Articles

The Growth of Japanese Science and Technology

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Several measures are used to delineate the remarkable growth in the Japanese technological position over the last decade. The share of U.S. patents issued to Japanese inventors has been rising at 1 percent per year. These patents are the most frequently cited patents in the U.S. system. By 1984, Japanese inventors obtained more U.S. patents than inventors in the United Kingdom, France, and West Germany combined, and the gap has been widening ever since. As measured by publications, the Japanese scientific position is more modest, with a 0.5 percent rise per year in papers and with barely average citation performance. These indicators characterize Japan as a technological powerhouse, with highly innovative technology, and an expanding but far less powerful scientific position.

WHEN FUTURE GENERATIONS OF HISTORIANS LOOK BACK on the second half of the 20th century, one of the most significant historical developments they are likely to identify will be the phenomenal growth of Japanese economic strength. In the relatively short period of four decades, Japan has grown from modest economic means to become the second most powerful economic entity in the world. Historians will note that this growth was based not on the acquisition of territory or natural resources, but on the wise acquisition and employment of technology.

In this article we examine the growth of Japanese technology and science in recent years. We have taken an empirical approach, focusing on five quantitative indicators of technological and scientific capacity: the number of U.S. patents held by Japanese inventors (a measure of Japanese technological size); the extent to which these patents are cited by other patents (a measure of Japanese technological impact); the extent to which these patents cite the nonpatent literature (a measure of the linkage of Japanese technology to science); the number of Japanese papers published in the world's mainstream scientific literature (a measure of Japanese scientific size); and the extent to which these papers are cited in the literature (a measure of Japanese scientific impact).

The Japanese as Borrowers

Like many other cultures, Japan has been a great borrower of foreign ideas. Its written characters, style of painting, and religions originated abroad and were then adapted and developed within the Japanese context. One notable foreign acquisition since the Meiji restoration has been Western technology, which was initially obtained largely through reverse engineering and patent licensing. Japanese dependence on foreign technology was high in the post–World War II years, which led to the perception that Japan was a copycat country incapable of producing original work. However, the Japanese status as borrower of technology and ideas is not unique: borrowing seems to be a common mechanism for the attainment of national scientific and technological capabilities. For example, to a significant degree the U.S. technological dominance achieved in the first half of the 20th century was built on science and technology borrowed directly and indirectly from Europe, including technology transfer through immigration.

In the first part of this article we review recent Japanese technological developments to determine if the copycat characterization of Japanese technology is valid today. An examination of the patenting activity of the Japanese in the United States can provide insights into the technological capabilities of Japan for the following reasons: (i) The U.S. market is the largest and most sophisticated market in the world. Any company that wants to earn a substantial return from its technology will patent it in the United States. Consequently, technology patented in the United States reflects the world's most significant technology. (ii) Any technology patented in the U.S. system is, by definition, original, since patents are only issued for products and processes that are novel and unobvious. Therefore, focusing on Japanese technology patented in the United States ensures that one is looking at original work.

The Patent Database

Our database used here includes all U.S. patents issued between 1975 and 1985. Each patent has been tagged according to its U.S. Patent and Trademark Office (USPTO) classifications (*1*) and by the country of origin of both the inventor and assignee. This information allows examination of patent trends over time according to type of technology and national origin.

Each patent has also been tagged with information specifying the references made by patent examiners to related patents and other published works. The purpose of these examiner citations is to describe the limits of the technological claims made in a patent. This citation information enables one to investigate how separate patents are linked to each other and to the scientific literature.

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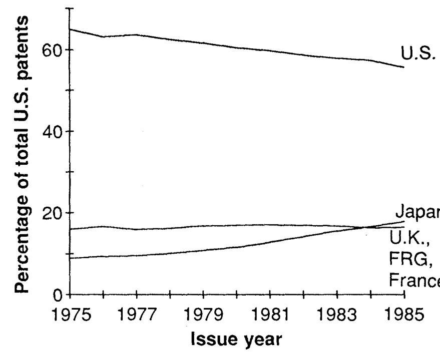
The Growth of Japanese Patenting in the United States

The most dramatic feature emerging from a review of patenting in the United States in recent years is the declining share of patents being issued to U.S. inventors and the corresponding increase in the share of patents being issued to Japanese inventors. United States patent counts for U.S., Japanese, and the combined British (U.K.), French, and West German inventors from 1975 to 1985 are shown in Fig. 1.

