has been particularly typical of Asian computer companies that started as making PC clones or manufacturing key components of computer systems, and later migrated to providing the system designs and (for some) eventually to developing their own brand and market distribution channels. Indeed, this migration strategy from process to product know-how has been proposed by Hobday(1995) as a common route for technological upgrading by indigenous firms from Asian developing economies ranging from Taiwan and Korea to Singapore and Malaysia. However, we believe that he has indiscriminately lumped together this migration strategy with another quite distinct route that we have called the “Reverse Product Life-Cycle” Route (see (b) below). As a result, he was unable to distinguish vital differences between the two approaches, and ended up giving a misleading picture of commonality of approach to quite diverse firms (e.g. big Korean chaebols and smaller Taiwanese firms) that are in reality pursuing quite different strategies.

The key emphasis of this strategy is to leverage the experience of supplying to sophisticated customers as a means to learn about the product technology as well as the end-user market requirements further downstream. The move from manufacturing to design is often first effected through providing feedback from manufacturing know-how to the buyers to improve design for manufacturability (DFM). However, the viability of this "reverse value chain" learning strategy depends on the availability and willingness of buyers to outsource their manufacturing activities, and later on, their design activities as well. This outsourcing propensity varies with industries and the nature of the technology involved. For example, the successful entry of Taiwanese and Singaporean firms into electronics contract manufacturing in the early 1980s owed largely to the willingness of many US electronics companies to outsource the more labor-intensive parts of their manufacturing activities to East Asian firms in order to reduce cost. Many of these East Asian firms were able to continue to upgrade their manufacturing capability until they were able to undertake the entire manufacturing process on a "turnkey, ship-drop" OEM basis. In Taiwan, many of these firms also moved on to innovate their own designs to become ODM producers. A few further ventured to become OBM manufacturers, while some others pioneered the OIM business model. The same migration pattern can also be observed in the bicycle industry earlier, where a number of Taiwanese firms had emerged as leading brands in the world.

b) "Reverse Product Life Cycle" Innovation Strategy ("Late-follower" to "Fast-follower")

An important variant of the above "reverse value chain" strategy is for the indigenous latecomer firms to move from being late-followers to fast-followers in product markets, culminating eventually in parity with or even leapfrogging over the established leaders. The latecomer firms start by producing relatively mature products, either under technology license from the leading companies themselves (or other independent technology suppliers where these exist) in the advanced nations, or through imitative learning where the technologies involved are not proprietary or where third party consultants are available to facilitate the transfer of know-how. The initial products tend to be based on technologies several generations away from the latest leading edge version and are usually targeted at the low-price market segments. This entry strategy allows the firms to leverage initial lower-cost advantage to take over low-end products from the market leaders. By mastering the mature product and process technologies quickly, the firms seek to shift towards making products of higher sophistication and involving technologies that are closer to the leading edge. Over time, by investing heavily in learning and following the development directions of the technological leaders through imitative R&D and rapid incremental product innovation, the firms seek to close the technological gaps between themselves and the technological leaders, becoming in effect fast followers. Some may eventually overtake the leaders by out-matching the leaders in terms of R&D

efforts, capacity investment in times of industry downturn, or aggressive pricing for market leadership. Examples include the success by Japanese and later Korean firms to enter the automobile industry and the semiconductor memory industry (see e.g. Cho, Kim and Rhee(1998)).

In contrast to the Reverse Value Chain route, firms pursuing this strategy must pursue product and process technological learning simultaneously, and they must compete directly in the end user markets from the beginning, often under their own brand, albeit starting at the low-price end. The execution of this strategy thus requires significant financial resources to not only develop the vertical integration of product and process know-how, but also the concomitant investment in marketing and brand development. Moreover, the firms need to be able to re-position their image as low-end, low-tech producer to high-quality, high-sophistication manufacturers over time, which is often a difficult task especially for mass consumer products and requires significant continuous investment in distribution channel development. Finally, as they move closer to the leading edge products, they will be increasingly perceived as competitive threats by the major market leaders, and hence technology licensing will become increasingly unavailable, forcing them to invest substantially more in their own product and process R&D.

c) Process Capability Specialist Strategy

Rather than seeking to move into the OBM business of product innovation, with the attendant higher risk of product commercialization and developing one's own marketing and branding capabilities, some firms have chosen to focus their energies and resources on becoming dedicated manufacturing specialists in the service of product developers. Instead of diverting resources to master product technologies, they concentrate on honing their manufacturing capabilities by mastering the latest process technologies and embedding them into operational processes that yield the best performance as demanded by the market, whether they be lowest cost, highest quality, maximal flexibility, or some combination thereof. One variant of this process specialist strategy is to progressively expand the vertical scope of process capabilities until the firm is able to become a turnkey contract assembler that takes over the entire supply chain responsibilities from the customers. Another variant strategy is for the firm to concentrate on becoming the supplier of specialized niche components or process steps. Either way, however, the firm needs to constantly invest resources in process innovation to stay at the production frontier. To do so, the firms need to focus all their resources on constantly improving their operational performance, either through acquiring the latest process technologies available from external suppliers and incorporating them into production as soon as possible to reap first mover advantage of learning economies, or through in-house process R&D to develop their own proprietary process know-how. Besides working closely with leading equipment and components suppliers, the firms also need to keep close touch with customers to anticipate future process requirements and to jointly develop customized solutions. Eventually, the firms will need to invest increasing amount in process R&D to move with the technology frontier.

Besides avoiding the market risk of commercializing new products, firms pursuing this strategy has the advantage of avoiding potential conflict of interest between themselves as manufacturers and the buyers, thereby strengthening the loyalty of the buyers towards them. Indeed, the ability of the process specialists to continuously innovate their processes depend critically on their being able to have close interaction with their customers, enabling them to gain intimate insights into the current and future product requirements of their customers. Such supplier-buyer trust is difficult to develop if the customer perceives that the supplier poses a threat to vertically integrate forward in the future.

