Understanding Patterns of International Scientific Collaboration

Terttu Luukkonen
Academy of Finland
Olle Persson
Inforsk, University of Umeå, Sweden
Gunnar Sivertsen
Institute for Studies in Research and Higher Education, Norway

International scientific collaboration has increased both in volume and importance. In this article, the authors study the interpretation of macro-level data on international coauthorship collaboration. They address such questions as how one might explain country-to-country differences in the rates of international coauthorship, networks of international scientific collaboration among countries, and patterns of international collaboration in scientific fields. Attention is drawn to cognitive, social, historical, geopolitical, and economic factors as potential determinants of the observed patterns. They present a methodology that gives one a measure, independent of size, of countries' propensities to collaborate internationally.

The first collaborative scientific paper was published in 1665,[1] and the number of collaborative papers has increased ever since, first slowly, then dramatically after the middle of the eighteenth century. Beaver and Rosen noted collaborative linkages across national borders as early as the nineteenth century.[2] These linkages increased toward the end of the century, and international collaboration has grown in importance throughout the present century.

AUTHORS' NOTE: A preliminary version of this article was presented at the International Conference on Science and Technology Indicators (Bielefeld, Germany, 10-12 June 1990) and will be published in the conference proceedings. The Academy of Finland, Inforsk, the Institute for Studies in Research and Higher Education, and the Nordic Science Policy Council (under the aegis of the Nordic Council of Ministers) supported this study. We gratefully acknowledge comments by Diana Hicks, Jussi Huttunen, Phoebe A. Isard, Stephen Isard, Ben R. Martin, Geoff Oldham, C. Marciano da Silva, James E. F. Skea, Robert Tijssen, and Thomas G. Whiston.

Science, Technology, & Human Values, Vol. 17 No. 1, Winter 1992 101-126

Previous studies have emphasized different determinants of scientific collaboration. Beaver and Rosen concluded that scientific collaboration represented a response to increasing professionalization of science.[3] Collaboration provided a means to both professional advancement and increased knowledge. It offered access to resources (both information and equipment) and association with the scientific elite, which enhanced the visibility of aspiring young scientists in particular.[4] Hence Beaver and Rosen explained collaboration by the intellectual and material resources collaboration offers and by factors that are related to the social stratification of science as a profession. Edge[5] and Stokes and Hartley[6] have taken the view that coauthorship reflects mutual intellectual or social influence.

Price has emphasized the importance of economic factors in collaboration. In his essay "Citation Measures of Hard Science, Soft Science, Technology, and Nonscience," he reflected that collaborative authorship "arises more from economic than from intellectual dependence and that the effect is often that of squeezing full papers out of people who only have fractional papers in them at that particular time."[7] He went on to assert that "the amount of collaborative authorship measures no more than economic value accorded to each field by society."[8] Price referred to the amount of money society allocates to research. We could think of other meanings of economy, such as the advantages of sharing the resources to buy and maintain expensive research facilities or, a more expanded meaning, the increased productivity gained from collaboration.[9]

The variety of the explanations of collaborative authorship stemmed from the different perspectives and approaches of their authors. Most of the studies mentioned considered research collaboration at the micro level and examined either collaborative networks of particular scientists or the benefits that collaboration provides for research work.[10] By and large, these studies employed three sets of factors, economic, cognitive, and social, to explain collaboration. We maintain that the relative importance of these factors varies, depending on the type of analysis and the kinds of aggregates we are studying. For example, different factors might be relevant for explaining field-to-field differences in the rates of collaboration from those that explain country preferences for collaborative partners or patterns of collaboration between scientists in a particular country.

All the factors mentioned above are more or less internal to the scientific enterprise. There are other factors in present-day society that are external to science but nonetheless enhance scientific collaboration, especially international collaboration. Such factors include easier and less expensive communication (e.g., via travel, fax, and electronic mail). Governmental initiatives to increase international contacts in science through travel money and intergovernmental science programs (e.g., the European Community's science program) also enhance collaborative efforts. The establishment of such programs reveals that international scientific collaboration is seen as good per se and has become a political objective.

In this study we explore the interpretation of macro-level data of institutional coauthorship collaboration, especially when it is international. We address the question of how to explain country-to-country differences in the rates of international coauthorship. We pay particular attention to factors that influence networks of international scientific collaboration between countries, including geopolitical and historical factors and language. Last, we examine patterns of institutional collaboration in scientific fields. We explore the importance of social, intellectual or cognitive, and economic factors for explaining our findings.

Our data reflect institutional, not individual, coauthorships. We are aware that these represent only some of the possible indicators of collaboration. Not all collaborative efforts end up in coauthorship, nor does the writing of coauthored papers necessarily imply a close collaboration between the authors. Nevertheless, we assume that in most cases coauthorship indicates a fairly active cooperation between the partners, closer and more active than the exchange of material, information, and comments, which shows up, for example, in acknowledgements.

That our data are based on institutional affiliations of the authors provides a limitation for a study of national collaborations. Collaborations within an institution are not counted. We cannot argue that the frequency of national institutional coauthorship accurately reflects the relative frequency of national collaboration within a given field. This is not a serious limitation in relation to international collaborations, because they are in most cases interinstitutional (there are a few exceptions, such as when scientists spend longer periods in international institutions or the case of visiting graduate students or postdoctoral fellows without a permanent home country address).

Data

Our data are from the Computer Horizons/National Science Foundation Science Literature Indicators Database (hereafter CHI), in particular its international institutional coauthorship data set. The data cover six years, 1981-86, which in our analysis are aggregated, and they are based on the *Science Citation Index* (*SCI*) 1981 source journal set. One international institutional coauthorship is defined as a paper for which the authors give institutional affiliations from more than one country. The data include the number of coauthorships between all pairs of countries in a set of ninety-seven countries. For most of our analysis, however, we use a thirty – country set, for reasons of economy and because most of the cells of the ninety-seven-country matrix would be empty. The selection of these thirty countries was based on the number of papers in the data base (size).[11] The CHI data also provide the number of papers coauthored with other countries, the number of papers with authors from single versus multiple institutions, and the number of papers with authors from multiple institutions within one country.

Scientific Size of Country and International Collaborations

Figure 1 gives a frequency plot of the size of the country and the percentage of international coauthorships for ninety-seven countries. The size of the country is measured in publications. Size seems to be inversely related to the rate of international coauthorships: With a decreasing volume of publications, the share of internationally coauthored papers grows. Nevertheless, there is a large scatter in the percentage of international coauthorships, especially for the countries with small output. Consequently, the linear correlation is not high; it explains only 11% of the variance in the coauthorship rate.[12]

This relationship might be an artifact of the coverage of the data base. Collaboration with foreign colleagues could be an important prerequisite for submission to *SCI*-covered journals from scientists from smaller countries. At the smallest, the total sum of publications per country in 1981-86 was less than one hundred.

We think that there are also other reasons for the relationship between size and the rate of international collaboration. The tendency toward increasing specialization in science makes research areas more narrowly focused. Scientists who come from scientifically peripheral countries are likely to find few, if any, colleagues in their own country. In order to avoid isolation, they have to look for partners from other countries. Another reason for their higher rates of international collaboration might be their greater need for cost sharing.

