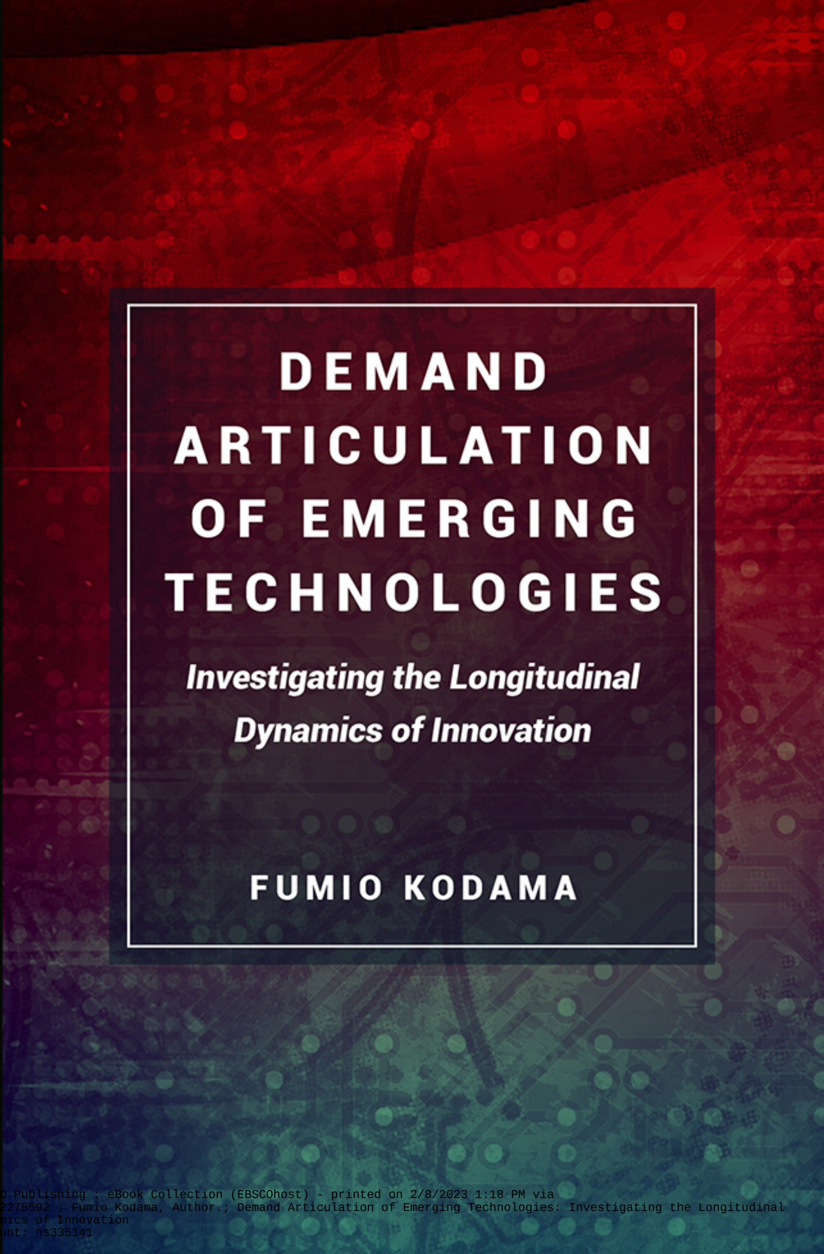

DEMAND ARTICULATION OF EMERGING TECHNOLOGIES

Investigating the Longitudinal Dynamics of Innovation

FUMIO KODAMA

Demand Articulation of Emerging Technologies

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By

Fumio Kodama

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PREFACE

The concept of "demand articulation" came to my mind in the late 1970s, when my colleague and I were teaching a course of science and technology policy at a liberal arts college in upstate New York. It was in a context of why nuclear energy application to submarines was so successful while its application to merchant ships had failed all over the world.

After I came back to Japan, I tried to find a Japanese word for demand articulation. However, I could not find any appropriate expression. Some executive directors in some major Japanese companies, though, had a deep understanding of this English expression, since they had been trying to find the reasons why some of them did not manage the corporate R&D well. And they came to appreciate the concept of demand articulation, although they also could not find an appropriate translation.

Then at the beginning of the 1990s, when I was teaching at Kennedy School of Government at Harvard University, I expanded the use of this concept in explaining, for example, Japanese successes in developing LCD (Liquid Crystal Display) technologies. And I found that many of the graduate students were interested in this explanation. Moreover, I found that a teaching colleague for this class, Lewis Branscomb, who had been a chief scientist at IBM and became a Harvard professor, appreciated this concept as well. I also met several US corporate executives who liked my expression of demand articulation.

After I came back to Japan, again, I was striving to find a good translation, but did not succeed. When several Internet sites compiling citation data of refereed papers in academic journals became available, I found that not a few papers cited some of my papers about demand articulation. And I also find that this concept has become somewhat standard terminology in some areas, including marketing science. Due to the reasons mentioned above, I came to write about this concept in a more systemic way.

I would like to express my thanks to many people who helped me in this endeavor. My sincere thanks go to Dr. JinHyo Yun of DGIST in Korea, who encouraged me to contribute several papers, some of which are chapters of this book, to his international journal of the Society of Open Innovation (JOItmC). My thanks also go to Mr. Sozaburo Okamatsu, a director of Syoukoukaikan (Japanese clubhouse on commerce and industry) in Tokyo, who has let me organize a research meeting on the subject of this book every year since 2011. I had several important inputs to this book from all the members of this research meeting, and in particular from Prof. Tamotsu Shibata, Prof. Jun Suzuki, and an IT journalist, Mr. Yasushi Baba.

May 2019
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INTRODUCTION

Many scientists have become aware that scientific leadership does not necessarily translate into industrial or product leadership. Therefore, they have begun to consider the connection between science and product[1]. Usually, this connection is described as a type of *pipeline* in which a new technology emerges successively from basic research, applied research, exploratory development, engineering, and manufacturing[2]. Gomory[3] has called this progression the *ladder process*: the step-by-step reduction of new scientific knowledge into a radically new product. In the ladder process, a new technology *dominates*, and a product is *created* around it. The customers' needs are *taken for granted*.

Economists, on the other hand, have noted the intrinsic *dynamics* of technology development. Rosenberg[4], for example, argues that the ordinary messages of the marketplace are not *specific* enough to indicate the *direction* in which technical change should be sought. He concludes, therefore, there must be forces *outside* the marketplace that point in certain directions. Furthermore, Hippel[5] of MIT studied several cases in which users who understand the needs of the market usually develop the technology first. He has come to propose a concept of “user innovation.” From the technologists' viewpoint, Kline[6] argues that innovation can be interpreted as a *search* and *selection* process among technical *options*. In this *intricate* process, Nelson’s "alternatives out there *waiting* to be found" is somewhat force[7]. The most important element in technology development, therefore, is the process in which a specific demand for a technology *emerges* and R&D effort is targeted toward developing and *perfecting* it.

In the 1960s, meanwhile, most markets were relatively *homogeneous*, based on a mass-production and mass-consumption society. The marketing discipline responded to this situation by developing and refining theories that centered on *customers* and *markets*. Sheth and Sisodia[8] labeled these theories as *market-driven* orientation. In recent years, however, the market orientation literature's core message is "be close to your customers"—listen to your customers—while the *innovation* literature's core message is "being *too close* to the customer can *stifle* innovation." This dichotomy needs to be resolved by studying the applicability of the *market-driven* and *market-driving* mind-sets. They argue that *market-driving* firms seek to *uncover* the latent *undiscovered* needs of current and potential customers, while *market-driven* firms reinforce *existing* frameworks. This *market-driving* view, moreover, suggests an *iterative* process in which marketing strategy *shapes* as well as *responds* to buyer behavior. By doing so, the firm obtains a competitive advantage, which *in turn* shapes the *evolution* of the marketing strategy.

Given this, we have to find a new and *accurate* way of describing the *dynamic* process of technology development. We have to give science policy administrators and research managers a *vocabulary* and a framework for talking *proactively* about the choices they must make in the high-tech environment. In this context, it is important to conceptualize "a sophisticated translation skill that *converts* a vague set of *wants* into well-defined products". To do so, we will come to the concept of "demand articulation." According to Webster's dictionary, *articulate* comes from the Latin *articulare*. The word "articulate" has two conflicting meanings: (1) to *divide* into parts; and (2) to put together by *joints*. Thus, the word encompasses two opposite concepts: analysis (decomposition) and synthesis (integration). In fact, both are necessary in technology development, and the heart of the problem concerning technology development is how to manage these conflicting tasks[9]. Therefore, we can define demand articulation as a dynamic *interaction* of technological activities that involves *integrating* potential demands into a product concept and *decomposing* this product concept into development agendas for its individual component technologies. Articulating demand, therefore, is a *two-step* process: market data must be *integrated* into a product concept, and the concept must be *broken* into development projects. However, potential demands are often derived from *virtual* markets. The fact that the technology is still considered *exotic* should not be a *deterrent* in setting development agendas.

Indeed, Sheth and Sisodia[10] summarized that "demand articulation" is an important *competency* of market-driving firms. Most firms are more comfortable in a world of *pre-articulated* demands, wherein customers know exactly what they want, and the firm's challenge is to *unearth* that information. Firms that are able to sustain success over a long period of time, therefore, need to be market-driven and market-driving *simultaneously*; most corporate cultures, however, are attuned to one or the other orientation. Over its history, they argue, the marketing function and discipline have been shaped by a number of *contextual realities*. On the basis of this fundamental contextual change, they classified their arguments into *four* categories:

location-centric, *time*-centric, *market*-centric, and *competition*-centric.

In order to better understand the concept of "demand articulation," therefore, we will organize this book based on our *four* categories, which are slightly different from these categories suggested by Sheth and Sisodia. The *first* two categories for a contextual change in innovation are: *defense* policy-centric and *commercialization* policy-centric (in public and corporate policy). These are based on the accumulation of technology management in the defense sector first and in its subsequent transfer from the defense to the civilian sector. They are also based on a shift in pattern of innovation from the product to the manufacturing.

As to the *first* category, we will *revisit* the origin of demand articulation in the US defense sector with regard to nuclear and IC (Integrated Circuit) development. We will demonstrate how the concept of demand articulation was decisive in setting the development agenda and also in ensuring the successful outcomes. The first analysis is about the technology development process in the application of *nuclear energy.* However, as everyone knows, this longitudinal outcome is very mixed between the successful accomplishment or the termination of a project. Then, we will move to the technology whose longitudinal achievements are obviously successful. This is the development process of IC technologies. We will analyze how this development was triggered by defense strategies, in the context of how a *defense strategy* articulation was implemented.

As to the *second* category, we will analyze how the *commercialization* of the IC technologies is implemented by industrial policies in Japan. Specifically, we will describe the commercialization in the context of how an industrial research consortium led to a solid building of manufacturing infrastructure, *i.e.* an idea of *collective* articulation by a research consortium. And this idea of collective research was later implemented in US public policy. In the public policy area of environmental protection, past industrial experiences will be formulated as the regulatory articulation in terms of interindustry competition and collaboration.

The demand articulation will be also found to be effective in corporate policies for *competency* building. This core competency articulation is a critical factor in the diversification strategy and its successful management. More recently, many of the innovations and cost savings that could be achieved have already been achieved. Our greatest focus is on business *model* innovation, which is where the greatest benefits lie. It is not enough to make a difference to product quality or delivery readiness or production scale. It is important to innovate in areas where competition does not exist[11]. In this context, the creative part of activity in business model innovation will be formulated as a *proactive* mode of demand articulation.

The remaining *two* categories are related to the long term perspectives on technologies: the *third* category concerns the long *wave* of innovation and the *fourth* category concerns the industrial *revolution*. As is widely discussed, the duration of the Kondratief cycle is estimated to be 50–54 years. Indeed, the Japanese machine tool industry stayed at the top in the world for almost 40 years. By analyzing the longitudinal development of this industry in Japan from 1975 to 2015, therefore, we will demonstrate that the *wave* articulations in the arriving patterns of innovation were implemented in the right timing and the right sequence.

The *final* category is related to the forthcoming industrial revolution, in order to demonstrate the effectiveness of demand articulation and of its updated version in the coming age of the 4th industrial revolution. Indeed, the introduction of the IoT (Internet of Things) and services into the manufacturing environment are leading the 4th industrial revolution. Therefore, we will present several case studies on how the IoT evolved, particularly in contrast to the IT (Information Technology) revolution. The IoT is described: the system itself is embedded with network *connectivity*. Based on these case studies, we will discuss how the concept of demand articulation can survive in quite a new environment, in terms of *connectivity* articulation.

Notes

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[1] Gomory, R. and Schmitt, W. (1988). Science and Product. *Science*, *240*, 1131–1132, 1203–1204.

[2] Alice J. and Branscomb L. (1992). *Beyond Spinoff.* Boston: Harvard Business School Press.

[3] Gomory R. (1989). From the 'Ladder of Science' to the Product Development Cycle. *Harvard Business Review, 67*(6), 99–105.

[4] Rosenberg N. (1976). *Perspectives on Technology.* Cambridge: Cambridge University Press.

[5] Hippel, E. (2005). *Democratizing Innovation.* Cambridge, MA: MIT Press.

[6] Kline S. and Rosenberg N. (1986). An Overview of Innovation. In: R. Landau and N. Rosenberg (Eds.), *The Positive Sum Strategy* (pp. 275–305). Washington D.C: National Academy Press.

[7] Nelson R. and Winter S. (1982). *An Evolutionary Theory of Economic Change.* Cambridge, MA: Harvard University Press, Belknap Press.

[8] Sheth J. and Sisodia R. (1999). Revisiting marketing's lawlike generalizations. *Journal of the Academy of Marketing Science, 27*, 71–87.

[9] Kodama F. (1995). *Emerging Patterns of Innovation.* Boston: Harvard Business School Press.

[10] Sheth J. and Sisodia R. (1999). Revisiting marketing's lawlike generalizations.

[11] Amit, R. and Zott, C. (2012). Creating Value through Business Model Innovation. *MIT Sloan Management Review*, *53*(3), 41-49.

CHAPTER ONE

ORIGIN OF DEMAND ARTICULATION: NUCLEAR POWER AND INTEGRATED CIRCUITS (IC) DEVELOPMENT

It was the US navy's development of the nuclear *submarine* that established "technology management" as a *discipline*. Admiral Hyman G. Rickover played a decisive role in the historic event where an *explosive* nuclear bomb was successfully transformed into a *sustainable* energy source[1]. He confirmed the way he went about the project and the lessons his experiences could teach were as important as the project itself[2].

However, as is well known, the long term outcome of nuclear applications is very mixed between the successful accomplishment or the termination of a project. Therefore, we will study the context in which the four applications (submarine, aircraft carrier, electric power generation, and merchant ship) have been implemented, and find that a good *articulation* of demand, rather than good technology management, has been a critical factor for the success of nuclear projects. Without good demand articulation, some nuclear application projects could not sustain the momentum of further progress, or have been terminated.

George Kennan maintained in *retrospect* that it would not be until the Kennedy administration that an awareness of “the basic *unsoundness* of a defense posture based primarily on nuclear weapons” would begin to develop[3]. Indeed, the shift from a strategic stance emphasizing “massive retaliation” under the Eisenhower Administration to the Kennedy Administration's goal of achieving capabilities for a “flexible response” put a *premium* on precision *delivery* of nuclear weapons[4]. Prior to the development of IC (Integrated Circuits) technology, programs sponsored by the US Department of Defense were driven by technology rather than by the *need* for technology.

In the case of IC technology, however, the US Government *articulated* and *shaped* the problem which the innovative candidate technology was required to address. The resulting “articulated demand” for *miniaturization* and *reliability* in missile control systems went beyond what was possible using vacuum tubes or transistors. Although they did not receive direct government funding for their work, Texas Instruments and Fairchild *responded* to this military demand in developing the first IC.

1. Comparing Nuclear Applications

1.1 Nuclear Submarines

The US Congress passed a bill establishing an Atomic Energy Commission (AEC) in 1946. By the end of 1946, however, the AEC and the Bureau of Ships had no *articulate* policy concerning nuclear propulsion. Meanwhile, World Wars I and II had demonstrated to the world that the *submarine* was a critical weapon. However, the *old* S-48 submarine was a “cramped boat,” and was limited in its submersion and speed capacities[5]:

> The submarine was powered by storage *batteries* when submerged and by *diesel* when surfaced. The submersion period was limited by battery life: the boats had to surface frequently to recharge the batteries and to resupply the crew with fresh air. In addition, a battery fire could produce toxic gases and multiple explosions. A submarine was almost called as “dangerous as the enemy”.

A critical issue of submarines was that, as long as they relied on *diesel* and the storage *battery* to power the electric motor, they would be limited in their utility. In 1947, the "true submarine" conference was organized and recommended operational *criteria* for the design of new submarines in the light of the experience of World War II.

> The "true submarine" would be an *underwater* craft that would *remain* submerged *indefinitely* and that would operate in the sea much as *aircraft* did in the sky. Such a craft had to be able to dive to great depths to reduce *detectability* and had to be able to cruise beneath the surface for *unlimited* time at a rate which would approximate the speed of surface vessels.[6]

The conference suggested *nuclear* propulsion as the *answer*. When an Undersea Warfare Symposium was held afterwards, most of the AEC commissioners were there. Admiral Earle W. Mills claimed that the naval reactor had not really been given any *priority*, and urged that the Commission should establish a high priority for a naval reactor program as soon as possible[7]. By the spring of 1948, the AEC had confirmed the Navy's position that the challenge of the naval propulsion reactor was a *distinctive* one. The Navy brought private contractors into the new project. By the end of 1950, the pressurized light-water thermal reactor known as *Mark I* was being constructed by Westinghouse. In 1953, the Mark I went *critical*. Then, it accomplished a test which simulated a submerged trans-Atlantic voyage. This test was solid *evidence* that the world of undersea propulsion had fundamentally changed. It was a great achievement. It can be thought of as a *landmark* in the history of technology, because it was the first time that a nuclear reactor had produced s*ustained and usable* amounts of energy.

1.2 Aircraft Carriers

The *criticality* of demand articulation as a determinant to the performance of nuclear energy in various applications was further validated by another example of its application in the Navy. The demand for an aircraft *carrier* can be well *articulated*, *i.e.* a carrier can stay on the ocean for almost several years without any *refueling*[8].

In addition to the two submarine projects, Rickover was soon involved with the study of nuclear aircraft *carriers*[9]. He and his people had investigated the possibility of nuclear propulsion for large *surface* ships in early 1950, and they had recommended that so long as uranium was in short supply, it did not seem wise to use it for this purpose. Indeed, they viewed the idea of a nuclear-powered carrier as a *distraction* from the important task of developing the nuclear submarine, where the advantages of nuclear propulsion were unquestionable.

But Admiral Forrest P. Sherman had become CNO (Chief of Naval Operations), and he was a strong believer in *carriers*. After the invasion of Korea, and about the same time that President Truman authorized the construction of the Nautilus, Sherman asked the Bureau of Ships to *examine* the feasibility of constructing *a large carrier* with an *atomic* power plant, and to determine time factors, cost factors, and characteristics. Meanwhile, Westinghouse completed its study in 1952, and presented *six* possible reactor types. The Naval Reactors group was asked to choose one. The group recommended that the pressurized-water design was best, and this choice was endorsed by both the Navy and the AEC. The AEC assigned the development of the carrier prototype to Westinghouse and asked Rickover to direct the project. In 1961, the construction of the nuclear aircraft carrier, the USS *Enterprise*, was completed. After 1975, the constructions of the USS *Minitz*, the USS *Dwight D. Eisenhower*, and the USS *Carl Vinson* followed. In order to accompany the aircraft carriers, several nuclear guided-missile cruisers including the USS *Long Beach* had also been built[10]. Thus, the demands for nuclear aircraft carriers have been well *articulated*.

We can make a tentative summary of the analysis in terms of the "demand articulation" scheme. First of all, we have to ask why the utilization of nuclear energy was first realized successfully in the navy (submarine and aircraft carrier), rather than in electricity power stations on land. This was because there was no *alternative* but nuclear as the energy source for realizing the ideal of the "true submarine" and the "true aircraft carrier." In order to make the concept of demand articulation *explicit*, however, these trajectories of the technology's developmental paths should be contrasted with those of other applications of nuclear energy, in particular, in the context within which the electric power station and the merchant ship projects were conducted.

1.3 Electric Power Stations

The nuclear navy was progressing. The second nuclear submarine, the *Seawolf,* would take the liquid sodium-cooled plant being developed by General Electric (GE). But President Eisenhower was dreaming: to develop the “Peaceful Atom” to counteract the image of Hiroshima as the atom’s only *legacy*. The United States organized the first international “Atoms for Peace” conference in Geneva, and succeeded in the establishment of an International Atomic Energy Authority, headquartered in Brussels.

Indeed, Eisenhower had been anxious to demonstrate some concrete action toward achieving the goal of the commercialization of atomic energy, in particular, nuclear programs for power stations:

> President Eisenhower was dreaming of developing the Peaceful Atom, to “deliver electricity to the factories, farms, and homes of all the peoples of the world." He was determined that the atomic arrows in one *talon* of the American eagle would be complemented by a credible atomic *olive branch*. And Rickover’s commercial central station power plant at Shippingport, Pennsylvania, was to be his means to that end.[11]

Since Eisenhower was keen on achieving the goal of commercial atomic power, his ceremony at Shippingport in September of 1954 took place before many of the key design *parameters* for the plant had been set. In April of 1955 Rickover made the important decision that the reactor fuel elements would be made of uranium oxide clad in zirconium-alloy tubes. This was a totally *different* design concept from the naval reactors and required the development of an entirely new technology. But this development was remarkably successful, and it became the basis for nearly all the world's nuclear power plants. In October of 1957 the first reactor *core* was installed, and in December the plant reached *criticality*. On 23 December of 1957, Shippingport reached a design capacity. Commercial atomic power was now realized. It was only four and a half years after the task had been assigned to Admiral Rickover. Three years later, commercial plants based on this design began to emerge around the country, and shortly after that, around the whole world.

Indeed, the nuclear power generation projects did demonstrate spectacular success in the early stages. However, in retrospect, as everyone knows, they were destined to follow a mixed *trajectory* of development. In this context, we will make a comparison between the demand articulation for submarines and for electric power generation. We can notice that demand articulation for nuclear submarines was much different from that for power stations. A major difference was that the *former* articulation can be translated into the *intrinsic* demand characteristics of the project to be produced, while the *latter* was a *political* articulation rather than a techno-economic one. And what is more important is the fact that the nuclear submarine had no alternatives to nuclear power in terms of the intrinsic nature of the product, so the demand articulation was *straightforward*, while, in retrospect, power generation had several alternatives besides nuclear. After all, the nuclear option in power stations turned out to be not quite what Eisenhower had hoped for in his political statement. When we entered the twenty-first century, the nuclear option for power stations had become dubious and uncertain. While US nuclear power generation still composes about *one third* of the world’s total nuclear power generation, its share in the total US electricity generation decreased drastically in the 2000s.

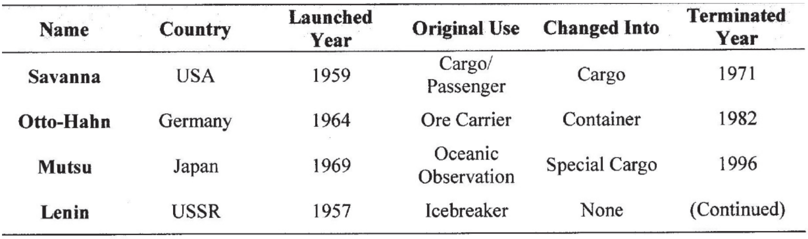
1.4 Merchant Ships

The importance of demand articulation in nuclear projects become even more conspicuous when the utilization of nuclear power for *merchant* ships was attempted in various countries including the United States, Germany, and Japan. However, these civil merchant ships did not develop beyond a few experimental ships.

In 1955, President Eisenhower proposed building a nuclear-powered merchant ship as a *showcase* for his "Atoms for Peace" initiative. The following year, Congress authorized the *Savannah* as a governmental project. It was completed in 1962, but it was too small and expensive to operate economically as a merchant ship. The design was neither that of an efficient freighter nor of a viable passenger liner. Civilian nuclear ships also suffered from the costs of specialized infrastructure specific to the merchant ship. The *Savannah* was expensive to operate since it was the only vessel using its specialized nuclear shore staff and servicing facility. A larger fleet could share fixed costs among more operating vessels, reducing operating costs.

In Germany, the construction of the *Otto Hahn* as an ore carrier was initiated in 1964. It sailed some 650,000 nautical miles (1,200,000 km) on 126 voyages over 10 years *without* any technical problems. However, it proved too expensive to operate commercially and was converted to a diesel-driven “container” ship. In 1969, Japan launched the *Mutsu* project for the purpose of constructing a nuclear ship for oceanographic observation. However, this project was dogged by technical and political problems. Its reactor had significant radiation leakage and fishermen protested against the vessel's operation. In a context that is somewhat different from the above-mentioned countries, the first nuclear ship program had been launched already by the USSR in 1957. The purpose of the nuclear ship program, however, was to develop an *icebreaker*. A comparison of these programs is depicted in **Table 1-1** below[12].

Table 1-1. Country comparison of merchant ship programs



Name	Country	Launched Year	Original Use	Changed Into	Terminated Year
Savanna	USA	1959	Cargo/ Passenger	Cargo	1971
Otto-Hahn	Germany	1964	Ore Carrier	Container	1982
Mutsu	Japan	1969	Oceanic Observation	Special Cargo	1996
Lenin	USSR	1957	Icebreaker	None	(Continued)

As can be seen in the table, we can discover that there were big and varied differences among these four countries concerning how the nuclear ship was to be used originally, how each country changed the original purpose as the project progressed, and when the project was finally terminated. Among the various programs, it has been said that the Japanese nuclear ship was inaugurated on the basis of the definition which had been given at the International Conference on Safety of Life at Sea, which was held in London on June 17, 1960. In this conference, a nuclear ship was defined as “a ship with a nuclear power plant.” Compared with the cases of the nuclear submarine projects described before, therefore, we can say that the demand for nuclear merchant ships was far from being *articulated*, except for the development in the USSR where the objective was clearly set to build an *icebreaker*. In the frozen North Sea, cargo transportation is only possible by using a nuclear icebreaker that has a long cursing range with a strong capacity of ice-breaking and that does not need any intermediate refueling. Indeed, the Russian nuclear ship project is still alive today.

2. A new cooperation scheme: Option sharing

After three nuclear disasters were experienced (the 1979 Three Mile Island (TMI) accident in the USA; the 1985 Chernobyl *disaster* in the USSR, and the 2011 Fukushima accident caused by a tsunami in Japan), it became clear that various factors (safety and fuel recycling) were more serious than previously thought. Ironically, we can say that the demand for nuclear power generation has now been newly *articulated*, but the technical *routes* to be taken have not yet been articulated.

In 2006, meanwhile, the Toshiba Corporation made a bold decision to purchase Westinghouse Electric Corporation for ¥490 billion, in order to become a sole supplier of both types of light water reactors: PWR and BWR. At that time, Toshiba seemed to manage a deliberately research *portfolio*, but they are indeed within the same form of technology. Thus, we will find that Toshiba's action was not based on the idea of portfolio research management, but rather to accommodate the nuclear renaissance which advocated clean energy and being environmentally friendly, which was triggered in 2005 by the Bush administration's initiatives in the United States and later diffused all over the world. And the implication of Toshiba's bold decision became especially obvious after the 2011 *meltdown* accident at the Fukushima nuclear power plant caused by a tsunami due to an earthquake, and the construction and operation of nuclear power plants came to a *standstill*, at least in Japan[13].

The advanced reactor technologies being developed in the United States are *safer*, more *efficient* and need a fraction of the *space area* compared to existing LWRs. New plants could be powered entirely with *spent* nuclear fuel, built at a lower cost than LWRs and *shut down* more *easily* in an emergency. While *water* does a good job of cooling and moderating the atomic fissions of nuclear reactors, the next generation of nuclear reactors is looking to broaden our *options*[14]. These include liquid metal, high temperature gases, and molten salt. Nuclear reactors using these coolants can be even safer than most light water reactors. Small modular reactors (SMRs), defined by the International Atomic Energy Agency as anything less than *300 MWe* (or less than one quarter of the size of a typical LWR), might hold the key to a transition toward advanced nuclear reactors. SMRs are at the final stages of commercial development. With a lower initial capital investment and a shorter construction time than LWRs, SMRs could replace aging and carbon-emitting coal power plants. Third Way has found nearly *50* projects in companies and organizations that are developing plans for new nuclear plants[15]. In short, we can find a trend in the evolution from the light water reactor to the small modular reactor and to the advanced reactor.

The cumulative nature of technological advancement has been described by Nelson and Winter[16] as following a natural *trajectory*: today's research produces successful new technology and the natural beginning place for tomorrow's searches. They discuss a "neighborhood" concept of a quite *natural* variety: once a system has proved to be a success, it is possible only to make minor changes. However, a set of technological possibilities sometimes consists of a number of different classes of technology. Within any of these classes, however, technological advancement may follow a particular trajectory. At any given time, all R&D may be focused on one class of technologies with no attention paid to other classes of technologies. These path *dependencies*, which are often involved in technology development, indicate the possibility that the system will *lock* into paths that are not globally optimal[17]. Therefore, our task right now is to *unlock* the path dependencies and to explore all the possible technology *options* which might satisfy the newly-articulated demands. In other words, we should try to create new varieties of natural trajectories which might accommodate these newly articulated demands.

In order to accommodate the intrinsic dynamics of national programs, we are proposing international cooperation based on *option sharing*. Option sharing entails dividing up the burdens and responsibilities for pursuing each possible scientific and technological option in a given area. A thorough search of all possible options, therefore, should be the main objective of future international cooperation. Conventional schemes of international cooperation, such as cost-sharing and task-sharing, have been developed by economists, not derived from the logic of science and technology itself.

In option sharing, in the early phase of the development of large projects involving international cooperation, scientists in each nation would pursue the approach of their own choosing, which would be explored on an affordable scale. By international agreement, all information about each approach would be open to scientists pursuing complementary projects in other countries, and, as each project matured, scientists could elect to work on the project of their own choice, regardless of national location.

Of course, this cooperation scheme should not permit one country to force the option it has selected on other countries. Each country should have the right to choose which option it wishes to pursue. Given the need to ensure that all possible options are covered, of course, there would have to be a certain amount of compromise and adjustment. In the case of projects like the super collider, in which scientific value outweighs the merits of diversity, prior agreement would have to be sought for sharing costs and tasks to implement the scientific principles as a truly international facility[18]. However, the soaring costs involved in large engineering projects is due, at least in part, to the increasing number of options and to the pressure imposed on a single government to cover all the costs involved in exploring all the options simultaneously. Only through international cooperation, therefore, is it possible to pursue all potential options.

