Spin-Outs and Patterns of Subsequent Innovation: Technological Development of Laser Diodes in the US and Japan

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Abstract

By exploring the technological development of laser diodes in the US and Japan, this study examines how the existence or absence of an entrepreneurial strategic choice for spin-outs influences patterns of subsequent technological development. The results show that spin-outs could hinder the subsequent development of existing technology when that technology is still at a nascent level, because the cumulative effects of technological development could disappear if research and development personnel left their parent firms in order to target different sub-markets.

Keywords: innovation, R&D competition, technological trajectory, spin-out, sub-market, laser diode

JEL:O31, O32, O33, M13, L63

1. Introduction

Do entrepreneurial spin-outs promote innovation? This study explores how entrepreneurial spin-outs influence the ways in which technology with a considerable number of areas of application evolves over time, by investigating the technological development of laser diodes in the US and Japan.

Spin-outs have played a vital role in industry, especially in technology-intensive industries. Internal resources have been spun off from parent firms to be marketed separately and to generate additional value. Spilling over from intellectual hubs, numerous engineers have established technology-intensive businesses. A notable example is Fairchild Semiconductor and its spin-out firms in Silicon Valley. Spin-outs have an important industrial function of fulfilling untapped demand by utilizing existing technology laterally. Entrepreneurial activity based on this pattern of knowledge spillovers is considered to drive economic and technological development.

Although employee start-ups generate great interest in different fields such as entrepreneurship, regional clusters, open innovation, and corporate finance, few studies have considered the impact of employee start-ups on subsequent technological development. It is reasonable to assume that the productivity of the parent firm is reduced if skilled personnel leave and launch start-ups, because a core source of the competitive advantage of a firm in a knowledge-intensive industry is strongly embodied and embedded in the human capital of its employees. Thus, a society in which we can observe a high level of employee entrepreneurship and spin-outs can display different technological development patterns from a society in which entrepreneurial spin-outs are rarely observed.

This study focuses on how entrepreneurial spin-outs influence the ways in which technology that has the potential to be utilized in a wide variety of products and processes is developed after its original invention. Since newly invented technology is at a nascent stage, its subsequent cumulative development plays a very important role in the full realization of its potential (Nathan

Rosenberg, 1979). Subsequent cumulative technological development is of significant importance in the case of highly versatile technology, otherwise known as general-purpose technology (GPT), and can have a critical impact on economic and industrial growth (Elhanan Helpman, 1998, Richard G. Lipsey et al., 1998, Richard G. Lipsey et al., 2005).

The laser has generally been considered to belong to the class of versatile technologies.[1] The laser diode, which is the most widely used type of laser, is a kind of laser that emits a narrow beam of coherent light. Typical examples of the domains in which laser diodes are used are telecommunications, optical information storage, sensors, pointers, displays, measurements and medicine; and they are also used for pumping other lasers. The laser diode was one of the most important technologies underpinning the dramatic changes that occurred in information technology during the latter half of the twentieth century. As will be described in Section 3, US and Japanese organizations have been the main actors throughout the history of laser diode research. Throughout the 1960s and 1970s, US and Japanese firms targeted the same markets, encountered the same technological problems, and aimed to achieve the same goals. However, US scientists and engineers began to diverge from their Japanese counterparts in the 1980s when they started to leave their parent organizations and launch start-ups, while Japanese firms continued to compete in the same technological areas (Hiroshi Shimizu, 2010).

Section 2 of this paper reviews the current literature on employee start-

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[1] As discussed in Section 2, general-purpose technologies (GPTs) have several positive characteristics, such as versatility and a high impact on macroeconomic productivity. On the basis of the four characteristics of GPTs (a wide scope for improvement and elaboration; applicability across a broad range of uses; potential for use in a wide variety of products and processes; and strong complementarities with existing or potential new technologies), it has been suggested that historical patent data should be examined to explore whether electricity should be considered to be a GPT (**Moser, Petra and Tom Nicholas.** 2004. "Was Electricity a General Purpose Technology? Evidence from Historical Patent Citations." *American Economic Review*, 94(2), 388-94.) The main purpose of this study, however, is not to explore whether laser diodes are actually GPT.

ups, the technological development of highly versatile technology, and patterns of subsequent technological development. Section 3 explains the data and approach of this study. Section 4 describes the processes of laser diode development in the US and Japan, and explains the technological developments in two major applications: optical communications and optical information storage. Focusing on the research and development (R&D) spin-outs in the US and the absence of spin-outs in Japan, Section 5 scrutinizes how US firms withdrew from the subsequent technological development and gained competitiveness in customized and untapped markets, while Japanese firms continued to compete in the same technological areas. Section 6 discusses how entrepreneurial R&D spin-outs influence patterns of subsequent technological development. To conclude, Section 7 summarizes the findings of this study, considers their implications, limitations and suggests directions for future research.

2. Literature Review

This paper attempts to create a bridge between the literature on employee start-ups and the literature on innovation patterns. Employee start-ups have been one of the most important focuses in innovation studies, and have been explored from various perspectives such as entrepreneurship, regional clusters, and knowledge spillover. The main aspects explored by the previous literature on employee start-ups have been the identification of entrepreneurs (Thomas M. Begley and David P. Boyd, 1987, Michael J. Crant, 1996), the location of employee start-ups (Arnold C. Cooper, 1985, David A. Garvin, 1983, AnnaLee Saxenian, 1994), the initial market focus of employee start-ups (James J. Anton and Dennis Yao, 1995, Steven Klepper and Sally Sleeper, 2005, Steven N. Wiggins, 1995), the relationships between employee start-ups and their parent firms, and how the performance of employee start-ups differs from that of their parent firms (Rajshree Agarwal et al., 2004, Benjamin A. Campbell et al., 2012).

Employee start-ups can be classified into two categories: spin-offs and spin-outs. The former is where the employee start-up has a capital investment from its parent firm, which is a type of divestiture. The latter is where the employee start-up does not have any capital ties with its parent company; this type is the focus herein. While much of the previous literature on employee start-ups explores spin-offs, it also provides important insights for spin-outs.[2]

The previous literature on the relationship between employee start-ups and their parental organizations has observed that conflict between the founder of the start-up and the parent firm can be an antecedent of the formation of the employee start-up (Steven Klepper and Peter Thompson, 2010, Peter Thompson and Jing Chen, 2011). An employee who plans to spin out tends to transfer as many tangible and intangible assets as possible (such as his/her specific expertise and interpersonal networks) to the new workplace (Rajshree Agarwal and David B. Audretsch, 2001). A negative impact on the parent firm has therefore been observed because the firm’s capable human resources leave and transfer to employee start-ups (Benjamin A. Campbell, Martin Ganco, April M. Franco and Rajshree Agarwal, 2012). It is assumed that the conflict would be larger in the spin-out case because a spin-off has support from its parent firm whereas a spin-out does not.

The size of the negative impact of the loss of talented personnel on the parent firm depends on the firm’s ability to source replacements with similar skills and other relevant attributes from the labor market or to cultivate such personnel internally. When firm-specific skills, tacit knowledge, or special expertize play an important role, and when the pool of talented personnel is limited in the labor market, a firm generally requires time to regain these human resources (Russell W. Coff, 1997, Harry M. Collins and R G. Harrison, 1975, Ikujiro Nonaka and Hiro Takeuchi, 1995, Lynne G. Zucker et al., 1998). Explorations of start-ups in Silicon Valley and observations of employee start-ups have shown that they contribute greatly to knowledge spillovers and high-tech

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[2] For a detailed literature review on employee start-ups, see **Klepper, Steven.** 2001. "Employee Startups in High-Tech Industries." *Industrial and Corporate Change*, 10(3), 639-74.

clustering; the corollary being that they might delay the ongoing R&D projects of their parent organizations (Richard L. Florida and Martin Kenney, 1990). Even though these potential delays have been suggested in the extant literature, they have not been explored in detail.