Figure 2 presents a similar plot, including a regression line, for the thirty largest countries in terms of science production. The variation explained is slightly larger than for the ninety-seven countries, 19%. There are notable

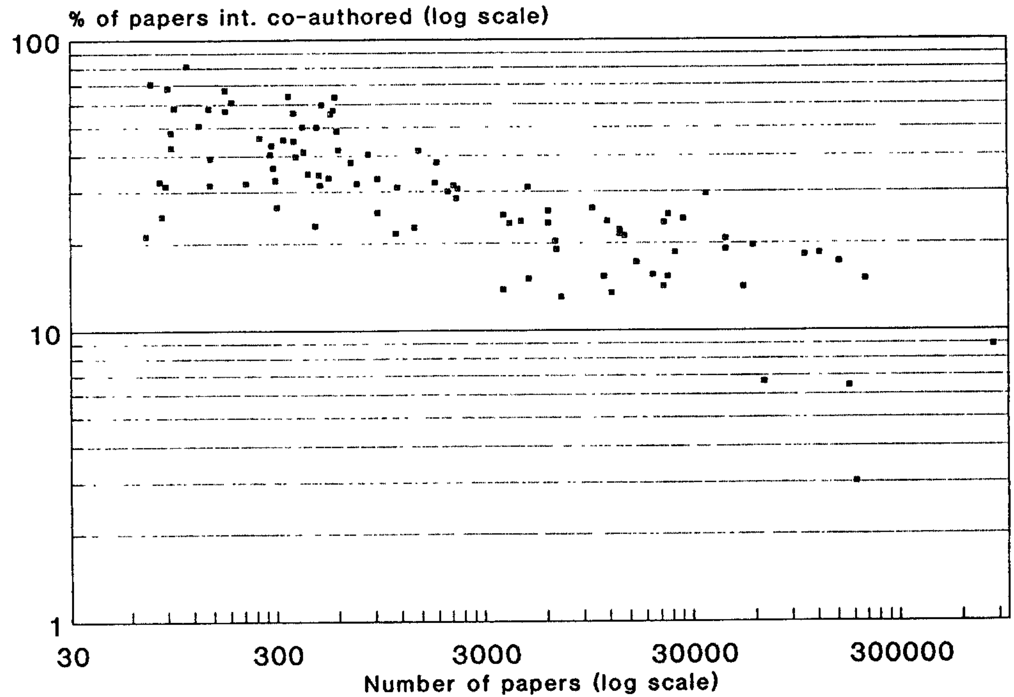

Figure 1. Size and internationally coauthored papers, ninety-seven countries.

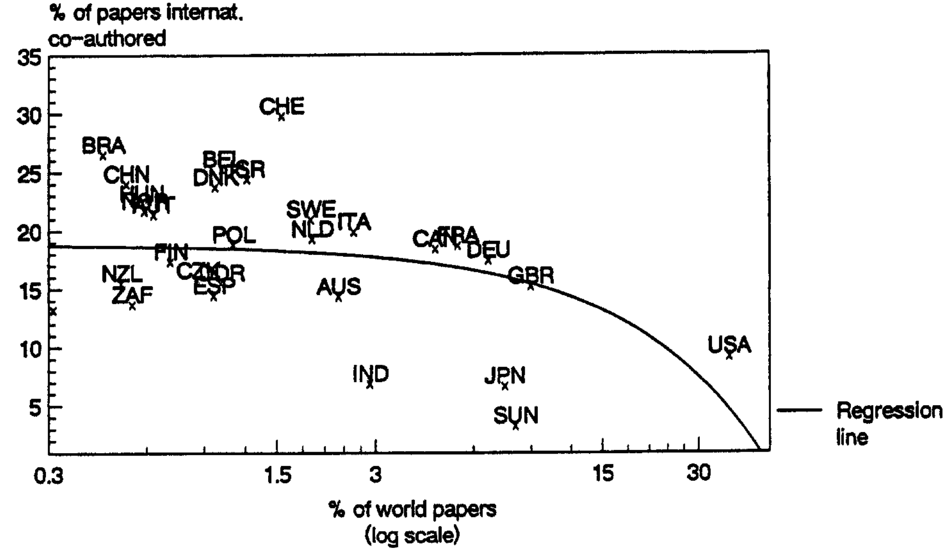

Figure 2. Size and internationally coauthored papers, all fields, thirty countries.

NOTE: In Figures 2-12 the following country abbreviations are used: ARG = Argentina; AUS = Australia; AUT = Austria; BEL = Belgium; BGR = Bulgaria; BRA = Brazil; CAN = Canada; CHE = Switzerland; CHN = People's Republic of China; CZK = Czechoslovakia; DDR = German Democratic Republic; DEU = Federal Republic of Germany; DNK = Denmark; ESP = Spain; FIN = Finland; FRA = France; GBR = Great Britain; HUN = Hungary; IND = India; ISR = Israel; ITA = Italy; JPN = Japan; NLD = the Netherlands; NOR = Norway; NZL = New Zealand; POL = Poland; SUN = USSR; SWE = Sweden; USA = USA; ZAF = South Africa.

exceptions to the general pattern also for the large science producers. The USSR, Japan, and India are remarkably below the regression line. The reasons for their low rate of international collaboration might include factors such as language (the USSR and Japan), large indigenous science production (India), and isolation due to political or cultural reasons (the USSR and Japan). Switzerland is well above the regression line, partly because of the siting of large international scientific establishments there, for example, CERN, the European particle physics facility.

All these exceptions and the relatively small percentage of variance that is explained by size highlight that many other factors are important influences on the propensity of countries to collaborate internationally.

Countries' Collaboration Networks

To examine which factors influence coauthorship linkages between countries, we produced a "map" of the network of international institutional collaborations. This map is based on the ratios of observed to expected coauthorship frequencies that indicate country preferences. We started with a matrix of observed coauthorship frequencies of the thirty most productive countries. The observed/expected ratio of coauthorship for each pair of countries was calculated by the following formula:[13]

$$(C_{x,y} \times T)/(C_x \times C_y), \text{ where}$$

$C_{x,y}$ = number of collaborations between countries X and Y
C_x = total number of collaborations country X has with other countries in the matrix of thirty countries
C_y = total number of collaborations country Y has with other countries in the matrix of thirty countries
T = total number of collaborations in the matrix of thirty countries

When the index value exceeds one, there are more collaborations between a pair of countries than expected, given their size and tendency to collaborate internationally.

The matrix based on the index values of the observed/expected ratios provided the input values for a multidimensional scaling program. Figure 3 presents the best two-dimensional solution to the input values (the stress value is 22%, which represents a rather poor fit; this means we need more than two dimensions to describe the structure).[14] This map illustrates the underlying structure of collaborative linkages between the countries. The closer the countries are to each other on the map, the more intensively they

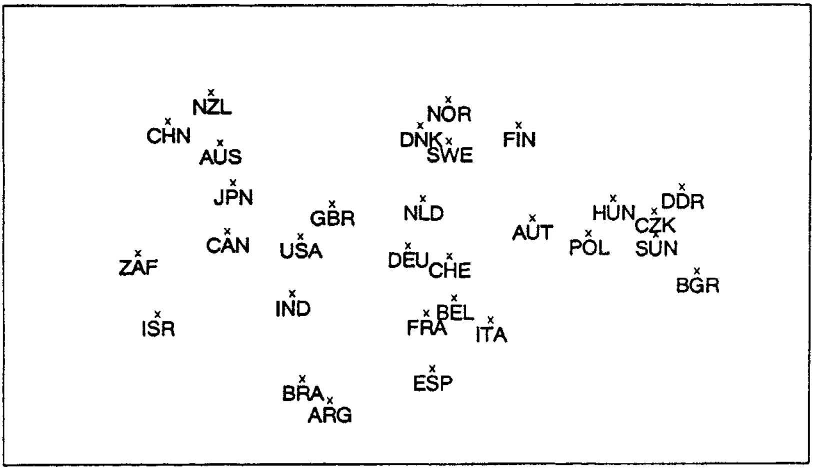

Figure 3. International coauthorship network, all fields, thirty countries, 1981-86.
NOTE: See Figure 2 note for abbreviations.

collaborate. Nevertheless, as this map is influenced by all the collaborative relations in the thirty-country matrix, it does not give an accurate picture of the relations between any pair of countries. To study them, we have to examine the country profiles (Figures 4 to 11).