The process specialist route has been widely adopted by many East Asian firms in the discrete manufacturing industries. For example, many firms from Singapore that have initially started as subcontractors and contract manufacturers for world class electronics MNCs have adopted this strategy (e.g. Ventures, Natsteel Electronics, JIT). Indeed, Singapore has now emerged as a leading hub for contract manufacturing specialists in the world. In semiconductor wafer fabrication, TSMC and UMC of Taiwan has pioneered the "pure foundry" strategy, which has since been imitated by others like Singapore's Chartered Semiconductor Manufacturing (CSM). In precision engineering, a number of Singaporean companies have become highly competitive suppliers to major disk drive makers by innovating new processes (e.g. MMI in baseplate technology).

d) Product Technology Pioneering Strategy

A few firms from the late-industrializing countries have opted for the much more difficult strategy of becoming a product technology pioneer or product innovator in the global market. In this strategy, the firm seeks to leapfrog others to become the pioneer of new products through radical product technology innovation, and to establish their innovations as the dominant designs through subsequent rapid incremental innovations. Although this is actually widely regarded as the normal innovation strategy for firms from the advanced countries, it is the most difficult strategy for latecomer firms from late-industrializing countries to aspire to. As pointed out earlier, all latecomer firms from late-industrializing countries need to overcome two inherent disadvantages compared to firms from the advanced countries: distant from lead-user markets distant from the main sources of advanced science and technological knowledge. These two disadvantages are particularly severe for latecomer firms attempting to pioneer new products, since the need to have close access to lead-user market is most critical, and access to novel, upstream technologies is particularly important for radical product innovation.

To overcome these disadvantages, those latecomer firms from the late-industrializing countries that have succeeded in being product technology pioneers appear to have adopted one of four approaches. One is to establish a strong presence, despite great cost, in the lead-user market to pursue product technology or market distribution channel development, while tapping supporting resources in the home base. This is what was done by Creative Technologies from Singapore in first pioneering the computer sound-card technology in the US, near to the home of the many computer game software developers who were the lead users of computer audio technology. Such an approach calls for either extraordinary entreprenuership, or the backing of financially strong corporate groups with long-term vision and deep pockets. A key part of this strategy is the heavy investment in brand name development through advertising and channel development, which typically will take a long time to get payoff.

The second approach is to invest in, or acquire outright, promising high-tech start-ups in the advanced countries to jump-start the entry process. This tends to be risky, as firms from late-industrializing countries typically lack the ability to evaluate such investment, given that much of the assets of such companies are actually intangible and embodied in the founders and could easily be lost through mobility of key personnel. Managing across cultures may represent another problem. Nonetheless, windows of opportunities to acquire small new high-tech start-ups or relatively established but financially distressed firms do occur from time to time.

The third approach is to lure highly qualified personnel who embody the advanced technological know-how to relocate to the late-industrializing countries. Many latecomer firms in East Asia have specifically targeted the highly trained and experienced overseas ethnic Asian (Chinese, Korean, Indian, etc.) professionals working in the US. Many recent high-tech start-ups in countries like Taiwan and to a smaller extent Singapore, especially in software and biotechnology, are founded through such infusion of high tech entrepreneurs and senior product development managers from the advanced countries who have had previous experience in the entire product innovation process from product idea to production. Besides the existence of large corporations with strategic intent to become product pioneers, the existence of a venture capital industry of sufficient depth is a critical factor facilitating such a strategic development.

The last, but not the least, approach is for the latecomer firms to engage in substantial R&D aimed at new product technological breakthroughs, either on their own or in collaboration with others such as local universities, other local firms or foreign firms, with the hope of achieving technological leadership over competitor firms in advanced countries. To offset the advantages that firms from advanced countries may have, the local firms must believe that they have access to compensating factors. These could include cheaper R&D manpower, special regional advantage (e.g. Chinese software), special government support (e.g. government R&D subsidies or low-interest capitals, technology transfer from public research institutes, government procurement, etc.), some earlier technological breakthrough conferring leadership opportunity, or special insight on a niche area overlooked by firms from advanced countries.

A variant of this strategy is to locate R&D in countries in the region that have abundant R&D manpower but lack product commercialization infrastructure (e.g. China, India, Russia). The comparative advantage of Singaporean, Taiwanese or Korean firms in this case may be due to geographic/cultural proximity or prior business network contacts established.

Some of the more successful companies from East Asia have adopted more than one of the above approaches, either simultaneously or at different growth stages. For firms that have already achieved at least some product innovation capabilities of their own, strategic alliances with advanced firms will become an increasingly important option as well, but this option is typically not available to firms in the early stage when they have little technology to offer.

To overcome the barriers of entry in mass end product markets, some latecomer firms pursuing this strategy may eventually opt to become a pure technology innovation services provider, whereby the firm focuses entirely on product technological innovation, with the appropriation of returns from its innovation efforts taking the form of licensing know-how and or providing contract R&D/design services rather than going into the end product development and commercialization itself. However, this is unlikely to be a viable route for technological capability development until the late-industrializing country has developed sufficiently to provide the necessary complementary assets that support such a strategic focus, e.g. the development of process specialists who can serve as strategic manufacturing partners, the development of a critical mass of design capabilities to establish the necessary reputation to gain the confidence of large established firms seeking design/innovation services, and the establishment of strong enforcement of intellectual property protection.

e) Applications Pioneering Strategy

This last strategy entails the latecomer firm to aim to become an innovator not of new product technologies, but in the application of existing technologies in new innovative ways, typically in a business area where the organization has considerable complementary skills. Three examples of Singaporean firms that have done well in this regard can be used to illustrate this generic technological capability development route. The first example involves the Port of Singapore Authority (PSA), which has pioneered the application of a relatively mature technology (neural networks/fuzzy logic) in automating and speeding up container handling. As the second example, a firm called Eutech Cybernetics has pioneered the use of well-established digital signal processing (DSP) technologies to pioneer new analytical instrumentation that are highly portable and easy to use. The last example is that of Singapore Network System (SNS), which used established EDI technology to pioneer the development of a paperless trade document processing system called TradeNet, the first such system in Asia. TradeNet dramatically improved the efficiency of the export/import trade transaction process.