Further, most of the literature has indicated that employee start-ups initially tend to target a new sub-market so that they are not directly challenging the parent firm (James J. Anton and Dennis Yao, 1995, Clayton M. Christensen, 1993, Steven Klepper and Sally Sleeper, 2005, Steven N. Wiggins, 1995). Sub-markets are defined as "islands of activity that are insulated from the rest of an industry on both the demand and supply side."[3] Sub-markets appeal to different users and require different knowledge and methods of production from existing markets (Guido Buenstorf and Steven Klepper, 2010). Sub-markets are areas in which new entrants can launch their own businesses by utilizing existing technology (James J. Anton and Dennis Yao, 1995, Guido Buenstorf and Steven Klepper, 2010, Clayton M. Christensen, 1993, Steven Klepper, 1996, Steven N. Wiggins, 1995). For example, by utilizing valuable discoveries and expertize that a founder has accumulated at an incumbent firm, an employee start-up in a high-tech industry may produce a product that is sufficiently differentiated not to jeopardize the viability of its parent's position in a related market in the short term (Clayton M. Christensen and Joseph L. Bower, 1996, Steven Klepper, 2001). This suggests that employee start-ups diffuse R&D resources from existing R&D projects into different sub-markets. It implies that employee start-ups influence the subsequent development of existing technology, which has not been explored in the previous literature on employee start-ups.

The literature on economic history shows that the extent to which the eventual potential of a technology is realized depends on the level of subsequent technological development (Robert C. Allen, 2009, Joel Mokyr, 1990, Nathan Rosenberg, 1979). Subsequent technological development is very important,

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[3] **Bhaskarabhatla, Ajay and Steven Klepper.** 2014. "Latent Submarket Dynbamics and Industry Evolution: Lessons from the Us Laser Industry." Ibid.23(6), 1381-415., p.1381.

especially in the case of technologies that can be used in a wide variety of products and processes, so-called general-purpose technologies (GPTs). A GPT is defined as “a technology that initially has much scope for improvement and eventually comes to be widely used, to have many uses, and to have many Hicksian and technological complementarities.”[4] Electricity, the steam engine, lasers, and computers are generally regarded as some of the most important GPTs. One of the reasons why GPTs have received attention is that the occasional arrival of a new GPT yields large positive externalities on macroeconomic outcomes (Elhanan Helpman, 1998). However, it must be noted that the initial impact of GPTs on overall productivity growth is minimal. The realization of the eventual potential of a GPT may take several decades or, even, hundreds of years.

Subsequent technological development has been discussed in two different streams of research. One research stream is based on the concepts of paradigms and trajectories. Thomas Kuhn introduced the concept of paradigms to explain the pattern of development in science (Thomas S. Kuhn, 1962). A paradigm is rather loosely defined as a distinct pattern of finding, reasoning, and solving problems in science and technology. Based on Kuhn’s discussion of paradigms, Dosi defined a technological trajectory as “a cluster of possible technological directions whose boundaries are defined by the nature of the paradigm itself” (Dosi, 1982, p.154). In other words, the paradigm defines the direction of subsequent technological advances. Once a certain technological trajectory emerges, it provides the direction for subsequent technological development. Technological trajectories are not created by a single actor. In a similar way to the normal science paradigm, as described by Kuhn (1962), technological trajectories emerge through interactions involving several actors. That is, a certain technological trajectory emerges when the majority of the actors take a cumulative technological approach to the same technological problem.

The other research stream involves management studies vis-a-vis the

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[4] **Lipsey, Richard G.; Cliff Bekar and Kenneth Carlaw.** 1998. "What Requires Explanation?," E. Helpman, *General Purpose Technologies and Economic Growth.* Cambridge, Mass.: MIT Press, 15-54., p.43.

concept of dominant design. Dominant design is a key technological feature that has become a de facto standard of industries; it determines the direction(s) of subsequent technological development (William J. Abernathy, 1978, Fernando F. Suárez, 2004, James M. Utterback and William J. Abernathy, 1975). Even though the interpretations of the concepts, underlying causal mechanisms, and units of analysis have varied in the extant empirical literature on dominant design (Johann Peter Murmann and Koen Frenken, 2006), that literature reveals that several new designs and a variety of new materials are created before a dominant design emerges. After the emergence of a dominant design, the subsequent technological development becomes incremental, cumulative, and standardized along a certain technological trajectory.

Even though the research fields and terminologies do not entirely correspond to each other, both research streams suggest that the subsequent cumulative technological development will be diminished if the majority of the actors do not invest their resources into the same technological problems with the same technological approach. While the extant literature on technological trajectories and dominant design describes the pattern of technological development in general, it does not articulate how the pattern varies according to R&D resource dispersion. Following Florida and Kenney (1988, 1990), it can be assumed that the subsequent development of existing technology is hampered if the sub-markets are highly cultivated by entrepreneurial spin-outs. However, the impact of spin-outs has not been explored in the literature in relation to patterns of innovation. Therefore, this paper attempts to shed light on how R&D spin-outs influence patterns of subsequent technological development.

Bhaskarabhatla and Klepper (2014) take a similar approach and explore a similar field to this paper. Examining the US laser industry from the 1960s to the beginning of the twenty-first century, they posit a model of industrial evolution that features the creation, destruction, and fusing of independent sub-markets. Since they describe industrial evolution in terms of sub-markets and they explore lasers, their paper provides significant insights into this research, even though the research focus is different. The unit of analysis herein is much smaller than it was in this comparator study. To elaborate, Bhaskarabhatla and Klepper (2014) lump together different types of lasers such as CO_2, He-Ne, ion, gas, dye, solid state, and laser diodes, and consider them as a single industry. However, the performance specifications of these lasers are fairly diverse. Many of the lasers are used in completely different and independent markets and they are not technically closely related to each other, even though the fundamental physics of lasers is shared. This means that the potential for them becoming substitutes for each other is fairly limited, even if the technology is sufficiently improved. These different types of lasers are utilized in quite diverse applications, such as compact disk players, missile tracking, welding, and inertial confinement fusion. Further, even if we focus on just one type of laser, for example the laser diode, which this paper is exploring, this has been used in very different ways—for optical communications, optical disks, medical uses, sensors, and printers, for example. Therefore, if we take all lasers as a single industry and each type of laser as a sub-market, we may overestimate the number of employee start-ups in the same industry and underestimate the emergence of sub-markets, because this operationalization of the industry and the sub-markets is too large to capture the creation of sub-markets. By taking a closer look at the laser diode and its sub-markets, this paper brings into focus spin-outs in sub-markets and subsequent technological development.

3. Data and Approach

This study uses three different types of data. Since each type of data has its own advantages and disadvantages, multiple data types can reduce the impact and importance of disadvantages, and shed light on the technological developments from spin-outs.