Covering all possible options through international cooperation would have a profound effect on the development of technology. While science aims at an absolute truth, technology aims at relative superiority. Determining the most meritorious technical option, therefore, is not possible unless all the options are demonstrated and compared. Option sharing should not be looked upon as a country relying on advances made by competing projects of other countries. Instead, the other countries would provide a *calibration* of the state of art technical advance, with transparency provided through international cooperation in its role as the evaluator of various options being pursued in a parallel manner. Information sharing could be ensured by allowing a free flow of researchers across national borders. After researchers had freely chosen the option they wished to pursue in accordance with their own views, convictions and career objectives, they would work in the country pursuing that option. Once the best option had been determined, researchers would return to their respective countries, thus ensuring information on the option will be disseminated throughout participating countries.

Through option sharing, it is possible to resolve the inherent tension that exists between international cooperation and national autonomy. Through the principle of *cooperate and compete*, nations in the industrial world may capitalize on parallel interests. There are growing fears that the shift toward technological protectionism will turn into a minus-sum game for the world as a whole. It can be said that only through option sharing can a plus-sum game be ensured. In a world in which "techno-nationalism" is the prevailing mood, international cooperation through option sharing may offer the breakthrough that can make the ideal of "techno-globalism" the new reality.

3. Integrated Circuit Development in the US defense sector

In the defense sector, the concept of demand articulation is effective for describing how product development challenges at the component and systems levels are addressed in an integrated manner. One important historical case is the impact that shifts in US strategic defense policies had on IC (Integrated Circuit) development in the 1950s and 1960s. An OECD study[19] concluded:

> Although the two basic patents and key technological contributions that *underlie* IC technology in the United States were made by private companies *without* government support.

In other words, although government influence helped create the *landscape* these companies viewed, it did not *dictate* the nature of the technological *route* to be taken. The need was *articulated*, the *means* to satisfy it was *not*[20]. In short, breakthroughs were brought about by the in-house R&D efforts of those companies that responded to the *articulated* demand of the military.

3.1 Deterrence Strategy

According to Gaddis[21], George Kennan maintained in *retrospect* that it would not be until the Kennedy administration that awareness of “the basic *unsoundness* of a defense posture based primarily on weapons as being accidentally destructive and *suicidal* in their implications" would begin to develop[22]. Indeed, the shift from a strategic stance emphasizing “massive retaliation” in the Eisenhower administration to the Kennedy administration's goal of achieving capabilities for a “flexible response” put a *premium* on the precision *delivery* of nuclear weapons and highly survivable systems, including *missiles* and command and control systems[23].

Prior to the development of IC technology, programs sponsored by the US Department of Defense were driven by technology rather than by the *need* for technology. In the case of IC, however, the US Government *articulated* and *shaped* the problem which the innovative candidate technology was required to address. The resulting “articulated demand” for *miniaturization* and *reliability* in missile control systems went beyond what was possible using *vacuum tubes* or *transistors*, the available technologies at the time. Although they did not receive direct government funding for their work, Texas Instruments and Fairchild *responded* to this military demand in developing the first IC.

The chronology of strategic defense changes and of technology developments has been studied in-depth by the author[24], by itemizing the strategic changes around the concept of “containment” [25] and the occurrences of IC-related innovations[26], as described below:

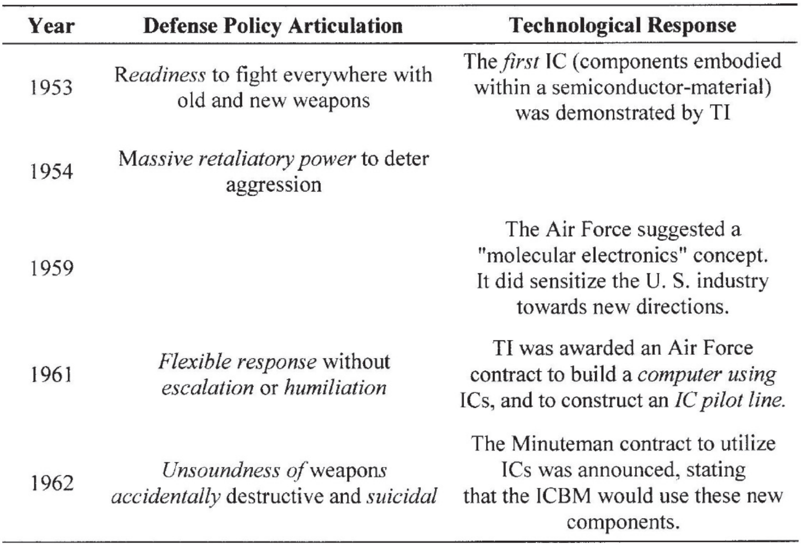
- Immediately after World War II, *Truman's strategy* would have required a *readiness* to fight everywhere, both with old weapons and with new weapons.
- In 1951, the military services sponsored an effort to *improve vacuum tube* circuitry. The *first* major effort made specifically in the *miniaturization* mode was "Project Tinkertoy”[27] to miniaturize and *completely automate* the manufacture of selected electronic components.
- Texas Instruments (TI) initiated an *in-house* program to seek basic *new* directions. By mid-1953, the first IC, *i.e*., electronic components indivisibly *embodied* within a semiconductor material, was demonstrated by TI.
- John Foster Dulles explained how a *strategic initiative* could be combined with *budgetary restraint*. It could be done by relying on the deterrent of “massive *retaliatory power*.” We would be willing and able to *respond vigorously* in *places* and with the *means* of our own *choosing*.

In 1958, the Air Force suggested a concept dubbed "molecular electronics." In brief, “components using this technology would have various electronic functions *without* specifically *fabricating* such individual electronic parts as transistors, diodes, capacitors and resistors. The material used would *simulate* the electronic function of oscillators and amplifiers"[28]. With much fanfare the Air Force awarded a contract to *Westinghouse.* The molecular electronics concept *per se* proved quite controversial and did not *achieve* its goals. However, it did *sensitize* the US semiconductor components industry to *new* directions.

- Kennedy, possessed of an economic rationale for *disregarding* costs, placed his emphasis on minimizing *risks* by giving the United States sufficient *flexibility to respond* without either escalation or humiliation. He declared, "we believe in maintaining effective *deterrent strength*, but we also believe in making it do what we wish, neither *more nor less*"[29].
- Texas Instruments was awarded an Air Force contract. It built a *computer* using IC components. It offered impressive *advantages* and served as a *showcase* vehicle to illustrate IC's potential utility.
- The Cuban missile *crisis* between October 16 and October 28, 1962 made explicit the basic *unsoundness* of a defense posture based on primarily on weapons that were accidentally destructive and suicidal in their implications[30].
- The *Minuteman* contract to *utilize ICs* was announced, publicly stating that the advanced version of the ICBM (Intercontinental Ballistic Missile) would use these new components. Its orders were the largest IC *purchases*.

In order to demonstrate the dynamic interaction between political/policy *articulation* and technological *response*, **Table 1-2** has been prepared, at least as far as the IC development in the US defense sector is concerned.

Table 1-2. The dynamic interaction between defense policy articulation and technological response



Year	Defense Policy Articulation	Technological Response
1953	R*eadiness* to fight everywhere with old and new weapons	The *first* IC (components embodied within a semiconductor-material) was demonstrated by TI
1954	M*assive retaliatory power* to deter aggression	
1959		The Air Force suggested a "molecular electronics" concept. It did sensitize the U. S. industry towards new directions.
1961	*Flexible response* without *escalation* or *humiliation*	TI was awarded an Air Force contract to build a *computer using* ICs, and to construct an *IC pilot line.*
1962	*Unsoundness of* weapons *accidentally* destructive and *suicidal*	The Minuteman contract to utilize ICs was announced, stating that the ICBM would use these new components.

3.2 Offset Strategy

The dynamic interaction between defense policy articulation and technological response has continued since the 1960s. In the spring 1982 issue of *International Security* (MIT Press), William Perry made the technical arguments as to why ICs should not be equated with complexity: that in fact they would decrease costs and increase reliability. From Eisenhower's presidency until Carter's, the United Sates *offset* the large Red

Army with nuclear weapons, both strategic and tactical[31].

In 1977, however, the United States was confronted with two serious security *challenges* in terms of nuclear weapons. First, although the deterrence of a Red Army attack on Western Europe was dependent upon US superiority in strategic nuclear weapons, the Soviets had reached strategic parity by that year. Second, the strategy of using battlefield nuclear weapons on the territory of US allies was a dangerous and reckless idea, even if the US had superiority in strategic nuclear weapons. In a world dangerous as never before, the United States needed a *new* offset strategy which was compatible with the realities they were facing.

The new strategy was *defined* as a plan to develop not tactical nuclear weapons but *innovative* conventional weapons that would enable revolutionary, decisive battlefield prowess even against considerably larger forces, *i.e.* the new offset strategy was based on the emerging *digital* technology[32]. And the policy was *articulated* as an entirely new way to *configure* military aircraft that would make them *immune* from attack by radar and/or infrared-guided antiaircraft missiles. This so-called *stealth* technology would give the US Air Force a sudden and overwhelming advantage in tactical close air support, even when engaging a numerically superior opposing force: the foe's antiaircraft defenses could be rendered ineffective, which in turn could enormously multiply the effectiveness of all the US ground and naval operations.

Success ultimately depended on three interrelated *components*: a new family of intelligent *censors*; a new family of *munitions* that could strike those targets with great precision; and a new way of designing attacking aircraft and ships to allow them to *evade* enemy sensors. A revolutionary component of the offset strategy was the Global Positioning Satellite (GPS) system; this has since become ubiquitous in the civil sector. In summary, the new "system of systems"—stealth, smart sensors, and smart weapons—was developed with the highest priority during the late 1970s, produced in the early 1980s and fielded in the late 1980s, just in time for Desert Storm. The weapons of the offset strategy, which led to the remarkable military success of Desert Storm, remain important to the continuing dominance of the US military as well as to ensuring deterrence.

4. Structure of demand articulation

A complex national system is necessary to articulate the demand for such a radical innovation as integrated circuit technology. Such a complex system is characterized by its hierarchical and multipolar structure and by a higher mobility of scientists. In the next chapter, we will describe the process of transition from the defense sector to the civilian market, and that a leadership in IC technology shifted from the United States to Japan. Although the importance of demand articulation remained the same, they are different in terms of the three categories of the national system's characterization.

First, the *hierarchical* nature of demand articulation could be clearly observed in both markets and countries. In the defense sector, the hierarchy was a *policy* hierarchy: the successful translation of the defense strategy into a technological concept contained a national security policy level, a system requirements level, and a component technological level. In the civilian sector, as will be described in the next chapter, the hierarchy was a *manufacturing* hierarchy: the articulation of the demand for equipment and materials for chip making involved the successive translation of the demand from chip manufacturers to first-tier suppliers, and from first-tier suppliers to second-tier subcomponent suppliers.

Second, demand articulation is also *multipolar* when it involves public policy. As described above, the Air Force hoped that molecular electronics would eliminate unnecessary materials and consequently greatly simplify and improve the life and reliability of future electronic circuitry. The molecular electronics concept (the knowledge at a microscopic level that would allow the proper utilization of every essential atom and molecule) *per se*, however, proved quite controversial, and the Air Force came to support two parallel and competing programs: the much more ambitious and risky effort of Westinghouse and the less risky program of Texas Instruments. In the spring of 1959, it awarded a $2 million research contract to Westinghouse, but later in the year, as we have already noted, it awarded a two-and-half-year contract to TI. In 1961, Westinghouse exhibited a radio receiver demonstrating its molecular electronic principle. As a digital system, however, the TI equipment was a better example of IC technology.

As will be described in more detail in the next chapter, a project by the MITI (Ministry of International Trade and Industry) *articulated* the demand for optical steppers and materials, while a project by the NTT (Nippon Telegraph and Telephone) corporation articulated the demand for testers. Although MITI's research consortium paid little attention to the importance of testers, NTT conducted joint research on the next generation of testers with a company which then became the major supplier of memory testers. In this joint research, detailed requirements for the new tester were collected from the major VLSI manufacturers. However, the fundamental requirements were eventually set by NTT after several meetings to work out the joint specifications.

Thirdly, the mobility of scientists is an important factor for creating a solution and diffusing a created technology throughout the relevant industries. Although the TI project had been initiated as an in-house program without government support, Jack Kilby, the inventor of the integrated circuits, had worked at Centralab, a company that had pursued miniaturizing electronic components in earlier work with the National Bureau of Standards (NBS) before joining TI. Centralab's "Project Tinkertoy," which was sponsored by the US Navy's Bureau of Aeronautics, was perhaps the first major miniaturization effort. The work, however, was performed under the auspices of the NBS. Furthermore, a key staff member who contributed to Kilby's work at TI had pioneered the use of photolithographic techniques for semiconductor devices at the army's Diamond Ordnance Fuze Laboratories (DOFL). In 1957, DOFL had begun to work on ways to fabricate smaller electronic assemblies via a two-dimensional construction.

In Japan, research consortia are widely used to implement government R&D policies. The research consortia, which are of limited duration, are made up of competing firms that share researchers and costs. The government subsidizes the research through funds and tax benefits for the consortia. This approach was adapted from the British model and reformulated as the Engineering Research Association (ERA) in 1966. There are various built-in mechanisms to accelerate the technological diversification of firms participating in these ERAs. One such mechanism is *venturing*. Although venturing is common and supported by government subsidies in the United States, ventures are not in-house[33]. In Japan, on the other hand, ventures are usually in-house.

We suggested that ERAs were being used by big Japanese firms as springboards into in-house ventures. It is standard practice for a firm participating in an ERA to set up an in-house project team that has roughly the same number of members as the research team that the company sends to the ERA. The project team supports its colleagues on assignment and assimilates the data generated by the ERA. In this way, the project team is an in-house venture unit. When the ERA disbands and the employees on assignment return to the company, they add their weight to the project team. Thus, the team serves, in effect, as the headquarters of a venture-capital business[34]. Indeed, the choice of an ERA research project is often related to the product fields that are considered marginal by participating firms so that it causes fewer conflicts of interest among them[35]. We can call this type of mobility a "scheduled mobility."

Conclusion

In order to clarify what the author means by demand articulation, in this chapter, we have revisited the classic cases of technology developments in nuclear applications and in integrated circuits.

As to the outcome of these developments, we find very mixed results in nuclear applications. The demand was well articulated for nuclear submarines and aircraft carriers, since there were no alternatives but nuclear power as the energy source for realizing the ideal of the "true submarine" and the "true aircraft carrier." In the case of nuclear applications in electric power generation, they followed a mixed trajectory of development, although they demonstrated a spectacular success in the early stages. In the case of nuclear applications in merchant ships, all the development projects were terminated, except the icebreaker development of the USSR. We found that the projects were initiated by political articulation rather than by the intrinsic demand articulations. In retrospect, there existed several alternatives besides the nuclear option in these nuclear applications.

After we had experienced three nuclear disasters, it became clear that various factors were more serious than previously thought. The demand for nuclear power generation has newly articulated, but the technical routes to be taken have not yet been articulated. The advanced reactor technologies being developed in the United States are safer and more efficient. New power plants could be powered entirely with spent nuclear fuel, and shut down easily in an emergency. Nearly 50 projects in US organizations are working to commercialize an innovative and advanced nuclear reactor.

When it comes to the development of integrated circuits (IC), on the other hand, the shifts in US strategic defense policies articulated and shaped the problem for which IC's development was required. Under the Kennedy administration, the awareness of the basic unsoundness of a defense posture based primarily on the nuclear bomb began to develop, and the strategy of a flexible response rather than a massive retaliation put a premium on the precision delivery of nuclear weapons, including missiles. The demand for miniaturization and reliability in missile control system was articulated. Although they did not receive direct government funding for their work, Texas Instruments and Fairchild responded to this military demand in developing the first IC.

The dynamic interaction between defense policy articulation and technological response has continued. In 1977, the Soviets reached strategic parity, and the United States needed a new offset strategy: a plan to develop innovative conventional weapons that would enable decisive battlefield prowess against larger forces. And the strategic defense policy was articulated as a new way to configure military aircraft that would make them immune from attack. The stealth technology gave the US Air Force a sudden and overwhelming advantage in tactical close air support. The new "system of systems"—stealth, smart sensors, and smart weapons—was produced in the early 1980s and fielded in the late 1980s, just in time for Desert Storm.

Notes

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[1] Lewis, E. (1980). *Public Entrepreneurship: Toward a Theory of Bureaucratic Political Power*, Bloomington: Indiana University Press.

[2] In his address to the Naval Post Graduate School (March 16, 1954), he declared: "The development of naval nuclear propulsion plants is a good example of how one goes about getting a job done. It is a good subject to study for methods" (Lewis, 1980).

[3] Original Source: George Kennan, *Memoirs, 1925-1995*, pp. 474-75.

[4] National Research Council (1999). *New Strategies for New Challenges: Corporate Innovation in the United States and Japan* (Committee on Japan Office of Japan Affairs, Office of International Affairs). Washington, D.C: National Academy Press.

[5] Lewis, E. (1980). *Public Entrepreneurship.*

[6] Ibid.

[7] Ibid.

[8] Ando Y. (1996). *Nuclear Ship "Mutsu": Its Technology and History* [in Japanese]. Tokyo: ERC Publishing Co.

[9] Rockwell, T. (1992). *The Rickover Effect: How One Man Made a Difference*. Annapolis: Naval Institute Press.

[10] Ando Y. (1996). *Nuclear Ship "Mutsu": Its Technology and History*.

[11] Rockwell, T. (1992). *The Rickover Effect.*

[12] Ando Y. (1996). *Nuclear Ship "Mutsu": Its Technology and History*.

[13] Kodama, H. (2017). *Nishida and Toshiba's fall* [in Japanese]. Tokyo: Shyou-Gakkan-Books.

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[14] According to Third Way, a new generation of professionals in the United States are now working to commercialize innovative and advanced nuclear reactors. There are nearly 50 companies, backed by more than $1.3 billion in private capital, developing plans for new nuclear plants. The mix includes startups and big-name investors like Bill Gates, all placing bets on a nuclear comeback, hoping to get the technology to win in an increasingly carbon-constrained world. See Third Way (2015). *The Advanced Nuclear Industry*, retrieved from https://www.thirdway.org/report/the-advanced-nuclear-industry.

[15] Third Way (2015). *The Advanced Nuclear Industry*.

[16] Nelson, R. and Winter, S. (1982). *Evolutionary Theory of Economic Change.* Cambridge, Mass.: University of Harvard University Press, Belknap Press, p.257.

[17] Cowan, R. (1990). Nuclear Power Reactors: A Study in Technological Lock-in. *The Journal of Economic History*, *50*(3), 541-67.

[18] Branscomb, L. (1991). The Road from Resentment to Understanding in U.S.-Japan Science and Technology Relations. Paper presented at the 100th Anniversary of the Electrotechnical Laboratory, Tsukuba, Japan, E-27.

[19] OECD (Organization for Economic Cooperation and Development). (1977). *Case Study of Electronics with Particular Reference to the Semiconductor Industry.* Paris: Joint Working Paper of the Committee for Scientific and Technological Policy and the Industry Committee on Technology and the Structural Adaptation of Industry, pp. 133–63.

[20] Ibid.

[21] Gaddis, J. (2005). *Strategies of Containment*, Oxford: Oxford University Press.

[22] Original Source: George Kennan, *Memoirs, 1925-1995*, pp. 474-75.

[23] National Research Council (1999). *New Strategies for New Challenges: Corporate Innovation in the United States and Japan* (Committee on Japan Office of Japan Affairs, Office of International Affairs). Washington, D.C: National Academy Press.

[24] Kodama, F. (2016). The Concept of Demand Articulation: How It Was Effective and How It Will Remain Useful. *Journal of Contemporary Management*, *7*(2), 1-15.

[25] Gaddis, J. (2005). *Strategies of Containment.*

[26] OECD. (1977). *Case Study of Electronics with Particular Reference to the Semiconductor Industry.*

[27] The Tinkertoy construction set is a toy construction set for children. It was created in 1914 by Charles H. Pajeau, Robert Pettit and Gordon Tinker. Pajeau designed the toy after seeing children play with sticks and empty spools of thread. He and Pettit set out to market a toy that would allow and inspire children to use their imaginations. *Source*: Cole, D.J., Browning, E. and Schroeder, F.E.H. (2003). *Encyclopedia of Everyday Inventions*. London: Greenwood Press.

[28] OECD. (1977). *Case Study of Electronics with Particular Reference to the Semiconductor Industry.*

[29] Gaddis, J. (2005). *Strategies of Containment.*

[30] Allison, G. and Zelikow, P. (1999). *Essence of Decision: Explaining the Cuban*

Missile Crisis, Second Edition. New York, Longman, Inc.

[31] Perry, W (2015). *My Journey at the Nuclear Brink*. Stanford: Stanford University Press.

[32] Ibid.

[33] Roberts, E. (1977). New Ventures for Corporate Growth. *Harvard Business Review, 58*(4), 134-142; and, Hippel, E. (1977). Successful and Failing Internal Corporate Ventures: An Empirical Analysis. *Industrial Marketing Management, 6*(3), 163-74.

[34] Kodama, F. (1984). Policy Innovation at MITI. *Japan Echo, 6*(9), 66-69.

[35] Kodama, F. (1985). Direct and Indirect Channels for Transforming Scientific Knowledge into Technical Innovations, in B. Bartocha and S. Okamura, eds., *Transforming Scientific Ideas into Innovations: Science Policy in the United States and Japan* (pp. 198-204). Tokyo: Japan Society for the Promotion of Science.

CHAPTER TWO

PUBLIC POLICY ARTICULATION: RESEARCH CONSORTIA AND REGULATORY CHANGE

As a technology shifts from the defense sector to the civilian sector, particularly the development of *manufacturing* technology becomes more important because cost is a critical factor in the civilian sector. Furthermore, as the shift to civilian sector occurs, many companies in different industries become involved in bringing the new technology into the consumer-products market, while only a few selected, technologically elite companies are involved in the defense sector. In other words, the policy agenda shifts to building a national manufacturing *infrastructure*. Many companies, in different industries, have been involved in bringing a new technology from the defense sector into the consumer-products market.

Research in the innovation systems approach has long paid most attention to the components of systems. Less has been said about the dynamic processes that occur within the systems and how they change. To address what occurs within systems of innovation, Edquist[1] argues, one can consider what is referred to activities: factors that influence the direction and the speed of the development and diffusion of innovations. In this context, the concept of demand articulation becomes even more powerful when a national technology policy is analyzed. This suggests that national policy can be discussed better using the concept of a "national system of demand articulation" rather than the oft-cited concept of a “national system of innovation”[2].

In order to appreciate a national system of demand articulation, in this chapter, firstly, we will study the government-sponsored research consortia for IC development both in Japan and the United States. Secondly, we will demonstrate the response to environmental regulatory changes required the various abilities of demand articulation from fact findings to the dynamic competition and/or collaboration between different industries.

We can also find that environmental problems caused by a wider diffusion of a technology were solved by a successful *articulation* for a regulatory change. We can call this *social* demand articulation. In the Japanese car makers’ response to the environmental regulatory changes, the articulated demand in different stages of environmental problems led to a different pattern of problem-solving: the early stage of local pollution problem was articulated and solved by inter-firm competition, while the later stage of local pollution was articulated by inter-industry competition. When the environmental problem shifted to global pollution, the problem articulation and solution was conducted in the form of inter-industry collaboration.

1. Japanese experience of VLSI research associations

As the shift to civilian sector occurs[3], the policy agenda shifts from developing a technology to building a national manufacturing infrastructure. In Japan, the government played a significant role in this transition by organizing a research consortium for very large scale integration (VLSI) development.

When first formed, the consortium included all of Japan's major IC chip manufacturers, who then *articulated* their demand for manufacturing equipment for chip-making. In this way, an internationally competitive infrastructure was established. In 1976, the MITI (Ministry of International Trade and Industry) orchestrated the establishment of the ERA (Engineering Research Association) for VLSI development. The association existed from 1976 to 1979 and forty percent of the total cost was paid by the government on a project funding basis. The members of the association were Fujitsu, Hitachi, Mitsubishi, NEC, and Toshiba. Although we originally developed the concept of demand articulation to analyze the development processes conducted by a single firm, the dynamic process of collective action by rival firms creates the functional equivalent of demand articulation in a *single* firm. We can call this the *collective articulation of demand*.

1.1 Articulation mechanism

The collective articulation of demand should be viewed in and can be explained by the overall framework of industrial technological linkages. It can assist in creating a national technological infrastructure. Sometimes it results in establishing upstream technological linkages. Indeed, the association for VLSI development made possible *demand articulation* for manufacturing equipment for chip making. The five member companies established a joint research laboratory within the association.

However, a great deal of the research and development carried out in the joint laboratory was *subcontracted* to supplier companies that were not members of the association, *e.g.* camera manufacturers, silicon crystal suppliers, and printing companies. Although cooperative research sounds good in theory, it is often difficult in practice. In joint research by rival firms in the same industry, in particular, success hinges on ensuring that the research is *basic* and of *common* interest to all the participants. Therefore, rather than focusing on the method of producing chips, the association centered its research efforts around developing a *prototype* for IC manufacturing equipment and analyzing a process for the crystallization of silicon, a basic material in chip production[4]. No manufacturers of production equipment or chip materials were among the members. **Figure 2-1** depicts the major actors involved in the Japanese development of VLSI and the technical linkages between them[5].

1.2 Power of articulation

A pervasive *uncertainty* not only characterizes basic research, where it is generally acknowledged, but also the realm of government-sponsored development projects. Consequently, as Rosenberg[6] asserted, the pervasiveness of uncertainty suggests that the government should ordinarily *resist* the temptation to play the role of the *champion* of any one technological alternative. He argues, therefore, that it would seem to make a great deal of sense to manage a *deliberately diversified* research portfolio, a portfolio that is likely to *illuminate* a range of alternatives in the event of a reordering of social and economic priorities.

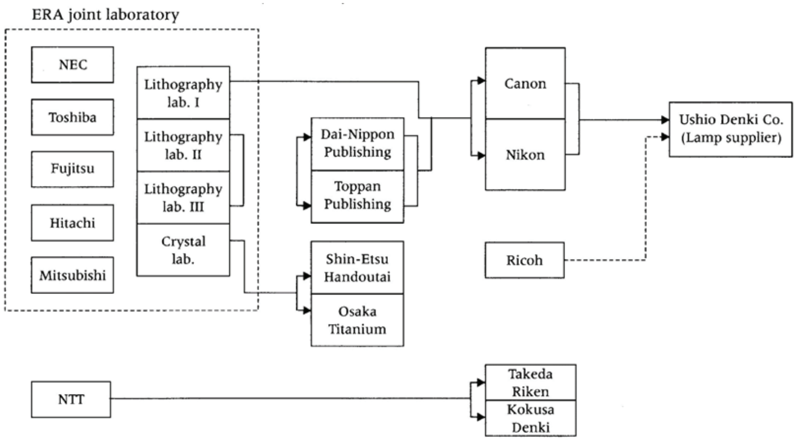

Figure 2-1. Upstream Technical Linkages in Japanese VLSI Development

In this context, the *power* of demand articulation in research consortia has been manifested most vividly in *exploring* all the spectrum of possible equipment technologies. It used to be a mainstream method to let the circuit-diagram mask contact the wafer directly and print on it. When the micro-manufacturing progressed further, a new idea emerged. The original circuit-diagram was projected through the *lens* on the wafer by reduction *ratios* of one-tenth or one-fifth. In actuality, the wafer moves *stepwise* in four directions, while the mask stays in a fixed position. This equipment has become known as a “stepper.”

At the beginning of the ERA for VLSI development, two methods other than the stepper, *i.e.* direct printing by electron beam and X-ray lithography, had already been much advanced and their prototypes were existent. Therefore, the stepper was assumed as the *third* candidate for safety reasons after these two methods. None could deny this *priority*, because no one expected the lens technology to print *40* lines on the *width* of a hair. What made steppers into multi-million-dollar pieces of sensitive equipment was the need to maintain focus within a fraction of a micron and to control the wafer's position with similar accuracy. Therefore, steppers use sophisticated optical feedback mechanisms and stringent control to keep the conditions across the surface of the wafer as uniform as possible.

Meanwhile, an engineer, who later became the CEO of Nikon Co., had been confident about *three* kinds of critical technologies which made the "stepper" competitive: an ultra-high resolution *lens*; the *staging* technologies moving the wafer; and the *censor* of the photo-electric tube. As to the high resolution lens, Nikon had developed a hit commercial product, which was about to be procured for manufacturing photo-mask lenses, specified by both domestic and overseas producers. As to the staging technology, Nikon had the experience to provide Tokyo University's astronomical observatory with the staging mechanism for precise positioning of the telescope[7].

Thus, companies such as Nikon and Canon succeeded in the development. Through the development process described above, the "stepper" has become a mainstream piece of equipment for semiconductor manufacturing. After ten years of demand articulation efforts, which were initiated by the VLSI association, Japanese companies in the upstream sector of chip manufacturing are beginning to emerge as dominant players in world production. Because we have said that collective demand articulation can create a national engineering infrastructure, we also need to consider *second-tier* suppliers. The suppliers of steppers, first-tier suppliers, were not the only beneficiaries of the joint effort. The real beneficiary was a second-tier supplier. Ushio Denki, the supplier of the lamp used for the optical stepper (see **Figure 2-1**), ended up dominating the world market for lamps. In 1983, Ushio had a market share of 100 percent for aligner lamps in Japan and 50 percent for the global market.

2. Generalizing the Japanese experience

We will try to generalize the Japanese experience of VLSI consortium internationally and empirically. During the early and mid-1980s, the US semiconductor industry lost about half of its global market share—particularly in memory chips—to Japanese integrated-circuit producers. The decline in semiconductor manufacturing equipment by domestic makers was equally drastic. That was the background against which the principal American chip manufacturers organized the SEMATECH (Semiconductor Manufacturing Technology) consortium to foster research and development on advanced semiconductor technology.

In order to verify empirically the importance and effectiveness of demand articulation in collective research, we will study the rivals' participation behavior in a research consortium. We will contrast the process and structure of demand articulation with the *pipeline* view of product development. If collective research is organized to gain common basic knowledge, *i.e.* based on the public goods concept, we can assume that participation behavior in a project mirrors the participants' pipeline view of product development. If, however, collective research is organized to acquire and to develop basic technologies, which can be commercialized by participating firms, *i.e.* based on the private goods concept, we can assume that participation behavior in a project reflects the demand articulation view of product development. By studying rivals' participating behavior in government sponsored-research consortia, we will find an almost opposite statistical *phenomenon* between the pipeline and demand articulation views.

2.1 US experience: SEMATECH consortium

We will demonstrate that the concept of demand articulation was evident and visible beyond national borders in organizing the research consortia by investigating the brief history of the SEMATECH consortium, which was established in 1987. SEMATECH is one of hundreds of consortia that have been organized ever since the 1984 passing of the National Cooperative Research Act, which gives companies engaged in cooperative research and development partial *exemption* from *antitrust* laws. Fearing that the integrity of the US defense apparatus was threatened by a growing dependence on foreign semiconductors, the federal government agreed to contribute $100 million annually to SEMATECH's operations.