It is remarkable how closely the map (Figure 3) corresponds to a geographical map. Regionally based factors such as geopolitics, history, language, and cultural similarity seem to be very important for the collaborative networks. For example, there is a distinct cluster of collaboration among the Nordic countries. Frame and Carpenter made a similar network analysis based on the *SCI* 1973 data.[15] One of their findings was that Sweden was anomalously not placed in the networks. The reason for their finding apparently was that they did not include other Nordic countries in their analysis. This example highlights the fact that collaboration matrices are sensitive to variations that depend on which countries are included in or excluded from the analysis. If an important collaborative partner or partners of a particular country have been excluded from the analysis, that country's position will change. This factor might affect the position of Brazil and Argentina to a certain extent, because they are the only Latin American countries in our analysis.

East European countries provide another example of a well-defined cluster that collaborates intensively within the group. Figure 4 gives the coun-

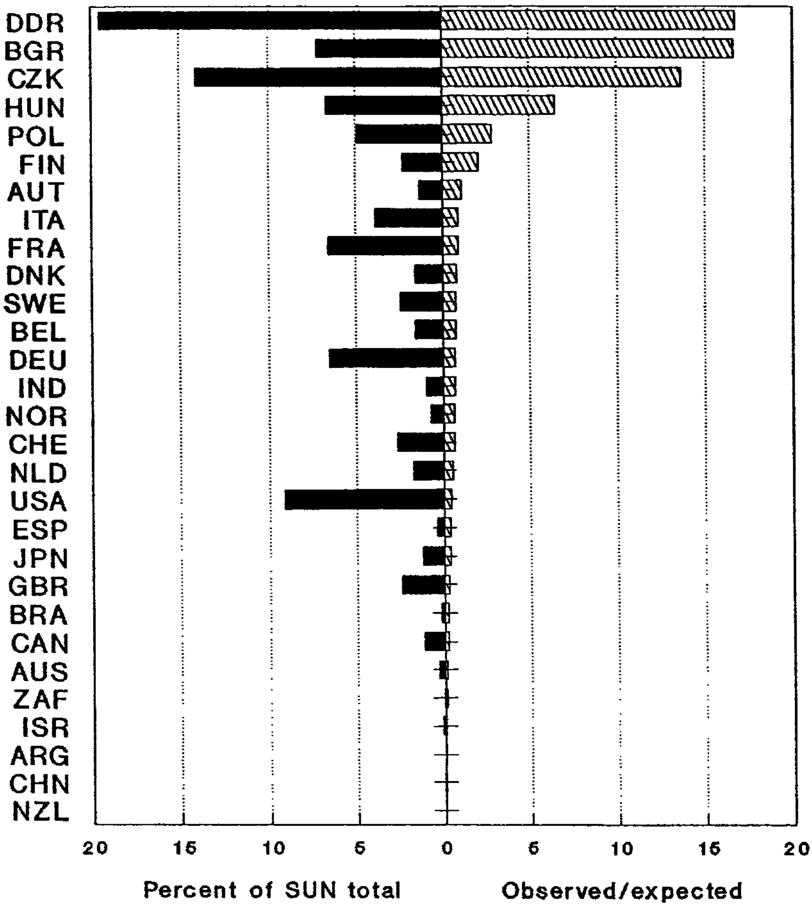

Figure 4. Soviet Union: priorities in coauthorship relations, all fields combined, 1981-86.

try profile for the USSR and shows how important the other East European countries are for Soviet international collaboration, both in absolute and relative terms. This pattern is repeated in the country profiles of the other East European countries.

Central and southern Europe form a slightly less interconnected group than northern and eastern Europe. The United States is at the center of a group of several countries but does not form a clear-cut cluster with any of them. The ten most important partners of the United States are the countries that

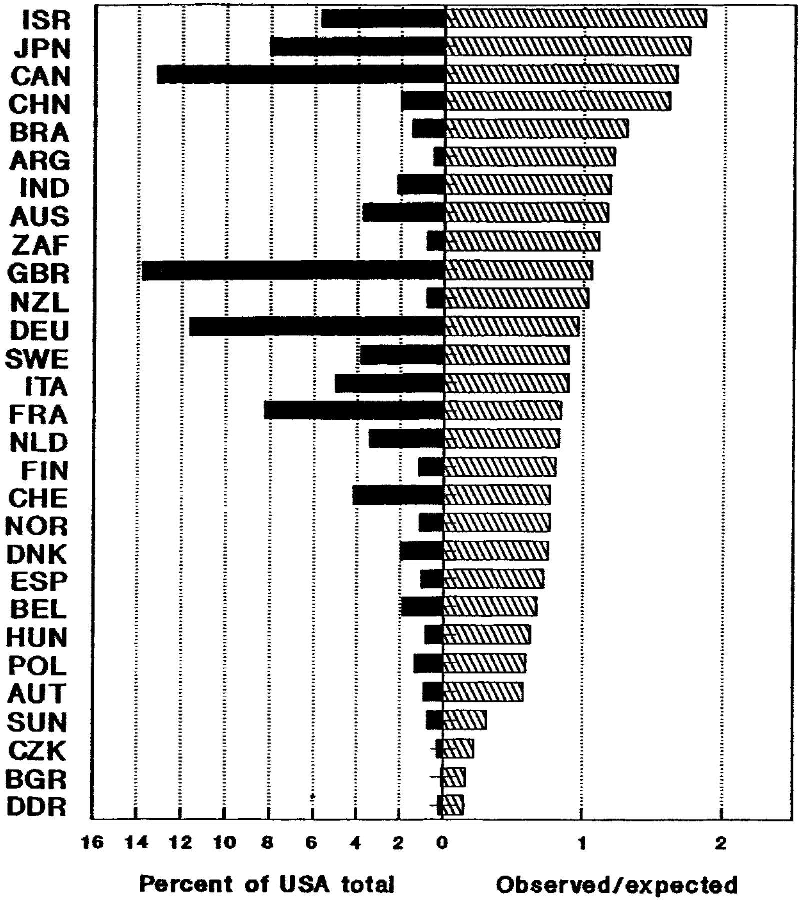

Figure 5. United States: priorities in coauthorship relations, all fields combined, 1981-86.

are all loosely scattered around the United States on the map. (For the relative importance of these countries for the United States, see Figure 5).

From a geographical point of view, Israel and South Africa seem anomalously placed in the left-hand corner of the map. This is because they are, first, the most important collaborative partners for each other (see Figures 6 and 7). For Israel, the United States is the second and West Germany the third most important collaborative partner; South Africa has a slightly more even

