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Collaborative Research Networks in Semiconductor Laser Technology, 1960-2000: A Comparative Perspective on Networks and Breakthroughs in the United States and Japan

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The semiconductor laser was one of the most important technologies underlying the dramatic changes that took place during the last half of the twentieth century in information technology, and it has been the most widely used laser since the 1980s. In this essay, we investigate collaborative networks and breakthroughs by exploring collaborative research in semiconductor laser technology from 1960 to 2000. Development of this technology began in the early 1960s; by the 1980s, inter-organizational collaborative research was occurring. By mapping breakthroughs, we show that, since the 1980s, organizations involved in inter-organizational research produced many of the breakthroughs. By exploring six examples, we observe different patterns in network formation in the United States and Japan. In the United States, many "star" engineers were involved in inter-organizational collaboration and played a nodal role in the networks before achieving significant breakthroughs, whereas in Japan, the star engineers played a nodal role only after achieving a breakthrough.

By exploring research networks in semiconductor laser technology from the 1960s to 2000, we aim to further the understanding of collaborative research networks among scientists and engineers. Such collaboration has received considerable attention since the 1970s, when many information technology (IT) business ventures from the 1960s spilled over in Silicon Valley, California. As Alfred D. Chandler, Jr., Takashi Hikino, and Andrew Von Nordenflycht observed, in-house R&D (research and development) was traditionally an important source of innovation and a competitive

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advantage for firms.[1] However, with the increasing complexity of technology it becomes irrational for a firm to internalize all resources for in-house R&D, and accessing knowledge created by other firms, universities, and research institutes and utilizing external resources give firms an important competitive advantage.[2] Because networking among scientists, engineers, and entrepreneurs is an important means of accessing external resources, that process began to attract wider attention.

A laser is an optical source that emits a narrow beam of coherent light. The power in a continuous beam ranges from a fraction of a milliwatt to more than a megawatt. Laser uses are broad in scope, ranging from commercial to special military applications. The semiconductor laser, invented in 1960, is only one of several types of lasers, but it was an important technology, underlying many dramatic changes during the last half of the twentieth century. It has become the most widely used laser since the 1980s, mainly for information storage such as the compact disc and the digital videodisc system, which can store a thirty-volume encyclopedia of information on a single disc and access an arbitrary element of information with great speed. Its use for fiber-optic communication permits digital data transmission over long distances and at higher data rates than electronic communication.

By exploring collaborative research in semiconductor laser technology, we show how academic and corporate engineers collaborated and how they developed breakthroughs. We examine research networks among engineers through co-authored papers on semiconductor laser technology published in *Applied Physics Letters*. Because many levels and types of collaboration exist, there is no single method or index to investigate research networks. Collaborative networks can take various forms, from formally contracted and organized research to casual conversation over a pint of beer. We use co-authored papers as a proxy measure of collaborative research among scientists and engineers.[3] Of course, co-authored papers do not cover all collaborative research among practi-

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[1] Alfred D. Chandler, Jr., Takashi Hikino, and Andrew Von Nordenflycht, *Inventing the Electronic Century: The Epic Story of the Consumer Electronics and Computer Industries* (New York, 2001); David C. Mowery, "The Relationship between Intrafirm and Contractual Forms of Industrial Research in American Manufacturing, 1900-1940," *Explorations in Economic History* 20 (Oct. 1983): 351-74.

[2] Walter W. Powell, Kenneth W. Koput, and Laurel Smith-Doerr, "Interorganizational Collaboration and the Locus of Innovation: Networks of Learning in Biotechnology," *Administrative Science Quarterly* 41 (March 1996): 116-45; Ranjay Gulati, "Network Location and Learning: The Influence of Network Resources and Firm Capabilities on Alliance Formation," *Strategic Management Journal* 20 (May 1999): 397-420.