The primary data sources for this study are patents and academic publications. Patents do not necessarily cover all technological developments, because not all technologies are patentable; moreover, a firm might strategically decide to keep its invention(s) secret (Zvi Griliches, 1990, Adam B. Jaffe and

Manuel Trajtenberg, 2002). However, patents have been widely used to examine technological change in a particular area of technology or a particular industry because they provide important information such as the names of the inventors, the name and address of the assignee, a technological description, and the date of application. This study examines patents granted by the United States Patent and Trademark Office (USPTO) and the Japan Patent Office to explore how R&D has diverged over time in the US and Japan. Patents are categorized into technological classifications with International Patent Classification (IPC) codes. This study utilizes the IPC codes to identify laser diode technologies; the details of this will be discussed in Section 5. Moreover, by examining changes in the assignees and the addresses of the top inventors, this study examines inventors' mobility.

In addition to patents, academic studies on laser diodes are explored to examine the technological performance of firms and research institutions. Since laser diodes constitute a highly knowledge-intensive and science-based industry, scientists and engineers in both the US and Japan have published numerous relevant papers in academic journals. These publications permit a thorough investigation into the performance of laser diodes achieved by the research groups, because it is necessary for the authors to report laser diode performance, such as wavelength and power consumption, as well as how this performance was attained, in their publications. While patents describe manufacturing processes in detail, they do not necessarily report in detail on the laser diode performance that can be achieved by the invention. This is because a laser diode cannot work with a single patent. For instance, several technologies need to be combined to make a laser diode perform laser oscillation. Therefore, a single patent would not necessarily report well on laser diode performance. Therefore, by examining the authors, their affiliations, the year of publication, and the laser diode performance reported in individual papers published in specific journals from 1960–2010, this study explores the technological developments in the US and Japan. The journals explored for this study are *Applied Physics Letters*, *Electronics Letters*, *Journal of Applied Physics*, *IEEE Journal of Quantum Electronics*, and *Japanese Journal of Applied Physics*.[5]

In addition to academic publications, patents, and archival records such as industrial reports, the authors conducted 165 interviews between September 2004 and June 2015 with scientists, engineers, and corporate managers engaged in laser diode R&D in the US and Japan.[6] Many of the interviewees are top inventors selected from the patents and journal publications described above. This study uses the interviews to supplement the academic papers and patents and to explore the validity of arguments. Further, the interviews allow us to avoid a double counting problem.

From this longitudinal exploration of technological development in two different national settings, this study scrutinizes the extent to which subsequent technological development may fade away when spin-outs from incumbent firms to start-ups are active; this cannot be examined if one only studies technological development in one such institutional setting.[7] The longitudinal international comparison of detailed case studies allows a careful investigation of R&D activities to be carried out. We show that these activities started almost simultaneously, and that their results, which have become increasingly divergent in the two different countries, are highly path-dependent and are embedded in their institutional contexts.

4. Laser Diodes and Technological Developments

This section briefly describes the technological development of laser diodes, also known as semiconductor lasers. Among the many varieties of lasers

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[5] All these journals are recognized as top journals in laser diode research; this was confirmed by the interviews that were conducted by the authors.

[6] The list of interviewees is available on request.

[7] We define an incumbent firm as a firm that was already in existence when the first laser diode was invented in 1962.

(e.g., CO_2, YAG, He-Ne, ruby, and laser diode), laser diodes are the biggest selling lasers in the world. They have various applications such as biomedical uses, light for high-speed cameras, material processing, optical sensors, laser pointers, measurement, optical disks, printers, barcode readers, and optical fiber communications. The specifications required (such as wavelength and power of light) vary depending on the application. The two biggest application areas are optical communication and optical information storage. Long-wavelength laser diodes (1300nm–1550nm) are used for optical communication appliances. Short-wavelength laser diodes (470nm–850nm) are used for optical information storage and processing in equipment such as optical disks and laser printers.

Four American institutions—General Electric (GE), International Business Machines (IBM), the University of Illinois at Urbana Champaign (UIUC), and Massachusetts Institute of Technology (MIT)—simultaneously but independently developed the first laser diodes in 1962, their potential being recognized early by physicists. The laser diodes developed in 1962 functioned efficiently only at minus 196 degrees Celsius (i.e., the temperature of liquid nitrogen). Unless laser diodes could operate at room temperature, their potential would be fairly limited. Therefore, after the invention of the first laser diode, the R&D focus was on developing a laser diode that could operate at room temperature. Electronics and telecommunications enterprises (such as GE, RCA, Bell, IBM, Xerox, Hitachi, NEC, and Mitsubishi Electric) competed to develop such a laser diode.

It took eight years for engineers to solve this technological problem. In 1970, a Bell Laboratory research team developed the first laser diode that operated at room temperature. They called this new laser diode a double-heterostructure (DH) laser. Although the laser diode developed by Bell was unstable, its development was a turning point because it stimulated competition among many firms to develop reliable and stable laser diodes that could operate at room temperature.

The only application of laser diodes in the early 1970s was in long-distance telecommunication. Scientists and engineers faced two technological challenges. One was to extend the longevity of laser diodes. It was necessary for firms to develop laser diodes with greater longevity because it would be very difficult, if not impossible, to replace the laser diodes that were installed in marine cables for long-distance telecommunication. Another challenge was the oscillation spectrum of laser diodes. If the oscillation spectrum was multimode, the light transmission in the optical fiber would be significantly disturbed; thus, creating single-mode oscillation was critical. The wavelength at which laser diodes had minimum energy loss in optical fibers shifted from 800nm to 1300nm and then to 1550nm as a result of advances in optical fiber technology. Therefore, firms competed to develop laser diodes to achieve these two technological goals at the most appropriate wavelength.

Figure 1 illustrates the technological development of optical communications systems and laser diodes, with a plot of the transmission capacity and optical communication distance reported in the papers published in the academic journals described in the previous section. Since increasing communication capacity and distance was considered the most important goal in optical communication, all the firms and research institutions that targeted the optical communication market competed in this field. Long-lasting and reliable laser diodes have been the most important component in every phase of the development of optical communication systems. Exploring the papers published in the academic journals noted in Section 3, Figure 1 indicates the organization that achieved a particular technological development in each phase. Transmission capability has increased steadily since the 1960s. Figure 1 also reveals that US organizations took the lead in technological development until the 1970s, and that Japanese organizations began to dominate after the 1980s.