After struggling unsuccessfully for more than a year to organize a research program suitable for its diverse membership, the consortium decided that the best opportunity it had to aid the US semiconductor industry was *not* to emphasize *direct* cooperation between its members but rather to concentrate on improving the *position* of the domestic companies that make semiconductor manufacturing *equipment*. The consortium focused in particular on *lithography* technology[8]. The US share of the lithography market had slid from 71 percent in 1983 to just 29 percent by 1988. Most of the dramatic decline was accounted for by the GCA Corporation[9]. A global downturn in the semiconductor manufacturing equipment industry and the rapid emergence of Japanese competition brought GCA to the brink of bankruptcy. In 1988, GCA was bought by the General Signal conglomerate. Despite the highly visible failure of GCA[10], the years since SEMATECH was founded have seen an improvement in the competitive position of the US semiconductor industry. In 1993 American companies captured 43.4 percent of the global semiconductor market, *surpassing* the Japanese share for the first time in eight years, and US semiconductor manufacturing equipment companies once again held 50 percent of the global market, compared with Japan's 42.9 percent. Something of a consensus has emerged that SEMATECH deserves much of the credit for these gains, even though a number of other factors also contributed to the recovery[11].

According to Randazzese[12], SEMATECH's greatest accomplishment was probably not its technical achievements in and of themselves but rather its role in improving *relations* between chipmakers and their suppliers. Once almost *antagonistic*, these companies are now *cooperating* closely. These accomplishments, along with the consortium's apparent contribution to the fortunes of the US semiconductor industry, have been widely appreciated by observers. In 1994, SEMATECH invested about $8 million in Silicon Valley Group Lithography Systems (SVGL). In 2001, however, ASML (which had become independent from Philips of the Netherlands in 1984) had acquired SVGL. By acquiring several important technologies from SVGL, ASML has now become the world's largest lithography manufacturer[13]. However, we can argue that demand articulation directly or indirectly made these changes possible in the relations between the chipmakers and suppliers of the United States.

2.2 Empirical evidence of demand articulation

In order to contrast the process and structure of demand articulation with the pipeline view of product development, we need a classification scheme for collective research. As described above, one obvious taxonomic question to ask is whether the collective research is centered on the concept of public goods, or of private goods. Usually, international collaboration is based on the public goods concept of technology. To date, the majority of international collaborations, with a few exceptions, have been scientific projects, such as international collaborative Antarctic expeditions and global climate research projects. These collaborations aim at gaining common, basic knowledge. Thus, they are organized and managed according to the pipeline view. In collective research with a pipeline view, each firm will decide *independently* whether or not to participate in a project. We can *deduce* intuitively that this independent decision-making will produce a *bell-shaped* frequency distribution of the number of participants: a certain number of participants, somewhere between one and all the possible participants, can be expected, with a maximum probability of participation around the average (see **section 2.3**).

Most collective research projects conducted within national borders, on the other hand, are framed on the private goods concept of technology. The most appropriate database for this study would be a research collaboration system in which only *rival* firms participate. At the same time, however, the sample must be large enough for statistical inference. NTT (Nippon Telegraph and Telephone Corporation) and communication equipment manufacturers have conducted a substantial number of joint research projects. NTT used to be a public company until 1985, and there are many similarities between the projects organized by NTT and the projects in an MITI research consortium. Because the telecommunication business can be inherently monopolistic, NTT is prohibited by law from manufacturing. Therefore, its business configuration is that of a service industry firm and similar to public service. Furthermore, joint research organized by NTT is between rival firms, as is often the case in a research consortium.

Although the number of joint research projects organized by NTT is not known, we can estimate it by counting the joint applications for patents. Although we cannot always assume that a joint patent application is the result of joint research, it is hard to imagine joint patent applications not having come about from joint research. And, we are interested only in those joint applications with more than two rival firms.

In 1985, NTT, together with more than two of the four equipment manufacturers, applied for as many as 105 patents. The time-series data (1980-1985) of such joint applications is shown in **Table 2-1**.

Table 2-1 Number of joint allocations with rival equipment manufacturers before privatization[14]

Year	Total number	two firms	three firms	all four firms
1980	106	50 (47%)	7 (7%)	49 (46%)
1981	243	59 (24)	20 (9)	164 (67)
1982	173	33 (19)	8 (5)	132 (76)
1983	168	49 (29)	25 (19)	94 (56)
1984	166	28 (17)	5 (3)	133 (80)
1985	105	18 (17)	15 (14)	72 (69)

Note: percentage share in parenthesis

As we can see from the table, NTT cooperated most frequently with all four equipment manufacturers, and cooperation with two or three manufacturers was less frequent. Although the number of cases involved is substantial, this pattern of participation is quite stable over the six-year period. Roughly speaking, cooperation with all four manufacturers accounted for 46 to 80 percent, while cooperation with two manufacturers and with three manufacturers accounted for 17 to 47 percent and 5 to 19 percent, respectively. This is an obvious manifestation of *U-shaped* distribution, *i.e.* an inverse of the bell-shaped curve. Now we know that the distribution of the number of participating rival firms in collective research has a U-shape. How is this somewhat counterintuitive phenomenon related to interdependent decision-making on participation? We can argue that this interdependent decision-making is the result of the demand articulation view of product development. Through the articulation of demand, participants expect to acquire a better identification of product specifications and thus a better cost estimation. Therefore, a firm's decision to participate is based on its estimation of benefit and cost. This type of decision is interdependent because the benefit each participant will receive and the cost each would have to pay depend upon the other participants[15].

2.3 A bell-shaped frequency distribution

From the several possibilities, we have chosen the international joint projects sponsored by the International Energy Agency (IEA). The IEA was established in November 1974 on the recommendation of the Organization for Economic Cooperation and Development (OECD) and its membership covers twenty-four countries. As of 1984, there were sixty projects.

Because participation varies from country to country—for example, the United States and Sweden have participated in 70 percent of all the projects while Mexico and Finland have participated in only one project—we selected for the final database only those countries that have participated in more than two projects as a lead country. There were ten countries that satisfied this condition. The frequency distribution of the number of the ten countries that participated in the sixty projects is displayed in **Table 2-2**, which is *bell-shaped*.

Table 2-2. Frequency of participation in IEA projects

Number of Participants	Observed Frequency
1	1
2	2
3	11
4	13
5	10
6	10
7	4
8	6
9	2
10	1
TOTAL	60

3. Regulatory articulation

So far we have been describing how a successful articulation helped in generating a new technology and also in establishing the manufacturing infrastructure for this newly generated technology. This section describes how the environmental problems caused by a wider diffusion of a technology were solved by a successful articulation for a regulatory change. We can call this *social* demand articulation.

Successful *social* demand articulation requires, *first of all*, environmental knowledge and information to flow between firms and societal stakeholders, such as the public, governments, and non-governmental organizations (NGOs). *Secondly*, management must take a long-term view of product development. This means a long-term *commitment* to providing stable and adequate financial and human resources for research and development. *Thirdly*, demand articulation requires brisk *competition* between companies, almost to the point of excess. The competitive environment spurs high-tech companies on to experiment with alternatives that they might not explore if competition was less intense. Indeed, competition in technology development is ultimately competition over how skillfully demands can be articulated.

Finally, a given industry's capacity for demand articulation depends on the technological level of *related* industries. The more competent the industry as a whole, the higher the absorption rate of technologies from other industries. Thus, all industries involved in a product's development must have a high level of technological capability before a high degree of demand articulation can take place[16]. In order to test these hypotheses, empirical evidence of demand articulation for environmental problems will be described with regard to the automobile industry.

3.1 Knowledge and information flow

While an in-depth empirical analysis of social demand articulation requires an examination of a broader range of data, current results show knowledge and information flows have a strong impact on inducing environmental innovations. The knowledge flow was measured by the number of research papers and the information flow by the number of newspaper articles that contained environment-related keywords. It is assumed that firms use the generated environmental knowledge flow (or stock) for environmental innovation. We then measured environmental innovation by firms' R&D investment for environmental protection, assuming that such R&D expenditures largely resulted in successful environmental innovations. **Table 2-3** shows the annual data for the period 1985–1997 for R&D expenditure on environmental protection by firms and those research papers and newspaper articles that contain the keywords “air pollution”, “water pollution”, and “soil pollution”.

Table 2-3. Historical trends in research papers, newspaper articles, and corporate R&D expenditures related to environmental protection

Year	No. of research papers	No. of newspaper articles	Corporate environmental R&D (100 M Yen in 1995 value)
1985	37	358	1216
1986	31	433	1185
1987	26	626	1160
1988	24	796	1314
1989	52	1337	1535
1990	42	1834	1806
1991	60	2689	1873
1992	49	2586	1856
1993	39	2445	1764
1994	64	2195	1927
1995	44	1960	2191
1996	146	2322	2382
1997	159	5983	2562

Source: Lee and Kodama, 2006

Our regression analysis of environmental protection R&D expenditure on the number of research papers and newspaper articles shows environmental knowledge and information flows strongly impact environmental innovation[17]. It is noteworthy that the coefficient of the information flow (newspaper articles) is statistically more significant than that of the knowledge flow (research papers), which implies that demand-induced innovation could be more effective than knowledge-induced innovation.

$$\text{R\&D Expenditure} = 3.97\cdot\text{Research Papers} + 0.170\cdot\text{Newspaper Articles} + 1179;$$

$$R^2=0.825,$$

T-statistics = 1.84 (90% level) for Research Papers and 2.45 (95% level) for Newspapers.

Note that research papers and newspaper articles as well as environmental R&D expenditure sharply rose around 1991 and 1997. Those years were when the Rio Earth Summit and the Kyoto Convention were held, respectively. At this time in Japan, the Federation of Economic Organizations (*Keidanren*) announced the Global Environment Charter in 1991, and Keidanren’s Nature Conservation Fund along with financial support for NGOs was established in 1992. Further, the Keidanren Appeal on Environment—Declaration on Voluntary Action of Japanese Industry Directed at Conservation of Global Environment in the 21st Century was made in July 1996. All of these moves by the Japanese *Keidanren* deeply impacted company executives to be more environmentally conscious.

3.2 Commitment by top management

The compound vortex controlled combustion (CVCC) engine was the first technology that met the US Muskie law, which required a drastic reduction of auto emissions to one-tenth of the previous level. Various air pollution incidents occurred in Japan during the 1960–1970s, which captured the public's attention to auto emissions. At the same time, doctors in the Tokyo area saw unusually high *sulfur* content levels in the blood of those residents who lived around traffic intersections. The doctors attributed this fact to the lead used in gasoline, reporting potential health damage due to auto emissions. A strong social pressure for higher environmental standards as a result of the public attention to photochemical smog issues and various pollution incidents eventually led to the adoption of a strict emission standard, the 1978 law. The 1978 regulation induced competition for low emission vehicles among automobile manufactures. Honda acknowledged the social responsibility of the auto industry and immediately directed a great amount of financial and human resources to the R&D of a new engine. At the same time, it was believed that developing an engine to meet the US Muskie law would make the company highly competitive in the international automobile industry.

The Air Pollution Research Center was subsequently established, where the basic measurement and analysis of auto emissions was first carried out. It was found out that the combustion *process* had to be innovated in order to reduce emissions to the level required by the 1978 law. While other auto manufacturers sought a catalyst approach, Honda, with its management vision, went on its way to develop the CVCC engine, which enabled lean-burn, controlled fuel injection technology. As a fully developed product, the Honda Civic with the CVCC engine recorded the best fuel efficiency in the American auto market until 1980. It was at this time that Honda was able to establish a high reputation for energy-saving quality vehicles and a solid market share in the US. Behind the development of the CVCC engine, we can find the strong commitment and technological rationale of the founder, Souichiro Honda, who *articulated* the essence of the problem by saying:

> Emission standards and improvement in fuel economy were different, but are two sides of the same *coin* as far as R&D efforts are concerned.[18]

Indeed, Mr. Honda directed the company's researchers to focus on a deeper understanding of the burning processes of fuel inside the cylinder. This resulted in the invention of the CVCC. In hindsight, burning fuel *cleanly* is technologically equivalent to burning it *efficiently*. So Honda really benefited or technologically profited from that kind of change in situation.

3.3 Inter-industry competition

Honda's invention of the CVCC engine triggered the Japanese government to drastically reduce the allowable limits for emissions by automobiles in the 1970s. The Japanese auto manufacturers responded to this change in regulation by commercializing the *three way catalyst* technology (a multicomponent material containing the precious metals rhodium, platinum and palladium, ceria (CeO_2), γ-alumina, and other metal oxides)[19]. This development involved a wide range of industries, including the materials industry and its chemical firms.

However, it is to be noted that the final stage of problem-solving did not include the chemical industry. The three-way catalytic converter was designed to remove exhaust pollutants such as carbon monoxide, unburnt hydrocarbons and nitrogen oxides. The conversion efficiency of the three-way catalyst, however, differs among different kinds of pollutants, depending upon the air/fuel ratio, as shown in **Figure 2-2.**

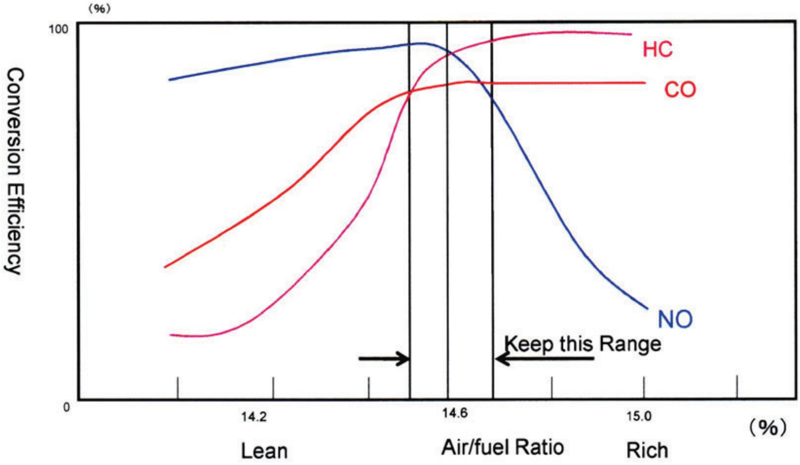

Figure 2-2. Change of conversion efficiency of three pollutants along the air/fuel ratio

As can been seen in Figure 2-2, the conversion efficiency can be quite high for all three pollutants, but only in the *middle* range of the air/fuel ratio. Therefore, the chemical industry assumed that they could only solve the problem if they could delete all three kinds of pollutants all at once. But the auto industry *articulated* the needs for emission control by interpreting this diagram in a different way. Why not just control the engine operation so that the air/fuel ratio always remains in this narrow range? The auto industry thought that they could achieve this control by the use of electronics, *i.e.* the conversion efficiency could be kept high for all different pollutants if the air/fuel ratio could be kept in a certain range. This competition, which is inter-industry, not inter-company in the industrial sector, created a new industry called the *catalyst* industry. In fact, the catalyst manufacturers association was established in 1969 by leaving chemical companies out of the membership and now includes 60 companies among its members.

3.4 Inter-industry collaboration

During the 1980s, the environmental concern grew from local issues (*i.e.* nitrogen oxide emissions and human health) to global issues (*i.e.* fossil fuel use and climate change). The hole in the ozone layer over the South Pole was confirmed. Unusually hot and lengthy summers in North America and unexpected floods and drought around the world warned the global society of climate change. These various global warming-related incidents around the world, combined with the scientific investigation of the Intergovernmental Panel on Climate Change (IPCC), culminated in the Kyoto Convention in 1997, which specifically asked for reductions of carbon dioxide (CO_2) emissions from industrial activities to 5% below the 1990 level.

In order to cope with the enlarged social demand for global climate protection, the automotive industry has been seeking a new *path* for automobile technology developments including hybrid, electric, and fuel cell vehicles. Toyota was the first to develop and market a gasoline engine–electric motor hybrid vehicle, the *Prius*. The hybrid system of the Prius employs a combination of a gasoline engine and an electric motor depending on the driving conditions. Under a light load, only the motor drives the vehicle to save energy and reduce emissions. When the vehicle is under a heavy load, the gasoline engine is started to power the vehicle and charge the battery for the motor. The hybrid system offers substantial improvements both in fuel efficiency and in reductions in CO_2 emissions. Carbon monoxide (CO) and nitrogen oxide (NO_x) emissions are also drastically reduced to one-tenth of their previous levels. Over a 3-year period after its introduction, the Prius had achieved remarkable worldwide sales of over 50,000 by the end of the year 2000.

It should be noted that the success of the hybrid system was possible because the management of Toyota clearly *articulated* the two design goals—*double* fuel efficiency and *extra* low emissions—from the beginning. Toyota was then able to create an automobile system by integrating component technologies for the engine, motor, inverter, battery and brakes. In order to overcome this integration problem, it was necessary for Toyota to absorb a technology from outside the company as well as to develop a new technology by themselves. In order to complete the development of Hybrid engine, Toyota had to outsource the electric battery technology. We will therefore describe how Toyota outsourced the battery and gradually digested its technology. This is about the dynamics of open innovation on hybrid car development

Toyota's recognition that they were lacking in experience in the electric battery led to their cooperation with Panasonic, resulting in their outsourcing the development of the battery to Panasonic. Thus, the first Prius, introduced in December of 1997, had a battery installed that was manufactured totally by Panasonic. The dynamics of *collaboration* can be made explicit by investigating the joint patent application statistics. The joint patent application began in late 1997, and five joint patents were applied for before the sales of the first Prius. The joint application was implemented through the jointly established company, Panasonic EV

Energy (PEV) Co. The number of joint applications increased drastically and peaked in around 2000. During this period, a joint effort was made to develop a lighter and smaller battery, which brought minor changes in the 2000 model.

In September of 2003, the brand new Prius model was introduced, in which the volume of the battery was reduced by half and the weight to forty percent of the first model. Thereafter, the number of joint applications drastically reduced and Toyota became the largest stock holder of PEV Co. The number of patent application with the IPC patent code H01M is plotted in **Figure 2-3**, in which the number of single applications and those of joint applications are depicted separately.

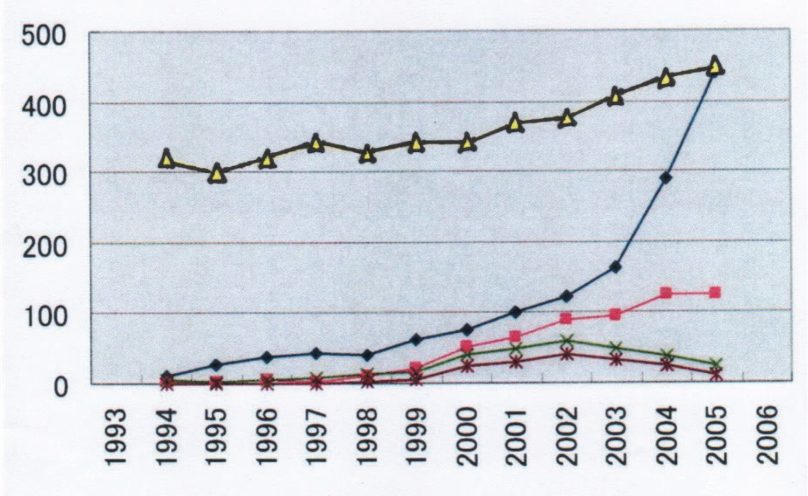

Figure 2-3. Battery patent applications by Toyota and Panasonic[20]

As can be seen in the figure, the number of Panasonic patents (△) far outnumbers that of Toyota (♦), and the majority of joint applications had Panasonic as the principal applicant. This reflects that the technical leadership was executed by Panasonic. After the joint development was finished, however, the number of Toyota's patent applications persistently increased and became the same as Panasonic. This indicates that Toyota had successfully acquired the knowledge of battery manufacturing through their participation on the joint development with Panasonic. In other words, Toyota had succeeded in *internalizing* and transferring the battery technology in order for this technology to fit the specific needs of automobiles better.

4. Dynamics of problem articulation

As is well known, the environmental regulations have *shifted* from local to global problems such as the rise in global temperature caused by global carbonation. The regulations for global problems were mainly implemented in the form of international agreements: the Vienna Convention for the Protection of the Ozone Layer in 1985, the Montreal Protocol on Substances that Deplete the Ozone Layer in 1985, the Intergovernmental Panel on Climate Change（IPCC）in 1988, and the United Nations Framework Convention on Climate Change in 1992.

In the inter-industry *competition* of developing the three way catalyst technology, as described above, the automobile industry could commercialize this technology by highly utilizing its own competencies. In order to reduce CO_2 emissions in terms of enhancing the fuel efficiency, on the other hand, the hybrid engine system was developed by the use of the electric battery provided by an electric company. Only after their outsourcing to Panasonic could Toyota *articulate* the need for a battery for a hybrid engine. Indeed, Toyota reduced the volume of the battery by half, and the weight to forty percent of the original model, through their efforts to absorb battery technology from Panasonic. In other words, inter-industry *collaboration* was necessary to solve the problems of the global environment, and it is obvious that a further widening of industrial participation will be an absolute necessity, as the problem is ever shifting in its nature.

In this context, we are interested in visualizing the shift in the problem solving pattern from inter-industry competition to collaboration. In other words, the widening scope of problem articulation for environmental protection should be measured[21]. Put another way, the search space of critical industrial competency should be widened across industrial boundaries. The unusually rich Japanese R&D statistics, available for every year since 1970, indeed, provide us with industry's intramural expenditures for a specific objective: environmental protection. Furthermore, industry's intramural expenditure is disaggregated into *22* manufacturing sectors. By highly utilizing this unique data base, therefore, we can visualize the *dynamics* of problem articulation for environmental protection. For our study on environmental protection, those 22 industrial sectors are aggregated into the ten industrial sectors that are shown in **Table 2-3**, with each sector's R&D expenditure and its share of the total expenditure of all Japanese industry depicted.

Table 2-4. Industrial R&D expenditure for environmental protection (as of 1995)

Industrial Classification	R&D Expenditure (¥billion)	Percentage (%)
Pulp & paper	34.3	5.30
Chemicals	78.3	12.10
Petroleum	29.4	4.50
Steel	71.5	11.00
General machinery	5.8	0.90
Electrical machinery	22.2	3.45
Transport machinery	18.4	2.80
Precision machinery	1.8	0.30
Other manufacturing	102.7	15.80
Non-manufacturing	283.7	43.70
Total	648.6	100.00

By estimating the degree of *uncertainty* in *identifying* which industrial sector has the capacity to solve the on-going problem of environmental protection at each specific time, we will try to visualize the dynamics of industry's participation on the problem-solving of environmental protection, and thus draw the *trajectory* of problem articulation in environmental protection. In order to measure the uncertainty, we can employ the concept of "entropy" developed in the field of information sciences. On the basis of this assumption, we can construct a measurement scheme for problem articulation[22].

The time-series entropy values from 1972 to 1997 are drawn in **Figure 2-4**. As can be seen in the figure, clear-cut trends in the early years are apparent. The entropy value of environmental protection continued to decrease until 1987. In other words, the problem articulation for local pollution exhibits a tendency of decreasing entropy. We can interpret from this trend that the uncertainty is being reduced, *i.e.* in terms of which industry could solve the on-going environmental problems. This decreasing entropy is due to the fact that the problems for *local* emissions were articulated and solved mainly by the automobile industry. Thus, the R&D efforts for environmental protection had come to be concentrated in the automobile industry. We can therefore infer that the decreasing entropy indicates that the problem articulation for local environmental protection had also converged in the automobile industry.

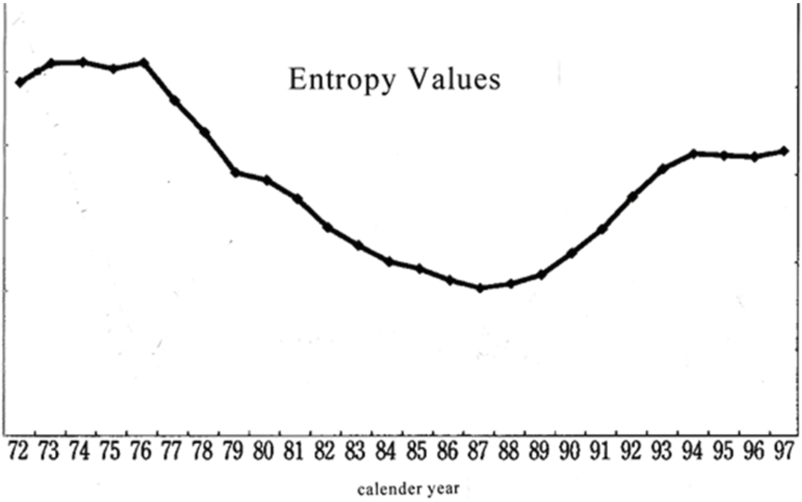

Figure 2-4. Entropy dynamics of problem articulation for environmental protection

However, as described above, the environmental problems have shifted from local to global problems such as the rise in global temperature caused by global carbonation. As seen clearly in the figure, indeed, the continually decreasing curve *bent* sharply upward in 1988, and continued to rise constantly thereafter. The problem articulation in environmental protection went back in 1988 to an *uncertain* pattern again, and its entropy continuously rose up and remained high thereafter. All these trends indicate the need for a wider inter-industry collaboration. As described above, in order to reduce CO_2 emissions, a typical issue in global environmental problems, the hybrid engine system was developed by the inter-industry collaboration between Toyota and Panasonic. In other words, inter-industry *collaboration* was necessary to solve the problems of the global environment, and it is obvious that a further widening of industrial participation will be an absolute necessity, as the problem is ever shifting in its nature.

In the future, we will have to widen the range of industrial technologies across industrial boundaries further, to articulate the intrinsic problem of global environmental protection. It will take several decades for us to articulate a true problem and to emerge with a reasonable solution both in terms of technology and social structure building. We can also generalize this kind of argument beyond environmental problems**.** Even if we limit the scope of argument within the automobile industry to the current argument about “self-driving vehicles,” it is obvious that the IT industry is going to be a major player in the problem-solving game. Indeed, the current argument is about which industry, auto or IT, will solve the intrinsic problems concerning self-driving vehicles, or if a new industry for a new mode of personal mobility should be established.

Conclusion

In the public policy arena, we have demonstrated the effectiveness of demand articulation by illustrating how it was implemented in organizing a research consortium and in responding to changes in environmental regulation.

In the case of the VLSI research association, the demand for manufacturing equipment was articulated by getting all the Japanese chip manufacturers together in this research consortium. This arrangement helped in exploring the entire spectrum of possible candidates for equipment technologies. In the case of the SEMATECH consortium in the United States, the joint articulation for steppers helped to improve the relations between chipmakers and their suppliers. American chipmakers again captured the largest percentage of the global semiconductor market, and US semiconductor equipment companies once again held fifty percent of the global market.

In the Japanese car makers' response to the environmental regulatory changes, the articulated demand for environmental problems led to different patterns of problem-solving at different stages: at the early stage of local pollution, the problems were articulated and solved by inter-firm competition, while the later stages of local pollution were articulated by inter-industry competition. When the environmental problem shifted to global pollution, the problem articulation and its solution were conducted in the form of inter-industry collaboration. These findings indicate that problem articulation will be conducted by global alliances in the future.

Notes

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[1] Edquist, C. (2019). Towards a holistic innovation policy: Can the Swedish National Innovation Council (NIC) be a role model? *Research Policy*, *48*(4), 869-879.

[2] Freeman, C. (1987). *Technology Policy and Economic Performance*. London: Pinter Publishers; Nelson, R., ed. (1993). *National Innovation Systems: A Comparative Analysis*. New York: Oxford University Press; Lundvall, B., ed. (1992). *National Innovation Systems: Towards a Theory of Innovation and Interactive Learning*. London: Pinter Publishers.

[3] Although the US government was the primary customer for the semiconductor industry in the early stage of IC technology, its influence on the market decreased significantly in the years that followed. In 1963, the share of the federal government was 35.5 percent, in 1970, 20.6 percent, in 1972, 11.9 percent, and in 1973, 5.8 percent.

[4] This assertion is based on the author’s interview (in 1986) with Dr. Yoshiyuki Takeishi of Toshiba Corporation, who led this association on behalf of the industry. He was a vice director in technology of the association.

[5] Sigurdson, J. (1986). *Industry and State Partnership in Japan: The Very Large Scale Integrated Circuits Project* (Research Policy Institute, discussion paper no. 168). Lund: University of Lund, 86–93.

[6] Rosenberg, N. (1994). *Uncertainty and Technological Change*. Paper presented at Growth and Development: The Economics of the 21st Century. Center for Economic Policy Research, Stanford University, June 3–4.

[7] Yoshida, S. (2007). *My Autobiography*. Tokyo: Nikkei Shimbun [Japan Economic Newspaper].

[8] Randazzese, L. (1996). Semiconductor Subsidies. *Scientific American, 274*(6), 46–49.

[9] In the late 1970s, the GCA had invented the step-and-repeat (or stepper) technology that soon became the workhorse of the semiconductor manufacturing industry.

[10] As part of its exit from the semiconductor manufacturing equipment industry, General Signal put the GCA up for sale in January 1993 and, unable to find a buyer, shut it down by the summer of that year.

[11] These include an extended recession in Japan, the rising value of the yen, trade agreements in which Japan conceded that imports should account for 20 percent of its domestic semiconductor market, competition from low-cost Korean makers of memory chips, and the continued dominance of US semiconductor companies in the microprocessor market (Randazzese, 1996).

[12] Randazzese, L. (1996). Semiconductor Subsidies.

[13] Takahashi, T. (2006). *The History of Lithography* [in Japanese]. Tokyo: National Science Museum.

[14] From Kobayashi, M. (1987). *A Mathematical Model of Collective Research* [in Japanese]. Master's thesis, Saitama University.

[15] Analytical modeling of these two contrasting phenomena concerning

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participation in collective research has been conducted by Kodama (1995). However, we will not look at this in detail in this book.

[16] Kodama, F. (1995). *Emerging Patterns of Innovation*. Boston: Harvard Business School Press, 150.

[17] Lee, G., Gemba, K., and Kodama, F. (2006). Analyzing the innovation process for environmental performance improvement. *Technological Forecasting & Social Change, 73*, 290-301.

[18] The author's personal interview with Mr. Honda.

[19] The 2002 Honda Prize was awarded to Dr. Barry John Cooper, who developed the systems for the reduction of harmful hydrocarbons for the gasoline engine by using three-way catalysts and CRT systems to remove carcinogenic carbon particles from a diesel engine.

[20] From Hayashi, M. (2008), MS dissertation, Shibaura Institute of Technology.

[21] Kodama, F. (1990). Technological Entropy Dynamics: Towards a Taxonomy of National R&D Efforts. In J. Sigurdson, ed., *Measuring the Dynamics of Technological Change* (pp. 146-67). London: Pinter Publishers.

[22] Let E_i be i-th industry's R&D expenses on environmental protection.

Let p_i be the share of i-th industry, where $p_i = E_i / \Sigma_j E_j$.

Then, p_i is supposed to be the probability distribution over the possible industrial options to the environmental R&D. Let H be the entropy, then, it can be calculated by the following formula:

$H = -\Sigma_i p_i \cdot \log_2 p_i$.