[3] On the analysis of co-authored academic papers, see Mapheus Smith, "The Trend toward Multiple Authorship in Psychology," *American Psychologist* 13 (Oct. 1958): 596-99.

tioners. In particular, it is difficult to capture informal research networks, many of which do not visibly appear in academic journals. However, exploring co-authored papers allows the longitudinal and systematic investigation of collaboration across various countries. Additionally, in this study, we identify some key engineers in network formation, which will allow us to conduct more qualitative research, such as interviewing key engineers to examine informal research networks, in future research.

Scientists and engineers publish their findings in a wide variety of academic journals in semiconductor laser technology, from well-circulated journals such as *Science* and *Science of America*, to more technical and specialized journals, such as the *Journal of Applied Physics*, the *IEE Journal of Quantum Electronics*, and the *Journal of Quantitative Spectroscopy and Radiative Transfer*. Among these journals, we used *Applied Physics Letters* to explore collaborative research in semiconductor laser technology. *Applied Physics Letters*, published by the American Institute of Physics, is a widely recognized international journal. Since 1962, the weekly journal has offered up-to-date reports on new experimental and theoretical findings in applied physics. The weekly reports provide richer data on collaboration than monthly and semi-monthly journals.

In the first two decades of semiconductor laser technology's development, collaborations among scientists and engineers were limited to in-house R&D. Network formation and breakthroughs began during the 1980s; organizations that were involved in inter-organizational research produced many of the breakthroughs, as did organizations that played a nodal role in the networks. Exploring the chronological relationship between network formation and breakthroughs by examining six cases reveals that different patterns of networking existed in the United States and in Japan. "Star" scientists participated in inter-organizational collaboration before achieving breakthroughs in the United States, while star scientists in Japan were involved in inter-organizational collaboration only after achieving a breakthrough.

Semiconductor Lasers

The first theoretical conception of the laser originated with Albert Einstein in 1905, when he described the photoelectric effect, which became a fundamental theoretical backbone of the laser.[4] Extending this theory, in 1917 Einstein predicted stimulated emission of radiation. This first theoretical finding, however, remained unexplored until after World War II.

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[4] Albert Einstein, "Über die von der molekularkinetischen Theorie der Wärme geforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen" [On the Motion-Required by the Molecular Kinetic Theory of Heart of Small Particles Suspended in a Stationary Liquid], *Annalen der Physik* 17 (May 1905): 549-60.

Toward the end of the 1930s, as German torpedoes began sinking U.S. ships, the U.S. government and military turned to the problem of how to protect their ships.[5] The U.S. military began to mobilize physicists and set clear research goals for them, one of which was to develop microwaves for radar and weapons. With government guidance, the physicists began to develop various radio and microwave weapons, such as radar, electronically guided anti-aircraft guns, and radar-guided bombing systems.

Microwave research would lead to laser technology after the war. With the financial support of the U.S. Air Force, Army, and Navy, Charles H. Townes, a physicist at Columbia University, in 1953 applied Einstein's theory to invent the first maser, a device operating on principles similar to those of the laser, but producing microwave, rather than optical, radiation. Gordon Gould, a graduate student at Columbia, came up with a stimulated emission and noted his idea in his notebook in 1957. He named this idea LASER (Light Amplified by Stimulated Emission of Radiation). However, because Gould did not publish his idea and did not promptly apply for a patent, other physicists did not immediately recognize his findings.[6] Townes and Arthur Schawlow also investigated the possibility of an optical maser, a prototype of the gas laser. They published the first detailed proposal for building an optical maser in *Physical Review* in 1958.[7] Gould, Townes, and Schawlow provided theoretical background for the laser. However, it was Theodore H. Maiman, an electronics engineer at Hughes Aircraft Research Laboratories in California, who developed the first laser. In 1960, he used a solid body pink ruby to amplify visible light. It was the first successful light amplification by stimulated emission of radiation. Because Maiman used a pink ruby to amplify the laser beam, it was named the "ruby laser." Many lasers were developed after Maiman's success.

