Technology in Society 36 (2014) 39–51

Contents lists available at ScienceDirect

Technology in Society

journal homepage: www.elsevier.com/locate/techsoc

Long-term collaboration between university and industry: A case study of nanotechnology development in Japan

Yasuyuki Motoyama [a,b,*]

[a] Center for Nanotechnology in Society, University of California, Santa Barbara, United States
[b] Research and Policy, Ewing Marion Kauffman Foundation, United States

ARTICLE INFO

Article history:
Received 4 December 2011
Received in revised form 25 September 2013
Accepted 27 September 2013

Keywords:
Science and technology policy
Innovation
University–industry linkage
Nanotechnology

ABSTRACT

Much has been studied about university–industry collaboration, with the past studies almost exclusively focused on the explicit outputs out of university, such as patents, publications, licensing, and spin-offs. This article examines the little researched aspect of less explicit and more informal collaboration through two cases of nanotechnology development in Japan. The cases reveal that university and industry collaborate at a deep level, integrates various disciplines of knowledge, and university functions as a hub to develop networks of researchers, and to train corporate researchers to acquire the epistemological thinking process, much more than to transfer technologies. These findings sharply contrast with the conventional theoretical understanding of university–industry collaboration based on the linear model of development. It also provides policy implications to promote more substantial collaboration between university and industry beyond explicit intellectual property outputs.

1. Introduction

Since science has become a crucial input for technological innovation, economic competitiveness, and hence economic growth [1], academics and government officials alike have tried to strengthen the ties between universities and industry both at the national level and regional level [2–4]. However, despite this collaboration taking many forms of relationships between universities and industry, the past research in this subject has almost exclusively focused on the highly explicit aspect, such as spin-offs, patents, publications, and licensing [5–8].

Those attempts to measure university–industry collaboration in explicit terms is based on the so-called “linear model” of innovations and development in which university focuses on basic research and generates knowledge, while industries apply such research and technology for commercialization. However, scholars have repeatedly challenged this linear model [9] and identified other forms of university–industry collaboration, such as through informal interactions and consulting [10]. Furthermore, recent empirical studies revealed the in-depth nature of the iterative relationship between university researchers and industrial researchers in creating major innovations such as probe microscopy technology [11] and computing technology for music and acoustics [12].

Thus, we know that other forms of university–industry collaboration exist. Nonetheless, we know little about what exactly they are, how they evolve, and how they function. The primary objective of this paper is to highlight university–industry collaboration in its less explicit format through two cases of novel technology development, and to extend our theoretical understanding of these complex relationships and their benefits. This research uncovers several findings that run counter to the dominant linear model. I demonstrate how the development of collaborative research between industry and university evolves in forms other than explicit outcomes. I focus specifically on

---

* Center for Nanotechnology in Society, University of California, Santa Barbara, United States.
E-mail address: ymotoyama@kauffman.org.

0160-791X/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.techsoc.2013.09.001

how academic and corporate researchers at the frontline conduct advancement of 'knowledge' and 'technology' and develop such knowledge and technology in a long, complex process.

This article will employ an in-depth case study of nanotechnology development in Japan. Studying the Japanese case is important because the less explicit and more informal aspect of university–industry collaboration often takes place in the phase of basic research. Japanese firms have maintained a strong basic research capacity despite the economic downturn since the early 1990s, in contrast to the sharp reduction of the basic research capacity among U.S. firms. Therefore, Japanese firms are well suited to collaborate with universities in the basic research phase. Additionally, past bibliometric studies have demonstrated that Japanese universities are among the top players in the broad field of nanotechnology [13,14]. The two cases presented in this article are good examples of cutting-edge nanotechnology research.

2. Literature review

A number of studies have examined the role of university in technology development and commercialization. However, those studies have focused on explicit outputs of universities, such as patents, publications, licenses, and spinoffs (e.g. Refs. [15–25]). The implicit assumption is that university generates science, knowledge, and technology that will be applied in the industry. This "linear model" with its focus on explicit "outcomes" continues to shape the literature on university technology transfer.

While this linear model is typically traced to Vannevar Bush and the creation of the National Science Foundation (NSF) [26,27], its roots go back to the pre-World War II time when the National Research Council coordinated industrial research for war purposes [28]. Based on that planning effort, Bush further developed the strategy to substantially expand the scope of science policy. In his paper titled *Science: The endless frontier*, he asserted that "Without scientific progress no amount of achievement in other directions can insure our health, prosperity, and security as a nation in the modern world" [29].

The linear model produced at least two major consequences. First, it created the standard three-stage model of innovation: 1) basic (pure) research, 2) applied research, and 3) development. Though not explicit, this model assumed that the flow of innovation is one-way, and that universities are involved in basic research while the private sector is in charge of applied research and development [30]. Further, it indicated that basic research can and will be applied in commercial settings.

Second, and perhaps more importantly, the establishment of the NSF came with its mandate to measure scientific and technological activities in the United States [31]. This statistical collection was defined as "systematic, intensive study directed toward fuller knowledge of the subject studied and the systematic use of that knowledge for the production of useful materials, systems, methods, or processes" [32], and the "comprehensive" annual report of the NSF was supposed to cover all research and development activities by the federal government, industry, nonprofit institutions, and other manpower; exchange; and the state of scientific information [33]. Thus, this statistical effort set the tone that the data gathered by the NSF on such topics as publications, patents, spin-offs, and R&D expenditure, represents the 'comprehensive' picture of science, technology, and development outcomes from university and industries. Other developed countries followed the NSF strategy as the OECD incorporated the same definition and scope in the 1960s [34,35].

These consequences of the linear model have shaped the highly positivist approach often used in examining the university–industry relationship, and the types of outcomes scholars have focused on in this subject. In sum, the model assumes that university research precedes applied research, and that the nature of collaboration can be examined through explicit outcomes. Additionally, the assumption is that the more explicit the measures are which come from university, the better they are for the private sector, which creates substantial policy implications that will be discussed in a later section.

Scholars have periodically challenged the "linear model" in which commercial technologies are the outcome of a path from basic to applied research [9,36–38]. There have been a few survey-based studies that identified various other channels of science and technology flows between universities and industry. The widely cited Carnegie Study demonstrated that patents (17.2%) and licenses (9.5%) are ranked substantially lower as sources of information, as perceived by private firms, than are publications (41.2%), informal interaction (35.6%), meetings or conferences (35.1%), and consulting (31.8%) [39]. These figures are consistent with innovation-intensive sectors, such as pharmaceuticals and semiconductors. Similar findings were echoed by Kodama and Suzuki [40], Bekkers and Bodas Freitas [41], and Agrawal and Henderson [42].

Despite a good amount of disagreement about the linear model, as well as the relative value it places on research and development activities, the interaction between universities and industry in forms other than those explicit measures remains an under-studied subject. In their literature review on university–industry collaboration, Foray and Lisoni called the task to expand the scope of analysis "the most important challenge for years to come" [43]. Lester urged that "universities need a stronger awareness of the pathways along which local industries are developing and the innovation processes that are associated with those pathways" [44].

Thus, the primary objective of this article is to fill in this gap of knowledge about less explicit aspects of university–industry collaboration. Findings by those survey-based studies are valuable in pointing out the importance of informal interaction, conferences, and consulting. However, the survey-based studies do not reveal what exactly, for instance, those informal interactions or consulting works are, how they evolve, or what kind of knowledge and technologies are exchanged. In short, we have little understanding about how exactly university and corporate researchers collaborate. This process is important to characterize as the techno-economic system becomes even more critical and more complex. Furthermore, the survey-based method still perceives each examined category as an output of university–industry collaboration, but fails to perceive that each category also can be a process to produce something else, particularly intangible outcomes such as knowledge. For instance, the importance of publications gives an impression that corporate researchers read publications by university professors and acquire knowledge and technology from published materials. Yet publications can be both a means and an end in cases where corporate researchers acquired knowledge through collaborative research projects with professors that eventually were developed into coauthored publications. Without identifying who was involved in the publication (university and/or corporate researchers) and what the publication meant for those researchers, its importance as a source of information has little practical implication. Thus, understanding what kind of knowledge—and in what kind of context—university and industry researchers collaborate will provide much more nuanced understanding of the nature of collaboration.

