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Innovation, Entrepreneurial Spin-Outs, Technological Trajectory, R&D Competition, Sub-markets, General Purpose Technology

Abstract
By exploring the patterns of laser-diode technological development in the U.S. and Japan and theoretically examining market conditions and institutions that promote entrepreneurial spin-outs from a parental company, this study reveals how the existence and absence of entrepreneurial spin-out influence the ways in which technological trajectories emerge. It shows that vibrant entrepreneurial spin-out could hinder technological development, since the cumulative effects of incremental innovations on the technological trajectories could vanish if many firms spun out to target untapped sub-markets.

Introduction
Do vibrant entrepreneurial spin-outs promote innovation? This study aims to explore how competition for sub-markets among entrepreneurial spin-outs from a parental firm influenced cumulative technological developments along the technological trajectory by exploring the different patterns of technological development of laser

diodes in the U.S. and Japan.[1]

Large, vertically integrated firms internalize technological knowledge in their R&D laboratories and place a high priority on knowledge creation in their business strategies. In addition to such Chandlerian firms, smaller, less vertically integrated start-ups have played a vital role, especially in technology-intensive industries. Internal resources have been spun off from a parent firm to be marketed and to generate additional value. Spilling over from intellectual hubs such as Fairchild Semiconductor, Stanford University, and Massachusetts Institute of Technology (MIT), numerous engineers began to establish technology-intensive businesses. Start-ups in Silicon Valley in California and on Route 128 in Massachusetts are notable examples. Spin-outs have an important industrial function in fulfilling untapped demand by laterally utilizing the existing technology. It is considered that entrepreneurship based on this pattern of knowledge spillovers and spin-outs drives economic and technological development.

Although entrepreneurial spin-outs are generating great interest from different perspectives such as entrepreneurship, regional clusters, open innovation, and corporate finance, few studies have considered the impact of spin-outs on technological development. It is reasonable to assume that competition among entrepreneurial spin-outs reveals different technological development patterns than those displayed by vertically integrated firms, since many start-ups spin out and laterally utilize technological knowledge developed by a parent organization for new sub-markets.

This study focuses on how entrepreneurial spin-outs influence the ways in which technology with the potential to be utilized in a very wide variety of products and processes is subsequently developed after its original invention. Since new technology is usually invented at a nascent level, its subsequent cumulative development plays a very important role for the full realization of potential (Rosenberg 1982). Following the concept of technological trajectory (Dosi 1982), this paper explores how entrepreneurial spin-outs influenced the ways in which technology with considerable areas of application subsequently evolves over time along with the technological trajectory by

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[1] Technically speaking, spin-out and spin-off can be classified into different categories. The U.S. Securities and Exchange Commission defines a spin-off as a firm whose parental firm receives equity stakes in the newly spun-off firm. Spin-out is generally regarded as a firm formed when an employee or group of employees leaves an existing entity to form an independent start-up firm. Since this paper pays attention to scientists who leave their existing affiliation to launch a start-up, it does not make a clear distinction between spin-out and spin-off. It uses them interchangeably unless it needs a specific distinction.

investigating the technological development of laser diodes in the U.S. and Japan.

The laser diode is a kind of laser that emits a narrow beam of coherent light, which is highly versatile and is generally regarded as General Purpose Technology.[2] Typical examples of application areas are telecommunications, optical information storages, sensors, pointers, displays, measurements, medical uses, and 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 20th century. As will be described in the third section, U.S. and Japanese organizations have been the main actors throughout the history of laser-diode research. Throughout the 1960s and 1970s, U.S. and Japanese firms followed the same technological trajectory, encountered the same technological problems, and aimed to achieve the same targets. However, U.S. scientists and engineers began to diverge from this trajectory in the 1980s when they began to spin out from parental organizations and launch start-ups, while Japanese firms remained competing on the same technological trajectory (Shimizu 2010).

The next section of this paper reviews previous literature on technological development of highly versatile technology, technological trajectory, and spin-outs. The third section describes the process of laser-diode development in the U.S. and Japan and shows technological trajectories in two major applications: optical communications and optical information storage. Directing its attention to the R&D spin-outs in the U.S. and the absence of spin-outs in Japan, the fourth section scrutinizes how U.S. firms withdrew from the technological trajectory and gained competitiveness in customized and untapped markets, while Japanese firms remained competing on the same technological trajectory. The fifth section theoretically examines market conditions and institutions that are conducive for scientists and engineers' entrepreneurial R&D spin-outs. The sixth section discusses how the entrepreneurial R&D spin-outs influence patterns of technological trajectory formation across countries. The concluding section

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2 As reviewed in the following section, General Purpose Technology has several positive characteristics, such as its versatility and high impact on macroeconomic productivity. Based on the four characteristics of General Purpose Technologies, which are a wide scope for improvement and elaboration, applicability across a broad range of use, potential for use in a wide variety of products and processes, and strong complementarities with existing or potential new technologies, it has been indicated that historical patent data should be examined to explore whether electricity matches these four criteria (Moser and Nicholas 2004). The main purpose of this paper, however, is not to explore whether laser diodes are actually General Purpose Technology or not.

summarizes the findings, considers implications, and discusses limitations for future research.

Previous Literature

Technologies that can be used in a wide variety of products and processes are often called General Purpose Technology in economics and have received much attention. General Purpose Technology 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" (Arrow 1962). Electricity, steam engine, lasers, and computers are generally regarded as being among the most important examples.

One of the reasons why General Purpose Technology has received attention is that the occasional arrival of new General Purpose Technologies yields large positive externalities on macroeconomic outcomes (Helpman 1998). However, it must be noted that the initial impact of General Purpose Technologies on overall productivity growth is minimal. The realization of its eventual potential may take several decades or hundreds of years. The previous literature of Economic History shows the extent to which the eventual potential of a technology is realized depends on the level of subsequent technological development (Rosenberg 1982, Mokyr 1990, Allen 2009).

The previous literature on the innovation process has indicated that technological paradigms and trajectories play important roles in the direction of subsequent technological development. A technological paradigm is defined as following the concept of a paradigm in science (Kuhn 1970) and a "technological trajectory" has been defined as "a cluster of possible technological directions whose boundaries are defined by the nature of the paradigm itself" (Dosi 1982). In other words, the paradigm defines the direction of subsequent technological advances. Once a certain technological trajectory emerges, it provides a direction for subsequent technological development. Technological trajectories are not created by a single actor. Similar to the emergence of the normal science paradigm described by Thomas Kuhn, rather, they emerge through interaction between several actors. In other words, a certain technological trajectory emerges when a majority of actors take a cumulative technological approach to the same technological problem.

Management studies have indicated a similar point from the perspective of dominant design. Dominant design is a key technological feature that has become a de facto standard of industries and determined the directions of subsequent technological development (Suarez 2004, Utterback and Abernathy 1975, Abernathy 1978). Even though interpretation of the concepts, underlying causal mechanisms, and units of analysis have varied in the empirical literature on dominant design (Murmann and Frenken 2006), the previous literature reveals that varieties of new designs and new materials are created before a dominant design emerges. After a dominant design has arrived, the subsequent technological development became incremental, accumulative, and standardized along a certain technological trajectory.

As will be described in the following section, the different pattern of subsequent technological development was actually observed in laser diodes developed in the U.S. and Japan for example (Shimizu 2010). This paper reveals that the patterns of subsequent technological development and the ways in which technological trajectories emerge vary according to whether or not vibrant R&D spin-outs occur (especially about the time at which the existing technology becomes middle aged).

