Technological Strength Needs and Feeds a New Research Infrastructure in Japan

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Competition between Research Systems

There are great differences among countries in the efforts of their institutions in the areas of science and technology. In almost all countries we find institutions of higher education doing academic research and firms engaged in product development. Beyond that, however, it becomes very difficult to generalize.

There are some critical differences in how the funding of research and development (R&D) is divided between government and private sources, how government funds are distributed according to social objectives, where governments prefer to spend their R&D funds for a certain objective, and the extent to which firms carry out research of a more fundamental or general kind than that associated with the development of a specific product.

What concerns us here is that part of the total R&D system that functions as a research infrastructure for the development of industrial technology. Organizations belonging to that infrastructure may include research groups at universities, government laboratories, other types of freestanding nonacademic research establishments, and corporate research laboratories.[1] The mix of organizations and their relative weight will vary between countries and fields.

What is the significance of these differences between countries in the institutional makeup of their research infrastructures? Do the differences affect the economic payoff of public investments in industrially related research? Do they affect the ability of a country to benefit from new developments internationally in science and technology? In short, do some countries have research systems that are more competitive than others, in the sense that they provide better support for the development of their domestic industries?

There are signs that these questions are becoming increasingly important. There is, for example, a growing concern in the United States, the United Kingdom, and Sweden that publicly funded research, although proving itself on the international scientific scene, does not create the domestic economic benefits sought, but is instead primarily supporting innovation elsewhere.

One could certainly argue that such disappointments are caused by false expectations about the nature of the linkage between scientific research and industrial innovation, and that it disregards the intrinsically international nature of science and technology. Nevertheless, there may still be some structural factors at work that put some countries in a better position than others to translate progress in scientific research to success in the development of industrial technology.

Furthermore, the importance of taking advantage of research at the scientific frontier may be growing. It is often suggested that the link between science and innovation has become more direct. With today's sophistication in technology, specific pieces of research can frequently have direct relevance for the solution of technical problems, while in the past the economic benefits of scientific research were for the most part much more diffuse and achieved mainly indirectly through the general knowledge instilled in graduates from universities or engineering schools. There may consequently be more to win today from an effective linkage between science and innovation, and more to lose from the absence of such a linkage.

Japanese industry is generally considered to be very effective in translating research into commercial success. A popular image has been that in Japan the government and the business sector have contributed little in terms of developing new basic technologies, and instead have concentrated on combining and refining technologies developed elsewhere. Consistent with this view there has been a great deal of criticism, from both inside and outside Japan, of Japanese universities for not maintaining a sufficiently high standard in their research and for not contributing to the international advancement of knowledge to an extent commensurate with the economic stature of Japan. Since universities are highly dependent on governments for the financing of their research, such criticism is ultimately aimed at the Japanese government.

There is little reason to doubt that Japan and its industry have benefitted enormously from the importation or copying of technology developed in the West, and especially in the United States. In most areas, however, Japanese industry has now progressed far beyond the "catch-up" phase and is aggressively pursuing basic technology development of its own. A powerful research infrastructure is being established as an integral part of this development, but it has a different structure than in many other countries, especially in the very strong participation of the corporate sector in long-term research.

The purpose of this paper is to examine the dynamics of the growth of the industrially oriented research infrastructure in Japan with a focus on the changing role of universities in this context.

The leading role of the business sector in the expansion and structural transformation of the Japanese research landscape is first illustrated by presenting some data on the growth of basic research in Japanese industry. This presentation is contrasted with similar data for other types of research institutions. The difficulties Japanese universities encounter in responding to and matching developments in the business sector are discussed on a general level. In order to better understand the institutional dynamics of the Japanese research system, some results from a case study of the field of molecular beam epitaxy (MBE) are reported. The chapter concludes with a discussion of what will determine the future evolution of the institutional structure of the Japanese research system.

The Business Sector Takes a Leading Role in Basic (Technology) Research

During most of the postwar period, Japanese industry has a remarkable record of expansion, which has been interrupted on only a few occasions and then only for short periods. This expansion has gone hand in hand with a continuous upgrading of the technical level of products and production facilities, a process in which investment in research and development has become increasingly important.

The first substantial growth in the establishment of research laboratories in Japanese industry occurred in the early 1960s. In response to liberalization of imports, Japanese firms felt under strong pressure to upgrade their technology to an internationally competitive level. One of the primary functions of the new laboratories was facilitating the importation and adaption of foreign technology.

Government programs for support of industrial R&D were set in place to further support raising the technical level in Japanese industry. Gradually, a system of government-sponsored collaborative research was developed.[2]

The 1970s saw a slowing in R&D growth (Fig. 1). For the Japanese electronics industry this was, however, a crucial period during which it established itself as a serious contender on the international scene. There is evidence that government R&D programs played an important role in this development.[8]

A second boom in laboratory building in Japanese industry occurred during the 1980s. It differed from the one in the 1960s in that now the emphasis was on research for the development of "new, original, basic technologies" and required an environment and management style that would support creative research.

Already around 1980 there emerged a consensus in Japan that the country had to put greater emphasis on basic (technology) research.[9] This idea has since remained the leading theme of Japanese science and technology policy. In the Japanese policy debate three major motives for strengthening basic research in Japan have been put forward. First, it has been suggested that Japan, after having gained from generous access to foreign technology, ought now to do its part and return something to the rest of the world. A second argument has been that now that Japan has caught up with the international frontier in technology, what can be found of new technology abroad is not enough to support the further growth of the Japanese economy. Finally, some have warned that in the future the United States and Europe will be more restrictive in their sharing of technology with Japan. All these arguments have been used to support the thesis that Japan has to take a leading role in the development of new basic technologies.

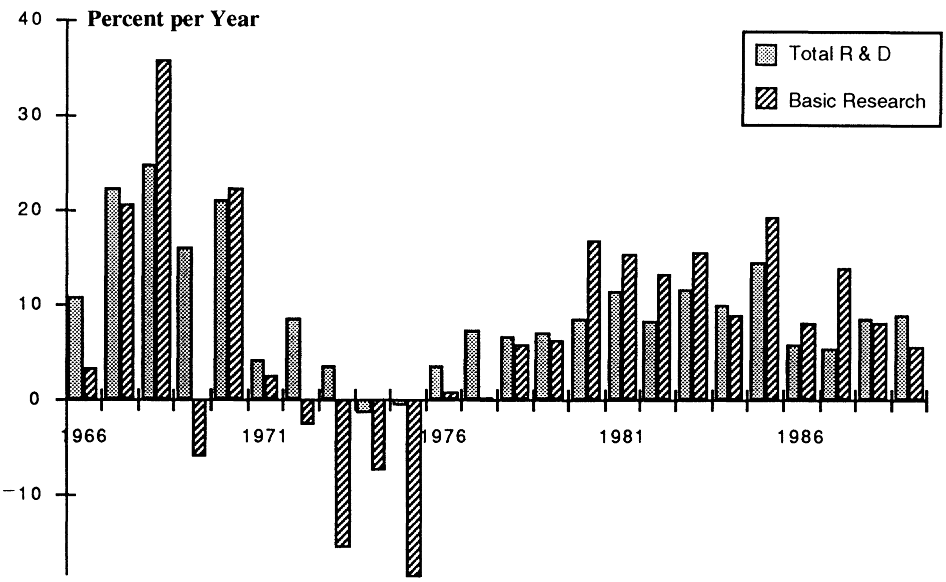

Figure 1. Year-to-year real growth in total R&D and in basic research for all industry in Japan 1965–1989. (*Source:* Statistics Bureau [3–7, 10])

The concern with development of new basic technologies is often translated into a call for a stronger emphasis on basic research. This call is interpreted in very different ways, depending on the vantage point. Some would have it mean that the government now should spend more money on the basic sciences and especially on fields of little interest to industry. Others see it rather as a change in the emphasis of industrially oriented R&D.

As it turns out, the largest share of growth in basic research has occurred in the business sector, which can be seen both in the data on basic research in the available R&D statistics and in the mushrooming of new corporate research laboratories.

In Japan, as in most other countries, it has been very difficult for the public sector to contribute to the strengthening of basic research, due to the generally austere fiscal climate during the 1980s. Within these limitations, however, there has been an increasing emphasis on basic research both in the research carried out in many of the governmental research institutes and in the research supported by the government in the private sector. There have also been significant changes in the organization of research and in the procedures for its funding, which are intended to improve, in particular, the conditions for basic research.

The overall result has nonetheless been that the business sector in Japan has acquired not only a more prominent role in applied R&D than in probably any other country but is also increasingly moving to center stage in a number of fields of rather basic research, simply by outgrowing the research capacity of universities and public research institutes. Figure 2 illustrates a decade's change in the relative weight of basic research in different types of research institutions in Japan.

Basic research in industry is more focused than that in universities, which means that for fields of current or potential industrial interest universities today in all

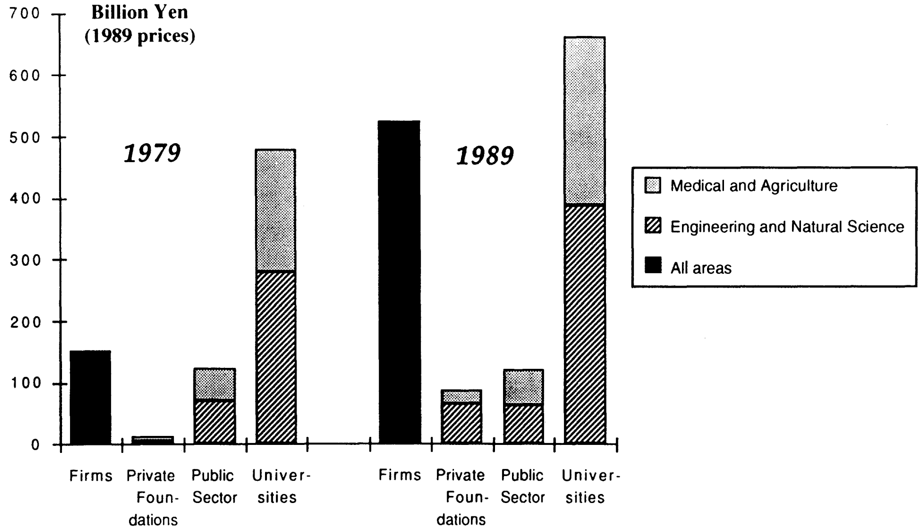

Figure 2. Expenditure on basic research in Japan during 1979 and 1989 by type of research organization. (*Source:* Statistics Bureau [10, 11])

likelihood spend less than industry. It is quite remarkable for this structural reshaping of the Japanese research landscape to have occurred over only a decade.

Basic research is carried out in very different contexts in different types of institutions. In those firms that carry out such research at all, basic research is a small part of their total R&D (for all of Japanese manufacturing industry the fraction was 6.4 percent in 1989) and could be regarded as overhead for more applied R&D. In universities, on the other hand, basic research is a major occupation, representing more than half of all R&D even in engineering departments, and is intimately tied to the function of graduate education. Research institutes vary widely in character, and therefore also in the relative weight of their basic research.

Firms invest in basic research for a number of reasons,[12] though for many Japanese firms diversification has been an important motive. For the electronics industry, however, diversification has not been a major factor because of the huge potential for growth. Thus, the issue in this industry has been to realize this potential by aggressively investing in new generations of products, some of which, one could argue, have been genuinely new.