In sum, this is an exploratory project to investigate the less explicit forms of collaboration between universities and industry by focusing on the following questions: How and why do university and industry researchers start the collaboration? What kinds of knowledge do academic and corporate researchers exchange and produce? How long does it take? Do we find basic research that was applied in a commercial setting? If not, what is happening in the process?

3. Method

This article investigates two cases of university–industry collaboration: 1) how a university and Sony developed a semiconductor laser diode system and 2) how a university and a venture firm invented a method to mass produce lithium-holding C_{60} fullerenes. While this article does not intend to provide a comprehensive picture of informal collaboration, these two cases can address some patterns and processes demonstrating how a university collaborates both with a large firm and with a venture firm.

I selected the two cases related to nanotechnology development because nanotechnology is a new and dynamically evolving field, and it is heavily knowledge, science, and innovation intensive. This case study follows the general methodological framework developed by Yin [45,46], and the one tailored in business administration by Eisenhardt and Graebner [47,48]. Additionally, I combined a detailed archival search with interview methods for this study, applying a corporate historical analysis pioneered by Hounshell and Smith [49]. I first started with an archival search of cases with university–industry collaboration. In the nanotechnology field, the National Institute of Materials Science and Advanced Institute for Science and Technology, two Japanese government-related research institutes, publish bimonthly newsletters. The two particular cases identified in this study were so successful that the involved professors and corporate researchers were published in top-tier academic journals, such as *Applied Physics Letters* and *Nature Chemistry*, and I traced who was involved in each case. Based on this background information, I interviewed university professors, technology license officers, corporate researchers and executives, and government officials. Additionally, I collected supplementary information through corporate documents, press releases, and journalistic articles by and about the two companies.

The studied university is Tohoku University, commonly regarded as one of the top three national universities in Japan, along with the Tokyo and Kyoto universities. With regard to nanotechnology, Tohoku University is one of the top research institutes in the world. A widely cited bibliometric study by Kostoff et al. [13] ranked Tohoku University fifth in the top twenty nanotechnology research institutes, ahead of Tsing Hua University, Cambridge University, and University of California, Berkeley.[1] Tohoku University is located in Sendai, Miyagi Prefecture, approximately 360 km north of Tokyo.

4. Case 1: Tohoku University and Sony

The collaboration between Sony and Tohoku University started when Dr. Hiroyuki Yokoyama, a professor of New Industry Creation Hatchery Center (NICHe) at Tohoku University, was invited in 2003 for an informal site visit at Sony's Shiroishi Semiconductor Facility, 45 km southwest of Tohoku University. Sony keeps a high secrecy level for its technology centers and does not invite outsiders, even academics. However, Sony made an exception for Yokoyama for two reasons. First, Yokoyama's senior colleague, another engineering professor at Tohoku University, had a close relationship with Sony. Second, Yokoyama was an established researcher who had spent the past twenty years at NEC's Central Research Lab and had published extensively in the field of semiconductor devices; as an example, his work "Physics and Device Applications of Optical Microcavities" was published in *Science* [50]. Yokoyama started his tenure at Tohoku University in 2002, and Sony was willing to make a connection with the renowned researcher.

There, Yokoyama made a controversial presentation. Instead of discussing the cutting-edge semiconductor technologies, he questioned the potential of the profitability in the semiconductor market, in which world-class manufacturers had invested millions into the latest technologies, yet generated little profit due to extremely high competition and rapidly changing technologies. Yokoyama's critical analysis looked refreshing to Sony's researchers, and they wanted to develop a further collaborative relationship.

Sony and Yokoyama quickly agreed that Sony would support the research of Yokoyama by providing physical and financial resources to his lab at Tohoku University. Sony would also supply researchers to the lab so that they would participate in Yokoyama's research projects. A self-pulsating laser diode (SP-LD) device, a type of semiconductor laser device that they would use, ranged in cost around a few million dollars, which was unaffordable for university researchers. Thus, Sony would purchase and own such a facility at its Shiroishi Technology Center [51].

---

[1] Other top players are the Chinese Academy of Science, Russian Academy of Science, and CERN (European Organization for Nuclear Research), and are hard to compare with conventional universities.

Yokoyama provided ideas for the design and needed functions for such a device.

Additionally, Sony proposed to Yokoyama that he obtain research grants from the government. Yokoyama had not had any previous experience in public research grants and did not know specific sources or processes. Sony's researchers took the initiative, formed an alliance with Tohoku Electronics Industry and Tohkin, which was later acquired by NEC, and applied for a grant. They successfully received the grant under the funding scheme of New Regional Consortium Projects administered by Miyagi Association of Small and Medium Enterprises, indirectly subsidized by METI[2] [52]. The grant amount was approximately one million dollars. However, from the perspective of the Japanese innovation model, it is important to note that this funding scheme was established before the series of recent reforms, and the budget was constructed under the framework of small and medium enterprise policy and regional policy, not under that of the new science and technology policy.

There were two things that Yokoyama and Sony carefully undertook with the collaborative work: the training of researchers and the communication between Yokoyama's lab and Sony's researchers. First, Yokoyama considered that his primary mission was to train researchers who could lead medium-to-large research projects at Sony in the coming years. Given his past experience, Yokoyama knew that it was a long process to learn, and would take at least three years until a researcher started to demonstrate acquired knowledge in the lab setting. What knowledge exactly is required for researchers has a highly tacit dimension. If one could explicitly state what such knowledge is, then by definition, it would not take years to acquire it. Both the professor and Sony's researchers frequently used the term "know-how" in this regard. In summary, it is the knowledge about how to conceptualize research, such as how to identify problems, how to propose alternatives, and how to implement such alternatives (Endo, interview, August 26, 2010). The final, tangible output, whether in technology, patent, or product, mattered little for Sony in this sense; it was more critical for Sony to understand the whole process of research, its failures, and its successes. Such an understanding of the process could provide better ideas about how to create, modify, and apply new technology. Yokoyama admitted that not every corporate researcher or graduate student could acquire this knowledge. While the need for a replacement did not occur frequently, there was a case in which Yokoyama requested the replacement of a Sony researcher who was not fit for such learning (Yokoyama, interview, August 30, 2010).

Second, the communication between Yokoyama's lab and Sony's researchers was crucial for the collaborative relationship. This communication had two layers. First, there was the communication among Yokoyama, his graduate students, and Sony's researchers stationed at Yokoyama's lab. Yokoyama had fewer concerns about this layer of communication because the researchers were all located at one place, and he could supervise them closely. What he and Sony cared about was the communication between Sony's researchers stationed at Yokoyama's lab and other researchers stationed at Sony's Advanced Material Lab in Atsugi, Kanagawa. Atsugi was located 340 km south of Tohoku University. However, with the Tohoku Shinkansen, the Japanese bullet train, it was commutable within 4 h one way. Sony's researchers at Atsugi participated in weekly meetings at Yokoyama's lab to get the closest and the most updated information about the research project. Once a month, they organized a larger meeting for semi-formal updates, in which senior research managers from Atsugi also participated (Toyoda, interview, August 29, 2010).

Details of technologies that they created are beyond the scope and understanding of this article. However, a few examples highlight the complexity and difficulty that the team faced. The technology they developed was high-intensity optical pulses from laser diodes (LDs) in the blue–violet wavelength region [53]. This technology had wide applications, such as for next-generation optical data storage [54,55], ultraprecise three-dimensional nanoscale devices [56], and nonlinear bioimaging that enabled one to obtain images of biotissues at depths of up to 1 mm [57,58]. The technology required the generation of a light pulse duration of a few picoseconds, as well as a stable, nonlinear pattern. It essentially was a challenge for generating the shortest pulse width and the highest peak power of the optical source [59]. However, previous techniques, generally using mode-locked lasers with titanium and sapphire, were not convenient because they were bulky, expensive, and required high maintenance. Furthermore, the long-term stability of the hardware was in question because controlling the repetition rate and electronic synchronization was difficult [52].

To shorten the pulse generation, they installed a narrow band optical filter (0.6 nm) between the laser chip and external mirror [59]. Instead of the previously available mode-locked solid-state LD, they focused on the gain-switching LD, which had been developed by Yokoyama earlier. This gain-switching method was more desirable because it used current-only excitation with a single-chip LD, requiring a simpler and inexpensive optical component. However, the relatively low power levels of this gain-switching method restricted their potential applications for nonlinear optics [60]. Thus, in order to further shorten the laser length and increase the pulse level, they fabricated a thick electron blocking (EB) layer, further divided by two layers of double-quantum-well with different mixture of gallium (Ga), indium (In), and nitrogen (N). The thickness of this EB layer was 30 nm [60].