The importance of spin-outs has been described by the history of technology, in which the actual development, elaboration, and utilization of highly versatile technologies has been well documented. For instance, the history of the machine tool industry in the U.S. reveals that spin-out machine tool firms played an important role in making full use of the technology into various fields from the middle of 19th century (Rosenberg 1976).

To formally examine what caused the observed difference in the technological trajectories in the U.S. and Japan, this paper presents a simple model of R&D spin-outs based on game theory. The empirical literature has documented a certain set of spin-out regularities. For instance, better performing firms spawn more spin-outs, more profitable spin-outs come from better performing firms, M&A promotes spin-out rate, and the most likely time for spin-outs is at the time the parent firms reach middle age. Although there have been offered several models that account for the first three regularities such as those by (Hellmann 2007, Klepper and Sleeper 2005, Thompson and Chen 2011, Klepper and Thompson 2010, Franco and Filson 2006) among others, none except Klepper and Thompson (2010) considers the last one. In their model, Klepper and Thompson (2010) set internal disputes between scientists and managers as a driving force of spin-outs and considered little of the market competition. In contrast, the model developed in this paper takes into account all of these regularities and also incorporates more of the effects of the difference in market environments such as the flexible labor market, flexible risk capital supply and so on.[3] Relying on a

[3] However, it considers little of the detail on internal disputes. So, one may say that our model is complementary to the extant models in some sense.

game-theoretic framework, it also analyzes the possible effect of the interaction among scientists and engineers on their spin-out decisions. And it explores how spin-out competition for sub-markets influences the subsequent technological development, which has not previously been investigated.

Laser Diodes and Technological Trajectories

This section briefly describes the technological development of laser diodes, also known as semiconductor lasers. Laser diodes are the biggest selling lasers in the world among many varieties of lasers (e.g., CO2, YAG, He-Ne, ruby, laser diode). They are used in various areas of application such as biomedical, light for high-speed cameras, material processing, optical sensors, laser pointers, measurement, optical disks, printers, barcode readers, and optical fiber communications. The required specifications, such as wavelength and power of light, vary depending on application. The two biggest application areas have been 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. 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 20th century.

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. The development of the laser diode was exciting news for physicists involved in laser-related R&D since it opened up huge possibilities for lasers. Before the invention of the laser diode, lasers were very bulky and required significant energy input. However, the invention of the laser diode revolutionized the concept of lasers, since laser diodes were very compact lasers that would eventually fit on tiny chips and efficiently operate from a small battery. The size of the laser-diode chip was less than one millimeter; the diameter of the packaged laser diode was around five millimeters.

The laser diode was still at a nascent level, even although physicists recognized its huge potential. The laser diodes developed in 1962 functioned efficiently only at minus 196 degrees Celsius (i.e., liquid nitrogen temperature). 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 developing a laser diode that could operate at room temperature.

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 newspapers predicted that this newly invented DH laser would revolutionize optical engineering in the same way that the transistor transformed electronic engineering.

Many U.S. electronic, telecommunication, and electronics enterprises (such as GE, RCA, Bell, and IBM) competed to develop laser diodes that could achieve stable operation with long life times at room temperature. Japanese electronics and telecommunication firms (including Hitachi, Toshiba, Mitsubishi Electric, and Nippon Electric Company (NEC)) became involved in laser diode research in the 1960s as well. Since laser beam amplification was noisy and unstable and the semiconductor used had a short life span, all firms competed to develop stable, long-life laser diodes that could operate at room temperature.

The main application of laser diodes in the early 1970s was long-distance telecommunication. At that time, long-distance telecommunication used electric wires, the quality of which were poor. Their main problem was energy loss; it was necessary to use a relay device (called a repeater) every few kilometers. Using too many relay devices produced time lags, created background noise, and caused lines to be cut off. Engineers believed that the laser optical fiber would resolve these problems by reducing energy loss. Since they estimated that an optical fiber would require one relay device every 180 kilometers, they believed that the optical fiber would enable clear, instant, and stable long-distance telecommunication. They predicted that optical fibers would replace electric wires for long-distance telecommunication if a practical optical fiber and a reliable laser diode could be developed.

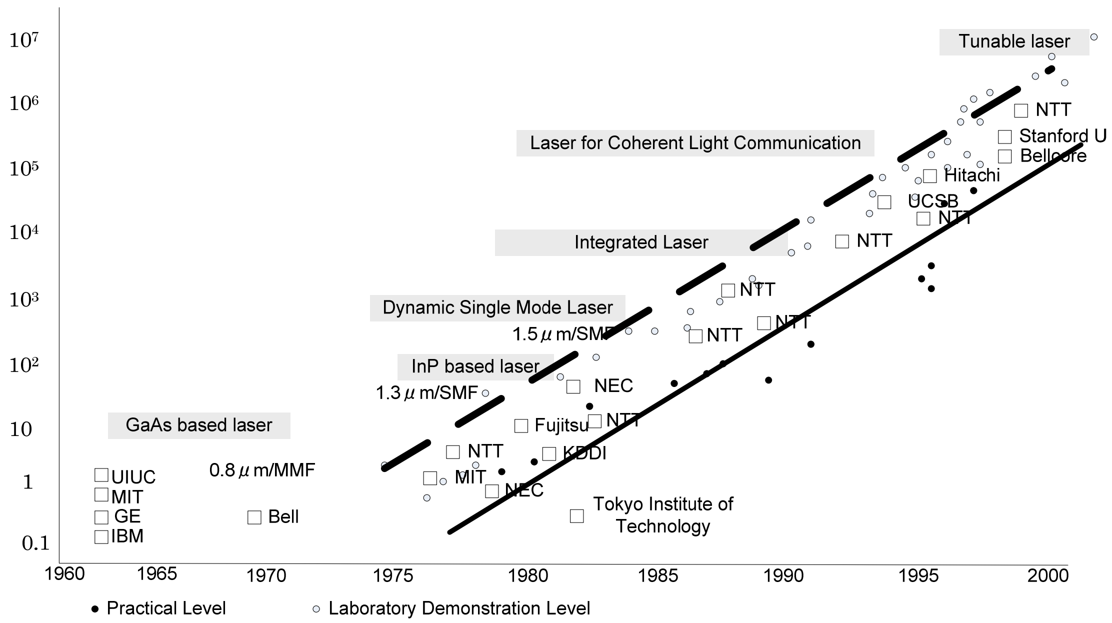
Scientists and engineers faced two technological problems. One was the low longevity of laser diodes. The laser diodes that operated at room temperature in 1970 were so unstable that they stopped operating after a few seconds or minutes. It was necessary for firms to develop laser diodes with high longevities because it would be very difficult, if not impossible, to replace laser diodes installed in the marine cables for long-distance telecommunication. Another problem was the oscillation spectrum of laser diodes. If the oscillation spectrum was multimode, light transmission in the optical fiber would be significantly disturbed; thus, creating single mode oscillation was critical.

From the late 1960s, firms competed to develop laser diodes that satisfied these technological targets. Since the wavelength at which laser diodes had minimum energy loss in optical fibers shifted from 800nm to 1300nm and 1550nm due to advances in optical fiber technology, firms competed to develop laser diodes to achieve these two technological goals at the most appropriate wavelength.