The success of this strategy hinges on the company being an early and innovative adopter of new but available technologies, rather than a creator of radically new technologies. The company must in addition have good insight into the business it is competing in, so that the new technologies can be leveraged to best improve the competitiveness of the company in its chosen business. In essence, this is a form of vertical "fusion" of an upstream, externally available technology with internal, often proprietary, knowledge of a downstream domain of business application. Although it is in principle possible for an upstream technology-based firm to leverage its core technology into a downstream application, it is more likely for a downstream business enterprise to exploit new technologies to enable it to innovate its business services or products. Eutech Cybernetics, for example, started with a deep knowledge of analytical chemistry and sought available digital signal processing know-how to innovate new portable analytical instrument.

The five strategic routes to technological capability development identified above are not exhaustive, but they do appear to cover the major variations in strategic approaches towards technological capability development by latecomer firms from late-industrializing economies. Some firms may switch from one strategic route to another over time, although most are found to pursue a single strategy route consistently for a long time. Moreover, it is possible that some combination of generic routes may tend to go together in that firms pursuing one route may become complementary to other firms pursuing another generic route; for example, a product technology pioneer can collaborate with a process specialist to the mutual benefit of one another.

As highlighted in Table 1, different technological learning processes are implied by the five different generic technological catch up routes. These differences in technological learning processes in turn suggest different innovation network requirements and facilitating state roles. Such characterization suggests an analytical link between the types of generic technological catch up routes at the *firm* level and the characteristics of the innovation system at the *national* level. This we will examine next.

The Influence of National Innovation System and State Role on the Technological Catch Up Strategies of Latecomer Firms

Our suggestion of the existence of multiple generic routes to technological capability development by latecomer firms from late-industrializing countries suggests that while the environmental contexts of late-industrialization shape the strategic choice of these latecomer firms, they do not constrain them to only one catch up path. On the other hand, while each of these generic routes is potentially a viable route for all latecomer firms, in reality some are more likely for firms from some countries than others. Indeed, as we shall argue in the next section, firms from the three East Asian NIEs of Taiwan, Korea and Singapore exhibit significant differences in the choice of generic technological catch up routes adopted. This diversity in the national pattern of technological catch up routes is to be expected because the latecomer firm's choice of technological capability development routes takes place within specific national innovation systems, i.e. the effects of late-industrializing contexts are mediated and made unique by the specific national innovation system characteristics that shape the incentives and availability of resources for technological learning by the individual latecomer firms.

We suggest four major elements that need to be taken into account in examining the influence of national innovation systems on the latecomer firm's technological catch up behaviour. First is the initial industrial organization structure of the countries concerned – the typical size, concentration pattern and prior competencies/industry experience of firms – which obviously influence the amount and type of resources that these firms can command for new technological learning. Large, multi-divisional firms may have deeper pockets to finance large scale technological investments than small firms. On the other hand, small firms may be more flexible in entering new technology-based business, and their exit barriers may also be lower.

Second is the strategic intent of the founders of these latecomer firms as shaped by their historical experiences, educational backgrounds and social-cultural values. For example, countries where the founders of firms are strongly possessed by a nationalist conviction to catch up with other advanced countries are likely to devote more resources to technological catch up than otherwise.

Third is the structure of competition faced by the latecomer firms in their domestic market, and by extension, the structure of competition among their domestic suppliers and customers. The existence of large, protected local markets for a temporary period may provide incentive for new product innovation to exploit the window of opportunity. On the other hand, prolonged protection from competition will dull incentives of incumbent firms to innovate.

Last, but not least, is the network of external resources that the individual latecomer firms can leverage outside of their own boundaries. Besides local universities/public research institutes and the existing pool of suppliers and customers, the access to new technological resources of foreign firms, and the availability of a pool of potential returnee scientists, engineers and technical managers from advanced countries all represent major external network resources that the latecomer firms can leverage, but the accessibility of these resources are highly influenced by the national innovation systems that the latecomer firms belong to (OECD(1998)). Not only are there significant path dependency in the development of such 'innovation networks" in a particular country, they tend to be strongly influenced by past state intervention policies. In particular, there appears to be significant agglomeration economies in capabilities in particular technological areas, resulting in persistence in the pattern of specialization by technology areas among countries over time. Despite rapid technological catch-up, the national pattern of technological catch up may be constrained within particular technological trajectories or specific technological clusters.

While none of the above four elements for characterizing national innovation system is new, we believe that new insights can be obtained by examining the interaction between these elements of the national innovation system and the generic technological catch up routes identified earlier. In particular, we suggest that there is a systematic relationship between these key elements of the national innovation system and the likely viability of specific generic technological capability development routes. As shown in Table 1, the different generic technological catch up routes emphasizes different technological learning processes, which in turn have different implications for internal resources vs. leveraging of external resources through innovation networks.

The implications for state intervention roles are also different for the different generic routes to technological catch up (see Table 1). For example, the Reverse Value Chain route suggests possible facilitating state policies such as the encouragement of subcontracting by foreign MNCs, the establishment of public research institutes to help diffuse process technologies and product design know-how, and the promotion of standardization of product architecture and modular design of component technologies to facilitate ODM. Similarly, the Reverse PLC route suggests the need for a deliberate state policy to promote the growth of large-sized firms with sufficiently deep pocket to undertake the heavy investment in simultaneous product, process and market/brand development. On the other hand, product technology pioneering is better promoted through policies that facilitate new entrepreneurial start-ups, e.g. the promotion of venture capital industry, incentives for public research institutes to spin-off technologies, etc.

In summary, we believe that our proposed typology of technological catch up routes at the *firm* level provides a useful framework to analyze the impacts of innovation system structure at the *national* level. Our hypothesis is that the pattern of technological catch up routes is systematically influenced by the nature of the national innovation system model adopted in the countries concerned. To test the usefulness of the proposed framework, we turn in the next section to apply the framework to interpret the rapid yet distinctively different technological catch up performance of Taiwan, Korea and Singapore.