The first theoretical idea for a semiconductor laser emerged in a letter written in 1953, by John von Neumann, a Hungarian mathematician.[8] However, he did not present this idea to any academic society. The first

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[5] On the wartime research in applied physics, see Charles H. Townes, *How the Laser Happened: Adventures of a Scientist* (New York, 1999), 33-46.

[6] Ibid., 101-4 and 120-24. Gould brought his idea of a laser to the Technical Research Group (TRG) in New York. TRG and Gould presented their research proposal to the Department of Defense Advanced Research Project Agency (DARPA) to receive research funding. The agency accepted their research proposal and offered $1 million to support Gould's research at TRG. Gould and Townes went to court to claim their invention. When Townes and his colleague Arthur L. Schawlow presented the laser light and applied for a patent in 1958, Gould went to court and appealed, stating that the laser was his idea. The final judgment supported Gould's appeal in 1977.

[7] Arthur L. Schawlow and Charles H. Townes, "Infared and Optical Maser," *Physical Review* 112 (Dec. 1958): 1940-49.

[8] Marius Grundmann, *Nano-Optoelectronics: Concepts, Physics, and Devices* (New York, 2002), 3.

publicly released material on light amplification using a semiconductor was a patent for a "semiconductor maser" granted to Nishizawa Junichi, a physicist at Tohoku University, in 1957. This maser, run with principles similar to those of the laser, reinforced the feasibility of stimulated emission in semiconductors.

In the two years following the invention of the first laser in 1960, four different research groups almost simultaneously developed the semiconductor laser.[9] In September 1962, Gunther Fenner, a member of the research group headed by Robert N. Hall at the General Electric Development Center, successfully operated the first semiconductor laser. A few weeks later, Nick Holonyak at the University of Illinois at Urbana-Champaign (UIUC), Marshall I. Nathan at the IBM (International Business Machines) Research Laboratory in Yorktown Heights, and Robert Rediker at the Lincoln Laboratory, Massachusetts Institute of Technology (MIT), successfully developed the first semiconductor lasers in the same year, simultaneously but independently.

The semiconductor lasers developed by GE, IBM, UIUC, and MIT worked properly only at minus 196 degree Celsius (the temperature of liquid nitrogen), severely limiting their potential. Therefore, the focus of R&D was to develop a semiconductor laser that could work at room temperature, and many organizations began to conduct such research It took eight years for the engineers to solve the technological problem.

A Bell Laboratory research team developed the first semiconductor laser to work at room temperature in 1970. Named the double-hetero-structure laser (DH), it was one of the most important technological breakthroughs in the industry.[10] Even though many problems remained with the DH, it was an important turning point in the technological development of the semiconductor laser, and the advance stimulated competition. Many firms developed reliable and stable semiconductor lasers that could work at room temperature. Newspapers reported that this newly invented DH laser would fundamentally change optical engineering and that it would be as important as the transistor, which had produced an earlier fundamental change in electronic engineering.[11] After this invention, the focus of research and development in semiconductor laser

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[9] On the invention of four semiconductor lasers, see Russell D. Dupuis, "The Diode Laser: The First 30 Days, 40 Years Ago," *Optics & Photonics News* (April 2004), 30-35.

[10] Morton B. Panish, Izuo. Hayashi, and Stanley Sumski, "Double-Heterostructure Injection Lasers with Room-Temperature Thresholds as Low as 2300 A/cm2," *Applied Physics Letters* 116 (April 1970): 326-27.

[11] For instance, the Japan Electronics Apparatus Industry Association stated, "the laser diode attained a continuous amplification at room temperature in 1970. It is projected that it will be used in optical telecommunication and data communication soon. " Nihon Denshi Kikai Kogyo Kai, *Denshi Kogyo 30 nenshi* [A 30-year History of the Electronics Industry] (Tokyo, 1979), 269.

technology shifted to developing semiconductor lasers for specific applications, such as optical fiber and information storage.