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, Stanford University and Minnesota Mining and Manufacturing (3M) started researching laser technology for data storage on photographic video discs in 1961. At that time, information was stored as analogue signals. The goal of researchers at Stanford and 3M was to store data as digital signals. Unfortunately, their efforts failed because laser technology was still immature. Even though their research attracted little attention at the time, theirs was the first attempt to use optoelectronic technology for data storage. Ten years after Stanford and 3M's attempts, some firms began to conduct research on video disc technology and ultimately developed several video disc systems based on advances in laser technology. Adopting different formats, electronics firms such as Philips, RCA, Mitsubishi Electronics, and Toshiba competed to develop video discs. As firms committed to laser-diode R&D, it became clear that the laser diode would find applications in optical data storage, such as video discs, compact discs, and laser discs. Moreover, the expectation was that the potential market for short wavelength laser diodes would be huge; laser diodes would be utilized in various applications, including barcode readers, laser pointers, and laser printers. Data storage, barcode readers, and laser printers were new product markets for the laser diode. As expectations for these markets grew, more firms (including Xerox, Sony, Sharp, and Panasonic) began to develop laser diodes in both the U.S. and Japan. 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 manufacture. In 1982, Sony and Philips released the compact disc, the first major consumer electronics product for laser diodes. The compact discs player used GaAlAs laser diodes with an output wavelength of 780 nm. In 1985, NEC, Sony, and Toshiba developed barcode readers that used InGaAlAh laser diodes with an emission wavelength of 670 nm. Digital versatile discs (DVD) using laser diodes with an output wavelength of 650 nm were introduced in Japan in 1996, in the U.S. in 1997, and in Europe in 1998. AlGaInN lasers with an output wavelength of 400 nm were developed in the late 1990s and were released for high-definition optical data storage in 1999.

The following figures illustrate the technological trajectories in the main application areas: optical communication and information storage and processing. Figure 1 shows a plot of the transmission capacity and optical communication distance; it illustrates the technological trajectory of optical communications systems and laser diodes. Since the increase in communication capacity and distance was considered the most important point in optical communication, all of the firms and research institutions targeting the optical communication market competed in this technological paradigm. Figure 1 also indicates the organization that achieved the technological development at each phase. The transmission capability has increased steadily since the 1960s. This figure also reveals that U.S. organizations took the lead in the trajectory until the 1970s, while Japanese organizations dominated after the 1980s.

Figure 1: Technological Trajectory of Laser Diodes for Optical Communication

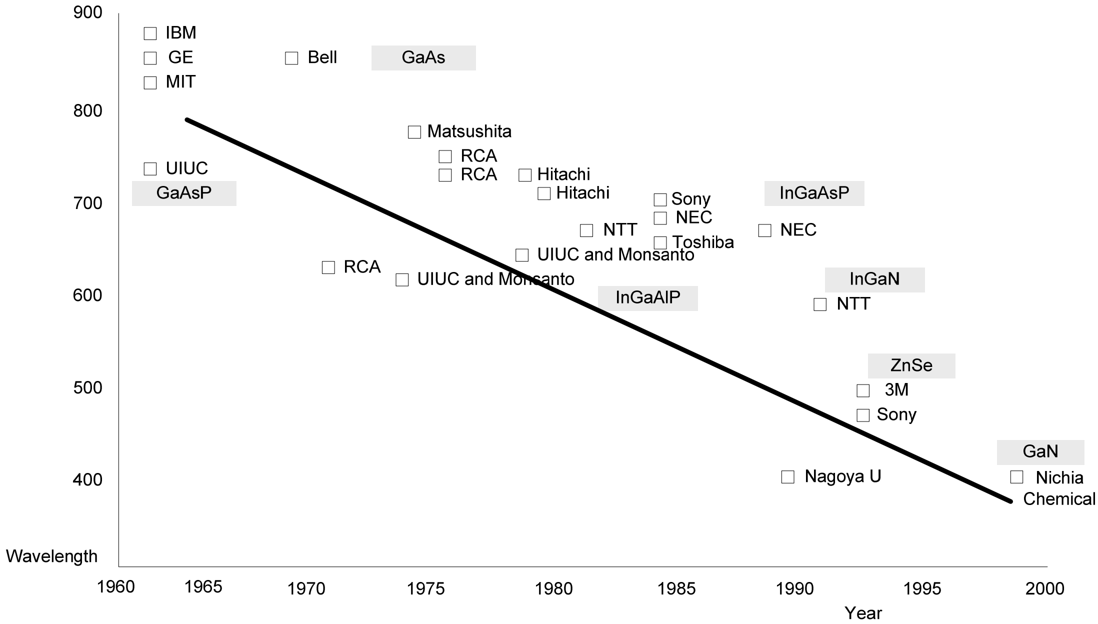


Source: drawn based on (Yoshikuni 2009)

Based on wavelength data from papers published in academic journals, Figure 2 illustrates the technological trajectory in laser diodes for optical data storage and processing. As mentioned above, developing laser diodes that could emit shorter wavelength light was critical because more information could be stored with a shorter wavelength laser diode.

Figure 2: Technological Trajectory of Laser Diodes for Information Storage and

Processing



Source: drawn based on (Hatakoshi 1997)

As Figure 2 illustrates, U.S. organizations such as IBM, GE, MIT, UIUC, and Bell were achieving breakthroughs by 1970. Japanese organizations made no significant breakthroughs in this early phase of laser-diode development, but began to do so with the development of shorter wavelength laser diodes in the 1980s. Both Figures 1 and 2 demonstrate that U.S. firms and universities achieved important developments on the technological trajectories until the 1970s. However, U.S. firms almost disappeared from the trajectories beginning in the 1980s.

Behind the Shift: Entrepreneurial R&D Spin-outs and Concentrated R&D Efforts

Directing its attention to the R&D spin-outs in the U.S. and the absence of spin-outs in Japan, this section explores how U.S. firms withdrew from the technological trajectory and gained competitiveness in customized and untapped markets, while Japanese firms obtained a dominant market share.

In the 1960s and 1970s, big enterprises played an important role in laser-diode R&D in both the U.S. and Japan. Many U.S. electronic, telecommunication, and computing enterprises (such as GE, RCA, Bell, and IBM) competed to develop laser diodes that could operate with longer life times at room temperature. Japanese vertically integrated electronics firms (such as Hitachi, Toshiba, Mitsubishi Electric, NEC, and Fujitsu), and telecommunication firms (such as NTT and KDDI) also became involved in laser-diode research at the end of the 1960s. Targeting telecommunications and information storage and processing applications, both U.S. and Japanese firms competed on the same technological trajectory until the 1970s.

The first catalyst for change was the decline of the U.S. consumer electronics industry, which began in the 1970s. The increased cost of raw materials and production reduced the profitability of diversified businesses of U.S. electronics firms (Chandler 1994). Competition against foreign rivals became fiercer in the 1980s. The market share of U.S. electronics in the global market dropped from 71% in 1960 to 27% in 1986 (Chandler 1994). Large U.S. electronics, computing, and office equipment enterprises began to focus on profitable markets in the mid-1970s as they lost position in the global market due to fierce competition from new Asian rivals.

In this context, RCA, GE, and IBM, the leading firms in laser-diode R&D, decided to retreat or exit R&D competition in laser diodes. However, scientists and engineers engaged in laser-diode research at these organizations did not suddenly disappear. Many leading scientists in this area left to launch or to join new businesses at the same time that large companies began to withdraw from the R&D race on the technological trajectories. Actually the spin-outs had begun before the leading firms began to retreat from R&D competition in laser diodes. The first major spin-out was in 1967, from RCA, as will be described in the following section. This spin-out had occurred clearly much before RCA decided to withdraw from laser-diode R&D. As will be described below, many of the spin-outs occurred before their parental firms withdrew from the laser-diode R&D race.