Growth in the sales base has thus been the main factor behind the electronics industry's growth in R&D (Figs. 3–5). There has also been a 50 percent increase in R&D intensity. Basic research has followed the development of overall R&D very closely. On the other hand, sales growth has been slower in most other industries, which has led firms to allocate a growing portion of their R&D to basic research for the purpose of building a base for future diversification. As a result, basic research has expanded as fast or even faster in these other industries than in the electronics industry.

According to official statistics, the electrical equipment industry increased its basic research expenditure by a factor of around 3 in real terms from 1979 to 1989,

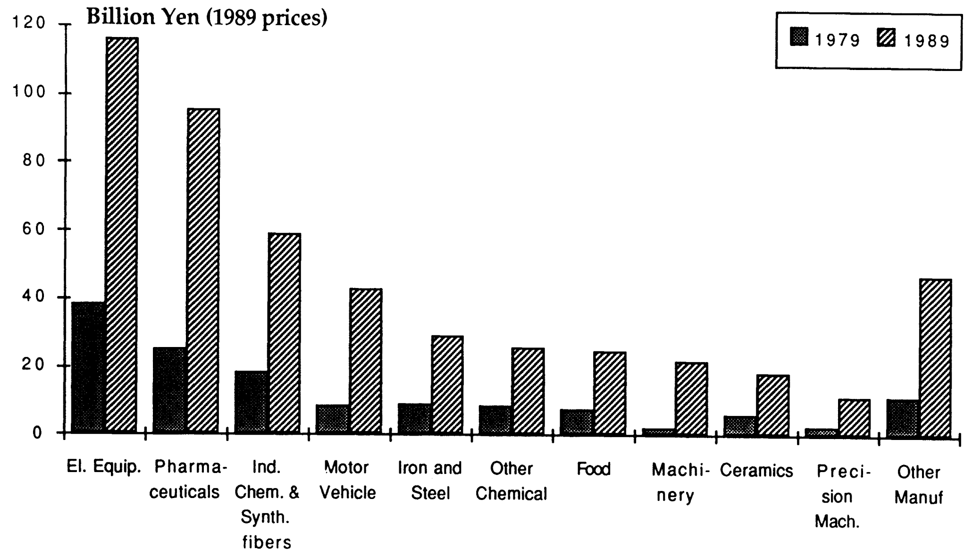

Figure 3. Basic research in manufacturing firms in Japan, 1979 and 1989. (*Source:* Statistics Bureau [10, 11])

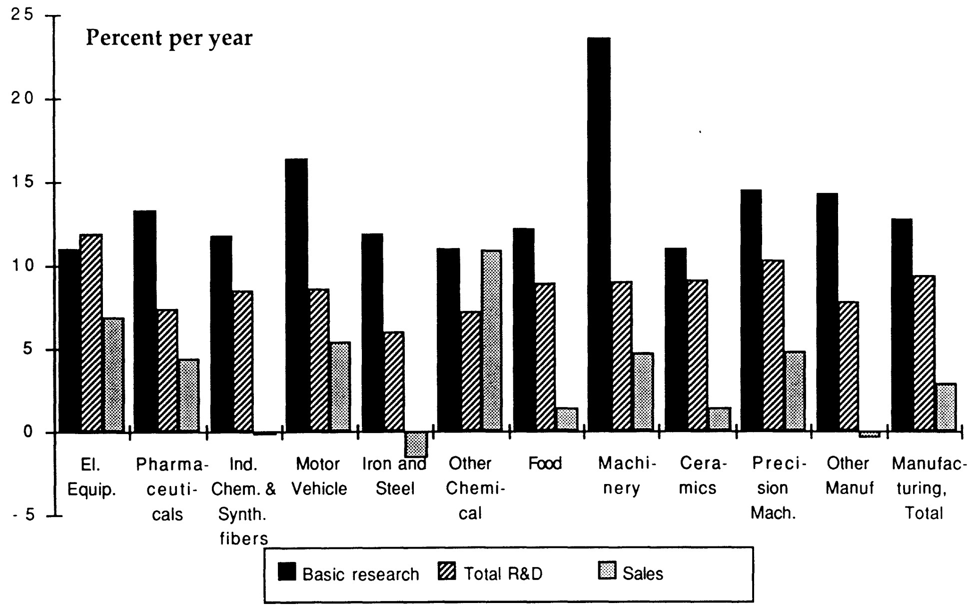

Figure 4. Average annual real growth in basic research, total R&D, and sales in manufacturing firms in Japan 1979–1989. (*Source:* Statistics Bureau [10, 11])

reaching a total amount of ¥116 billion in the latter year. This increase represented a little over 4 percent of overall R&D in that industry. The number of researchers engaged in basic research grew from some 2500 to 5000 during the same period, reflecting the greater resources available to each researcher at the end of the period.[13]

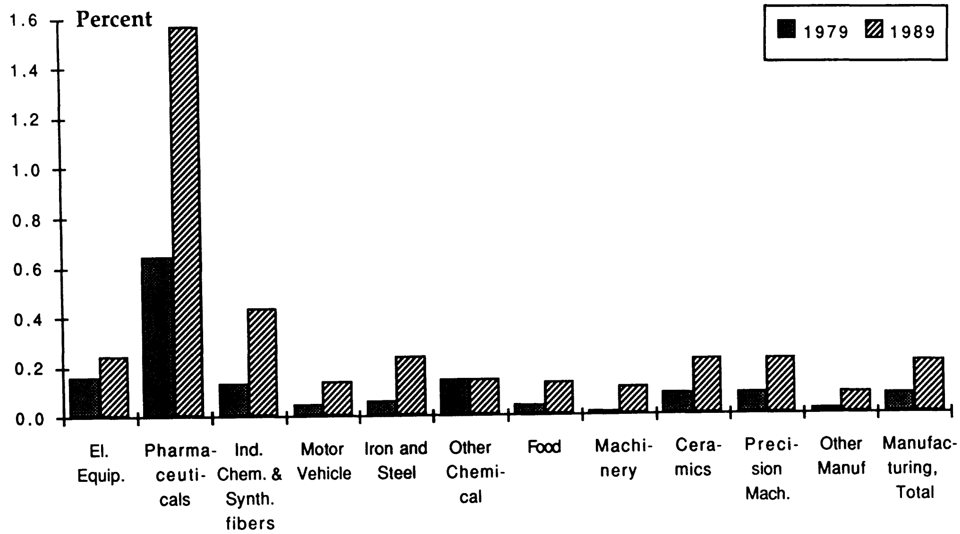

Figure 5. Basic research as a share of sales by industrial sector in Japan, 1979 and 1989. (*Source:* Statistics Bureau [10, 11])

The increase in R&D intensity is comparable to that in the electronics industry in the United States, but the sales growth has been faster in Japan, and there appears to have been a stronger commitment in Japan to expand basic research at the same rate as overall R&D.[14]

Economic Constraints on the Development of Research at Japanese Universities

A rather negative view is often expressed of Japanese universities by Japanese as well as foreign observers, although instances of positive testimony appear to be on the rise. One problem in evaluating the criticism often leveled at the research function of Japanese universities in particular is that, in order to provide arguments for budget requests, representatives of universities as well as public authorities have a stake in painting a picture of Japanese universities as being in a state of disrepair and hopelessly lacking in research funds. It needs to be remembered, however, that universities everywhere complain about a shortage of funds.

The best available source for comparing the amount of resources invested in university research in different countries is a study by Irvine, Martin, and Isard,[15] which looks at government funding of "academic and related research." Although governments dominate university research funding, for our purposes it is a weakness of this study that it does not also include information on private funding. This lack is especially significant for both the United States and Japan inasmuch as these two countries have a large number of private universities, which to an increasing extent rely on private funds in various forms and which in the United States are among the leading universities in terms of research. This weakness and the general problem of accurately distinguishing between resources being spent on education and research notwithstanding, the study provides a valuable basis for some international comparisons.

On a per capita basis, the Japanese university system as a whole does indeed seem to be undersized compared to those of the other countries studied (Fig. 6). There are, however, very large differences between fields. For example, Japan is up to par in engineering sciences, but allocates far fewer resources to other fields, such as the physical sciences, than most other countries.[16] In terms of research infrastructure for industrial technology the Japanese universities must, therefore, be said to be doing better than their reputation in terms of the resources that they command (see Fig. 7).[17]

Another indicator of the research capacity of Japanese universities is the training of research students. This is a role that traditionally has been thought to distinguish universities from other research environments and is therefore of special interest. Comparative data for the United States, Sweden, and Japan for engineering and physics and chemistry, respectively, clearly illustrate the difficulty Japanese universities are having in attracting doctoral students (Fig. 8), while statistics for the last few years show rapid growth in the number of students from other Asian countries enrolling in doctoral degree programs in Japanese engineering schools.

A special feature of the Japanese system is the so-called thesis doctorates, which are usually granted to researchers who have joined a company or research institute immediately after receiving a master's degree and subsequently done research work of a quality deemed sufficient for the award of a doctoral degree.

The research effort in the higher education sector in Japan is concentrated in fewer universities than in the United States. The distribution of granted doctoral degrees between universities can serve as an approximate indicator of the degree of concentration of university research in Japan (Figs. 9 and 10).

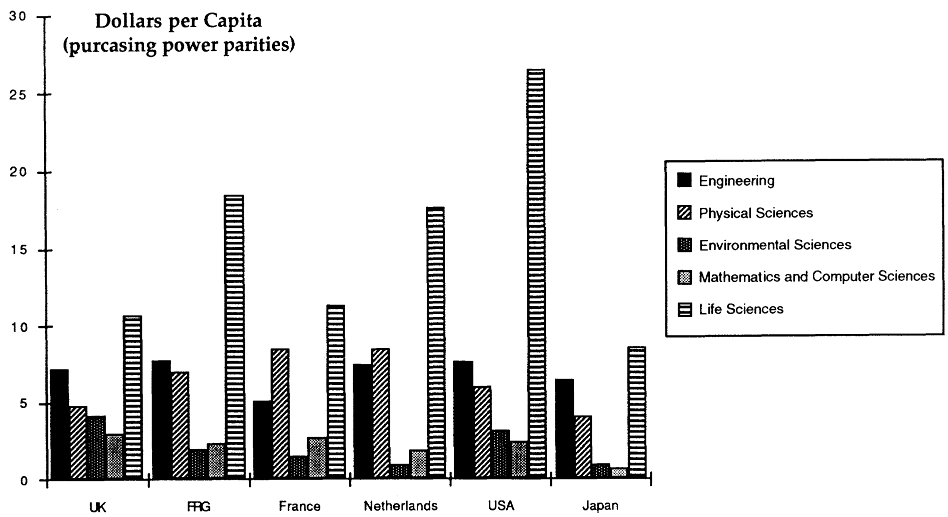

Figure 6. Government funding of research at universities in 1987. (*Source:* Irvine et al.[15])

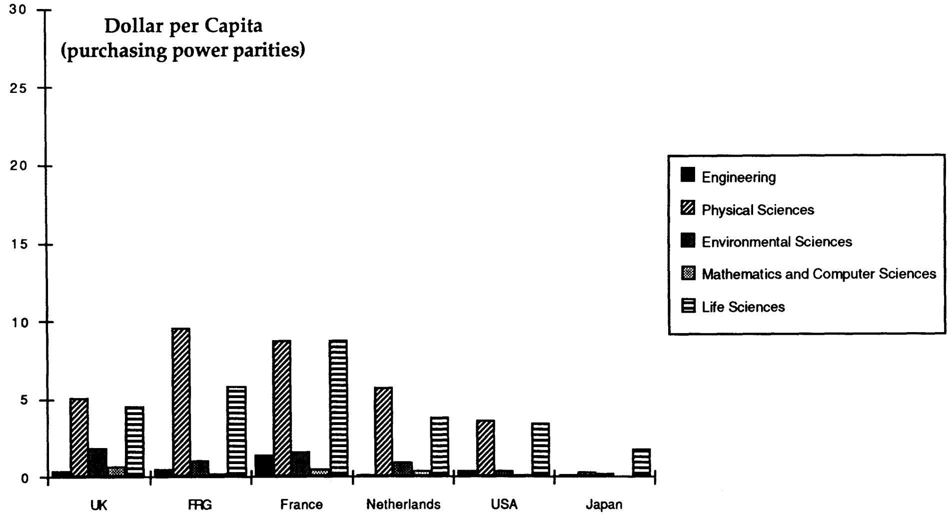

Figure 7. Government funding of academically related research outside universities in 1987. (*Source:* Irvine et al.[15])

