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**Dynamic Catch-Up Strategy, Capability
Expansion and Changing Windows of
Opportunity in the Memory Industry**

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Abstract

The memory industry has twice experienced a change of market leadership, from the US to Japan in the early 1980s and from Japan to Korea in the 1990s. More than two decades have now passed, however, without further leadership change. This paper examines the reasons for this and discusses its implications for catch-up strategies and changing windows of opportunity for latecomers. It identifies the catch-up strategy that is imperative in the memory industry as a “dynamic catch-up strategy” and investigates how it worked for Japan and Korea until the middle of the 1990s. It then explores why the strategy later became more difficult to implement successfully.

Key words

Catch-up, capability expansion, industrial leadership changes, windows of opportunity, firm strategy, unbalanced growth, the memory industry, Japan, Korea

1. Introduction

The semiconductor industry consists of three main segments, i.e., microprocessors, memories and ASICs (application-specific integrated circuits), and each is characterized by quite different design and capital requirements. Microprocessors, which function as “brains” for electronic devices including PCs (personal computers), are the most design intensive and the most highly capital intensive in the semiconductor industry. ASICs, which mainly function as the “neurons” of electronic devices, are highly design intensive but less capital

¹ Discussions on the case of Samsung Electronics are drawn heavily from my unpublished paper co-authored with Sung-Won Jang (Shin and Jang 2005). I thank the editors of this special issue and the reviewers of this paper for their incisive comments.

intensive than either microprocessors or memories.² Memories, which are used for information storage, are the most capital intensive but least design intensive.³

The three segments have undergone different experiences of industrial leadership change.⁴ In microprocessors, there has been no noticeable leadership change. Intel, which created the microprocessor in 1971, has maintained its leadership for more than four decades. The second-largest microprocessor producer in the world, AMD, is also a US company. In ASICs, there has been no discernible leadership change either: The leaders are still US chip-design houses like Qualcomm and Broadcom. They have maintained their leadership through the “decoupling” of design and manufacturing, whereby they focused their competence on design and outsourced manufacturing to other companies, mainly to Taiwanese foundries such as TSMC and UMC. One can say that the leadership in ASICs is currently shared between design houses and foundries, but it would be difficult to argue that a leadership change has taken place.

Memories, however, have clearly seen the industrial leadership change twice, from the US to Japan (1980) and then from Japan to Korea, with Samsung Electronics becoming the number-one memory producer among companies in 1993 and Korea overtaking Japan as the number-one country in 1999. This implies that catch-up opportunities for latecomers in this most capital-intensive segment of the semiconductor industry were different from those in the more design-intensive segments, microprocessors and ASICs. On the other hand, in the two decades since Korea emerged as the leader in memories, there has been no leadership change. This implies that, during the period, some important changes occurred in the memory segment that affected catch-up opportunities. The history of memories is divided into two distinct periods: that of successive leadership changes and that without leadership change.

Gerschenkron (1962, 1968, 1970) provided a framework for understanding the catch-up process in capital-intensive industries in the 19th century, and Shin (1996) elaborated on and

² It should be noted that the capital intensity of ASICs manufacturing is very high compared to that of other industries. Saying “less capital intensive” evokes a comparison with microprocessors and memories only.

³ It should be also noted that the design intensity of memories is very high compared to that of products in other industries. Memories are “the least design intensive” in comparison with microprocessors and ASICs, but not in comparison with many other goods.

⁴ In dealing with “industrial leadership”, this paper is mainly concerned with “a commanding position in terms of global market share in the industry”, following Lee and Malerba (2015a). Technological leadership is indeed a very important part of leadership, but only one part. In contrast, market leadership is a result of the combination of technological, managerial and other competencies. Moreover, technological leadership is often difficult to pin down. For instance in the semiconductor industry, Toshiba was quicker in developing new-generation NAND memories in the 2000s, but Samsung was quicker in mass producing them and became the market leader as a result (Section 5.2). Moreover, Toshiba is still competing as the second-largest NAND producer in the world, while it seems to retain development capability comparable to Samsung’s. In this situation, it is difficult to say whether technological leadership in NAND memories has changed from Toshiba to Samsung. But market leadership has certainly changed, and it seems easier to study industrial leadership changes through changes in market leadership than changes in technological leadership.

extended it to industry-level analyses by comparing the cases of the steel and semiconductor industries in the 20th century. Perez and Soete (1988) introduced the concept of “windows of opportunity”, and Lee and Malerba (2015a; 2015b) extended that to industry-level analyses by combining it with studies of sectoral innovation systems.⁵ By weaving Gershenkronian analyses of catch-up with those of changing windows of opportunity, this paper examines why industrial leadership changes occurred in the most capital-intensive segment of the semiconductor industry, as well as why they did not continue, and discusses general implications to catch-up strategy.

2. The Gershenkronian catch-up strategy in the capital-intensive sector and changing windows of opportunity

From his studies of European industrialization in the 19th century, Gershenkron observes that the latecomers “were slow to assimilate production of machine tools ... where very special technological skills are required”. In the steel industry, however, he says “it is instructive to see ... how German blast furnaces so very soon become superior to the English ones, while in the early years of this [20th] century blast furnaces in still more backward southern Russia were in the process of outstripping in equipment their German counterpart.”⁶

Gershenkron later puts forward some sweeping propositions regarding catch-up in capital-intensive industries.⁷

1. “The more backward a country’s economy, the greater was the stress upon producers’ goods as against consumers’ goods.”
2. “The more backward a country’s economy, the more pronounced was the stress in its industrialization on bigness of both plant and enterprise.”
3. “The more backward a country’s economy, the greater was the part played by special institutional factors designed to increase the supply of capital to the nascent industries ...”

Gershenkron elaborated on the relationship among these propositions in his later works, and Shin (1996) attempted a more systematic exposition of his framework as follows:

First, the overall strategy of the latecomers was to promote unbalanced growth by focusing on the technologically dynamic industries of the day. During the latter half of the

⁵ Malerba (2002, 2004).

⁶ Gershenkron (1962, p. 10).

⁷ Gershenkron (1962, p. 353-54) in fact advances six propositions, but I focus here on the three propositions most relevant to catch-up strategy in capital-intensive industries. I also reorder the three propositions here for convenience of explanation.

19th century, when Germany and Russia embarked on industrial catch-up, heavy industries were the most technologically dynamic ones, reflecting the trend of the Second Industrial Revolution. At the time, latecomers focused on these industries because they thought this strategy would increase their chances of catching up with forerunners.⁸ Gerschenkron therefore emphasizes that “... it was largely by application of the most modern and efficient techniques that backward countries could hope to achieve success, particularly if their industrialization proceeded in the face of competition from the advanced country”.⁹

Second, Gerschenkron noted that the critical technological trend in heavy industries involved “growing capital-output ratios and ... increases in the optimal size of plant”.¹⁰ In this technological trend, latecomers had a better chance to win against forerunners if they employed the most advanced technologies, which required building “bigger and bigger” plants. In other words, the strategy of the European latecomers was to leapfrog the forerunners in the size of plants and enterprises.¹¹ And latecomers also had advantages because they could build the most modern plants and fully exploit economies of scale available at the time by starting from scratch, while forerunners had already built their plants with old technologies that offered smaller-scale economies.¹²

Third, institutions played an important role in “increas[ing] supply of capital” and concentrating it on large-scale investments in heavy industries. For Gerschenkron, institutions are basically enablers of the catch-up strategies of latecomers. He thus points out that “these differences in the speed and character of industrial development were to a considerable extent the result of application of institutional instruments for which there was little or no counterpart in an established industrial country”.¹³

Shin (1996) extended Gerschenkron’s framework to the 20th century by interpreting it as an historical model, i.e., a model constrained by space and time. General model elements in the framework were the three-country paradigm and competition among those countries. However, technologies and institutions evolve over time, and institutions are also different across countries, reflecting their historical specificities. When extending historical models, it is therefore important not only to separate general model elements from historical

⁸ Shin (1996, p. 49-53, p. 145-46). There is no doubt that these economic needs were closely intertwined with Germany’s and Russia’s ambitions to mount military forces capable of challenging Britain and France. (Gerschenkron 1962, p. 131, p. 360-61).

⁹ Gerschenkron (1962, p. 9).

¹⁰ Gerschenkron (1970, p. 113).

¹¹ This argument should not be confused with the issue of factor intensity at the level of the national economy. Latecomers, which by definition have less capital than forerunners, cannot leapfrog the latter in capital-output ratio at the national level. However, it is possible for them to achieve higher capital-output ratios in some plants, enterprises or industries if they concentrate their resources on them

¹² Landes (1969, p. 263) similarly points out the importance of the size of plants in Germany’s catch-up in the steel industry: “Around the turn of the century, the biggest British mills were turning out only as much as the average Westphalian works. ... new British plants in the 1890s were a quarter to a third of the size of their German competitors”.

¹³ Gerschenkron (1962, p. 7).

elements, but also to use them together in explaining historical phenomena. Shin (1996) detected a similar three-country paradigm in the latter half of the 20th century among the US, Japan and Korea, which were clearly separated by their different degrees of development and the intense competition among them. He then attempted to explain the catch-up experience of Japan and Korea by comparing different technological imperatives in the steel and semiconductor industries and by examining the institutional responses of the two countries.

The essence of the Gerschenkronian analysis seems to lie in the interaction among technological imperatives, consequent catch-up strategies and institutional responses on the part of latecomers. Expanding on Shin (1996), this paper attempts to analyze catch-up in the semiconductor industry in this manner. Technological imperatives in this industry were rather different from those in the steel industry: With continued generational changes of products, the former is characterized by a more rapid product and process innovation than the latter. But there should be some reasons that the catch-up phenomenon was most pronounced in the most capital-intensive segment of the semiconductor industry. Companies and countries devise their own catch-up strategies by observing technological imperatives in an industry, then attempt to utilize, and sometimes to create, their institutions to carry out those strategies.

However, a limitation of the Gerschenkronian analysis is that it does not explain unsuccessful cases of catch-up because its framework was basically derived from successful latecomers. The most it can say about unsuccessful cases is that expected institutional responses somehow did not materialize.¹⁴ In this regard, the concept of “changing windows of opportunity”, which was initially suggested by Perez and Soete (1988) and later refined by Lee and Malerba (2015a; 2015b), would complement the Gerschenkronian analysis.