Eventually, they developed a method using a self-pulsating LD, which was even simpler because it could be operated with a single-chip semiconductor and required no external optical component [61]. This series of changes produced tangible changes in the peak power of LD as they could have had only 0.5 W before 2007, but increased to 2.4 W in 2008 [62], 10 W in 2009 [51], and 55 W in 2010 [60]. These results bore fruit in peer-reviewed academic publications: one article in 2007, one in 2008, three in 2009, and six in 2010. Thus, it took four years for them to

---

[2] The official applicant of this grant for Sony's side was Sony Shiroishi Semiconductor, but the researchers involved with Yokoyama's research were all affiliated under Sony's Advanced Materials Lab based in Atsugi, Kanagawa, southwest of Tokyo.

produce a first tangible publication and six to seven years to reach the most productive period. Over the course of this effort, Sony stationed nine researchers at Yokoyama's lab, whose names appeared in the publications.[3]

Coming from a private firm, Yokoyama had been explicitly conscious about what kind of knowledge and technology he had produced and how it could be used in practice. He considered that the technologies he had produced had a high practical use, such as the bioimaging and next-generation semiconductor storage, as stated earlier. Such orientation toward practice was in line with the institutional culture of his division within the university, the New Industry Creation Hatchery Center (NICHe), in which they pursued research with the intersection between engineering, medical, and pharmaceutical fields. Nonetheless, Yokoyama did not think that Sony revealed its true intention about how the company might use the developed technologies for its business. "It ultimately is in the realm of the company, and I have no intention to interfere," Yokoyama mentioned (interview, August 30, 2010). He additionally stated that creating a commercial value should not be the only motivation for either the company or a university professor, and that it should not be the only or the main criteria for measuring success. The success, in his case, should be how satisfied the company was and whether they would like to renew the collaborative work continuously. Sony and Yokoyama planned to extend their research work further. Furthermore, Yokoyama obtained four patents related to the LD technologies. However, the patent applications were all submitted between 2003 and 2005 [63], before the tangible results with Sony's collaboration started to appear, and therefore owned by himself. Sony did not plan to own patents directly related to this LD technology. Hence, commercial profit or patents were not the objective of Sony.

5. Case 2: Tohoku University and IdealStar

The second case of collaboration is between Tohoku University and IdealStar, a venture firm. We will start by reviewing the background of the key person, Dr. Yasuhiko Kasama, the president of the company. Kasama received his bachelor's degree in physics from Tohoku University, started his research career at Oki Electronics in 1971, and moved to Alps Electronics in 1983 [64]. His main research area has been thin film transistor liquid crystal displays (TFT-LCDs), and he developed an LCD with 11 lines/mm in the early 1990s, a very high precision at that time. He successfully sold prototypes to NHK, the largest Japanese media company. However, the higher the precision he tried, the more limitations of the technology he realized. Even if he could eventually develop as high as 36 lines/mm, the level that humans could maximally detect, there would be no semiconductor device that could store, analyze, and transcend such a high level of information, certainly not in the 1990s, and not even today in the early 2010s. Even if such mega data storage would become available, the increase in expected heat would be enormous, and no known semiconductor material could handle it. In contrast, human eyes can detect light and handle chemical changes induced by photons by keeping the body temperature at 37 °C. These thoughts led him to conclude that technological development would eventually reach its limits using the inorganic materials silicon (Si) or gallium (Ga), and he wanted to develop new organic materials. Thus, he started to pay attention to the production of carbon-based fullerenes [65].

While working at Alps Electronics, Kasama went back to Tohoku University for doctoral training in electrical engineering, and participated in the Ultra Clean Room Project led by Dr. Tadashi Omi, who was a well-established professor in the field of semiconductors. Kasama completed all the requirements in his doctoral training, the equivalent of obtaining a doctoral degree in the U.S. university system. With this background in physics and engineering, Kasama learned that Professor Rikizo Hatakeyama, also of the engineering department, had invented the plasma method of installing an atom inside a fullerene, but the method had been unused. Since 2000, the focus of carbon-based nano materials research has shifted from ball-like fullerenes to carbon nanotubes (CNTs) because CNTs have been believed to have wider applications [66]. Kasama and Kenji Omote, his colleague at Alps Electronics, decided to start a venture to explore possibilities with fullerenes and established IdealStar in September 2002.

There were three major difficulties that IdealStar faced in the course of development. Between 2002 and 2006, the first challenge was to create a new method to combine lithium (Li) and C_{60}. The second challenge, occurring between 2003 and 2008, was to create a purification method to differentiate lithium holding C_{60} (Li@C_{60} hereafter) and other undesired materials. Finally, the third challenge, between 2008 and 2010, was the structural analysis of the extracted Li@C_{60} to prove its existence.

Kasama first researched whether there had been any patents filed for methods similar to the plasma method developed by Hatakeyama. Being an academic, Hatakeyama did not file a patent. Kasama did not find any, thus confirming that this method has commercial opportunities. However, precisely because the plasma method was at a nascent, experimental stage, there was no machinery available except for the prototype that Hatakeyama used. Their journey had to start with creating equipment that they could use for the method they further wanted to develop. Kasama searched for potential manufacturers and eventually asked Techno Clean, a semiconductor manufacturer based in Takabatake, Yamagata, 98 km southwest of Sendai. Techno Clean's Mikiya Ishikawa, a sales director, and Takuya Endo, an engineer, recalled the beginning of the journey: "We received a strange and impossible order from Mr. Kasama, who requested us to replicate the plasma equipment in the university lab but with no design or structural explanation" [67]. "We were not sure if we could do, but tried to recreate one section after another. We went to IdealStar every day, discussed if the component was right or wrong until late in the night, and finally completed after six months" [68]. It is worth noting what motivated Techno Clean to work with IdealStar. Minewo Gowa, the

---

[3] In this field, the primary author (Yokoyama) comes last in publications. Therefore, all citations of their publications in this section start with names other than Yokoyama.

president of Techno Clean, decided to transact with IdealStar because he trusted the personality of Kasama. Their relationship had extended more than 20 years, since Kasama had used equipment made by Techno Clean when he was at Alps Electronics and at Tohoku University (Kasama, interview, August 30, 2010). Endo, the engineer, added that he "wanted to support the challenging spirit of IdealStar, whose mission was to create new things where no one tried before" [69]. The sales director more explicitly said, "I did not think there was any chance for a profit with this first order from IdealStar. I did not tell my company, but thought that we would be fortunate to recover only the minimum input cost with this project" [68].

There are reasons that IdealStar decided to develop a new molecule based on fullerenes. The existence of fullerenes had been first theoretically predicted by Eizji Osawa in 1970, but its actual discovery by Sir Harold Kroto occurred only in 1986. Consequently, Kroto, Richard Smalley, and Robert Curl received the Nobel Prize in chemistry in 1996 [70]. Among different types of fullerenes (see Fig. 1 below), C_{60} fullerene has been considered the most promising for a wide range of practical applications because of its high productivity, its almost completely spherical shape, and the flexibility of its electrical and chemical properties [71]. Its applications may extend to solar cells [72,73] and field-effect transistors [74,75]. Furthermore, if an atom is held inside, a vacuum space of 0.4 nm diameter, such C_{60} would have fundamentally different characteristics, though such ideas have been proposed only theoretically and need to be tested empirically (Tobita, interview, August 30, 2010).

Previously, there were at least two major methods to create atom holding fullerenes, using arc-processed soot or solvent extracts [77–79]. However, these methods had major limitations, such as low-volume production and little capacity to purify the target fullerenes. Furthermore, they could produce only with so-called higher fullerenes, such as C_{82} and C_{84}, but not with C_{60}.

We have to keep in mind that the scale of fullerenes and these scientific inquiries was extremely small, at the nanoscale. Making one or a few successful atoms holding C_{60} has no relevance to industrial use, and thus a completely different mass production was needed. They had to deploy an entirely different method, and that is why they selected the plasma method by Hatakeyama. By 2002, Hatakeyama's group had succeeded in creating nitrogen-holding C_{60} [80]. Targeting a different atom inside and mass producing it was the next goal.