CHAPTER THREE

CORE COMPETENCY ARTICULATION: TOWARDS BUSINESS MODEL CREATION

When it comes to those Japanese *camera* companies such as Canon, Nikon, and Olympus, they successfully diversified their business from their original camera-making. Although their diversification trajectories differ substantially from each other, all of them skillfully utilized their own technologies in optics for managing different trajectories of diversification: Nikon extended its technology successfully into lithography, *i.e.* "steppers" in IC manufacturing; Canon skillfully navigated its technologies into "copying" machines, and thereafter into the "printer" businesses; and Olympus became the largest supplier of gastro-intestinal "endoscopes" in medical equipment, and it retains almost a 70% share of the global market[1].

Therefore, what kinds of strategies were used for these diversifications? Or, did any strategic thinking exist at all behind these successful Japanese diversifications? Their strategic characteristics become clear in the notion of core competency[2], which is defined as "collective learning in the organization." Prahalad and Hamel argued that recent studies have focused on core competencies as key elements to a firm's success in dynamically changing businesses. And Christensen [3] introduced the concept of "disruptive" innovation as contrasted to "sustaining" innovation, and the expression of "nonconsumption" to refer to the situation where a job needs to get done but a good solution has historically been out of reach[4].

Using these new two notions, the importance of *demand articulation* in technology and the market development of commercial products is illuminated by investigating the half-century long history of Liquid Cristal Display (LCD) technology. We will also analyze the rationale behind Canon's bold decision to enter into copiers and printers.

It is widely held that a "new economy" is emerging, one in which conventional wisdom about the innovation process will become obsolete. Since "new economy" can be easily translated as "digital economy," we have to think about what is new about the "digital economy." In this context, the author of this book has been quoted as saying: "In the analogue world, things cannot be easily combined. However, with digitalization, all sorts of combinations are possible and we can end up with something greater than the *sum* of the merger" (*Newsweek*, June 21, 1999). In the age of the digital economy, therefore, we can argue that the emergence of a new *business model* can be a source of discontinuity and disruption as well as of technical breakthroughs and innovations [5]. It also goes in parallel with the sophistication of information technologies. In other words, we have come to technological and business environments in which the "demand articulation" is better framed in a more *proactive* manner.

1. Market, Product, and Process: LCD development

Although Europeans discovered the liquid crystal phenomenon more than a century ago, the basic idea of using them in display devices came about only when RCA (Radio Cooperation of America) invented the dynamic scattering mode (DSM) in 1967. Thereafter, RCA demonstrated various prototype products[6]. All the products, however, were *premature* given the then-available technologies, and RCA gave up on their commercialization efforts. At the time RCA was trying to commercialize liquid crystals, the standard technology for display devices was the *cathode-ray tube* (CRT). A flat panel display was nothing more than a *dream*, and other technological alternatives to liquid crystals existed, including electroluminescence and plasma display. Manufacturers agonized over which to use. Since RCA had developed liquid crystal technology as a display method for *general* purposes, it chose to stick with CRT technology, as did most manufacturers of CRT screens.

1.1 Co-development of market and product

Sharp Corporation followed a *demand approach* when it translated the customer's *desire* for a more powerful and sleek electronic *calculator* into a set of specific R&D projects for a thinner, lower powered, easy-to-read display. These R&D projects included research in LCDs and in low-powered complementary metal oxide semiconductors (CMOS). Sharp was quick to identify the liquid crystal display as a *promising* technology, and the fact that the technology was still considered *exotic* was not a deterrent. Instead, Sharp saw LCDs as a way to solve *specific* technical problems and change the rules of competition in the marketplace.

Generally speaking, demand articulation flourishes when an industry is very competitive and technically sophisticated. Brisk competition, almost to the point of excess, motivates companies to keep their attention on the customer. And the more technically competent the industry is as a whole, the higher the *absorption* rate of technologies from other industries. In the case of Sharp, indeed, the competition included the likes of Hewlett-Packard and Texas Instruments, both pioneers in electronics. Such a competitive environment spurred Sharp on to *experiment* with alternatives that it probably would *not* have explored had the competition been less intense.

After Sharp introduced an electronic calculator into the market in 1964, the market for electronic calculators flourished and many companies entered this growing market[7]. Around 1971, however, when Texas Instruments started supplying the standard chips for calculators in the open market, many small-sized manufacturers that had assembling capacities but no design abilities suddenly appeared in the Japanese market. This market entrance reduced the market price of calculators suddenly and drastically. Existing larger manufacturers of calculators were involved in the price-cutting competition, and some of them left the market. Sony and Uchida left in 1973, Bisicon and Sigma Electronics did in 1974, and so did Ricoh in 1975. Even the market share of Sharp decreased dramatically.

It was in this context that *LCD* was introduced into electronic calculators for the first time, namely in the circumstances of such a price-cutting competition. Responding to that situation, Sharp introduced LCD-based calculators in 1973 in order to bring a *functional* differentiation, while other remaining competitors continued to introduce *cheaper* products. By making the product much thinner and reducing the cost by mass production, Sharp succeeded in differentiating their products from those made by small-sized manufacturers. This change in Sharp's strategies can best be demonstrated by the rapid decrease in thickness from 1973 to 1983, as shown in **Figure 3-1**. As shown in the figure, the thickness of the 1976

Sharp product was more than 2 cm; four years later in 1979, however, it became less than 1.6 mm. As a newcomer, Casio reduced the thickness of their product to 0.8 mm in 1983 from 1.5 cm in 1976. They named their products "pocket calculators."[8]

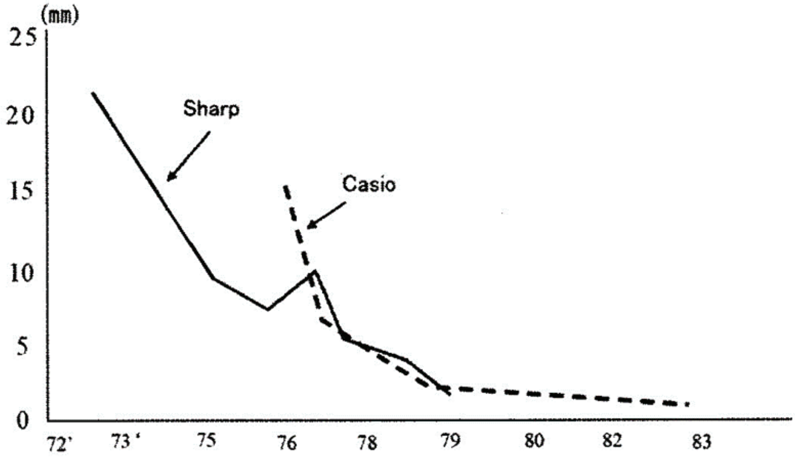

Figure 3-1. Changes in thickness of calculators (1973-1983)
Note: This graph was drawn by the author, based on numerical data provided by Numagami (1999).

Under this severe cost-cutting competition, Sharp chose to adopt a radical innovation in spite of this letting their products become more highly priced. As a result of these decisions, Sharp could overcome its difficulties and keep a stable market position. We can summarize that Sharp was successful in *articulating* the demand for *pocket* calculators by developing and bringing the LCD technology into the market with the right timing. In adopting LCDs in its calculators, Sharp not only achieved effective demand articulation for the technology, but subsequently became the technology and market leader in LCDs. During the 1970s and 1980s, Sharp and other Japanese companies made a number of improvements in LCDs, and they are now a widely used, high value added component of portable electronic products such as laptop computers. Indeed, Sharp gradually expanded its application of LCD technologies as various innovations followed, bringing larger screens, greater precision, quicker responses, color displays, and greater *legibility*. Moreover, Sharp quite successfully *navigated* the development, including a shift from the *duty* drive to the *active matrix* drive, as indicated in Sharp's development and marketing history (**Figure 3-2**).

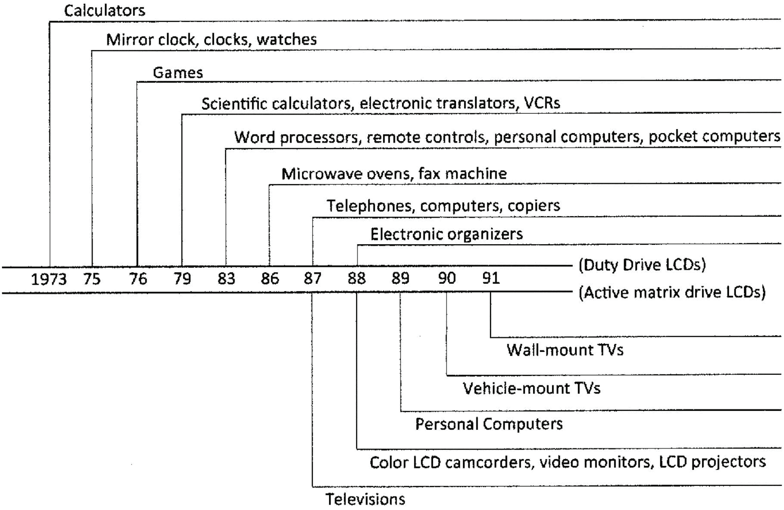

Figure 3-2. Development and marketing history of Sharp LCD products (1973～1991)
Source: Sharp Technical Report Vol. 1, 1991, pp. 66-67.

1.2 Simultaneity between product and process innovation

One of the most conspicuous elements of high-tech development has been the “co-development” of product and process technologies [9]. The development of a product is conducted *concurrently* with the development of its production technology. Without opportunities to accumulate production experience, high-tech development is not possible.

Having navigated the process skillfully, Sharp Corporation became one of the world’s largest leading consumer-product manufacturers, holding a major position in the markets for TV sets, calculators, solar cells, and thin-film transistor LCD flat panel displays. From the standpoint of the company’s history, the use of LCD for flat panel displays for *television* sets might have been the *final* target in terms of the upgrading process of utilizing the LCD, as is clearly indicated in the figure depicted above. Indeed, Sharp had been leading the process of applying LCD into flat panel television sets, and had been quite successful in the early stages of this application. However, Korea and Taiwan then entered into the LCD business around 2000. After that, global leadership of LCD manufacturing shifted from Japan to Korea and Taiwan, as shown in **Figure 3-3**.

Nevertheless, Sharp continued to invest in LCD and established the *Kameyama* plant in 2004 for a vertical integration of LCD panels and LCD televisions. There existed several cases of co-developments among equipment-vendors and material-suppliers in the LCD production lines at the Kameyama plant. To understand how Sharp navigated the process of *simultaneous* development between product and process technologies, Nakata[10] drew *two types* of experience curves: one is related to the product and the other to the *process*.

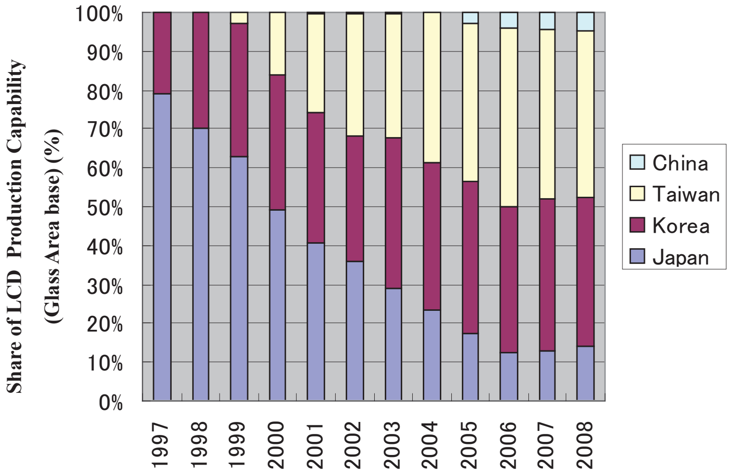

Figure 3-3. Share of LCD Production Capability

The experience curve of the product is based on the fact that the LCD panel size itself matters because it can display large images. If the *glass substrate* is enlarged, larger LCD panels can be obtained; this would strengthen the product's competitiveness in the market. Therefore, LCD manufacturers competed with each other and used larger glass substrates to make larger LCD panels. **Figure 3-4** shows the *experience curve* for the product, showing how rapidly the glass substrate size (measured by m^2) expanded as the experience of LCD production accumulated (measured by the total area of *accumulated* production: m^2 base). The production of Sharp's LCD took place through coordination between LCD manufacturers, equipment-vendors, and material-vendors worldwide. Therefore, the *global* accumulated volume of LCD production was plotted in the X-coordinate.

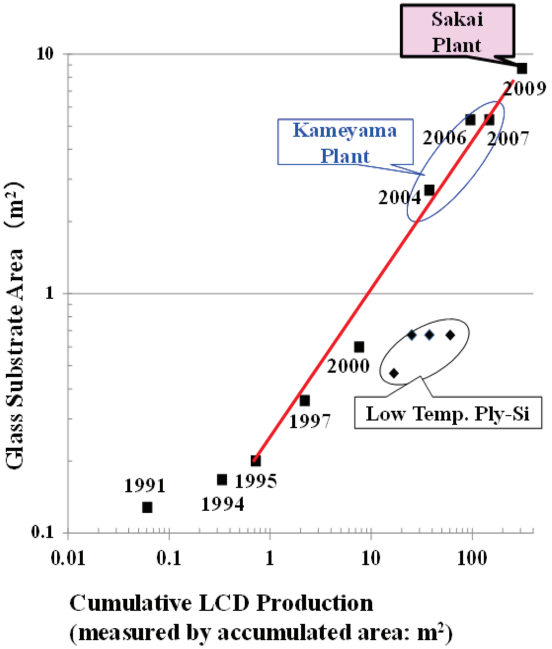

Figure 3-4. Experience Curve of Glass Substrate Size

Source: Nagata (2005), estimated from Nikkei Micro-devices (2007) and Sharp news release.

As is shown clearly in the figure, the glass substrate area rapidly increased. The glass substrate area *doubled* approximately every 2.5 years, while the accumulated LCD production *quadrupled*. At Sharp Corporation's Kameyama plant, the 6th generation LCD production line has been installed since January 2004, and the 8th generation LCD line since August 2006.

At the *Sakai* plant, the 10th generation LCD (world's largest size) production line has been in operation since October 2009. As observed from the product experience curve depicted in the figure above, the decision to invest in the 10th generation product appears to have been appropriately timed. At the time the Sakai plant went into operation, however, Sharp might not have successfully navigated the *simultaneous co-development* of product and process technologies. In order to analyze the progress of matching between product and process technologies, the investment cost per glass substrate area for each production line at each Sharp plant has been calculated, and is shown in **Figure 3-5**.

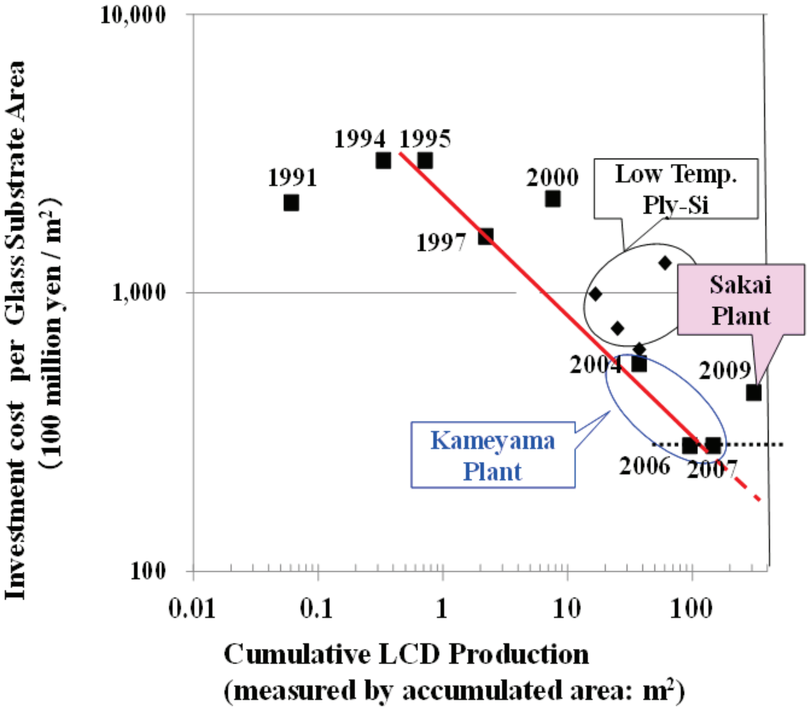

Figure 3-5. Experience curve for the investment cost per glass substrate area

Source: Nakata (2005)

As shown in the figure, the investment cost per glass substrate area was drastically reduced to one-tenth of its initial size in 12 years from 1995 to 2007, while the global accumulated LCD production increased by more than 100 times. In the case of the Sakai plant, however, the investment cost per glass substrate area did not decrease. Instead, it actually *increased* to double that of the Kameyama plant. This indicates that over-investment could have occurred at the Sakai plant, *i.e*. large investment *without* process innovation. This means that Sharp was not successful in navigating the simultaneous development of product and process technologies.

2. Strategic articulation for diversification

Michael Porter [11] argues operational effectiveness is not *strategy*. Competitive strategy is about being *different*. The essence of strategy is choosing to perform activities differently than rivals do. It means deliberately choosing a different set of activities to deliver a unique mix of values. As to Canon's bold decision to enter into the copiers market and adopt a PPC (plain paper copier) instead of photosensitive coated paper, this was described by Dr. Keizo Yamaji, who later became the CEO of Canon, as follows:

> What made up my mind was a report, published in the 1960's by the Arthur D. Little Corporation, a research company in the United States. It was a forecast of the copier market and predicted there would be no real rivals to Xerox in the 1960's and 1970's. Reading this, I had the feeling there were no limits in the world of technology and that there must certainly be *other* approaches.[12]

Then, he speculated that if an authoritative research company like this was making such a prediction, then other companies would not attempt to enter the PPC market. If we could break the first wall with new technology, we could take an oligopolistic position in the market with Xerox. He felt this was a challenge worth taking on. Indeed, this machine was quite successful as a *desktop* copier.

Christensen[13] described the saga of "good-companies-hitting-hard-times": well-managed companies that have their competitive antennae up, listen astutely to their customers, invest aggressively in new technologies, and *yet* still lose market dominance. Yamaji's approach is obviously that of disruptive innovation, in spite of Canon's established position as a camera maker. In a similar way, Nikon was established in 1917 and kept a leading position in a high end camera market. And Olympus has been an optics technology-based company since 1919. Olympus's development of the endoscope was a result of a disruption of the prevailing trajectory of X-ray photographing, including CT scanners. Christensen's arguments[14], therefore, could not explain why these established Japanese camera companies accomplished disruptive innovations. Indeed, these disruptive innovations were "sustaining" innovations as far as the diversification of these established Japanese camera manufacturers is concerned.

2.1 Direction of diversification articulated

Based on the characterization of Japanese camera companies described above, neither strategic positionings nor disruptive innovations are effective in analyzing their successful diversification. Therefore, we are going to make an in-depth analysis on what types of demand *articulation* were made when Canon skillfully navigated its core competences of optical technologies. Indeed, their direction of diversification had been well *articulated* when they made their decisions to extend their core competences of camera manufacturing into such product lines as copiers and printers. In the early 1960s, Canon was in a situation whereby it would come to a standstill if it stuck only to the camera and lens businesses. Hamel and Prahalad argue that protecting core competencies from erosion takes continued awareness on the part of top management. They explain that there is no way to protect a firm's core competencies from erosion if the health of those competencies is not visible to top management.

According to Dr. K. Yamaji[15], they needed to diversify into other fields. They first tried the auto-focus (AP) camera, but failed to create a market version, because the peripheral technology was not ready at that point. Then, the theme which became the main priority after surviving the recession of the 1960s was the *copying* machine. In launching the new project, Dr. Yamaji used the following logical reasoning:

> Copiers have a mechanism which is something like a large camera, containing a development system *inside*.

Therefore, they thought it was a new field that seemed comparatively easy to enter for a camera maker. The first PPC based on the new method that was different from that of the Xerox Corporation was the NP1100, which was completed in 1970. They provided the photoreceptor *drum* and *developer* which had to be replaced at regular intervals free of charge, in addition to paper and repair parts[16]. The response to the new product was good. The NP-L7, their first *desktop* copier, was completed in 1972. In 1979 they completed the NP-200J, offering superior images and higher speeds in a full *desktop* model.

Together with copiers, *printers* have come to form a pillar of Canon's non-camera operations. The explanation used for launching the printer business was:

> The printers and copiers are closely related in terms of operating principles, with copiers copying from *documents* and printers from *memory*. They are the same in that they both reproduce information on paper.

When the laser beam printer was exhibited at the NCC (National Computer Conference) in 1975 in the United States, it proved to be a sensation. This Canon product became the first laser beam printer to be demonstrated to the public. Meanwhile, Hitachi brought Canon their semiconductor laser that had been developed for optical communications. Canon immediately decided to apply the technology to their laser beam printers. After much effort from both sides, Canon finally completed the LBP-10 in 1979. When the LBP-CX, the first compact *laser beam* printer, was completed in 1983, Yamaji personally carried the new printer around the United States to demonstrate it and talk business. Apple was fastest in showing interest in the project. Steve Jobs attended a demonstration and decided to use it on the *spot*, saying it was just the kind of printer he had been looking for. Hewlett-Packard was also quick to come to an agreement. They left the development and production of laser beam printers in Canon's hands and concentrated on software and sales.

On the basis of the Japanese companies' experiences of diversification, illustrated vividly by the case study of Canon, we have to find an appropriate phrasing beyond strategic positionings and disruptive innovations. This can be called "strategic articulation." It is defined as a kind of demand articulation which leads the company in the right direction towards diversification into an emerging business area, and which sometimes implies a successful *metamorphosis* of the company as a whole. As to the disruptiveness, the above-described innovations which these Japanese camera makers had to confront are definitely disruptive innovations. The copier/printer innovations of Canon, the stepper innovations of Nikon, and the endoscope innovations of Olympus are all disruptive innovations. In strategic articulation, they can do it by strategically choosing the path of disruptive innovation instead of sustaining innovation. But they did it by highly utilizing and advancing their core competences they owned before.

All of these innovations, however, were accomplished by those companies that had stayed at the top of the camera industry. In this sense, these innovations turned out to be "sustaining" innovations for the companies who skillfully diversified and extended their originally owned technologies into a growing area of high-tech products. This is because these camera makers saw an opportunity for growth and to extend their core competences quite naturally, consistently, and *persistently*. In this context, these Japanese camera makers can best be described as "persistent innovators," instead of "occasional innovators," by following the dichotomy presented by Malerba[17]. Their innovations are not based on conventional "creative destruction," but on "creative accumulation." In short, "persistency" is the most valuable asset in surviving in radically changing technology and market environments.

2.2 Managing core competencies: Canon's diversification

Canon's business structure history (non-consolidated net sales) and its diversity (represented by entropy)[18] are illustrated in **Figure 3-6**. Canon's business diversity has had a persistent tendency to increase, which it has done continuously for 35 years with steep rises in the late 1960s and the early 1980s. The former steep rise corresponds to the growth in sales of electronic calculators, and the latter corresponds to sales of printers, word processors and facsimiles. The rise in sales of copiers compensated for diminishing sales of electronic calculators.

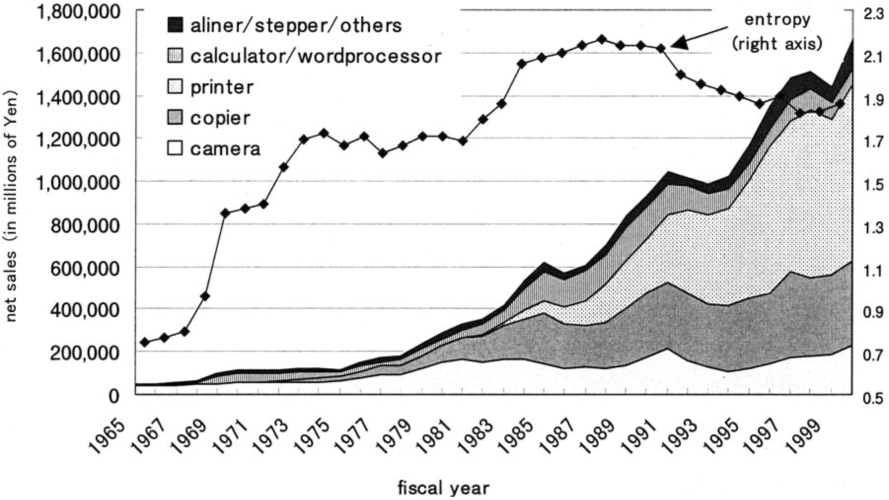

Figure 3-6. Canon's history of business structure and its diversity represented by entropy

Source: Suzuki and Kodama (2004).

Our investigation of Canon's technological history combined with its business history reveals that the firm has developed *four* major technology *cores* continuously, and each of these is closely related to the respective business domain. Their "camera technology" core has accumulated and evolved due to the persistent development of cameras and optical instruments. Their "digital processing technology" core, which originated from development of the Synchroreader, has evolved into electronic calculators, word processors, personal computers, and so on. The "electrophotographic technology" core has been extended to copiers and printers, and this was the largest business domain of Canon as of 2000. The "semiconductor manufacturing technology" core has evolved with photolithography.

The patent application count is taken as a proxy for the accumulation of knowledge in each technology core, thus showing technological trajectory. **Figure 3-7** illustrates Canon's technological accumulation and diversity represented by patent application counts and entropy. It is apparent that the progression of technology diversity went in parallel with that of business diversity.

In order to make it explicit that Canon's diversification was conducted based on the dynamics of extending their competency, we adopted the *bibliometric* approach of patent analysis.[19] In concordance with each business domain, the technological domain was identified and codified using the International Patent Classification (IPC) version 5. Data on patent applications from 1965 to 1999 came from the Patent On-line Information System (PATOLIS) database based on the official bulletin of the Japanese Patent Office (JPO). We also used the JPO's specific "facet code" for classification. A facet code is applied to some (not all) patents in addition to the IPC code. It offers a more detailed description or a categorization that is different from what the IPC code offers.

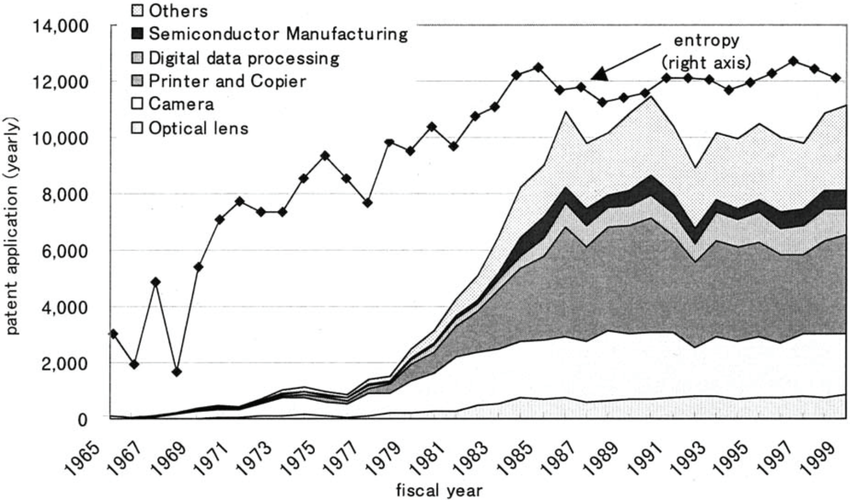

Figure 3-7. Canon's technological accumulation and diversity

Note: In patent statistics, "printer" is not differentiated from "copier".
Source: Suzuki and Kodama (2004).

In order to identify a firm's technological domains, frequently observed IPC codes and facet codes in the firm's patent records were identified and sorted in rank order. Top ranking IPC codes and facet codes were classified into technology fields representing the respective firm's major business domains such as "camera technology" and "copier technology", etc. Patent applications in each field indicate an accumulation of knowledge and advancement of technological trajectory. Japanese patent application records have single or multiple IPC codes. The IPC code placed at the primary position, namely the “primary IPC”, has a special meaning. The primary IPC represents the core technology to which the invention pertains. Any additional IPC code which may exist represents the specific application field or a closely related technology field pertinent to the invention. When multiple IPC codes exist in a single patent and those codes belong to different technology fields, we call this a case of “IPC co-occurrence”. The relationships among “primary IPC”, “additional IPC” and “IPC co-occurrence” are depicted schematically in **Figure 3-8**.

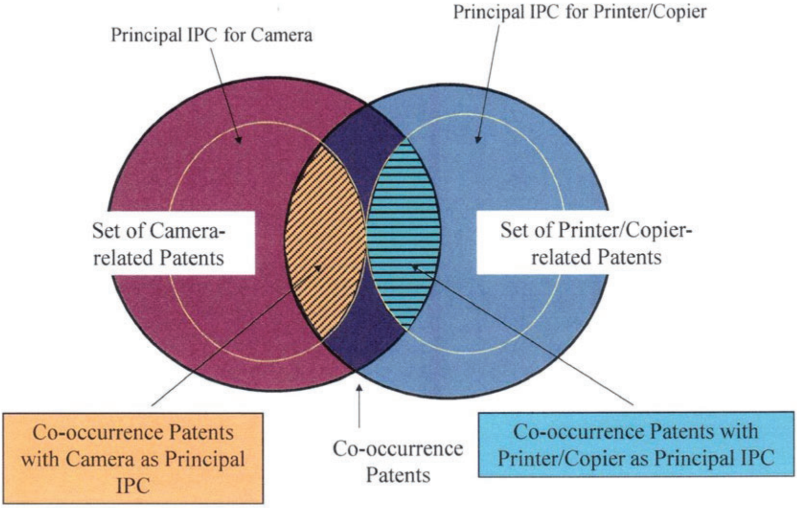

Figure 3-8. Co-occurrence of Camera and Printer/Copier Patents

In this chapter, we will show here that the application of the “primary IPC” and “IPC co-occurrence” approach in an analysis of a firm’s patent application history gives us a useful tool for a better understanding of the linkages between technological trajectories and their dynamics. Specifically, the quantitative “IPC co-occurrence” and “primary IPC” analyses were applied to shed light on the relationships between Canon’s technological trajectories.

In 1965, Canon applied for a total of 126 patents. Among those, according to their respective primary IPC codes, were 91 for camera technologies, 14 for copier technologies, 7 for optical equipment technologies, 4 for semiconductor manufacturing technologies, 3 for digital data processing technologies, and 7 for other technologies. **Figure 3-9** illustrates detailed data on IPC co-occurrence in the period from 1965 to 1979 between the fields of “camera” and “copier and printer technology”.

The camera patent applications count is graphed in the left column, and the patent applications count for “copier and printer technology” is graphed in the right hand column. In the left side of the middle column, the number of co-occurrence patents in which the camera is placed as the primary IPC is graphed, and on the right side, the count of the co-occurrence patents in which copier and printer technology is placed as the primary IPC is graphed. The middle column demonstrates that the persistent IPC co-occurrence implies interaction between these fields. As can be seen in this figure, IPC co-occurrence with primary IPC in “camera technology” was dominant until 1977, but those with primary IPC for “copier and printer technology” overtook them in 1978.