At the outset of this time period, American inventors held 64.9% of U.S. patents, while Japanese inventors held 8.9%. By the end of the time period, the U.S. inventor share dropped by 9.4 percentage points to 55.5% of the total, while the share held by Japanese inventors doubled to 17.9% of the total. For the three European countries the shares were relatively constant, with West Germany rising slightly from 8.5 to 9.5%, the United Kingdom declining slightly from 4.2 to 3.5%, and France remaining constant at 3.3 to 3.5%. A further indication of the erosion of the patent position of U.S. inventors occurred in 1986, when Hitachi became the number one recipient of U.S. patents with 896 U.S. patents, 1.26% of all U.S. patents granted in 1986, covering a wide range of electrical, electronics, chemical, and other technologies. The erosion continued into 1987, at which time the top three U.S. patent recipients were Hitachi, Canon, and Toshiba. Between 1985 and 1987, General Electric dropped from first to fourth place. Because the total number of U.S. patents granted was 71,981 in 1975 and 70,880 in 1986, it can be seen that the drop in U.S. inventor patents was absolute as well as relative.

Beginning in 1984, Japanese inventors obtained more patents in the United States than inventors in the United Kingdom, France, and West Germany combined (Fig. 1). If U.S. patents are a measure of inventiveness, then it would appear that the Japanese are as inventive as the British, French, and West Germans combined.

Fig. 1. U.S. patent grants by inventor country.



Areas of Japanese Technological Strength

In introducing their products and processes into the United States, the Japanese focus their efforts on a limited range of technologies. This is reflected in the U.S. patent statistics, which show that 80% of the U.S. patents held by Japanese companies are associated with 26% of USPTO's patent classes (*2*). The Japanese typically patent in a narrow band of the commercially most viable technologies. In contrast, 80% of U.S. patents held by American firms are associated with 37% of the patent classes, indicating that U.S. company patents are spread over a much broader range of technologies.

Table 1 shows the ten U.S. patent categories that experienced the greatest absolute growth in Japanese-invented patents between 1975 and 1979 combined, and between 1980 and 1984 combined. The technologies covered by these classifications are among the commercially most viable: automobile engines, drugs, computers, consumer electronics, and office automation. The Japanese are exploiting technologies that will give them substantial returns on their technological investments.

The Japanese tend to hold a large share of the patents in each of these classes, far out of proportion to the fraction of patents they hold in the U.S. patent system overall. For example, in 1980 to 1984, they held 57.6% of the patents in the photography classification (USPTOC 354), 43.6% of photocopying patents (USPTOC 355), and 41.1% of recorder patents (USPTOC 346). Many of these Japanese recording patents pertain to ink jet printing.

The growth of the Japanese share of patents in these classes has been astounding, considering the relatively short period of time being examined. For example, the Japanese share of U.S. patents in electrical computing (USPTOC 364) nearly doubled in the two time periods examined, from 10.9% of the class to 18.3%. It grew by more than 80% in recorder technology (USPTOC 346), from 22.6% of the class to 41.1%. It grew by about 65% in photocopying (USPTOC 355), from 26.3% of the class to 43.6%.

Table 1 examines only the ten technologies that in absolute terms witnessed the greatest growth of Japanese patenting in the U.S. patent system. Japanese patenting strength is also seen in other areas that have less patenting activity but are technologically crucial nonetheless. Japanese patent performance in these information systems areas is as follows: (i) Dynamic magnetic information storage and retrieval (USPTOC 360): Japanese share of U.S. patents in 1975 through 1979, 29.4%; share in 1980 through 1984, 44.0%. (ii) Dynamic information storage and retrieval (USPTOC 369): Japanese share of U.S. patents in 1975 through 1979, 30.5%; in 1980 through 1984, 43.2%. (iii) Static information storage and retrieval (USPTOC 365): Japanese share of U.S. patents in 1975 through 1979, 12.2%; in 1980 through 1984, 30.0%. (iv) Electrical computing and data processing systems (USPTOC 364): Japanese share of U.S. patents in 1975 through 1979, 10.9%; in 1980 through 1984, 18.3%.