While Perez and Soete were interested in the opening of windows of opportunity for latecomers during periods of techno-economic paradigm change, Lee and Malerba extended the concept of windows of opportunity to successive catch-up cycles in industrial sectors regardless of techno-economic paradigm changes. They identified three windows – technological, demand and institutional. A “technological window” refers to an opportunity provided by a new technological development in an industry. It may broaden or narrow catch-up opportunities on the part of latecomers, depending on what kind of technological change actually occurs. A “demand window” refers to an opportunity emerging due to a new type of demand both in local and foreign markets. A demand window also broadens or narrows catch-up opportunities, depending on actual changes in demand. An

¹⁴ Gerschenkron (1962, p. 232-34, p. 361-64) acknowledged this limitation and mentioned the need to analyze “nodal points”, or the threshold, of catch-up for latecomers. Shin (1996, p. 122-25, p. 139-42) discussed this kind of threshold for catch-up in relation with Korea’s inability to stage technological catch-up in the semiconductor industry in the 1960s and up to the middle of the 1970s, as well as in relation with Hirschman’s criticisms of Gerschenkron’s view on catch-up.

“institutional/public policy window” refers to opportunity emerging from changes in public intervention in the industry or changes in broad institutional conditions (including some macro-variables). It also broadens or narrows catch-up opportunities for latecomers depending on the actual working of those institutions. Lee and Malerba’s concept of “changing windows of opportunity” provides room to analyze unsuccessful cases of catch-up, which are not clearly examined in the Gerschenkronian analysis.

Lee and Malerba also employ the concept of “responses”, together with the notion of “windows of opportunity”. In the Gerschenkronian analysis, “responses” normally refers to the strategies and institutions of latecomers, but Lee and Malerba include responses by forerunners as well as latecomers. Depending on their responses, forerunners may utilize and expand on the forerunners’ advantages that they enjoy or fall into “incumbent traps”. Similarly, latecomers may exploit latecomers’ advantages or remain behind, depending on their responses. They argue, therefore, that “... the evolution of a sectoral system may open up several ‘windows’ that create different ‘responses’ by latecomers and incumbents, and generate changing industrial leadership”.¹⁵ Their framework allows us to understand what is happening on the side of forerunners, in contrast with the Gerschenkronian analysis, which focuses on responses by latecomers.

It may be worthwhile to note that the Gerschenkronian analysis and that of Lee and Malerba tend to emphasize different aspects of the same phenomena: The former pays more attention to catch-up that happens “despite” the difficulties or the narrowness of windows of opportunity latecomers face, while the latter pays more attention to what happens “because of” changing windows of opportunity. This difference is reflected in their different treatment of institutions. For Gerschenkronians, institutions are mainly internal enablers of catch-up, separated from external conditions. Lee and Malerba, on the other hand, separate “institutional windows” from institutional “responses”.

In this paper, an analysis of both catch-up and non-catch-up in the memory industry will be carried out by combining the two approaches.¹⁶ It starts by analysing the technological characteristics of the memory industry and ways in which they have changed. It then investigates how latecomers and forerunners in the industry overcame their disadvantages and utilized their advantages -- or failed to utilize their advantages or to overcome their disadvantages -- and how changing windows of opportunity affected the outcome of catch-up and forge-ahead.

A catch-up strategy identified in this paper is termed the “dynamic catch-up strategy”. As will be detailed in the following section, it is dynamic in two senses. First, it chases rapidly moving targets and, at a certain stage, aims at developing two generations of technologies

¹⁵ Lee and Malerba (2015a, p. 7)

¹⁶ The term “memory industry” will be used hereafter, instead of “memory segment”. The former is often used in academic papers and newspapers when memory production is mentioned in isolation. The latter is used when it is dealt with as a subsector in the semiconductor industry, which is why “segment” is employed in the introduction.

simultaneously. Second, there were elements of “leapfrogging” because latecomers overtook forerunners in terms of cost and quality of products through their emphasis on process innovations. Lee and Lim (2001) identified the catch-up strategy of Korea in the semiconductor industry as a “stage-skipping” one. But it seems better to term it “stage-contracting” or “stage-compressing” because neither Japanese nor Korean latecomers “skipped” a stage during crucial periods of industrial leadership change. In comparison with Perez and Soete’s (1988) “leapfrogging”, where latecomers choose different paths from those of forerunners and outstrip them in plant size, the dynamic catch-up strategy can be considered partial leapfrogging because latecomers follow the same path as forerunners but overtake them in process innovations. Following sections will examine how the dynamic catch-up strategy emerged and worked for Japan and Korea, and how it became more difficult to implement the strategy later.

This paper also argues that a common theme that explains both the catch-up and the non-catch-up periods is the building and expansion of mass-production capability. It is conventionally acknowledged that development capability is critically important in high-tech industries like semiconductors. However, the paper points out that mass production capability, which is centred around aggressive investment, speedy “ramp-up” or “upscaling”, and process innovations to reduce costs and to improve quality, seems more important in explaining the catch-up and non-catch-up in the memory industry because it was a factor common to the Japanese catch-up in the early 1980s, the Korean catch-up in the early 1990s, the Japanese falling behind in the 1990s, and Samsung’s dominance for more than two decades thereafter.

3. The emergence of the “dynamic catch-up strategy” and Japan’s leadership in the memory industry

The semiconductor industry, whose products change generations every 3-4 years, is characterized by much more rapid technological progress than the steel industry. In the latter industry, latecomers did not need to worry much about the possibility of the emergence of radically new products and processes sometime after initial investments had been made to exploit the larger economies of scale provided by new technologies. Lee and Ki (2015) characterize the industry as one with “low frequency of innovation” in this context. Here, the forerunners were disadvantaged when new technologies emerged because they were stuck with investments already made with old technologies. On the other hand, once the latecomers had embarked on a Gerschenkronian catch-up strategy and executed it successfully, leadership shifted from the forerunners to the latecomers. This pattern emerged when Germany overtook Britain in the latter half of the 19th century, and it was repeated in the latter half of the 20th century when Japan overtook the US with the early adoption of basic oxygen furnaces (BOFs) and continuous casting (CC).¹⁷

¹⁷ Gerschenkron (1962); Shin (1996); Yonekura (1991).

In the semiconductor industry, however, both forerunners and latecomers are in a constant race to develop new products and processes, and, to keep up, they must invest continuously and heavily in both research and development (R&D) and facilities. There is little of the room for forerunners' disadvantages or latecomers' advantages that was seen in the steel industry because both forerunners and latecomers need to replace their facilities with every new product generation. These different technological imperatives brought about the adoption of the "dynamic catch-up strategy", a modified Gerschenkronian strategy, by Japan's latecomers.

From the 1950s when the semiconductor industry was born, Japan had been eager to catch up with the US in this new, technologically dynamic industry. Japanese integrated electronics manufacturers -- NEC, Fujitsu, Hitachi and Toshiba, and so on -- along with the Japanese government, were making concerted efforts at narrowing the technological gap with their US counterparts in semiconductors and related computer technologies.¹⁸ These efforts were quite successful. For instance, Borrus et al. (1983, p. 208) say, "Japanese semiconductor-computer firms had developed a significant LSI [large scale integration] capability, and by 1976 they dominated their domestic market in all but the most advanced IC devices".

However, the US again forged ahead with new products and technologies. One significant market development at the time was "the introduction by US computer companies of low-cost, LSI-based plug-compatible mainframes (PCM)" in 1975.¹⁹ Moreover, IBM's plan to develop a new generation of computer based on VLSI (very large scale integration) technology posed a further threat to Japanese competitors.²⁰ The Japanese intention to "enter international competition in LSI-based mainframes had been rendered moot" by these two developments in the international market.²¹

A new catch-up strategy came about at this juncture, coinciding with the VLSI Project (1976-80), a public-private partnership designed to develop Japan's semiconductor industry.²² One of its two elements was a Gerschenkronian unbalanced growth strategy.

¹⁸ Refer to Fransman (1990); Gregory (1986); Okimoto et al. (1984).

¹⁹ Borrus et al. (1983, p. 207).

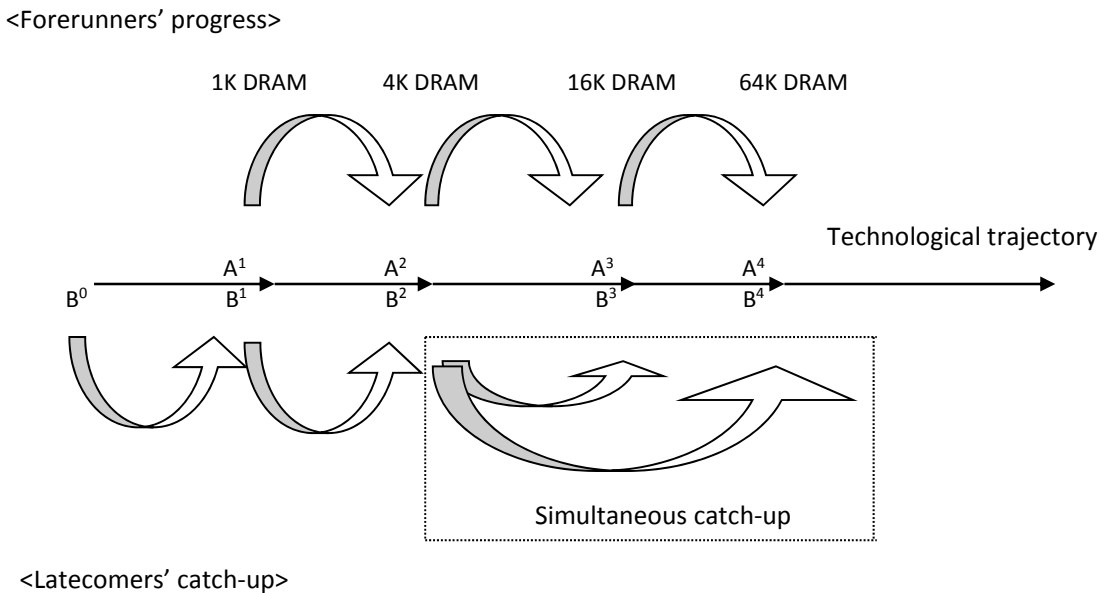
²⁰ Fransman (1990, p. 57).

²¹ Borrus et al. (1983, p. 208).

²² I am emphasizing here a new catch-up strategy that emerged during the period of the VLSI Project, not the effect of the Project itself. Still controversial among researchers and industry watchers are whether or not the VLSI Project was decisive in allowing the Japanese memory industry to overtake that of the US, to what extent competing Japanese companies cooperated with each other under the Project, and so on. While US House reports and trade journals published in the early 1980s tended to stress the importance of the VLSI Project, later researchers like Fransman (1990), Nakayama et al. (1999) and Langlois and Steinmuller (1999) point out that its achievement was limited to cooperation in developing electron-beam equipment and that only 15-20 percent of its total budget went to joint laboratories. It seems to me, however, that the Project provided public and private participants in the Japanese industry with overall direction, moving the catch-up strategy

Japan opted for concentrating its catch-up efforts on memories, especially DRAMs, the most capital-intensive segment of the semiconductor industry. The other element was peculiar to the semiconductor industry. All previous efforts had been aimed at narrowing the existing technology gap with the forerunner, and Japanese companies had been frustrated repeatedly because, at the very moment they appeared to have succeeded in doing so, their US competitors forged ahead with new technologies: When Japan was closing the gap in the 1K DRAM, the US forged ahead with the 4K DRAM; when Japan had nearly succeeded in producing a 4K DRAM, the US again forged ahead, this time with the 16K DRAM.