3. Interpreting the Different Technological Catch Up Patterns of Taiwan, Korea and Singapore

While various existing studies have highlighted the distinctive characteristics of the industrial and technological development experience of each of these three countries individually, we believe that an application of our proposed typology of generic technological catch up routes to the three NIEs provides some new insights on how and why their national technological catch up patterns differ so much.

Table 2 summarizes our interpretation of how the three countries' technological catch up patterns differ from the perspective of the relative dominance of generic routes adopted by firms in the respective countries. The summary interpretation is derived from our extensive review of the existing empirical literature on each of these countries (see e.g. Wong and Lee(1999) for the extensive references consulted). As can be seen, the Taiwanese pattern shows the Reverse Value Chain route to be the dominant route, followed by the Process Specialist route. In more recent years, the Reverse PLC route and the Product Technology Pioneering route have become more visible, but they remain subordinated to the other two routes. In contrast, in Korea, the Reverse PLC route appears to be have been the dominant route, after a short initial period of emphasis on the Reverse Value Chain route. Finally, in the case of Singapore, it is suggested that the Process Specialist and the Reverse Value Chain routes are the dominant forms, but of reverse order of importance compared to the case of Taiwan. However, the Application Pioneering route also appears to have been an important route. An emerging trend of Reverse PLC route by large, state-owned firms on the one hand, and product technology pioneering by small entrepreneurial firms on the other hand, can also be detected.

How can such differences in national technological catch up pattern be explained ? In essence, based on our conceptualization of how the choice of generic routes are influenced by key elements of national innovation system as summarized in Table 1, we believe that such differences can be best understood as the result of the co-evolution of three different national innovation models: the SME-Public Research Institute (PRI) innovation network model in the case of Taiwan, the large integrated firm model in the case of Korea, and the DFI-leveraging model in the case of

Singapore. We briefly highlight the key features of these three stylized models and how they contributed to the pattern of technological catch up observed.

The SME-Public Innovation Network Model of Taiwan

It is by now well known that Taiwanese firms were among the first and largest OEM subcontractors to many firms from the advanced countries in a wide range of industries, ranging from bicycle assembly to electronics and computer assembly. Over time, Taiwanese OEM firms had also made significant progress into ODM activities, particularly in the PC-related industries. An increasing number of Taiwanese ODM firms had also gone on to become OBMs, good examples being ACER in PCs, and Giant in bicycles. It is indeed fair to say that it is the Taiwanese that have invented the ODM and OBM concept, and more recently, the concept of OIM as well.

A significant number of Taiwanese firms have also pursued the Process Specialist route. In particular, in the semiconductor industry where Taiwanese firms have achieved remarkable catch up, firms like TSMC and UMC pioneered the pure foundry business, which represents the first successful application of the process specialist route by latecomer firms in the semiconductor industry.

What national innovation system characteristics of Taiwan facilitated such a pattern of technological catch up? To begin with, most of the Taiwanese firms that pursued the Reverse Value Chain strategy started as SMEs engaging in labor-intensive manufacturing activities. Because of their limited resources, they were unable to invest much R&D efforts. Hence, the state played an important role in diffusing process technologies to the SMEs in the early stage. In a later stage, through the establishment of various product technology consortia (Hou and Gee 1993), the state also helped diffuse various design know-how to many Taiwanese SMEs to enable them to enter the ODM phase, the most successful example being the notebook computer consortium coordinated by the Industrial Technology Research Institute (ITRI). The ability of Taiwanese firms to dominate the manufacturing of notebook computer today owes much to the coordinating role of ITRI in standardizing key technology components and their interfaces to facilitate ODM. The state played an even more central role to jump-start the process specialist strategy being pursued in the semiconductor industry (Mathews 1995). Indeed, the current leading Taiwannese semiconductor wafer fabrication firms, TSMC and UMC, were both spun off from technologies acquired through ITRI.

In short, the Taiwanese model can be aptly described as a SME-Public Research Institute (SME-PRI) Innovation Network model (Wong, 1995). The high technology sectors where Taiwanese firms have achieved rapid technological catch up are primarily industries where Taiwanese firms have excelled through the Reverse Value Chain and Process Specialist routes. The SME-PRI innovation network model can be best characterized as one involving the promotion of indigenous small and medium sized enterprises (SMEs) coupled with the large scale development of public research institutes (PRIs) to facilitate technology assimilation/transfer and cooperative R&D promotion in support of the indigenous SMEs. Among the NIEs, Taiwan has probably been most successful in using PRIs to promote the diffusion of industrially-relevant technologies. ITRI has been widely credited with helping to create an advanced semiconductor industry cluster in Taiwan through a well-thought out and well-executed strategy of assimilating foreign technology and transferring them to local enterprises through spin-offs (see e.g. Mathews 1995 and Lin1994). The successful execution of this strategy depended on a number of factors, including careful long-term technology development planning and vision at the top ("Electronics Industry Development Project (EIDP)"), an abundant supply of well-trained engineers, and significant presence of, and strong linkage with, competitive local electronics industries which provided significant markets and customer feedback. It is also important to note that "reverse brain drain", in the form of returnees from the US who were well-qualified and experienced technologists, had played a critical role. Besides staffing critical technological transfer functions, they also provided the competent top leadership (e.g. the chairman of ITRI who helped guided the semiconductor spin-off strategy was Dr. Morris Chang, who was formerly a top manager in Texas Instruments.)

Besides the successful spin-offs in semiconductor wafer fabrication, there are also many examples of PRI-orchestrated R&D consortia in Taiwan (Hou and Gee 1993, Lin 1994); over the last 15 years, it has been estimated that over 60 such R&D consortia had been established in various industrial sectors in Taiwan. Although the records of these R&D consortia in terms of eventual market commercialization are mixed, it is undeniable that they have contributed significantly towards supporting the OEM-ODM-OBM migration strategy of many Taiwanese SME firms.