Overall, the patent counts suggest that Japan is highly inventive technologically. It is rapidly increasing its technological strength and focusing its efforts on those areas that will reap the greatest economic returns.

Patent Examiner Citations to Japanese Patents

A portion of each U.S. patent is dedicated to reporting patent examiner citations to related art. Most of these citations are to other patents. We have collected and analyzed data on the number of examiner citations that are directed toward Japanese-held U.S. patents. The reason for looking at examiner citations to patents is that these citations appear to identify seminal technology. Research shows that heavily cited patents represent key advances from which other advances emerge and that patents associated with important discoveries are relatively frequently cited (*3*).

We identified the most highly cited patents in the U.S. patent system. To do this, we tabulated examiner citations found in 1975 through 1984 U.S. patents that were made to 1975 through 1982 U.S. patents. For each cited year, patents were rank ordered according to the number of examiner citations received. This was done in two ways. One data set rank orders patents for the patent system as a whole, irrespective of technological classification. The most active technologies (for example, electronics and pharmaceuticals) tended to dominate the list of heavily cited patents, whereas lower tech items (for example, cardboard box construction) were at the bottom of the list.

A second data set examines citations on a class-by-class basis. With this data set, patents were rank ordered within each patent classification to identify the patents cited most often for specific technological areas. Here attention focuses on, for example, the most highly cited photography or internal combustion engine patents.

With both data sets, we focused on the top 10% of highly cited patents because patent citation distributions are skewed, with up to two-thirds of the patents never cited, or cited only one or two times in the first 5 to 10 years after issue. Because there are many ties, that is, patents receiving identical numbers of citations, in the citation distribution, more than 10% of the patents in any group fall into what we have labeled the top 10% category. For example, of the 678 U.S. patents issued in 1980 in class 340—communications, electrical—70 were cited ten or more times by 1988, and 608 were cited zero to nine times. The 70 patents cited ten or more times (including the ties—the 11 patents cited exactly ten times) constitute 10.3% of all patents in that class in that year and are considered to be in the top 10%. For smaller patent classes, the percentage of patents in the most highly cited 10% is in fact often 12 to 15% (*4*).

In both data sets, there is a higher proportion of Japanese-held patents in the listings of highly cited patents than we would expect statistically. For example, in the first data set, based on all classes combined, 13.9% of all 1982 patents fall into the top 10% highly cited category, and 19.1% of Japanese-held patents fall into this category. The ratio of these two values is 1.37, indicating 37% more Japanese patents in the highly cited list than statistically expected. For the time period 1975 to 1982 overall, the ratio for Japanese-held patents is 1.35. In contrast, for American-invented patents it is 1.06; for U.K.–invented patents, 0.94; for French-invented patents, 0.80; and for West German–invented patents, 0.79.

Table 1. Japanese-held U.S. patents experiencing growth. Classes are arranged in descending order from the class with the largest growth in the number of Japanese-invented patents.

USPTO class no.	Classification	Number of Japanese-invented patents		Japanese percentage of USPTO class	
		1975–1979	1980–1984	1975–1979	1980–1984
123	Internal combustion engines	985	1721	26.0	35.9
424	Drugs, body treatment compounds	636	1183	7.7	12.3
428	Stock material or miscellaneous articles	583	1113	13.1	20.0
364	Electrical computers, data processing systems	359	843	10.9	18.3
430	Radiation imagery chemistry	895	1378	29.9	38.9
358	Pictorial communication, TV	486	946	22.2	31.4
355	Photocopying	410	793	26.3	43.6
346	Recorders	211	591	22.6	41.1
354	Photography	909	1258	46.8	57.6
219	Electrical heating	299	642	12.5	21.5

Table 2. Major areas with highly cited Japanese-held patents. Shown are citations to U.S. patents issued from 1975 through 1981, as cited by all U.S. patents issued from 1975 through 1984.