Figure 1. Dynamic catch-up strategy in the memory industry



An innovative aspect of the new Japanese strategy was its shift in focus toward “developing semiconductor technology for *the next generation* of computers”.²³ It aimed not only at catching up with forerunners in the current-generation technologies but also at developing the next generation of technologies at the same time the forerunners were doing so. <Figure 1> is a graphical presentation of the strategy. The forerunner (A, the US) continued to progress by developing new generations of memories. The latecomer (B, Japan) initially tried to catch up with the forerunner by aiming at the existing frontier technologies (A¹). Around the time the latecomer reached the frontier (B¹), the forerunner had already pushed the frontier ahead and developed a new generation of products (A²). A similar frustration was repeated when the latecomer chased the new existing frontier (from B¹ to B²). But the latecomer now aimed at two generations of technologies (A³ and A⁴)

toward an emphasis on hastening the pace of developing new-generation technologies, and that its focus on process technologies paid off.

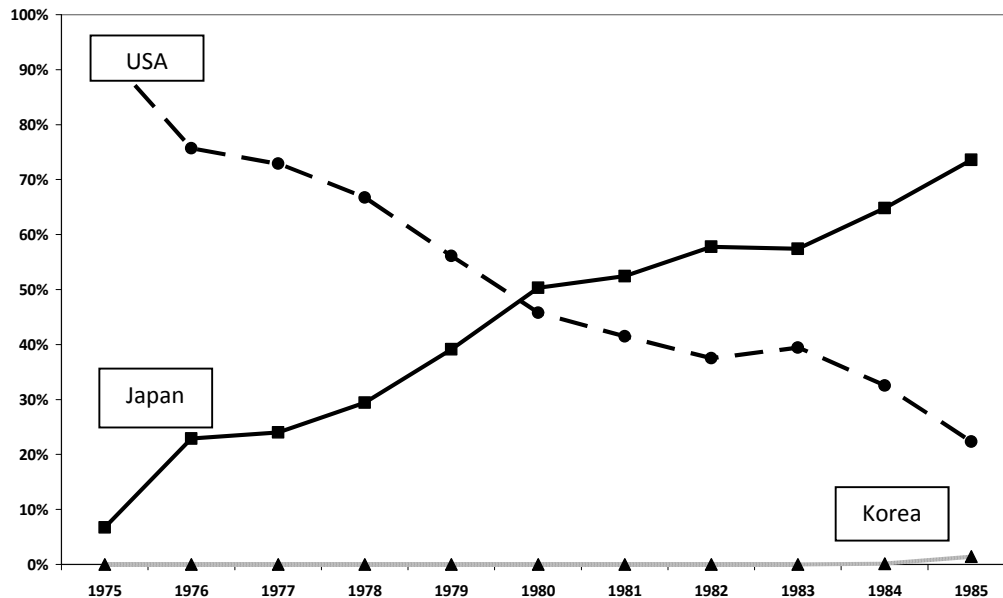
²³ Borrus et al. (1983, p. 209). Emphasis added.

simultaneously, and this time its efforts met with success (B³ and B⁴). Japan developed the next-generation DRAM, the 64K DRAM, in 1979, at nearly the same time as the US did.

This strategy can be characterized as a “dynamic catch-up strategy” in two senses. First, as discussed above, it chased rapidly moving targets and aimed at developing two generations of technologies simultaneously. Second, there were elements of “overtaking”. To be effective in their catch-up efforts, Japanese manufacturers focused their R&D more on process than on product technologies. The VLSI Project itself produced more than 1,000 patents, most related to incremental innovations, among them improving electron-beam lithography and adoption of “a more conservative design and a better ceramic package”.²⁴

The cumulative effects of these process innovations were significant. When Japanese producers succeeded in developing a 64K DRAM, which they did at just about the same time as their US counterparts, their product convincingly beat that of their US competitors in both quality and cost. According to a 1980 HP (Hewlett Packard) evaluation comparing the quality of 16K DRAMs from three American and three Japanese manufacturers, “the parts that came from the very best American firm showed six times as many errors as those from the worst Japanese firm”.²⁵ Japanese companies supplied these better-quality chips at lower prices than their American competitors. Changes in DRAM market share between the US and Japan reflected this decisive change in their relative competitiveness (Figure 2). Most US manufacturers, including Intel, had no choice but to fold their DRAM businesses.

Figure 2. Changes in DRAM Market Shares among the US, Japan, and Korea (1975-1985)



²⁴ Weinstein et al. (1984, p. 39, p. 52-53, p. 70).

²⁵ Jackson (1997, p. 247).

Source: Dataquest. Acquired from Samsung Electronics.

This catch-up pattern of Japan, as well as that of Korea later, can be understood as a “stage-contracting” or “stage-compressing” catch-up, if Lee and Lim’s (2001) term of “stage-skipping” catch-up is modified.²⁶ Japanese latecomers developed 16K and 64K DRAMs simultaneously and thereby “contracted” or “compressed” the two stages. They did not “skip” or put less importance on 16K DRAMs. In fact, the mass production of 16K DRAMs, which offered lower costs and better quality than those of US counterparts, was mainly responsible for the leadership change, as mentioned above. Japan then extended its lead by mass-producing 64K DRAMs.²⁷ Similarly, after a decade, Samsung Electronics developed 4M and 16M DRAMs simultaneously, and the mass production of 4M DRAMs was mainly responsible for the market leadership change from Japanese producers to Samsung.²⁸

In comparison with Perez and Soete’s (1988) “leapfrogging”, the dynamic catch-up strategy can be understood as a partial leapfrogging. Unlike in the steel industry, Perez and Soete’s main reference industry, where latecomers “leapfrogged” with new technologies while forerunners were stuck with old technologies, the latecomers in the memory industry followed the same path of generational product development as their forerunners did. But the latecomers “leapfrogged” their forerunners in process innovations.

It should be noted that this strategy of simultaneous catch-up in overlapping generations of products requires tremendously high levels of investment as well as related capabilities in the areas both of mass production and of dealing with the financial risks involved. Japan fared better than the US in financing the continuous investments needed, mainly through its institutional structure: the *keiretsu* system and the developmental state. Japan’s investments in semiconductors increased more rapidly than those of the US all through the 1970s.²⁹ And after the first oil shock in 1973, when US semiconductor manufacturers restricted their investments for the development of new technologies and production capacity, Japanese producers continued investing at a high rate. Whereas US producers’ average ratio of capital spending to sales remained at only 12 percent during the period

²⁶ Lee and Lim (2001) identified Korea’s catch-up in the semiconductor industry as a stage-skipping one by focusing on the fact that Korean manufacturers skipped 1-16K DRAMs and started developing from the 64K DRAM when they first entered production in the middle of the 1980s. This decision in the initial stage of participation in the industry was in a sense inevitable because the latecomers should skip previous generations anyway, although they need to make a decision on how many previous generations of DRAMs they should skip. After some period of gradual catch-up with the forerunners had been made, industrial leadership changes in the memory industry occurred in Lee and Malerba’s (2015a) “later stage of forging ahead”. In this leadership changes, neither Japanese nor Korean latecomers skipped a stage and it does not seem appropriate to employ the term, “stage-skipping” catch-up.

²⁷ Refer to Langlois and Steinmuller (1999, Table 2.9).

²⁸ Samsung Electronics (2001, p. 306, pp. 385-36).

²⁹ Flaherty and Itami (1984, p. 165).

1973-78, Japanese producers' ratio for the same years was 17.8 percent. In 1983, the total capital spending of Japanese semiconductor makers surpassed that of their US competitors.³⁰

Japan's approach to the investment race can be interpreted either as the Gerschenkronian institutional response of the latecomer or as Lee and Malerba's "institutional window". Japan undertook catch-up with the US in almost all major industries during the postwar period and, for this purpose, built its developmental state and regrouped former *zaibatsu* companies into the *keiretsu* system. The *keiretsu* system proved proficient in developing systems of mass production, and Japan soon established itself as the world's leader in consumer electronics. Japanese companies employed this same mass-production capability in their catch-up in the memory industry. The diversified structure of their businesses also supported long-term stable investment in their semiconductor divisions by cycling to them money earned in other divisions. Technological progress in semiconductor divisions was also facilitated by close interactions among different electronics divisions, including computer and telecommunication divisions, within the same company.³¹

The Japanese government also supported the long-term investment race with its "easy-money policy" and various other industrial-policy measures. In a stable and expansionary financial environment, the Japanese industrial sector as a whole could pursue ambitious expansion without fear of a monetary crunch.³² The government was also active in promoting its high-tech industries, among them computers and semiconductors. The VLSI Project was one of the projects that the Japanese government was initiating on a continual basis beginning in 1962, among them FONTAC, VHSCS, 3.5 Generation and the PIPS project. The government also maintained a protective trade regime until Japan's semiconductor industry had gained international competitiveness.³³

On the other hand, the structure of the US semiconductor industry was peculiar, and it can be said that this opened an institutional window to its competitors. Due to strong anti-trust regulations, AT&T and IBM were not allowed to sell semiconductors on the open market, and this resulted in the dominance of merchant producers in the US industry.³⁴

³⁰ Gregory (1986, p. 95, p. 209). The same differences between US producers' and Japanese producers' investment behaviour were evident during the 1985-86 recession: Whilst the US producers shrank from investment, the Japanese kept their pace steady (Hobday 1989: 235-36).

³¹ Gregory (1986, p. 69).

³² The Japanese state maintained a twofold "over-lending" system: The banking system as a whole was 'over-lent' through the central bank's lending to the banks on the one hand, and the industrial sector was over-lent through the *keiretsu* system on the other. Refer to Zysman (1983, p. 247); Ueno (1980, p. 403); Johnson (1982, p. 203-207); Borrus et al. (1983, p. 195); Shin (1996, pp. 110-102).

³³ According to Okimoto (1984, p. 109), "Japan's tariff rates for ICs stood for many years at 15 percent ... In 1972, Japan's effective rate dropped to 12 percent; by 1980, as Japanese industry became more competitive, the rate was brought into line with America's at 10.1 percent".

³⁴ Borrus et al. (1983); Langlois and Steinmuller (1999).

Merchant producers are at a structural disadvantage to integrated *keiretsu* manufacturers in sustaining long-term investments: The former tend to reduce investment during a downturn in the semiconductor sector, whereas the latter can support continuing investment in semiconductors out of earnings and credit from other businesses.