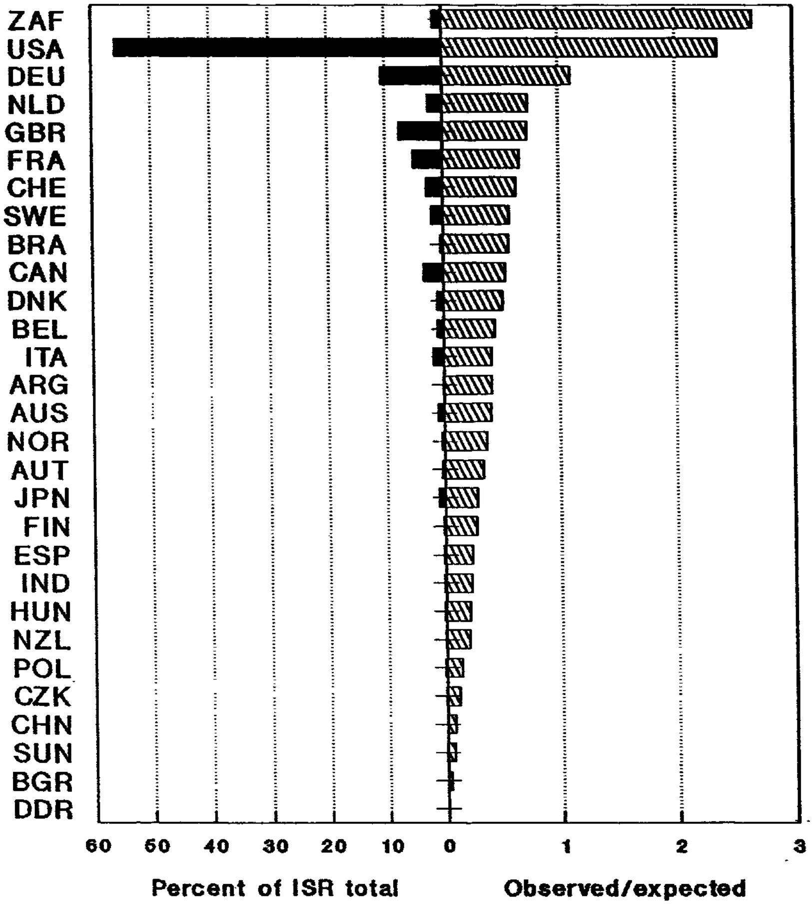

Figure 6. Israel: priorities in coauthorship relations, all fields combined, 1981-86.

profile of collaboration. Nevertheless, they have relatively few contacts with the rest of the countries and a much less even profile than, for example, the United States. Political reasons obviously account for their uneven collaborative profiles and their relatively frequent mutual contacts.

Australia and New Zealand provide an interesting case of high mutual dependence: Both collaborate with each other over eight times more frequently than expected (Figures 8 and 9). The United Kingdom is relatively

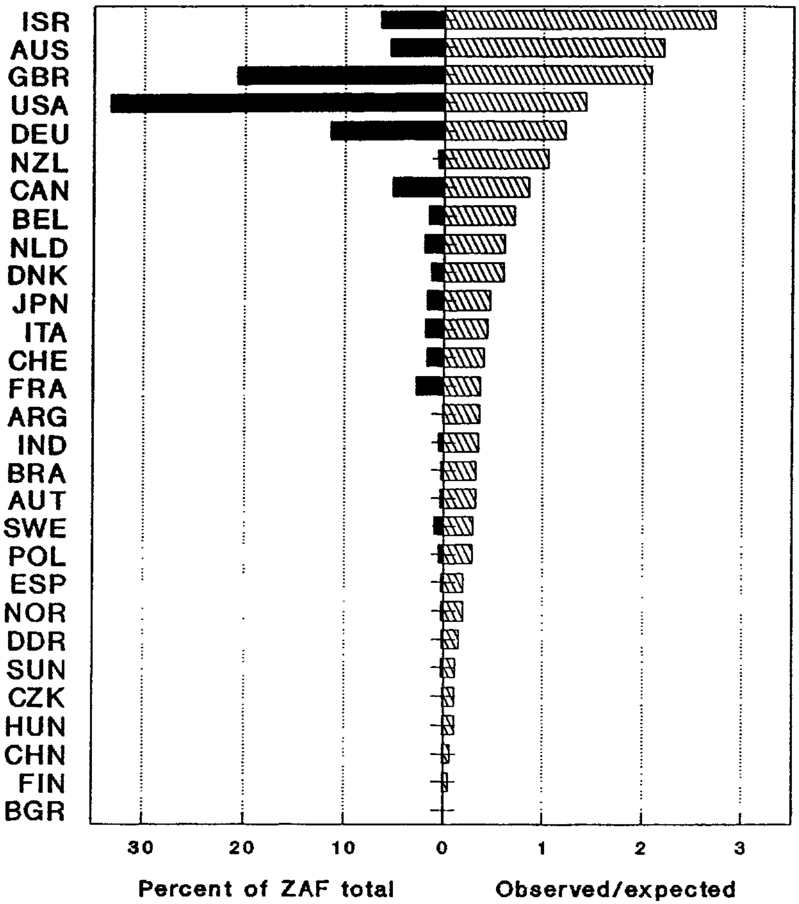

Figure 7. South Africa: priorities in coauthorship relations, all fields combined, 1981-86.

important for them but far less in absolute terms. They are also among the most important collaborative partners of the United Kingdom (Figure 10). Their mutual dependence and relatively strong links with the United Kingdom provide another indication of the importance of historical, political, and cultural relations for scientific collaboration.

Our last country profile (Figure 11) presents the collaborative profile of Japan. Even though in absolute numbers the United States is by far the most important partner of Japan, in relative terms it collaborates frequently with

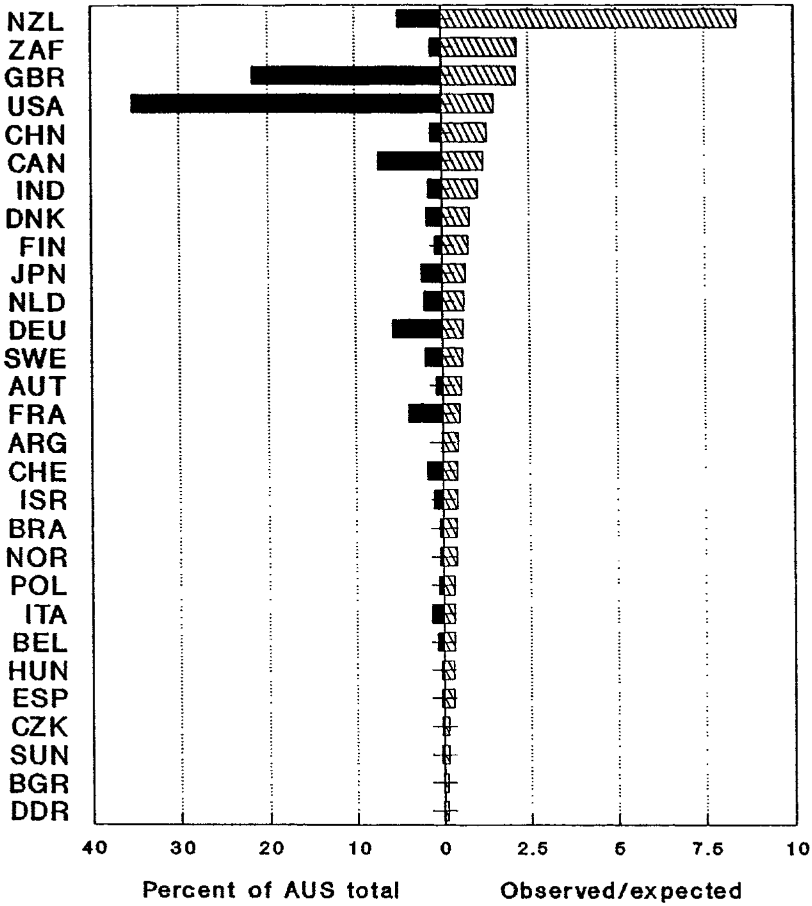

Figure 8. Australia: priorities in coauthorship relations, all fields combined, 1981-86.

its big Asian neighbors, the People's Republic of China and India. The importance of regional location is shown even by Brazil and Argentina, which have strong mutual linkages.[16]

To produce the observed/expected ratios of collaboration for the country profiles,[17] we used a formula that gives an asymmetrical picture of collaborations. To calculate the relative importance of country Y for country X we used the following formula:

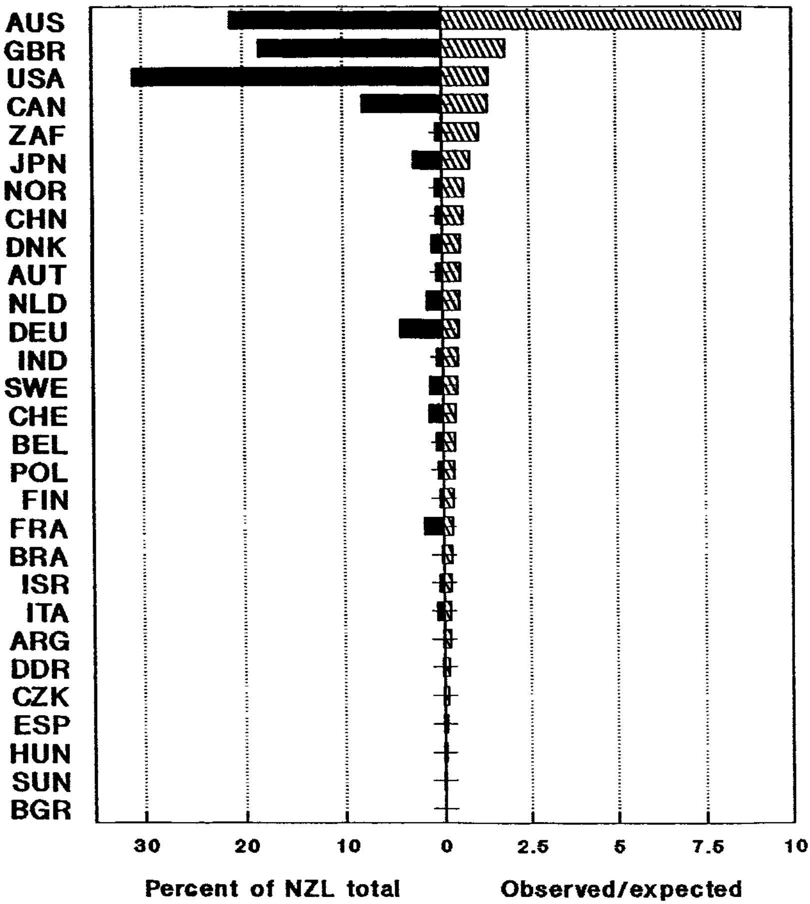

Figure 9. New Zealand: priorities in coauthorship relations, all fields combined, 1981-86.

$$[(C_{x,y} \times (T - C_x)]/(C_x \times C_y), \text{ where}$$

$C_{x,y}$ = number of collaborations between countries X and Y
C_x = total number of collaborations country X has with other countries in the matrix of thirty countries
C_y = total number of collaborations country Y has with other countries in the matrix of thirty countries
T = total number of collaborations in the matrix of thirty countries

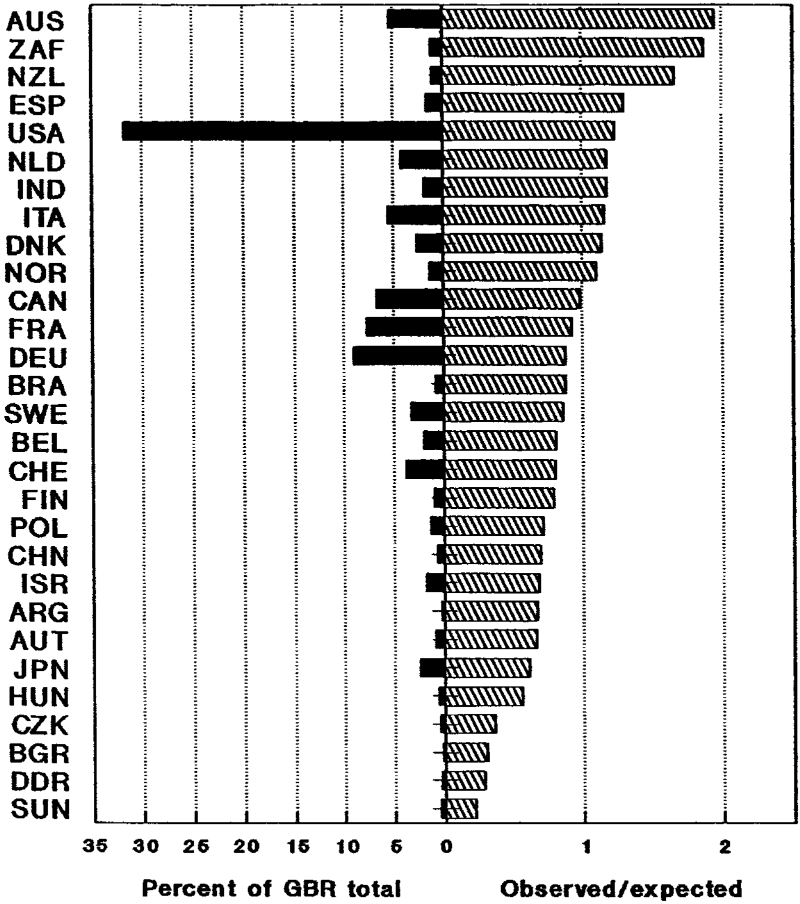

Figure 10. Great Britain: priorities in coauthorship relations, all fields combined, 1981-86.

The formulas used to calculate the observed/expected ratios (both symmetrical and asymmetrical values) overemphasize countries that have a highly skewed distribution of collaborations with one or two dominant partners. To give an example: Large numbers of scientists from country A seek to go to country B for doctoral studies. This eventually results in many papers coauthored with supervisors in country B, relatively speaking. If scientists in country A have very few scientific contacts with countries other than B, B

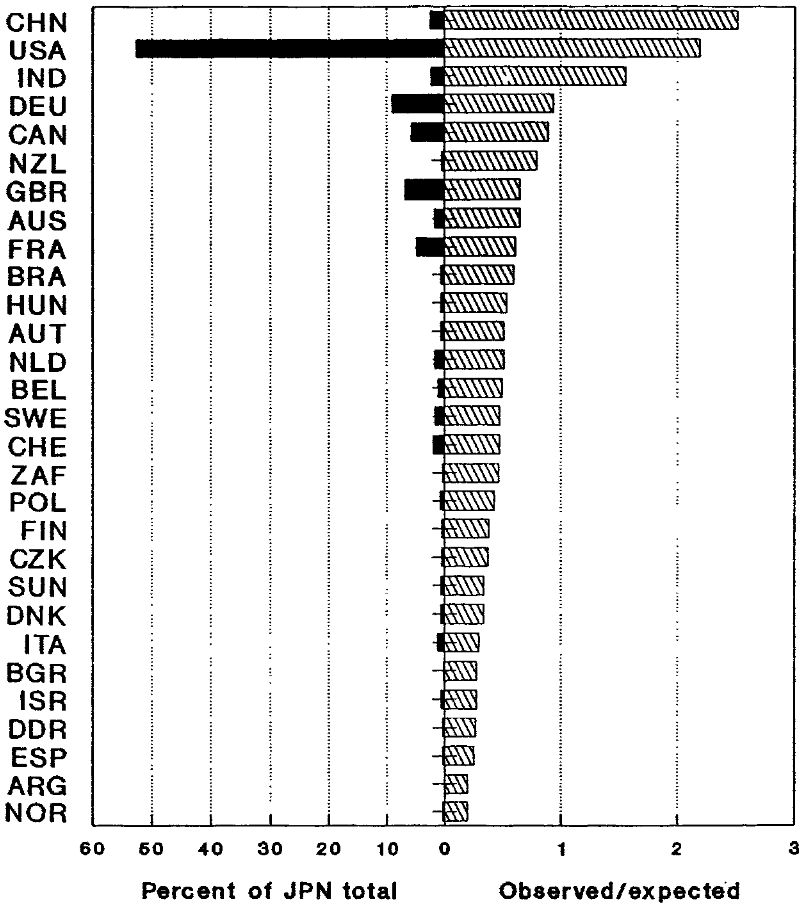

Figure 11. Japan: priorities in coauthorship relations, all fields combined, 1981-86.

features as the most important collaborative partner for A. As far as B is concerned, A seems important, since A's collaborations are highly concentrated with B and therefore the observed values far exceed those expected.