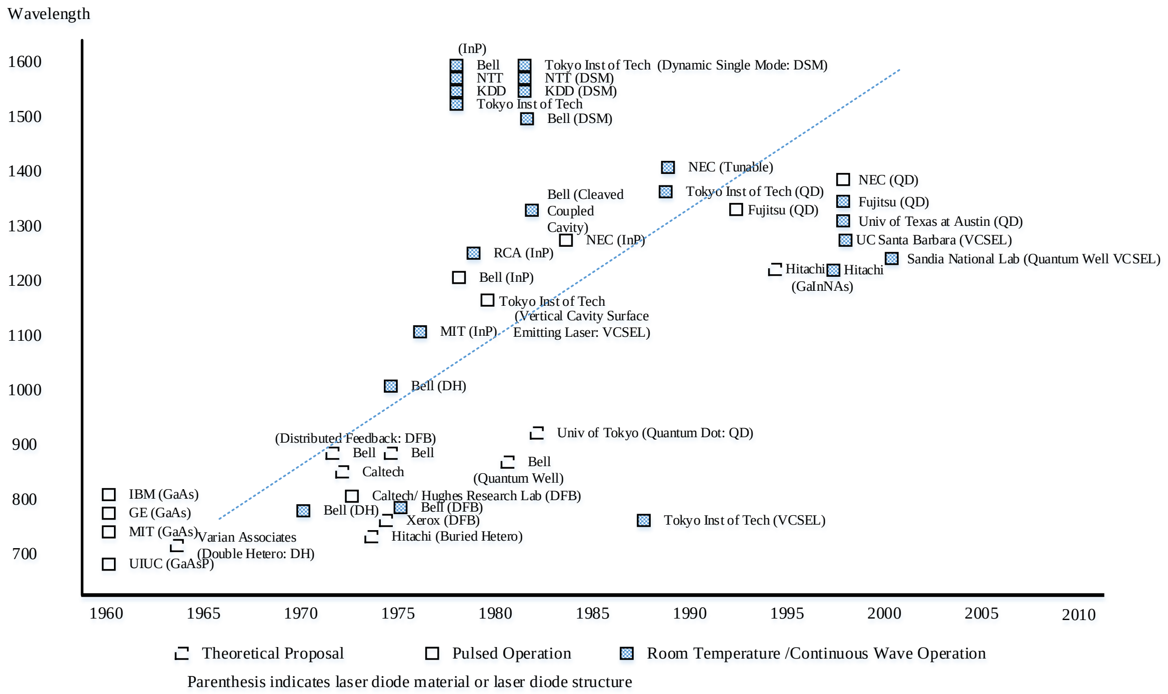

Figure 1: Technological development of laser diodes for optical communication

Source: Papers on laser diodes published in *Applied Physics Letters*, *Electronics Letters*, *Journal of Applied Physics*, *IEEE Journal of Quantum Electronics*, and *Japanese Journal of Applied Physics* during the period 1960–2010.

Other applications of laser diodes were expected to emerge in the mid-1970s. While many firms competed to develop a laser diode for optical communication, electronics firms such as Philips, RCA, IBM, Xerox, Mitsubishi Electronics, Toshiba, Sharp, and Sony began to conduct research on video disks and compact disks using advances in laser technology. As firms began to commit to laser diode R&D, it became clear that the laser diode would find applications in optical data storage, such as video disks, compact disks, and laser disks. Moreover, the potential market for short-wavelength laser diodes was expected to be huge: laser diodes would be utilized in various applications, including barcode readers, laser pointers, and laser printers. Developing laser diodes with shorter wavelengths was critical because more information could be stored with a shorter-wavelength laser diode. The wavelengths emitted by a laser diode depend on the semiconductor materials used in its layers. Changes in materials required all the technologies associated with manufacturing and reliability to be revised. On the basis of the wavelength data obtained from the papers published in the academic journals, Figure 2 illustrates the technological development of laser diodes for optical data storage and processing reported in the papers published in the same academic journals as for Figure 1.

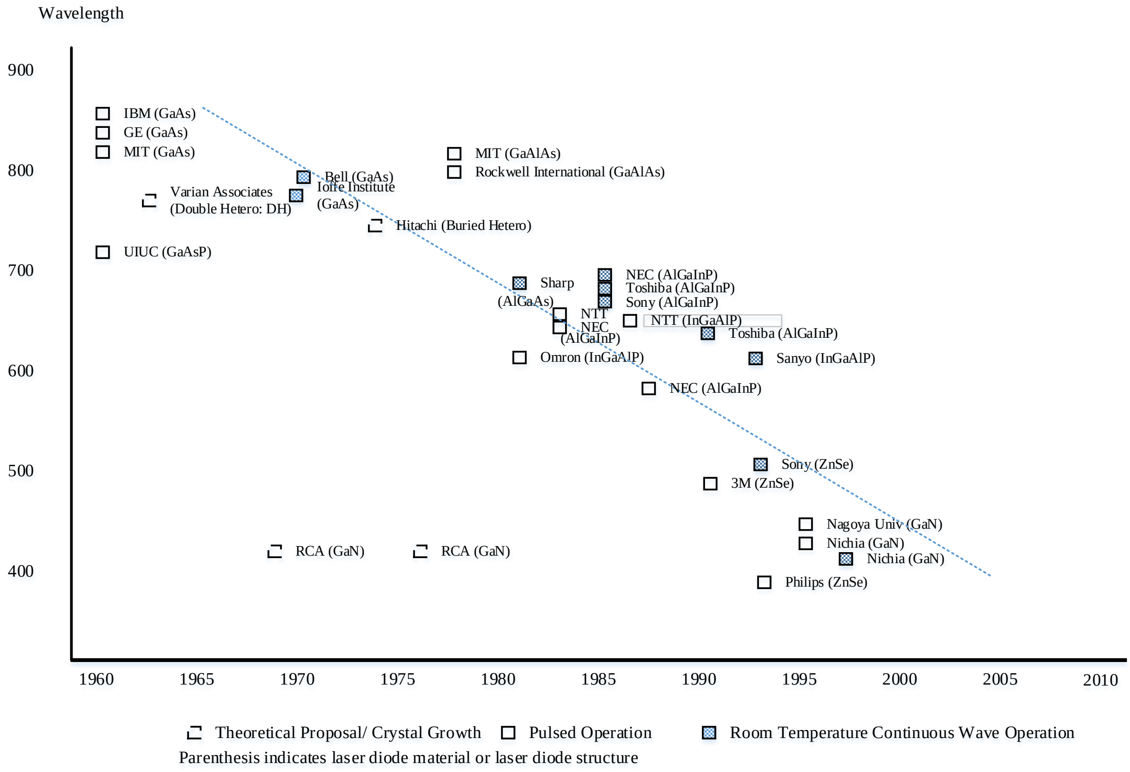

Figure 2: Technological development of laser diodes for information storage and processing

Source: Papers on laser diodes published in *Applied Physics Letters*, *Electronics Letters*, *Journal of Applied Physics*, *IEEE Journal of Quantum Electronics*, and *Japanese Journal of Applied Physics* during the period 1960–2010.

As Figure 2 illustrates, US organizations such as IBM, GE, MIT, UIUC, and Bell began to make breakthroughs by 1970. While Japanese organizations made no significant breakthroughs in this early phase of laser diode development, they began to do so with the development of shorter-wavelength laser diodes in the 1980s. Figures 1 and 2 demonstrate that US firms and universities achieved important results in subsequent technological developments until the 1970s. However, many US firms seem to have disappeared after the beginning of the 1980s.

5. R&D Spin-outs

In the 1960s and 1970s, large enterprises played an important role in laser diode R&D in both the US and Japan. Many US electronics, telecommunications, and computing enterprises (e.g., GE, RCA, Bell, IBM, and Xerox) competed to develop laser diodes that could operate with longer lifetimes at room temperature. Japanese electronics firms (e.g., Hitachi, Toshiba, Mitsubishi Electric, NEC, and Fujitsu) and telecommunications firms (e.g., NTT and KDDI) also became involved in laser diode research toward the end of the 1960s. Targeting the same telecommunications and information storage and processing applications, US and Japanese firms took the same approach to the same technological challenges and competed until the 1970s.

However, many leading scientists and engineers in this area began to leave the incumbents to launch or join new businesses in the US from the late 1960s onwards. One might suppose that they left the incumbents because the US consumer electronics industry began to decline, as Chandler indicated (Alfred Dupont Chandler, 1994). The increased cost of raw materials and production reduced the profitability of diversified businesses of US electronics firms. The market share of US electronics in the global market dropped from 71 percent in 1960 to 27 percent in 1986 (Chandler, 1994). In this context, RCA, GE, and IBM, the leading firms in laser diode R&D, decided to retreat from or exit R&D competition in laser diodes.