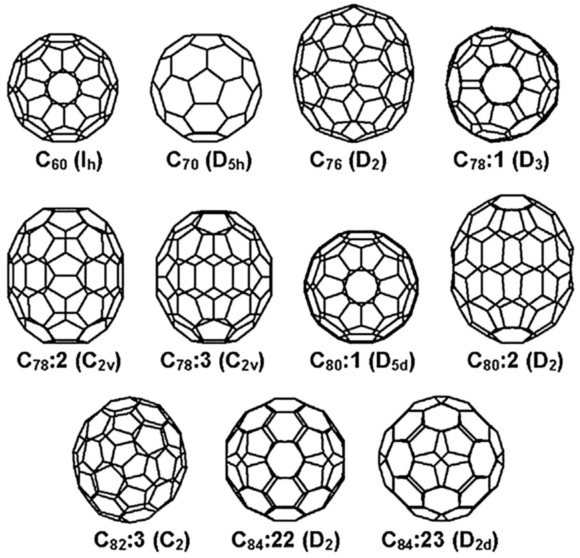

Fig. 1. Various types of fullerenes [76].

The plasma method had the ability to discharge electricity into large areas and to ionize a number of target atoms [80]. Thus, the method could produce the expected fullerene in a large volume. However, how much more it could handle and how exactly researchers could manage the process was not known to researchers at IdealStar or anyone else. Researchers and technicians at the university and IdealStar had to figure it out. First, researchers at IdealStar approached technicians at Tohoku University. Under the national university system in Japan, particularly with the seven former Imperial universities, there were technicians who supported any technical aspects needed for research. Three technical associates visited IdealStar weekly to collaborate, and advised on Tuesdays. A senior technician recalled:

> My role was to create and maintain machines needed for lab experiments by professors, and I worked for Professor Hatakeyama for a long time. Based on his idea about what kind of experiments to conduct, I thought about how he could do so and created all required equipment. I made all equipment. I designed, went to the factory, used lathe machines, etc.
>
> One day, a young researcher from IdealStar was watching me. He explained that they were using the equipment I created a while ago, and they needed instructions about how to use it. I went there soon (of course, after the regular working hours). With a first glance, I could tell that the capacity of magnetic field and voltage was too low. I yelled "Who chose this power source?" [*laughs*].
>
> Then, we tried to solve problems one by one. I instructed them how to use the equipment. Sometimes, Mr. Komatsu [of IdealStar] called me "Help!" when I was drinking at home in the night. [Since I could not drive after drinking,] I asked my wife to give me a ride.
>
> I help them because I love equipment just like my children, and want to help anyone using it. IdealStar has a dream! They are trying to create something that does not exist in the world! As a technician, it is an ultimate dream that my machine is used by others to create something for the society. This project gave a dream to me and every technician at the university [81].

Wataru Ohara, an assistant professor, and Toshiro Kaneko, an associate professor at the Hatakeyama Lab,[4] also participated in this project [82]. Two of them joined the

---

[4] Under the national university in Japan, the standard personnel arrangement was that each lab was headed by a full professor, followed by one associate professor and one assistant professor. Post-doctoral researchers and graduate students are all affiliated with this lab unit system.

studying group organized by IdealStar on Saturdays. Kaneko was aware that researchers at a commercial firm tended to look at only the outcome, and he particularly emphasized "why" questions, such as why they went through such a lab experiment process and why they thought such a result was obtained. These two professors were interested in this project because a new fullerene created by IdealStar would be a totally new molecule with fundamentally different functions [83].

As the number of professors and technical associates at Tohoku University grew, the Office of Cooperative Research and Development (OCRD), the Technology License Office within the university, started to notice the research projects of IdealStar. There was no patent or licensing involved with this research activity, at least not from the perspective of professors of Tohoku University, so there was no direct support that this office could provide. However, OCRD made a movement to provide indirect support. Given the public status of the university, all the staff under the university, both professors and technical associates, were not supposed to engage with private firms during regular business hours. This regulation limited the flexibility of support to IdealStar because the consulting works, studying groups, and other interactions had to take place outside regular business hours, at least officially. Thus, OCRD decided to provide an institutional framework to support the engagement between the university and IdealStar. With endorsements from several professors, OCRD launched the Super Atom Project, in which university staff could engage with IdealStar as the university's official mission (Shishido, interview, August 30, 2010). Now, professors and technical associates could visit IdealStar anytime, and their consultation to IdealStar would be credited in their performance review.

IdealStar focused on producing lithium-holding C_{60}. This was based on input from Hidenori Mitsumura and Yoichiro Kajio, a professor and associate professor, respectively, of the Research Institute of Electronics at Shizuoka University. Mitsumura, whose expertise was in imaging sensor, found the potential of Li@C_{60} in his own area, but soon proposed applications in solar batteries [84]. Being an alkali metal and belonging to the Group 1 (the leftmost) in the periodic table, Li was highly active and softer than other metals. The highly active nature meant high responsiveness to external conditions, thus potentially producing higher efficiency. Additionally, Li required low ionization energies, thus requiring low energy in the chemical conversion process.

Another layer of professors at Tohoku University supported the research project. Shoichi Ono, an emeritus professor and President Kasama's former adviser, agreed to come to a weekly studying group organized by junior researchers of IdealStar on Thursdays. It was like a tailored seminar course in which the junior researchers went through articles or textbooks in physics, and Ono advised and answered questions raised by them. Ono further invited Kuniyoshi Yokoo, another emeritus professor of Tohoku University, to supervise daily lab works and analysis [85,86]. No monetary incentives were needed, but the emeritus professors still wanted to interact with people who were learning, and to support their dreams (Kasama, interview, August 30, 2010).

With much advice and numerous trials and errors, IdealStar succeeded in combining Li and C_{60} by May 2006 [87]. It further invented a method to generate plasma ionized atoms on negatively charged substrates, which resulted in a production volume 100 times larger than before [88]. IdealStar filed a patent for this method, called the Plasma Shower Method. Although IdealStar continued to improve the method to increase the volume of the production, their first goal to mass produce C_{60} started to materialize.

Compared to the first challenge, in which IdealStar focused mostly on the matter of physics, the second challenge was a matter of chemistry. The issue was how to extract Li@C_{60} from other molecules, because the newly created Li@C_{60} was polymerized with empty C_{60}. In other words, the Plasma Shower Method could create Li@C_{60}s, but the purity was not 100 percent, and created a polymer, a collection of various molecules together. This was a critical issue for the nanoscale engineering. One could not see the created product and check its purity, at least not easily and visibly. However, they had to understand why such polymerization happened and how they could separate Li@C_{60} and pristine C_{60}. Otherwise, there would be no industrial use. Unfortunately, that was where the cutting-edge scientific knowledge ended. A group of German researchers had been also known to succeed in creating metal holding fullerenes, but they had concluded that the polymerization prevented the accurate determination of the structure and physical properties of the polymer [89–91]. Thus, since the 1990s, the bulk production and isolation of metal-holding fullerenes has been "a persistent object of study for researchers working with fullerene-based nanomaterials" [92,93].

IdealStar approached a group of chemistry professors led by Hiromi Tobita at Tohoku University. Tobita, whose specialty was the interaction between organic molecules and metals, not only understood the great challenge faced by IdealStar, but also demonstrated a substantial interest in the nature and potential use of Li@C_{60}. IdealStar also hired Hiroshi Okada, who had completed a doctoral degree under Tobita in 2005 (Okada, interview, August 30, 2010). However, there was no easy answer for them. Tobita recalled:

> We experimented a lot and researched a lot. I think the very beginning was probably 2003. We soon found out the polymerization, as well as a layer of hydrogen covering such polymer. I advised them and also conducted research about why such phenomenon happened. Later, we discovered the charge transfer interaction causing it.
>
> The next step was how to extract the target Li@C_{60} while 90 percent of other undesired molecules existed in the polymer. That was a tough process. We first experimented [with] the heating method [in] 2005 and then concluded that it did not work. We later employed the current oxidization method.
>
> My contribution was to provide a place for discussion and to lead such discussion for the next step. There were a few times in this lengthy process that we all felt the dead end, especially in the first few years. The weekly discussion on Wednesday afternoon was lively, but we

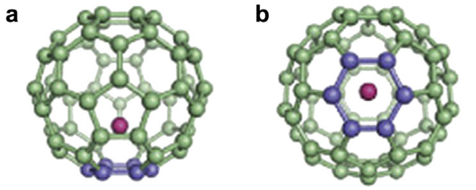

Fig. 2. The off-centered location of Lithium in C_{60} (Based on IdealStar [96]).