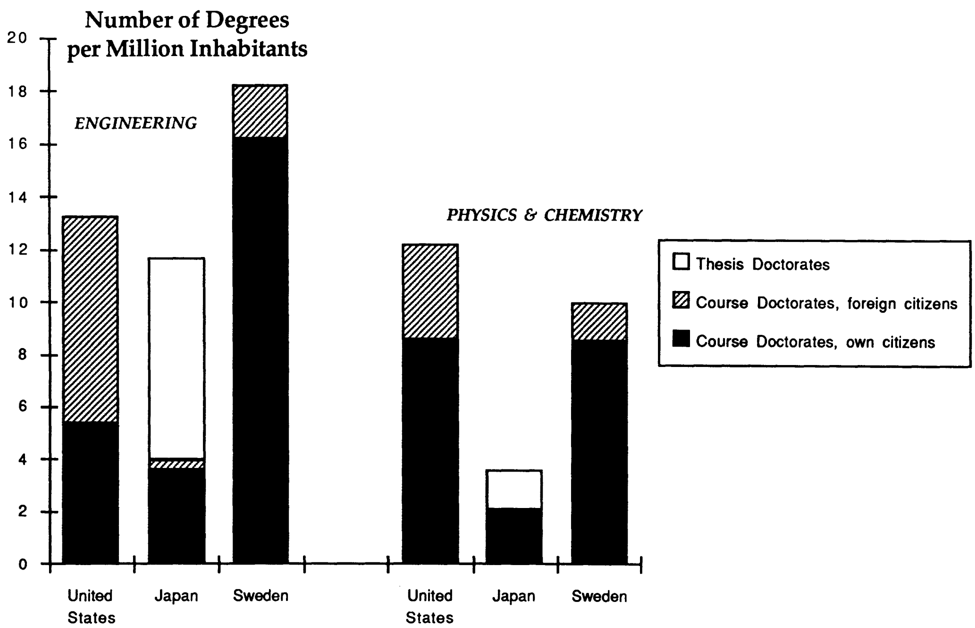

Figure 8. Doctoral degrees granted in the United States, Japan, and Sweden in 1985. (*Sources:* NSF,[18] Monbusho,[19] and Statistics Sweden[20])

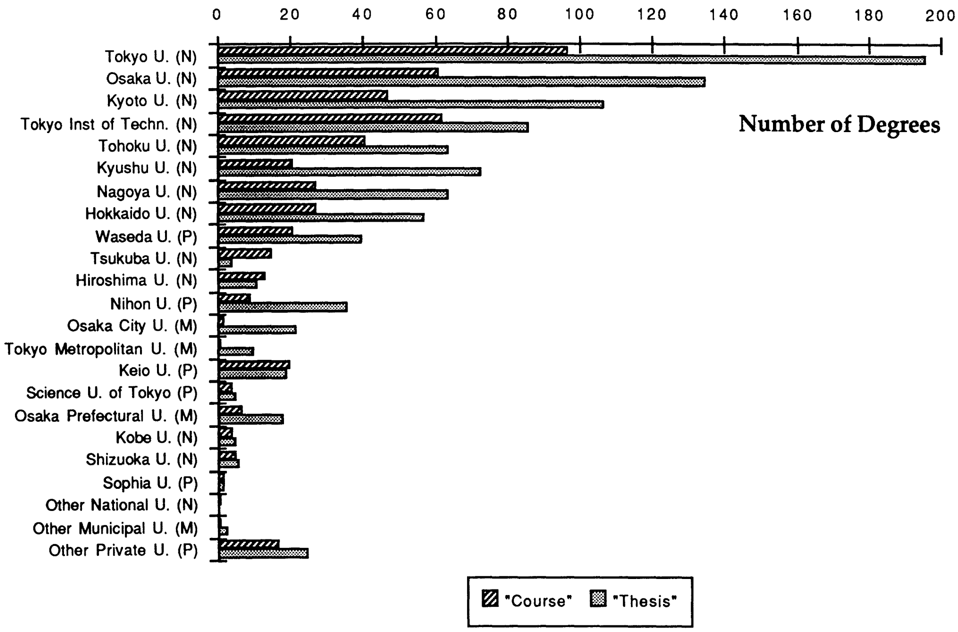

Figure 9. Doctoral degrees in engineering granted in Japan in 1986 by university. (*Sources:* Monbusho[19, 21])

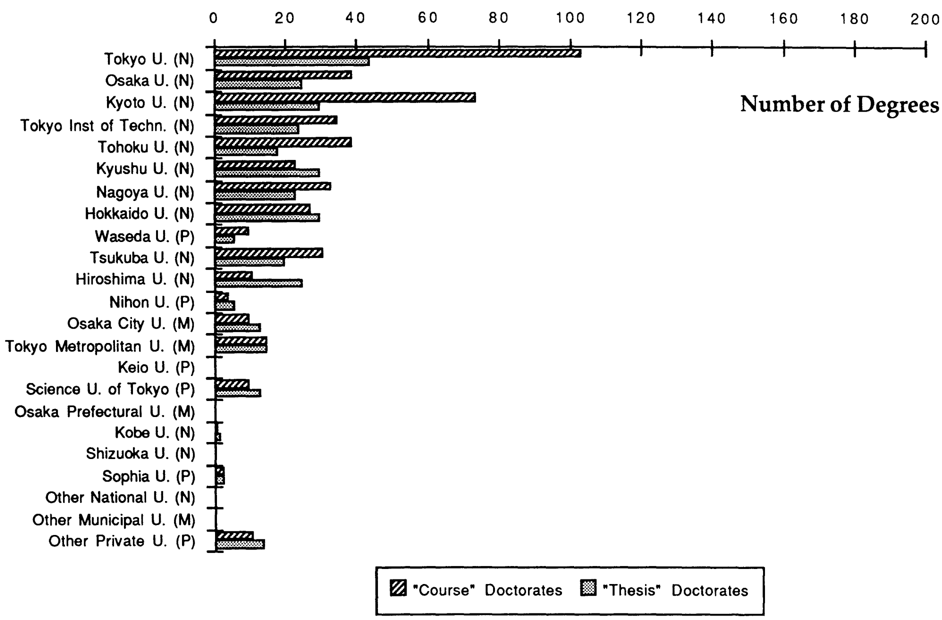

Figure 10. Doctoral degrees in physical sciences granted in Japan in 1986 by university. (*Sources:* Monbusho[19, 21])

The Case of Molecular Beam Epitaxy

In order to arrive at a better understanding of what factors are shaping the evolution of the Japanese research system and how these factors may be changing in their relative importance, a field at the intersection of science and technology was selected for detailed study. Molecular beam epitaxy (MBE), a technique for the highly controlled growth of crystals, represents a suitable case, being a fairly well-delineated field, attracting the attention of researchers in academic circles as well as in industry, and having a research community of manageable size for intensive study.

The approach taken was to study the evolution of the community of MBE researchers in Japan. Using bibliometric data, Japanese researchers active in the MBE field and the organizations for which they worked were identified for different time periods. Similar data were also gathered for other countries so that the institutional structure of the research communities in Japan could be compared with those in other countries. Information on the qualitative aspects of the development of MBE research in the leading Japanese organizations was obtained through interviews.

Research on MBE was started in the United States in the late 1960s by Arthur and Cho at Bell Labs. After technological breakthroughs around 1979 and 1980, which made possible the fabrication of high-quality lasers as well as the realization of the high electron mobility transistor (HEMT), the field grew very rapidly during the 1980s. The appearance of commercial MBE machines around 1980 and the subsequent improvement of their reliability and ease of operation have been crucial factors for the growth of the field. MBE technology, although used today for commercial production of HEMTs, lasers, and certain other devices by some firms, is still mainly used as a "research technology" for explorative studies of new artificially engineered materials and related new types of devices. Its main use is for the growth of semiconductor materials, but there are also examples of applications to high T_c superconducting materials and organic materials. MBE is one of several alternative techniques for epitaxial growth.

Comparing Research Systems Using Bibliometric Data

Figure 11 summarizes MBE publication data for Japanese organizations retrieved on-line from the Inspec database hosted by ESA-QUEST. Shown are the number of researchers who appear at least once, during the indicated three-year periods, as authors of publications considered to belong to the MBE field.[22] Each author was counted only once in each three-year period during which he or she published. The time periods refer to the time when the publications were indexed in the Inspec database.

Assuming that it takes, on average, one year for Inspec to index a publication and one to two years from the actual performance of a certain piece of research until it appears in a publication, Figure 11 can be roughly translated to represent the number of researchers involved in the performance of research during a certain time period by shifting each column one step to the left. Thus interpreted, Figure 11

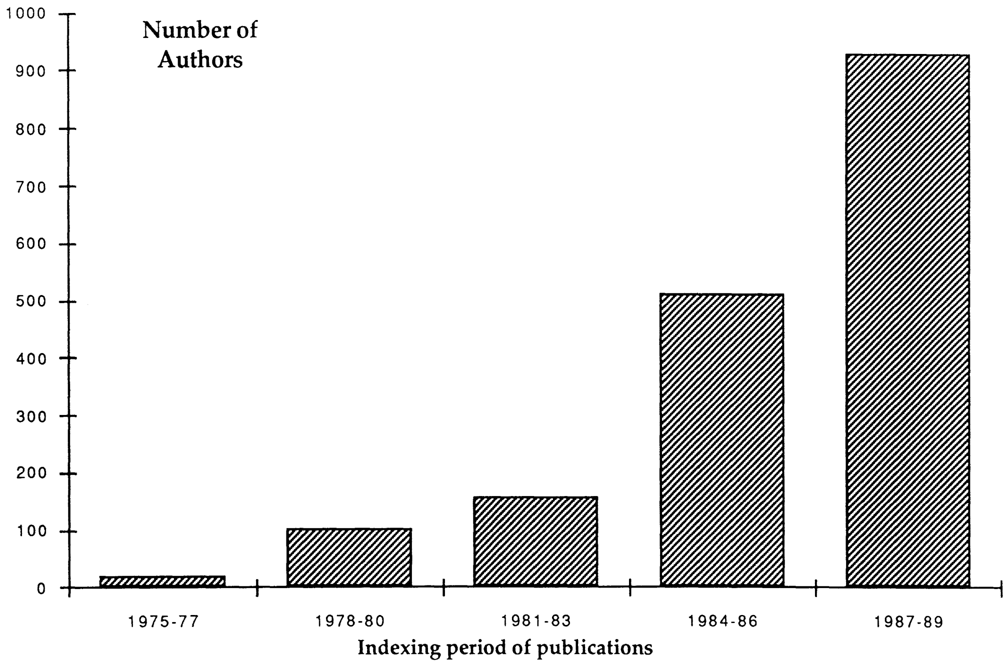

Figure 11. Number of Japanese researchers appearing as authors in the field of MBE. (*Source:* Raw data retrieved from on-line search in Inspec)

suggests that MBE research started in Japan on a very small scale during the period 1972–1974, and then expanded around the mid-1970s. This expansion seems to have run out of steam in the late 1970s, only to be followed by a new period of rapid growth in the early 1980s. Growth has continued after that, but at a slower rate. This development conforms well with the information obtained through interviews.