Since laser technology seemed to have a bright future, venture capital became a major catalyst in bringing risk capital to laser-diode spin-outs. In addition to venture capital, the Department of Defense provided research funds for laser-diode research. The importance of optoelectronics increased during the Cold War and furnished a range of new military applications, including guided missiles and radar. Research on lasers and related fields began receiving support from the Department of Defense in the mid-1950s. While total U.S. spending on military R&D declined in the late 1960s as the Vietnam War began to wind down, lasers were to become a strategically important technology under Ronald Reagan's Strategic Defense Initiative, which was popularly known as the "Star Wars" program. The Department of Defense research funding was favorable to spin-outs. Since the government did not directly commission research for industrial applications, the strategy among small, specialized firms, with a focus on

R&D and lack of manufacturing facilities, to seek research funding as a source of revenue seemed reasonable. It was these firms that were competing for Department of Defense research funding.

Spectra Diode Laboratories (currently named SDL, Inc.) was one of the first significant commercial suppliers of quality high-power laser diodes. The company was founded in 1983 by spin-out scientists from Xerox (Jacobs and Scifres 2000). EPITAXX, a fiber-optic detector manufacturing start-up, was launched by a scientist spin-out from RCA in 1984. The founder, Greg Olson, founded another start-up in 1992, Sensor Unlimited, which specialized in near-infrared sensing devices. Lytel, founded in1984, was another example of a spin-out from a scientist who had worked for RCA. In 1998, its founder launched another start-up, Alfalight, a company that designed and manufactured high-power laser diodes for industrial, defense, and telecommunication applications. A spin-out scientist from IBM joined a start-up, Optical Information Systems, funded by Exxon in 1978, when IBM decided to exit laser-diode research. Spin-outs were formed from Bell Laboratories. Emcore, currently 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 Optoronics when it was founded in 1983. Optical Concepts was founded in 1990 by scientists who had worked for Bell Laboratories. Multiplex was launched in 1997 by a Bell Laboratories spin-out scientist as well.

Spin-outs arose not only from big enterprises, but also from academic institutions. One such example is Lasertron, founded by a professor who developed the first one-micrometer waveband laser diode at MIT in 1976. The founder of Lasertron created another start-up, Sheaumann Laser, which manufactured packaged laser diodes, in 2005. A high-speed laser diodes manufacturing start-up, Ortel, later acquired by Lucent Technologies, was founded in 1980 by graduate students with the assistance of a professor at California Institute of Technology. Micracor, where new technology such as the high-power, optically pumped, surface-emitting laser diode was developed, was spun off from MIT Lincoln Laboratory.

While many entrepreneurial spin-outs emerged in the laser-diode industry in the U.S., such spin-outs were virtually non-existent in Japan. Neither corporate scientists nor university professors would leave a parental organization to launch a spin-out in Japan. Based on data from 1960 to 1990, the mobility of highly cited scientists was higher in the U.S. than Japan. Nearly 52% of top U.S. scientists changed affiliation at least once, while 90% of the top Japanese scientists retained their affiliations (Shimizu 2010, Shimizu 2011). This implies that scientist mobility, which plays a key role not only for a scientist in launching a spin-out but also for a firm in acquiring external knowledge, was comparatively very low in Japan. As past research on the Japanese labor market has shown (Itoh 1994, Aoki 1988, Hazama 1997), it has been quite rare for scientists to transfer from one company to another in the laser-diode industry in Japan.

This difference between the U.S. and Japan has had an impact on the technological development of laser diodes and their market positions. Industrial report revealed these trends well. The Japan Technology Evaluation Centre (JTEC) report indicates that U.S. start-ups played an important role in the technological development in the U.S. by specializing in untapped markets (Forrest et al. 1996).

> "Japan's lead in high-volume consumer optoelectronics and related technologies gave it a dominant share of the overall global optoelectronics market…"
> "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.
> (Forrest et al., 1996)

Figures 1 and 2 illustrate that U.S. organizations such as IBM, GE, RCA, MIT, UIUC, and Bell Laboratories were achieving breakthroughs until the beginning of the 1980s. However, U.S. start-ups emerged at the end of the 1970s and targeted customized and untapped sub-markets such as short distance communications, sensors, and optical pumping by utilizing laser-diode technology. Sub-markets appeal to different users and require different knowledge and methods of production (Buenstorf and Klepper 2010). Thus, sub-markets were areas where new entrants could launch their own business by utilizing the existing laser-diode technology. These markets tended to be customized and segmented for two reasons. Start-ups usually did not 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 individual markets was usually smaller than those of long-distance telecommunication and information storage. Few breakthroughs by U.S. firms appeared in technological trajectories not because U.S. organizations were losing their R&D capabilities, but because R&D investment in laser-diode technology was scattered and dispersed in various sub-markets in the U.S. via the entrepreneurial spin-outs. In other words, beginning in the 1980s, U.S. scientists shifted their R&D focus from on-trajectories (Figures 1 and 2) to off-trajectories.

Big enterprises such as Hitachi, Mitsubishi Electric, NEC, Fujitsu, Toshiba, Sharp, Panasonic, and Sony played a dominant role in R&D of laser-diode technology in Japan. Vertically integrated large enterprises tended to target mass markets because the high fixed costs incurred in building high-throughput facilities demanded high-volume sales (Chandler 1994). Such enterprises developed laser diodes for growing mass markets such as optical communications, compact discs, DVD, scanners, and laser printers. The R&D focus of Japanese scientists remained on the trajectories throughout the period. For instance, Japanese firms competed to develop a shorter wavelength laser that could handle high-volume information storage and capture 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 long telecommunications and information storage markets. A certain technological trajectory emerged when many firms developed technology for the same targets, shared a common definition of relevant problems, and tackled these problems with the same approach. Since many vertically integrated large firms competed on the same technological trajectories for the mass markets, the cumulative effects of incremental innovations on the trajectories eventually emerged in the 1960s and the 1970s, as Figures 1 and 2 demonstrate.

Why did Japanese firms not retreat from the unrelenting competition and target niche markets, as did many U.S. firms? Japanese electronics firms were enjoying a favorable economic climate for R&D investment, while American electronics firms were facing a decline from the mid-1970s (Chandler 1994). Because the laser diode was regarded as the most important key component in the development of optoelectronics products, it was necessary for Japanese firms to source it internally in order to have a secure and reliable laser supply.[4] Compared to the U.S., the inter-organizational research networks in Japan were not as well developed (Shimizu and Hirao 2009). The less developed research networks prevented engineers from accessing external complementary knowledge, which played an important role in the lateral utilization of existing technology for new targets. Furthermore, as will be theoretically explored in the next section, factors such as limited access to risk capital and poor re-employment conditions discouraged Japanese corporate scientists from leaving their parental firm to target untapped sub-markets by launching start-ups. Thus, many Japanese firms were channeled to compete in the same technological trajectory due to the less developed research networks and low engineer mobility.

Japanese firms gained a competitive edge in high-volume markets, cornering a huge share of the market (Forrest et al. 1996, Wood and Brown 1998). However, this did not necessarily mean that the profitability of Japanese firms was high. Many firms such as Hitachi, Toshiba, Mitsubishi Electric, Matsushita, NEC, Fujitsu, Sony, Sharp, and Sanyo competed to develop reliable and long-lasting lasers for an optical information storage market undergoing a high-volume expansion. Severe R&D competition over the long term in the same markets lowered profitability. As a number of firms competed in the same technological area for an extended period of time, the aggregate amount of R&D investment in the area gradually grew. The increase in R&D investment enhanced the potential for making technological breakthroughs on the one hand, but lowered the profitability of Japanese firms on the other.