The firms and research organizations involved in R&D in semiconductor laser technology rarely collaborated with other organizations through the 1960s and 1970s (see Table 1).

TABLE 1

Co-Authored Papers in the *Journal of Applied Physics*

Decade	**# of Papers**	**# of Co-Authored Papers[a]**	**# of Inter-Organizational Papers[b]**	**Average # of Authors**
1960s	8	7 (87.5)	1 (12.5)	2.25
1970s	230	204 (88.7)	21 (9.13)	3.18
1980s	1,155	1,081 (93.59)	176 (15.24)	4.07
1990s	1,667	1,623 (97.36)	469 (28.13)	4.73

Source: *Applied Physics Letters*, 1960-1999.
Notes: This documents the number of papers on semiconductor lasers published in *Applied Physics Letters* from the 1960s to the 1990s, including the number of co-authored papers, average number of authors, and number of inter-organizational papers in the journal.
[a]The parentheses indicate the ratio of co-authored papers to the total number of articles on semiconductor lasers.
[b]The parentheses indicate the ratio of inter-organizational co-publications to the total number of articles on semiconductor lasers.

In the 1980s, organizations began to collaborate on research projects. By mapping breakthroughs in inter-organizational networks, we can explore where breakthroughs emerged at different times. We identify breakthroughs by using the number of citations of each paper on semiconductor laser technology published in the *Journal of Applied Physics*.[12]

In **Figure 1**, we show the inter-organizational collaborative research networks among firms, universities, and research institutions and the top ten breakthroughs from the 1960s to 1970s.[13] The editors of *Applied Physics* published a substantial number of papers on semiconductor lasers during the 1980s and 1990s. The high ratio of co-authored papers, shown in Table 1, indicates that engineers collaborated to develop semiconductor

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[12] We obtained the number of citations from the ISI Web of Science in March 2008.

[13] To view the figures in this essay, readers should follow the links and then use the zoom or enlarge function in Word in order to increase the figure size to a legible scale.

lasers. The average number of authors steadily increased from the 1970s to the 1990s. This is consistent with previous studies examining research collaboration. For instance, Walter W. Powell, Kenneth W. Koput, and Laurel Smith-Doerr indicated that when technology becomes complex and when the sources of expertise are widely dispersed, engineers begin to collaborate and networks rather than individual organizations are the locus of innovation.[14] The focus of semiconductor laser R&D shifted from basic research to applied research during the 1980s. In the fourth column of Table 1, we see that the number of papers resulting from inter-organizational collaboration remained small (fewer than ten until 1983). However, the rate of inter-organizational collaboration on papers continued to increase and reached its peak, which was almost 30 percent, during the 1990s. A variety of firms and organizations researched and developed semiconductor lasers and collaborated in the related fields.

In addition to what we can infer from Table 1, in Figure 1 there is evidence that research networks did not begin to develop fully until the 1980s. Organizations on the right in Figure 1 published research outcomes on semiconductor laser technology, but were not involved in inter-organizational collaboration. Thus, many organizations individually studied and developed semiconductor lasers during this period. There are also indications from the data in Figure 1 that organizations not involved in any inter-organizational collaboration made many of the breakthroughs. No inter-organizational collaborative paper was in the top ten breakthroughs during this time: although inter-organizational networks gradually grew beginning in the 1970s, the breakthroughs did not emerge in such networks.

Figure 2 shows the relationship between the networks and breakthroughs from the 1980s to 1990s, illustrating how much more extensive network development was during this period. It also shows that many of the breakthroughs emerged in the networks. Organizations that were involved in inter-organizational collaborations made four of the top ten breakthroughs. Furthermore, many breakthroughs emerged in the center of the networks, which suggests that organizations that played a central role in the networks had more breakthroughs than organizations located at the periphery or outside the networks.