Product area	Number of top 1% patents
Automotive	69
Semiconductor electronics	52
Photocopying and photography	38
Pharmaceuticals and pharmaceutical chemicals	25
Sewing machines	9
Dispersed areas	32
Total Japanese patents in "top 1%"	225

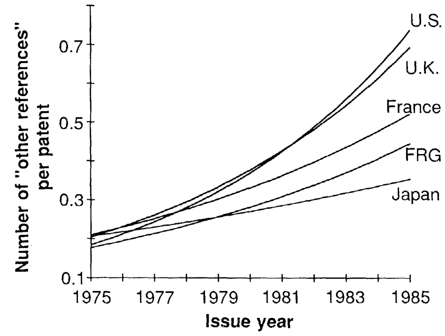


Fig. 2. Patent to science linkage.

Japanese performance is exceptionally high in the all-classes-combined data set because the Japanese tend to patent in the hottest technological areas where there are substantial numbers of citations. The second data set, which examines citation performance on a class-by-class basis, removes the bias that favors these important technologies. Even here there is an overrepresentation of Japanese patents in the list of highly cited patents. For example, the top 10% fraction of patents encompasses 17.8% of all 1982 U.S. patents class by class; however, 19.4% of Japanese-held patents fall into this category.

Table 2 shows the product areas associated with the most highly cited Japanese-held U.S. patents (in this case, the top 1% of highly cited patents). The data confirm what American consumers and manufacturers have suspected for the past few years: that the Japanese excel in automotive, electronic, photographic, and photocopying technology.

Data on patent counts demonstrate a burgeoning Japanese inventive vitality, and the patent citation data suggest that the impact of the inventions is high. The U.S. patent statistics do not support the view that the Japanese are unoriginal copycats.

Examiner Citations to the Nonpatent Literature

United States patent examiners not only cite other patents, they cite the nonpatent literature as well. These citations appear on the patent in a section titled "References Cited—Other Publications." Most of these citations are to scientific works, including scientific books, monographs, and articles. Because so many of these citations are to scientific works, a count of examiner citations to the nonpatent literature gives a sense of the extent of linkage of the patented technology to science.

Figure 2 shows a smoothed fit of the average numbers of citations to the nonpatent literature for the U.S., Japanese, British, French, and West German inventors. Although the science linkage for patents held by inventors from all these countries was roughly equal in 1975 (about 0.2 nonpatent citations per patent), it had diverged dramatically by 1985, at which time the science linkage of U.S.–invented patents was twice as great as for Japanese-invented patents. In addition, Japanese-invented patents have shown the least rapid growth of science linkage.

This difference in science linkage can also be witnessed at the level of individual companies. For example, for IBM patents the number of examiner citations to the nonpatent literature tripled between 1976 and 1986, from 0.5 citations per patent to 1.6 citations per patent. While nonpatent citations more than doubled for Hitachi in this time period, its science linkage was still low in 1986, at 0.5 citations per patent. Fujitsu fared better, with science linkage growing fivefold from 1976 to 1986; but the science linkage of its patents in 1986 (1.1 citations per patent) was still considerably lower than that of IBM. The science linkage data suggest that although the Japanese may be highly inventive, their inventions are not based on scientific research as much as those associated with Western technological efforts.

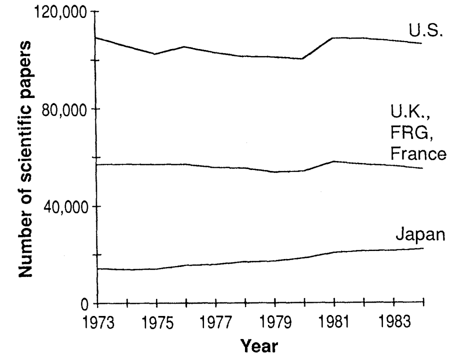


Fig. 3. Scientific papers by author country.

Japanese Scientific Performance: Counts of Papers

Scientific knowledge is to a large extent embodied in the scientific journal literature. By examining who is publishing what in the literature, one can obtain insights into the scientific strengths of different countries. We examined the national and subject origins of scientific papers appearing in the world's most central journals, as defined by the set of journals covered by the Institute for Scientific Information's *Science Citation Index* (*SCI*) (*5*).