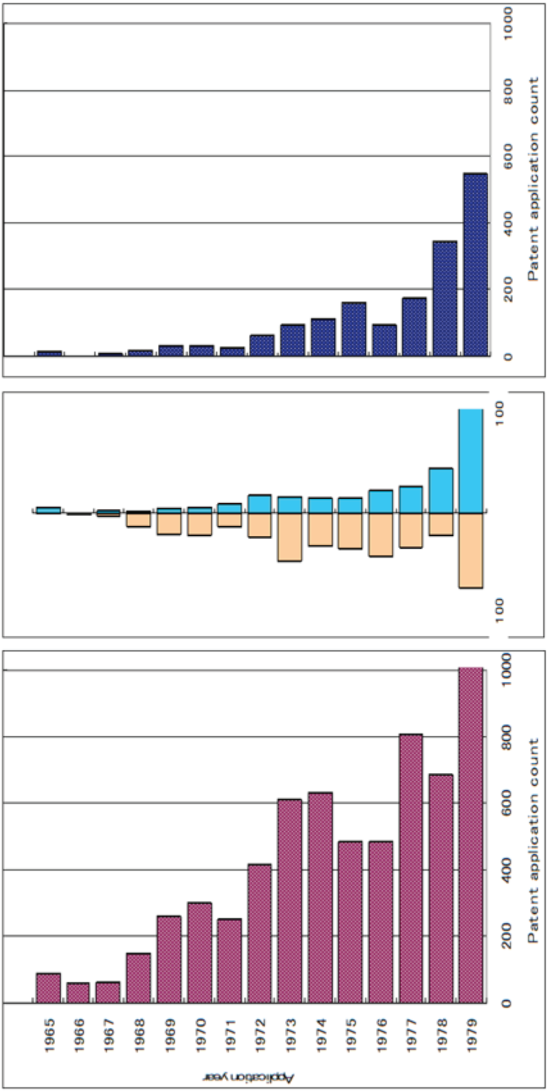

Figure 3-9. Canon's patent applications for cameras (left) and copiers and printers (right) (1966-1979)

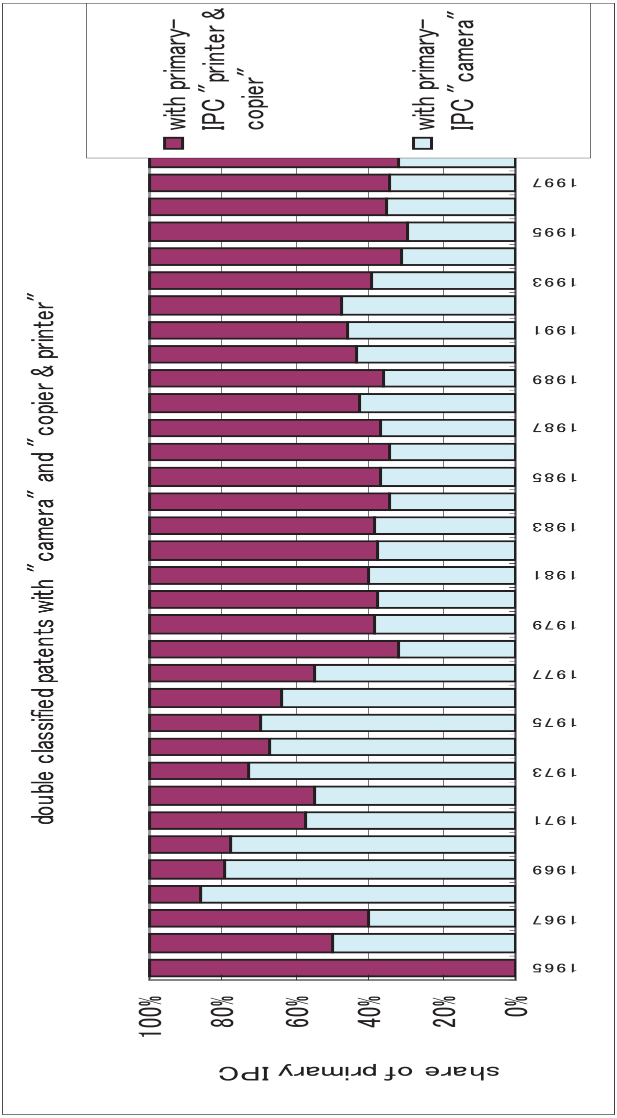

Figure 3-10. Change in share of primary IPC in double classified patents with camera and copier and printer technology

Source: Suzuki and Kodama (2004).

It can be concluded that the application of camera technology generated and helped to develop the technological trajectory of copiers throughout the 1960s and the early 1970s. However, the technological trajectory of copiers probably came to stand somewhat independently on its own legs in the late 1970s, and this contributed significantly to the copier and printer business, as seen in **Figure 3-10**, which depicts the share of primary IPC in co-occurrence patents in the period from 1965 to 2000. As can be seen in the figure, the share of patent applications with "printer and copier technology" as the primary IPC constantly increased during the 1970s, and remained over 60% after 1980. This implies that the transfer from camera technology to copier and printer technology was smoothly conducted. After 1980, copier and printer technology became able to stand apart from camera technology.

3. Business model innovation

When inventing the iPod, Steve Jobs is quoted as saying: "what's really interesting is if you look at the reason that the iPod exists and that Apple is in that marketplace. It is because these really great Japanese *consumer electronics* companies who kind of own the *portable music* market, invented it and owned it, couldn't do the appropriate *software*."

In the revolution of portable music, therefore, we could argue that Sony's *Walkman* was obviously a technical innovation derived from the notion of demand articulation. It was based on Sony's sophisticated translation skill to convert a vague set of distant human wants into well-defined product concept, *i.e.* "portable music." And it was also based on Sony's product development skills to decompose the concept into a set of development projects. This decomposition was feasible by mobilizing all of Sony's competencies: the recording and delivery of music owned by Sony Music Co.; the various audio technologies owned by Sony Corporation; regenerating the recorded music with tapes or CDs; good earphone technologies; etc. In any case, Sony completed the *first* cycle of portable music invention.

According to Anderson and Tushman[20], an industry evolves through a succession of *technology cycles*. Each cycle begins with a discontinuity based on new technologies, along economically relevant dimensions of merit. In each case, a process with *inherently* higher *limits* redefined the state of the art, increasing machine capacity by an order of magnitude while lowering costs and improving quality. To sum up, each discontinuity *inaugurates* a new cycle. Indeed, the iPod innovation by Apple inaugurated the *second* cycle of portable music. Steve Jobs is again quoted as saying: "Our idea was to come up with a music *service* where you don't have to subscribe to it. You can just buy music at 99 cents a song, and you have great digital – you have great rights to use it." As is clear from this quotation, it is based on a breakthrough in *system-of use*[21], *i.e.* the *creation* of a new business model. This is easy to understand if we give some thought to what kind of core competencies are owned by Apple, compared with Sony, in terms of physical technologies related to portable music. Therefore, we might generalize that while a breakthrough in technology starts the *first* cycle, a breakthrough in the business model will inaugurate the *second* cycle.

3.1 Proactive mode of demand articulation

Now, we have learned that the *second* cycle of innovation is triggered by the creation of a new *business model* rather than by technological discontinuity. It has also been revealed that the trigger at each stage came from different fields of knowledge areas. Furthermore, each time a change in the sources of innovation occurred, a dramatic upgrading in the inherent value (higher upper limit) of innovation was accomplished. In a technology cycle model of innovation, therefore, "demand articulation" is effective in starting the *first* cycle. When it comes to the *second* cycle, meanwhile, technological learning will follow a more *proactive* mode of demand articulation[22].

As described above, in the 1990s, we came to technological and business environments in which "demand articulation" is better framed in a more *proactive* manner. It has also become clear to everyone that a new *business model* can be a source of discontinuity and disruption as well as of technical breakthroughs and innovations. It went also in parallel with the sophistication of information technologies. Indeed, Steve Jobs clearly described this situation in the following words: "people don't know what they want *until* you show it to them. That's why I never *rely* on market research. Our task is to *read* things that are not yet on the *page*." In this situation, the demand can be *articulated* by *proactively* expressing what you think people want. In adopting multi-touch technology, he thought:

> So let's not use a stylus. We're going to use the best pointing *device* in the world. We're going to use our *fingers*. We're going to touch this with our fingers. And we have invented a new technology called multi-touch, which

is phenomenal. It works like magic.

In writing his book *Open Innovation*, Chesbrough is more *articulate* and provocative in identifying the importance of the business model rather than technology itself: technology by itself has no single objective value. The economic value of a technology remains *latent* until it is commercialized in some way. The value of an idea or a technology depends on its *business model*. There is no inherent value in a technology *per se*[23]. More recently, according to Amit and Zott[24], many of the innovations and cost savings that could be achieved have already been achieved. Our greatest focus is on business model innovation, which is where the greatest benefits lie. It is not enough to make differences to product quality or delivery readiness or production scale. It is important to innovate in areas where competition does not exist.

3.2. Innovation dynamics of business model creation

In her book on the history of the Internet, Abbate[25] summarizes its history as follows: computing technology underwent a dramatic transformation. The computer, originally conceived as an *isolated* calculating device, was *reborn* as a means of communication. When computers were scarce, expensive, and cumbersome, using a computer for communication was almost *unthinkable*. Innovations that occurred in the PC (personal computer), therefore, created new ways of using one after another. In other words, the PC technology created new *systems-of-use*[26].

The drastic innovations that had occurred in *printer* technologies, meanwhile, seem to have produced slightly different implications from the innovations that occurred in PCs. The printer was used only as a machine for outputting character-based information on paper during the 1960-1970s. It was also mainly used for business purposes. When *laser* and *inkjet* printers entered the market in the mid-1980s, the printer market expanded drastically as personal use began. There were two reasons for the expansion of the market for personal use. One was the ability to deal with high-resolution images and the other was the introduction of color printing. In this context, we can summarize that new technologies related to the printer greatly widened the *scope of usage*. However, the commercialization of new technologies was conducted within an *existing* framework, *i.e.* printing on paper. We can argue, therefore, that the printer did not necessarily create new systems-of-use as had happened in the case of PCs, although the nature of innovation in these products can be best described as a "radical breakthrough," in terms of a drastic widening of the scope of usage. It is now clear, however, that both printer and PC technologies did produce the "market-driving" pattern instead of a "market-driven" pattern, if we use the taxonomy proposed by Sheth and Sisodia[27].

Now we will move on to how different those two patterns of market-driving growth are, empirically and quantitatively. Foster[28] once formulated the difficulty in managing technological discontinuities as the movements from one technology to another with *inherently higher* upper limits. When it comes to the market-driving growth of products such as printers and PCs, therefore, it is reasonable to think that the product's potential market size could be increased by new value being added by the technological innovation of the product during the period of diffusion. Now, we are interested in *visualizing* the differences in the growth patterns between printers and PC technologies as well as the difference between market-driven and market-driving growths[29]. Sharif and Ramanathan[30] proposed a market-growth model in which the potential adopter (upper limit) increases over time in the following three models:

Model A: Potential market size does not change (simple logistic model)
Model B: Potential market size increases stepwise (N-step logistic model)
Model C: Potential market size increases continuously (binomial logistic model)

Market growth data was collected for televisions (yearly production data: 1956–1980) as an example of the ordinary market-driven growth pattern (model A) for the reference case of our market growth study. As far as the case of market-driving growth (models B and C) is concerned, market growth data was collected for printers (monthly production data: 1983.01–1998.08) and PCs (monthly production data; 1987.01–2001.06). To identify the market growth patterns for these three product categories, we conducted a statistical fitting of these three kinds of growth models described above[31].

We confirmed that the growth trajectories of the three different products followed three different paths: televisions can be identified best as following the simple logistic curve, where the upper limit does not change, as can be seen in **Figure 3-11**. In retrospect, this result is good quantitative evidence that the demand for televisions was *pre-articulated* from the beginning and that the essence of this demand did not change through all the time period studies.

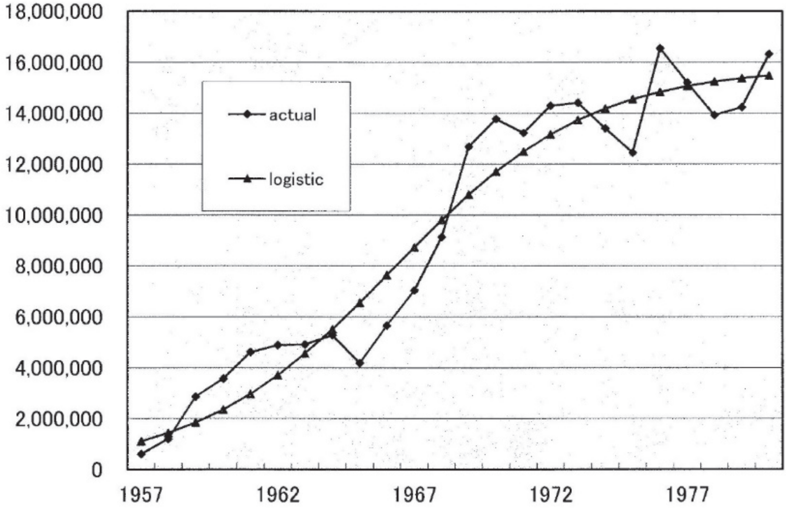

Figure 3-11. Graphical representation of regression analysis for televisions

Source: Osaki et al. (2001)

The growth pattern of market-driving products, as we can reasonably imagine, are found to follow S-shaped curves where the upper limits also increase. The market growth for printers turns out to be identified best as following the two-step logistic model (model B), as shown in **Figure 3-12**. As can be seen in the figure, a *stepwise* expansion of the potential market size is estimated to have occurred in 1987. Indeed, laser and inkjet printers entered the market in the mid-1980s. Based on these facts, we can generalize that "breakthrough" innovations such as laser and inkjet printers might be measured by a *stepwise increase* in potential market size[32]. Our findings concerning *printer* innovations described above, indeed, coincide with the following assertions by Anderson and Tushman[33]: the notion of a series of

S-curves suggests an industry evolves through a succession of *technology cycles*. Each cycle begins with a *technological discontinuity*. Discontinuities are based on new technologies whose technical *limits* are *inherently greater* than those of the *previously* dominant technology.

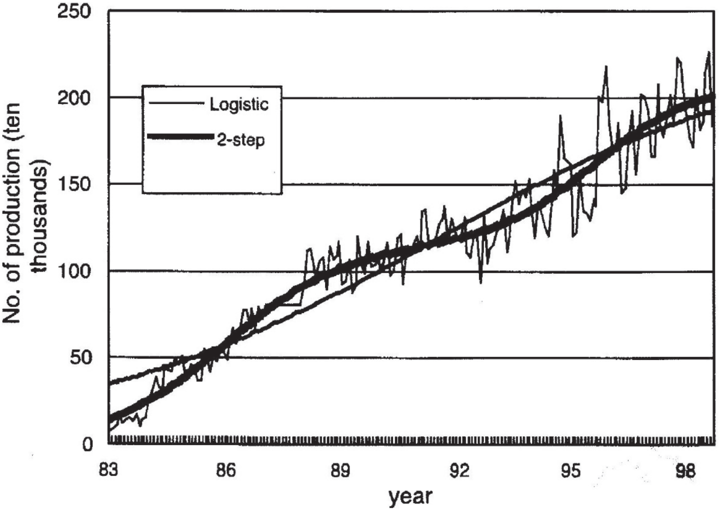

Figure 3-12. Graphical representation of regression analysis for printers

Source: Osaki et al. (2001)

Apart from the results on printer innovation, the market growth path of PCs, we find, is identified best as following the *binomial* logistic model (model C), where the upper limit of the potential adopters *continuously* increases by also following a logistic curve (we might call it a "*double*-logistic" curve), as seen in **Figure 3-13**.

This is very different from the patterns of discontinuous innovations. Indeed, a kind of consensus has been reached in several recent empirical studies on what the real implications are of the creation of a "business model"[34]. They describe how dynamic business models represent *continuous* change and therefore make firms *constantly* learn new and better ways of doing things.

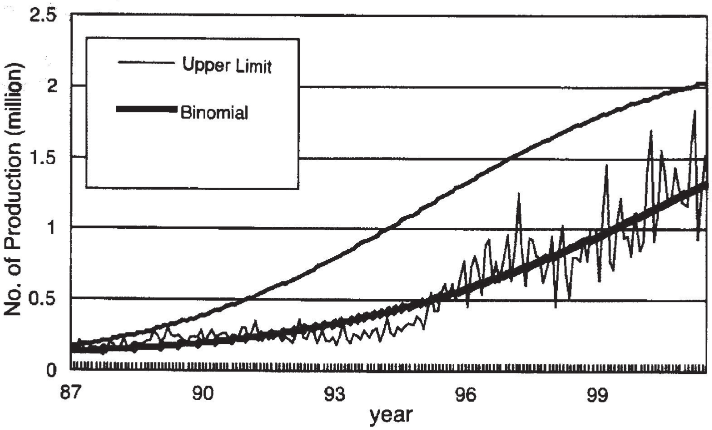

Figure 3-13. Graphical representation of regression analysis for PCs

Source: Osaki et al. (2001)

In commercializing new technologies, moreover, Chesbrough and Rosenbloom [35] argue that a new *business model* is required to commercialize a *disruptive* technology. They also argue that *new* technology creates only a little *disruption* if the business model of the related industry has not changed much. The printer technology is one such example that comes to mind immediately.

To summarize, we have discovered that the PC did continuously create new systems-of-use one after another. In other words, technical progress in PCs created new *business models* in terms of the utilization of these innovations[36]. This corroborates the description by Abbate[37] quoted in the first paragraph of this section: the computer, originally conceived as an isolated calculating device, was *reborn* as a means of communication.

Conclusion

In high-tech development, simultaneity between market, product, and process is conspicuous. The longitudinal analysis of LCD development by Sharp Corporation reveals that they were quite successful in the co-development of the market and product. Our further analysis, however, reveals that Sharp failed in its simultaneous development of product and process innovation, after the LCD development was globalized.

The successful cases of bold diversification by Japanese camera companies can be explained by the successful articulation of their core competency for directing their diversification trajectories. This can best be described by Canon’s diversification into the copiers and printers market. Using patent data, our analysis showed that Canon’s diversification was based on a creative accumulation of its own core competency.

When we enter the digital economy, the successful cases of demand articulation become proactive articulation, *i.e.* business model creation. From the technologist’s point of view, this can be translated as an invention of a new system-of-use of new technologies. In this context, we made an empirical study on the diffusion of innovation. We compared the diffusion patterns of three products: televisions, printers, and PCs. We found that the diffusion of PCs follows the logistic curve in which the upper limit increases continuously, while the diffusion of printers follows the curve in which the upper limit increases in two steps. This indicates that the PC technology created new systems-of-use one after another. This turns out to be empirical evidence of business model creation.

Notes

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[1] Olympus Corporation was established in October 1919. They initially specialized in microscope and thermometer businesses.

[2] Prahalad, C. K. and Hamel, G. (1990). The Core Competence of the Corporation. *Harvard Business Review, 90*(3), 79-90.

[3] Christensen, C. (1997). *The Innovator's Dilemma*. Boston: Harvard Business School Press.

[4] Christensen, C. and Ryanor, M. (2003). *The Innovator's Solution.* Boston: Harvard Business School Press.

[5] Kodama, F. (2000). Analyzing the Innovation Process for Policy Formulation: Research Agenda drawn from the Japanese Experiences. In *OECD Tokyo Workshop on Social Sciences and Innovation* (pp. 117–23). Paris: OECD Publishing.

[6] Included are a device displaying numerals and letters, a window curtain, still-picture display equipment, and a display panel for airplane pilots.

[7] Numagami T. (1999). *History of Liquid Crystal Display Technology* [in Japanese]. Tokyo: Hakuto Shyboh.

[8] This combination of technology and market strategies was not unique in Japan. The differentiation strategies of US manufacturers were different. Since they went forward to “programmable calculators,” a further thinning was not one of their major concerns (Numagami, 1999).

[9] The conventional paradigm is that the development of a generic technology automatically brings diversification by applying the technology to various kinds of products. In this view, a technology is developed first for a technologically demanding, high-end product, and then extended for the use of less technologically demanding, low-end products through the development of low-cost, quality-controlled mass-production processes. According to this view, diversification is based on the "spin-off" principle.

[10] Nakata, Y. (2005). Why is Asia Pacific so Strong in Liquid Crystal Display Industry? Approach from Industrial Architectures of Liquid Crystal Display. *Proceedings of PICMET'05 (Portland International Conference on Management of Engineering and Technology) August 2005, USA*.

[11] Porter, M. (1996). What is Strategy? *Harvard Business Review*, *74*(6), 61-78.

[12] Yamaji, K. (1997). *One proposes, God disposes*, Tokyo: Nikkei Publishing, Inc., 22.

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[13] Christensen, C. (1997): *The Innovator's Dilemma*.

[14] Ibid.

[15] Yamaji, K. (1997). *One proposes, God disposes*.

[16] Research and development and the production of consumables were necessary to create a new type of copier. If the photoreceptor drum and the development were left in the hands of others, the inventor would not have been able to create a new process.

[17] Malerba, F. and Orsenigo, L. (1995). Schumpeterian patterns of innovation. *Cambridge Journal of Economics, 19*, 47-65.

[18] The entropy value is an index of the degree of diversification defined by Σi P_i ln (P_i), where P_i is usually the product sales ratio and ln stands for natural log. The merit of using the entropy value in comparison with the Herfindahl index was reviewed by Gemba and Kodama (2001).

[19] Suzuki, J. and Kodama, F. (2004). Technological diversity of persistent innovators in Japan. *Research Policy, 33*, 531-549.

[20] Anderson, P. and Tushman, T. (1991). Managing through cycles of technological change. *Research Technology Management, 34*(3), 26.

[21] Christensen, C. and Rosenbloom, R. (1995). Explaining the attacker's advantage: technological patterns, organizational dynamics and the value network. *Research Policy, 24*, 233–57.

[22] Kodama, F. (2000). Analyzing the Innovation Process for Policy Formulation.

[23] Chesbrough H. (2003). *Open Innovation: The New Imperative for Creating and Profiting from Technology*. Boston: Harvard Business School Press.

[24] Amit, R. and Zott, C. (2012). Creating Value through Business Model Innovation. *MIT Sloan Management Review*, *53*(3), 41-49.

[25] Abbate, J. (1999). *Inventing the Internet*. Cambridge, MA: The MIT Press.

[26] Christensen, C. and Rosenbloom, R. (1995). Explaining the attacker's advantage.

[27] Sheth, J. and Sisodia, R. (1999). Revisiting marketing's lawlike generalizations. *Journal of the Academy of Marketing Science, 27*(1), 71–87.

[28] Foster, R. (1986). *Innovation: The Attacker's Advantage*. New York: Summit Books.

[29] Osaki, M., Gemba, K. and Kodama, F. (2001). Market growth models in which the potential market size increases with time. In *PICMET (Portland International Conference on Management of Engineering and Technology)* (pp. 788–96); Kodama, F. (2004). Measuring emerging categories of innovation: modularity and business model. *Technological Forecasting and Social Change, 71*, 623–33.

[30] Sharif, M. and Ramanathan, K. (1981). Binomial innovation diffusion models with dynamic potential adopter population. *Technological Forecasting and Social Change, 20,* 63–87.

[31] For the identification of the most appropriate model, we will use the criterion developed by Akaike. The AIC (Akaike Information Criterion) was developed for measuring the degree of fit of nonlinear regression analysis. A smaller AIC value means a better fit.

[32] Sood, A. and Tellis, G. (2005). Technological Evolution and Radical Innovation. *Journal of Marketing, 69*, 152-168.

[33] Anderson, P. and Tushman, T. (1991). Managing through cycles of technological

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change.

[34] Ritala, P. and Sainio, L. (2014). Coopetition for radical innovation: technology, market and business-model perspectives. *Technology Analysis and Strategic Management, 26,* 2; Tongur, S. and Engwall, M. (2014). The business model dilemma of technology shifts. *Technovation, 34,* 9; Mason, K. and Leek, S. (2008). Learning to build a supply network: an exploration of dynamic business models. *Journal of Management Studies, 4,* 774–99.

[35] Chesbrough, H. and Rosenbloom, R. (2001). The dual-edged role of the business model in leveraging corporate technology investments. In L. Branscomb and P. Auerswald, eds., *Taking Technical Risks* (pp. 57–68). Cambridge, MA: MIT Press.

[36] Kodama, F. (2004). Measuring emerging categories of innovation: modularity and business model. *Technological Forecasting and Social Change, 71*, 623–33.

[37] Abbate, J. (1999). *Inventing the Internet*.

CHAPTER FOUR

WAVE ARTICULATION: ARRIVING INNOVATIONS IN THE JAPANESE MACHINE TOOL INDUSTRY

As is well known, Soviet economist Nikolai Kondratieff was the first to bring economic cyclic observations to the international attention (1925)[1], and four phases of a cycle were identified: expansion, stagnation, collapse, and recession[2]. In 1939, Joseph Schumpeter suggested naming the cycles "Kondratieff waves" in his honor. In the innovation theory, the cyclic waves arise from the bundling of basic innovations that launch technological revolutions that in turn create leading industrial or commercial sectors. The duration of these waves was originally estimated to last 50–54 years.

The US National Academy of Science proposed an idea of an “innovation cycle” as the cyclic process of research, development, production, and distribution[3]. However, our review of the history of high-tech developments in Japan revealed that the leading innovators at each stage came from *different* industrial sectors while collaborating in joint research across industry boundaries. Furthermore, each time a change in leaders occurred, dramatic improvements in technological development were made. The innovation cycle, then, becomes a *spiral innovation model* with three-dimensional cycles[4]. The essential feature of this innovation model is the one-to-one correspondence between the technological approach and the industrial sector. Each industry tries to solve a problem using specific technological competencies accumulated in its industrial sector. Having successfully undergone several transitions during the period 1975-2015, however, the Japanese production of machine tools was able to maintain its top position in the world for a longer period than 40 years, as depicted in **Figure 4-1**.

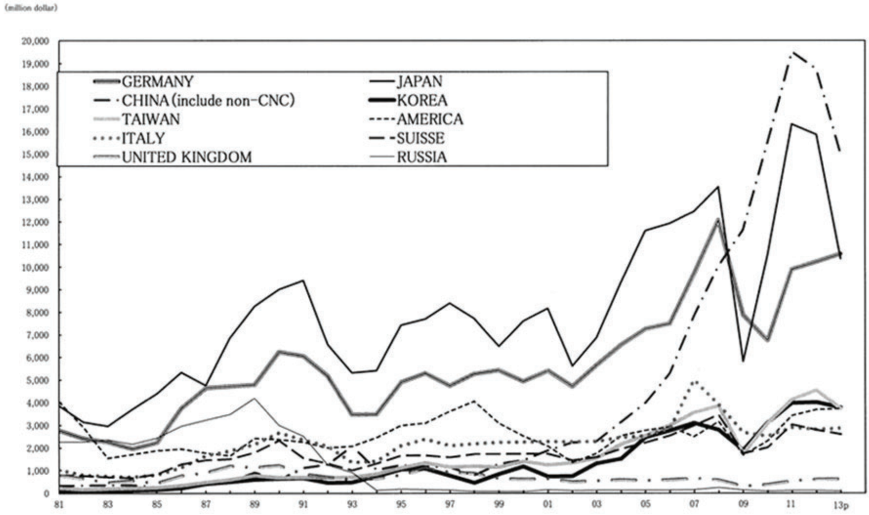


Figure 4-1. Trend of machine tool production volume in major countries (1981－2015)
Note: The Chinese volume of production includes that of non-CNC machines.

Therefore we have to explain the difference between what happened to the Japanese machine tool industry and our innovation *spiral* model where leaders are supposed to move from an innovation cycle in one industry to a new innovation cycle in a different industry. This difference, therefore, alludes to the fact that we need new concepts of innovation. In the 1990s, meanwhile, innovation research scholars proposed several new concepts, one after another, but independently, and in a chronological sequence: technology fusion, digital convergence, disruptive technology, platform leadership, and open innovation. All these concepts assume that incumbent firms will disappear because a new wave brought by a new innovation concept will appear. However, why could the Japanese machine tool industry overcome the drastic changes in patterns of innovation for so long and in a repeated way? We can argue that the industry could detect the *newly-arriving* wave of innovation early enough to prepare for these changes. In other words, they could *articulate* the arrival of the new waves. Therefore, we could call it "wave articulation." This is defined as a kind of demand articulation which leads a company in the right direction of sustainability over a long term wave of innovation.

1. Disruptive Innovation

The origin of NC (numerically controlled) machine tools with unprecedented levels of precision and reliability goes back to the late 1940s to US institutions such as Massachusetts Institute of Technology (MIT). They invented the numerical controller for the milling machine in 1952. The device, however, had 2,000 *vacuum tubes*, and its size was the size of a small *room*. While it controlled a machine tool automatically, it was huge and expensive, putting it out of reach of all but the largest industries, such as aircraft manufacturers. It implied that a huge market segment of mid-sized and small industrial customers was *neglected* because the NC was too costly and too large for them.

Having discovered a possible lucrative *niche* in mid-sized and small industrial customers, *Fanuc*, a spin-off of Fujitsu which is a supplier of communication equipment, set out to develop a controller that was cheaper, simpler, and more compact than those of the current generation. This is exactly the strategy which Christensen[5] described in terms of disruptive innovation, as is figuratively illustrated in **Figure 4-2**.

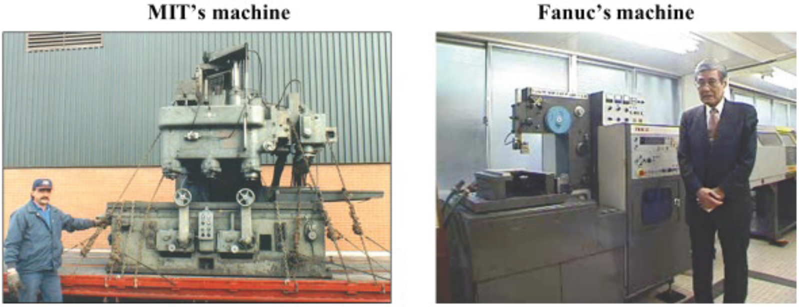
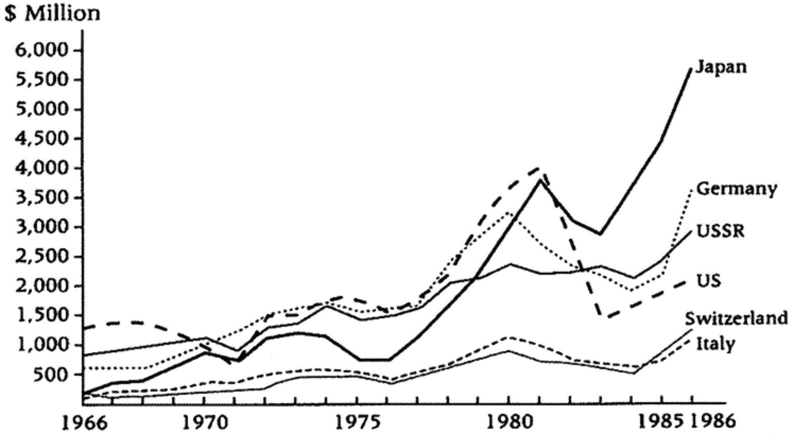

MIT's machine
Fanuc's machine

Figure 4-2. Photographic illustration of disruption

First of all, they designed a new type of servo motor, called an *electro-hydraulic* (EH) stepping motor, in which electrical control pulses are converted into mechanical movements known as *steps*. The motor removed many operational *complexities* and, in particular, eliminated the need for a *feedback* loop, since the operation of an EH motor is based on the *open-loop* principle. To complete the system, then, Fanuc returned to its need for a *controller*. Fanuc's controller was based on the scientific fact that it is possible to reduce most technical drawings to *arcs* (which can be expressed as a radius with starting and ending points) and straight *lines* (which can be defined as two points). Using this knowledge, Fanuc developed a machine that translates arcs and lines into pulses. The machine could be made smaller because of the switch from vacuum tubes to solid-state electronics.