There was also a factor that can be interpreted as the combined result of latecomers' institutional responses and an "incumbent's trap" affecting forerunners. Wafer size was to shift from 3 inches to 5 inches in the late 1970s. While the increase in the size of the wafer brings about a productivity increase, semiconductor firms face great technological and demand uncertainties when they introduce new wafer facilities. Although production volume can increase substantially in facilities that manufacture larger wafers, greater technical challenges are involved in stabilizing product quality.³⁵

In this situation, the US producers were, as market leaders, cautious about shifting wafer size radically. As latecomers, however, Japanese producers were more aggressive in experimenting with the new wafers, which would give them cost advantages if they succeeded in stabilizing the yield rate.³⁶ The incumbent trap ensnaring forerunners and the window of opportunity for latecomers that opened as a consequence had less impact than those observed in the steel industry around the introduction of Bessemer processes or of BOFs because, in the semiconductor industry, all major players are engaged in the unceasing game of pushing technological frontiers and therefore replace their facilities periodically. However, a similarity remains in that latecomers were more willing to take risks involved in new technologies than were forerunners, especially when those risks were related to increasing the scale of production and bringing about cost competitiveness.

4. The Korean catch-up in the memory industry – A more unbalanced dynamic catch-up strategy

Korea became involved in the semiconductor industry from the middle of the 1960s, when major US semiconductor firms relocated their assembly processes to East Asia.³⁷ While Japan undertook its ambitious catch-up efforts at the beginning of the 1960s, Korea could not act then because the technological gap separating it from the forerunners was too big to overcome. Instead, it joined this high-tech industry simply as a provider of low-cost unskilled labor for assembly processes, importing 100 percent of the equipment, materials and technologies it needed directly from foreign MNCs and exporting 100 percent of the products it assembled through MNCs' global marketing networks. In this respect, the Korean

³⁵ More detailed discussions on improvement in potential productivity with increase in wafer size will be made later (Refer to Section 4 and Table 1).

³⁶ Refer to Okimoto (1984); Gregory (1986); Chin (2002).

³⁷ For this globalization of semiconductor firms, refer to Henderson (1989).

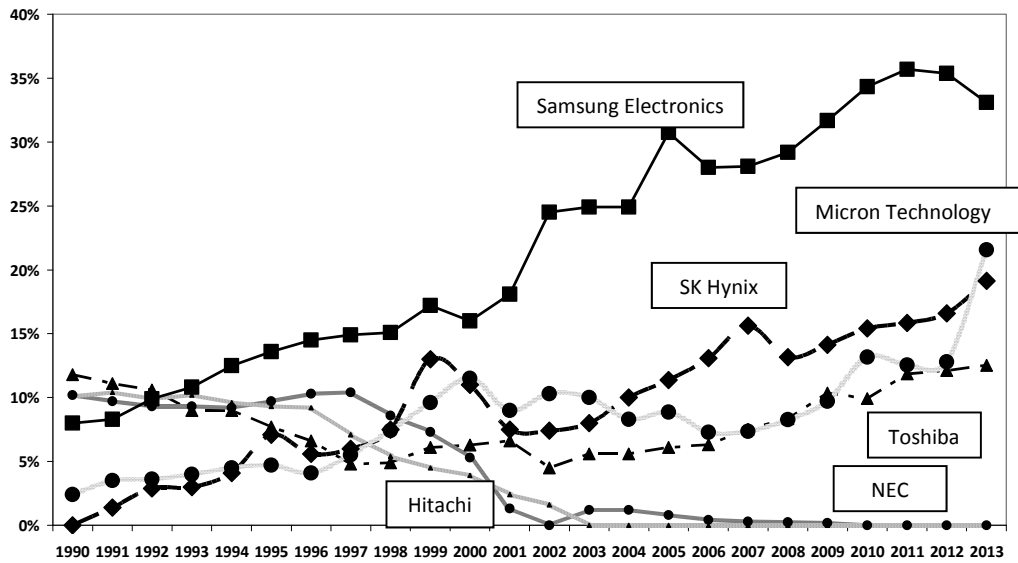
semiconductor industry began as an “enclave development” that did not have any linkage effects with its local economy, something that occurred at the time in other developing countries as well.³⁸

Korea’s catch-up in the semiconductor industry started in earnest only in the early 1980s, by which time the Korean *chaebols*, family-controlled diversified business groups, had built up their managerial and financial resources as a result of the country’s Heavy and Chemical Industrialization Drive (HCI Drive) of the 1970s and had also acquired considerable mass-production capabilities thanks to their consumer-electronics businesses. Having witnessed the Japanese success in overtaking the US in the memory industry, the Koreans wanted to emulate it, so they began investing heavily in the semiconductor industry and turned out their first commercial DRAM product, a 64K DRAM, in 1984. From that time, Korea worked continuously at narrowing the gap with its forerunners until, eventually, it succeeded in overtaking them. Samsung Electronics emerged as the world’s number-one producer of DRAMs in 1992 and the number one in memories overall in 1993 (Figure 3). Korea’s overtaking of Japan was slower than Samsung’s overtaking of its Japanese competitors, a fact that reflects the former nation’s smaller size: In 1995, for instance, Korea’s population was 36 percent, and its GDP 13 percent, of Japan’s.³⁹ Korea emerged as the number-one memory producer on a national basis in 1999. After a dip in its production mainly due to a financial crisis at Hynix (which changed its name to SK Hynix after its acquisition by the SK Group in 2011), Korea re-emerged as the number-one memory-producing country in 2002, and it has maintained its leadership ever since (Figure 4).

Figure 3. Changes in Memory Market Shares by Major Firms (1990-2013)

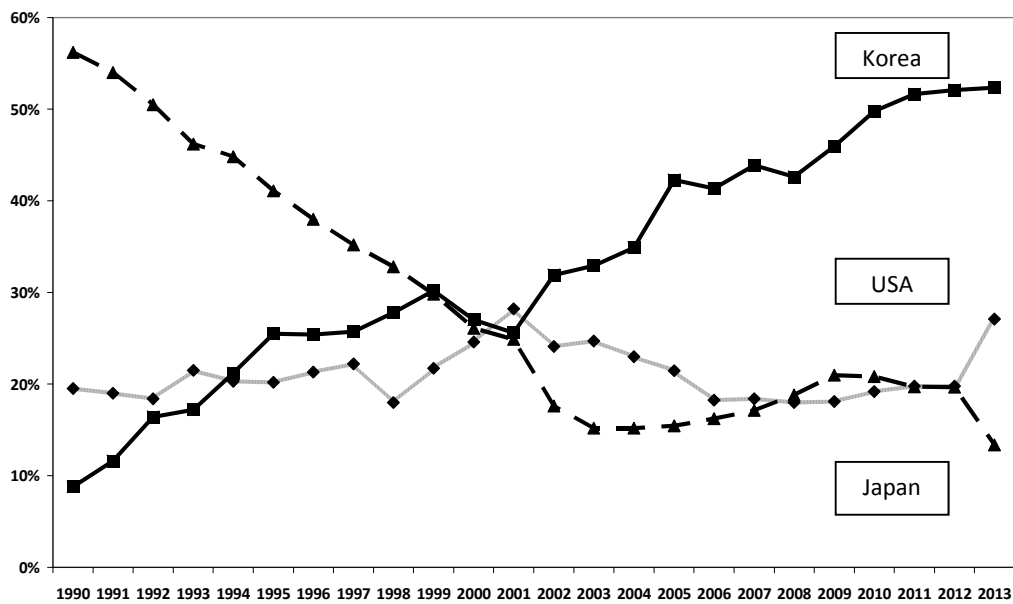
³⁸ Shin (1996, p. 123-25).

³⁹ UN World Population Prospects (<http://esa.un.org/wpp/>. Accessed on April 3, 2015) and World Development Indicators (<http://data.worldbank.org/data-catalog/world-development-indicators>. Accessed on April 3, 2015).



Source: Dataquest for numbers during 1990-2004 and iSuppli for numbers during 2005-2013.
 Note: The market share of Micron Technology jumped from 12.8 percent in 2012 to 21.6 percent in 2013, mainly due to its acquisition of Elpida Memory, a company that was created by the merger of the DRAM businesses of NEC and Hitachi in 2000 and that in 2003 acquired the memory businesses of Mitsubishi.

Figure 4. Changes in Memory Market Shares among the US, Japan, and Korea (1990-2013)



Source: Dataquest for numbers during 1990-2004 and iSuppli for numbers during 2005-2013.

The Korean catch-up strategy was basically a repetition of the Japanese. First, Korean semiconductor manufacturers adopted an unbalanced growth strategy by focusing on DRAMs in their initial catch-up efforts, as their Japanese counterparts had done. Second, after rapidly narrowing the technological gap with the forerunners, Korean producers embarked on a dynamic catch-up strategy by developing a 4M DRAM and a 16M DRAM nearly simultaneously. Third, Korean manufacturers attempted an overtaking by reducing production costs and mass producing better-quality products. While it took three years for the forerunners to mass-produce 16M DRAMs after development concluded, it only took two years for Samsung, and this made the company the first in the world to mass produce the 16M DRAM, in 1991.

However, reflecting their relative backwardness compared to Japanese competitors, Korean manufacturers were obliged to take the riskier bet. First, Koreans focused much more on DRAM manufacturing than Japanese did, almost disregarding the development of semiconductor equipment. Japanese producers had been able to reduce the ratio of equipment imports to purchases of domestically produced equipment from 70-80 percent in 1976 to around 50 percent by 1980.⁴⁰ But Korea was importing 97 percent of its equipment and 90 percent of its raw materials even in 1989, when it established itself as a major DRAM producer.⁴¹ Japan could embark on catching up in equipment manufacturing and in DRAM manufacturing almost in parallel, mainly because it already had a relatively developed capital-goods sector. But that option was not available to Korea.

Second, Korean DRAM manufacturers relied more heavily on exports than their Japanese competitors did. The Japanese semiconductor industry developed initially based on its domestic market and then, as its volume of production was increased, the ratio of exports to total production increased gradually.⁴² The Korean semiconductor industry started with virtually no domestic market: About 90 percent of the semiconductors it produced were exported even in 1989.⁴³ This high degree of export-orientation can again be attributed to the relative backwardness of Korea, as its forward-linkage industries like computers and telecommunications did not develop to the point that they could provide the semiconductor industry with sufficient demand pull.

From the viewpoint of the original Gerschenkronian pattern, a more unbalanced and riskier strategy of this kind should be supported by stronger government intervention in a latecomer like Korea than in a forerunner like Japan. In the overall management of economic development, it was certainly true that the Korean government was much more interventionist than its Japanese counterpart.⁴⁴ The Korean semiconductor industry was, however, an exception. Samsung began investing heavily in the memory industry largely out

⁴⁰ Borrus et al. (1983, p. 210).

⁴¹ Kim et al. (1992, p. 242).