To give some impression of the variety of publication activity among different authors, Figure 12 distributes authors during each three-year period according to how many times they were published. During the 1980s around half the authors published only once in a three-year period, while around 30 percent published three or more papers during the same time. Combining Figures 11 and 12, it seems a reasonable estimate that in the mid-1980s the Japanese MBE research community comprised about 300 active researchers.

We will soon turn to a comparison of the institutional structure of the Japanese MBE research community with that in other countries. For this comparison we will have to rely on the number of publications instead of the number of authors as a measure of the size of the research effort.[23] This is certainly less than ideal. A comparison of the two types of data for Japanese organizations suggest, however, that there is a fair amount of correlation between the number of authors and the number of publications for the organizations most active in publishing. During the period 1987 to 1989, a weighted average for the ratio between number of authors and number of publications was around 1.5 in Japan. Of the top dozen organizations, ranked by number of authors, all except two had ratios in the range 1.0 to 1.75. The two ex-

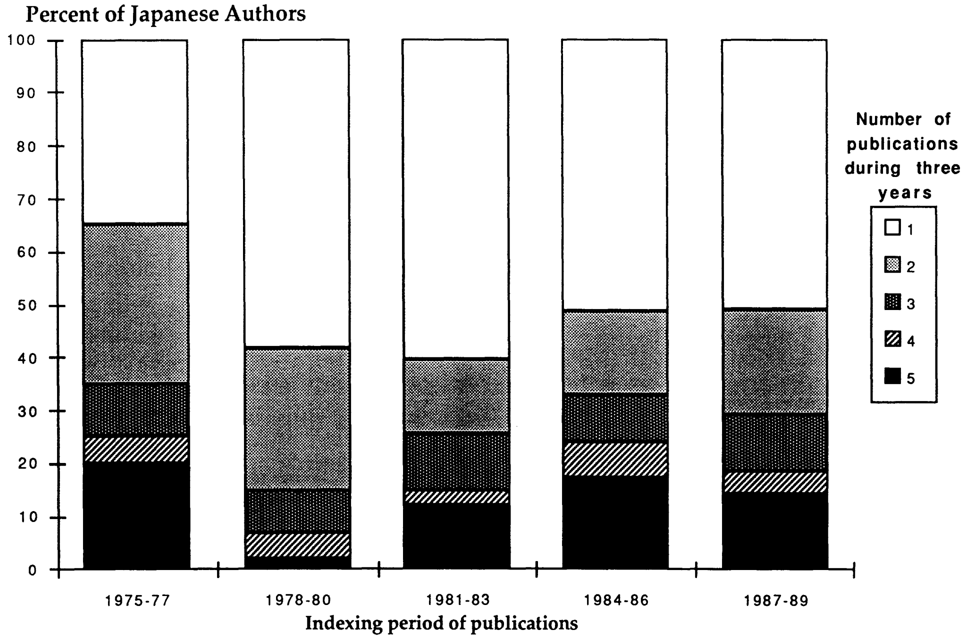

Figure 12. Distribution of Japanese authors in the field of MBE by number of papers published. (*Source:* Raw data retrieved from on-line search in Inspec)

ceptions had ratios of 2.3 and 3.1, respectively. Among organizations with fewer authors the variation was larger (Fig. 13). As long as interpretation of the data is restricted to identifying broad patterns of institutional structure and does not focus too much on individual organizations, data showing the number of publications should be acceptable as a rough proxy for the more direct measure using the number of researchers.

Of a total of some 6500 publications indexed in the Inspec database during the period 1969 to 1989, 48 and 19 percent came from organizations in the United States and Japan, respectively (Fig. 14). Overall, there has been a very rapid growth in MBE publications in all parts of the world. In absolute numbers most of that growth has occurred since the early 1980s. The growth was slower in Japan than elsewhere during the indexing period 1981 to 1983, and more rapid during the next three-year period. As explained earlier, publications indexed 1981–1983 correspond approximately to research done between 1978 and 1980.

In order to broadly compare the evolution of the MBE research communities in Japan, the United States, and the three largest western European countries in terms of R&D, each research organization was categorized into one of the following six groups:

- Telecommunications research organizations
- Three largest industrial firms in terms of total number of MBE publications (excluding those covered in the previous group)
- Other firms

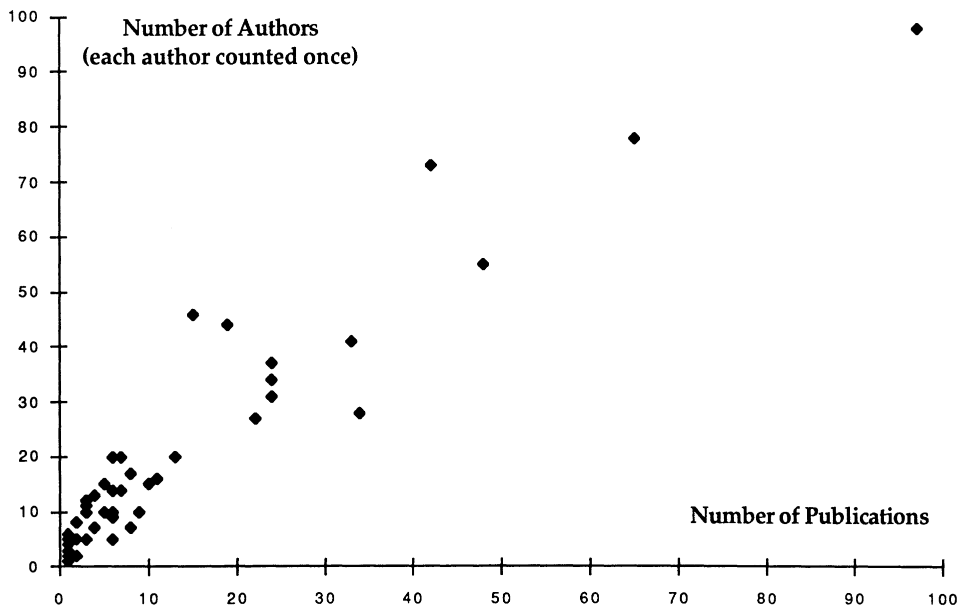

Figure 13. Number of publications versus number of authors for different Japanese organizations in the MBE field for the indexing period 1987–1989. (*Source:* Raw data retrieved from on-line search in Inspec)

- Government research laboratories/institutes and cooperative research organizations
- Three largest universities in terms of total number of MBE publications
- Other universities (and other higher education institutions)

Due to fundamental differences in the organization of research in the different countries, the six categories are not in all respects strictly comparable. As an example, in the United States, Japan, and the United Kingdom telecommunications research organizations have the legal status of companies, while the Bundespost in West Germany and the Centre National pour des Etudes de Telecommunication (CNET) in France are government research organizations. Also, AT&T differs somewhat from the telecommunications research organizations in the other countries in that it has a production arm.

Figures 15 and 16 show how the number of publications developed for each group over three-year periods in the United States and Japan, respectively. It should be noted that the scale for the United States is twice that for Japan, roughly corresponding to the ratio between the two countries' populations.

In the United States, Bell Labs and IBM pioneered the field, while in Japan the same role was played by the Electrotechnical Laboratory (ETL) and Tokyo Institute of Technology (TIT). However, NTT, the Japanese counterpart to Bell Labs, entered the field early on and expanded its activities rapidly to achieve the position of the largest Japanese organization in terms of MBE-related papers published. This is a position similar to that of Bell Labs in the United States. Fujitsu, the largest

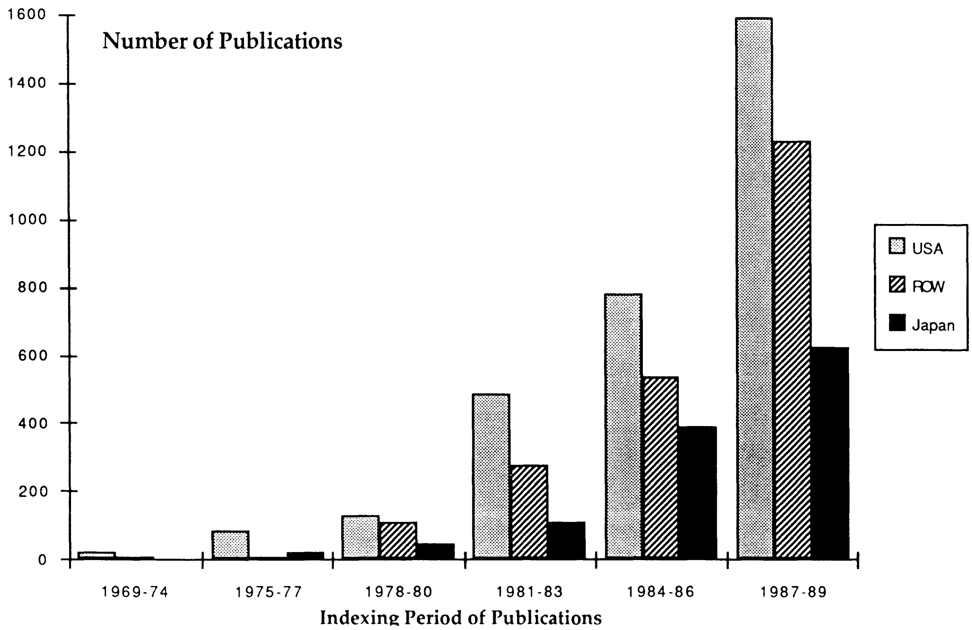

Figure 14. Distribution among the United States, Japan, and the rest of the world of publications in the field of MBE. (*Source:* Raw data retrieved from on-line search in Inspec)

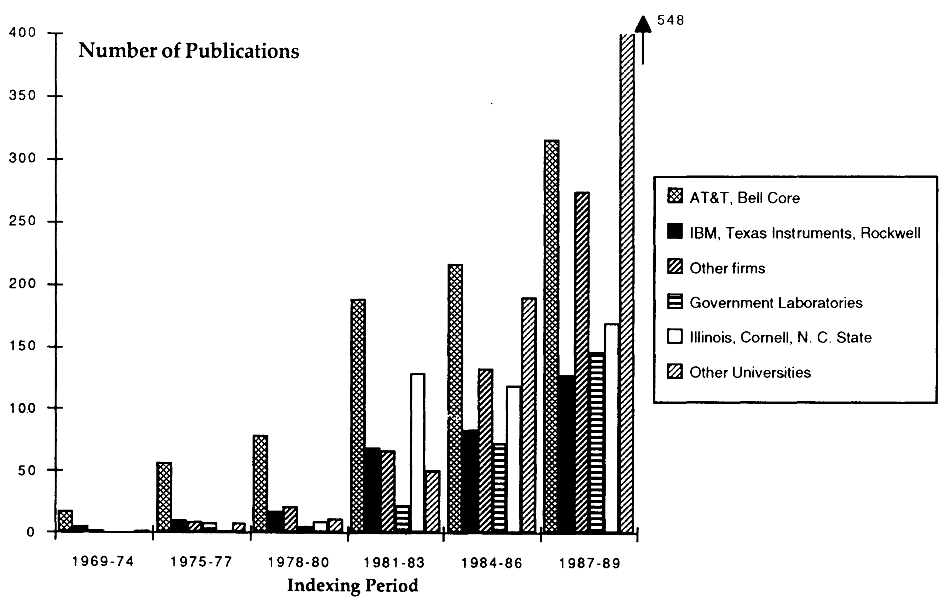

Figure 15. Distribution of publications in the field of MBE among organizations in the United States. (*Source:* Raw data retrieved from on-line search in Inspec)