By this example, we also want to highlight that observed collaborative linkages are the result of choices made in *both* partner countries. By looking at the numbers alone, we cannot draw conclusions about the direction of the choices in terms of who takes the initiative.[18]

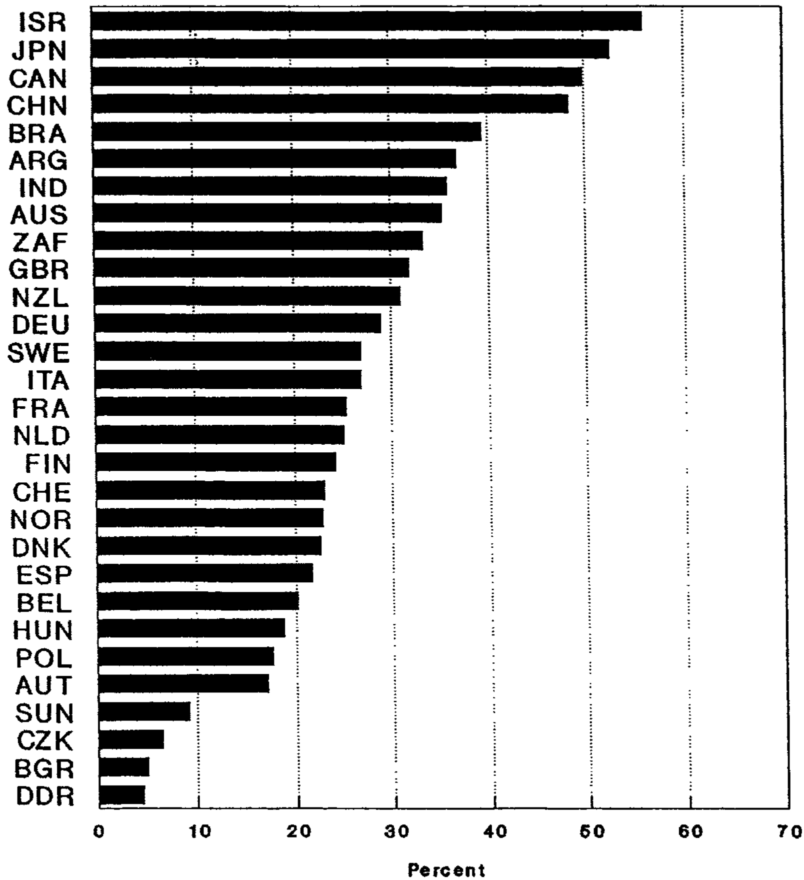

Figure 12. **Coauthorships with the United States: percentage of all bilateral coauthorships for each country, all fields combined, 1981-86.**

In Figures 4 to 11 we give the percentage distribution of the absolute numbers of collaborations. For most countries, the United States is a significant partner (Figure 12). Even though this result is to a large extent a consequence of the large absolute size of the U.S. scientific effort, it also highlights the central position of the United States in present-day science.

The collaboration networks among countries, as well as country-to-country relations, are somewhat different when we examine them by field.

Table 1. Percentage of Papers with International Institutional Coauthorships

Subject Area	*CHI 1973 Fixed Journal Set*[a] *1973*	*CHI 1973 Fixed Journal Set*[a] *1983*	*CHI 1981 Fixed Journal Set*[a] *1981-86*
Earth and space	5.38	11.80	11.09
Mathematics	5.47	10.78	11.35
Physics	4.39	9.45	9.79
Biomedicine	3.51	6.93	7.22
Biology	3.01	5.84	5.77
Chemistry	2.42	5.37	5.68
Engineering and technology	2.04	5.16	5.69
Clinical medicine	2.47	4.77	4.98

a. No new journals were added to the set after the specified date. The 1981 set is larger than the 1973 set.

The picture presented in Figures 4 to 12 reflects an average situation when all fields are taken together. The tendency of particular countries to concentrate differentially on the eight fields also affects their positions on the map. Countries that collaborate closely tend to have similar field profiles (in terms of published papers). This was confirmed by a comparison of the similarity of countries' field profiles and the collaboration clusters.

International Collaboration by Scientific Field

To see if there has been any change in the percentage of international coauthored papers, we examined their shares in 1973 and 1983 using the CHI 1973 fixed journal set data (i.e., with no new journals added between 1973 and 1983). Table 1 presents these data, together with the findings based on the 1981 expanded journal set.

The percentage of international institutional collaboration has about doubled over all fields in ten years. This is a very rapid rate of increase. The two right-hand columns cover nearly the same time period, and consequently they are approximately the same. The small variations are due to different coverage in the data sets.

The three fields that show the most collaboration in both the 1970s and 1980s are earth and space science, mathematics, and physics. The relative position of clinical medicine decreased most between the two periods, and by 1983 (as in the 1981-86 data) it had become the least internationally collaborative field.

Our findings corroborate the observations made by Frame and Carpenter in their study of international coauthorship patterns in eleven countries in 1973.[19] They concluded that the order of the fields in terms of their degree of international collaboration was linked with the basic and applied dimensions of research. They explained this finding by referring to the international orientation of more basic fields: Scientists in basic fields achieve recognition from the international research community and therefore are oriented toward this community and seek to foster international collaboration.

Nevertheless, there might be even more important reasons for collaborating internationally in some fields. Latour has eloquently described some early examples of the coordination of observations internationally in astronomy and geography; the coordination of observations was a prerequisite to the accumulation of scientific data.[20] Beaver and Rosen have confirmed that in early scientific collaboration, collaborative work centered on fields like astronomy that involve recording many routine observations and using routine techniques.[21]

There are several fields within earth and space science that require an international coordination of research resources and facilities, for example, astronomy, oceanography, and atmospheric and space science.[22] Unfortunately, we cannot disaggregate earth and space science data and ascertain the relative levels of international collaboration in the various fields and subfields. Nonetheless, we assume that at present an important reason for a large amount of institutional coauthorship collaboration in earth and space science might result from the high-cost telescopes, observatories, and other facilities that are internationally maintained and bring scientists from various countries together. This apparently holds even for physics, where in experimental high-energy physics internationally maintained accelerators provide an impetus for a high degree of international collaboration. If this is true, then financial as well as cognitive reasons (the need to coordinate observations made in various geographical sites, the international orientation of basic fields) might be important in explaining field-to-field differences in the degrees of international coauthorship.