As a result, from 1975 to 1985, Japan's production of machine tools rose from *fourth* after the USSR to the top position in the world (see **Figure 4-3**). Such growth in the world market in so short a time would not have been possible without substantial innovation in the industry.



Source: Ministry of International Trade and Industry, *Vision for Industrial Machinery* (in Japanese) (Tokyo: Tsushou-Sangyou-Chousakai, 1984).

Figure 4-3. Production of machine tools in major economies (1966－1986)

Indeed, this phenomenon of *leapfrogging* cannot be explained only by technological disruption, but also by the new-market disruption to accommodate the *unfulfilled* needs of the small- and medium-sized companies that had been neglected by the expensive NC machine tool providers of the United States[6]. And the argument that disruptive innovation comes first, before the other innovation concepts, might *not* be so surprising, if one considers the following prototypical example compiled by

Christensen of disruptive innovation by a Japanese company[7]: the venerable RCA (Radio Corporation of America) was *vaporized* by Sony's "transistorized portable radio" in 1955. Indeed, this event sets a starting point, which is followed by various innovations in consumer electronics. And Fanuc's inventions also disrupted the trajectory of the conventional mode of technological development in the machine tool industry. We might generalize that a new Kondratieff wave arises whenever a disruptive innovation occurs.

2. Technology Fusion

In 1975, the Japanese created a new word, *mechatronics*, by combining the words *mechanics* and *electronics*. Essentially, mechatronics is the marriage of electronic technology to mechanical technology. From this union came a more sophisticated range of technological products, such as NC machine tools and industrial robots, as well as a series of products in which a part, or the whole, of a standard mechanical product was superseded by electronics, such as digital clocks and electronic calculators.

The device that harnesses the EH stepping motor to the worktable in a NC machine tool is called a *ball screw*. The ball screw was developed by Nippon Seiko Co. (NSK), Japan's leading maker of bearings. The ball screw's great advantage over its predecessor, the friction screw, lies in the lubricated ball bearings inserted between the screw's nut and bolt, which made a precise positioning possible. Without the development of a ball screw with perfect pitch, it would not have been possible to hook up Fanuc's EH servo motor in an *open-loop* control system.

A further contribution came from *material* suppliers such as Daikin Co. A coating of *Teflon* on the sliding bed of the machine tool enabled the hook up of the servo motor, which is good for precise adjustment but weak in *torque*. This also made low speed but uniform movement possible, a necessity for the operation of a machine tool. Through the development process described above, we can assert that Fanuc's NC system was realized by *fusing* three technologies developed in different industries into one, as can be seen in the two photos of **Figure 4-4**.

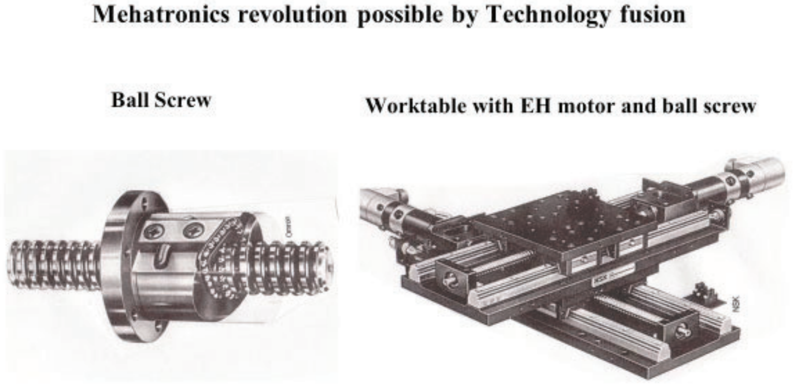


Figure 4-4. Fusing of technologies developed in different industries into a new product

The idea of "technology fusion" was proposed in order to characterize the then-emerging technologies such as *mechatronics* and *optoelectronics*[8]. And this conceptualization was identified as a unique Japanese capability to innovate[9]. Indeed, the innovation pattern was shifting from technical breakthrough to technology fusion, and the management implications of this shift have also been discussed[10]. It was argued that the difference between success and failure is not how much a company spends on research and development but in how it defines it. There are two possible definitions. Either a company can invest in R&D that replaces an older generation of technology—the “breakthrough” approach—or it can focus on combining *existing* technologies into hybrid technologies—the “technology fusion” approach. The former is a linear, step-by-step strategy of substitution. Technology fusion, on the other hand, is nonlinear, complementary, and cooperative. It blends *incremental* technical improvements from several previously *separate* fields of technology to create products that revolutionize *markets*.

In terms of the sequencing problem, however, we can learn why the concept of disruptive innovation[11] *preceded* that of technology fusion[12] as far as the machine tool industry is concerned. Only after we had disruptive innovations in component technologies such as EH stepping motors and small numerical controllers could we attain the *fusing* of technologies in different sectors such as the electronics, mechanical and materials industries into a machine tool. We discussed above that the technology fusion approach focuses on combining *existing* technologies into hybrid technologies. This description, however, is *not* quite right in the sense that technology fusion cannot be realized without preceding disruptive innovations at the level of component technologies. In other words, technology fusion is not *effective* with only the available component technologies. To be effective, we need to have disruptive component innovations. The existence of disruptive innovations is a necessary condition for technology fusion to be realized. Only by the realization of technology fusion can the market need be met and the demand for disruptive component technologies be articulated and pulled into the market[13].

3. Open Innovation

Having brought disruptive technologies into the machine tool industry in the early 1970s, the Japanese machine tool industry was able to attain and maintain its number one position until 2015. How did the Japanese industry sustain the momentum of innovation, or at least survive for more than a quarter of a century?

After Fanuc made major innovations, they had to confront the major shifts both in the economic and in the technological *landscape*. In other words, Fanuc had to undergo two major *transitions*[14]. In these transitions, the company was faced with the dilemma of either switching to a new technology or sticking with the tried-and-true old technology. The *first* transition involved servomotor architecture, a key NC technology, entailing a major change from an *open-loop* architecture to a *closed-loop* architecture. The *second* technology shift involved the NC logic unit architecture from a hard-wired logic to a soft-wired logic based on a MPU (Micro Processor Unit). How did Fanuc overcome these two transitions successfully? Fanuc *articulated* the management scheme to overcome these transitions.

In a celebrated work on "open innovation" by Chesbrough[15], he argued that there are two sides to the open innovation model. One side is "outside-in," bringing external ideas and technologies into the innovation process. The other side is "inside-out," enabling *unused* internal ideas and projects to go outside for *others* to use instead. The way in which Fanuc overcame each of these two transitions, indeed, provides us with a rich illustration both of the outside-in (inbound) and of the inside-out (outbound) innovation models. In fact, Fanuc overcame the first transition by following the *inbound* model of open innovation. And the second transition produced a positive outbound model of open innovation. This was because the MPU technology which Intel developed in close collaboration with Fanuc was successfully transferred to the PC (personal computer) industry throughout the world.

3.1 Outside-in (inbound) Model

Fanuc Ltd was established as a subsidiary start-up business by Fujitsu in 1956. Fanuc was then spun off as an independent company from Fujitsu in 1972, just in time to be challenged by the first oil crisis in the fall of 1973. This oil crisis caused users to start turning away from the electro-hydraulic (EH) pulse motor, a technology due to which Fanuc enjoyed an overwhelming competitive advantage. The EH pulse motor is an *open-loop* control servomotor with significant advantages in versatility and flexibility, and Fanuc had an undeniable position in this technology as holder of the patent rights. However, the EH pulse motor used a lot of *oil*.

The oil crisis of 1973 thus made users extremely uneasy about continuing to use the EH pulse motor in the future, as it pushed up the price of oil to unprecedented levels. At that time there were two basic motor technology *options* available: a pulse motor with open-loop control, and a DC servomotor with closed-loop control. The first task was to *exploit* the technological limits of an “electrical pulse motor” with the same architecture as the EH pulse motor, proposed by President Inaba, who invented the EH motor. The second task was to *scrutinize* the work of the US-based DC servomotor manufacturer Gettys Manufacturing Company Inc. to determine the viability of DC servomotors. In this situation, President Inaba of Fanuc at that time adopted the *management scheme* in which those two basic options were compared and tested, as shown in **Figure 4-5.**

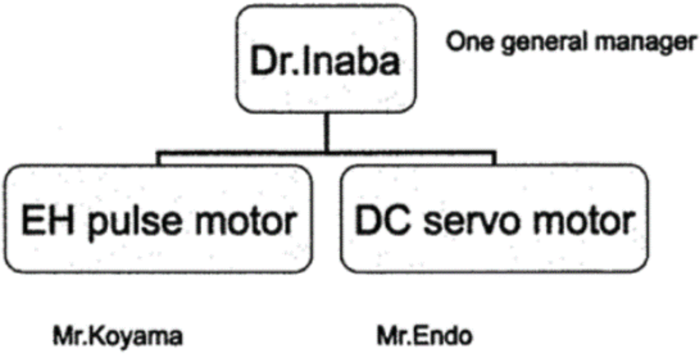


Figure 4-5. Management arrangement for motor technology transition[16]

How did the scheme work? The assignment to develop an electrical pulse motor revealed that it was extremely *noisy* and would be difficult to install. Inaba immediately *discarded* the pulse motor and switched over to the DC servomotor. An agreement with Gettys regarding the DC servomotor was reached. Two months later, Fanuc engineers finished work on the DC servomotor, and in September 1974, the company unveiled a new line of NC products equipped with the DC servomotor at the International Osaka Machine Tool Products Fair.

It is to be noted that open-loop control has never been an optimal choice in the United States[17]. In fact, the US machine tool industry essentially disappeared after the CNC revolution around the 1980s[18], as is vividly shown in **Figure 4-6** in which the production of CNC lathes are compared for the period 1975-1987 for Japan, Europe and the USA. Therefore, we would rather argue that the United States missed the transitional experiences in the early stages of development in which NC machine tools became available all through the entire economy, including in small- and medium-sized companies, as described in a HBS book entitled *When the machine stopped*, authored by Holland[19].

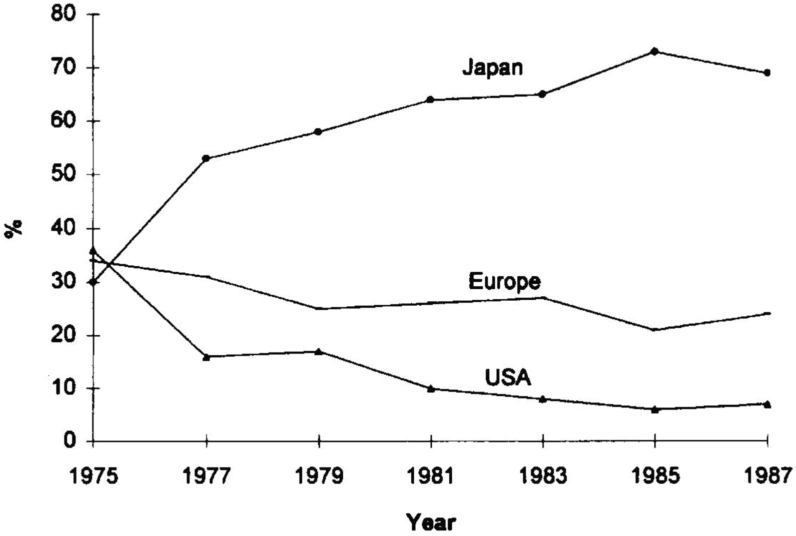


Figure 4-6. The production of CNC lathes in Japan, Europe and USA in 1975-1987 (in % of units)[20].

The drastic shift also occurred in the technological landscape. The logic unit experienced a technology transition: from a hard-wired logic unit to a soft-wired logic unit based on a microprocessor unit (MPU). In 1975, Fanuc possessed a stable technology and a dominant share of the NC market, based on its hard-wired NC system: the logic unit implemented with *transistors*, *diodes*, and other *integrated circuits*. In this system, however, at each *run* of the work process, a *paper-tape* has to be mounted into the tape-reading device. In contrast, the use of MPUs means that logic operations are carried out by software. Therefore, if a soft-wired NC becomes available, it would mark a significant transition.

Meanwhile, Intel Corporation was established only in 1968 as a start-up company spun off from Fairchild. At the dawn of the IC and MPU age, much *uncertainty* existed about its *performance* and *reliability*. Three hurdles had to be cleared before MPUs could be applied to NCs: performance, cost, and reliability. In particular, a high reliability to withstand significant noise and temperature fluctuations in factory environments was critically important as NCs are used in factories. In other words, Fanuc was not completely confident in the MPU-based soft-wired NC, although Fanuc was aware of the limitations of the hard-wired NC. Here again Fanuc found itself facing an intractable dilemma of having to choose between the old hard-wired NC and the new soft-wired NC.

Confronted by this impasse, Fanuc chose to pursue both technologies at the same time, as depicted in **Figure 4-7**. In other words, Fanuc used the scheme of managing evolutionary and revolutionary changes, and managed organizational separation through a tightly integrated senior team. Tushman and O’Reilly [21] call this kind of scheme "ambidextrous organization." They claim that they provide a practical and proven model for forward-looking executives seeking to pioneer radical or disruptive innovations while pursuing incremental gains.

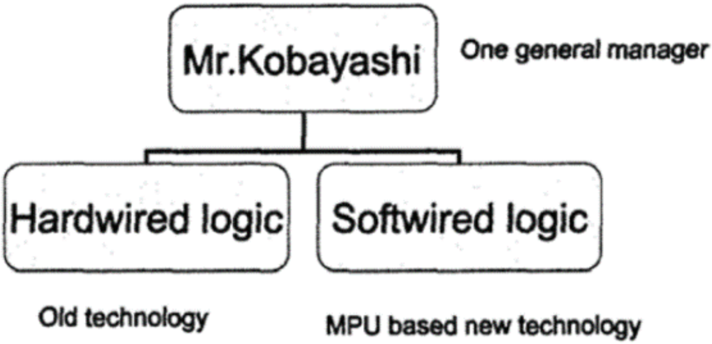


Figure 4-7. Management arrangement with logic unit technology transition[22]

A new soft-wired NC department was specifically set up to introduce MPUs to NC systems. The hard-wired NC department continued to develop mass production systems. Their objective was to develop the most cost-effective and reliable hard-wired NC system possible. The soft-wired NC department focused on the latest semiconductor and MPU-related developments; how these cutting-edge technologies could be incorporated into NC systems; and whether these technologies could satisfy the reliability and performance requirements of NC systems.

With one person overseeing both departments, this made it possible to objectively weigh the relative limitations of a hard-wired NC against the future potential of a soft-wired NC. Fanuc thus created an organizational *balance* for transitioning to new technology by the split into two separate departments but retaining the command of one general manager. With this arrangement, the MPU-based soft-wired NC technology was *nurtured* and developed until it *surpassed* the hard-wired NC in performance and reliability. Once it was achieved, the hard-wired NC department and soft-wired NC department was *merged*. In other words, so long as Fanuc remained *unsure* as to which technology it would pursue, both technologies continued to coexist.

3.2 Positive outbound model: Emergence of PC industry

Shibata[23] described in detail how Fanuc *built* its architectural knowledge through *collaboration* with Intel. In 1978, Intel developed the 8086, a technologically advanced and sophisticated 16-bit MPU, the first single-chip MPU in the world that enabled customers to write their own programs. In 1979, the Fanuc system 6 series, which used the Intel 8086 16-bit MPU, was completed. To develop this advanced system 6 series, Fanuc aggressively pursued intensive *collaboration* with Intel to absorb and build architectural knowledge *centered* on the Intel 8086. It was, in fact, a two-way and *reciprocal* collaboration between Intel and Fanuc.

It gradually became clear that the 8086 had many *problems*, because it used advanced semiconductor technology and was newly developed. Testing at the Intel USA site did not identify all of these *defects*, because it was tested in *stand-alone* systems. Many other defects were identified during testing by Fanuc, following installation into the system 6 series. The 8086 in a system 6 series NC was tested at the Fanuc site, in terms of increasing and decreasing the voltage. But Intel USA could *not* identify the same defects that appeared at the Fanuc site. It was sent to Intel USA due to its problems, but it was shipped back to Japan, because it had passed testing at the Intel USA site. When installed in the system 6 series, the 8086 is in a complicated *interdependence* with other devices in the NC system, in contrast to when the 8086 stands alone. For this reason, faults in the 8086 were identified only after installation in the system 6 series. The 8086 also had *interface* problems with other devices. Fanuc did not *leave* the problem solving activity only to Intel. Solving these problems required both *architectural* knowledge of NC systems and *component* knowledge of MPUs. Therefore, Fanuc and Intel had to collaborate to *share* each other's knowledge and experience in the field. Intel USA dispatched *four* 8086 engineers to Fanuc, and Fanuc assigned several engineers from the system 6 series to solving these problems. At Fanuc's factory in Hino City, Tokyo, engineers of both companies worked together, repeatedly testing the 8086 every day.

It is also noteworthy that Fanuc shared technical *documents* on the system 6 series with Intel engineers. These technical documents described in detail the technical specifications of the system 6 series hardware and ordinarily would have been kept *confidential*. However, Fanuc provided Intel with these technical documents to investigate the interface mechanism between the 8086 and other devices within the system 6 series. Through these intensive collaborations, they gradually overcame the technological *uncertainty* about MPUs and semiconductor technology. In this way, Fanuc gradually acquired new MPU-based architecture knowledge and developed new communication channels and information filters within the organization reflecting the new architecture knowledge.

Indeed, Fanuc went *ahead* and used semiconductor technology, but the technology was so new and infrequently used at that time that even the MPU manufacturers could not advise Fanuc with any certainty. For example, the ICs were mounted on printed circuit boards, and they wanted to know if copper wiring was the best way to interconnect the ICs, how to reduce the noise and improve the reliability of the circuit boards, and so on. But amazingly there was no one, including the vendors themselves, who had sufficient experience for their answers to be relied upon. They finally identified the fault and fixed it. The success of adopting the 8086 into the system 6 series made Fanuc competitive in the NC machine tool industry. Beginning in 1979, one year after the introduction of the 8086 MPU, Fanuc became its *first* high volume user in the world, for its system 6 series NC.

It should be noted that Fanuc utilized the semiconductor technology for product development *earlier* than the computer industry. In 1981, Intel developed the 8088 MPU, a partially *improved* version of the 8086, which was used commercially for *IBM PCs*. From this time on, Intel began to devote its managerial resources to the MPU business, decreasing its DRAM business. In that sense, the 8086 MPU could be called the *foundation* for Intel's prosperity, as well as being a *turning* point in Intel's history. Chesbrough phrased his outbound model as enabling *unused* internal ideas and projects to go outside for *others* to use instead. In the Fanuc-Intel interaction, however, Fanuc highly utilized the 8086 MPU for the development of their own machine tool. IBM conquered the PC market by the use of the 8086 MPU supplied by Intel. Indeed, all the companies involved in this development prospered afterwards. In this context, we could name it a *positive* outbound model of open innovation, since it plays a positive-sum game.

As to the sequencing, technology fusion produces a converged unit of a product for technology diffusion. That is necessary for an open innovation paradigm. In the inbound model, this converged unit can make explicit what kind of new emerging innovation can be brought into a unit of a product. As to the outbound model, this unit becomes the unit of technology transfer to another industry.

4. Digital Convergence

Yoffie[24] argued that digital convergence should be defined as the *unification* of formerly *distinct* technologies into a common application domain, in which one of the antecedent technologies is already applied. This is exactly what happened to the Japanese NC machine tool industry. Even after digitization was realized, the NC machine tools had a long way to go towards digital convergence in which NC machine tools controlled by personal computers (PC) was realized.

This was because NC and PC evolved independently through their own evolutionary paths[25]. The two systems had reached different *modular* architectural structures through their own evolutionary paths; the PC reached "open" architecture, while the NC reached "closed" architecture. In other words, many PC modules, such as *displays*, *motherboards* and *keyboards*, can be purchased separately on the open market, whereas NC modules, such as display units, control units and servo units, cannot be purchased on the *open market*. Therefore, it was difficult for these two systems to be integrated, although both are *modular* structures.

The PC controlled NC (PC－NC) was realized only after the NC system became an open architecture system in which three functions, *display*, *calculation*, and *drive*, were modularized and worked independently without any interferences. Under these circumstances, PC modules have been *mounted* to the display units in NC systems and PCs and NCs have been integrated, and the PC–NC was created. Thus, the digital convergence between NC and PC finally materialized. Ever since 1975, when the MPU was first incorporated into NC equipment architecture, searches have been made for appropriate module *partitions* to accompany the latest advances in elemental technologies. As a result, NC architecture has achieved three different module partitions, as shown in **Figure 4-8**. Indeed, this development by Fanuc can be formulated as learning-by-*partition*, almost opposite to the oft-called learning-by-integration[26].

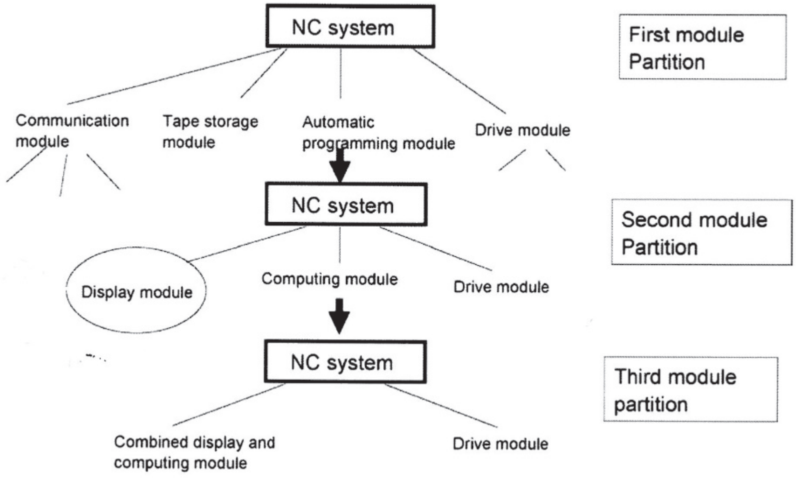


Figure 4-8. Changes in module partition of an NC machine tool[27].

After the MPU was adapted into NC equipment, efforts continued to design products with modularity, with hardware modularity achieved for the series 0 (zero) of Fanuc developed in 1985. Functions such as communications, tape storage, and automatic programming became independent hardware modules, each equipped with an MPU, with a Fanuc bus (a proprietary Fanuc common interface) used between these modules to form a linked architecture. A printed circuit board was used to implement each group of function elements. In that sense, the relationship between the function and structure elements is simple. Owing to this modularity, functions can be freely added and selected in accordance with requests from machine tool manufacturers. This was the *first*-generation NC architecture and the first module *partition*.

Subsequently, innovative mounting technology, using printed circuit boards in three dimensions, was adopted for NC equipment, enhancing the ability to mount electronic parts densely. This use of advanced elemental technology influenced the method of module *separation* and stimulated new module separation in NC equipment. As a result, NC hardware could be divided into three major modular units: *display, computing,* and *drivers*. An architecture emerged in which the units were linked with an interface based on proprietary Fanuc rules. Series 16, which employed this architecture, was released in 1991. The architecture consisted primarily of display, computing, and drivers, physically linked by fiber-optic cables forming the Fanuc Serial Bus proprietary standard interface. This was the *second*-generation NC architecture and the *second* module partition. It is to be noted that the PC－NC digital convergence was attained at this second module partition.

Further advances in elemental technology led to greater miniaturization. The display and computing units were *combined* into a single body, and an NC with two main units, the combined display and computing unit and the driver unit, was introduced in 1997 as Series 16i.

Surface mounting and other technologies made it possible to mount NC control boards on the rear of LCD devices, combining the two into a single unit. As a result, it was possible to achieve an ultra-thin NC control board of just 60 mm, which reduced the space in a conventional NC unit by about one half. This was the *third* module partition. In this way, companies followed a repeated process of recreating module partitions in order to find the optimal modularity that met advances in elemental technologies.

Now it becomes clear why open innovation precedes digital convergence. Through the process of open innovation, we can come more or less to the optimal module *partition* of a system. Only after the optimal module structure has been reached can two different digital systems (PC and NC) start *converging*. This observation leads us to the sequencing in which the digital convergence comes after the open innovation. We can summarize it thus: open innovation makes the modular structure an open architecture so that the structure becomes visible to outsiders. Then, by trying all the possible combinations, we can reach a converged digital system.

5. Platform Leadership

According to Gawer and Cusumano[28], platform leadership is the character of the modern high-tech platform—an evolving system made of interdependent pieces that can each be innovated *upon*. In the case of PCs, a solid platform leadership was established by Intel, when the Universal Serial Bus (USB) was formulated by the Intel Architecture Lab (IAL). The USB was a new interface linking a PC to external devices such as the keyboard, scanner, or printer. It was a "universal" plug into the PC: a user could connect several peripherals into one USB plug, which was not possible with legacy serial connectors such as those using the small computer system interface (SCSI). The problem was the architecture: IBM and other PC manufacturers had designed the PC so that each peripheral device needed its own individual plug in the back of the PC. The USB removed this limitation.

In the case of the NC (numerical controller), as described above, a hardware *modularity* was achieved for the Series 0 of Fanuc developed in 1985. In this *first* partitioning architecture, independent hardware modules do form a *linked* architecture with a Fanuc *bus* (a proprietary Fanuc common interface) used between these modules. The *second* partitioning architecture, as described above, consisted of the three units of the human interface, display, computing, and drivers, but it was physically linked by fiber-optic cables, forming the *Fanuc Serial Bus* proprietary standard interface. It is to be noted that the PC–NC digital convergence was attained at this second module partition.

A clear manifestation of Fanuc's platform leadership position can be seen by its high degree of market share (♦) and its duration, as depicted in **Figure 4-9.** As seen in the figure, this high share can be somewhat equated to that of the MPU by Intel in PCs, in which the original expression of "platform leadership" was introduced.

However, the figure of the market share is not available for after 2002, partly because the market segmentation of NCs is not viable as an industrial statistic. A more reliable and stable indicator might be that of how long Fanuc has kept a dominant position in a sustainable way. In this context, we collected the long term, time serious data of its profit (operating) ratio during the period from 1993 to 2014, shown in **Figure 4-10.**

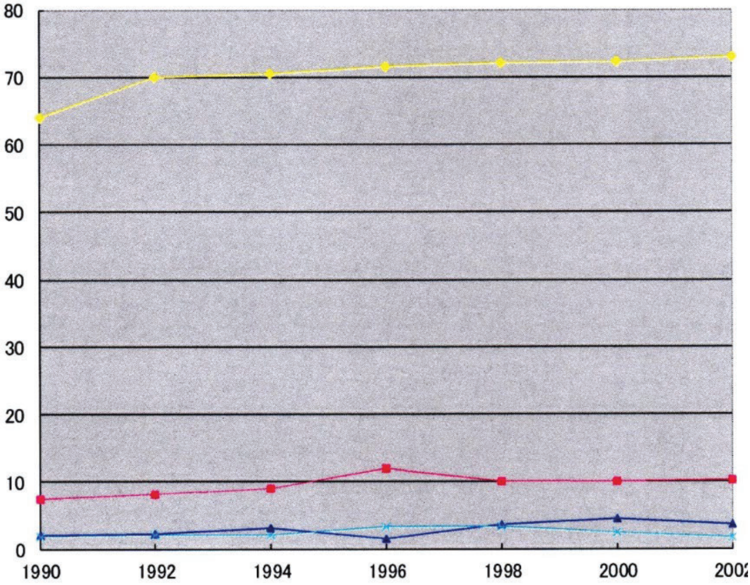


Figure 4-9. The market share of Fanuc's numerical controller amounted to all the machine tools displayed at JIMTOF (Japan International Machine Tool Fair)
Note: Mitsubishi (■); Okuma (▲).

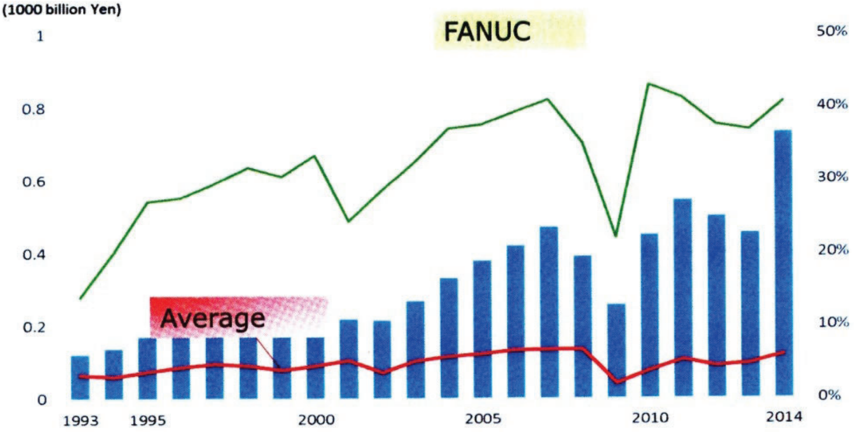


Figure 4-10. Fanuc's operating profit in 1993-2014
Note: Fanuc's revenue displayed in bar graph

In this figure, the revenue of Fanuc is plotted in the bar graph, and Fanuc's operating profit ratio to total sales is displayed and compared with the average figure of companies listed in the first section of the Tokyo stock market. It is to be noted that Intel's profit ratio was around 20% in the period of 1992–2000. We can see how high Fanuc's figure is as well as how stable this figure is in the longer term.

Another important aspect of platform leadership is to establish an evolving system made of interdependent pieces that can be innovated upon. Indeed, the integration of a PC function into the display unit of an NC could launch a *renewed* process of digital convergence into the *downstream* sector, *i.e.* machine tool industry, as will be described below. Through the process of digital convergence, we come to the optimal partitioning of the system. This optimal partition provides the platform, and this partitioning also helps in establishing the platform leadership.

By reviewing the findings made so far in this chapter, especially in the sequence of proposed innovation concepts, we suggest the following sequencing based on the evidence of the development of the Japanese machine tool industry since the 1970s: disruptive technology[29]; technology fusion[30]; open innovation[31]; digital convergence[32]; and finally platform leadership[33]. In other words, having successfully undergone several transitions that occurred during the period 1975-2015, the Japanese production of machine tools was able to maintain its top position in the world, as far as the production of CNC (Computerized Numerical Control) machines is concerned, for a long period that spanned over more than a quarter of a century, as was depicted before in **Figure 4-1**.