Our database is comprised of all papers appearing in a fixed set of 2300 journals, the 1973 constant journal set, published from 1973 through 1984. By focusing on a fixed set of journals, there is some assurance that the changes we observe in national publishing patterns are not an artifact of changes in the journals that underlie the database. To check the validity of our findings we created a second database similar to the first, but we included all journals covered by *SCI* since 1981. The second database contains counts of papers appearing in a broader set of about 3000 journals.

Although the second data set is substantially larger than the first for the 1981 through 1984 time period, the basic national trends in the two data sets are nearly identical. For example, the Japanese-authored shares for the 2300 journal set are 7.0, 7.3, 7.3, and 7.6% for 1981 through 1984, respectively. The corresponding shares for the 3000 journal set are 6.7, 6.9, 7.0, and 7.3%.

Figure 3 shows the number of Japanese and U.S. papers appearing in the 2300 journal set for 1973 through 1984. In contrast to the strong Japanese technological efforts, the dimensions of the Japanese scientific effort appear to be fairly modest. Americans hold 2.5 U.S. patents for each Japanese-held patent, and American scientists publish about five scientific papers for each paper published by a Japanese scientist. Although Japan holds more U.S. patents than the U.K., France, and West Germany combined, scientists in these three European countries publish more than 2.5 times the number of papers published by Japanese scientists.

There has been a steady, although not dramatic, increase in the number of Japanese-authored papers appearing in the 2300 journal set. In the 1973 through 1984 time frame, the number of Japanese-authored papers increased by 53%. In contrast, the number of U.S.–authored papers remained almost unchanged (Fig. 3).

Figure 4 provides a field-by-field profile of Japanese and U.S. scientific publishing in 1973 and 1984. The Japanese effort focuses heavily on the physical sciences. In 1973, 46% of the Japanese papers appearing in the 2300 journal set were in either physics or chemistry. This is typical of the publishing pattern of Eastern European countries and of developing countries that are in the midst of a heavy industrialization effort, such as India (*6*). In contrast, 21% of U.S. papers in 1973 were in physics and chemistry. The U.S. effort, along with that of the most advanced Western countries, places greater emphasis on life science research (that is, clinical medicine, biomedical research, and biology). There has been a movement on the part of the Japanese toward more research in clinical medicine and biomedical research. Although the pattern of Japanese science is still far removed from the U.S. pattern, it appears to be moving gradually in that direction.

We also examined Japanese publication efforts at the subfield level. Each paper in the database is assigned to one (or fractionally assigned to more than one) of 98 scientific subfields. Of particular interest are data on subfields in which Japanese papers make up a large share. A list of the top ten such subfields for papers published from 1973 through 1982 includes the following (percentages of the Japanese papers in the subfield are in parentheses): pharmacy (24.7%), polymers (18.3%), marine biology and hydrobiology (13.7%), general chemistry (12.9%), electrical engineering and electronics (12.0%), applied physics (11.6%), agriculture and food science (11.3%), microscopy (10.6%), organic chemistry (10.0%), and general physics (9.7%).

To appreciate how active Japanese scientists are in the top ten areas, it should be noted that Japanese papers made up only 6% of the total database for 1973 through 1982. Thus in an area such as pharmacy, Japanese scientists are four times more active than we would expect, based on their overall presence in the database, although this may be partially an artifact of the inclusion of the Japanese *Chemical and Pharmaceutical Bulletin* in the database (*7*).

The most distinguishing feature of the list of scientific subfields in which the Japanese are active is their close link to commercially