By visualizing research networks and mapping breakthroughs onto the networks, we show in Figures 1 and 2 that inter-organizational research networks remained small during the 1960s and 1970s, and that organizations not involved in inter-organizational collaboration made many of the breakthroughs. The figures clearly illustrate the extensive network development that began during the 1980s. Organizations began to collaborate with each other, and those positioned in the central parts of the networks made many breakthroughs.

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[14] Powell, Koput, and Smith-Doerr, "Interorganizational Collaboration and the Locus of Innovation."

High Centrality or Breakthrough?

We can also see in Figure 2 that organizations that played a nodal role in the networks likely made many of the breakthroughs. This finding is consistent with theoretical literature on networks, which have generally confirmed that players with higher centrality have advantages in accessing information and resources within the networks.[15]

One lingering problem with this approach, however, is the "chicken or egg" causality dilemma. We must explore which came first, the higher centrality or the breakthroughs. On the one hand, as theorists have discussed, a player in a nodal role in the networks can have an advantage in accessing information and resources within the networks and be in a better position to achieve breakthroughs. On the other hand, it is possible that an organization comes to play a nodal role after achieving important breakthroughs because other players wish to access resources and new knowledge produced by these breakthroughs.

We explore the chronological relationship between the centrality of organizations and scientific breakthroughs, through examining six cases of inter-organizational collaboration at the level of individual engineers. We include three breakthroughs made by U.S. organizations and three breakthroughs produced by Japanese organizations. Because the research networks developed beginning in the 1980s, we examined breakthroughs that emerged from 1980 to 2000. We selected the breakthroughs from the papers that received the most citations. By exploring the networks and breakthroughs and comparing the two countries, we present evidence of different patterns in network formation and breakthroughs in the United States and Japan.

We show the breakthrough provided by Brown University and Purdue University in 1991 in **Figure 3**. Engineers from Brown University and Purdue University published "Blue-green injection laser diodes in (Zn,Cd)Se/ZnSe quantum wells" in 1991 in *Applied Physics Letters*.[16] This paper is the second most highly cited paper published by the U.S. organization from 1980 to 2000.

In Figure 3 we see that the star engineers had developed inter-organizational networks with the University of Notre Dame and Bell Laboratories before achieving their breakthrough. After achieving the breakthrough, they collaborated with Northwestern University and MIT.

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[15] For example, Joseph Galaskiewicz, *Exchange Networks and Community Politics* (Beverly Hills, Calif., 1979).

[16] Heonsu Jeon, Jian Ding, William Patterson, Arto V. Nurmikko, W. Xie, Donald C. Grillo, Masakazu Kobayashi, and Robert L. Gunshor, "Blue-green injection laser diodes in (Zn,Cd)Se/ZnSe quantum wells," *Applied Physics Letters* 59 (Dec. 1991): 3619.

Among the star engineers, Heonsu Jeon and Jian Ding played a nodal role in developing inter-organizational networks.

We illustrate the breakthrough produced by Bell Laboratories in **Figure 4**. In 1992, Samuel L. McCall, Anthony F.J. Levi, Richart E. Slusher, Stephen J. Pearton, and Ralph A. Logan, all affiliated with AT&T Bell Laboratories when they made this breakthrough, published "Whispering-gallery Mode Microdisk Lasers" in *Applied Physics Letters*.[17] This paper is the third most highly cited paper on semiconductor lasers published from 1980 to 2000 by U.S. organizations.

With many red-signed engineers, this figure shows that the star engineers collaborated with many engineers after the breakthrough. They developed in-house collaborations, as well as inter-organizational collaborations with institutions such as UIUC, Colorado State University, and the University of Southern California. Furthermore, we must note that the star engineers had developed inter-organizational relationships with other schools, such as the University of Berne, the University of California (UC) Santa Barbara, and the University of Maryland before achieving this breakthrough.

Figures 3 and 4 present the case that the star engineers were involved in inter-organizational collaboration before achieving important breakthroughs and that they developed new inter-organizational networks after the breakthroughs. In other words, the star engineers who had played a nodal role in the network achieved important breakthroughs and developed the network after the breakthrough.