6. Cautious Globalization

The integration of a PC function into the display unit of an NC made possible an NC system with flexible and enhanced PC functions such as databases and *networking*. The database function, for example, enabled the NC operator to manage tool files, customize operation screens, and freely build human interfaces. The PC's networking function could also be used to operate the NC in a factory from a remote location via the internet. In this context, Mori Seiki Co. Ltd., a leading Japanese machine tool manufacturer and user of NC controllers, developed their own PC－NC by inserting consumer PCs into the display module of their NC system, and thus enabling networking via the internet. Development began in 1997, and the MAPPS (Mori Advanced Programming Production System) was released in 2000. Mori Seiki has now completed an improved version, MAPPS III. This has enabled Mori Seiki to produce their own common specifications for operation and display methods *independently* of NC controller manufacturers, as depicted in **Figure 4-11**.

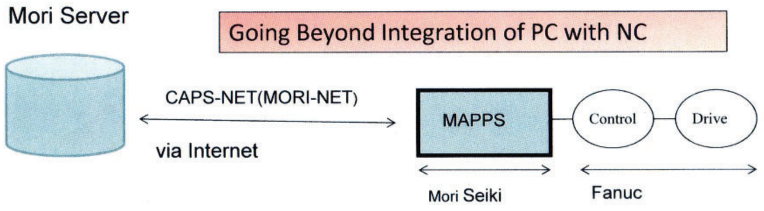


Figure 4-11. Going beyond the integration of PCs with NCs[34]

As far as globalization is concerned, a *cautious* stance in strategic positioning is conspicuous when Japanese companies extend their business into the global landscape. This implies that priority is placed on business *integration* rather than on the termination of unprofitable parts of business. In May 2015, an M&A (merger and acquisition) between the Japanese Mori Seiki Co. and the German DMG Co. (Gildenmeister Aktien Gesellschaft) was formally announced. It was reported in Germany that a "mouse" had swallowed a "cat" (*Nikkei Business*, May 25, 2015). Indeed, Mori Seiki (the world's 5th largest machine tool company as of February 2014) acquired 52.4% of DMG's stock (the 2nd largest in the world). While DMG had been established in 1870 and its total sales were ¥289.8 billion in 2014, Mori Seiki, which was established only in 1948, had total sales of ¥117.8 billion. Thus, DMG-Mori Seiki Co. became the largest company in the world, surpassing a Chinese company. It is interesting to note that this DMG-Mori merger occurred in coincidence with the time at which the German machine tool production volume caught up with Japanese production volume (see **Figure 4-1**), approximately 30 years after the Japanese number had caught up with the German number in 1982 (see **Figure 4-3**).

It is also to be noted that Mori Seiki spent a rather long period of *6 years* to complete this merger. In most cases of M&A, priority is often placed on the termination of unprofitable businesses and the reduction of the number of employees, rather than on business integration such as joint product development and the sharing of distribution channels. For this purpose, *two* specific methods were employed, which are almost opposite to the conventional wisdom and practice in M&As. The *first* is about "double staffing in management," where two managers from each company were assigned to the same management position, because they thought the German system was better in procedures and rule-making for systems integration, while the Japanese system was stronger in production scheduling and operation strategy.

The *second* is that enough time and budget was allocated to make possible good *communication* between the employees of the two companies. Their basic philosophies on the designs were different from each other. DMG's lathe uses more common parts, and thus costs less than Mori's machine, while Mori tries to accommodate every detail of the customers' demands and thus uses fewer common parts, even in situations where a cost reduction is possible. Thus they came to a common understanding with each other: there was no difference in accommodating customers' requirements, but customers' demands in Germany and in Japan are different from each other. In short, an M&A will not work properly unless the two parties know each other well.

While all the other Japanese machine tool builders increased their reliance upon the Chinese market, this alliance between DMG and Mori worked in keeping their market more reliant on the advanced countries. This might work favorably for DMG-Mori in the event of the drastic decline of the Chinese market in the midst of the US-China trade dispute (*Nikkei*, September 12, 2018). In order to receive the order of a higher grade, in addition, DMG-Mori internalized the production of critical components such as the "ball screw," and this enabled them to shorten the delivery time (*Nikkei*, December 20, 2018).

Conclusion

In the 1990s, innovation research scholars proposed several new concepts, one after another, but independently and in a chronological sequence: technology fusion; digital convergence; disruptive technology; platform leadership; and open innovation. We have shown that the Japanese machine tool industry could overcome these changes in patterns of innovation systematically during the period 1975-2015.

Fanuc’s inventions in the early stages of this development *disrupted* the trajectory of the conventional mode of technological development in the machine tool industry. Based on this finding, we might generalize that a new Kondratieff wave arises whenever a disruptive innovation occurs. We also find that the existence of disruptive innovations is a necessary condition for technology fusion to be realized. However, by the realization of technology fusion can the market need be met and the demand for disruptive component technologies articulated and pulled into the market.

Technology fusion produces a converged unit for technology diffusion, which leads to the phase of open innovation. Through the process of open innovation, we can come more or less to the optimal module *partition* of a system. Only after the optimal module structure has been reached can two different digital systems (PC and NC) start *converging*. By trying all the possible combinations, we can reach a converged digital system. And this converged system then becomes a platform, and also provides a platform leadership.

By reviewing the findings made so far in this chapter, especially in the sequence of proposed innovation concepts, we suggest the following sequencing based on the evidence of the development of the Japanese machine tool industry since the 1970s: disruptive technology; technology fusion; open innovation; digital convergence; and finally platform leadership. In other words, having successfully undergone several transitions that occurred during the period 1975-2015, the Japanese production of machine tools was able to maintain its top position in the world, as far as the production of CNC (Computerized Numerical Control) machines is concerned, for a long period that spanned over more than a quarter of a century.

Notes

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[1] Encyclopedia.com

[2] More recently, Perez placed the phases with the following labels: the beginning of a technological era as *irruption*, the ascent as *frenzy*, the rapid build out as *synergy* and the completion as *maturity*. See Perez, C. (2002). *Technological Revolutions and Financial Capital: The Dynamics of Bubbles and Golden Ages*. Cheltenham: Edward Elgar.

[3] National Research Council (1983). *International Competition in Advanced Technology: Decision for America.* Washington, D.C.: National Academy Press, 28-38.

[4] Kodama, F. et al. (1986). *The Innovation Spiral: A New Look at Recent Technological Advances*. Paper presented at the Second US-Japan Conference on High Technology and the International Environment, Kyoto, Japan.

[5] Christensen, C. (1997). *The Innovator's Dilemma*. Boston: Harvard Business School Press.

[6] Christensen, C. and Ryanor, M. (2003). *The Innovator's Solution*, Boston: Harvard Business School Press.

[7] Ibid.

[8] Kodama, F. (1986). Technology fusion as a new pattern of innovation and its analysis [in Japanese]. *Bulletin of Japanese Society for Mechanical Engineers, 89*(80), 44-49; Kodama, F. (1986). Inter-disciplinary research: Japanese innovation in mechatronics technology. *Science and Public Policy, 13*(1), 44-51.

[9] Kodama, F. (1992). Japan's Unique Capability to Innovate: Technology Fusion and its International Implications. In T. Arrison, C. Bergsten, E. Graham, and M.S. Harris (Eds.), *Japan's Growing Technological Capability: Implications for the U.S. Economy* (pp. 149-164). Washington, D.C.: National Academy Press.

[10] Kodama, F. (1992). Technology Fusion and the New R&D. *Harvard Business*

Review, 70(4), 72－75; Tidd, J., Bessant, J., and Pavitt, J. (1997). *Managing Innovation*. Chichester: John Wiley & Sons; Lee, G. (2008). Relevance of organizational capabilities and its dynamics: What to learn from entrants' product portfolios about the determinants of entry timing. *Strategic Management Journal, 29*, 1257–1280; Lee Kong-rae, ed. (2017). *Managing convergence in innovation: The new paradigm of technological innovation*. London: Routledge.

[11] Christensen, C. and Rosenbloom, R. (1995). Explaining the attacker's advantage: technological patterns, organizational dynamics and the value network. *Research Policy, 24*, 233–57.

[12] Kodama, F. (1986). Inter-disciplinary research: Japanese innovation in mechatronics technology. *Science and Public Policy, 13*(1), 44-51.

[13] Kodama, F. (2017). Beyond fusion towards IoT by way of open innovation. *Journal of Open Innovation*, *3*, 23.

[14] Shibata, T., and Kodama, M. (2008). Managing technological transition from old to new technology: Case of Fanuc's successful transition. *Business Strategy Series, 9*(4), 157–162.

[15] Chesbrough, H. (2003). *Open Innovation: The New Imperative for Creating and Profiting from Technology*. Boston: Harvard Business School Press.

[16] Shibata, T., and Kodama, M. (2008). Managing technological transition from old to new technology.

[17] Mazzoleni, R. (1997). Learning and path-dependence in the diffusion of innovations: Comparative evidence on numerically controlled machine tools. *Research Policy, 26*, 405–428.

[18] The top ten companies list of total sales of machine tools shows that Japanese manufacturers dominated in 1987 except for Cincinnati Milacron of the US, while the US companies had dominated in the list of 1971. See Heinrich, A. (2001). *The recent history of the machine tool industry and the effects of technological change.* Available at
http://www.bwl.unimuenchen.de/forschung/diskus_beitraege/working
paper/1833.pdf.

[19] Holland, M. (1989). *When the machine stopped.* Boston: Harvard Business School Press.

[20] Ehrnberg, E. and Jacobsson, S. (1997). Indicators of discontinuous technological change: an exploratory study of two discontinuities in the machine tool industry. *R&D Management, 27*(2), 107-126.

[21] Tushman, M. and O'Reilly, C. (1997). *Winning through Innovation*. Boston: Harvard Business School Press.

[22] Shibata, T. and Kodama, M. (2008). Managing technological transition from old to new technology.

[23] Shibata, T. (2011). Managing the change of architecture knowledge. *Int. J. Innov. Manage, 15*(5), 1093–1112.

[24] Yoffie, D. (1996). Competing in the Age of Digital Convergence. *California Management Review, 38*, 31-53.

[25] Shibata, T. (2009). Product innovation through module dynamics. *Journal of Engineering Technology Management, 26*, 46–56.

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[26] Kodama, F. (1998). Innovation formulated as a learning process [in Japanese]. *Journal of the Japanese society for quality control, 28*(4), 5-14.

[27] Shibata, T. (2009). Product innovation through module dynamics.

[28] Gawer, A. and Cusumano, M. (2002). *Platform Leadership: How Intel, Microsoft, and Cisco Drive Industry Innovation.* Boston: Harvard Business School Press.

[29] Christensen, C. (1997). *The Innovator's Dilemma*.

[30] Kodama, F. (1992). Technology Fusion and the New R&D.

[31] Chesbrough H. (2003). *Open Innovation*.

[32] Yoffie, D. (1996). Competing in the Age of Digital Convergence.

[33] Gawer, A. and Cusumano, M. (2002). *Platform Leadership*.

[34] Shibata, T. (2016). IoT and innovation [in Japanese]. *Newscom*, 27: 4–13.

CHAPTER FIVE

CONNECTIVITY ARTICULATION: JOURNEY TOWARD THE 4^{TH} INDUSTRIAL REVOLUTION

The German National Academy of Science and Engineering[1] published a report about what is now called "Industry 4.0." It says that Germany is uniquely positioned to *tap* into the potential of a new type of industrialization—Industrie 4.0—since Germany is a global leader in the manufacturing equipment sector.

The first *three* industrial revolutions came about as a result of mechanization, electricity and IT (Information Technology). Now, the introduction of the Internet of Things (IoT) and services into the manufacturing environment is leading to a *fourth* industrial revolution. In the future, businesses will establish global *networks* that incorporate their machinery, warehousing systems and production facilities in the shape of *Cyber-Physical Systems* (CPSs).

> In the manufacturing environment, these CPSs comprise smart machines, storage systems and production facilities capable of autonomously exchanging information, triggering actions and controlling each other independently. This facilitates fundamental improvements to the industrial

> processes involved in manufacturing, engineering, material usage and supply chain and life cycle management.

In a similar context, Schwab[2] asserted that the 4th Industrial *Revolution* is characterized by a *fusion* of technologies that is *blurring* the lines between the physical, digital, and biological spheres. The relentless shift from *simple* digitization (the 3rd Industrial Revolution) to innovation based on *combinations* of technologies (the 4th Industrial Revolution) is forcing companies to reexamine the way they do business[3].

Indeed, the 4th Industrial Revolution is being called a "paradigm shift," as far as a pattern of innovation is concerned. This was also true when the preceding industrial revolutions occurred[4]. Therefore, we can formulate these changes as a change in the mode of technological learning. As is well known, the existence of "learning-by-doing" was first emphasized by Arrow[5]. This is a form of learning that takes place at the manufacturing stage after a product design has been specified. When it comes to those industries characterized by a high degree of systemic complexity such as the *computer* industry, however, learning-by-doing becomes a very *subtle* process. In this context, Rosenberg[6] proposed a clear distinction between "learning-by-doing" and "learning-by-using."

While the computing capacity of the US increased a hundredfold in the 1970s and 1980s, labor productivity growth slowed from over 3 percent in the 1960s to roughly 1 percent in the 1980s. This perceived *paradox* was conceptualized as Solow's computer paradox[7]. It was defined as a perceived discrepancy between measures of investment in information technology and measures of output at the national level. In this same article, Solow argued, it would depend not just on the possibilities the technologies represent, but also on how effectively they are *used*.

In her study on the invention process of the Internet, meanwhile, Abbate described the transformation of computer technology: the computer, originally conceived as an isolated calculating device, was *reborn* as a means of communication[8]. We had to wait until 2012 for the total value of market capitalization of the four major oil firms (Exxon, Shell, BP, and Chevron) to be surpassed by that of the four major data firms (Alphabet, Apple, Facebook, and Amazon), as shown in **Figure 5-1**.

Indeed, IT has obviously brought about new *modes* of technological learning by both IT giants and by IT module suppliers. However, the mode of learning becomes even more different when it comes to the 4th Industrial Revolution, in which the Internet is supposed to play a major role. The IoT is *defined* by the ITU (International Telecommunication Union) as a global *infrastructure* for the information society, enabling advanced services by *interconnecting* (physical and virtual) *things* based on existing and evolving interoperable information and communication technologies. When it comes to building CPSs, the ITU[9] declared:

> When the IoT system is *augmented* with *sensors* and *actuators*, the technology becomes an instance of the more general class of CPS, which also encompasses technologies such as smart grids, smart homes, intelligent transportation and smart cities.

For a realization of Industry 4.0, therefore, we need to understand the learning mode of module suppliers for CPSs, particularly, in the areas of *sensors* and of *actuators*. Thereafter, we will try to comprehend how the *fusion* of physical and cyber spaces will be implemented.

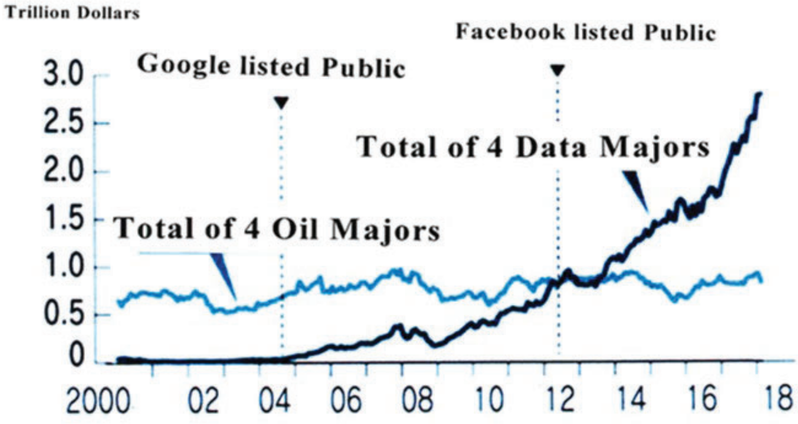

Figure 5-1. Change in market capitalization value of major oil and data firms (*Nikkei*, April 3, 2018)

1. Unexpected arrival of IT innovations

The United States–Japan dialogues[10] from 1984 to 2000, organized by the US National Academies of Sciences and Engineering (NAS/E) and the Japan Society for the Promotion of Science (JSPS), were part of a larger context of science and technology relationships that took on added urgency and complexity when Japan emerged as a technological power in the 1970s. Viewed from a US perspective, the central factor stimulating interest in new initiatives in the late 1970s and early 1980s was concern about US technology leadership—in terms of both the threat and the opportunity that Japan presented[11].

Unlike government-to-government meetings, bilateral meetings of the type convened by the NAS/E and the JSPS were not negotiations designed to lead to formal agreements. Nevertheless, these meetings and related activities provided unique opportunities for leaders from the private sectors in the two countries to exchange views about pressing issues. This dialogue was one stream of activity among many related to US-Japan relations. What distinguished them, however, was the participation of leaders from the S/T (Science and Technology) community, including business people, in informal discussions focusing on the science and technology dimensions of the bilateral relationship, with particular attention paid to the economic implications. At the very end, the US chairman of this US-Japan dialogue, Harold Brown (the former Secretary of Defense in the Carter administration), summarized the dialogue thus[12]:

> In manufacturing, Japan's pursuit of automation has been less important than the use of information technology by US firms to get a better handle on the processes. US firms took Japanese practices like just-in-time systems and added information technology. This greatly strengthened US industry, which has been comparatively strong in services but also in other areas as well. We learned, but the Japanese failed to adjust. Although the Japanese did well in computer hardware, US firms did much better in software where the *freewheeling* use of younger people made a big difference. IBM was worried in the 1980s about the Japanese firms as major competitors, but Microsoft and Intel brought IBM low. Japan could never make a Microsoft.

This assertion, we could argue, contains substantial implications, when we put this statement in a broader context: 1) why the Japanese did well in computer hardware; 2) how Microsoft and Intel brought IBM low; and 3) why the *freewheeling* use of younger people made a big difference.

1.1 Emergence of IT giants: Learning-by-comprehending

In order to answer these questions, we have to review the arguments made on the *unique* nature of the computer revolutions. We will bring these arguments into a more general perspective on technology learning. The innovation process can be best formulated as a *learning* process by society. As is well known, the existence of “learning-by-doing” was first emphasized by Arrow[13] in his article "The Economic Implications of Learning by Doing." This is a form of learning that takes place at the manufacturing stage after a product design has been specified. Learning at this stage consists of developing increasing skills in production. This has the effect of reducing real labor costs per unit of production.

When it comes to those industries characterized by a high degree of systemic complexity such as the computer industry, however, learning-by-doing becomes a very *subtle* process. In this context, Rosenberg[14] proposed a clear distinction between “learning-by-doing” and “learning-by-using.” He argues that one of the basic purposes of the learning-by-using process is to determine the optimal *performance* characteristics of a durable *capital good* as they affect the length of useful *life*. He also suggested that the creative use of learning-by-using as a business strategy may be an important factor in the computer industry, which relies on complex *software* products to make its systems useful to a broader range of users. The development of effective software is highly dependent upon *user* experience. Indeed, many computer companies routinely provide extensive software support that involves software modification when bugs are discovered by customers by whom the software is *used*.

However, it is obvious that IT businesses are going beyond a simple software development business and are becoming *networking* businesses. Abbate[15] described a network's best-known legacies as the introduction of packet switching and other new techniques and the establishment of a unique tradition of decentralized, user-directed development. Electronic mail and the World Wide Web are prominent examples of informally created applications that became popular, not as the result of some central agency's marketing plan, but through the *spontaneous* decisions of thousands of independent *users*.

Only after we had finished the process of learning-by-using in a sufficient way, therefore, did we arrive at the age of IT. Thereafter, Microsoft and Intel brought IBM low. If you try to formulate IT innovations as a learning process, therefore, we will find that neither learning-by-doing nor learning-by-using is appropriate: the former is appropriate only in the manufacturing industry and the latter is appropriate only for software development businesses. And, as everyone knows, it is also true that the *freewheeling* use of younger people in the United States made a big difference.

In this context, we need a much more *systemic* explanation on this phenomenon. Apple, for example, selectively procured all the goods for *functional* parts from all over the world, and integrated them into their unique systems. Without *comprehending* the characteristics of each individual component and the interactive relationships among them, however, it could not have been possible for Apple to succeed in its system development. For the Macintosh, Apple utilized Sony’s Trinitron TV screen and Canon’s laser printer. For the iPad, it used multi-touch technology, according to Jobs’s saying that the best pointer is your *finger*[16]. Indeed, the IT revolution was realized by the freewheeling use of young talents in the United States. With their deep *comprehension* of the intrinsic value of emerging component technologies, they could *articulate* the demand for components making up their IT system. Therefore, we can introduce "learning-by-comprehending" as a learning mode for IT giants. The evidence for this argument is vividly demonstrated by **Figure 5-2**, in which the cumulative number of companies acquired by the IT Big Five (Apple, Google, Alphabet, Amazon, and Facebook) since 2000 is depicted. As can be seen, the number of acquisitions has increased drastically since 2010. The integration of functional parts procured from all over the world was implemented in the form of their acquisitions of various companies throughout the world.

1.2 Intel’s platform leadership: Learning-by-accommodation

It is to be noted that IT giants emerged only after a platform leadership was accomplished in critical IT components such as Intel’s MPU (Micro Processor Unit). Therefore, we are interested in formulating the learning process which occurred for Intel’s MPU, especially before MPU 8086 was adopted by IBM PCs in 1981. We will discover that Intel successfully *accommodated* the different customers’ specific demands one after another. Therefore, we can call this learning “learning-by-accommodation.” In order

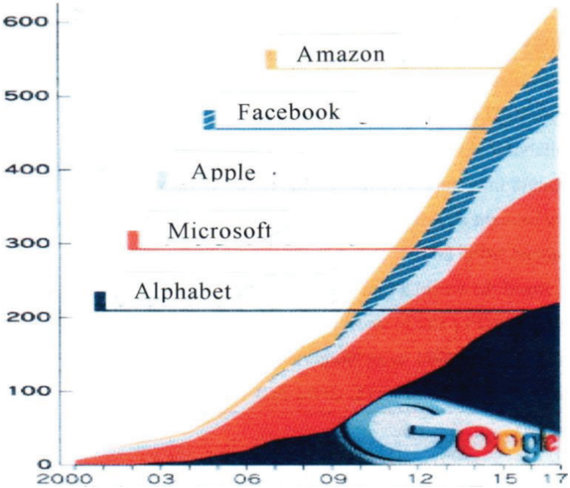

Figure 5-2. The cumulative number of companies acquired by the IT Big Five (*Nikkei*, February 12) 2018)

to validate this argument, we have to answer the question about *who* really discovered the market for the MPU, *i.e.* how the demand for Intel's MPUs was *articulated* and by whom. Consequently, the chronology of MPU development in the first ten years after Intel was established has been compiled, and is shown in **Table 5-1**.

As is shown in the table, several Japanese companies, including Fanuc, were involved in this kind of *demand articulation* for MPUs in Intel's first ten years of existence, its *embryonic* stage. A Japanese calculator company, *Bisicom* (named after "Business computer"), had the idea of designing a calculator on the basis of general-purpose large-scale integration (LSI), and sent an order to Intel in 1970. However, Bisicom did not hold on in the severe market competition which followed after this order was made. The manner in which Intel developed MPU 4004 by accommodating this order by Busicom has been well documented by Shima[17], who developed an idea in Bisicom and was later recruited by Intel. Becoming aware of its future potential, meanwhile, Intel purchased the right of outside sales from Bisicom in 1971.

Table 5-1. Chronology of mounting MPUs in products

In 1971, Busicom (calculator supplier) of Japan marketed 141-PF (mounted MPU 4004)
In 1971, Intel brought MPU 4004 to market
In 1972, Intel collaborated with Seiko of Japan for MPU 8008
In 1972, Seiko brought a programmable calculator with MPU 8008 to market
In 1973, Toshiba Tec brought a cash register (with MPU 4004 mounted) to market
In 1974, Intel announced MPU 8080
In 1975, Fanuc developed the world's first NC system (Fanuc 2000C) built on Intel 3000.
In 1976, Apple mounted MOS 6502 in its Apple-I
In 1979, Fanuc mounted MPU 8086 in its Numerical Controller
In 1981, IBM mounted MPU 8086 in its PCs

Compiled by Yasushi Baba based on Okuda[18]

The company that brought MPU 4004 into its first mass-produced application was Toshiba Tec Corporation, which succeeded in applying it to its "cash register." It is to be noted that Toshiba Tec introduced

MPU 4004 into its cash register *earlier* than NCR Corporation of United States did[19]. In 1973, Toshiba Tec sold nine thousand units of its register to German gasoline stations. In Japan, their products were used in a different environment to the office, such as in *fish* markets. Since the conditions in which Toshiba Tec's registers were being used were very demanding and gave a heavy load to the machine, they had to solve many malfunctions in its early stage of development. At that time, Intel was confronted with a difficult financial situation, but the order of magnitude of several thousand units per week did help Intel in solving this financial problem. When developing the MPU 8008, Seiko Co. of Japan collaborated with Intel, in order to introduce its "programmable calculator," the S-500 model. Indeed, it was the first LSI desktop computer in the world[20].

In Chapter 4, we described in detail how Fanuc had *built* its architectural knowledge through their *collaboration* with Intel. In 1978, Intel developed the 8086, a technologically advanced and sophisticated 16-bit MPU, the first single-chip MPU in the world that enabled customers to write their own programs. In 1979, the Fanuc system 6 series used the Intel 8086 MPU. To develop this advanced system 6 series, Fanuc aggressively pursued an intensive *collaboration* with Intel to absorb and build architectural knowledge *centered* on the Intel 8086. As described in Chapter 4, it was a two-way and *reciprocal* collaboration between Intel and Fanuc. The success of adopting the 8086 into the system 6 series made Fanuc competitive in the NC (Numerically Controlled) machine tool industry. Beginning in 1979, one year after the introduction of the 8086 MPU, Fanuc became its *first* high volume user in the world for its system 6 series NC. It is also *surprising* that a machine-tool supplier utilized the MPU technology for product development *earlier* than the PC (personal computer) industry.

In 1981, Intel developed the 8088, a partially *improved* version of the 8086, which was installed for *IBM PCs*. After that, Intel started allocating their resources to the MPU business, away from DRAM (Dynamic Random Access Memory). In that sense, the 8086 turned out to be the beginning of Intel's *platform* leadership of the PC industry. What characterized the way in which Intel became a dominant supplier in the PC industry? How did Intel learn the way in which a series of different demands by early customers could be accommodated successfully? We can answer these questions with the concept of "learning-by-accommodation"; neither learning-by-doing nor learning-by-using.

2. Connectivity articulation in IoT innovations

In 2006, when the financial crisis was not yet visible, no IT company except Microsoft was in the list of the top 20 companies in terms of market capitalization value. As many as five financial institutions, including three American companies (City Group, the Bank of America, and American International Group), were listed. After the financial crisis was over, as many as seven out of the top ten companies were IT giants. In terms of the growth in the market capitalization value of these IT giants since 2008 (the value in September 2008 is displayed as 100), we can note that the gap between Amazon/Apple on the one hand and Google/Facebook on the other drastically widens in 2015-2018 (*Nikkei*, October 3, 2018). We might be able to argue that this demarcation is related to that which exists between the IoT and pure IT companies. As of January 2019, moreover, Amazon has finally obtained the top position among the GAFAM (Google, Apple, Facebook, Amazon and Microsoft) by surpassing Apple, a status which it achieved 22 years after its stock went public.

The IoT is defined as the internetworking of physical devices, vehicles, buildings and other items (embedded with electronics, software, sensors, actuators). Its network *connectivity* enables these objects to collect and exchange data. The IoT allows objects to be sensed and/or controlled remotely across existing network infrastructure, creating opportunities for a more direct integration of the physical world into computer-based systems, and resulting in improved efficiency, accuracy and economic benefit. IoT will bring us a new mode of learning. Therefore, we are interested in analyzing how *connectivity* is to be articulated in IoT's development.

2.1 Building connectivity: The Komtrax system

A good example of connectivity articulation can be found in a construction machinery company. A Japanese construction machinery supplier, Komatsu Co. Ltd., turned out to be the *first* company that introduced disruptive technologies such as RFID (Radio Frequency Identification) and GPS (Global Positioning System) for the development of building lots, and now is a market leader in construction businesses[21]. As is shown in **Figure 5-3**, RFID sensors are inserted inside their machines that are operating all over the world, and all the data collected about their operating conditions is sent to Komatsu headquarters in Tokyo via *satellite* communication. The system Komatsu developed is called the "Komtrax" system. They started its operation in 2001.

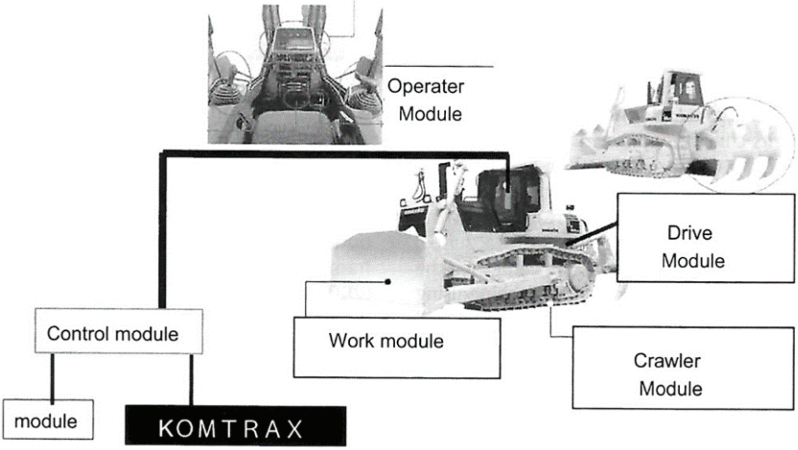

Figure 5-3. Komtrax system[22]

Having developed Komtrax, Komatsu could enhance its customer service drastically by providing customers with a timely exchange and repair of parts and also with theft prevention. Generally speaking, the running cost of construction machinery is three times as high as the purchase cost. The elimination of all the wasted actions and out-of-order situations, which becomes possible by the use of the operating data collected by Komtrax, is therefore very advantageous to customers. The sales agents located around the world can also benefit by reducing their inventory.

Upgrading the use of the Komtrax system to the *corporate* management system became possible by the following sequences and events. The data about the operation conditions of their machines, which becomes available due to Komtrax, is effectively utilized for discussions on demand forecasting conducted at the head office. Based on this demand estimate, production schedules and investment plans for equipment at each factory are decided. In 2004, for example, the Chinese economy was in a period of downturn, due to the financial policy implemented by the government. The data collected by Komtrax clearly showed that the operating ratios of their machines in China were abnormally low. Before the recession was officially announced by the Chinese government offices, Komatsu halted their production for three months. It gave Komatsu an enormous advantage over its competitors.

2.2 Learning-by-porting

When we entered the 2000s, the combination of ICTs (Information and Communication Technologies) with various kinds of machinery was expected to play a strategic role in the learning process associated with the emerging post-industrialized society. In the case of the Komtrax system, the introduction of ICTs provided machinery suppliers with a drastic widening of the range of service activities and also enhanced service quality. A qualitative leap in business activities was attained by the utilization of big-data provided by the Komtrax system in corporate decision-making. This had not been originally intended nor planned since it is obvious that the Komtrax system was developed mainly for the improvement of after-sales activities by construction machinery providers. This prototypical case of the enhanced use of big-data available through the on-line and world-wide aggregation of operation data, however, might trigger improvements in the quality of corporate decision-making countrywide, because the potential demand for this type of utilization of big operation data exists in any company in any industrial sector.