What seems most puzzling in Table 1 is that mathematics has the highest or second highest percentage of internationally coauthored papers. Mathematics is largely a theoretical field, and the reasons presented above about the need to coordinate research activities on an international scale do not hold. Since the field is theoretical, scientists are not bound by instruments to

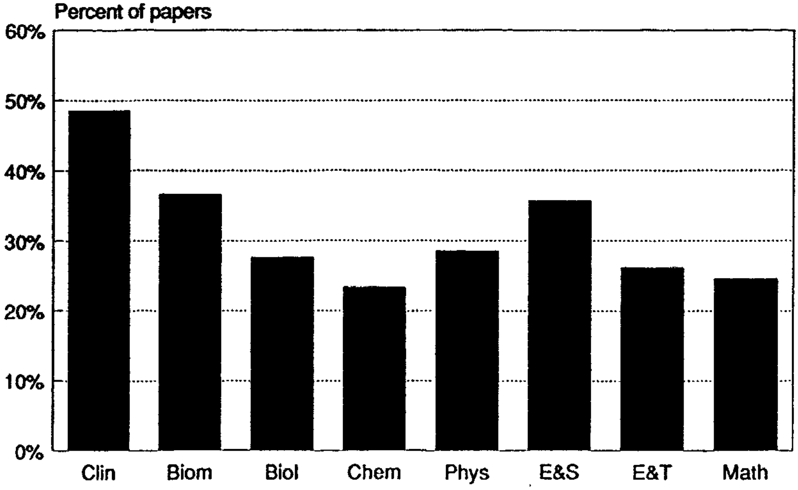

Figure 13. Multi-institutionally coauthored papers, ninety-seven countries, 1981-86.
NOTE: In Figures 13-15, the abbreviations of the fields are as follows: MATH = mathematics; E&S = earth and space science; PHYS = physics; BIOM = biomedicine; BIOL = biology; E&T = engineering and technology; CHEM = chemistry; CLIN = clinical medicine.

a given place and therefore, in principle, can easily move from one university or research institute to another. This fact might enhance their collaborative activities. This is, however, a question that needs to be studied further. We have also to bear in mind that mathematics is a small field, and to find colleagues in the same research area, mathematicians even in bigger countries may have to look abroad. The high rate of international collaboration in mathematics might also be partly occasioned by the limited coverage of the data base. According to Carpenter and Narin's study, mathematics is the smallest field in the *SCI*;[23] it is among the fields with the most limited coverage of journals in the *SCI* when compared with the more comprehensive set of journals in the British Library Lending Division. Also a relatively small proportion of the references from leading mathematics journals are given to journals that are included in the *SCI*.[24] In contrast, in biomedicine, clinical medicine, chemistry, and physics, leading journals give quite a high proportion of their references to *SCI* journals. This finding implies that the *SCI* covers a more selective part of mathematics literature, possibly the part in which international collaboration features most strongly.[25]

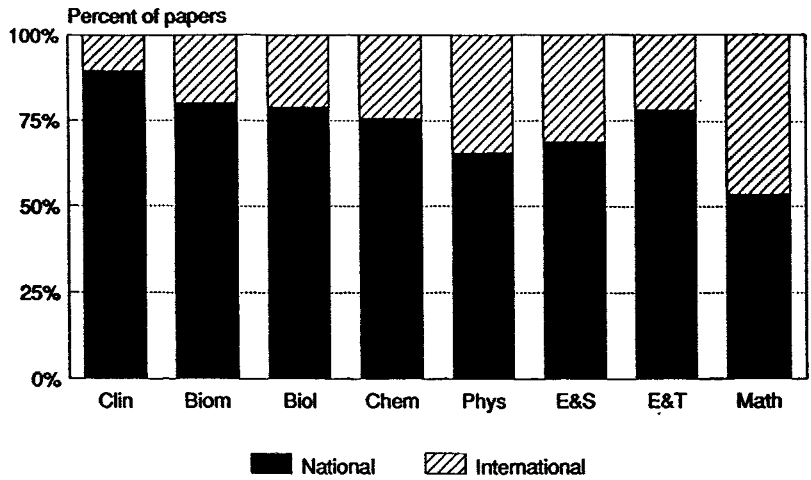

Figure 14. Multi-institutionally coauthored papers: national versus international coauthorships.

To complement our picture of the collaborative activities of scientific fields, we also studied their overall rate of institutional coauthorships and the importance of national versus international coauthorships (see Figures 13 and 14). Surprisingly, clinical medicine turned out to be the most collaborative field institutionally; we take this to be a close approximation of its overall level of collaboration. However, about 90% of all institutional collaborations occurred nationally. In clinical medicine, the incentives to collaborate might include the need to collect patient data from several hospitals (in order to have large enough sample sizes) and to complement clinical skills with experience in laboratory and statistical methods. Clinical medicine is a large field, the largest in the *SCI*,[26] and therefore scientists can expect to find collaborative partners in their own countries.

Because of the large absolute size of the U.S. scientific output, the average rate of national collaboration by scientific field (Figure 14) is largely determined by the U.S. figures. When we removed U.S. figures from the world average, there was a 20% decrease in the proportion of nationally coauthored papers (Figure 15).[27] The decrease was smallest in clinical medicine and largest in mathematics. Still, the relative differences in the rates of nationally coauthored papers by field remained nearly the same. This decrease high-

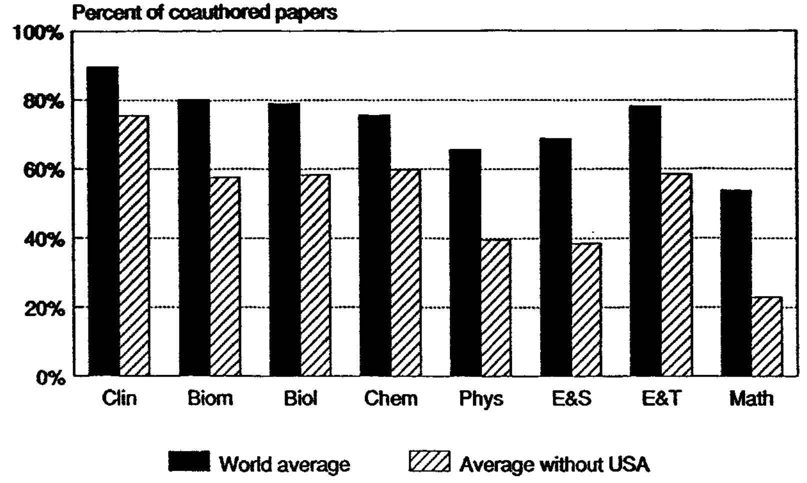

Figure 15. Nationally coauthored papers: world average with and without the United States.

lights the importance of a large national scientific community for national interinstitutional collaboration.

Mathematics is the field with the smallest proportion of nationally and largest proportion of internationally coauthored papers and with a low overall rate of collaboration.[28] When we removed the U.S. figures, the average percentage of nationally coauthored papers more than halved, which was a larger decrease than for other fields (Figure 15). This finding supports the view that if mathematicians wish to collaborate, they have to look for collaboration partners abroad.

This is still a preliminary investigation at a very aggregated level. More detailed studies are needed to ascertain patterns of collaboration in scientific fields. Such studies are also needed to understand the role and importance of national versus international collaboration in various scientific fields.

Conclusions

Data on institutional coauthorships provide an important tool for monitoring the effects of government programs that aim to encourage increased international cooperation either through bilateral and multilateral agreements or through other incentives. The availability of time-series data will also enable us to detect potential consequences of political changes, such as the recent political upheavals in Europe, which are likely to change relations between countries. Even though historical reasons appear in our data to be strong determinants of collaborative relations between countries, we can expect that there will be more East-West collaboration in Europe in the future.

When analyzing our data, we have had to consider all the possible factors that might explain differences in the degree of collaboration. Social factors (geopolitical aspects, history, language, and even cultural tradition) seem to be important influences on the collaborative networks among countries at the macro level. A closer analysis of the collaborative patterns of individual countries also points to relations of intellectual dependence: One country might be an intellectual center while others are more or less dependent on it.

Differences in the propensity of countries to collaborate internationally can be explained partly by intellectual influence: The less developed the scientific infrastructure of a given country, the higher the tendency for international coauthorship collaboration. We have outlined further reasons for this trend: With increasing specialization of science, scientists from countries with a small scientific output have to look for collaborative partners abroad; and there is also the need for cost sharing. Nevertheless, there is a large variation in the rates of international coauthorship collaboration between countries, and the relationship between the size of scientific output and the rate of international collaboration is relatively weak.