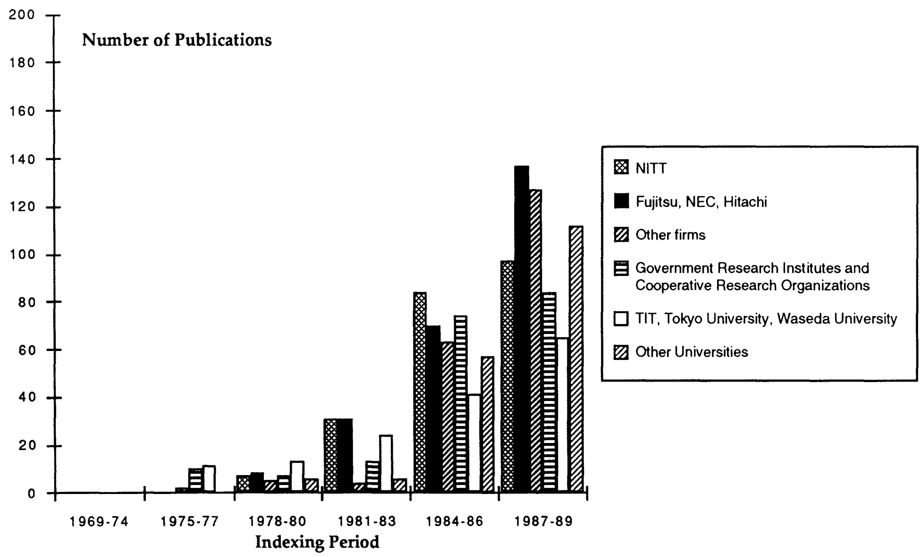

Figure 16. Distribution of publications in the field of MBE among orgfanizations in Japan. (*Source:* Raw data retrieved from on-line search in Inspec)

mainframe producer in Japan, also showed evidence of a strong capability at a fairly early stage, with the number of its papers published approaching that of IBM in the United States.

Judging from the publication data, universities initially played a more marginal role in the United States than in Japan, but developed a stronger presence from the early 1980s, first through a small core group and later including a very large number of universities. At the end of the period the relative role of the three leading universities in the field was similar in Japan and in the United States, while other universities represented a much stronger force in the United States than in Japan. In absolute terms the largest American universities published at more than twice the rate of the largest Japanese universities.

Research outside universities and the corporate sector has in Japan been mainly carried out by ETL and the Joint Optoelectronics Laboratory (OJL), the latter operating for only a six-year period. (Upon the dissolution of OJL, a new research cooperative, of different legal status and with different sources of funding, the Optoelectronics Technology Research Laboratory [OTL], was created.) It appears that ETL and the OJL played a relatively larger role in Japan than did the national laboratories in the United States. In absolute terms, however, the biggest government laboratories in the United States had about the same number of papers published as ETL and OJL during the period 1987 to 1989. No cooperative research organizations have been identified in the United States.

The telecommunications companies (Bell Labs, Bellcore, and NTT) aside, the top industrial companies in Japan almost reach the publication levels of their counterparts in the United States, but the number of companies in the United States is almost twice that of Japan. Predictably a large number of the American companies have their main business outside civilian electronics. Of the two leading manufacturers of MBE equipment in the United States, Varian and Perkin Elmer, Varian in particular had more papers published than their Japanese counterparts, Ulvac and Anelva.

Overall the research communities of the two countries exhibit rather similar development, with a strong concentration of only a few organizations during the 1970s, and then rapid growth in the 1980s in the number of organizations actively pursuing MBE research. On a per capita basis the Japanese business sector has a stronger publication record than its American counterpart, while the university sector is weaker. The leading Japanese industrial firms compare well with American firms even in absolute terms, while the same cannot be said for the universities.

If we compare what has just been described with developments in France, the United Kingdom, and West Germany (Figs. 17–19), the differences between Japan and the United States are in many respects smaller than are each of these countries' differences from the three West European countries.

The university sector in Japan, which among all the sectors exhibited the greatest difference from its counterpart in the United States, compares favorably with that in the European countries, falling somewhere between the United Kingdom and West Germany in terms of per capita publication counts and placing far ahead of France. In absolute numbers of papers published, the three largest Japanese universities had about 50 percent more than their counterparts in the United Kingdom and West Germany. One may therefore conclude that in the field of MBE, American universities are exceptionally strong and Japanese universities at least comparable to universities in the large European countries.

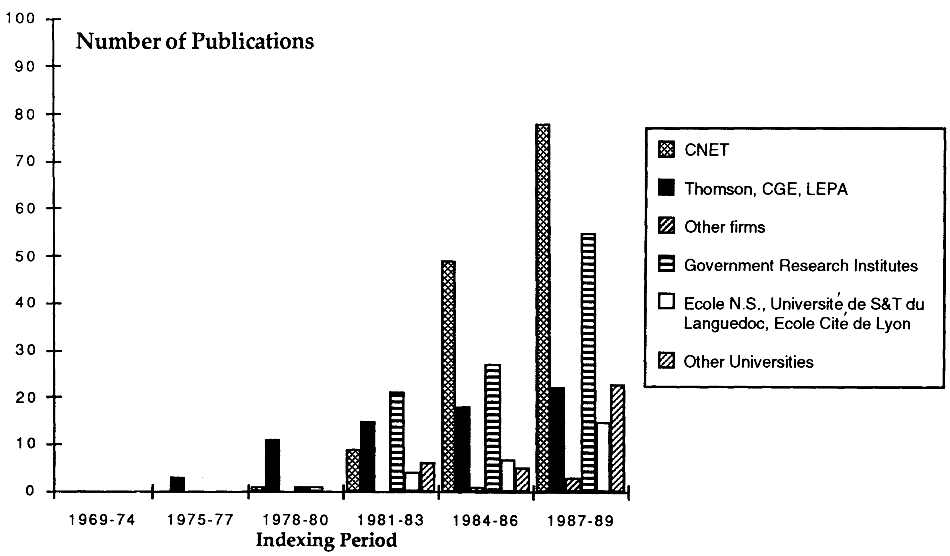

Figure 17. Distribution of publications in the field of MBE among organizations in France. (*Source:* Raw data retrieved from on-line search in Inspec)

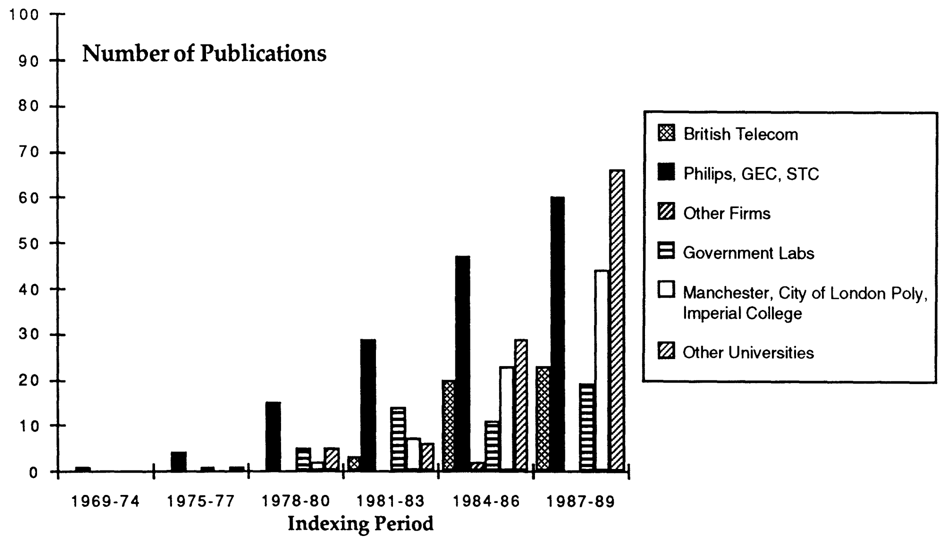

Figure 18. Distribution of publications in the field of MBE among organizations in the United Kingdom. (*Source:* Raw data retrieved from on-line search in Inspec)

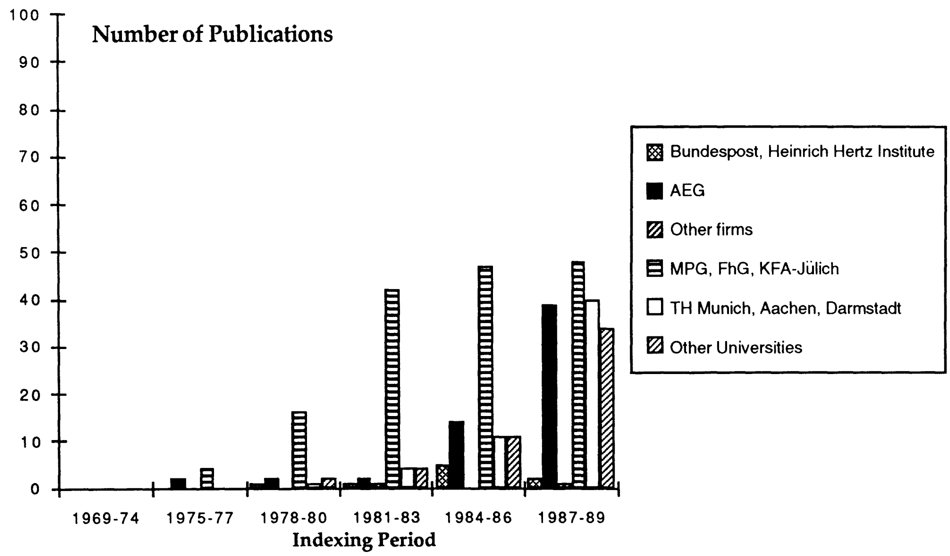

Figure 19. Distribution of publications in the field of MBE among organizations in West Germany. (*Source:* Raw data retrieved from on-line search in Inspec)

The weak showing of French universities is partly balanced by a large activity in government research institutes, most of which belong to the system of CNRS institutes, the major exception being LETI in Grenoble. West Germany also has a large institute sector. Until the latter half of the 1980s this sector was almost totally dominated by the Institute for Solid State Physics in Stuttgart, belonging to the Max

Planck Gesellschaft (MPG). This institute actually dominated the whole MBE research community in West Germany well into the 1980s. More recently the activity has broadened to other Max Planck institutes, some Fraunhofer Gesellschaft (FhG) institutes, and KFA in Jülich. In the United Kingdom only one government laboratory, the Royal Signals and Radar Establishment (RSRE), has published significantly in the MBE field.

Telecommunications research organizations stand out in France through the activities at CNET, which operates several laboratories in different locations. Its publication activity is about four times that of British Telecom, and on a per capita basis is comparable to that of AT&T and Bellcore combined. The Bundespost and the Heinrich Hertz Institute generate very few MBE publications, making West Germany an exception among the countries studied because it does not have a large MBE presence tied to telecommunications research.

The Western European countries most clearly set themselves apart from Japan and the United States by their rather narrow industrial participation in MBE. In West Germany MBE research in industry is concentrated to AEG, which has a strong research program in elemental semiconductor MBE. In France a smaller publication activity is divided rather evenly between Thomson and CGE. In the United Kingdom Philips started MBE research early and has more recently been joined by the GEC, both today publishing quite actively in the MBE field. Riber in France and Vacuum Generator in the United Kingdom are both world-class manufacturers of MBE equipment, but publish only very sporadically in the scientific and technical literature.