However, this dominant pattern of technological catch up is beginning to change in recent years. With the growth of some of the existing SMEs into large-sized firms with significant R&D capability of their own, there has been a questioning of the continued usefulness of this SME-PRI collaboration strategy. Indeed, some of the large firms as well as other small but innovative firms now argue that they would prefer pursuing their own proprietary R&D rather than share their technologies with rivals as bound to happen in the consortium approach. Moreover, the growing linkage between Taiwanese engineer returnees from the US and their prior contacts in the US, particularly the Silicon Valley, are facilitating an increasing number of new start ups in Taiwan that pursue the product technology pioneering route. This is further facilitated by the rapid growth of the venture capital industry which the government actively promoted.

The Large, Vertically Integrated Firm Model of Korea

In contrast to Taiwan, the Korea innovation system model is characterized by the existence of large conglomerates, the chaebols. Their large size and ready access to finance give them the "deep pockets" to undertake the Reverse Product Life-Cycle strategic route. This can be seen in the rapid technological catch up of the large Korean chaebols in such sectors as automobile, steel, consumer electronics, semiconductors (especially DRAM), and Active Matrix LCD. In all these cases, the large Korean chaebols have moved aggressively from late-followers to fast followers, and in the case of DRAM technology, to become the global technological leaders overtaking the Japanese. To achieve their rapid catch up via this strategic route, Korean firms have resorted to aggressive capacity investment to accelerate learning effect, accepting thin margin or loss bearing to build volume and gain market share, and deep investment in R&D (Cho, Kim and Rhee(1988)).

Such aggressive approaches are only possible with the deep pocket of the large conglomerates which can cross-subsidize across the conglomerate group, and which can tap large external financial resources under the state-controlled banking system. Another supporting state policy that facilitated the reverse PLC strategy is the protection of domestic market. Yet another is the adoption of "export contest" as the key mechanism for allocating credit in the early phase of Korean industrialization, which contributing to the emergence of the large chaebol system in the first place. Other facilitating state policies include incentives for imitative technological learning through capital goods import vs. relying on DFI, and turning over failing state enterprises to the chaebols.

Although there were notable failures in this heavy industry strategy, several of the big chaebols like Samsung, LG, Hyundai and Daewoo did develop significant technological capabilities in a wide range of export-oriented, capital intensive industries as a result. Where Korea differed from other developing countries in promoting big businesses in the 1970s and 1980s was in the discipline that the state exercised over these chaebols by penalizing poor performances and rewarding only good ones. This "contest"-based approach (Amsden,1989) enabled a number of high-performing chaebols to quickly establish large scale production, marketing/ distribution or R&D economies to compete successfully in several global industries like shipbuilding, automobile, consumer electronics, telecommunications equipment, and semiconductors. The large size of these chaebols enabled them to build global brand and distribution channels at the same time that they were pursuing product and process technological capability development. Besides investing heavily in in-house R&D, the chaebols also borrowed heavily to finance the acqusition of established companies in the advanced countries, e.g. Maxtor, NCR Microelectronics, and AST.

However, the Reverse PLC strategy adopted by the chaebols appear to be a source of disadvantage when it comes to competing in technologically dynamic industries like PCs, software, biotechnology and specialty chemicals where scale economies are not important or less critical, and where rapid product innovation capabilities are crucial. Furthermore, the ability of the large firms to monopolize access to finance led to their pursuit of indiscriminate and unrelated diversification in later years, which led to over-extension into marginal businesses and loss of strategic focus in core businesses. While such dysfunctional growth of the large conglomerate model is largely responsible for the financial crisis that Korea encountered in late 1997, it does not detract from the fact that Korea had achieved considerable technological catch up success in the past through these large vertical firms pursuing the Reverse PLC strategy.

In summary, we can describe the Korean national innovation system as one characterized by the domination of large, vertically integrated conglomerates pursuing the Reverse PLC strategy. It is useful to recount the historical origins of this national innovation model. Basically, Korea went through an early stage where the pursuit of the Reverse Value Chain route by SMEs was the dominant norm, just as in Taiwan. However, this model was soon abandoned, as the Park Chung Hee military rule implemented strong state intervention in promoting industrialization. Through mechanisms like industry targeting and state-directed bank credit allocation in favour of firms with good export performance and daring to enter new industries, a number of entrepreneurial firms soon grew extremely rapidly, laying the foundation for the emergence of the large chaebols. Motivated by the nationalist sentiments to catch up with Japan as well as national security concerns, the government then embarked in the 1970s on a program of promoting heavy industries, which further encouraged the growth of large-scale chaebols as an instrument to enter large scale, capital-intensive industries that were deemed "strategic".

The excessive development of big businesses in Korea had become evident in the light of the recent debt crisis faced by Korea, which exposed the vulnerability of this high financial gearing approach to industrial growth. Over reliance on state allocation of credit had created a moral hazard situation, where increasingly risky investments and unrelated diversification were undertaken with scant regard to the cost of capital. At the same time, the innovation system discourages the creating of new start-ups to pursue the product technology pioneering route, given the lack of a efficient financial system, lack of venture capital, and a rigid labor market.

The DFI-Leveraging Model of Singapore

In contrast to Taiwan and Korea, Singapore adopted a model of national innovation system that can be best characterized as one emphasizing government facilitation of MNC-induced technological learning. Ever since the government embarked on a strategy of encouraging foreign investment to jump-start industrial development in the 1960s, the Singapore government has continued to encourage MNCs to upgrade their manufacturing processes and to bring in successive waves of new and more advanced products to be manufactured in Singapore. Although some have criticized this MNC-led approach as stunting the growth of local firms, research evidence has shown that these MNC operations have spawned a large supporting industry in Singapore and induced substantial technological capability development among many local subcontracting and contract assembly firms (Wong 1995c, Wong 1997).