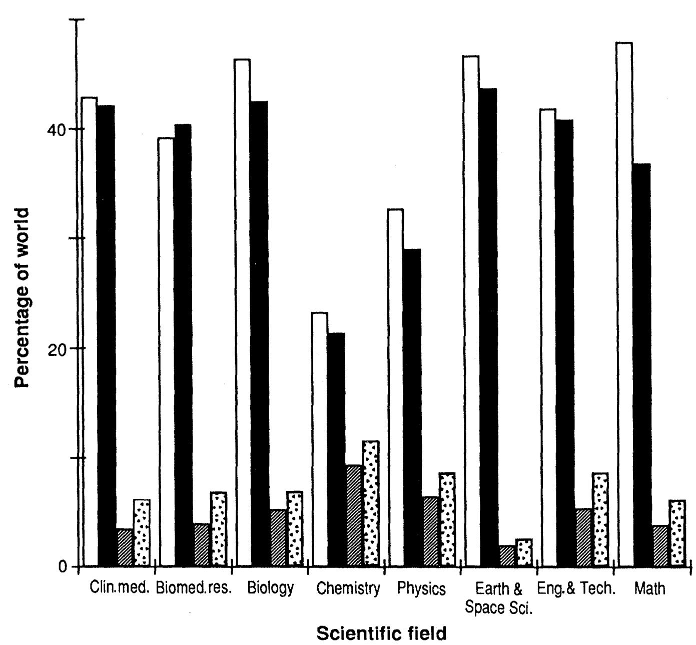


Fig. 4. The U.S. and Japanese shares of publications in the world. Open bars represent percentages of U.S. publications in scientific fields for 1973; solid bars, U.S. percentages, 1984; shaded bars, Japanese percentages, 1973; and dotted bars, Japanese percentages, 1984.

viable areas. Research in pharmacy (drugs), polymers (plastics), marine biology (food), microscopy (instruments), and organic chemistry (numerous industrial and biotechnology applications) yields obvious financial payoffs. The parallel here with Japanese technology with its heavy targeting of commercially viable areas is striking.

Citations to Japanese Scientific Papers

Counts of scientific papers published in the mainstream literature give a sense of the dimensions of the research efforts of scientists in different countries. However, the counts do not reveal anything about the impact of this research. To measure impact, we examined the degree to which research papers are cited in other literature. The assumption is that highly cited papers have a major impact on research; numerous studies suggest that this is a valid assumption (*8*).

A citation database was created for papers appearing in the 1973 to 1983 constant journal set that were cited in papers published in 1973 through 1984. The citation data are extracted from the computerized tapes of *SCI*.

The scientific citation data show that Japanese papers are relatively undercited. For example, the typical Japanese scientific paper published in 1980 received only 4.1 citations in papers published in 1980 through 1984. The corresponding American paper received 7.1 citations. A factor contributing to this underciting is language: papers in languages other than English are significantly less frequently cited than English language papers (*9*).

Although Japanese works appear to be undercited, the trend indicates an increase in the citability of these papers (Table 3). The numbers in Table 3 are relative citation ratios. For example, if a country's authors receive 12% of all citations issued and produce 10% of the world literature, then the relative citation ratio is 1.20. This ratio indicates that scientists in the country receive 20% more citations than one would expect on the basis of their share of the literature.

The overall relative citation ratio for Japanese papers is below 1.0 for each of the 3 years examined (Table 3). The ratio for 1973 shows that Japanese papers receive 23% fewer citations than expected statistically. However, the ratio is steadily climbing, and by 1983 it approached a break-even point, where Japanese papers received their statistically expected share of citations. In this same time period, the overall relative citation ratio for the United States was stable and strong, showing that U.S. papers received about 34 to 37% more citations than would be expected statistically.

By 1983 the most heavily cited Japanese papers were in engineering and technology. Papers in biology and chemistry also received more citations than statistically expected. Perhaps the least satisfactory citation performance was in physics, where papers were consistently undercited by 20 to 25% during the 1973 through 1983 time frame, and in clinical medicine where the underciting was 30% or more. Together, the publication and citation data show Japanese scientific performance to be much less impressive than Japanese technological performance.

Conclusions

The various patent and scientific literature indicators examined here are quantitatively consistent with what observers of Japan have sensed for several years: Japan's technological accomplishments are extraordinary, while its scientific achievements, at least up until 1984, are more modest. These results are not surprising when the manpower dimensions of Japanese science and technology are examined. For example, in Japan in 1985 there were 5.6 undergraduate engineering graduates for each natural science graduate (in the United States, by contrast, the ratio was 0.65:1). In 1985 Japan produced nearly as many undergraduate engineering graduates (71,396) as the United States (77,871) (*10*).