Entrepreneurial R&D Spin-Outs

U.S. organizations, which had achieved many developments in laser-diode research in the 1970s, started disappearing from the trajectory at the beginning of 1980. This is because, we have argued, many start-ups emerged in the U.S. from the end of the 1970s, causing their R&D investment to be scattered and dispersed across various sub-markets. To the contrary, how come such vibrant spin-outs were nearly absent in Japan? Or differently put, what determines the entrepreneurial spin-out decisions of scientists and engineers? Intuitively, the issue is complex, since it may be appropriate to consider several aspects of the market conditions as well as the competition among the

[4] This point is confirmed in interviews with Japanese engineers as well. This point was consistently confirmed by the interviews on corporate scientists. The author conducted 124 interviews with scientists, engineers, and managers engaged in laser-diode R&D in the U.S., Europe, and Japan between September 9, 2004 and December 13, 2013. The list of interviewees and interview data is available on request.

scientists and engineers. Using a game-theoretic framework, this section provides a formal analysis of the topic. For instance, the previous section pointed out that the U.S. experienced a sharp decline in the consumer electronics industry from the mid-1970s, had good access to risk capital and research funding, and exhibited a high mobility rate of scientists. In contrast, corporate scientist mobility was quite low and access to risk capital quite limited in Japan. Through a simple game-theoretic analysis, this section reveals that in general, these are all among the factors that accelerate entrepreneurial R&D spin-outs.

Model

Consider the following symmetric participation game where entry is rivalrous. Endowed with a certain level of technological knowledge, $l > 1$ corporate scientists are considering leaving to start up new businesses. The payoff to "leave" is the same for all scientists. Also, it depends on the number $k < l$ of scientists who choose to leave. We call this payoff $f(k)$.

As Forrest et al. (1996) observed, suppose that the targeted market for new businesses is niche. Specifically, the demand is not strong enough for it to be profitable to more than $m < l$ entrants. If there are m scientists or fewer choosing to leave, then they can all enter successfully. If, on the other hand, more than m scientists are leaving, then every scientist choosing to leave faces an equal probability $1 - m/k$ of failure. All successful entrants earn some fixed entrepreneurial π.[5] All unsuccessful entrants are re-employed at some wage level $z \geq 0$. Note that the model does not exclude the case of $z = 0$. A proposed interpretation of it is that there is no chance of being re-employed. A higher z, on the other hand, is related to ease of re-employment for each scientist and engineer. In this light, z is considered as a parameter related to the mobility of scientists.

In summary, a scientist's payoff to "leave" when k scientists are about to leave is

$$f(k) = \begin{cases} \pi, & \text{if } k \leq m, \\ (m/k)\pi + (1 - m/k)z, & \text{if } m < k \leq l. \end{cases}$$

Note that f is non-increasing in k. So, together with the limited size of the targeted

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[5] Note that the suppositions of bounded m and fixed π are both consistent with the observations of Forrest et al. (1996) that U.S. startups tend to specialize in filling narrow niches and to target a segmented market. Usually, startups do not have large manufacturing facilities in-house; so they tend to be capacity-constrained and produce some fixed amount, implying a segmented market.

market given by m, a larger k results in more congestion.

Every scientist choosing not to leave, on the other hand, continues to stay as a corporate scientist and receives a wage $w > z$.

An equilibrium of concern here is a symmetric Nash equilibrium. As shown below, one always exists and is unique. Typically, the game also has many asymmetric Nash equilibria. However, as with Dixit and Shapiro (1986), instead of determining the entire set of the equilibria, we rather focus on a symmetric one and stay away from the problem of how to select among them (Dixit and Shapiro 1986). (For a thorough and more general treatment of the entire set of Nash equilibria in this class of participation games, see, for instance, (Anderson and Engers 2007).)

Assumptions

Intuitively, there are many different factors that influence the optimal timing of entrepreneurial R&D spin-outs by scientists and engineers.[6] First, they may be influenced by the level of the development of the existing technology. If it is at a nascent level, then spin-out scientists utilizing this technology may fail to fill the demand of the targeted niche market. In that case, the optimal timing of entrepreneurial spin-outs may not be like t'' described in Figure 3, where the path of technological development takes the shape of an S-curve (Forster, 1986).[7] Actually, this happened in the laser-diode industry. Utilizing GaAs manufacturing technology, technicians spun out from RCA and launched Laser Diode Laboratories, Inc. in 1967. However, since GaAs manufacturing technology was immature, the operating life of the laser diode was quite short and reliability was very low. Large enterprises such as Bell Laboratories, RCA, IBM, NEC, Hitachi, and Mitsubishi had struggled to increase longevity and improve laser reliability until the middle of the 1970s (Shimizu 2010). So, Laser Diode Laboratories, Inc. could not successfully establish its own business because of its short longevity and low reliability. In short, it was too early for a spin-out to launch a start-up in the industry.

Formally, if the technological knowledge that is endowed by the l corporate scientists is at a nascent level and can only generate some small profit satisfying $\pi < w$,

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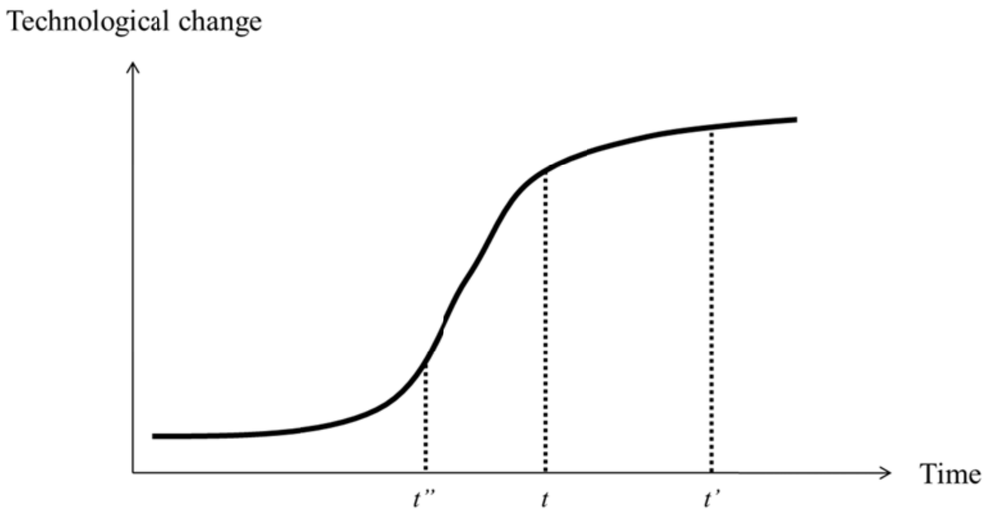
6 For instance, see Klepper and Thompson (2010) and the references therein.

7 As has been mentioned in the previous literature (Christensen 1992), S-curve does not fully account for the complexity of technological change. The thrust of the argument here is not whether the path shapes the S-curve, but the stylized fact that many entrepreneurial spin-outs occurred around the time of the existing technology becoming middle-aged and how they possibly influence the technological trajectory.

then a dominant strategy is choosing to stay, so none starts up a new business. To avoid such trivial cases, let us assume throughout the analysis $w < \pi$.

Figure 3: Entrepreneurial Spin-outs and S Curve



Also, if the targeted market is large enough, then the congestion effect caused by an increase in k becomes negligible. In that case, it may be optimal for R&D spin-outs to be postponed until the existing technology is fully mature (e.g., until t' in Figure 3), since the ability to capture the targeted niche market by corporate scientists is raised by then. Formally, it is considered as the case that m is large enough to satisfy $f(l) > w$ given π, w, z, and l. If it is not satisfied, then the congestion effect caused by an increase in k matters, implying that the optimal timing tends to lie about the time of the existing technology becoming middle aged, as with t in Figure 3. Forrest et al. (1996) observed that the target market is usually niche, and so we specified above. To be consistent with these, we also assume that m is small enough to satisfy $f(l) < w$ given π, w, z and l.