Both Japan and the United States thus seem to have better balanced MBE research systems than the large Western European countries in the sense that industrial companies are better represented in Japan and the United States.

If the large European countries have only one or two companies actively pursuing MBE research, smaller countries might be expected to lack significant corporate research altogether. When we compare the situation in the Netherlands, Switzerland, and Sweden (Fig. 20), we find that this expectation is only partly fulfilled, since all three countries have two or three research groups actively publishing in the MBE field. In the Netherlands and in Switzerland there is about equal contribution to the MBE literature from a single company on the one hand, and a number of publicly funded research organizations on the other, while in the Swedish case all the published papers come from technical universities. It is noteworthy that the technical universities in both Switzerland and Sweden reach a publication level only a little below the leading Japanese universities and are well in line with the leading universities in the larger European countries.

Toward a More Integrated Japanese Research System[24]

A striking feature of the evolution of the MBE field is that the early work was done primarily in industry, while the academic world only hesitatingly entered the field and then, with the exception of a small number of university research groups showing a more pioneering spirit, only after technological breakthroughs had been achieved in 1979.

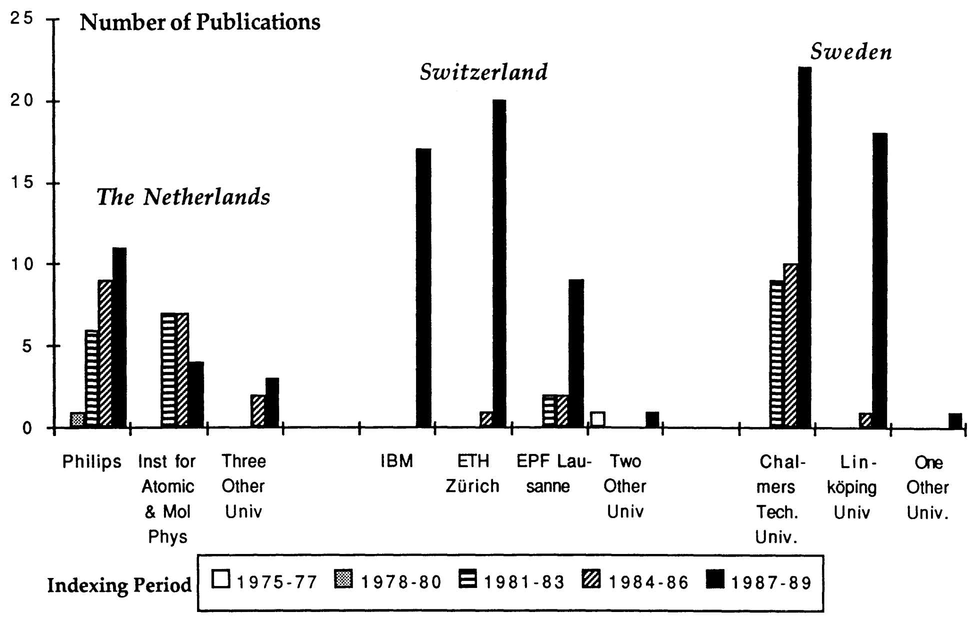

Figure 20. Distribution of publications in the field of MBE among organizations in the Netherlands, Switzerland, and Sweden. (*Source:* Raw data retrieved from on-line search in Inspec)

Also in Japan a handful of firms—Mitsubishi, Matsushita, Hitachi, Fujitsu, and NTT—became involved in MBE research fairly early, although ETL and a group under Professor Takahashi at the Tokyo Institute of Technology were the first to start such research. Around 1978, however, a widespread pessimism had developed in the Japanese MBE research community. The firms had grown increasingly impatient with the lack of substantial progress in making MBE a practical technology, and Mitsubishi and Matsushita were actually soon to discontinue their efforts. The same might also have happened at Fujitsu and Hitachi if the prospects of MBE technology had not suddenly become brighter. As a semipublic organization, NTT was in a special position and it had other main targets for its MBE research, in particular long-wave-length lasers for optical communication, so it is not surprising that it held out longer than the other firms.

Fujitsu played an important role in creating a brighter outlook for MBE through its invention of the HEMT, which was announced in 1980. Fujitsu was one of several organizations in the world working on the development of a new device based on the concept of modulation doping introduced by Dingle at Bell Labs in 1978. Through very effective collaboration between Dr. Mimura, an accomplished device physicist, and Dr. Hiyamizu, who led an MBE group that had accumulated several years of valuable experience in MBE growth of GaAs/GaAlAs heterostructures, Fujitsu was able to beat its competitors and secure a basic patent for the HEMT.

As a result of the HEMT patent, Fujitsu committed itself more strongly than the other Japanese electronics firms, excepting maybe NTT, to MBE technology. In addition to bringing the production of discrete HEMTs to commercial production, Fujitsu has invested considerable resources in R&D on HEMT ICs, and has also done considerable R&D on optoelectronic ICs (OEICs). In these efforts the company has received strong support from MITI as a participant in three of the latter's R&D programs, all started around 1980.[26]

During the 1970s, MITI encouraged MBE research in Japanese firms, mainly through financial support for the acquisition of MBE equipment. Through the almost simultaneous launching of three large R&D programs, which all had the development of MBE technology as an important component, MITI's involvement in this technology took on a totally different dimension. That the programs started about the time of the crucial breakthroughs in the technology is certainly an example of fortuitous timing.

Through the Superlattices Devices project, which was part of a larger research program[27] that was more exploratory in nature than previous research programs, MITI supported MBE research in three firms—Fujitsu, Hitachi, and Sumitomo Electric—in addition to providing a boost for MBE research at the ETL. The Supercomputer Project included support for MBE research at Fujitsu and Oki. The long-range horizon of both these projects, ten years for the former and eight for the latter, stimulated the participating firms to take a long-term view in the planning of their research, and thereby helped create very favorable working conditions for the researchers.

In the case of the OEIC project, the MBE work was done in the Optoelectronics Joint Research Laboratory (OJRL), which began its operation in 1981. Interest in MBE grew among the firms while the research program for the OJRL was being planned. While most industrial firms other than Fujitsu were still hesitant to invest their own funds heavily in MBE, they found it increasingly attractive to get a window on this technology through participation in joint research sponsored by the government. Soon the OJRL developed into a very well-equipped and productive environment for MBE research, with close links to a large number of firms built into the very structure of the organization.[28]

Together the OJRL and the ETL represented a very strong research infrastructure for the development of MBE research in the individual firms, and research managers at ETL played a decisive role in conceiving and launching the OEIC project and the OJRL. In terms of MBE the OJRL represented a more focused research effort than ETL, which pursued a wider range of topics. The two organizations' research was therefore complementary.

When the OJRL was discontinued upon completion of the OEIC project, 13 firms—all but two of which had been members of the OJRL—set up a new laboratory, the Optoelectronics Technology Research Laboratory (OTL), to continue joint research in largely the same field as the OJRL, including a major effort in MBE. Although this new joint laboratory gets most of its financing from the Japan Technology Center, which is a semigovernmental organization, it is legally a private enterprise.[29]

In retrospect the OJRL represented a crucial step in the development of cooperative research in Japan. By focusing on fundamental research topics it became possible for the OJRL to become a truly joint laboratory with very open communication between researchers from different firms. It was followed by what literally amounted to a wave of joint research laboratories, the OTL being only one of them. It should be noted that while the OJRL was to prove a very effective vehicle for raising the level of MBE research in Japan, its establishment was, at least initially, not favored by the leading semiconductor firms. They would have preferred that the government instead invest the money in the firms' own internal research efforts.

In the early 1980s only Fujitsu and NTT were strongly committed to invest their own funds in MBE research, and the two firms have since remained at the cutting edge of this field in Japan, more precisely the dominating III-V segment of it. In contrast, early research at Hitachi, Sumitomo Electric, and Oki seem to have relied significantly on moral and economic support from MITI, while other firms that began MBE research did so without any direct financial support from MITI. Mitsubishi Electric and Sanyo were among the earliest to start MBE research in "the second wave," focusing, respectively, primarily on III-V and II-VI optical devices. A large number of firms started MBE research around 1982/1984. NEC and Matsushita developed rather diverse research programs, with optical devices representing a minor part, while Sharp, Rohm, and Omron concentrated almost totally on the development of short-wave-length lasers. Sony and Toshiba, although engaging in MBE research, came to favor MOCVD as their technique of choice for high-quality epitaxial growth. In the latter part of the 1980s an additional 5 to 10 firms, some, for example Toyota, outside the electronics industry, have started MBE research for the most part on a limited scale.

Today's research problems are naturally not the same as those of a decade ago, but the spectrum of MBE R&D activities has broadened considerably both in the sense that a wider range of materials systems is being studied today and that R&D extends from very basic research on quantum effect devices to the development of more effective processes for the growth of materials used in the commercial production of devices. Some of the most challenging problems facing MBE researchers today are related to the fabrication of low-dimensional structures such as the so-called quantum wires and quantum dots, which is a field receiving a lot of attention but still waiting for a breakthrough. In some respects the situation resembles that of MBE growth of heterostructures in the late 1970s.

If anything, the commercial payoff is probably more uncertain now than it was then. That half a dozen or more Japanese electronic firms are nevertheless pursuing extensive research in the field of low-dimensional structures can be viewed as a concrete example of the growing commitment to basic research in Japanese industry. It is also an example of how it has become more costly to do leading-edge research. There are now several alternative epitaxial growth processes, and the number seems to continue to grow. Furthermore, the MBE machines are increasingly becoming part of larger and more complex UHV processing systems combining equipment for epitaxy, lithography, etching, implantation, and analysis. Investment in the necessary equipment has thus grown considerably, especially for those firms that are exploring several epitaxial growth techniques in parallel.

The role of government research support has less relative weight today than a decade ago, but is probably still of some importance, especially for the second-tier firms. On the government side, MITI is also less dominant. MITI's instruments remain pretty much the same as before, but on a smaller scale, and are now complemented by initiatives from other ministries, notably the Science and Technology Agency (STA) and the Ministry for Education, Science and Culture (Monbusho). While the operation of joint laboratories was regarded as a daring experiment in 1980, it is today a rather well-established practice, even if the system of their continued financing is still open to question.

As a consequence of trade disputes between Japan and the United States in the semiconductor field, MITI now has to proceed with some caution when providing research support to Japanese semiconductor firms. There is, of course, some research on low-dimensional structures at ETL. Such research is also carried out at the OTL, and on a smaller scale at the Advanced Telecommunications Research Laboratories (ATR), another joint research laboratory. Although OTL has a total of only 20 researchers, they are all looking at the problem of how to fabricate low-dimensional structures from different angles and have at their disposal a very generously and innovatively equipped laboratory. Its member companies, including those lacking significant in-house research in the field, therefore have a good window on the status of relevant technologies.

There will be some direct support for research in individual firms forthcoming under a new 10-year project on Quantum Functional Devices, which represents a follow-up of *two* earlier projects, the Superlattices Devices and the Three-Dimensional ICs projects. In planning this project MITI has been faced with a very different situation than when it planned the Superlattices Devices project 10 years earlier. The international trade frictions, already referred to, have forced MITI to consider the invitation of foreign firms to participate in the program.[30] On the home front STA and Monbusho have already started similar programs, making it harder for MITI to convince the Ministry of Finance that its program is really needed. Finally, the firms themselves are less and less in need of encouragement from MITI.