Table 3. Relative citation ratios for Japanese and U.S. papers. The relative citation ratio is the percentage of total citations for the field divided by the percentage of papers published in the field.

Scientific field	Japan			United States		
	1973	1978	1983	1973	1978	1983
Clinical medicine	0.60	0.71	0.72	1.36	1.35	1.35
Biomedical research	0.76	0.82	0.88	1.43	1.38	1.37
Biology	0.86	0.89	1.09	1.09	1.13	1.08
Chemistry	0.87	0.95	1.08	1.66	1.75	1.61
Physics	0.80	0.80	0.74	1.50	1.51	1.48
Earth and space science	0.56	0.73	0.90	1.40	1.36	1.39
Engineering and technology	0.76	1.11	1.25	1.26	1.26	1.16
Mathematics	0.85	0.89	0.79	1.21	1.33	1.27
Average ratio for all fields	0.77	0.86	0.91	1.36	1.37	1.34

The relative weakness of Japanese science carries with it an interesting implication for future developments in technology. Technology is becoming increasingly science-based (*11*). The important technologies of today—computers, optics, and biotechnology—are built on a scientific foundation. The patent data show that Japanese technology appears to be less science-based than technology produced by inventors from other countries. The question is, can Japan continue its advances in technology without building a stronger science base to draw upon?

This issue of the relative weakness of Japanese science has not been lost on Japanese policy-makers. Over the last few years, various initiatives have been undertaken to strengthen national scientific capabilities; these actions range from the building of science cities such as Tsukuba City to reforming the education system in order to foster more creativity among school children. Considering the Japanese track record for identifying national goals and achieving them, it seems distinctly possible that within one or two decades Japanese science will catch up with Japanese technology.

REFERENCES AND NOTES

1. *Manual of Classification*, Documentation Organizations, U.S. Patent Trademark Office, Department of Commerce (Government Printing Office, Washington, DC, 1985).
2. Ninety-five percent of the patents granted to Japanese inventors are assigned to companies. Of those, 99% are assigned to Japanese companies. Furthermore, 99% of patents assigned to Japanese companies are Japanese invented. For U.S.–invented U.S. patents, approximately 75% are assigned to companies. Throughout this article, all data are for type I, regular U.S. patents. Plant patents, reissue patents, and other special categories have been omitted.
3. M. P. Carpenter, F. Narin, P. Woolf, *World Pat. Inf.* **3**, 160 (1981); F. Narin and D. Olivastro, in *Handbook of Quantitative Studies of Science and Technology*, A. F. J. van Raan, Ed. (Elsevier North-Holland, New York, 1988), chap. 15.
4. For a discussion of the rationale of examining the top decile of cited patents, see F. Narin and D. Olivastro [*Final Report: Identifying Areas of Leading Edge Japanese Science and Technology* (National Science Foundation, Washington, DC, 1988)].
5. *Science Citation Index* (Institute for Scientific Information, Philadelphia, 1973 through 1984).
6. J. D. Frame, F. Narin, M. P. Carpenter, *Soc. Stud. Sci.* **7**, 501 (1977).
7. Many of the Japanese papers covered in *SCI* in pharmacy are in one journal that carries many papers: the Japanese *Chemical and Pharmaceutical Bulletin*. This is not a highly cited journal, so the overall Japanese position in pharmacy may not be as strong as indicated. However, pharmacology and related basic biochemical research are relatively strong and growing subfields of Japanese science.
8. National citation performance has been studied thoroughly; for example, by T. Braun, W. Glanzel, and A. Schubert [*Scientometrics* **11**, 9 (1987); *ibid.*, p. 127; *ibid.* **12**, 3 (1987)]. National citation data have been used to analyze the dwindling role of British science [J. Irvine, B. Martin, T. Peacock, R. Turner, *Nature* **316**, 587 (1985); B. Martin, J. Irvine, F. Narin, C. Sterritt, *ibid.* **330**, 123 (1987)].