Notice that the assumption that π, w and m satisfy $f(l) < w < f(1) = \pi$ given z and l ensures no existence of a dominant strategy in this game. It follows that *the* symmetric Nash equilibrium to this game is a non-degenerate mixed-strategy equilibrium. In the analysis below, our interest is in the behavior of the Nash equilibrium, the so-called equilibrium spin-out rate at which each scientist chooses to leave and start up a new business. To this end, we first study the behavior of the expected payoff to scientist i choosing to leave and establish the existence and uniqueness of the equilibrium, followed by presenting the comparative statics results.

Equilibrium: the Existence and Uniqueness

For each scientist i, let p_i be the probability that scientist i leaves, and then $1-p_i$ the probability that i stays. If all the p_i are independent, a closed-form expression for the expected payoff to scientist i choosing to leave is

$$\sum_{k_{-i-j}=0}^{l-2}\left[\left(1-p_{\mathrm{j}}\right)b\left(k_{-i-j}\right)f\left(k_{-i-j}+1\right)+p_{\mathrm{j}}\,b\left(k_{-i-j}\right)f\left(k_{-i-j}+2\right)\right],$$

where k_{-i-j} is the number of scientists other than i and j choosing to leave, and $b(k_{-i-j})$, the probability that k_{-i-j} scientists choose to leave among $l-2$ scientists other than i and j. Note that it can be viewed as a function of p_j, the probability that each other scientist j chooses to leave.

Since $f(k)$ is constant for $k \leq m$ and strictly decreasing for $m < k \leq l$, clearly this is strictly decreasing in p_j. That is, every scientist's expected payoff to "leave" falls with the probability of each other scientist j choosing to leave.

Lemma. *The expected payoff to every scientist choosing to leave is decreasing in* p_j.

If all the p_j are identical and take the common value p, then the number of scientists choosing to leave follows a binomial distribution, so that

$$b\left(k_{-i-j}\right)=\binom{l-2}{k_{-i-j}}\,p^{k_{-i-j}}\,(1-p)^{l-2-k_{-i-j}}.$$

Hence, the expected payoff to scientist i choosing to leave can be thought of as a function of p. We denoted it by $V_i(p)$.

At a non-degenerate mixed-strategy Nash equilibrium, each scientist must be indifferent between staying and leaving; or else he would concentrate only on the preferred alternative. The indifference requires

$$w=V_i(p).$$

A symmetric non-degenerate mixed-strategy Nash equilibrium, if any, is a common probability $p^* \in (0,1)$ satisfying this equation for all i.

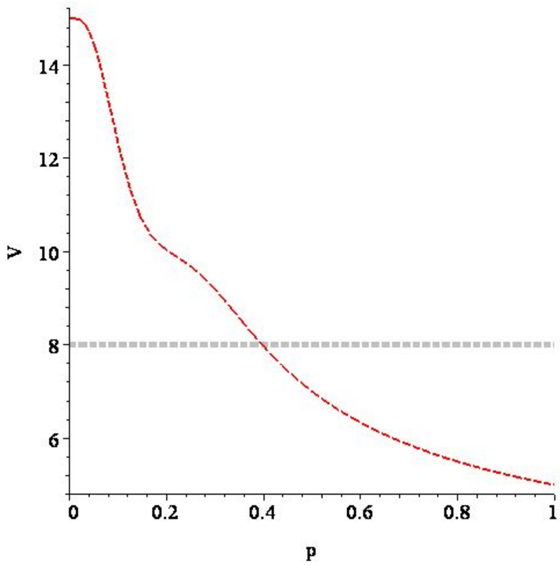
As established below, such a p^* always exists and is unique. So, the game always has a unique symmetric non-degenerate mixed-strategy Nash equilibrium.

Proposition 1. *There is a unique value* $p^* \in (0,1)$ *satisfying* $w=V_i(p)$ *for all* i.

Proof. $V_i(0)=f(1)$ while $V_i(1)=f(l)$. So, the stated monotonicity of $V_i(p)$ in Lemma ensures the existence. The uniqueness follows from the strict monotonicity. □

Figure 4 illustrates a simple example of the Nash equilibrium. The parameter values used are $\pi = 15$, $w = 8$, $z = 3$, $l = 30$, and $m = 5$. Note $f(l) = 5$, so the assumed condition holds. As can be seen, each scientist's expected payoff $V_i(p)$ from leaving strictly decreases with the common probability p. An equilibrium p^* that is a root of $V_i(p) - w$ is thus unique and given by $p^* = 0.4$.

Figure 4: The expected payoff $V_i(p)$ and the equilibrium p^*



Comparative Statics

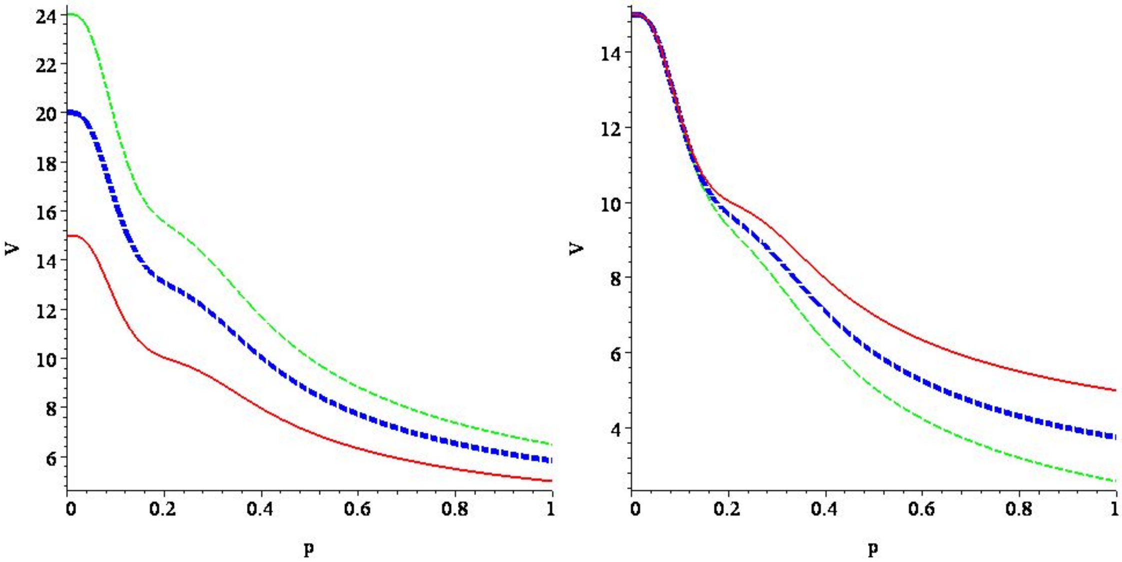
At *the* equilibrium, $w = V_i(p^*)$ holds. How does this equilibrium spin-out rate p^* change with the parameter values π, w, z, l, and m? The rest of this section considers the comparative statics results for this model.