By viewing technological progress as an evolutional process, therefore, we can suggest a new framework of analysis for IoT innovation. Two Harvard Business School scholars, Baldwin and Clark[23], in this context, tried to use the computer as the powerful lens through which to observe and study the evolution of designs, and the development of an industry. Strikingly, they found out that the changes that can be imagined in a modular structure are spanned by only six, relatively simple modular operators. These operators can generate all the possible evolutionary paths for the structure. The six modular operators are: splitting, substituting, augmenting, excluding, inverting, and porting. The "porting" operator, as the name suggests, ports the modules to other systems. The other five operators only work within their respective system. Porting occurs when a hidden module "breaks loose" and is able to function (via translation) in more than one system, under different sets of design rules, *i.e.* a different architecture.

We can comprehend the importance of porting by referring to the invention of the iPod, for which Steve Jobs asserted: "it is because of these really great *Japanese consumer electronics companies* who kind of own the *portable music* market, invented it and owned it, couldn't do the appropriate *software*"[24]. The iPod innovation by Apple inaugurated the new innovation cycle of portable music by coming up with a music *service* that you do not have to subscribe to; just by buying music at 99 cents a song, you have the rights to use it. In other words, Apple invented the system-of-use in which a portable receiver is to be *ported* into the system of a music delivery service.

In the early stage of Komtrax's development, its function was hidden in the Control Module, as was depicted earlier in the right-bottom corner of Figure 5-3[25]. This module was then *ported* to Komatsu's corporate management system. The porting process of the Komtrax module is shown in **Figure 5-4** by following the format suggested by Baldwin and Clark.

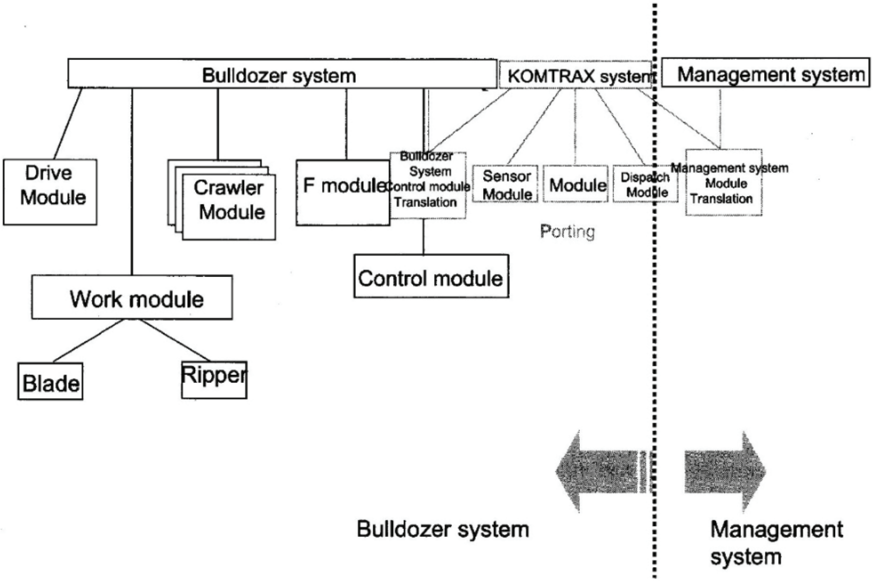

Figure 5-4. Porting of Komtrax to Corporate Management System[26]

The analyses described above have shown us how an evolutionary framework can be applied to the emerging pattern of IoT innovation. They also indicate that IoT innovation is made possible by applying the porting operator within the modular structures consisting of technology and service modules. Therefore, we can phrase "learning-by-porting" as the mode of learning in the IoT revolution.

2.3 Agent of articulation

Now, we are interested in how the *proces*s of demand articulation in IoT innovation differs from that of a stand-alone product. We will show the process is gradual, incremental, and, most importantly, it is essentially *additive*, *i.e.* value is added continuously. The next question is *who* triggers the articulation process. We will find an interesting example by investigating Komtrax's development in depth.

As you can easily imagine, the development of Komtrax was not as *straightforward* as we might expect. In the mid-1990s, the country's investment in the construction business fell significantly. Facing this reduced investment, companies had to revise the ways in which machinery was procured. This meant a shift away from ownership to *leasing* and *rental* (21 percent of machinery was either leased or rented by 1993, 30 percent by 1997, and 40 percent by 2006). In 1997, Mr. Masahiro Sakane, an engineer (who later became CEO of Komatsu Co. in 2001), was appointed as a director of the business planning and administration office. At the time, this office was staffed by people dispatched from various divisions. At the end of 1997, the office had received a 10 page-long business plan from engineers dispatched from the development department. This plan was for a *business model* for remotely monitoring machinery, which was in effect the prototype of the Komtrax system.

Having spent a long time in the service department, this new director had a deep appreciation of the *intricacies* of how to manage the maintenance of construction machinery, and hence well understood the value and potential of the Komtrax system, and thus, this idea proceeded into the development stage. In this regard, the Komtrax development was initiated as a kind of local project using the funds provided by the business planning and administration office. The company had completed five prototypes by 1998, and asked Mr. Chikashi Shike, the owner of Big Rental (a rental company in Koriyama in Fukushima prefecture), which had only started up in 1997, to test the five prototypes. At that time, Mr. Shike had also been thinking about a brand-new rental *business model* that entailed using IT for centralized management to raise the utilization rates of rental construction machinery, and because this remote construction machinery monitoring system fit well with his idea, he agreed to take on the prototypes for testing. Being engaged in a rental business, he had no difficulties in understanding the *inherent* value of the Komtrax system.

At the end of 1998, it was suggested at Komatsu that *fifty* pieces of equipment should be subsequently tested. However, at a development meeting, supervising executives took a *negative* view regarding continued testing. At that meeting, meanwhile, Mr. Shike of Big Rental was asked for his opinions about the commercial advantages of developing the remote monitoring system. He explained that the system was a piece of remote communications *infrastructure*, and thus it was not an appropriate time to discuss in detail what sorts of businesses would be enabled by it[27]. Unfortunately though, it was decided at Komatsu that the remote monitoring system development should be cancelled. The Komatsu development team had not been able to *paint* a picture of a business model using Komtrax, because they did not have an understanding of its *inherent* value.

Nevertheless, Mr. Shike of the rental company, who had understood the value of Komtrax, immediately placed an order for 1,000 units and paid Komatsu ¥150 million—despite Big Rental having only 500 pieces of rental construction machinery at the time. In those days, Komtrax units were *externally* attached and cost ¥150,000 per unit. Thus, such a large order enabled Komatsu to sustain this viable business, and so development was continued informally within Komatsu. At the beginning of 2000, Big Rental grew rapidly and within three years became the *top* rental company in Fukushima prefecture. Indeed, they quickly *retrofitted* all of Big Rental's construction machinery with Komtrax units as soon as the units arrived from Komatsu; at the time, the product consisted of a communications terminal and modem, GPS, a simple CPU, etc.

The capabilities and advantages of Komtrax in the remote management of machinery and in work on construction sites gradually became widely known. Komatsu, meanwhile, filed the *business model patent* for rental businesses. At that time, Komtrax was known as a business model for rental businesses, and was only available as a user option. In June 2001, Mr. Sakane who had launched the Komtrax project became the CEO of Komatsu. He had aggressively pursued the possibility of utilizing Komtrax, not only as a tool for customer service, but also as a tool for *visualizing* corporate management[28]. Mr. Shike of Big Rental, meanwhile, was recruited to Komatsu as an executive officer in 2014. This sequence of events in Komtrax's innovation alludes to the fact that a new type of management was emerging in IoT innovation in the digital economy. An interesting question, here, is who was the agent of demand articulation. In fact, the demand articulation for Komtrax had been made externally, *i.e.* outside of Komatsu headquarters, but within the larger network that involves distribution, manufacturing, and supplying. The person blessed with the capability of demand articulation is found within the eco-system of the construction network, but not necessarily in the core part of the system. But Mr. Shike was recruited to the core part of the total system.

3. CPS module supplying: Learning-by-preemption

As described at the beginning of this chapter, when the IoT system is augmented with *sensors* and *actuators*, the technology becomes an instance of the more general class of CPSs (*cyber-physical* systems). We argued the experience of the IT revolution made it clear that the learning consists of learning-by-accommodation by a key IT module suppler and of learning-by-comprehending by IT giants. In order for Industry 4.0 to be realized, therefore, we should analyze what the learning mode of CPS module suppliers is, particularly, in the areas of *sensors* and of *actuators*.

3.1 Learning-by-preemption

In 2015, Volkswagen AG admitted their years of *cheating* on emissions tests. The VW story of using the *defeat device* is well documented by Ewing[29]. However, it is less well documented that Horiba, Ltd., a Japanese manufacturer that makes up about 80 percent of the world's auto emissions testing system, played a key role in breaking a scandal involving Volkswagen (*Bloomberg*, October 2, 2015). Horiba was established in 1945 by Masao Horiba, with the goal of continuing the nuclear physics research that had been suspended by World War II. During Japan's 1960s postwar economic boom, however, Horiba diversified its products and completed its first emissions analyzer. Its entry into the market was in response to growing unease about air pollution. In 1998, Horiba began developing its first portable *onboard* emissions analyzer, *i.e.* a tool to analyze automotive emission gas while the vehicle is being driven.

But how did Horiba become a detector of Volkswagen's fraud? In fact, US researchers relied on Horiba's portable emissions measuring systems in a multi-year round of testing that ended up catching Volkswagen in a *falsehood* about their engines that it had portrayed as "clean" diesels. Horiba's equipment helped inform the researchers about a scheme in which the Volkswagen group's cars around the world polluted more on the road than in the stationed tests, exceeding the US limit by as much as 40 times above what the law allows. In Europe, the new regulation that enforces the measurement of *running* gas emissions called RDE (Real Driving Emissions) was legislated in September 2017[30]. According to Boston Consulting Group, the 2016 share of diesel cars in total worldwide sales was 19 percent, while in Europe the level remained at 48 percent. However, they forecast that the diesel share will decline down to 12 percent by 2030.

How can we best describe Horiba's accomplishment? Horiba accommodated the *unfulfilled* needs for environmental protection, and the onboard emissions analysis had been neglected by the US and European providers. And Horiba targeted the new markets of "nonconsumption," an expression proposed by Christensen and Raynor.[31] As Christensen argues:

> A new-market disruption is an innovation that enables a larger population of people who previously lacked the money or skill now to begin buying and using a product and doing the job for themselves. From this point onward, we will use the terms nonconsumers and *nonconsumption* to refer to this type of situation, where the job needs to get done but a good solution historically has been beyond reach. We sometimes say that innovators who target these

new markets are competing against nonconsumption.

In order to accommodate the *unfulfilled* needs for Industry 4.0, CPS module suppliers have to take a strategy of nonconsumption. By developing the portable and onboard emissions analyzer, Horiba *preempted* the innovation for the realization of the clean society[32], *i.e.* the realization of Industry 4.0. Therefore, the learning mode for the module suppliers of CPS will be “learning-by-preemption.”

A classic example of this mode of learning can be found in Sony's greatest technical challenge: the development of a high-image quality electronic camera based on charge coupled device (CCD) technology[33]. Sony managed eventually to mass-produce CCDs for their camcorders. Begun in 1973, this thirteen-year project had a development budget that grew from 0.1 percent to 0.36 percent of total company sales between 1974 and 1983, a very high percentage for a single-product program. In order to encourage his engineers, Dr. Iwama, Sony's president at the time, identified a "big target" for their efforts. "Our key competitor is Kodak," Iwama said[34]. With Kodak as the key competitor, the target was not just the replacement of imaging tubes in video cameras, but the creation of an electronic, rather than chemical, technology for taking pictures[35].

3.2 Management of preemption

The validity of the learning mode and the strategic concept implemented by Horiba in the sensor area—learning-by-preemption and the strategy for nonconsumption—can be tested further by examining another important component for the Industry 4.0 system, *i.e.* the *actuator*. Nidec Corporation is a Japanese manufacturer of electric *spindle motors*. The company has the largest global market share for the tiny spindle motor that powers hard-disk drives. As of 2015, the company had *230* subsidiary companies located across Japan, Asia, Europe, and the American continents. The company obtained *42nd* position in the 2005 edition of the BusinessWeek Infotech 100 list. Nidec was also featured on the 2014 Forbes World's Most Innovative Companies list.

The uniqueness of Nidec lies in how it grew up so rapidly, starting from a spindle motor for audio-devices to hard-disk drives for PCs, and it is now expanding its businesses into automobiles, by supplying every kind of actuator in every part of an automobile (*Nikkei*, December 5, 2017). Nidec has accomplished this by a successful and skillful series of *acquisitions* of both domestic and overseas companies: it has acquired a total of *49* companies over *33* years[36]. All the acquisitions have generated *synergies* by combining Nidec's competences with those of the acquired companies. And these synergies made it possible for Nidec to enter into new businesses such as car-related products, and this resulted in a drastic change in their portfolio from 2005 to 2015 (*Nikkei Business*, October 24, 2016). Indeed, the share of precision motors was 51 percent of the total company's sales in 2005, but this was slightly reduced to 38 percent in 2015. On the other hand, the share of motors used for commercial and industrial companies, including car and home appliance manufacturers, was only 7 percent in 2005, but became the largest segment of Nidec's total sales (47.1 percent) in 2015.

Acquisition is a quick way of absorbing necessary technologies, but it is sometimes dangerous to be over-dependent for critical technologies on outsourcing. It does not give any incentives for a progressive development of future businesses. What kind of indigenous R&D activities made possible the drastic growth observed at Nidec in such a short space of time? It was the R&D targeted at making possible technological independence in the midst of rapid acquisitions. We will illustrate a typical example of this kind of R&D activity. This concerns the bearing technology in hard disk devices (HDDs). The dominant design of bearings in HDDs used to be that of ball bearings. The ordinary ball bearings, however, would have a short life or cause high levels of noise and vibrations. *Fluid dynamic bearings* (FDB)[37], on the other hand, are both quieter and cheaper than the ball bearings they replace, as shown in **Figure 5-5**.

The most important performance criterion for an HDD is, of course, the capacity for memory. As the capacity gets larger and larger, the requirements for the motor also get more demanding. The engineers at Nidec become aware that the requirement would soon be beyond the technical evolution of ball bearings. At Nidec, therefore, while they were trying to improve the product based on ball bearing technology, they established an R&D center for FDBs, which is located physically and organizationally far away from the R&D center for ball bearings, *i.e.* according to an *ambidextrous* organization for managing evolutionary and revolutionary change[38].

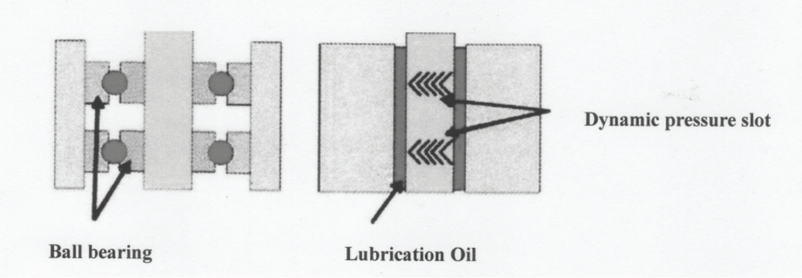

Figure 5-5. Comparison between ball bearings and fluid dynamic bearings[39].

Thus, the successful development of FDBs at Nidec made it possible to replace in a few years the ball bearings which had been the dominant design for the 20 years since HDD had been invented. This technological development put Nidec in a position where it had 78 percent of the market share in motors for HDDs. This pattern follows exactly that which we called "learning-by-preemption," and this strategy aims at "nonconsumption," which proved to be effective in sensor development.

As Nidec expand their products into the area of self-driving automobile systems, their development of actuators will follow the pattern of learning-by preemption and the strategy of nonconsumption much more than before. Otherwise, they will not be able to obtain a large market segment for their actuator business in the future self-driving systems.

4. Fusion between physical and cyber spaces: Multi-porting

As demonstrated in the case of the Komtrax system, an IoT system can be constructed based on learning-by-porting. In order to complete the system for Industry 4.0, *i.e*. a fusion between physical and cyber spaces, however, one porting is not enough. We need a multi-stage and multi-layered porting for an overall solution.

Before we go further into the fusion between physical and cyber spaces, we will look back into the past and revisit the fusion concept that prevailed in the 1990s. As more and more companies accepted fusion and made it a part of their overall technology strategies, it played an increasingly important role in product development. This opened the door to even more cross-industry R&D. In the 1970s and 1980s, technology fusion was limited to the manufacturing industries. It was predicted that, in the future, fusion would go easily beyond the scope of manufacturing. Indeed, two Japanese electronics companies took the first steps toward fulfilling this prediction: Sony acquired Columbia Pictures Entertainment in 1989, and Matsushita (now called Panasonic) purchased MCA Inc. in 1990. As Michael Schulhof, vice chairman of Sony Corporation of America at that time, noted, "The acquisition of a major film studio extends Sony's long-term strategy of building a total entertainment business around the *synergy* of audio and video hardware and software." Akio Morita[40], the chairman of Sony at that time, confirmed Sony's strategy by asserting that the possibilities and synergies created by the *merger* of Japanese hardware and American software were already yielding new products.

Thus, it was a prevailing opinion that the technology-service fusion would be realized in the 1990s without substantial difficulties as a mere extension of technology fusion. However, Panasonic sold MCA quite shortly after the purchase. In retrospect, Steve Jobs is quoted as saying: "What's really interesting is if you look at the reason that the iPod exists… it's because these really great Japanese consumer electronics companies who invented it and owned it, couldn't do the appropriate software"[41]. In summary, the fusion between manufacturing and service has turned out to be much more difficult than we expected. Instead of the simple fusion concept, the concept which can explain the success of the iPod is "porting," wherein a physical technology was ported into the cyber space of music delivery.

In the case of the IoT evolution which is occurring in the machine tool industry, as was described in Chapter 4, two different digital systems—PCs (Personal Computers) and NC (Numerically Controlled) systems—did start *converging*, but only after the PC *ported* into the NC system. Thereafter, the Internet has also been *ported* into the NC system. We can consider that the CPS evolution in the machine tool industry has been realized through the two-stage process of porting: in the *first stage*, the PC module is *ported* into the NC system and, in the *second stage*, the Internet module is *ported* into the PC-NC system, as depicted in **Figure 5-6**. Thus, a new manufacturing *architecture* is emerging wherein different factories are *interconnected* with each other. In short, the combination of PCs' abundant information processing with control functions *heralded* innovations at a more technologically-advanced level, *i.e.* towards CPS evolution.

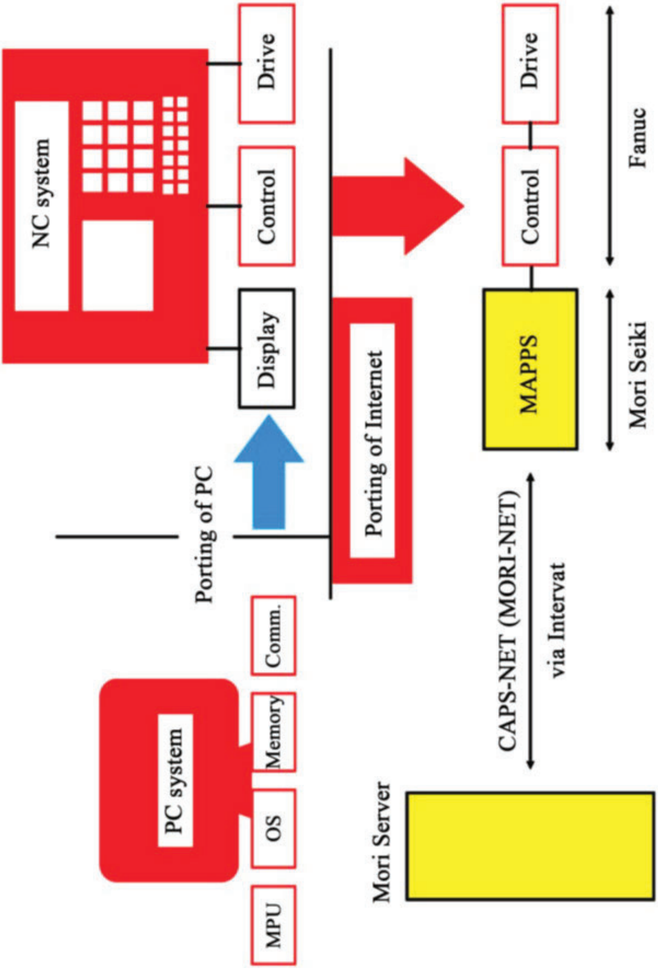

Figure 5-6. A new manufacturing architecture is emerging though two steps of porting[42].

In order to go forward towards CPS, several Japanese machine tool suppliers are initiating collaborations with IT giants both in the United States and Japan. In the development of the *security* system, DMG-Mori

Seiki is collaborating with Microsoft of Japan. In order to develop equipment to protect factory facilities from cyber-attacks, Yamazaki Mazak Corporation is conducting a joint project with US Cisco Systems, Inc. Fanuc is developing its unique system with Cisco Systems to combine IoT with AI (Artificial Intelligence). And Okuma Corporation is collaborating with Hitachi to enhance the efficiency of factories by using IoT (*Nikkei*, July 24, 2017). In 2016, Fanuc announced its plan to offer the FIELD (FANUC Intelligent Edge Link and Drive) system—an open platform used to power the smart manufacturing revolution from the factory floor[43].

The world's largest machine tool supplier, DMG-Mori Seiki, is developing a cyber-physical system: a total management system based on all the available operational data. The analysis of data obtained from the production line composed of various kinds of machines will be utilized for production planning and maintenance. They are planning to install their system in 100 companies locating in the US, Europe, and Japan. In 2017, DMG-Mori established ADAMOS (Adaptive Manufacturing Open Solutions), an IoT platform provider. It is a strategic alliance among DMG-Mori, Dürr, Software AG, ZEISS, and ASM PT. This platform performs a total management of machine tools, measurement instruments, robotics, etc. (*Nikkei*, January 13, 2018) This CPS can also predict the timing for parts changes and production plans. So far it has been difficult to exchange data among the machines, because not only DMG-Mori machines but also other manufacturers' machine tools and conveyer systems are installed. They have already secured several orders. They are going to provide 20 percent of receiving orders for full turn keys with the ADAMOS system.

Conclusion

In this chapter, first of all, we described that the IT revolution is more than just computer innovations, and investigated why the Solow computer paradox phenomenon has disappeared. We analyzed this paradox in terms of modes of learning by both IT giants and by an IT module supplier. Secondly, we moved to the 4th Industrial Revolution, and described that the 4th Industrial Revolution is more than just the 2nd IT Revolution. We analyzed this difference again in terms of learning modes and strategic concepts. It was ascertained that the overall system development of Industry 4.0 will only be constructed by *multi-layered, multi-stage* porting.

We also found that the innovation process for the 4th Industrial Revolution will be gradual, incremental, and, most importantly, essentially *additive*, i.e. the value is added continuously. The innovations in the coming industrial revolution, therefore, are not based on conventional *creative destruction*, but on *creative accumulation*. When the effects of accumulation go beyond a certain threshold level of fusion, however, we can expect that the "*Physical-Cyber Renaissance*" will arrive after we have been wandering through the "Dark Ages" of the 1st, 2nd, and 3rd Industrial Revolutions.

Notes

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[1] German Academy Science and Engineering/Forschungunion (2013). *Securing the Future of German Manufacturing Industry: Recommendations for Implementing the Strategic Initiative INUSTRIE 4.0*.

[2] Schwab, K. (2016). The fourth Industrial Revolution: What it means, how to respond. *Foreign Affairs*, 14 January 2016.

[3] The First Industrial Revolution used water and steam power to mechanize production. The Second used electric power to create mass production. The Third used electronics and information technology to automate production. Now a Fourth

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Industrial Revolution is building on the Third, the digital revolution that has been occurring since the middle of the last century.

[4] Kodama, F. (1991). *Analyzing Japanese high technologies: The techno-paradigm shift*. London: Pinter Publishers.

[5] Arrow, K. (1962). The Economic Implication of Learning by Doing. *Rev. Econ. Stud., 29*, 155–173.

[6] Rosenberg, N. (1982). *Inside the Black Box: Technology and Economics*. Cambridge: Cambridge University Press.

[7] Solow, R. (1987). We'd better watch out. *New York Times Book Review*, 12 July 1987.

[8] Abbate, J. (1999). *Inventing the Internet*. Cambridge, MA: The MIT Press.

[9] ITU (2012). *ITU-T Recommendations.* Available at http://www.itu.int/ITU-T/recommendations/rec.aspx?rec=y.2060

[10] The author of this paper was one of the Japanese core members of this dialogue.

[11] Harris, M. (2000). Mutual learning in US-Japan science and technology exchanges. In Society for Promotion of Sciences (ed.), *The Review of the Activities by the 149 Committee (1984-2000)* (pp. 140-218).

[12] Interview by Martha Harris with Harold Brown on February 10, 1999.

[13] Arrow, K. (1962). The Economic Implication of Learning by Doing.

[14] Rosenberg, N. (1982). *Inside the Black Box: Technology and Economics*.

[15] Abbate, J. (1999). *Inventing the Internet*.

[16] Cupertino Silicon Valley Press, ed. (2011). *Steve Jobs: His own words and wisdom.* Cupertino: Cupertino Silicon Valley Press.

[17] Shima, M. (1984). *How the Microcomputer was born: Behind the development of Intel 4004* [in Japanese]. Tokyo: Iwanami Publisher.

[18] Okuda, K. (2000). *When Intel Was Yet Small* [in Japanese]. Tokyo: Nikkan Kougyou Shimbun Publishing.

[19] Shibata, T. (2008). Japanese cases of parallel development of technologies [in Japanese]. In F. Kodama, ed., *Reading a Change in New Waves of Technology* (pp. 195–198). Tokyo: Nikkei BP Publishing.

[20] Okuda, K. (2000). *When Intel Was yet Small* [in Japanese].

[21] Nikkei Business 2007.

[22] Ibid.

[23] Baldwin, C. and Clark, K. (2000). *Design Rules: The Power of Modularity.* Cambridge, MA: The MIT Press.

[24] Cupertino Silicon Valley Press (2011). *Steve Jobs: His own words and wisdom.*

[25] Kodama, F. (2014). MOT in transition: From technology fusion to technology-service convergence. *Technovation, 34,* 505-512.

[26] Kawasaki, M. (2008). *A vision of construction industry in 2020.* MS dissertation, Shibaura Institute of Technology.

[27] The owner of Big Rental responded by saying that Alexander Graham Bell had not clearly understood what kinds of businesses would be brought about with the development of the telephone. Shike explained that the system was a piece of remote communications infrastructure, and thus there was no point in discussing what sorts of businesses would be enabled by it.

[28] Sakane, M. (2006). *Challenge to management of No.1 Company* [in Japanese].

Tokyo: Nikka-Giren Publishing Inc.

[29] Ewing, J. (2017). *Faster, Higher, Farther: The Inside Story of the Volkswagen Scandal*. New York: Penguin Random House.

[30] Horiba (2015). *Horiba Report 2015* [in Japanese]. Available at http://www.horiba.com/uploads/media/HORIBA_2015AR_jp_HQ.pdf

[31] Christensen, C. and Ryanor, M. (2003). *The Innovator's Solution.* Boston: Harvard Business School Press.

[32] Horiba is now expanding their businesses into areas related to the *self-driving* of automobiles. The performance of the *sensor* is critical to the stable running of self-driving vehicles. In 2015, Horiba acquired the 70-year-old British MIRA Ltd., which was inaugurated by the government's research establishment called the "Motor Industry Research Association." Expecting the *synergy* of Horiba's existing technologies with those owned by MIRA, Horiba is now expanding their business into engineering areas. For its self-driving tests, Horiba is going to use the testing facilities owned by the British MIRA. They are going to provide car manufacturers with a system in which the car-mounted camera will detect the pedestrian and the signpost, and which will thereby control the speed according to the limits displayed on the signpost. The commission Horiba received through this provision of business of self-driving vehicles amounted to as much as seven billion yen (*Nikkei*, June 17, 2017).

[33] The charge-coupled device was invented in 1969 in the United States at AT&T Bell Labs by Willard Boyle and George E. Smith. Several companies, including Fairchild Semiconductor, RCA and Texas Instruments, picked up on the invention and began development programs.

[34] Iwama died in August 1982; subsequently, a CCD chip was placed on his tombstone to acknowledge his contribution.

[35] Kodama, F. (1995). *Emerging Patterns of Innovation.* Boston: Harvard Business School Press, 46.

[36] It was founded in Kyoto in 1973 with only four employees. After working for an audio maker, Shigenobu Nagamori founded Nidec at the age of twenty-eight, setting their objectives as a non-family company, and not to be a sub-supplier, but to become a world enterprise. However, their company remained one of the small motor suppliers. The *first* opportunity of growth came in the mid-1980s, when the PC market suddenly and drastically expanded. Nidec developed a precision motor for the hard-disk drives which responded better to customers' needs, and became one of the top producers of the precision motor. The *second* opportunity arrived in the mid-1980s. They started M&As, aiming at leading the innovation of precision motors, by acquiring several companies such as *Shimpo* manufacturing in 1995, *Tosok* Co. in 1997, and *San-kyo-seiki* Co. in 2005. In other words, they grew rapidly up to annual sales of 485.5 billion yen by acquiring those domestic companies. The *third* opportunity came by expanding their business of the precision motor into other areas including cars and home appliances. This became possible by the acquisition of overseas companies, starting with acquiring a business unit of motors/actuators from Valeo Co., a French car motor company, in 2006, and other acquisitions of overseas companies followed. Through these acquisitions, they entered new markets including cars, home appliances, and industrial and commercial products.

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[37] A Fluid Dynamic Bearing (FDB) inserts the fluid substance (oil) to maintain the separation between the bearing races. The dynamic fluid pressure which occurs during rotation is used to sustain the spindle's rotating. Compared to the ball bearing, this mechanism makes possible not only a higher anti-shock level but also a smaller aptitude for vibration. It enhances the precision of rotation, and thus upgrades the memory capacity of HDDs. Since there is no physical contact, it is quieter, and further miniaturization easily becomes possible.

[38] Tushman, M. and O'Reilly, C. (1997). *Winning through Innovation.* Boston: Harvard Business School Press.

[39] Okayama, Y. (2012). *Technology management in a transition of HDD motors*. Term paper at Kwansei University Business School.

[40] Morita, A. (1992). Partnering for competiveness: The role of Japanese business. *Harvard Business Review*, *70*(3), 76-83.

[41] Cupertino Silicon Valley Press (2011). *Steve Jobs: His own words and wisdom.*

[42] Shibata, T. (2016). IoT and innovation [in Japanese]. *Newscom*, *27*, 4–13.

[43] Fanuc (n.d.). *FANUC's Industrial IoT Solutions.* Available at https://www.fanucamerica.com/products/industrial-iot

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