⁴² It increased from 19 percent in 1977 to 22 percent in 1980 and 32 percent in 1988 (Choi 1991, p. 15).

⁴³ Shin (1996, p. 125, Table 8.1).

⁴⁴ Refer to Jones and Sakong (1980); Shin (1996).

of its own entrepreneurial vision, and the Korean government was initially sceptical of Samsung's move.

In the early 1980s, the Korean government had already shifted its overall economic policy direction toward "stabilization" in its attempt at surviving the worldwide stagflation and resolving alleged "overcapacities" that had been created by its ambitious HCI Drive in the 1970s. The government was, naturally, unenthusiastic about a new large-scale investment plan from the private sector. The Korea Development Institute, a public research institute then under the Economic Planning Board, therefore handed in a confidential report to the government in which it argued as follows: "A semiconductor industry is possible only when a nation's population numbers over a 100 million, GNP per capita exceeds \$10,000, and domestic demand consumes more than 50% of the chip production".⁴⁵ In East Asia at that time, Japan was the only country that met these criteria, and the message was clear: "Japan could do it but Korea cannot do it." A high-ranking Korean economic official said privately of Samsung's move, "It would be the first business failure of Mr Lee Byung-Chul [founder and then-Chairman of Samsung Group]".⁴⁶

Nonetheless, Samsung went ahead with its planned investments. Lee Byung-Chul said of his decision: "The Korean electronics industry cannot survive in the world market if it only continues assembling parts like today. In order to stabilize the electronics industry, the development of a semiconductor industry is indispensable. Moreover, the semiconductor industry is the basis of every other industry".⁴⁷ Other Korean business groups like Hyundai and LG (Goldstar at the time) followed suit for the same reason. The Korean government later introduced policy programs to support the incipient memory industry, but it is undeniable that the initiative for this ambitious catch-up arose from the private sector, and especially from the *chaebols*.

The unbalanced emphasis on DRAM manufacturing and the prolonged investment it required were also largely sustained by the strategic concern of the *chaebols*. A main difference between the Korean *chaebol* and the Japanese *keiretsu* has to do with the difference in ownership. Whereas the Japanese *keiretsu* is a loose federation run by professional managers without its own central office, the Korean *chaebol* maintains a centralised coordination system whose power is concentrated at the top, mainly within the owner family. Once a strategic decision is made, therefore, the *chaebol* can mobilize and concentrate its resources on the strategic sectors with more determination and persistence. This seems to be a major reason why Korean producers, with electronics businesses much smaller and less developed than the Japanese, could embark on direct competition with their forerunners without significant support from the government. By concentrating their financial strength on the limited area of the memory industry, the *chaebols* sustained the prolonged investment race, maintaining an investment-to-sales ratio of over 50 percent in

⁴⁵ Quoted in Chin (2002, p. 5).

⁴⁶ The author's interview with a high-ranking Samsung official in May 2004.

⁴⁷ Quoted in Chin (2002, p. 5).

the 1980s. And, in 1989, Korea's facility investment amounted to 20 percent of total investment in the world semiconductor industry.⁴⁸

As in the Japanese catch-up of about a decade before, important technological choices presented themselves during the period of the Korean catch-up, but this time the task was more daunting. First, semiconductor producers faced another shift of wafer size, from 6 inches to 8 inches. Second, they had to choose between the trenching method and the stacking method: The former was designed to increase the complexity of chips by trenching, or digging, on the wafer surface to build underground layers, and the latter was designed to do so by stacking cells on top of one another to build above-ground layers. This choice was inevitable because, with the continued increase in density of chips, it had become impossible from the time when the 16M DRAM was under development in the late 1980s to house all the cells (capacitors) on the single, flat surface of a chip.

Facing this challenge of a twofold technological choice, Samsung, and later other Korean producers, went for the riskier bets. Samsung invested in 8-inch facilities first for DRAM manufacturing, then across the entirety of its semiconductor production, something only IBM had done up to that time. From its observation of Japan's experience, Samsung's top management decided that it would be better to invest early in larger-sized wafer facilities. The choice between the trenching method and the stacking method was more difficult because each had its own merits and drawbacks, and the leading manufacturers were evenly divided on the issue. Toshiba and NEC, then the number one and two DRAM manufacturers, respectively, chose the trenching method. Along with Hitachi of Japan, Samsung decided in favor of the stacking method on the grounds that the trenching method, while consistent in quality, presented difficulties when it came to shrinking the size of chips. Hyundai and LG followed suit in choosing the stacking method.⁴⁹

These decisions were very important in Samsung's becoming the number-one memory producer in 1993. <Table 1> shows productivity gains from choosing larger-sized wafers. 8-inch facilities require 1.4 times more investment than 6-inch facilities, but the former are 1.8 times more productive than the latter per wafer, resulting in substantial net productivity gains. Samsung gained another unexpected benefit from its early investment because it was able to reduce purchasing costs of new equipment substantially: The world semiconductor industry was in a recession and equipment suppliers were willing to offer heavy discounts for trials of new equipment.⁵⁰ Samsung was able to reduce its actual investment costs in 8-inch facilities from 1.4 to 1.2 times that of 6-inch facilities.

⁴⁸ Shin (1996, pp. 132-37). The leading Korean *chaebols* like Samsung or Hyundai were in fact not much smaller than the Japanese vertical *keiretsu* like Hitachi or Toshiba, though they were significantly smaller than the Japanese horizontal *keiretsu*. For instance, the total sales volume of Samsung Group was \$21.1 billion in 1987, whereas Hitachi's and Toshiba's total sales volumes were \$23.6 billion and \$20.2 billion, respectively.

⁴⁹ The author's interview with Samsung officials in May 2004.

⁵⁰ For a discussion of discounts for trials of machinery, refer to Rosenberg (1976, 1982).

Table 1. Relative Investment Costs and Productivity by Wafer Size
(times)

	8 inch over 6 inch	12 inch over 8 inch
Investment costs per wafer	1.4 (1.2)	1.7 (1.3)
Productivity	1.8	2.3

Source: Shin and Jang (2005). Original data from Samsung Electronics

Note: Numbers in parentheses are based on actual costs Samsung incurred, which were below market prices, as the company was the forerunner in mass purchasing the equipment and the semiconductor industry was then in a recession.

The choice of the stacking method also proved to be a wise one for the Korean manufacturers and Hitachi. Toshiba and NEC, which had chosen the trenching method, had to switch to the stacking method in the middle of the development process after experiencing a decline in production yields. They were therefore slow to mass produce 4M DRAMs, and the market leadership passed to Hitachi – whose leadership was short-lived, as Samsung soon overtook Hitachi both in 4M and 16M DRAMs. And Samsung became the world leader in DRAMs in 1992, when its 8-inch facilities began churning out DRAMs.

The differences in technological choice between Korean and Japanese manufacturers can be interpreted as an intricate combination of “incumbent traps” and institutional responses of latecomers. In the late 1980s, it was a common view among semiconductor companies that DRAMs were rapidly turning into “commodities”, leaving them with thin profit margins and vulnerable to huge price fluctuations. Japanese producers, once they had become world leaders in DRAMs, looked for new growth areas and began investing heavily in ASICs with the expectation that the sector would provide them with higher margins and greater stability.⁵¹ This would have made them complacent in facing the challenge from the Korean latecomers in DRAMs, as well as conservative both in shifting to 8-inch facilities and in the choice between the trenching and stacking methods.

From the viewpoint of Korean producers, however, the situation appeared far more disadvantageous than otherwise. They were moving into DRAM businesses just when DRAMs were starting to be considered “commodities”. But there was no way back from DRAMs because they had already invested a lot. Being latecomers compared to the Japanese and the Americans, moreover, there was no way to move out of DRAMs toward other semiconductor segments. It was probably their only option to do their best to survive in DRAMs. Samsung, and later other Korean producers, went for the riskier choice of technologies and had to do whatever they could to improve their cost competitiveness.

⁵¹ The author’s interview with Samsung officials in May 2004. Also refer to “Japan speeds DRAM to ASIC” (*Electronics News*, 20 April 1992)

Viewed in this way, it seems that the institutional responses of latecomers played a larger role than the possibility of opening a new window of opportunity in determining their technological choice.

It should be added, however, that there was a window of opportunity for Korea arising from changes in the “inverted institutional window” (Lee and Malerba 2015b). A typical response by market leaders to new entrants in capital-intensive industries is to lower prices, or even to employ a “predatory pricing strategy”, to drive the latter out of the market.⁵² It was alleged that Japanese producers employed a predatory pricing strategy in the middle of the 1980s when Korean memory producers began shipping their 64K DRAMS. In the US market, they were also charged with “dumping” DRAMS to increase their market share at the expense of US producers.⁵³

However, an unprecedented market situation was occasioned by the conclusion of the Semiconductor Trade Agreement (STA) between the USA and Japan in 1986. The STA effectively set a price floor for DRAMS, and average selling prices of 256K DRAMS not only stopped dropping but even increased slightly during the following three years, in contrast to the typical movements of DRAM prices. As a result of this unexpected market situation, Japanese producers were able to reap an estimated \$3-4 billion in windfall gains, or “bubble profits”, while US producers gained time to “restructure” themselves. But it also afforded new entrants like Korean and Taiwanese producers “respites” during which they could recoup their earlier capital investments and stay in the investment race.⁵⁴

5. Korea’s sustained leadership in the memory industry

The history of the memory industry after 1993 is that of Samsung’s dominance. Before it emerged as the world’s number one, there had been continual leadership changes: Whenever memories moved to next-generation products, the market leadership passed from an incumbent leading company to a new challenger. This pattern ceased, however, and Samsung has been the undisputed leader in the industry for the last two decades. Moreover, SK Hynix added to the Korean presence: It struggled until the early 2000s, following the shock of the 1997 Asian financial crisis and difficulties arising from mergers of two different companies (Hyundai and LG). But it emerged as the undisputed number-two manufacturer of DRAMS from 2004 and has maintained number-two or -three position in memories overall since then. (Figures 3 & 4).

Why did the catch-up phenomenon disappear in the memory industry from the middle of the 1990s? This can be understood as a combination of capability expansion on the part of

⁵² For “predatory pricing”, refer to OECD (1989).

⁵³ Langlois and Steinmueller (1999, p. 58-62).