> sometimes exhausted all possible alternatives. In a traditional Japanese university lab setting, the [full] professor often told others what to do. However, at this place, I was glad that we had a room where anyone could raise question[s] and propose ideas, including junior researchers. It probably was possible because people from different organizations were here, and the usual hierarchy did not constrain them (Tobita, interview, August 30, 2010).[5]

During the lengthy process, they tested dozens of organic solvents and finally, between 2008 and 2009, came up with the method, after five years of trial. There, they used an oxidizing agent to loosen the linkage between pristine C_{60} and Li@C_{60} and separated Li@C_{60} as [Li@C_{60}]($SbCl_6$). In other words, since Li was positively charged, they used a negatively charged molecule ($SbCl_6$) to create a single salt molecule [71].

While the first challenge was to mass produce and the second one was to extract, the third challenge was to prove what they had achieved. Once again, because this was a product at the nanoscale and they were unable to investigate visually, they had to employ special techniques to observe Li@C_{60}. By the very nature of the product that they created, it was difficult to observe one light atom of Li, surrounded by twice as heavy carbon atoms [88].

Takashi Komuro, an assistant professor at Tobita's Lab, specialized in structural analysis of compounds with metals and organic molecules. He used X-ray analysis to identify the structure of molecules [94]. However, he recommended a more thorough structural analysis with larger equipment. With a referral from Tobita, President Kasama contacted Hisanori Shinohara, a professor of chemistry at Nagoya University and a long-time specialist in carbon nanotubes. Shinohara decided to participate in the IdealStar's project, and further gave a referral to his colleague, Hiroshi Sawa, an engineering professor at Nagoya University, whose specialty was in structural analysis. Sawa soon started the analysis with two more researchers at the Riken Institute, a government research lab located in Sayo, Hyogo, west of Osaka. This facility owned the largest third-generation synchrotron radiation facility in the world to date, SPring-8,[6] and could detect the precise location of each atom. Yet this was a highly complex process, and required an integration of several methods, such as a direct method using SIR2004, a rigid body refinement method using SP, the maximum entropy method, full-matrix least-squares method, and rigid-body translation, liberation, and screw-rotation approach [95]. Finally, they were able to identify Li inside the cage of C_{60} in a slightly off-centered location (see Fig. 2).

There had existed no production of Li@C_{60} before this time, and absolutely no volume production of it. As of April 2011, IdealStar could produce Li@C_{60} at a scale of 1–10 mg with 85 percent or higher purity per hour. At a larger scale, they also provided 0.5–10 g with 7 percent purity. This volume was a million times larger than that produced through any previously available methods [96].

The achievement of IdealStar has received a wide range of praise. First, as their Plasma Shower Method and their extraction method were materializing, President Kasama and Vice President Omote were invited as keynote speakers to the 33rd Conference of Fullerenes and Nanotubes, organized at Kyushu University in July 2007. Two well-known academic scholars endorsed this invitation: Eiji Osawa, who theoretically predicated the existence of fullerenes, and Kunio Iijima, who created carbon nanotubes in 1985 [85]. Second, another highlight was their publication in *Nature Chemistry* 2010, an article with 19 coauthors from three research institutions: Tohoku University, Nagoya University, and RIKEN.

Lastly, it is worth noting that President Kasama organized the network without monetary incentives. "I did not want people who don't know me to invest in us because this was a risky business, perhaps too risky, and because I did not want investors only to seek for profits" (Kasama, interview, August 30, 2010). Thus, he did not offer equity options to professors and others involved in this project. IdealStar successfully received funds from venture capital groups, such as Tokyo Small and Medium Business Investment and Consultation (SBIC) in 2004, Tohoku Innovation Capital in Sendai, and S-K Ventures in Yamaguchi [85,97]. Additionally, about a dozen individual investors provided funds, but Kasama's policy stayed consistent. Several investors noted about their decision that they "fell in love with the passionate story of Kasama," and that IdealStar "can make society better by conducting basic research" [97].

6. Major findings

The two cases in this article uncover the collaboration between the university and industry beyond the conventionally discussed explicit forms of the university–industry relationship. More specifically, the collaboration-created networks of professors and corporate researchers, and the technologies they developed materialized in forms other than publications, patents, and spin-offs. In this section, I highlight findings based on the core research questions identified in the literature review section: How and why do university and academic researchers start the collaboration? What kind of knowledge do academic and corporate researchers exchange and produce? How long does it take? Do we find basic research that was applied in a commercial setting? If not, what is happening in the process?

With regard to the starting process, those university and corporate researchers collaborated not because the two

---

[5] The author would add that the lively discussion was facilitated by the moderate personality of Tobita and his excellent facilitation skills.

[6] SPring-8 is derived from Super Photon ring-8 GeV (giga electron volts, the power output of the ring).

firms had interests in acquiring the universities' technologies as patents, licenses, or other exclusive forms; their goals were contextually different. Sony's primary objective was to train researchers for their future research projects. More specifically, Sony was interested in acquiring some epistemological process that academics possess: Why did we proceed with the present method? Why did things happen or why did they not happen? What are the problems and how could we solve them? The way to ask these questions continuously in the research process and to answer them requires a set of conceptualization and operationalization skills, as well as much preparation and a long time to analyze.

This is a process that corporate researchers can learn not from publications or textbooks, but from participation in the whole research project because it has a highly tacit dimension. Moreover, researchers at firms, often under pressure to produce tangible results, may not ask these tough questions all the time, yet they are fundamental questions to go through, especially when basic research is involved and fundamentally new knowledge or technologies are needed. University is the best equipped institution to answer these questions, with knowledge related to such research know-how. Furthermore, it was unclear if Sony even intended to create products based on the developed laser diode system. Up to this moment, Sony has not filed any patents or produced any products related to the technology. In sum, it is inappropriate to assume that the acquisition of specific technologies at university or their commercialization was the primary objective of collaboration for these corporations. This not only challenges the theoretical understanding and metrics for success from the linear model, but provides insight into new measures for success and how firms benefit beyond intellectual property acquisition in ways that are of great use in achieving their long-term goals in human resource management and development.

The case of IdealStar presented an even clearer picture. President Kasama, along with several groups of professors from different universities including emeritus professors, pursued this project because they wanted to produce something that did not exist in the world, Li@C_{60}. In this sense, both academic scientists and corporate engineers were driven by one pure goal: to invest in and find a new thing. Thus, it is also inappropriate to categorize basic research and applied research simply based on the objective that the linear model conventionally employs: general knowledge to understand the nature and its laws, or research with thoughts of practical ends [30]. There can be substantial overlap between the two categories.

I acknowledge that the research methods in this article, interviews and archival search, may not necessarily capture the monetary aspect among objectives, as few people may be bold enough to express it. However, it is important to recognize that incentives other than money seemed to be the primary incentives in these cases of basic research.

With regard to the exchange of knowledge, in addition to the functions to train researchers and to discover a novel thing as mentioned above, university also functioned as a hub to develop and provide networks of researchers. The Tobita Lab was the best example here, facilitating a weekly studying group and connecting IdealStar with cutting-edge researchers at other departments of Tohoku University and at other universities. Professor Tobita did not assume that he or his team had solutions for the problem that IdealStar was facing: how to extract only lithium-holding C_{60}at a large volume among other undesired molecules. In the course of two to three years, Tobita admitted that, at a few times, they were facing dead ends. With all the academic knowledge they assembled, they could not find a solution. However, each time, his lab students and IdealStar researchers came up with solutions through experiments. Therefore, it is not appropriate to assume that knowledge or technologies possessed by university can be easily applied for commercialization, as the current theory suggests.

Moreover, when they started to achieve a decent level of chemical extraction, IdealStar had to go to the next step, analyzing the purity of extraction, which required structural physics. Since Tobita as a chemist did not have such expertise, he connected IdealStar to structural physics researchers at Nagoya University and Riken Institute. Thus, the university functioned as a facilitator of a network, not just as a creator of knowledge or technology.

With regard to project length, both projects took six to seven years to reach the most fruitful results. The Sony case started in 2003, and the prolific publication period by the professor and Sony researchers came in 2009 and 2010. As Yokoyama mentioned, it takes time to train researchers, often longer than to develop technologies, and this six- to seven-year span was needed. IdealStar as a firm started in 2002. While their Plasma Shower Method and the extraction method have improved over years, it was 2009 when IdealStar achieved marketable, mass-volume production, as well as when the firm and involved professors drafted the article for *Nature Chemistry* (Note that the review process took more than six months, resulting in publication in 2010.).