However, it must be noted that the spin-outs had begun before the leading firms began this retreat. The first major spin-out was Laser Diode

Laboratories, which was founded by RCA engineers in 1967. Another example of a spin-out from RCA was Epitaxx, which was a fiber-optic detector manufacturing start-up launched by a scientist spin-out from RCA in 1984. The founder, Greg Olsen, initiated another start-up, Sensors Unlimited, in 1992, specializing in near-infrared sensing devices.[8] Lytel, founded in 1984, is another example of a spin-out by a scientist who had worked for RCA. In 1998, its founder launched another start-up, Alfalight, which designed and manufactured high-power laser diodes for industrial, defense, and telecommunication applications.[9] RCA had actively invested in laser diodes and had been a leading firm in this area until 1986 when it was acquired by GE. Therefore, the reason why these spin-out scientists and engineers left RCA was not that it had begun to retreat from laser diode R&D competition.

SDL Inc. was one of the first significant commercial suppliers of quality high-power laser diodes. The company was founded in 1983 by scientists from Xerox (Ralph R. Jacobs and Donald R. Scifres, 2000).[10] A spin-out scientist from IBM joined a start-up, Optical Information Systems, which was funded by Exxon, in 1978.[11] Spin-outs were also formed from Bell Laboratories. Emcore, a leading supplier of compound semiconductor fabrication equipment and manufacturing services, was founded by a scientist from Bell Laboratories in 1984. Another scientist who had worked for Bell Laboratories and Hewlett Packard joined the start-up General Optronics when it was founded in 1983.

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[8] Interview with Dr Greg Olsen, founder of Epitaxx and Sensors Unlimited, on January 12, 2015 in Princeton, New Jersey.

[9] Interview with Dr Dan Botez, a founder of Lytel and Alfalight on August 7, 2009 in Madison, Wisconsin.

[10] SDL was a spin-off from Xerox and Spectra Physics. SDL bought all of its stocks from Xerox and Spectra Physics eight years after its foundation. Since many of the employee start-ups observed in the laser diode industry are spin-outs, SDL was an exception in its relationship with its parent firms. Interview with Dr Donald Scifres, a founder of SDL, on November 18, 2014 in Pala Alto, California.

[11] Interviews with Dr Peter Zory, a spin-out scientist from IBM, on September 1, 2010 and August 17-18, 2011 in Gainesville, Florida.

These are just a few examples of the numerous start-ups in this area. Dr Peter Zory has stated that "there are countless examples of start-ups in this industry in the US."[12] Obviously, AT&T's breakup in 1984 increased the number of spin-out scientists from the Bell laboratories. There are many more entrepreneurial start-ups in laser diodes than are listed in this paper. The following table indicates the numbers of projects and firms that gained SBIR (Small Business Innovation Research) or STTR (Small Business Technology Transfer) funding for their laser diode research from 1982 to 2010. The first SBIR award was given in 1983 and the first STTR award in 1995.

Table 1: Number of projects and organizations receiving SBIR/STTR awards for laser diode research

	Projects		Firms	
	SBIR	STTR	SBIR	STTR
1982–1989	55	0	23	0
1990–1999	334	0	117	0
2000–2010	178	20	73	11
Total	567	20	179	11

Source: Details of projects receiving awards are obtained from the SBIR/STTR website, https://www.sbir.gov/

In total, 587 projects received awards for laser diode research between 1982 and 2010. The total number of firms receiving awards between 1982 and 2010 reached 190. Since some firms gained SBIR/STTR awards sequentially, a simple aggregation of the number of awarded firms in each year can lead to an

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[12] Interviews with Dr Peter Zory, a spin-out scientist from IBM, on September 1, 2010 and August 17-18, 2011 in Gainesville, Florida.

overestimation. Therefore, overlapping awarded firms were identified and are counted as a single entity so that the number of awarded firms is not overestimated. Moreover, it must be noted that this figure captures only firms receiving SBIR/STTR awards. Therefore, the number of start-ups in this technological field indicated by Table 1 is, in fact, a modest estimation.

While many entrepreneurial spin-outs emerged in the laser diode industry in the US, such spin-outs were virtually non-existent in Japan. In Japan neither a corporate scientist nor a university professor would leave his/her parent organization to launch a start-up; this phenomenon is reflected more generally by the low labor mobility in Japan. Dr Tetsuhiko Ikegami, a retired director of Nippon Telephone and Telegraph confirmed that "such spin-outs were non-existent in Japan."[13]

Table 2 delineates the mobility of top inventors, based on patent data from 1960 to 2010. Mobility was calculated using the following steps. First, based on the International Patent Classification (IPC) codes provided by the Japan Patent Office, we collected information about all patents obtained from the US Patent Office up to 2010.[14] The total number of patents was 14,486. Second, we computed the H-index for individual inventors, based on the number of backward citations that each patent received. The H-index is used to measure the quality as well as the quantity of scientific research (J. E. Hirsch, 2005). Then, by looking at the patent assignee and the inventor's address, we examined the mobility of the top one percent of H-index inventors. The number of inventors in the top one

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[13] Interviews with Dr Tetsuhiko Ikegami conducted on June 27, 2012. This view is confirmed by all the Japanese interviewees.

[14] The IPC codes provided by the Japan Patent Office for laser diode technology are Japanese File Index (FI) =H01S5/00, H01S3/094, H01S3/091, H01S3/096, H01S3/103, H01S3/133, H01S3/18, H01S3/04, H01S3/08, and H01S3/23. The equivalent US Codes (USC) are 372/43$, 372/44$, 372/45$, 372/46$, 372/49$, 372/50$, and 372/75. The International Patent Classification (IPC) codes are H01S5/$, H01S3/018, and H01S3/019. $ indicates truncation of the subclasses. This study uses the USC and IPC codes for identifying patents on laser diodes granted by the USPTO.

percent of H-index inventors is 100 in the US and 90 in Japan. One top inventor transferred from an organization in Japan to one in the US. He is counted in both the US and the Japanese figures. No other inventors transferred organizations between the US and Japan. If an inventor changed his/her assignee once (e.g., from Bell Laboratories to SDL), a value of 2 is assigned to the inventor's affiliation. If an inventor did not change his/her assignee and address at all over this time period, a value of 1 is assigned.

Table 2: Top 1 percent h-index inventors and mobility

		Inventors in US Organizations	Inventors in JPN Organizations
Number of Inventors		100	90
Average Number of Assignees for each Inventor		2.47	1.1
Variance		1.63	0.11
Median		2	1
Maximum		7	3
Percentage of Inventors with one Assignee		25.74	82.83
Affiliation Type of Inventors with one Assignee			
	Incumbent Firm	14	82
	Start-up	8	0
	University	4	0
Number of Transfers of Inventors with more than two Assignees			
Transfer from	To		
Incumbent Firm	Incumbent Firm	13	5
	Start-up	41	1
	University/Research Institute	10	1
Start-up	Incumbent Firm	5	0
	Start-up	52	0
	University/Research Institute	3	0
University/Research Institute	Incumbent Firm	3	0
	Start-up	15	0
	University/Research Institute	5	2