In **Figure 5**, we see a different pattern of network formation illustrated by a breakthrough at 3M Company. In 1991, four 3M engineers, Michael A. Haase, Jun Qiu, James M. DePuydt, and Hwa Cheng, published "Blue-green laser diodes" in the *Applied Physics Letters*.[18] In this paper, they reported on the first semiconductor laser fabricated from wide-band gap II-VI semiconductors; they received the highest number of citations among the papers on semiconductor lasers published by U.S. organizations in *Applied Physics Letters* from 1960 to 2000.

This pattern of collaboration among engineers differs from those of other U.S. organizations in that the star engineer developed collaborative relationships after the breakthrough. However, those relationships were limited to in-house collaboration. Moreover, 3M had not been involved in inter-organizational collaborative research at all. This suggests that corporate strategy in developing inter-organizational collaboration plays an important role in determining how a certain firm accesses external knowledge and develops scientific and technological knowledge.

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[17] Samuel L. McCall, Anthony F. J. Levi, Richart E. Slusher, Stephen J. Pearton, and Ralph A. Logan, "Whispering-gallery Mode Microdisk Lasers," *Applied Physics Letters* 60 (Jan. 1992): 289.

[18] Michael A. Haase, Jun Qiu, James M. DePuydt, and Hwa Cheng, "Blue-Green Laser Diodes," *Applied Physics Letters* 59 (Sept. 1991): 1272.

In Figures 6, 7, and 8, we present the breakthroughs made by Japanese organizations during the 1980s and 1990s. These show a pattern of network formation and breakthroughs different from those of U.S. organizations. We show a breakthrough produced by the University of Tokyo in **Figure 6**. In 1982, Yasuhiko Arakawa and Hiroyuki Sakaki published "Multidimensional Quantum Well Laser and Temperature Dependence of Its Threshold Current" in *Applied Physics Letters*.[19] This paper received the highest number of citations of papers on semiconductor lasers in the *Journal of Applied Physics* from 1980 to 2000. In this paper, the authors studied a new type of semiconductor laser.

When they published this paper in 1982, Arakawa and Sakaki were at the Institute of Industrial Science at the University of Tokyo. This was their first paper published in the *Journal of Applied Physics*. After achieving this breakthrough, Arakawa published papers with engineers from Caltech and Ortel. In Figure 6, we see how they developed collaborative networks and inter-organizational networks only after achieving the breakthrough.

In **Figure 7**, we show the collaboration between Nichia Chemical Industries and Kyoto University and their breakthroughs. Nichia Chemical's engineers, Shuji Nakamura, Takashi Mukai, and Masayuki Senoh, published "Candela-Class High-Brightness InGaN/AlGaN Double-heterostructure Blue-light-emitting Diodes" in *Applied Physics Letters* in 1994.[20] This paper obtained the second highest number of citations among papers on semiconductor lasers published in the *Applied Physics Letters* from 1960 to 2000. The paper described the highest luminous intensity for a blue light laser ever documented.

Nakamura published many frequently cited papers with Nichia Chemical's engineers after this invention. Furthermore, Nakamura published the paper "Role of Self-Formed InGaN Quantum Dots for Exciton Localization in the Purple Laser Diode Emitting at 420 nm" with engineers from the Department of Electronic Science and Engineering at Kyoto University in 1997.[21] This paper received the third highest number of citations after University of Tokyo's 1982 article and Nichia Chemical's 1994 paper. In Figure 7, the star engineer is not involved in inter-organizational collaboration before achieving the breakthrough.

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[19] Yasuhiko Arakawa and Hiroyuki Sakaki, "Multidimensional Quantum Well Laser and Temperature Dependence of Its Threshold Current," *Applied Physics Letters* 40 (June 1982): 939.