Suppose first that the entrepreneurial profit π rises. Recall that in our interpretation, a rise in π results from higher ability to better capture the targeted niche market due to a more sophisticated technology to be adopted. All else being the same, this increases the payoff $f(k)$ from leaving for every k, and so does its expected value $V_i(p)$. For $V_i(p)$ to remain the same at w, the equilibrium spin-out rate p^* then must rise, since $V_i(p)$ is strictly decreasing in p as in Lemma. Therefore, a higher π results in more equilibrium spin-outs. It follows that a more sophisticated existing technology to be adopted causes more equilibrium R&D spin-outs.

Figure 5 (left) depicts the graphs of $V_i(p)$ for various π. The solid line is the graph for $\pi = 15$, while the thick break line is for $\pi = 20$ and the other break line for

$\pi = 24$. The other parameter values are $w = 8$, $z = 3$, $l = 30$, and $m = 5$. As can be seen, increased π raises the value of $V_i(p)$ for any p. So, *the* equilibrium spin-out rate p^* that is given by the unique root of $V_i(p) - w$ falls, since $V_i(p)$ is decreasing in p. In fact, the associated equilibrium spin-out rates are $p^* = 0.4$, $p^* = 0.57$ and $p^* = 0.7$, respectively.

Figure 5: $V_i(p)$ for various π (left) and z (right)



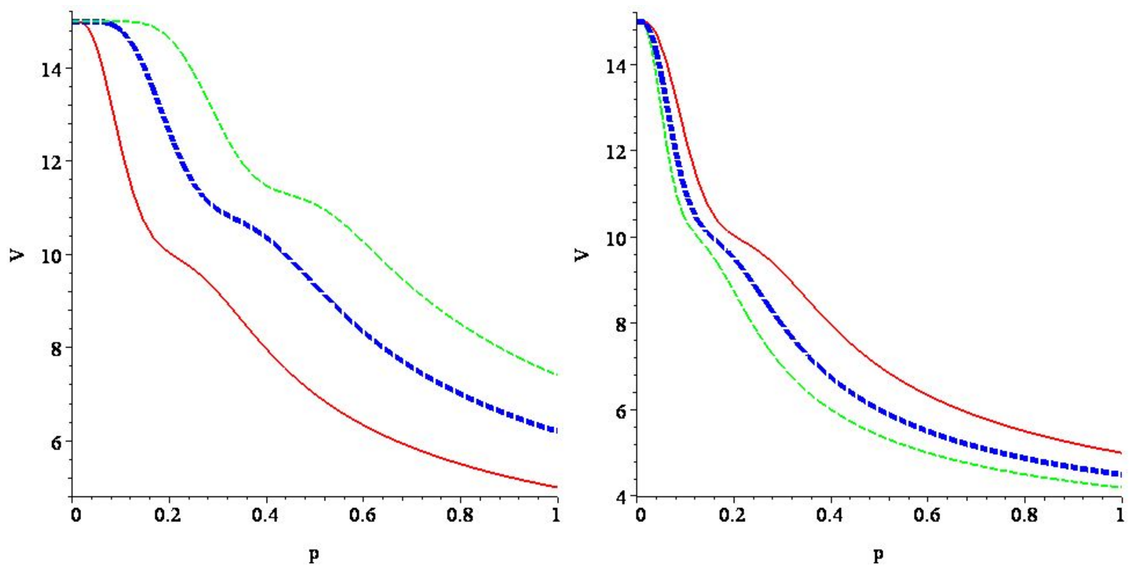
Likewise, Figure 5 (right) draws the graphs of $V_i(p)$ for various z. The solid line is the graph for $z = 3$, while the thick break line is for $z = 1.5$ and the other break line for $z = 0.1$. In our specification, a lower z is associated with an inferior re-employment environment and a higher z with an environment more favorable for scientists' mobility. The other parameter values are $\pi = 15$, $w = 8$, $l = 30$, and $m = 5$. Here, it is observed that as z falls, $V_i(p)$ remains the same for p close to zero and strictly decreases elsewhere. It is because an increase in z has no effect on the value of $f(k)$ for $k \leq m$ and strictly increases it for $k > m$. Since $V_i(p)$ is decreasing in p, it follows from the indifference condition $w = V_i(p^*)$ that the equilibrium spin-out rate p^* must fall, unless p^* is significantly close to zero. Differently put, a better environment for re-employment tends to promote the entrepreneurial spin-outs.

If the size of the market for the new business is larger (higher m), then successful entrance is easier for any scientist who chooses to leave their company. This in turn raises the payoff $f(k)$ from leaving, and so does its expected value $V_i(p)$.

Figure 6 (left) illustrates this point by plotting the values of $V_i(p)$ for different m. Here, the solid line is for $m = 5$, while the thick break line is for $m = 8$ and the other break line for $m = 11$. The other parameters are $\pi = 15$, $w = 8$, $z = 3$, and $l = 30$. As before, this together with the indifference condition and Lemma suggests a higher equilibrium spin-out rate p^*. That is, a larger size of the targeted market for the new business spurs more entrepreneurial spin-outs in an equilibrium.

On the other hand, if there are more corporate scientists (higher l), then each scientists choosing to leave faces a larger probability of failure in entry. As expected, this lowers the payoff $f(k)$ from leaving, and so does its expected value $V_i(p)$. In Figure 6 (right), we compute $V_i(p)$ for various l. The solid line is for $l = 30$, while the thick break line is for $m = 40$ and the other break line for $m = 50$. The rest of the parameters are $\pi = 15$, $w = 8$, $z = 3$, and $m = 5$. Since $V_i(p)$ is decreasing in p, the equilibrium spin-out rate p^* must fall to keep the expected value $V_i(p)$ at w. So, more competition among corporate scientists hinders the equilibrium entrepreneurial spin-outs.

Figure 6: $V_i(p)$ for various m (left) and l (right)



Lastly, consider the effect of a change in w. Increased w raises each scientist's payoff to staying as a corporate scientist, making choosing not to leave more attractive. So, this together with the indifference condition $w = V_i(p)$, as well as Lemma, then implies a lower equilibrium spin-out rate p^*. That is, a higher wage deters equilibrium spin-outs.[8]

Another interpretation of this result is stated as follows. U.S. electronics firms faced a severe decline from the mid-1970s and decided to withdraw from R&D competition in laser diodes from the 1980s, causing scientists and engineers engaged in laser-diode research at these organizations to expect to lose their jobs. The wage level w, in this case, may also be related to an economic climate surrounding the parental firms. A lower w is then interpreted as an indication of a more severe economic climate for the parent firms. According to this view, the result above also implies that a decline in economic climate causes more entrepreneurial R&D spin-outs.

All the predictions above are intuitive. Roughly, more scientists tend to leave if the technological knowledge to be adopted is more sophisticated, if spin-outs involve less risk, or if an economic climate is more severe. It merits emphasis that these predictions are consistent with what we have pointed out above as the observations for U.S. electronics firms in the 1980s, as well as the findings in the empirical spin-out literature. Before proceeding, the results are summarized as follows.

Proposition 2. *Suppose that $f(k)$ is the same for all scientists. Then, all else being the same, an increase in π, z, or m tends to raise the equilibrium spin-out rate p^*, whereas an increase in l or w lowers the rate p^*.*

We derived above the comparative statics properties for a case where all the scientists are symmetric. For further analysis, let us now introduce small asymmetries in the payoff to "leave." Specifically, suppose that scientist i is a top scientist, so that his payoff from leaving, $f_i(k)$, is increased, while those of the other scientists $j \neq i$, $f_j(k)$, are held constant. How does this change the equilibrium spin-out rate?