Source: Patents from US Patent Office, Interviews

Table 2 clearly shows that the mobility of top inventors was higher in the US than in Japan. The average number of assignees of the patents held by the inventors indicates that star Japanese inventors tended not to change their affiliation, while star inventors in the US tended to move once, on average. One might suppose that a change in affiliation does not necessarily mean that an inventor transferred from one organization to another. In particular, active mergers and acquisitions (M&A) in the US optoelectronics industry might result in an overestimate of the mobility of US inventors. This study, therefore, excluded from the estimation changes in assignee caused by M&As. The split of Bell Communication Research from Bell Laboratories is also excluded from the estimate of changes in assignee. Changes in affiliation were confirmed through the interviews. The percentage of inventors who held patents with a single assignee indicates that 82.8 percent of the star inventors in Japan did not change their affiliation, while 74.3 percent of the star inventors in the US changed their affiliation at least once.[15] The relatively low mobility of talented personnel in Japanese organizations observed in this study is consistent with the findings of previous studies. As prior research on the Japanese labor market has shown (Aoki, 1988; Itoh, 1994), it is relatively rare for scientists to transfer from one company to another in the laser diode industry in

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[15] This trend is reasonably consistent with results reported in the previous literature, which examined academic papers, and their citations, captured by *Web of Science* and estimated the mobility of star scientists in this industry by examining changes in their affiliation. Authors' affiliations are better documented in academic papers than inventors' affiliations are in patents. While this means that there is a clear advantage of using papers to identify scientists' and engineers' affiliations, such individuals do not necessarily publish papers, especially if they work for firms. Therefore, it is important to compare these two different data sources. The results for academic papers showed that nearly 62 percent of the top US scientists changed their affiliation at least once, and that 90 percent of the top Japanese scientists did not change their affiliation at all. These trends were corroborated in the interviews with corporate scientists in Japan and the US. Regarding the data appearing in Web of Science, see **Shimizu, Hiroshi.** 2007. *Competition, Knowledge Spillover, and Innovation: Technological Development of Semiconductor Lasers, 1960-1990*. London: London School of Economics and Political Science.

Japan.

Table 2 delineates mobility not only in terms of frequency, it also provides a breakdown to provide other useful information. First, it shows the affiliation of the top inventors with a single assignee. This indicates that in Japan all such inventors were affiliated with incumbent firms, while inventors in the US were affiliated with incumbent firms, start-ups, and university/research institutes.

Secondly, it provides disaggregated information as follows. If an inventor transferred from Bell Laboratories to RCA, we assign the number 1 to the "from incumbent firm to incumbent firm" cell. If he/she transferred from RCA to a start-up, we assign the number 1 to the "incumbent firm to start-up" cell. Again, if he/she transferred from a start-up to MIT, we assign the number 1 to "from start-up to university/research institute". Since the inventors in Japan were relatively static, the number of transfers is quite low compared to the numbers for the US. The figures show that in the US the type of organization to which top inventors transferred most often is clearly a start-up. Both mobility from incumbent firms to start-ups and mobility among start-ups are the dominant transfer patterns in the US. This suggests that the high mobility ratio in the US reflects the fact that inventors transferred from big businesses to start-ups. Bell Laboratories and Bell Communication Research (known as Bellcore) were the biggest incumbent firms from which scientists and engineers left and joined/launched a start-up. Bell Laboratories and Bell Communication Research account for 24 of the top 1% H-index inventors. Twelve out of 24 of these inventors joined/launched a start-up after leaving Bell.

The difference in spin-outs from parental firms between the US and Japan has been observed in the previous literature (Masahiko Aoki, 1988, Ronald Philip Dore, 2000). Much of that literature has explored the factors promoting spin-outs in the US, such as entrepreneurship, growth of venture capital, the knowledge pool and networks (William D. Bygrave and Jeffry A. Timmons, 1992, Richard Florida and Martin Kenney, 1988, P.A. Gompers, 1994, Paul A. Gompers et al., 2010, Jerry Kaplan, 1995, Martin Kenney, 2000, AnnaLee Saxenian, 1994). The rarity of spin-outs in Japan has been explained by the less developed venture capital system, the well-developed in-house labor market, the fact that pay is based on seniority, the assumption of life-time employment, and the poor conditions for re-employment (Masahiko Aoki and Ronald Philip Dore, 1994, Hiroyuki Itami, 1994, Hideshi Itoh, 1994). Even though it is still interesting to explore how this difference emerged over time, the important point for this study lies in exploring how the existence or absence of spin-outs influences the patterns of subsequent technological development, given the difference in the occurrence of spin-outs between the US and Japan.

6. Spin-Outs and Vanishing Technological Trajectory

The difference in spin-outs between the US and Japan has had an impact on the subsequent technological development of laser diodes and the market positions of the two countries. An industrial report reveals these trends well. The report was published by the Japan Technology Evaluation Center (JTEC), which is supported by US government agencies such as NSF, NASA, the Department of Energy, the Department of Commerce, and the Department of Defense, and indicates that start-ups played an important role in technological development in the US by specializing in untapped markets.

> Due to the vibrant entrepreneurial industry base that is an integral part of the U.S. economy and which is apparently nearly absent in Japan, numerous small companies have spun-off from their larger, parent companies... These small businesses, which generally specialize in the manufacture of photonic components, are rarely positioned to compete head-to-head with the larger, systems-oriented companies; instead, they tend to specialize by filling narrow niches. As companies become established, the niches expand with the manufacture of additional specialized, unique devices produced to fill the needs of particular subsets of

customers.[16]

Figures 1 and 2 illustrate that US organizations such as IBM, GE, RCA, MIT, UIUC, and Bell Laboratories made breakthroughs until the beginning of the 1980s. However, US start-ups emerged at the end of the 1970s and targeted customized and untapped sub-markets such as those for short-distance communications, sensors, and optical pumping, by utilizing laser diode technology. Sub-markets appeal to different users, and they require different knowledge and methods of production (Buenstorf & Klepper, 2010). The sub-markets constituted areas in which new entrants could launch their own businesses by utilizing the existing laser diode technology. These markets tended to be customized and segmented for two reasons. Start-ups did not usually have high-throughput manufacturing facilities in-house, and they expected untapped markets or customized markets to be more profitable if the firm was successful. The risk capital supplied by venture capitalists provided a great incentive to target such markets. The size of the individual markets was usually smaller than that of the long-distance telecommunications and information storage markets. Fewer breakthroughs by US firms appear in the subsequent pattern of technological development, not because US organizations were losing their R&D capabilities, but because R&D investment in laser diode technology was scattered and dispersed in the various sub-markets in the US as a result of entrepreneurial spin-outs. In other words, from the 1980s onwards, US scientists shifted their R&D focus from being “on trajectory” (Figures 1 and 2) to being “off trajectory.”

Major enterprises such as Hitachi, Mitsubishi Electric, NEC, Fujitsu, Toshiba, Sharp, Panasonic, and Sony played a dominant role in laser diode R&D in Japan. Vertically integrated large enterprises tended to target mass markets because the high fixed costs incurred in building high-throughput facilities

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[16] **Forrest, Stephen R.; Larry A. Coldren; Sadik C. Esener; Donald B. Keck; Fredrick J. Leonberger; Gary R. Saxonhouse and Paul W. Whumate.** 1996. "Jtec Panel on Optoelectronics in Japan and the United States Final Report," Baltimore, Maryland: Japanese Technology Evaluation Center/ International Technology Research Institute, p.xvii

demanded a high volume of sales (Chandler, 1994). Greg Olsen, who, as mentioned above, left RCA in 1984 and launched a start-up to develop photodetectors (one application of the laser diode technology), wrote: "To RCA the photodetector was no big deal–just a $1 to $2 million market," but "To me, however, a $2 million market didn't seem small at all" (Olsen, 2009, p.59).[17] Large enterprises developed laser diodes for the growing mass markets such as those for optical communications, compact discs, DVDs, scanners, and laser printers. The R&D focus of Japanese scientists remained on the subsequent technological development throughout the period. For instance, the Japanese firms competed to develop a shorter-wavelength laser that could handle high-volume information storage, and captured a significant market share in this sector, as indicated in the JTEC report (Forrest et al., 1996). Their R&D efforts were concentrated mainly on developing laser diodes for the long-distance telecommunications and information storage markets. A certain technological trajectory emerged when several firms developed technology for the same goals, shared a common definition of the relevant problems, and tackled these problems with the same approach. Since many vertically integrated large firms competed for the same mass markets, the cumulative effects of incremental innovations in the subsequent technological development eventually emerged in the 1960s and the 1970s, as Figures 1 and 2 demonstrate.