[20] Shuji Nakamura, Takashi Mukai, and Masayuki Senoh, "Candela-class High-brightness InGaN/AlGaN Double-heterostructure Blue-light-emitting Diodes," *Applied Physics Letters* 64 (March 1994): 1687.

[21] Yukio Narukawa, Yoichi Kawakami, Mitsuru Funato, Shizuo Fujita, Shigeo Fujita, and Shuji Nakamura, "Role of Self-Formed Ingan Quantum Dots for Exciton Localization in the Purple Laser Diode Emitting at 420 nm," *Applied Physics Letters* 70 (Feb. 1997): 981.

However, he collaborated with Kyoto University and achieved yet another breakthrough following the breakthrough in 1994.

In **Figure 8**, we show the breakthrough made by UC Santa Barbara and Hiroshima University. In 1988, Ikuo Suemune, Masamichi Yamanishi, and Yasuo Kan, affiliated with the Faculty of Engineering at Hiroshima University, and Larry A. Coldren of UC Santa Barbara jointly published "Extremely Wide Modulation Bandwidth in a Low Threshold Current Strained Quantum Well Laser."[22] This paper obtained the highest number of citations after those of the University of Tokyo and Kyoto University.

In Figure 8, we see a slightly different picture of networking and breakthroughs in Japanese organizations. First, two of the star engineers had already published papers at other institutions. Coldren published a significant number of papers from Bell Laboratories starting in 1973. Yamanaka published papers on semiconductor lasers at the University of Osaka Prefecture, where he obtained his Ph.D., as well as at Tohoku University and Purdue University. This suggests that he had already developed inter-organizational networks before achieving the breakthrough. Coldren collaborated with new partners and played a nodal role in the networks after the breakthrough, but Yamanaka and other star engineers of Hiroshima University did not develop their inter-organizational networks much. Even though this case is quite exceptional for Japanese organizations, it suggests that we need to look more closely at engineers' profiles and institutional settings.

Unlike the engineers involved in breakthroughs produced by U.S. organizations, the star engineers of Japanese organizations generally were not involved in inter-organizational collaboration before achieving a breakthrough. They began to play a nodal role in the network only after achieving the breakthrough. It suggests that the direction of the causal relationship between network formation and breakthroughs is that an important breakthrough led the star engineer to play a nodal role in the Japanese networks.

Discussion

We have examined inter-organizational collaborative networks in semiconductor laser technology from 1960 to 2000 by exploring the co-authored papers published in *Applied Physics Letters*. We have shown that collaboration among scientists and engineers was mainly limited to their in-house research until the 1980s. However, the amount of inter-organizational collaboration increased starting during the 1980s, at which time inter-organizational networks developed rapidly.

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[22] Ikuo Suemune, Larry A. Coldren, Masamichi Yamanishi, and Yasuo Kan, "Extremely Wide Modulation Bandwidth in a Low Threshold Current Strained Quantum Well Laser," *Applied Physics Letters* 53 (Oct. 1988): 1378.

By mapping breakthroughs onto research networks, we show that many of the breakthroughs were made by organizations that participated in inter-organizational collaborative networks. In particular, the figures suggest that organizations that played a nodal role in their networks produced many of the breakthroughs.

We have demonstrated the chronological relation between network formations and breakthroughs. By exploring the collaborative research networks, we show that the United States and Japan have different patterns in network formation. The star engineers tended to be involved in inter-organizational collaboration and to play a nodal role in the networks before achieving a significant breakthrough in the United States. In Japan, the star engineers played a nodal role only after achieving a breakthrough.

This key difference might reflect various institutional distinctions between the countries such as labor mobility, university-industry relationships, corporate competitive strategies for R&D, and propensity for inter-organizational collaboration. It is far beyond the scope of this paper to discuss why and how the different patterns exist in the two countries. However, we have identified some star engineers who played a nodal role in the networks, and we plan to interview these engineers to explore further the relationship between network formation and breakthroughs. In the future, we intend to increase our sample as well.