This time span is consistent with the findings of Mansfield [98], who identified 6.4–7.0 years as the time it takes to commercialize academic research. However, his method was based on a survey of firms and provided no context about what kind of technology was commercialized, or how and why such time span was needed. This article provides a more nuanced understanding in that context.

While the two cases differed in the size of the firm and the types of developed technologies, even within the field of nanotechnology, they presented strikingly similar patterns. On an essential level, neither case fits the description of the linear model in which universities conduct the basic research and firms apply such research or technology for products. The knowledge or technologies that professors possessed before university–industry collaboration were insufficient to produce applied products for firms. In other words, the original Plasma Method by Hatakeyama, or the knowledge of the laser diode system by Yokoyama, was insufficient to create a specific product because it simply was not designed to do so. Rather, it was a process in which both the professors and corporate researchers had to figure things out together. In this sense, it was a nonlinear, iterative, and evolving process of technological development between universities and firms. It is too simplistic to assume that technology created by a university is ready to be commercialized, or even to assume that the university's base technology can be readily combined with other university or industry technologies for commercialization. In both cases, what was needed was not a mere application of university's technology, but more and substantially different inputs about how to use it. In sum, it is better to avoid the description of application, but critical to recognize that the university–industry collaboration can require deep levels of interaction and substantial modification and integration of knowledge. Importantly, this process is not linear and a core element is the development of networks and human resource.

Furthermore, we should not underestimate the importance of mass production in the case of IdealStar. A creation of a single new atom or a molecule is an achievement. However, in the field of nanotechnology, in which the scale is exponentially small, it is a fundamentally different matter to mass produce for commercial use. The mass production method, as well as the extraction method, required totally different knowledge (chemistry and structural analysis) from the starting point of the Plasma Method, which was physics-based. Yet without mass production, commercialization as a product was simply impossible. The IdealStar case presents the need to integrate multiple layers of knowledge from different academic fields to produce a single product.[7] This is why it was so difficult and took as long as seven years.

7. Policy implications

The two groundbreaking collaborative projects in this article are at odds with the recent reforms undertaken by the Japanese government in science and innovation policy. The Japanese government recognized several limitations with the university research system: for example, the decreased budgets and loss of high-quality researchers from university to government labs and private firms [100] and little visible university-driven entrepreneurship [101]. As a result, Japanese firms collaborated more with foreign university—funding ¥157 billion in 2000—than with domestic universities (¥67.5 billion) [102].

The series of reforms started with the Basic Law for Science and Technology in 1995, which set a five-year plan to discuss the investment level and priority areas, and declared that university–industry cooperation was the fundamental factor required to promote science and technology [103]. This further led to the deregulation of patent ownership by university in 1995 [104], a replica of the U.S. Small Business Innovation Research (SBIR) program in 1998 [105,106], the law to establish technology license offices for up to five years [107], and a replica of the U.S. Bayh-Dole Act to allow private firms to own intellectual property rights generated by university research funded by the government [108].

Moreover, to be accountable, the Japanese government set up goals for evaluation. However, almost all of them focused on the explicit outputs discussed earlier in this article, such as to produce 10,000 postdoctoral researchers by 2000 [109], to create 1000 university spin-offs [110], and to increase revenue from patents [111].

Such orientation of science and technology policy in Japan is explicitly expressed in the goal of the Second Basic Plan for Science and Technology in 2000:

> By increasing technology transfer organizations quantitatively and qualitatively, by transferring patents from public research institutions, by spinning off a number of ventures from public research institutions, by transferring the outputs of public research institutions to the private sector, by proposing international standards, by increasing internationally granted patents, and by improving the productivity of industries[8] [109].

Essentially the same examples are repeatedly stated in the past three Basic Plans and other reform laws, and it is clear that the focus of the current reforms has been highly skewed to the explicit aspect of university–industry collaboration.

The findings from this case study provide three major cautions for policy setting in Japan. First, focusing only on the conventional and explicit outcomes can undermine other important elements of university–industry collaboration. The goal of the current policy is to generate more spin-offs, patents, and postdoctoral researchers, while the two cases in this article demonstrated alternative aspects of university–industry collaboration in transferring the academic epistemology about how to conceptualize the research process, and provide the hub to network from different researchers and to integrate different disciplines. Omitting these aspects of university–industry collaboration is detrimental because these alternative aspects of university–industry collaboration can and do lead to major breakthroughs in technological advancement and innovation.

Both cases demonstrate that the true outcome of the collaboration cannot be captured by simplistic, numeric goals. Yokoyama obtained a few patents from the laser diode system, but Sony submitted none. Yokoyama's patents will not generate any revenue to Tohoku University, yet Sony benefitted greatly by learning the research know-how. IdealStar has submitted at least seven patents to the U.S. Patent and Trademark Organization and thirteen patents to the World Patent Organization. All the patents were filed under IdealStar, and Tohoku University will not receive monetary gains. Thus, tracing patents owned and revenue generated by the university is meaningless in these cases. In sum, the scope of university–industry collaboration must be larger than patents and spin-offs. A considerable aspect highlighted in both cases is joint human resource and network development.

---

[7] This inter-disciplinary nature of technology and product development is also observed in the case of Toyota's hybrid technology and Canon's Bubble Jet technology [99] Motoyama Y. Global companies, local innovations: Why the engineering aspects of innovation making requires proximity. Surrey, UK: Ashgate; 2012.

[8] This is the translation made by the author. The Cabinet Office provides the English version of the Second Basic Plan. However, it does not exactly follow the original Japanese version and abbreviates several examples in this case.

Second, the time span specified in the recent reforms has been relatively short and set mostly because of political reasons. University technology transfer offices (TTOs) can receive subsidies from the government for establishment and operation, but the current legal framework forces TTOs to produce results within five years or have their government subsidies discontinued. Such short-term focus will deter any incentive for TTOs to promote more long-term collaboration that may not generate explicit outcomes for the university. While the seven-year time span uncovered in this case study coincides with Mansfield's findings, my intention here is only to point out the possibility of longer time spans than three to five years, not to propose that the target span of policy be seven years. I have uncovered only a couple of cases with limited, but highly innovative technological advancement. Further research is needed to explore the nature and duration of university–industry collaborations and commercialization.

Third, commercialization should not be the only or primary criteria for evaluation of the competition-based grant system used by the government, and university researchers should be aware of some consequences of their research projects ultimately leading to commercialization. The case of Sony shows that Sony made no products out of the learned laser diode system, yet their researchers benefited tremendously from the collaboration with Yokoyama as did the enterprise and its positioning for the future.

It is one thing to talk about evaluation criteria at the policy level, but we also have to consider another complex level of evaluation: how to evaluate university faculty performance. The current evaluation criteria of faculty overwhelmingly emphasize publications in peer-reviewed journals. Through the course of reform in science and technology policy, as well as reform in the university system, the government has been considering how to incorporate elements of explicit outputs in patents, licenses, and spin-offs. This will still be insufficient to promote a deeper level of collaboration between university and industry, such as informal consulting, advising, less explicit joint research, and organizing and participating in studying groups with firms. If the aim of the Japanese government is truly to promote science and technology for the economy, they must consider reforms incorporating and encouraging all these aspects of collaboration.

While this article has shed light on the non-linear processes involved in of university–industry collaboration, this is only an exploratory research in the vast field of less-explicit aspects of collaboration between university and industry. Since nanotechnology is cutting-edge research, I would anticipate that different forms of less-explicit collaboration exist for different fields of technologies. Further research is needed to advance theoretical and empirical understanding and the subsequent policy implications.

Acknowledgment

The author would like to thank interviewees for their time and valuable information. Unfortunately, Sendai, the primary interview site, is one of the cities most severely affected by the East Japan Earthquake of March 2011. The author would like to show his condolences to interviewees, their families, and people in the region. This research is based in part upon work supported by the National Science Foundation under Cooperative Agreement No. 0531184 and No. 0938099. The author is grateful for comments from Andrew Nelson, and acknowledges Sarah Gowen, Michelle St. Claire, and Arnobio Morelix for their assistance. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation, the Center for Nanotechnology in Society, or the Ewing Marion Kauffman Foundation.