Proposition 3. *Suppose that $f_i(k)$ is raised for each k, while $f_j(k)$ is held constant for all $j \neq i$. Then, the equilibrium spin-out rate of scientist $j \neq i$ rises, while that of scientist i does not.*

Proof. At the new non-degenerate mixed-strategy equilibrium, all scientists $j \neq i$ use a common probability, say, p_j^*. If $f_i(k)$ is raised, then the indifference condition for i, $w = V_i(p)$, and Lemma together suggests that p_j^* will be higher than the original level

[8] Note that this is consistent with the theoretical prediction by Klepper and Sleeper (2006) and agrees with the empirical findings of (Campbell et al. 2012).

p^*. Next, the expected payoff from leaving to scientist j depends on $f_j(k)$ and the probabilities of leaving of the others (i.e., scientist i and scientists other than i and j). If $f_j(k)$ is held constant, then the expected payoff from leaving to scientist j does not change if $l = 2$ (i.e., there is no scientist other than i and j), and strictly increases otherwise (since $p_j^* > p^*$ now holds). To maintain the indifference condition for j, Lemma then implies that the new probability of leaving of scientist i will be the same if $l = 2$ and fall otherwise. □

Proposition 3 says that an increase in the payoff from leaving to scientist i induces strictly more equilibrium entrepreneurial spin-out by the other scientists. The equilibrium spin-out rate of scientist i, on the other hand, does not rise. So, when the payoff from leaving rises for scientist i, it is the other scientists who will leave while he does not. An increase in the equilibrium spin-outs is thus due to scientists other than i in this case.

As discussed above, there are many sources for an increase in f. For instance, both increased π_i and increased z_i result in an increase in $f_i(k)$. Also, $f_i(k)$ rises if the probability of success in entry faced by scientist i choosing to leave is higher than those faced by the other scientists choosing to leave, given $k > m$. Roughly, it can be considered as an increase in m_i. According to the proposition, all of these raise the equilibrium spin-out rate of scientists $j \neq i$, but not that of scientist i. On the other hand, an increase in w_i should have the opposite effect to Proposition 3.

An important implication of Proposition 3 is that the competition among scientists and engineers for filling in limited sub-markets accelerates the equilibrium timing of R&D spin-out. It seems natural to say that this in turn implies the fiercer competition among spin-out scientists may also have accelerated the timing of entrepreneurial R&D spin-outs in the U.S.[9]

Spin-outs and Technological Trajectory

The previous section formally examined the market conditions that are conducive for scientists and engineers leaving their parental firms to start up new businesses, and also how the competition among themselves influences their spin-out decisions. Given these, this section explores how such entrepreneurial spin-outs influence the pattern of technological trajectories.

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[9] Note that if we raise the payoffs from leaving of the other scientists in turn, then the same changes occur. So, the final outcome is that all probabilities rise. In this light, Propositions 2 and 3 are consistent.

As described above, a technological trajectory emerges when a majority of actors take a shared and cumulative technological approach to the same technological problem. Technological trajectories in an industry cannot be created by a single firm, unless many other firms followed the leading firm. Therefore, the interaction among firms plays an important role in forming technological trajectories. It is revealed below that the competition among scientists and engineers for sub-markets actually occurred in the U.S., and this in turn evaporated technological trajectories in the U.S. much earlier than in Japan.

If many of the scientists engaged in R&D were to leave the trajectory to laterally utilize its technology and to launch a start-up targeting an untapped sub-market, the technological trajectory would eventually be under-developed. If supply of skilled scientists were ample, the technological trajectory would not have vanished so quickly in the U.S. because the parental firms could have hired new scientists to fill vacant positions made by spin-outs. However, the pool of skilled scientists does not usually become boosted instantly because it takes in such a highly knowledge-intensive area. It requires formal graduate-level education in physics and professional R&D experience at a laboratory to be a skilled scientist. Therefore, if one star scientist left a firm, it had a substantial impact on its R&D. Actually, it was star scientists who spun out and launched start-ups in the laser-diodes area.[10] The case of laser diodes suggests that if the supply of skilled scientists does not catch up with the pace of competition among corporate scientists for sub-markets, the technological trajectory will vanish.

The areas where technological developments occur shifted from "on" trajectory to "off" trajectory in the individual sub-markets. This is the reason why fewer breakthroughs from U.S. organizations were observed in the technological trajectories from the 1980s depicted in Figure 1 and 2. They do not necessarily show that U.S. scientists were losing their technological capabilities. Rather, they were tapping sub-markets by utilizing the laser-diode technology. As a result, as corporate scientists left their parental firms and launched start-ups to target sub-markets, the existing technological trajectories were vanishing. In other words, the existence of sub-markets and institutions that encourage entrepreneurial spin-out was bench-clearing for existing technological trajectories. Entrepreneurial spin-outs, which laterally utilize the existing technology and shift R&D for individual sub-markets, can fade out the technological trajectory much earlier at the lower level, compared to a trajectory in which no entrepreneurial spin-outs occur.

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[10] This point was consistently confirmed by the interviews on corporate scientists.

However, if many scientists were to remain engaged in R&D even after the technology was well developed and productivity of technological development was diminishing, depicted as t' in Figure 3, the profitability of the firms would decrease. This happened to laser-diode development in Japan. Why did vertically integrated Japanese firms not target small niche markets even after the laser-diode technology became mature? One of the important factors was the high fixed cost structure of the firms. The size of each sub-market is not usually quite large enough for vertically integrated firms, whose high fixed costs increase their break-even point. Therefore, the market was too small for vertically integrated firms to cover their high fixed costs and achieve a satisfactory level of profit.[11] The other important factors were that Japanese corporate scientists faced environments that discouraged spin-out from their parental firm, as theoretically explored above.

Conclusions

This paper demonstrated how vibrant entrepreneurial spin-out influenced technological trajectories by exploring the technological development of laser diodes in the U.S. and Japan. As mentioned above, the previous literature, such as Rosenberg (1982a), Dosi (1982), and Kuhn (1970), indicated that "progress" on the technological trajectory is likely to retain some cumulative features; the cumulative effect of numerous small improvements gradually increases productivity. This study revealed that cumulative features of technological development on the trajectory gradually disappeared due to the surge in entrepreneurial spin-outs in the industry in the U.S. Technological trajectory plays an important role when technological development is still in the nascent stage. In other words, R&D competition on the technological trajectory contributes to the technological development until the technology becomes fully matured. Vibrant entrepreneurial spin-out could hinder technological development when the technology is still at the nascent level, because the cumulative effects of incremental innovations on the technological trajectories could vanish if many firms were thinned out to target different sub-markets.

Of course, severe price competition will result if firms compete on the same technological trajectory even when technological development is fully saturated. This occurred in the laser-diode industry in Japan when firms targeted the same mass markets and competed on the same technological trajectories; this eventually boosted the

[11] This point was consistently confirmed by interviews with corporate scientists.

cumulative technological development of laser diodes. Therefore, it is important for firms to laterally utilize technology in new markets to exploit the technological trajectory after technological development on the trajectory has fully matured.

The findings of this study have implications for the question of why Japanese firms were good imitators and achieved great process innovations, while U.S. firms were good at product innovations and poor imitators (Rosenberg 1988). One of the general explanations given for this issue has been 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 vanishing technological trajectories that can promote subsequent cumulative technological development.

Since the findings of this paper are based on the case study of laser diodes in the U.S. and Japan, we must be cautious about making rigorous generalizations. The nature of institutions such as the labor market and a risk capital market that encourages or discourages spin-outs from a parental organization can be very different across countries. Careful examination of the technological development of other highly versatile technology and, if possible, the emergence of technological trajectories in other countries will provide useful comparisons for this study and for better understanding of cumulative subsequent technological development on the technological trajectory.

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