As in Taiwan, many of the indigenous manufacturing firms in Singapore originated as contract manufacturers and supporting industries to MNCs, and some of them had similarly adopted the OEM-ODM-OBM migration route. However, compared to Taiwan, many more Singaporean firms pursued the manufacturing process specialist route, focusing on process technological capability development. This difference can probably be attributed to the different industrial and technological promotion policies adopted in the two countries. While both countries encouraged DFI in the early years, Taiwan had increasingly sought to promote local industries in later years. In contrast, Singapore continued to encourage MNC investment in manufacturing, which provided a significant local demand for subcontracting and supporting industries. Rather than outsourcing the entire manufacturing and design activities to local OEM or ODM firms, many of these MNCs typically maintain substantial assembly operations of their own in Singapore. Thus, the relations that developed initially were less of the OEM/ODM type, but more of the subcontract type, where the local firms are responsible for making specific parts/components or providing specific manufacturing services. This contracting relationship thus encouraged more the development of Process Specialists among local firms.

Although the Singapore government also sought to establish PRIs to promote the diffusion of process technologies to local SMEs as in Taiwan, it has probably done less in facilitating the diffusion of product design know-how than Taiwan. In the early 1970s, the government established the Singapore Institute for Standards and Industrial Research (SISIR) to support SME technological upgrading, but the focus has been primarily on process, not product. Various training institutes were also established to train technical manpower for the various local supporting industries in precision engineering, metal fabrication, contract manufacturing and industrial automation. As the local manufacturing industries grew in sophistication, a Gintic Institute of Manufacturing Technologies (GIMT) was also established in the 1980s to provide R&D support to manufacturing industries. Similar process technology focus is also evident in the initial setting up of another PRI, the Institute for Microelectronics (IME).

In addition to the setting up of public R&D and training institutions, the Singapore government also extended various financial assistance schemes aimed at encouraging local manufacturing SMEs to upgrade their process technological capability. As the local firms became more advanced in their process capabilities and started to engage in substantial in-house innovation efforts, new innovative R&D incentives like Research Incentives Scheme for Companies (RISC) was introduced by the government to fund integrative process technology capability development efforts in these companies, recognizing that such efforts cannot be neatly packaged into specific R&D projects for funding under traditional R&D subsidy schemes (Wong 1995b).

Besides these technical support programs, the government also introduced an innovative scheme in the early 1980s designed to facilitate the "Learning by Transacting" process of local firms working as suppliers and contract manufacturers to MNCs. Called the Local Industry Upgrading Scheme (LIUP), the program enlisted the participation of leading MNCs operating in Singapore to provide one of their technical managers to work full-time on helping local suppliers to upgrade their process capabilities. In the 1990s, the focus on promoting technology transfer and process management know-how from MNCs began to shift increasingly to encouraging R&D collaboration between local firms and the MNCs. More public research institutes (PRIs) were being set up with an increasing focus on promoting collaboration between local firms and MNCs through R&D consortia. For example, the Ball-Grid Array (BGA) process technology consortium and the Marine Technologies consortium both aimed at accelerating the development of process technological capability among local firms working in collaboration with their MNC customers.

Unlike Taiwan and Korea, which depended heavily on manufacturing export as an engine for economic growth, Singapore also achieved a high level of competitiveness in many services sector, having established itself as a business, communications and financial hub in Asia. Thus, in addition to DFI-leveraging in the manufacturing sector, many Singaporean firms in the services sector also achieved rapid technological upgrading through the pursuit of Applications Pioneering strategy. In addition, the public sector itself has played a major technology lead-user role by investing aggressively in rapid adoption of new technologies to improve public services. This public policy focus on promoting the diffusion and adoption of advanced technologies is particularly evident in the IT area; the government has been among the most aggressive in the world to invest in information and telecommunications infrastructure (Wong 1998).

This significant focus on application pioneering notwithstanding, it is nonetheless correct to describe the national innovation strategy of Singapore as one of primarily emphasizing the leveraging of DFI to facilitate local technological capability development. Unlike Korea, the Singapore government did not strongly support the development of large local enterprises to undertake the Reverse PLC strategy of technological catch up. Rather than championing such large size local firms, the government instead pursued a policy of encouraging leading MNCs from the advanced countries to establish their high tech manufacturing operations in Singapore. Technological upgrading therefore took largely the form of internal technology transfer from MNC headquarters to their local subsidiaries, and the inducement of process technological development among local SMEs working as suppliers to these MNCs. The rapid growth of local firms pursuing this process specialist route is also facilitated by the movement of experienced technical professionals and managers from the MNCs to start up their own contract manufacturing firms. By pursuing the process specialist route, some of these firms such as Venture Manufacturing and Natsteel Manufacturing were able to grow quickly and to globalize their operations. It is this high emphasis on the process specialist strategy among local firms that Singapore has emerged as a leading electronics contract manufacturing hub in the world, with 4 of the top 10 contract manufacturers being Singaporean firms.

It is only in the 1990s that the state began to actively promote the other technological catch up routes. On the one hand, the government began to promote some degree of reverse PLC strategy to technological catch up in selected capital-intensive high-tech sectors where scale economy have been significant e.g. semiconductor wafer fabrication, chip design, aerospace repair and maintenance, systems software) (Wong,1998). This is done primarily through the setting up of a government-controlled group, the Singapore Technology Group. More importantly, the government has started to recognize the importance of product technology pioneering as a strategic route for technological capability development in the future. To support a shift to this route of technological development, the government has accelerated the establishment and funding of PRIs/university R&D, encouraged MNCs to start product R&D operations in Singapore, and more recently, launched an ambitious Technopreneurship Program to promote the growth of new technology start-ups. Besides promoting the development of new supporting infrastructure such as venture capital industry and IPR support services, the government is reviewing changes to existing business regulations (e.g. stock exchange listing regulations, stock option rules and tax incentives for business angel investment) to facilitate the growth of technopreneurship.

Flexible Convergence or Rigid Path Dependency Among the Three NIEs?

In comparing the distinctly different national patterns of technological catch up in the three countries described above, one is struck by the apparent high degree of clustering and path dependency in the choice of dominant generic technological catch up routes being pursued in these respective countries. For example, the dominance of the Reverse PLC strategic route in Korea has been sustained and indeed intensified since the 1970s with when the large chaebols first emerged. Similarly, despite significant refining, Singapore has basically pursued the DFI-leveraging model continuously since the early 1970s.