References

[1] Petrascu AS. Science and technology for economic growth: new insights from when the data contradicts desktop models. Rev Policy Res 2009;26:839–80.

[2] Plosila WH. State science- and technology-based economic development policy: history, trends and developments, and future directions. Econ Dev Q 2004;18:113–26.

[3] Geiger RL, Sa CM. Beyond technology transfer: US state policies to harness university research for economic development. Minerva 2005;43:1–21.

[4] Sa CM, Geiger RL, Hallacher PM. Universities and state policy formation: rationalizing a nanotechnology strategy in Pennsylvania. Rev Policy Res 2008;25:3–19.

[5] Becker B, Gassmann O. Corporate incubators: industrial R&D and what universities can learn from them. J Technol Transf 2006;31:469–83.

[6] Niosi J. Introduction to the symposium: universities as a source of commercial technology. J Technol Transf 2006;31:399–402.

[7] Sampat BN. Patenting and US academic research in the 20th century: the world before and after Bayh-Dole. Res Policy 2006;35:772–89.

[8] Breznitz SM, Feldman MP. The larger role of the university in economic development: introduction to the special issue. J Technol Transf 2011:1–4.

[9] Kline SJ, Rosenberg N. An overview of innovation. In: Landau R, Rosenberg N, editors. The positive sum strategy: harnessing technology for economic growth. Washington DC: National Academy Press; 1986. p. 275–306.

[10] Cohen WM, Florida R, Goe R. University-industry research centers in the United States. Report to Ford Foundation. Pittsburgh: Carnegie Mellon University; 1994.

[11] Mody C. Corporations, universities, and instrumental communities: commercializing probe microscopy, 1981–1996. Technol Cult 2006;47:56–80.

[12] Nelson AJ. Putting university research in context: assessing alternative measures of production and diffusion at Stanford. Res Policy 2012;41:678–91.

[13] Kostoff RN, Koytcheff RG, Lau CGY. Technical structure of the global nanoscience and nanotechnology literature. J Nanopart Res 2007;9:701–24.

[14] Motoyama Y, Eisler MN. Bibliometry and nanotechnology: a meta-analysis. Technol Forecast Soc Chang 2011;78:1174–82.

[15] Coupé T. Science is golden: academic R&D and university patents. J Technol Transf 2003;28:31–46.

[16] Mowery DC, Ziedonis AA. Academic patent quality and quantity before and after the Bayh-Dole Act in the United States. Res Policy 2002;31:399–418.

[17] Shane S. Academic entrepreneurship: university spinoffs and wealth creation. Cheltenham, UK: Edward Elgar; 2004.

[18] Benneworth P, Charles D. University spin-off policies and economic development in less successful regions: learning from two decades of policy practice. Eur Plan Stud 2006;13:537–57.

[19] Zucker LG, Darby MR, Furner J, Liu RC, Ma H. Minerva unbound: knowledge stocks, knowledge flows and new knowledge production. Res Policy 2007;36:850–63.

[20] Zucker LG, Darby MR. Star scientists, innovation and regional and national immigration. NBER Working Paper. Cambridge, MA: National Bureau of Economic Research; 2007.

[21] Harrison RT, Leitch C. Voodoo institution or entrepreneurial university? Spin-off companies, the entrepreneurial system and regional development in the UK. Reg Stud 2010;44:1241–62.

[22] Breznitz SM. Improving or imparing? Following technology transfer changes at the University of Cambridge. Reg Stud 2010; 45:463–78.

[23] Thursby JG, Thursby MC. University-industry linkages in nanotechnology and biotechnology: evidence on collaborative patterns for new methods of inventing. J Technol Transf 2011;36: 605–23.

[24] Motohashi K, Muramatsu S. Examining the university industry collaboration policy in Japan. Technol Soc 2012;34:149–62.

[25] Motoyama Y, Cao C, Appelbaum RP. Observing regional divergence of Chinese nanotechnology centers. Technol Forecast Soc Chang 2013. Online first:1–11.

[26] Alic J. A weakness in diffusion: US technology and science policy after World War II. Technol Soc 2008;30:17–29.

[27] Atkinson RC, Blanpied WA. Research university: core of the U.S. science and technology system. Technol Soc 2008;30:30–48.

[28] Godin B. The linear model of innovation: the historical construction of an analytical framework. Sci Technol Hum Values 2006;31: 639–67.

[29] Bush V. Science: the endless frontier. Trans Kans Acad Sci 1945;48: 231–64.

[30] Berkovitz J, Feldmann M. Entrepreneurial universities and technology transfer: a conceptual framework for understanding knowledge-based economic development. J Technol Transf 2006; 31:175–88.

[31] Godin B. The emergence of S&T indicators: why did governments supplement statistics with indicators? Res Policy 2003;32:679–91.

[32] National Science Foundation. Federal funds for science. Washington, DC: National Science Foundation; 1953.

[33] National Science Foundation. Science and public policy. Annual report of the National Science Foundation. Washington DC: National Science Foundation; 1953.

[34] OECD. The measurement of scientific and technical activities: proposed standard practice for surveys of research and development. Paris: Organization for Economic Cooperation and Development; 1962.

[35] OECD. The measurement of scientific and technical activities: proposed standard practice for surveys of research and development. Paris: Organization for Economic Cooperation and Development; 1970.

[36] Rosenberg N. Innovation and economic growth. Paris: Organization for Economic Development and Cooperation; 2004.

[37] Schmookler J. Invention and economic growth. Cambridge, MA: Harvard University Press; 1966.

[38] Price WJ, Bass LW. Scientific research and the innovative process. Sci Technol Hum Values 1969;164:802–6.

[39] Cohen WM, Nelson RR, Walsh JP. The influence of public research on industrial R&D. Manag Sci 2002;48:1–23.

[40] Kodama F, Suzuki J. How Japanese companies have used scientific advanced to restructure their businesses: the receiver-active national system of innovation. World Dev 2007;35:976–90.

[41] Bekkers R, Bodas Freitas IM. Analysing knowledge transfer channels between universities and industry: to what degree do sectors also matter? Res Policy 2008;37:1837–53.

[42] Agrawal A, Henderson R. Putting patents in context: exploring knowledge transfer from MIT. Manag Sci 2002;48:44–60.

[43] Foray D, Lisoni F. University research and public-private interaction. In: Hall BH, Rosenberg N, editors. Handbook of the economics of innovation. North Holland: Elsevier; 2010. p. 275–314.

[44] Lester R. Universities, innovation, and the competitiveness of local economies. IPC Working Paper Series. Cambridge, MA: Industrial Performance Center, MIT; 2005.

[45] Yin RK. Case study research: design and methods. 2nd ed. Thousand Oaks: Sage Publications; 1994.

[46] Yin RK. Case study research: design and methods. 3rd ed. Thousand Oaks, Calif: Sage Publications; 2003.

[47] Eisenhardt KM. Building theories from case study research. Acad Manag Rev 1989;14:532–50.

[48] Eisenhardt K, Graebner ME. Theory building from cases: opportunities and challenges. Acad Manag J 2007;50:25–32.

[49] Hounshell DA, Smith JK. Science and Corporate Strategy: Du Pont R&D. Cambridge: Cambridge University Press 1988:1902–80.

[50] Yokoyama H. Physics and device applications of opticla microcavities. Science 1992;256:66–70.

[51] Oki T, Kono S, Kuramoto M, Ikeda M, Yokoyama H. Generation of over 10-W peak-power picosecond pulses by a gain-switched AlGaInN-based self-pulsating laser diode. Appl Phys Express 2009;2. 032101–1-3.

[52] Kuramoto M, Kitajima N, Guo H, Furushima Y, Ikeda M, Yokoyama H. Two-photon fluorescence bioimaging with an all semiconductor laser picosecond pulse source. Optics Lett 2007;32: 2726–8.

[53] Tohoku University. New release: successful bioimaging based on ultrashort pulse optics of semiconductor laser. Sendai: New Industry Creation Hatchery Center (NICHe), Tohoku University; 2006.

[54] Strickler JH, Webb WW. Three-dimensional optical data storage in refractive media by two-photon point excitation. Optics Lett 1991; 16:1780–2.

[55] Walker E, Dvornikov A, Coblentz K, Rentzepis P. Terabyte recorded in two-photon 3D disk. Appl Optics 2008;47:4133–9.