⁵⁴ Refer to Flamm (1996); Tyson and Yoffie (1993); Langlois and Steinmueller (1999)

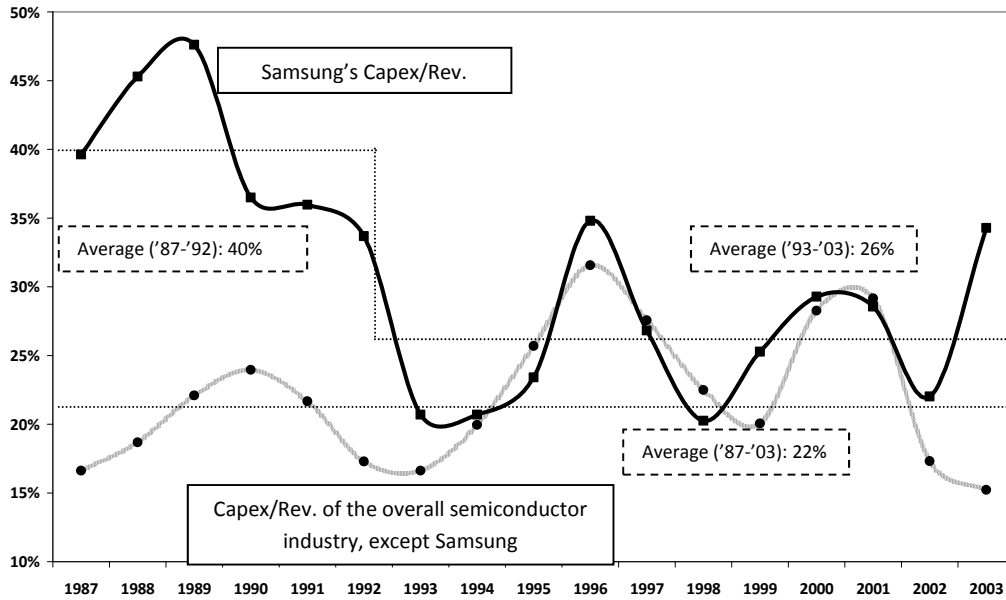
the forerunners, initially Samsung and later SK Hynix, and new technological and market developments that favored them. It can also be partly understood by Lee and Malerba's "windows of opportunity" and "responses". Below, Korea's persistent leadership in the memory industry will be explained mainly by focusing on the case of Samsung Electronics because, on the one hand, that company has incontestably been the dominant leader over the past two decades, and, on the other, the competitiveness of SK Hynix has also been critically related to what Samsung has achieved.⁵⁵ Four aspects of the leadership persistence will be discussed: (1) the expansion of investment capability to undertake aggressive and early investments in new facilities, (2) the expansion of speedy "ramp-up" and process-innovation capability, (3) the emergence of flash memories and increasing "economies of scope", and (4) a sharp increase in the number of technological standards that has favored forerunners.

5.1. Expansion of investment capability

Samsung's overtaking of Japanese memory producers critically depended on its aggressive investments in facilities and R&D, reflected in its early investments in 8-inch facilities and its choice of the stacking method, as discussed above. This investment capability of Samsung continued to expand and contributed to consolidating its leadership. <Figure 5> shows the trend of Samsung's investment compared with that of the overall semiconductor industry. The average capital expenditure over revenues of Samsung's semiconductor division during the period 1987-92 was 39.8 percent, nearly double the industry average of 20.5 percent. Samsung also surpassed its competitors by a wide margin in terms of investment in DRAMs. As <Figure 6> shows, Samsung's average annual investment in DRAMs was US\$396 million from 1988 to 1991, 2.3 times that of Toshiba, the heaviest investor among Japanese DRAM manufacturers, and 2.8 times the average of the four major Japanese DRAM manufacturers, Toshiba, NEC, Hitachi and Fujitsu.

Figure 5. Trend of Samsung's Investment in Comparison with Its Competitors
(%, capital expenditure/revenue)

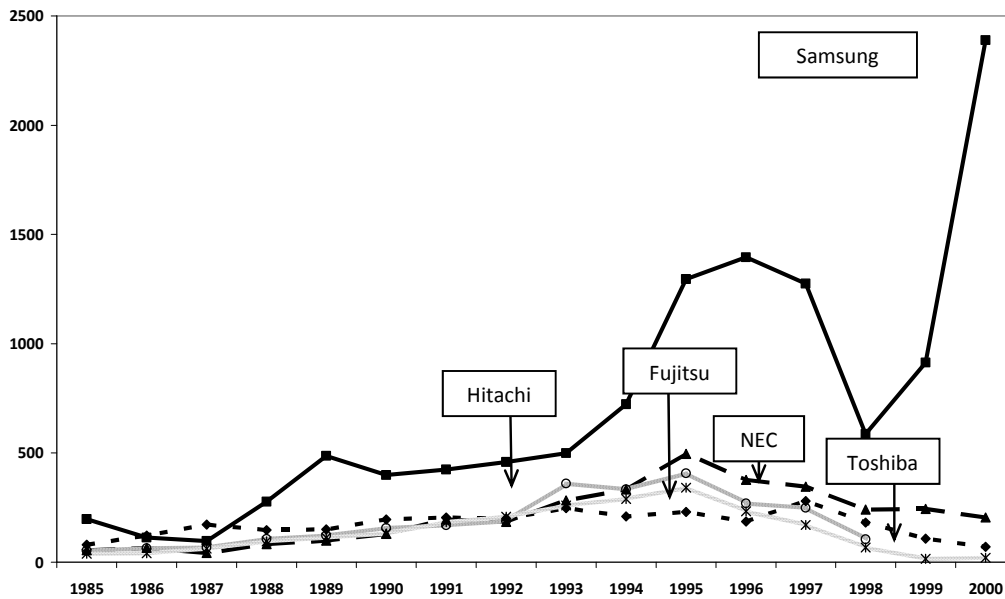
⁵⁵ A high-ranking Samsung engineer defected to SK Hynix (then Hynix) in 2001 and implanted the Samsung-style mass-production system there. This was crucial to the turnaround of Hynix in the middle of the 2000s. The author's interview with him in August 2007. Also refer to "An interview with Jin-Suk Choi, Vice President of Hynix" (*The DongA Daily*, 31 October 2009. In Korean).



Source: Shin and Jang (2005). Original data from Samsung Electronics and Dataquest.

After becoming the number-one producer of memories in 1993, Samsung continued to invest heavily in facilities and R&D, although its ratio of capital expenditure to revenue stabilized at a lower level than that during its catch-up period: The ratio was 26.0 percent on average during 1993-2003, while the semiconductor-industry average during that same period was 23.2 percent (Figure 5). In investment in DRAMs, the gap between Samsung and its competitors was even more marked, and it increased over time: During 1993-2000, Samsung's average annual investment in DRAMs was estimated to be US\$1,134 million, 4.7 times that of the average of the four major Japanese DRAM producers (Figure 6).

Figure 6. An Estimate of Major Firms' Investments in DRAMs (US\$ millions)



Source: Shin and Jang (2005). Their own calculation based on Gartner data

It is also notable that Samsung consolidated its leadership position by making investments in new facilities earlier than its competitors. <Figure 5> shows Samsung's capability for early investments. During 1994-1995, it substantially increased its capital expenditure before the industry-wide peak in 1996. It resumed increasing its investments in 1998, when competitors were reducing theirs. In 2003, Samsung's investment reached a peak at the same moment that investment by other semiconductor firms was at the bottom.

Samsung's early investments in the late 1990s were related to the transition of wafer size from 8 inches to 12 inches. Unlike Japanese producers a decade before, which lagged then-latecomer Samsung in shifting to 8-inch wafers from 6-inch wafers, the now-forerunning Samsung made an earlier move toward larger-sized wafer facilities than its latecomers did. It set up a task force and ran pilot facilities at the beginning of 1997, 2-4 years ahead of its competitors. After maturing the 12-inch wafer production technologies to its satisfaction, Samsung placed a volume purchase order with its equipment suppliers. While 12-inch facilities required 1.7 times more investment than 8-inch ones, the former brought about 2.3 times higher productivity per wafer than the latter. As the first mass purchaser of the equipment, Samsung could get heavy discounts, and it thus further reduced its actual per-wafer investment cost for 12-inch facilities to 1.3 times that of 8-inch facilities (Table 1). In 2001, it began mass producing DRAMs at the 12-inch facilities and widened the gap with its competitors.

In R&D investment, Samsung also expanded its capability considerably. As discussed above (Section 4), it employed a dynamic catch-up strategy by developing two generations of products simultaneously. As it moved to the position of technological leader, Samsung

stretched this simultaneous development to the extreme by developing three generations of DRAMs at nearly the same time: After making progress in developing 16M DRAMs, it started developing the 64M DRAM and soon thereafter the 256M DRAM—all before its production lines turned out 16M DRAMs.

Such simultaneous development was possible due to Samsung's close integration of development and production (Section 5.2). The development process benefited greatly from the continuous flow of information from the production process, which helped economize resources and reduce the time required to develop the next-generation product. This, in turn, enabled Samsung to develop the next-next-generation product.

5.2. Expansion of speedy “ramp-up” and process-innovation capability

Samsung's investment capability, discussed above, was closely related to its speedy ramp-up or upscaling capability. “Ramp-up” or “upscaling” is the process of moving from product development to full-capacity production. In the semiconductor industry, as well as in other high-tech industries, where prices of products are high in the initial period when customers are ready to pay a premium price, it is critically important for producers to reduce the time of ramp-up or upscale and to sell their products earlier than their competitors.⁵⁶ In fact, most facility investments are made during the ramp-up process. If a company is ahead of the others in facilities investment, this implies that it is also faster than others in establishing mass-production systems. Samsung's successful catch-up with its forerunners by 1993 owed greatly to its capability for speedy ramp-up (Section 4).

When it began producing the 4M DRAM in 1989, Samsung realized that its ramp-up capability rivaled, if not surpassed, that of its Japanese competitors. Once 16M DRAMs were introduced, Samsung's superiority in ramp-up capability became evident. Although Toshiba developed a 16M DRAM sample in 1989, slightly earlier than Samsung—and a sample that worked at a much higher speed than Samsung's—in 1991 Samsung became the first DRAM manufacturer to mass produce 16M DRAMs. Similar feats were repeated in the race to produce NAND Flash memories. Toshiba was often earlier than Samsung in developing new-generation NAND Flash memories, but Samsung brought commercial products to the market ahead of Toshiba (Details in Section 5.3).

Samsung's ramp-up capability is a competitive advantage about which “[o]ur competitors feel most curious and are most inquisitive,” according to a Samsung official.⁵⁷ While many of the details are confidential and cannot be fully reported here, Samsung's ramp-up capability has to do with its unique system of integrating development and production.

First, Samsung attempted full integration of development and production by directing engineers from every stage, from design to mass production, to take part in the entire

⁵⁶ For the concept and processes of “ramp-up”, refer to Terwiesch and Bohn (2001) and Salomon and Martin (2008).

⁵⁷ The author's interview in May 2004.

development process together. This facilitated problem-solving and information-sharing, which helped to speed ramp-up. Many engineering problems that might have arisen in production were detected during the development process, and production-side knowledge contributed to reducing the development time. This fuller integration between development and production was facilitated by the fact that Samsung was the only major semiconductor manufacturer in the world that had built design and production facilities at the same site.