As the three NIEs become more technologically advanced and approaching closer to the global technological frontier, it is interesting to speculate whether they can continue to sustain their rapid technological catch up through the same dominant pattern of generic routes. Given that the pattern of technological innovation in the advanced countries (especially the US) show a much larger proportion of firms pursuing the product innovation routes than can be observed in the case of the three NIEs, we believe that all three NIEs are likely to be approaching the limits of their respective technological capability development paradigms. To sustain technological development in the future, our analysis above strongly suggests that these countries will need to significantly redirect more of their technological capability development resources away from their current dominant routes in general and towards product technological innovation in particular. However, because of the close relationship that appears to have been established between the national innovation system structure and the choice of dominant generic technological capability development routes that evolved over time, it appears likely that the structural adjustments needed will not be easy to achieve. In particular, we believe that the strong dominance of the Large Firm-Reverse PLC model has become too rigidified and significantly hindering the emergence of alternative technological innovation models. Despite the financial crisis and the tremendous political pressure exerted on the big chaebols to restructure, few changes in the existing innovation system structure have been implemented. It is an open question whether Singapore's recent big push to promote local technopreneurship ala the Silicon Valley's product technology pioneering model will succeed in the medium term. Unlike Taiwan, which enjoys a much greater "reverse brain drain" and has established a stronger innovation network linkage with firms in the US, Singapore will probably have to compensate by emphasizing the use of public research institute and university R&D to create new sources of technology and to attract foreign talents.

4. Conclusions

Based on the resource-based view of the firm, this paper argued that latecomer firms from late-industrializing economies that seek to achieve rapid technological catch up need to pursue distinctive technology capability development strategies to overcome their late-comer disadvantages as well as to exploit their late-comer advantages. In particular, we proposed a typology of generic technological capability development strategies of latecomer firms from late-industrializing countries. We then used the typology to highlight the different patterns of technological catch up of firms in Taiwan, Korea and Singapore, and explored why such differences came about in terms of the national innovation system models adopted.

We believe that the analytical approach presented in this paper makes two useful contributions to the literature on technological development in late industrializing countries. Firstly, by highlighting the conceptual distinction between product and process technological capabilities, our proposed typology of generic technological capability development routes provides a strategic framework to analyze the generic technological catch up choices of latecomer firms that is analytically more complete than those previously proposed by Hobday(1995), Mathews(1995), Lall(1996) and Kim(1997), and offers more theoretical grounding in terms of the resource-based view of the firm.

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Secondly, by using the typology of generic routes to characterize differences in the national pattern of technological catch up and relating these to the specific contexts of late-industrialization (including both disadvantageous and advantageous factors), our analytical framework provides a new perspective for linking the strategic technology behavior at the level of the *firm* to the innovation system characteristics at the *national* level. We believe that this perspective offers a more complex and dynamic view of the design of national innovation systems for technological catch up by late-industrializing countries than previous works that emphasize the common "fundamentals" for rapid technological catch up (see e.g. Lall(1996), Enos(1992) and Dahlman(1994)). It also goes beyond the simple distinction between promoting technological innovation vs. diffusion (Mathews,1996). Instead, the choices are shown to be more complex and dynamic. While highlighting the existence of *multiple choices* for technological catch up at the firm level, our application of the analytical framework to the experience of the three Asian NIEs strongly suggests a tendency for strong clustering and path dependency in the choice of generic technological catch up routes at the *national* level. In particular, it suggests that state intervention policies play an important role in shaping the choice of dominant generic routes in the countries concerned. Consequently, major changes in state policies need to occur for the pattern of dominant routes to be altered. Our analysis suggests that this needs to happen for all three NIEs to sustain their rapid technological development in the future, particularly Korea.

Going forward, we believe that the proposed conceptual framework can be further extended in a number of ways. First, although we have applied our conceptual framework to interpreting the technological catch up experience of Korea, Taiwan and Singapore only, we believe that the framework can be extended to examine the technological catch up process in other late-industrializing countries, including some of the small European countries which went through the rapid technological catch up phase after the Second World War. For example, our preliminary review of the empirical literature on how Finland achieved rapid technological take off from the 1970s (see e.g. Lemola and Lovio 1988 and Numminen 1996) seems to suggest that relatively large Finnish firms in the core industries of forestry and metal products emphasized the adoption of the reverse PLC strategy, but the product innovation route was adopted by Finnish firms entering new industries like telecommunications and electronics. The growth of these industries in turn stimulated the development of small supporting firms that largely pursued either the product innovation or process specialist routes. Thus, the technological catch up patterns of Finland shared some similarities with Korea, but there were considerable differences as well. Similarly, the technological catch up pattern of Ireland bears some similarities to Singapore, with both relying significantly on leveraging DFI, but the cluster of local high tech firms that emerged in these two economies differed somewhat. By highlighting such differences in technological catch up pattern among countries, our proposed conceptual framework suggests interesting comparative research that promise to offer new insights on the influence of national innovation system on latecomer firms' technology catch up behavior.

Secondly, we believe that the framework needs to be further refined to take into account the co-evolutionary dynamics of firm behavior and national innovation system structure. While we have so far focused on how the initial industrial structure and national innovation policies influence the technological catch up behavior of firms, the latter in turn is likely to shape the evolution of the national innovation system structure. As suggested earlier, this co-evolution of national innovation system structure and the dominant choices of technological capability development routes is likely to create structural adjustment problems for late-industrializing countries as they become more advanced and the scope for further improvement within the chosen dominant routes are increasingly exhausted. Already, Korea is facing problems making structural adjustments away from its strong dependence on large chaebols pursuing Reverse PLC strategy. Similarly, Singapore is undergoing major structural adjustments to reduce reliance on attracting and leveraging MNCs to nurturing new local start ups pursuing product technology pioneering. Elucidation of how such structural adjustments can be effectively promoted before they become too rigidified will go a long way towards improving our understanding of how the rapid technological catch up process by the East Asia NIEs can be sustained into the future.