[56] Kawata S, Sun H-B, Tanaka T, Takada K. Finer features for functional microdevices. Nature 2001;412:697–8.

[57] Denk W, Strickler JH, Webb WW. Two-photon laser scanning fluorescence microscopy. Science 1990;248:73–6.

[58] Zipfel WR, Williams RM, Webb WW. Nonlinear magic: multiphoton microscopy in the biosciences. Nat Biotechnol 2003;21: 1369–77.

[59] Yamamoto N, Sotobayashi H, Akahane K, Tcuchiya M, Takashima K, Yokoyama H. 10-Gbps, 1-um waveband photonic transmission with a harmonically mode-locked semiconductor laser. Optics Express 2008;16:19836–43.

[60] Kuramoto M, Oki T, Sugahara T, Kono S, Ikeda M, Yokoyama H. Enormously high-peak-power optical pulse generation from a single-transverse-mode GaInN blue-violet laser diode. Appl Phys Lett 2010;96. 051102-1-3.

[61] Watanabe H, Miyajima T, Kuramoto M, Ikeda M, Yokoyama H. 10-w peak-power picosecond optical pulse generation from a triple section blue-violet self-pulsating laser diode. Appl Phys Express 2010;3. 052701-1-3.

[62] Miyajima T, Watanabe H, Ikeda M, Yokoyama H. Picosecond optical pulse generation from self-pulsating bisectional GaN-based blue-violet laser diodes. Appl Phys Lett 2009;94. 161103-1-3.

[63] JST. J-Global Patent Ownership. J-Global. Tokyo: Japan Science and Technology Agency (JST); 2011.

[64] IdealStar. Profiles of the executive board members. Sendai, Miyagi, Japan: IdealStar; 2010.

[65] Tohoku METI. Atom-holding shining star. Lively venture firms in Tohoku Region, vol. 27; 2011. Sendai, Miyagi.

[66] 77 Business support Foundation. Interview: IdealStar. Sendai, Miyagi, Japan: 77 Business Newsletter; 2005.

[67] IdealStar. IS Newsletter, vol. 31. Sendai, Miyagi, Japan: IdealStar; 2006.

[68] IdealStar. IS Newsletter, vol. 28–29. Sendai, Miyagi, Japan: IdealStar; 2006.

[69] IdealStar. IS Newsletter, vol. 32–33. Sendai, Miyagi, Japan: IdealStar; 2006.

[70] Nobel Foundation. Nobel prize in chemistry 1996; 2009.

[71] Aoyagi S, Nishibori E, Sawa H, Sugimoto K, Takata M, Miyata Y, et al. A layered ionic crystal of polar Li@C60 superatoms. Nat Chem 2010;2:678–83.

[72] Yu G, Gao J, Hummelen JC, Wudl F, Heeger AJ. Polymer photovoltaic cells: enhanced efficiencies via a network of internal donor-acceptor heterojunctions. Science 1995;270:1789–91.

[73] Li G, Shrotriya V, Huang J, Yao Y, Moriarty T, Emery K, et al. High-efficiency solution processable polymer photovoltaic cells by self-organization of polymer blends. Nat Mater 2005;4:864–8.

[74] Dodabalapur A, Katz HE, Torsi L, Haddon RC. Organic heterostructure field-effect transistors. Science 1995;269:1560–2.

[75] Meijer EJ, De Leeuw DM, Setayesh S, Van Veenendaal E, Huisman B-H, Blom PWM, et al. Solution-processed ambipolar organic field-effect transistors and inverters. Nat Mater 2003;2:678–82.

[76] fulleren.com. Carbon technologies & materials; 2011. St.-Petersburg, Russia.

[77] Diener MD, Alford JM. Isolation and properties of small-bandgap fullerenes. Nature 1998;393:668–71.

[78] Inoue T, Kubozono Y, Kashino S, Takabayashi Y, Fujitaka K, Hida M, et al. Electronic structure of Eu@C60 studied by XANES and UV-VIS absorption spectra. Chem Phys Lett 2000;316:381–6.

[79] Ogawa T, Sugai T, Shinohara H. Isolation and characterization of. J Am Chem Soc 2000;122:3538–9. Er@C60.

[80] Hatakeyama R. Creating gas holding fullerenes by the controlled plasma method. Sendai, Miyagi: Plaza Miyagi: Grant to effective research projects; 2002.

[81] IdealStar. IS Newsletter, vol. 20–21. Sendai, Miyagi, Japan: IdealStar; 2005.

[82] IdealStar. IS Newsletter, vol. 22. Sendai, Miyagi, Japan: IdealStar; 2005.

[83] IdealStar. IS Newsletter, vol. 18–19. Sendai, Miyagi, Japan: IdealStar; 2005.

[84] IdealStar. IS Newsletter, vol. 14–15. Sendai, Miyagi, Japan: IdealStar; 2005.

[85] IdealStar. IS Newsletter, vol. 42–43. Sendai, Miyagi, Japan: IdealStar; 2007.

[86] IdealStar. IS Newsletter, vol. 44–45. Sendai, Miyagi, Japan: IdealStar; 2007.

[87] IdealStar. IS Newsletter, vol. 37–39. Sendai, Miyagi, Japan: IdealStar; 2007.

[88] Hatakeyama R. Introducing the lab: plasma basic engineering. In: Ito Harajima, Matsuura Minami, editors. Plasma electronics group newsletter 2010. p. 3–6.

[89] Tellgmann R, Krawez N, Lin S-H, Hertel IV, Campbell EEB. Endohedral fullerene production. Nature 1996;382:407–8.

[90] Campbell EEB, Tellgmann R, Krawez N, Hertel IV. Production and LDMS characterisation of endohedral alkali-fullerene films. J Phys Chem Solids 1997;58:1763–9.

[91] Gromov A, Kratschmer W, Krawez N, Tellgmann R, Campbell EEB. Extraction and HPLC purification of. Chem Commun 1997;20: 2003–4. Li@C60/70.

[92] Shinohara H. Endohedral metallofullerenes. Rep Prog Phys 2000; 63:843–92.

[93] Kitaura R, Shinoara. Carbon nanotube-based hybrid materials: nanopeapods. Chem Asian J 2006;1:646–55.

[94] IdealStar. IS Newsletter, vol. 26. Sendai, Miyagi, Japan: IdealStar; 2006.

[95] Aoyagi S, Nishibori E, Sawa H, Sugimoto K, Takata M, Miyata Y, et al. Supplementary information. Nat Chem 2010;2:1–31.

[96] IdealStar. Products. Sendai, Miyagi; 2011.

[97] IdealStar. IS Newsletter, vol. 24–25. Sendai, Miyagi, Japan: IdealStar; 2006.

[98] Mansfield E. Academic research and industrial innovation. Res Policy 1991;20:1–12.

[99] Motoyama Y. Global companies, local innovations: why the engineering aspects of innovation making requires proximity. Surrey, UK: Ashgate; 2012.

[100] Yamamoto S. The role of the Japanese higher education system in relation to industry. In: Goto A, Odagiri H, editors. Innovation in Japan. Oxford: Oxford University Press; 1997. p. 294–307.

[101] Kenney M, Patton D. Reconsidering the Bayh-Dole Act and the current university invention ownership model. Res Policy 2009; 38:1407–22.

[102] Lynskey MJ. Transformative technology and institutional transformation: coevolution of biotechnology venture firms and the institutional framework in Japan. Res Policy 2006;35: 1389–422.

[103] Cabinet Office. Basic law for science and technology; 1995.

[104] Cabinet Office. First basic plan for science and technology (1996–2000); 1995.

[105] Ohmori H, Takada N, Motoyama Y. Japanese SBIR: a trigger for a new era. Tokyo: NRI Press; 1998.

[106] Saito Y. Toward successful policy proposals for the Japanese SBIR. Creating intellectual assets. Tokyo: Nomura Research Institute; 1999. p. 70–81.

[107] Government of Japan. Law for promoting university-industry technology transfer; 1998.

[108] Government of Japan. Law on special measures for industrial revitalization; 1999.

[109] Cabinet Office. Second basic plan for science and technology (2001–2005); 2000.

[110] METI. History of university-industry collaboration. Tokyo: Ministry of Economy, Trade, and Industry (METI); 2011.

[111] Cabinet Office. Progress report of intellectual property strategy. In: Intellectual property strategy council 2009. Tokyo.