STA became an active supporter of basic research in the life and materials sciences during the 1980s. It promoted creative research by trying to increase the mobility between research organizations in Japan and by breaking up their rigid boundaries. Exploratory Research for Advanced Technology (ERATO), in operation since 1981 under the auspices of the Research and Development Corporation of Japan (JRDC), an agency under STA, and the Frontier Research Program (FRP), started in 1986 at the Institute of Physical and Chemical Research (RIKEN), are two schemes set up for this purpose. Significant projects on MBE-related research on low-dimensional structures have been started under both programs.

One ERATO project, the Quantum Wave Project, which aims at fabrication of materials and structures that will permit study of quantum wave effects, is conducted under the leadership of one of the foremost academic authorities of MBE in Japan, Professor Sakaki of Tokyo University. This project was started in 1988, with research performed at three locations: the Research Center for Advanced Science and Technology (RCAST) of Tokyo University, NEC's Tsukuba Research Laboratories, and Matsushita Giken, which is also in the Tokyo area. Two other ERATO projects, this time under the direction of Professor Nishizawa of Tohoku University, have also explored advanced epitaxial growth techniques, although in this case procedures other than MBE were used. The Laboratory for Quantum Materials at RIKEN was one of the first laboratories to be established under the FRP, and it has been deeply involved in growing very high-quality crystals using MBE and other advanced epitaxial growth techniques.

In the previously mentioned STA schemes, the research staffs were recruited from different places for temporary assignment to the various projects and laboratories. For researchers from companies this normally means, as in the case of joint research laboratories like the OJRL and the OTL, that the researchers are on leave from their firms for a period, the length of which may be for the whole project or for a shorter period. At the same time, a similar arrangement has been much more difficult to realize for researchers with permanent employment at national universities or national research institutes. Both the ERATO and FRP projects, however, have succeeded in recruiting newly graduated doctorates and have thereby taken the first steps toward establishing a system of postdoctoral appointments that barely existed previously in Japan but is common in many other countries. Special efforts have also been made to recruit foreign researchers.

STA is charged with the responsibility of coordinating the government's science and technology policy, except for those parts relating to the higher education sector. The initiatives mentioned, as well as others, for example, research support through the Special Coordination Funds for Promoting Science and Technology, do indeed appear to serve the useful function of stimulating the expansion of the Japanese research system and increasing the mobility and communication between its different sectors. Traditional career paths and employment practices are definitely hindering an effective integration of the Japanese research system, but barriers are coming down. The practice of lifelong employment, although it obviously limits permanent changes in employment, may in fact present some advantages for the temporary shifting of research staff, as with the dispatching of researchers from firms to joint research laboratories or to universities. So far, this opportunity has not been widely utilized for public sector employees at universities or institutes, but this probably could be changed without tinkering in any fundamental way with the system of lifelong employment.

When comparing the situation before and immediately after the sudden increase in MBE research in the early 1980s with the recent conditions pertaining to research on low-dimensional structures, it appears that universities have strengthened their relative position. For example, the number of university groups involved in research on low-dimensional structures is quite large, while until the mid-1980s only half a dozen universities were doing significant MBE research in Japan. One reason for this increase in academic interest is simply that the research questions have become recognized as scientifically more challenging, and that their exploration requires a broader spectrum of scientific and technical expertise than the problems posed by the desire to grow heterostructures by MBE. Many alternative technologies—each one often drawing on a combination of several basic technologies—for fabrication of low-dimensional structures are still being explored, but so far there is no obvious winning candidate. Device concepts based on the use of low-dimensional structures are likely to represent a radical departure from existing types of devices, necessitating the development of a whole new set of concepts and theories, sometimes referred to as "mesoscopic electronics."

Theoretical work has thus become more important, as has interdisciplinary research, but universities will tend to be in a particularly strong position for the former. Universities also have a great potential for interdisciplinary work, but the realization of this potential usually requires special organizational efforts. Developments in university research funding and organization in Japan during the last decade have been supportive of interdisciplinary research. First there has been a trend, as in many other countries, to concentrate research facilities in "centers" that serve several departments and sometimes even several universities. This arrangement allows a pooling both of economic resources, which makes it easier to acquire costly equipment such as MBE machines and other semiconductor processing and analysis equipment, and of human resources, which increases the breadth of expertise that can be brought to bear on a particular research problem. Second, special research programs focusing on certain problems, but still basic in nature, have been launched with support from Monbusho and have had as their objective the combining of the resources of many research groups. One program, "Basic Studies on Electron Wave Interference Effects in Mesoscopic Structures," begun in 1990 under the leadership of Professor Namba, director of the Research Center for Extreme Materials at Osaka University, is a particularly interesting case in the context of research on low-dimensional structures.

The high cost of purchasing MBE equipment was probably one of the, if not the, most important reasons that MBE research developed more slowly at universities than it did in firms. Although industrial research laboratories still tend to be much better equipped than those at universities, the improvements in university equipment funding that occurred during the 1980s appear to have made the availability of equipment much less of a decisive bottleneck for university research than before. In addition to the previously mentioned trend toward a greater use of research centers and the like, a higher degree of selectivity has also been introduced in the allocation of research grants. For example, under a grants-in-aid program for "specially promoted distinguished research" introduced in the early 1980s, at least four university researchers obtained grants that were used to acquire new MBE systems.[18]

As already indicated, research on low-dimensional structures may require rather complex configurations of epitaxial growing, processing, and analysis equipment. Even if this raises the cost of equipment very significantly in comparison to a stand-alone MBE machine, and is likely to make it difficult for many academic research groups to participate in the research, several groups have already been able to acquire such equipment.

Research staff, and especially doctoral students, may be a scarcer resource for university research than funding. Generally speaking, Japanese universities have experienced great difficulty in attracting doctoral students. This, of course, limits the research capacity of universities and, some may argue, results in an inadequate supply of research manpower to industry. Traditionally universities have been thought to have a unique role in combining research and advanced research training. A closer look at the MBE case, however, presents us with a much more complex picture of alternative ways of training researchers, among which university doctoral studies represent only one possibility.

During the first phase of MBE research at Japanese firms in the 1970s, each company had to develop its own competence internally, since there was no opportunity to hire outside researchers already experienced in the field. There was some exchange of experience at conferences and through an informal group organized by Dr. Gonda at ETL, and there was some input from the scientific literature.

By the time industry expanded its MBE research in the early 1980s the situation had not changed very much. There was still very little university research in this area, and only a few doctoral graduates had taken up research in industry by then, primarily from Professor Takahashi's group at the Tokyo Institute of Technology. Only during the latter part of the 1980s did universities begin to supply doctoral students experienced in MBE to industry in any significant way, but still in rather small numbers and mainly from three groups.

The number of doctoral degrees granted for research in the field of MBE by 1990 was estimated through a combination of bibliometric searches and interviews for six leading and early established university research groups. A total of almost 30 doctoral degrees were granted for MBE research in these groups, just over half of which went to students in the two groups at the Tokyo Institute of Technology; the rest were divided equally between students at Tokyo University and the remaining three universities taken together. Around 20 of these graduates are continuing MBE research, and half of them—about ten researchers—are working in companies. Other universities may have contributed some additional doctoral degrees, but probably very few.

In a new field, such as MBE, wherein universities are actually lagging behind industry in acquiring experience, it becomes very difficult for universities to respond to industry's need for research manpower. In such a situation a joint research laboratory is a very interesting solution to the need to rapidly expand the training of researchers. The OJRL shows that under a small group of experienced scientists it is possible to develop very successful research in a new field, and, in the process of doing so, to train young researchers in that field. None of the researchers recruited by that laboratory had any previous experience with MBE. In 1990 approximately ten researchers were actively pursuing MBE research after having returned to their companies. Twenty researchers are currently working in the OTL, which can be seen as continuing the educational mission of the OJRL. In many respects the laboratories operating under the ERATO and FRP programs serve a similar function.

The rapid growth in the number of thesis doctorates awarded in engineering indicates that a large and growing portion of advanced research training is occurring "on the job" in corporate research laboratories (Fig. 21). In quantitative terms this has been by far the most important mode of research training for industry in the MBE field. The backgrounds of the pioneers of MBE in Japanese industry vary, but most of them already had research experience from some other field and some had previously obtained a course doctorate. It should also be mentioned that it is fairly common for firms to send their young researchers to a Japanese or foreign university for one or two years as special students. Some examples of this were encountered in the MBE field.

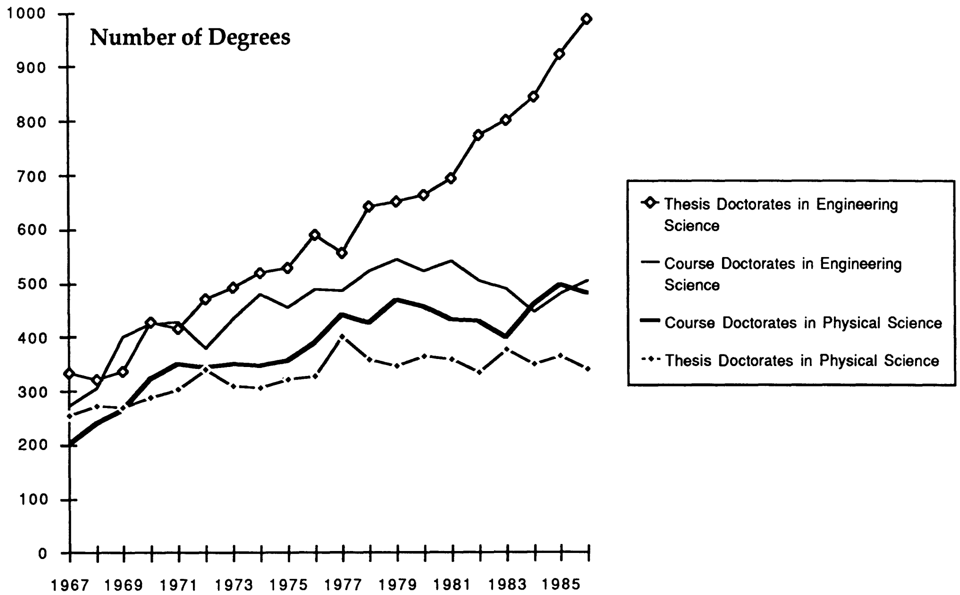

Figure 21. Doctoral degrees granted in Japan in 1967–1986 in the physical sciences and engineering. (*Sources:* Shigen Chosa Sho[32] and Monbusho[19, 21])

There is of course no simple way of comparing the research experience obtained from doctoral studies with that of working in a joint research laboratory or the like, but considering that research at the latter tends to be at the cutting edge, one probably should not assume that research training in the joint laboratories is necessarily inferior to that of doctoral studies. On-the-job research training in a company can be a somewhat more narrow experience, since it takes place in a more homogeneous environment. A period as a special student can counteract this by broadening their horizons. These comments on research training are only suggestions and need further support for any stricter claim to validity. They do show, however, that the whole question of the institutional framework for research training needs to be looked at with fresh eyes.

A recent and very important development is that several of the top MBE researchers in industry and at ETL have been recruited as professors to establish new university research groups. The most striking instance is Osaka University, which during a short period has hired no less than four prominent MBE researchers, one each from Fujitsu, Hitachi/OJRL, NTT, and ETL. Similarly, Tokyo and Hiroshima Universities have hired leading researchers from Hitachi and ETL, respectively. In a very concrete way this illustrates how basic research competence acquired in a new field in industrial laboratories is fed into the university research system, thereby allowing the areas of knowledge opened up by industry to be consolidated and further deepened. This transfer of competence from industry to academe has the effect of both bringing the research level of universities up to par with that of industry and improving the conditions of communication between academic and industrial research. The described development is unique neither to Japan nor to the field of MBE, but appears to apply to much of electronics research in a number of countries.