Economic reasons, for example, building and maintaining expensive international installations for experimental work, might largely explain the high rate of international collaboration in physics and in earth and space science. Nevertheless, these fields were not the most collaborative ones. Medical fields, and especially clinical medicine, had the highest rates of institutional collaboration when national collaborations were included. In the latter fields, collaborations were predominantly national. The reasons for the high rate of institutional collaboration in medical fields and for the high rate of international collaboration in mathematics are probably intellectual and social: a need to exchange skills and data in medicine and, given the small size of mathematics communities, a need to look for collaborative partners abroad in mathematics.

In medicine, the incentives to collaborate might be enhanced by the phenomenon of "publish or perish," which, according to our observations, is particularly pronounced in medical fields. The most obvious way to increase one's publication count is (1) by collaborating, through adding the "fractional papers" one has to those of others, and (2) through intellectual cross-fertilization, which collaboration enhances. As Price wrote, "The most prolific man is also by far the most collaborating."[29] Increasing pressures to publish or perish provide additional incentives to augment collaboration in all fields.

The recent finding of Narin and Whitlow (1990) concerning the higher rate of citations obtained by internationally collaborative European papers versus other European papers might bring about further political pressures on institutions to collaborate internationally. Nevertheless, when interpreting these findings, we have to remember that the better performance of internationally collaborative papers could not be attributed solely to the benefits of collaboration. It is conceivable that the individuals and institutes that collaborated internationally represented an elite group, which might have performed better than others even without international collaboration. Here again, there is a need for more micro-level studies of the patterns of collaboration of individual scientists and of the role of collaboration in professional achievement.

Notes

1. Beaver and Rosen (1978).
2. Beaver and Rosen (1978, 78).
3. Beaver and Rosen (1978, 71).
4. Beaver and Rosen (1979).
5. Edge (1979).
6. Stokes and Hartley (1989).
7. Price (1986, 160).
8. Price (1986, 160).
9. Price (1986, 126).
10. For a list of such benefits, see Beaver and Rosen (1978, 70).
11. According to the CHI data base, the thirty largest countries produced 97% of the world's scientific output in 1981-86.
12. In their study of twenty-six countries and twenty-eight fields of science, Narin and Whitlow (1990) also noted a weak correlation between size and coauthorship rate.
13. Cf. Tijssen and Moed (1989).
14. According to Kruskal (1964), the stress value of 20% represents poor, 10% fair, 5% good, 2.5% excellent, and 0% perfect goodness of fit. A "perfect" goodness of fit means that there is a "perfect monotone relationship between dissimilarities and the distances" (Kruskal, 1964).
15. Frame and Carpenter (1979).
16. Schubert and Braun (1990) claimed the opposite in their study of 167 countries. This is presumably because they used Salton's measure to gauge the strength of coauthorship links. Compared with our formula, Salton's measure tends to underestimate the strength of links between small science producer countries.
17. Observe that the scales of the observed/expected ratios are not equal in Figures 4 to 11, because of large differences between the country profiles.

18. Assumptions about the direction of choices of affinity are, nevertheless, made by Miquel and Okubo (1990). Besides, they do not control the size of countries, and consequently, their measure of collaboration combines the number of coauthorships and the volume of countries' scientific output.

19. Frame and Carpenter (1979).

20. Latour (1987, 215-28).

21. Beaver and Rosen (1978, 73-74).

22. Miles (1972).

23. Only 3.8% of the periodicals covered by the *SCI* in 1973 were in mathematics (Carpenter and Narin 1981).

24. This percentage ranges from 30% to 56%, while, for example, in biomedical research the corresponding percentages are from 82% to 90% (Carpenter and Narin 1981).

25. We would have liked to know whether theoretical and applied mathematics differ in their collaborative patterns. Unfortunately, given the limitations of our data, we could not study this question.

26. A total of 29% of the periodicals covered by the *SCI* in 1973 were in clinical medicine (Carpenter and Narin 1981).

27. By contrast, when we removed U.S. figures from multi-institutionally authored papers, world averages with and without U.S. figures were very close to each other.

28. The figures in Figure 14 are, nevertheless, very rough proxies of the patterns of interinstitutional collaboration in scientific fields. For example, if a particular paper has three coauthors, one from the United States and two from different institutional addresses in the United Kingdom, the paper has been classified as "institutionally coauthored." The papers that have authors from more than one institutional address, but all from the same country, have been classified as "nationally coauthored."

29. Price (1986, 126).

References

Beaver, D. deB., and R. Rosen. 1978. Studies in scientific collaboration. Pt. I, The professional origins of scientific co-authorship. *Scientometrics* 1:65-84.

———. 1979. Studies in scientific collaboration. Pt. 2. Scientific co-authorship, research productivity and visibility in the French scientific elite, 1799-1830. *Scientometrics* 1:133-49.

Carpenter, M. P., and F. Narin. 1981. The adequacy of the Science Citation Index (SCI) as an indicator of international scientific activity. *Journal of the American Society for Information Science* 32(November): 430-39.

Edge, D. 1979. Quantitative measures of communication in science: A critical review. *History of Science* 17:102-34.

Frame, J. D., and M. P. Carpenter. 1979. International research collaboration. *Social Studies of Science* 9:481-97.

Kruskal, J. B. 1964. Multidimensional scaling by optimizing goodness of fit to a nonmetric hypothesis. *Psychometrica* 29:1-27.

Latour, B. 1987. *Science in action.* Milton Keynes: Open University Press.

Miles, E. 1972. Transnationalism in space. In *Transnational relations and world politics,* edited by R. O. Keohane and J. S. Nye, 252-75. Cambridge: Harvard University Press.

Miquel, J.-F., and Y. Okubo. 1990. Indicators to measure internationalization of science. Paper presented at a conference organized by the Organization for Economic Change and Development, Consequences of the Technology Economy Program for the Development of Indicators, Paris, 2-5 July.

Narin, F., and E. S. Whitlow. 1990. *Measurement of scientific cooperation and coauthorship in CEC-related areas of science.* Vol. 1. Brussels: Commission of the European Communities (EUR 12900 EN).

Price, D. de S. 1986. *Little science, big science . . . and beyond.* New York: Columbia University Press.

Schubert, A., and T. Braun. 1990. International collaboration in the sciences, 1981-1985. *Scientometrics* 19:3-10.

Stokes, T. D., and J. A. Hartley, 1989. Coauthorship, social structure and influence within specialties. *Social Studies of Science* 19:101-25.

Tijssen, R.J.W., and H. F. Moed. 1989. Literature-based statistical analyses of international scientific co-operation: An exploratory case study of the Netherlands. In *Science and technology indicators: Their use in science policy and their role in science studies,* edited by A.F.J. van Raan, A. J. Nederhof, and H. F. Moed, 129-45. Leiden: DSWO Press.

Terttu Luukkonen, a Visiting Fellow at the Science Policy Research Unit, University of Sussex, England, when this study was completed, is Researcher at the Academy of Finland (P.O. Box 57, 00551 Helsinki, Finland). She has pursued research on women's scientific careers, bibliometrics, and research evaluation. She currently working on the uses and impacts of science policy evaluations.

Olle Persson is Associate Professor at the Inforsk group, University of Umeå, Sweden. He has completed studies in scientific communication, and his present work focuses on the use of bibliometric methods as science indicators.

Gunnar Sivertsen is Researcher at the Institute for Studies in Research and Higher Education, Oslo, Norway. His main areas of research are scientific publishing in the Nordic countries and bibliometric indicators.