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Figure 1 :
Generic Technological Capability Development Strategies of Latecomer Firms from Late Industrializing Economies

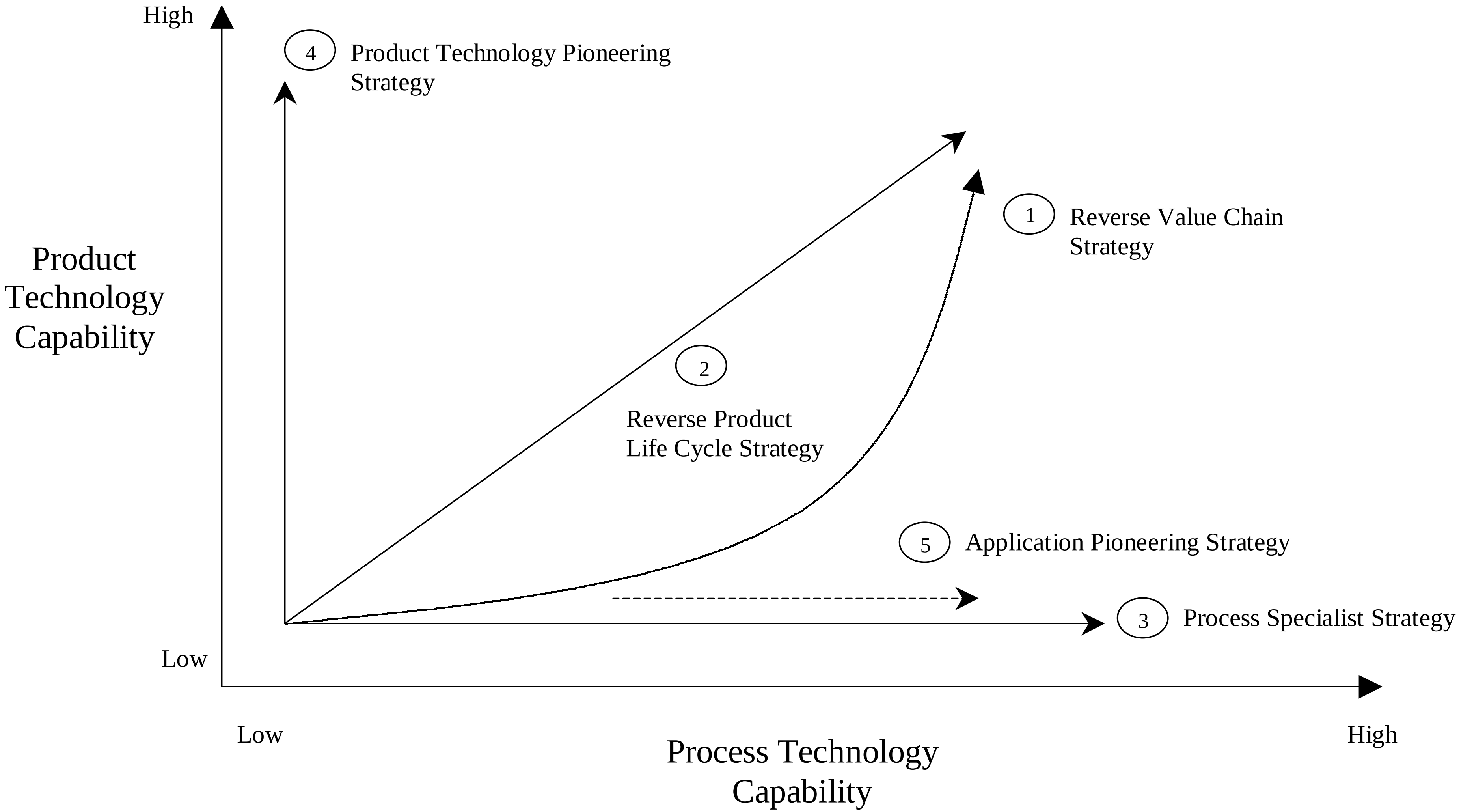

Table 1 Key Technological Learning Processes for the Five Generic Technological Capability Development Routes

Generic Technological Capability Development Routes	Key Technological Learning Processes	Innovation Network Implications	Possible Facilitating State Policies
Reverse Value Chain	Learning by Doing Learning by Transacting R&D	Close interaction with customers; Coordination among firms to standardize product-process interface and modular design	Promote MNC-local contract manufacturing; Coordinate and fund R&D consortia of local firms to diffuse design and product know-how
Reverse PLC	Learning by Doing Reverse Engineering Imitative R&D	Internalization of product and process capabilities; Access to third-party consultants; "Reverse brain drain"	Promote growth of large firms with "deep pocket" to undertake Reverse PLC; (Temporary) protection of domestic market; bargain for technology transfer in exchange for market access; Encourage "reverse brain drain"
Process Specialist	Learning by Doing Learning by Transacting R&D	Close interaction with customers, suppliers and technology vendors	Promote process technology acquisition and R&D; Promote PRI/ University-Industry collaboration in process R&D
Product Pioneering	R&D Market Research	Close interaction with universities/research institutes; Close to lead-user market; "Reverse brain drain"	Promote Venture Capital industry development; Fund PRI/University R&D; Commercialization & start-up incentives; Encourage reverse brain drain
Application Pioneering	Technology Scanning Integration with Domain Knowledge	Close interaction with technology vendors	Promote diffusion & adoption of advanced technologies; Fund diffusion infrastructure development

Table 2 Dominant Generic Technological Capability Development Routes In the 3 NIE National Innovation System Models

National Innovation System Models	**Dominant Generic Technological Catch Up Routes**
Taiwan's SME-PRI Innovation Network Model	Reverse Value Chain Strategy, followed by Process Specialist Strategy Strong emergence of Product Pioneering Strategy since the late 1980s
Korea's Large Firm Internalization Model	Reverse Product Life Cycle Strategy
Singapore's DFI-Leveraging Model	Process Specialist Strategy, followed by Reverse Value Chain Strategy on a smaller scale Application Pioneering strategy strong among services firms Emergence of Reverse PLC Strategy and Product Pioneering Strategy in the 1990s