Second, Samsung managed to create a unique task-force system, which it called a “Samsung-style TF”. This operated like a cobweb of networks in which design, manufacturing and operating functions were intertwined. One advantage of this system was an accelerated problem-solving capability that was based on Samsung’s mastery of parallel problem-solving techniques. In other companies, it was common practice when technical problems arose to look for their causes in the most probable area, and, if they were not found there, to move on to the next most probable area in serial fashion. Samsung, in contrast, developed proprietary know-how allowing it to ascertain that the causes were within, say, five major areas, which it was able to investigate simultaneously.

Third, Samsung developed a system to test yield rates with pilot lines. Semiconductor companies normally got to know yield rates of new products only after they started mass production. However, Samsung managed to accumulate knowledge and to institute a system capable of roughly ascertaining yield rates of new products at the stage of development. Therefore, it could solve many potential production problems at the development stage. Thanks to this new system, Samsung attained a yield rate approaching “the golden yield rate (80 percent)” in the initial full production run of the 12-inch line in 2001, which until that time had been inconceivable in the industry.

The combination of the company’s mass-production capability and its technological leadership in development brought about yet another innovation in process technologies, which enabled it to shrink the size of chips significantly. Samsung began applying cutting-edge design and micro-fabrication technologies acquired at the development stage of future-generation chips to the production of current-generation chips. Semiconductor production had up to that time required a strict match between circuit density and design rule. For instance, 256K DRAMs were produced only by applying the design rule corresponding to a circuit width of $1.1\mu\text{m}$, and 1M DRAMs were produced only by applying the design rule corresponding to a circuit width of $0.7\mu\text{m}$. In developing the 64M DRAM in the early 1990s, however, Samsung applied the design rule for the 64M DRAM, devised for a circuit width of $0.35\mu\text{m}$, to the production of existing 16M DRAMs, for which the $0.42\mu\text{m}$ design rule had previously been required. This inter-generational application of technologies was more widely adopted in subsequent generations of DRAMs. For instance, the 64M DRAM progressively adopted design rules corresponding to $0.25\mu\text{m}$, $0.18\mu\text{m}$ and $0.13\mu\text{m}$ in place of the design rule corresponding to a circuit width of $0.35\mu\text{m}$, with which it had initially been developed.

The adoption of next-generation design rules brings about substantial cost savings. For instance, if the 0.11 μ m design rule is applied to a 256M DRAM chip that was previously made using the 0.18 μ m design rule, its size can be reduced to about 30 percent of the original size. Samsung utilized its leadership in shrinking technologies to great advantage. After producing a commercial sample of the first-generation 16M DRAM (chip size 126.7mm²) in 1991, it shrank the chip size and successfully mass produced second-generation 16M DRAMs (93 mm²) in 1993, which was critical in solidifying Samsung's position as the market leader in 1995. Samsung also began mass producing third-generation 16M DRAMs (60 mm²) at the end of 1995 by applying design and process technologies from the 256M DRAM that improved its productivity by 60 percent over the second-generation product. The story was all but repeated for the 64M DRAM: Japanese competitors, late in producing first-generation 64M DRAMs, hoped to catch up with second-generation 64M DRAMs, but Samsung preempted this challenge by churning out second-generation 64M DRAMs, which improved productivity by 40 percent over the first generation.

According to Samsung's internal assessments, its competitors were considerably weakened from losses during the 16M DRAM and 64M DRAM life cycles, and had a diminished capacity to compete in 256M DRAMs. Moreover, Samsung's high productivity, which provided it with the power to reduce prices substantially and even force its competitors to lose money, contributed to preempting the market by discouraging potential competitors from entering.

5.3. The emergence of flash memories and increasing "economies of scope"

Samsung was quick and aggressive in diversifying into mobile-related technologies from the 1990s. Samsung's top management saw enormous business potential in mobile technologies and considered the company to be in an advantageous position with respect to its competitors: As one of the most diversified integrated electronics companies, it had already made significant inroads into mobile electronics products, including mobile communication handsets and equipment. Getting the company prepared for the emerging mobile era was, throughout the 1990s, the mantra of Samsung's top management, which set as its goal making its semiconductor division grow into a "total mobile-solution creator".

Flash memory was the lead item in this diversification drive into the mobile-related businesses.⁵⁸ The flash-memory market grew exponentially, from \$1.8 billion (3.5 percent of the memory market) in 1995 to \$18.6 billion (38.3 percent) in 2005. It surpassed the size

⁵⁸ Flash memories retain their contents even if electrical power goes off, while DRAMs lose their contents when power is off. Retention capability, or non-volatility, is crucial for mobile devices running on battery power.

of the DRAM market in 2012 and grew to \$33.3 billion (49.7 percent) in 2013.⁵⁹ Within flash memory, Samsung focused on NAND flash over NOR flash because it thought the former held out better potential for the mass market.⁶⁰ Samsung's technological choice was again successful: By 2000, the size of the NAND flash market was US\$370 million (3.5 percent of the flash memory market), but it surpassed the size of the NOR flash market in 2005 and grew to \$28.9 billion (86.5 percent of the flash-memory market) in 2013.⁶¹

Samsung was successful in gaining the leadership position in NAND flash memories thanks to the application of its superior ramp-up and process-innovation capability (Section 5.2). Toshiba was often the first to develop new generations of NAND flash memories, but Samsung introduced the product to the market earlier than Toshiba and continually increased its market share. As a Japanese expert bitterly commented, "Samsung Electronics tends to throw out its hand slightly later than others in the scissors-paper-stone game".⁶² Samsung became the number-one producer of NAND flash in 2002 and number one in flash memories overall in 2003. Due to the explosive growth in demand for flash memories in mobile devices, flash memories replaced DRAMs as the company's top-selling item in 2006.

Samsung's technological leadership position in DRAMs was an important factor in gaining competitiveness in flash memories because the company could easily apply design and process technologies developed in DRAMs to flash memories. It was also able to reduce production costs of flash memories substantially by using existing wafer-manufacturing facilities more intensively. In general, flash memories are of lower density than DRAMs, and it is therefore possible to produce cutting-edge flash memories on outdated DRAM production lines.

When Samsung aggressively diversified into flash memories, these "economies of scope" increased significantly.⁶³ Samsung could lengthen the life cycles of its expensive production lines, which would otherwise have become obsolete much sooner, and utilize them more intensively as well. For instance, the sixth production line, which was initially built for the 16M DRAM and the 64M DRAM in 1995, was utilized for producing flash memories, graphic memories and SRAMs, all of which require less density than DRAM products at similar levels of technical sophistication. Newer production lines were designed similarly in order to

⁵⁹ http://www.usitc.gov/publications/332/journals/rise_flash_memory_market.pdf (accessed on April 7, 2015);

<http://www.digikey.com/en/articles/techzone/2012/dec/flash-memory-market-surpasses-dram-for-the-first-time> (accessed on April 7, 2015).

<http://www.statista.com/statistics/266987/forecast-of-worldwide-semiconductor-sales-from-memory-components/> (accessed on April 7, 2015).

⁶⁰ While NOR flash has faster access time, NAND flash has faster erase and write time, higher density, lower cost per bit and ten times higher endurance than NOR flash.

⁶¹ Wong (2010, p. 2). http://www.usitc.gov/publications/332/journals/rise_flash_memory_market.pdf (accessed on April 7, 2015); <http://koreajoongangdaily.joins.com/news/article/article.aspx?aid=2989903> (accessed on April 7, 2015).

⁶² The author's interview with a Samsung official in May 2004.

⁶³ For the concept of "economies of scope", refer to Teece (1980) and Panzar and Willig (1981).

produce a variety of products. The capacity to produce diversified products, in turn, allowed Samsung to invest in larger-size facilities.

5.4. A sharp increase in the number of technological standards

In the earlier discussions, it was emphasized that, within the semiconductor industry the Gerschenkronian catch-up pattern was most evident in memories because they are more capital intensive and less design intensive than either microprocessors or ASICs. A dynamic catch-up strategy worked when latecomers built up capabilities to engage in a continuous investment race and rapidly ramp up production. As DRAMs were like “commodities” that were perfectly replaceable as long as they met a few specifications that matched related electronic devices, latecomers could focus on manufacturing products that were cost effective and of good quality.

However, technology began to change in the memory industry from the 1990s, and there was a substantial increase in the number of standards applying to DRAMs. In the early 1990s, when DRAMs and other memories operated at a speed of 33MHz, there were only about 10 technology standards for command and package. However, the speed of DRAMs had increased to 100MHz by the late 1990s, and the number of technology standards skyrocketed. For instance, the second-generation DDR (double data rate DRAM, a high-speed DRAM), DDR2, alone had about 330 technology standards (Table 2).

Table 2. Technology Standards for DDR2
(the late 1990s)

	Major Items	Number of Standards
Function	Circuit, Addressing, Logic, Read/Write, etc.	About 100
Specification	Power, Test, Temperature, etc.	About 200
Package	Pin-out etc.	About 10
Module	UDIMM, RDIMM, SODIMM etc.	About 20

Source: Shin and Jang (2005). Original data from Samsung Electronics

This change benefited the incumbent technology leader, which could initiate standards or wield greater power in setting them. The leader could prepare for new systems and technologies more effectively than its competitors and take the lead in the investment race because it would know the specifications and direction of technologies earlier. The same kind of forerunner’s advantages emerged in mobile-related memories, including flash memories, because they required numerous technical standards in order to allow interfaces with other new products to be easily established.

5.5. Capability expansion and windows of opportunity

The combination of changing windows of opportunity and capability expansion would explain the persistence of Korea's leadership. There emerged two new technological developments that favored incumbent leaders during the non-catch-up period: the weakening of commodity-like characteristics of memories due to a sharp increase in the number of technological standards, and the increasing "economies of scope" that mainly emerged in the production of DRAMs and flash memories. These changes can be understood not only as Lee and Malerba's "competence-enhancing" changes in technologies and market demand for forerunners, but also as the narrowing of the "technology window" for latecomers. If latecomers had competed only in DRAMs, the catch-up cycle might have repeated. However, due to the new technological and market developments, it became more difficult for the latecomers to embark on and succeed in dynamic catch-up strategies.

Internal capability expansion was also a crucial part of leadership persistence. The expansion of its capability to make aggressive and timely investments constituted an important competitive edge for Samsung. The company's investment in 12-inch facilities in the late 1990s was a heavy blow to its Japanese competitors. The expansion of Korean producers' speedy ramp-up and process-innovation capability was also very important to explaining their leadership position. During the catch-up periods, latecomers tended to surpass their forerunners in building strong mass-production capability even though they were weaker in development capability. Korean producers maintained their superiority in mass-production capability even after they became the forerunners, and this made it more difficult for potential latecomers to stage their own catch-up.