Figure 3 illustrates the cumulative number of patents taken out for technology related to the basic structure of laser diodes, and their application years.[18] It shows that US organizations began to apply for patents for their R&D

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[17] This point was confirmed in the interview with Dr Greg Olsen conducted on January 12, 2015 in Princeton, New Jersey.

[18] Basic laser diode technology is identified by the International Patent Classification number H01S5. H01S5 is given to technology specifically related to laser diodes such as structure, processes, apparatus for excitation, and arrangements for controlling the laser output parameters. If H01S5 was assigned as the first IPC for a patent, we regarded it as an invention related to the basic laser diode structure. H01S5 was introduced in Version 7 of the IPC, which was adopted in 2006. Therefore, H01S5 was not assigned to patents taken out before Version 7 was introduced. Accordingly, this paper uses the patent

in the early 1960s. The cumulative number of patents taken out by US organizations outnumbered that for Japanese organizations until 1984. However, Japanese organizations began catching up from the 1970s onwards, and the cumulative number was greater from 1985 onwards. Figure 3 indicates that the patterns of subsequent technological development of the basic laser diode diverged between Japan and US from the middle of the 1980s. It is evident that Japanese firms accumulated their technology on the basic structure from the 1970s onwards, while the US firms moved away from the subsequent technological development from the middle of the 1980s. The divergence from basic laser diode structure R&D is one of the signs that the US inventors shifted their R&D focus to other fields in markets that start-ups tried to tap. One of the areas that start-ups targeted was high-power lasers, which was mentioned in the previous section. High-power lasers have been used in numerous different sub-markets such as satellite communication, measurements, and processing, each of which is a highly customized and segmented market, as indicated in the JTEC report mentioned above. This created “space” for subsequent technological developments for Japanese firms, which allowed them to catch up with and overtake the US firms despite the early leadership of US firms. Note, however, that these figures do not necessarily show that the US scientists were losing their technological capabilities. Rather, they were tapping the sub-markets by using laser diode technology laterally.

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database provided by Thomson Innovation, which updated the old IPCs with the current IPCs.

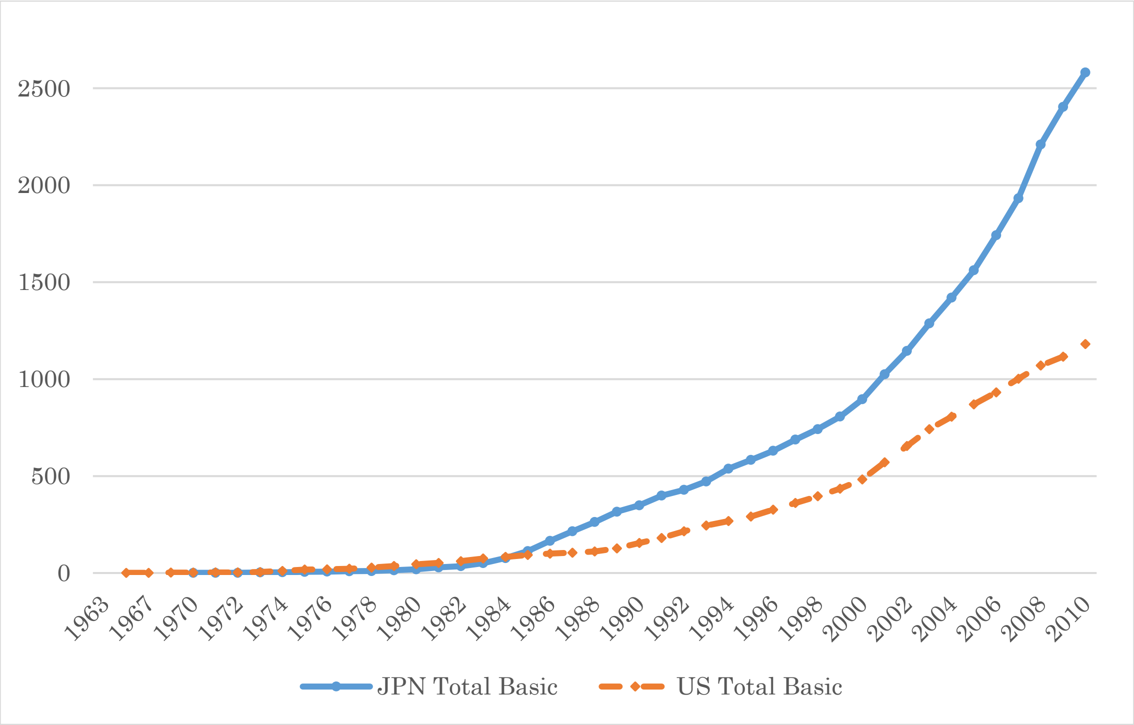

Figure 3: Cumulative number of patents in basic laser diode technologies

Source: Patents from US. Patent Office

How do different spin-out patterns influence the subsequent development of a technology? Let us suppose that many of the scientists engaged in R&D are leaving their parent firms to use their accumulated technological knowledge laterally and to launch start-ups that are targeting an untapped sub-market. If the supply of skilled scientists is ample, this trend does not have a significant impact on the subsequent technological development, since the incumbent firms can immediately hire new scientists to fill the vacancies created by the spin-outs. However, the pool of skilled scientists is not boosted instantly, since skilled scientists have a high level of knowledge: formal graduate-level education in physics, and professional R&D experience at a laboratory, are usually necessary before a scientist would be deemed as skilled in this domain. Therefore, entrepreneurial spin-outs tend to cause a slowdown in subsequent technological development, relative to the development when there are no entrepreneurial spin-outs.

Star scientists usually contribute more to their parent firms' R&D output. Moreover, it is difficult to substitute star scientists with other scientists. Therefore, if star scientists decide to leave their parent firms for entrepreneurial spin-outs, this has a substantial impact on the subsequent technological development. In fact, in many cases, it was the star scientists who spun out and launched start-ups in the laser diode industry, according to the interviews with corporate scientists. Since the development of technology is cumulative, the earlier the star scientists' entrepreneurial spin-outs emerge, the more substantial is their impact on subsequent technological development. Consequently, as corporate scientists left their parent firms and launched start-ups to target sub-markets, the subsequent development of the existing technology vanished.

Suppose that the typical pattern of technological development takes the shape of an S-curve (Richard N. Foster, 1986). As the previous literature discusses, the S-curve does not necessarily fully account for the complexity of technological change (Clayton M. Christensen, 1992a, b). The thrust of the argument is not whether technological development is an S-shaped function, but how spin-outs influence the technological trajectory.