Conclusions

The Japanese research system has been characterized by a high degree of rigidity and segmentation. Career systems, employment practices, and anxious guarding of jurisdictional boundaries between ministries have contributed to limited communication and infrequent mobility of researchers across institutional boundaries. Other factors relating to the nature of the research have further amplified these tendencies. For one thing, each institution has usually learned more from contacts with foreign groups than from domestic contacts. Industry, busy catching up with Western technology, has had limited interest in the research being done at Japanese universities, especially since the latter have themselves been trying to catch up with the West in their more academic realms.

Of course, integrating factors have not been totally absent. National laboratories, especially those under MITI, such as the ETL, have played an important role as focal points and communication centers for the exploration of new technologies first developed abroad. The various R&D programs launched by MITI also served to conserve scarce resources and foster the exchange of technological knowledge among firms. Initially, the conception and management of these programs depended heavily on the technological expertise of the national laboratories. Through the emergence of a system of joint research laboratories, however, the coordinating and focusing role of the national laboratories has been challenged.

Although direct research cooperation between industry and universities has been very limited and still needs to be improved, two types of relations, which appear more advanced in Japan than elsewhere, have existed to support communication between these two arenas. One is the very close relations between university professors and their students, which are usually maintained long after graduation. The other is the firms' practice of sending young researchers as special students to universities in Japan or abroad.

As the relative level of science and technology in Japan has progressed in comparison to the rest of the world, the benefits to be gained from domestic mobility, communication, and cooperation are growing. The fact that Japanese industry is advancing to a leading position in many fields of technology is fostering a stronger commitment to basic research in all parts of the Japanese research system. Japanese firms have shown themselves willing to allocate a small, but valuable, part of their rapidly growing R&D budgets to long-term explorative research. The aggressive investment in new technology by these firms makes it natural for the government to increasingly focus its scarce resources on long-term research and high-risk noncommercial technological development.

As a result, Japanese research organizations that belong to different sectors are developing increasingly overlapping interests at the basic research end of the R&D spectrum. Even within the existing institutional framework, this stimulates competition as well as communication and cooperation between research groups in different sectors. Competition can be expected to enhance the quality level of the research. Efforts to develop cooperation that come up against institutional obstacles will create pressure for institutional reform and innovation to overcome them. Such institutional changes are clearly already underway, but the process has only recently been started, so most of the changes are still to come.

Great uncertainty still remains about the future institutional shape of the Japanese research infrastructure in fields relevant to the development of industrial technology. Thus, the extent to which ministries other than Monbusho will be able to fund research in universities will be of vital importance and will strongly affect the resources available to universities, the extent to which extrauniversity research organizations will be augmented, and the kind of cooperative arrangements that can be reached between these organizations and universities. As long as MITI, STA, and other ministries are effectively barred from providing significant research funds to universities, they have to channel their funds to other organizations such as individual firms, national laboratories, or other nonuniversity organizations.

For some time there has been a cap on personnel growth in national laboratories and there is little reason to believe that this cap will be lifted. If Monbusho retains its virtual monopoly of government funding of university research, research funds from other ministries will have to be channelled to firms or to nongovernmental, nonuniversity laboratories. If, on the other hand, these other ministries were free to fund university research, the picture could change dramatically. In that case, the future development of joint research of the kind currently supported by, for example, the Japan Key Tech Center could also be affected. Reallocation of such research to universities along models common in the United States would then become possible. The long-term sustenance of joint research laboratories is, in any case, open to question, considering that the system for financing them is still in many ways a temporary one.

The ability of universities to attract doctoral students may be the most crucial factor affecting their future position in the Japanese research system. In this respect, universities face a very difficult situation, since there is currently a shortage of researchers in Japan. As a result, firms are forced to outbid each other in trying to recruit fresh masters degree recipients. At the same time, the economic conditions for doctoral students are poor. It would not take enormous resources to change the latter condition, however, and the leading engineering schools are currently trying to convince industry to donate money for stipends for doctoral students. An alternative or a complementary approach being discussed is for companies to encourage researchers to pursue some of their research at the universities and to make this a condition for the granting of thesis doctoral degrees.

The practice of lifelong employment is a key factor behind the readiness of Japanese firms to commit resources to basic research. A very important result of basic research is the development of competence on the part of the researchers. One consequence of lifelong employment is that Japanese firms can be confident that they will be able to reap the full benefit of the competence thus acquired by their researchers. An added result is that the firms are prepared to provide much of the training for their researchers either in-house, or externally in joint research laboratories, or through their assignment to universities as special students. Were the employment system to change in a way that drastically increased the mobility of researchers among organizations, the basis for Japanese firms' heavy investment in long-term research and competence development might well be undercut, leading to a higher value being placed on doctoral-level research training at universities. Even without such a change, the increasing emphasis on "original and creative research" could in itself increase the demand that researchers develop more varied viewpoints by working in a wider range of environments, universities being prime candidates.

The challenges facing Japanese universities differ in intensity rather than in character from those facing academic research elsewhere in the world. This forces Japanese universities, which in many respects are very traditional, to be particularly innovative in defining their unique contribution to the Japanese research system.

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Notes

1. The results of long-term research in firms are often shared rather openly with outside researchers, which justifies identifying corporate research, at least partly, as part of the research infrastructure.
2. Jonah D. Levy and Richard J. Samuels, *Institutions and Innovation: Research Collaboration as Technology Strategy in Japan* (Cambridge, Mass.: Dept. of Political Science, M.I.T., April 1989).
3. Statistics Bureau, Management and Coordination Agency, Japan, *Kagaku Gijutsu Kenkyu Chosa Sogo Hokokusho* (Tokyo, March 1986).
4. Statistics Bureau, Management and Coordination Agency, Japan, *Report on the Survey of Research and Development 1985* (Tokyo, March 1986).
5. Statistics Bureau, Management and Coordination Agency, Japan, *Report on the Survey of Research and Development 1986* (Tokyo, March 1987).
6. Statistics Bureau, Management and Coordination Agency, Japan, *Report on the Survey of Research and Development 1987* (Tokyo, March 1988).
7. Statistics Bureau, Management and Coordination Agency, Japan, *Report on the Survey of Research and Development 1988* (Tokyo, March 1989).
8. Kenneth Flamm, *Targeting the Computer* (Washington, D.C.: The Brookings Institution, 1987).

9. This consensus is well articulated by the Council for Science and Technology.
10. Statistics Bureau, Management and Coordination Agency, Japan, *Report on the Survey of Research and Development 1989* (Tokyo, March 1990).
11. Statistics Bureau, Management and Coordination Agency, Japan, *Report on the Survey of Research and Development 1980* (Tokyo, March 1981).
12. Nathan Rosenberg, "Why do firms do basic research (with their own money)?" in *Research Policy,* Vol. 19, 1990, pp. 165–174.
13. These estimates are based on the assumption that R&D expenditure per employed researcher is the same for different types of R&D in the electrical equipment industry.
14. The numbers just quoted should of course only be considered as rough indicators. The definitional problems surrounding basic research in industry are so large that NSF in recent years only reluctantly has published such data for the United States. It seems, however reasonable to assume, that there has at least been some consistency in the way the concept of basic research has been interpreted by those answering surveys of R&D, whatever objections one might have to those interpretations.
15. John Irvine, Ben R. Martin, and Phoebe A. Isard, *Investing in the Future. An International Comparison of Government Funding of Academic and Related Research* (Aldershot, England: Edward Elgar, 1990).
16. It should be noted that the comparisons are based on currency translations using purchasing power parities rather than market exchange rates. For Japan the dollar amounts would be almost 50 percent higher if exchange rates were used instead.
17. Governments also provide funding of basic research at research institutions other than universities. Irvine et al. have selected certain institutions as qualifying for the category of "academically related research." It appears, however, that this selection has a bias against the engineering sciences. For example, none of MITI's institutes are included, although an institution such as the Electrotechnical laboratory (ETL) most definitely must be regarded as performing a large amount of quite basic research. The issue of government funding of basic technology research outside universities is thus not settled by this study. As far as the physical and life sciences are concerned, the inclusion of academically related research outside universities lends further support to the view that government funded research in these fields is smaller in Japan than elsewhere.
18. National Science Foundation (NSF), *Science and Engineering Doctorates: 1960–88* (Washington, D.C., 1989).
19. Monbusho, "Daigaku Shiryo," No. 101 (Tokyo, 1987).
20. Statistics Sweden, *Utbildningsstatistisk årsbok 1986* (Stockholm, 1986).
21. Monbusho, "Daigaku Shiryo," No. 109 (Tokyo, 1988).
22. Molecular beam epitaxial growth was introduced as a "controlled term" in the INSPEC database in 1979. In order to capture MBE publications prior to 1979 the search was designed to include MBE and alternative expressions as "uncontrolled terms." The publication set thus obtained was for the period 1979–1989 in the case of Japan, and was about 40 percent larger than that retrieved using the controlled term and 50 percent larger than for all countries taken together. An additional reason for choosing a generous search strategy was the fact that the data were used to identify as many organizations with any degree of involvement in MBE research as possible.
23. With the search techniques used it was much less time-consuming to count the number of publications per organization than the number of authors.
24. The case is developed in more detail in Stenberg 25.

25. Lennart Stenberg, "Molecular Beam Epitaxy—A Mesoview of Japanese Research Organization," in *Dynamics of Science Based Innovation*, ed. Hariolf Grupp (Heidelberg: Springer-Verlag, 1992).
26. The three programs are "Optical Measurement and Control System" (often referred to as the OEIC project) (1979–1985), "High Speed Computing System for Scientific and Technological Uses" (often referred to as the Supercomputer Project) (1981–1989) and "The Superlattices Devices Project" (1981–1990).
27. "Research and Development Project on Basic Technologies for Future Industries."
28. Fujitsu, Hitachi, Mitsubishi Electric, NEC, Toshiba, Furukawa Electric, Matsushita, Oki, and Sumitomo Electric all sent research staff to the OJRL, and the five first firms, occupying a leading role in the OEIC project, each furnished the OJRL with a research group leader. An additional six firms were members of the OJRL without sending any researchers.
29. The Japan Key Technology Center, operated under the joint supervision of MITI and the Ministry of Post and Telecommunication, was set up in the mid-1980s with a major portion of its capital made up of dividends from government ownership of NTT shares. It invests up to 70 percent of the capital needed by new joint research laboratories.
30. The decision to open MITI's programs to foreign firms has also lead to a transfer of the management responsibility for these programs from the Agency for Industrial Science and Technology (AIST) to a revamped NEDO, a semiprivate organization. As of early 1992, of a total of eight firms applying for participation in the program, two were non-Japanese.
31. In 1990 a total of at least 35 different research groups at 25 to 30 universities in Japan may have actively pursued MBE research.
32. Shigen Chosa Sho (National Institute of Resources), *Kagaku Gijutsu Shihyo no Kaihatsu ni Kansuru Kiso Chosa* (Basic study regarding the development of science and technology indicators) (Tokyo: Science and Technology Agency [STA], October 1987).
33. The Council for Science and Technology, "Recommendation of the Council for Science and Technology on the 11th Inquiry Titled 'Comprehensive Fundamental Policy for Promotion of Science and Technology from the Long-term View' " (Transl.) (Japan, November 1984).