9. E. Garfield, *Curr. Contents* **46**, 3 (16 November 1987).
10. *Science and Engineering Indicators—1987* (National Science Board, Washington, DC, 1987), p. 133.
11. Not only are references to the scientific literature increasing in U.S. patents, but the age of the references is shortening. In 1975, the median age of an examiner reference to nonpatent literature was approximately 8 years. In 1986, this decreased to about 7 years [F. Narin and E. Noma, *Scientometrics* 7, 369 (1985); W. J. Broad, "Science and technology: The gap is shrinking fast," *New York Times*, 5 April 1988, p. C1.
12. Supported by NSF grant SRS-8507306. We thank J. Bond for support. Development of the literature and patent data and analysis techniques were partially supported under NSF Science Indicators contract SRS-8607471 and Small Business Innovation grant ISI-8521261. The final report under the NSF grant is cited in (*4*); it contains most of the data underlying this article. We also thank D. Olivastro for computer analysis of the patent data and K. A. Stevens for preparation of the literature data.

Ocular Dominance Column Development: Analysis and Simulation

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The visual cortex of many adult mammals has patches of cells that receive inputs driven by the right eye alternating with patches that receive inputs driven by the left eye. These ocular dominance patches (or "columns") form during early life as a consequence of competition between the activity patterns of the two eyes. A mathematical model of several biological mechanisms that can account for this development is presented. Analysis of this model reveals the conditions under which ocular dominance segregation will occur and determines the resulting patch width. Simulations of the model also exhibit other phenomena associated with early visual development, such as topographic refinement of cortical receptive fields, the confinement of input cell connections to patches, monocular deprivation plasticity including a critical period, and the effect of artificially induced strabismus. The model can be used to predict the results of proposed experiments and to discriminate among various mechanisms of plasticity.

IN THE VISUAL SYSTEMS OF MANY MAMMALS, INCLUDING CATS, monkeys, and humans, the optic nerves from the two eyes project to separate layers of a relay nucleus, the lateral geniculate nucleus (LGN) of the thalamus. Fibers from the LGN in turn project to cortical layer 4, the input layer of the primary visual cortex. There they terminate in alternate patches called "ocular dominance columns" serving the left eye and right eye, respectively (Fig. 1). The nonoverlapping pattern of connections evolves during development. Initially the connections representing the two eyes are distributed throughout layer 4, overlapping completely. Subsequently, they become segregated into two sets of patches, one for each eye.

Ocular dominance patch formation appears to depend on competition between the activity patterns originating within the two eyes (*1*). The patches do not develop when neural activity is blocked in the eyes or in the cortex or when a pattern of neural activity is given synchronously to the nerves from both eyes. They do develop when the activity patterns in the nerves from the two eyes are asynchronous. Closing one eye during a critical period early in development (monocular deprivation) results in larger patches for the open eye and smaller patches for the closed eye. Closing of both eyes during the same period causes no abnormal effect. Thus, both development of ocular dominance patches and the effects of monocular deprivation involve competition between activity patterns; they do not result simply from the presence or absence of activity.

This competition provides a model system for understanding activity-dependent synaptic plasticity. We presume that the strengthening of some synapses and the weakening of others are governed by cellular-level rules involving the patterns of neural activity onto and by each cortical cell. These small-scale changes, occurring on many individual cells during development, result in the large-scale structure of ocular dominance.

Various cellular-level mechanisms for plasticity have been proposed (*2*). Simulations by von der Malsburg and others (*3*) have demonstrated that some of these mechanisms can produce ocular dominance patches. We have developed a mathematical model that describes several such mechanisms. From it, we can determine the ocular dominance structure that would result from each mechanism, given experimental values for biological parameters (*4*).

Our analysis focuses on four biological features that are thought to play a role in organizing ocular dominance patches (Fig. 2):

1) The patterns of initial connectivity of the geniculocortical afferents (inputs from geniculate to visual cortex) onto the cortical cells. These patterns involve the spread of afferent arbors and of cortical dendrites and are described by an "arbor function," A.

2) The patterns of activity in the afferents. These patterns are described by a set of four "correlation functions," C^{LL}, C^{RR}, C^{LR}, and C^{RL}. They describe correlations in activity between afferents serving the same eye, left or right (C^{LL} and C^{RR}) or serving different eyes (C^{LR} and C^{RL}).

3) Influences acting laterally within the cortex, whereby synapses on one cell can influence the competition occurring on nearby cells.

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