If a firm spins off before time *t* in Figure 4, it faces huge technological uncertainty. This actually happened in the laser diode industry. Utilizing Gallium Arsenide (GaAs) manufacturing technology, engineers spun off from RCA and launched Laser Diode Laboratories, Inc. in 1967. However, since the GaAs manufacturing technology was immature, the operating life of the laser diode was short and it was unreliable. Large enterprises such as Bell Laboratories, RCA, IBM, NEC, Hitachi, and Mitsubishi were competing to increase longevity and to improve laser reliability until the middle of the 1970s (Hiroshi Shimizu, 2010). Therefore, Laser Diode Laboratories, Inc. could not develop its business in the industrial market successfully because of its immature technology.

Even though it would be rational for engineers or scientists who plan to spin-out from their incumbents, to postpone until technological development has matured, the spin-off can occur earlier provided that the expected sizes and profitability of individual sub-markets are different and the total number of sub-markets is limited. In other words, since scientists have to rush to choose a preferred sub-market, the timing of the spin-out can be brought forward from *t* to *t*'' if limited but promising-looking sub-markets exist. The existence of factors promoting spin-outs, such as venture capital and a flexible labor market, promote competition. The fiercer the competition for filling untapped sub-markets, the earlier the timing of the spin-out.

If many of the scientists engaged in R&D disengage from trajectory oriented activities to utilize its technology laterally and to launch a start-up, the technological trajectory will eventually be under-developed, as depicted for Scenario B in Figure 4. Spin-outs, which utilize the existing technology laterally and shift R&D for individual sub-markets, can make the technological trajectory fade out much earlier and at a lower level than would be seen if no entrepreneurial spin-out occurred, as depicted for Scenario A. The areas in which technological development occurs are shifted from “on trajectory” to “off trajectory” in the individual sub-markets.

If many scientists remain engaged in R&D on the current technological trajectory, the aggregate amount of R&D investment in the area gradually increases. The increase in R&D investment in the existing technological trajectory enhances the potential for making technological breakthroughs on the one hand, but lowers the profitability of firms on the other. If many scientists remain engaged in R&D even after the technology is well developed and the productivity of technological development is diminishing, as depicted by *t*' in Figure 4, the profitability of the firms decreases. This happened to laser diode development in Japan.

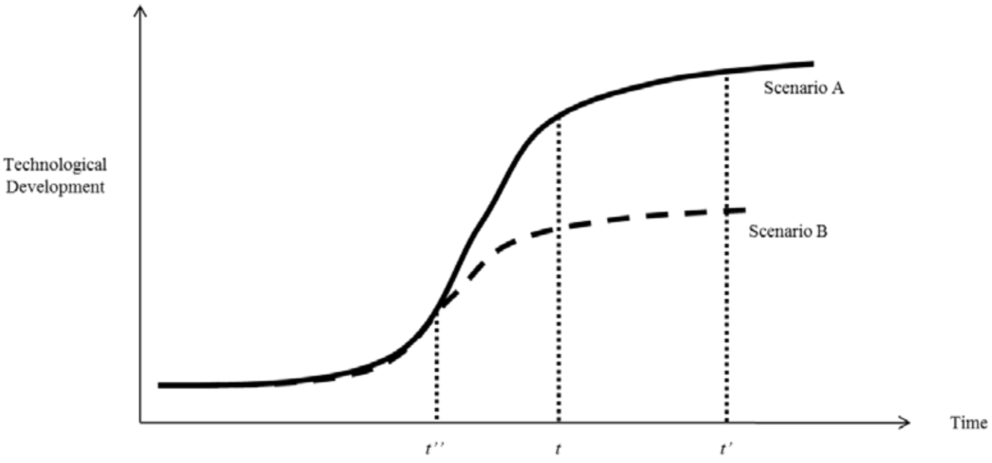

Figure 4: Spin-outs and subsequent technological development

The existence of sub-markets and institutional conditions that encouraged spin-outs had a bench-clearing effect for existing technological development. Entrepreneurial spin-outs—which laterally utilize the existing technology and shift R&D toward individual sub-markets—can cause subsequent technological development to fade out much earlier than usual and make it remain at a lower level than it would have achieved if no entrepreneurial spin-out had occurred (as in Japan). If we had explored the technological development only in one institutional setting, the development pattern that we observed would have been either Scenario A or Scenario B. In this case, we would not have known the extent to which the subsequent technological development was underdeveloped or over-developed. In other words, if, for instance, we had explored the technological development only in the US, we might have underestimated the possibility for the subsequent technological development that could have been achieved in a different institutional setting.

7. Conclusions

This study has demonstrated how entrepreneurial spin-outs influence subsequent technological development, by exploring laser diodes in the US and

Japan. Prior studies have indicated that progress on the technological trajectory is likely to retain some cumulative features: the cumulative effect of numerous small improvements gradually increases productivity (Giovanni Dosi, 1982, Thomas S. Kuhn, 1962, Nathan Rosenberg, 1979). This study revealed that the cumulative features of technological development gradually disappeared due to the surge in entrepreneurial spin-outs in the industry in the US. Subsequent technological development plays an important role when a technology is still in a nascent stage. Thus, R&D competition in cumulative technological development contributes to technological development until the technology fully matures. According to the technological trajectory perspective, entrepreneurial spin-outs could hinder technological development when the technology is at a nascent stage, because the cumulative effects of incremental innovations on the technological trajectory could disappear if the R&D personnel are thinned out to target different sub-markets.

Of course, severe price competition would result if firms were to compete in the same subsequent technological development, even when technological development is fully saturated. This occurred in the laser diode industry in Japan, when the firms targeted the same mass markets and competed in the same markets, and this ultimately boosted the cumulative technological development of laser diodes. Therefore, it is important for firms to utilize technology laterally in new markets after technological development has fully matured.

The findings of this study explain why Japanese firms were good imitators and achieved great process innovations, while the US firms were successful in terms of product innovations, but were poor imitators (Nathan Rosenberg, 1988). One of the general explanations given for this observation involves entrepreneurship and cultural differences. However, the findings of this study suggest that factors such as the labor mobility of corporate scientists and re-employment conditions play an important role in establishing or hampering technological trajectories for the promotion of subsequent cumulative technological development.

Since the findings of this study are based on a case study of the laser diode industry in the US and Japan, we must be cautious about asserting generalizations. Moreover, other factors not explored herein could explain the observed patterns. A classic explanation might be that the Japanese firms tended to have advantages in incremental process innovations, while the US firms tended to allocate more resources to radical and revolutionary product innovations. One could attribute this difference to the cultural differences between the US and Japan. This explanation assumes that the US culture prefers revolutionary innovation, while the Japanese culture prefers cumulative innovation. The ideal way to counter the confounding effects would be to give another example for the same two countries in which the case is reversed. There were industries in which US firms were the industrial leaders on the basis of cumulative innovations (such as the gas turbine, automobile, and aerospace industries) and in which spin-outs for sub-market exploitation were relatively limited. However, it is quite unlikely that several early spin-outs would be observed in Japan and not in the US, because active entrepreneurial spin-outs were virtually absent in the knowledge-intensive industries in Japan. Since this study focuses on a longitudinal scrutiny of the laser diode industry and a discussion of the different patterns of innovation between the US and Japan, and because of space limitations, we have not explored other examples. However, detailed and longitudinal case studies in future research could unravel the mechanisms in which the different patterns emerge, and provide useful comparisons for a better understanding of the patterns of subsequent technological development.

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