It seems to me that the interaction between changing windows of opportunity and capability expansion was also an important part of leadership persistence in the memory industry. The imminent transition toward mobile technologies was common knowledge among industry experts in the 1990s, and most companies tried to prepare for the new competition ahead. But Samsung was the only one that set its sights on becoming a "total mobile-solution creator", and it developed the most diverse competences in mobile technologies. This can be understood as one of Lee and Malerba's "responses" and also as a result of the continuation of Samsung's capability expansion aimed at diversifying into new growth areas.

6. Conclusions

Looking back on the history of the semiconductor industry, the success of a Gerschenkronian catch-up strategy appears more an exception than a rule: There were only two incidences of successful leadership change, both limited to the memory sector and

neither lasting as long as two decades, in more than five decades of the semiconductor industry's overall history. However, the low probability of incidence does not diminish its importance to management or policy. It seems that the Gerschenkronian catch-up strategy, which was modified into a dynamic catch-up strategy in the memory industry, is still the best-established option open to latecomers that aim to make inroads into a technologically dynamic industry. As latecomers, they do not have sufficient resources to stage catch-up on all fronts but have to focus their efforts on certain areas. And capital-intensive segments or industries are relatively more promising than design-intensive segments or industries "where very special technological skills are required".

There is no doubt that this strategy is difficult to carry out and involves high financial risks. Latecomers need to draw on financial resources and to continue making heavy investments while they are racing to build up their production and R&D capabilities. This requires determination, institutions to support the prolonged race, and sometimes strokes of luck, including the opening or widening of various "windows". Latecomers even face the possibility of going bankrupt while attempting this kind of ambitious catch-up strategy. For instance, Samsung's memory business incurred losses for seven years in a row in the beginning, and it could have folded without intra-group assistance and an overall financial environment that, at the time, exercised "patience" toward such long-term projects.

However, there is a great reward in the strategy because it provides those who apply it with competitiveness in mass production. Latecomers build their capabilities in mass production first, then move up to more complex design capabilities. In the semiconductor industry, memories were central to mass-production capabilities. This was why Gordon Moore, the co-founder and then-chairman of Intel, was very reluctant to pull out of the DRAM business in the 1980s. He was convinced that DRAMs were the industry's manufacturing-technology driver for two reasons: First, their cells all have the same structure, and it is easier to experiment with new designs on them than on more complex chips; and, second, they require the largest-scale mass-production system, and manufacturing improvements are critically dependent on volume production processes.⁶⁴

Moore's conviction still seems to be warranted today. An aspect common not only to the successful catch-up by both Japan and Korea before the middle of the 1990s, but also to the persistence of leadership by the Koreans thereafter, has been superior mass-production capability, part of which has consisted in "rapid ramp-up and process-innovation capabilities" (Section 5.2). In contrast, the Japanese failure to maintain leadership in the 1980s had to do with neglect of the DRAM business. They feared too much the possibility that DRAMs would turn into "commodities" and were too eager to move up to "higher-end" semiconductors. Samsung and other Korean producers were able to exploit this opportunity in catching up with the Japanese and did not repeat Japan's failure after they became forerunners in DRAMs.

⁶⁴ Jackson (1997).

The fact remains that memories are still the most capital-intensive segment in the semiconductor industry. To be successful in catch-up or to sustain a leadership position, achieving and expanding mass-production capability seems to be crucial. Although it is certainly necessary to develop products before ramping up toward mass production, development capability was even employed to improve mass-production capability, as can be observed from Samsung's case to shrink the size of chips by applying design rules of next-generation technologies (Section 5.2). This importance of mass production capability would constitute a reason that we witness no separation between design and manufacturing in major memory producers, although the "decoupling" between design and manufacturing has progressed substantially in ASICs and to some extent in microprocessors.

References

- Borras, M., Millstein, J.E., Zysman, J., 1983. Trade and Development in the Semiconductor Industry: Japanese Challenge and American Response. In: Zysman, J., Tyson, L. (Eds.) 1983. American Industry in International Competition. Cornell University Press, Ithaca & London.
- Chin, D.-J., 2002. An Insider's View of the Development Strategy of Samsung's Semiconductor Business. mimeo.
- Dosi, G., 1984. Technical Change and Industrial Transformation: The Theory and Application to the Semiconductor Industry. Macmillan, London.
- Flaherty, M.T., Itami, H., 1984. Finance. In: Okimoto, D. et al. (Eds.) 1984. Competitive Edge: The Semiconductor Industry in the U.S. and Japan. Stanford University Press, Stanford.
- Flamm, K., 1996. Mismanaged Trade? Strategic Policy and the Semiconductor Industry. Brookings Institution Press, Washington D.C.
- Fransman, M., 1990. The Market and Beyond: Cooperation and Competition in Information Technology in the Japanese System. Cambridge University Press, Cambridge.
- Gerschenkron, A., 1962. Economic Backwardness in Historical Perspective. Harvard University Press, Cambridge Mass.
- Gerschenkron, A., 1963. The Early Phases of Industrialization in Russia: Afterthoughts and Counterthoughts. In Rostow, W.W. (Ed.) 1963. The Economics of Take-Off into Sustained Growth. Macmillan, London.

- Gerschenkron, A., 1968. *Continuity in History and Other Essays*. Harvard University Press, Cambridge Mass.
- Gregory, G., 1986. *Japanese Electronics Technology: Enterprise and Innovation*. John Wiley & Sons, New York.
- Henderson, J., 1989. *The Globalisation of High Technology Production*. Routledge, London.
- Hobday, M., 1989. Corporate Strategies in the International Semiconductor Industry. *Research Policy* 18, 225-38.
- Jackson, T., 1997. *Inside Intel: Andy Grove and the Rise of the World's Most Powerful Chip Company*. Dutton, New York.
- Johnson, C., 1982. *MITI and the Japanese Miracle: The Growth of Industrial Policy 1925-1975*. Stanford University Press, Stanford.
- Jones, L.P., Sakong, I., 1980. *Government, Business, and Entrepreneurship in Economic Development: The Korean Case*. Harvard University Press, Boston.
- Landes, D., 1969. *The Unbound Prometheus: Technological Change and Industrial Development in Western Europe from 1750 to the Present*. Cambridge University Press, Cambridge.
- Langlois, R.N., Steinmueller, W. E., 1999. The Evolution of Competitive Advantage in the Worldwide Semiconductor Industry, 1947-1996. In Mowery, D., Nelson, R. (Eds.) 1999. *Sources of Industrial Leadership: Studies of Seven Industries*. Cambridge University Press, Cambridge.
- Lee, K, Kee, 2015. Changes in industrial leadership and catch-up by latecomers: Toward a theory of catch-up cycle from the case in the world steel industry. (to be filled)
- Lee, K., Malerba, F., 2015. Toward a theory of catch up cycles and changes in industrial leadership: windows of opportunity and responses by firms and countries in the evolution of sectoral systems. (to be filled)
- Lee, K., Malerba, F., 2015b. Catch-up Cycles and Changes in Industrial Leadership in Six Industries. (to be filled)
- Malerba, F., 2002. Sectoral systems of innovation and production. *Research Policy*, Volume 31, Issue 2, 247–264.

- Malerba, F., 2004. Sectoral Systems of Innovation: Concepts, Issues and Analyses of Six Major Sectors in Europe. Cambridge University Press, New York.
- Méthé, D.T., 1992. The Influence of Technology and Demand Factors on Firm Size and Industrial Structure in the DRAM Market 1973-1988. *Research Policy* 21, 13-25.
- Nakayama, W., Boulton, W. Pecht, M., 1999. The Japanese Electronics Industry, Chapman and Hall, London and New York.
- OECD., 1989. Predatory Pricing. OECD, Paris.
- Okimoto, D. et al. (Eds.) 1984. Competitive Edge: The Semiconductor Industry in the U.S. and Japan. Stanford University Press, Stanford.
- Panzar J.C. and R.D. Willig., 1981. Economies of Scope. *American Economic Review*, Vol. 71, No. 2.
- Perez, C., Soete, L., 1988. Catching-up in Technology: Entry Barriers and Windows of Opportunity. In Dosi, G., Freeman, C., Nelson, R., Silverberg, G., Soete, L., 1988. *Technical Change and Economic Theory*. Pinter Publishers, London.
- Rosenberg, N., 1982. *Inside the Black Box*. Cambridge University Press, Cambridge.
- Salomon, R., Martin, X., 2008. Learning, Knowledge Transfer, and Technology Implementation Performance: A Study of Time-to-Build in the Global Semiconductor Industry. *Management Science*, Vol. 54, No.7.
- Samsung Electronics, 2001. Thirty Years' History of Samsung Electronics, Samsung Electronics, Seoul (in Korean).
- Shin, J.-S., 1996. *The Economics of the Latecomers: Catching-Up, Technology Transfer and Institutions in Germany, Japan and South Korea*. Routledge, London & New York.
- Shin, J.-S., Jang, S.-W., 2005. *Creating First-Mover Advantages: The Case of Samsung Electronics*. mimeo. (The content of this paper was expanded and later published as a book in Korean, Shin, J.-S., Jang, S.-W., 2006. *An Anatomy of the Technological Leadership of Samsung Electronics: Strategy and Organization for Creating First-Mover Advantages*. Samsung Economic Research Institute, Seoul).
- Teece, D.J., 1980. Economies of Scope and the Scope of the Enterprise. *Journal of Economic Behavior and Organization Science*, Vol. 1 No. 3.

- Terwiesch, C., Bohn, R., 2001. Learning and Process Improvement during Production Ramp-up. *International Journal of Production Economics* Vol. 70
- Tyson, L., Yoffie, D., 1993. Semiconductors: From Manipulated to Managed Trade. In Yoffie, D. (Ed.) 1993. *Beyond Free Trade: Firms, Governments, and Global Competition*. Harvard Business School Press, Boston.
- Ueno, H., 1980. The Conception and Evaluation of Japanese Industrial Policy. In Sato, K. (Ed.) 1980. *Industry and Business in Japan*. Sharpe, White Plains, N.Y.
- Weinstein, F.B. et al., 1984. Technological Resources. In Okimoto, D. et al. (Eds.) 1984. *Competitive Edge: The Semiconductor Industry in the U.S. and Japan*. Stanford University Press, Stanford.
- Wong, G., 2010. Market and Applications for NAND Flash Memories. In Micheloni, R., Crippa, L., Marelli, A., (Eds.) 2010. *Inside NAND Flash Memories*. Springer.
- Yonekura, S., 1991. The Postwar Japanese Iron and Steel Industry: Continuity and Discontinuity. In Abe, E., Suzuki, Y. (Eds.) 1991. *Changing Patterns of International Rivalry: Some Lessons from the Steel Industry*. University of Tokyo Press, Tokyo.
- Zysman, J., 1983. *Governments, Markets, and Growth: Financial System and the Politics of Industrial Change*. Martin Robertson, Oxford.