International collaboration in science: a new dynamic for knowledge creation
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Chapter IV

Six Case Studies of International Collaboration in Science

Access to knowledge is important as a motivator [for collaboration]. But the social part is important, too. You are looking for an interesting topic, you want to work with someone you respect, someone you know. The result is more creative, more than just a joining together of capabilities.

—J.D. Hamkins, a mathematician interviewed for the project
Six case studies of international collaboration in science

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Six case studies of international cooperation at the subfield level are presented and compared. The cases examine international collaboration by detailing co-authorship links among researchers by field, evidenced at the level of the nation. Cases are offered based on possible drivers for collaboration: sharing ideas, cooperating around equipment, cooperating around resources, and exchanging data. Scientometric and network analysis of linkages are presented and discussed for each of the six cases: astrophysics, geophysics, mathematical logic, polymers, soil science, and virology. Visualizations of the cosine matrices within each field are compared for 1990 and 2000. The research shows that international collaboration grew in all the fields at rates higher than the international average. The possibility that rapid increases in international collaboration in science can be attributed in part to certain drivers related to access to resources or equipment sharing could not be upheld by the data. Other possible explanations for the rapid growth of collaboration are offered, including the possibility that weak ties evidenced by geographically remote collaboration can promote new knowledge creation.

Context for this research

A number of studies have demonstrated that international collaboration in science and technology is increasing. (NARIN, 1991; LUUKKONEN et al., 1992 and 1993; MIQUEL, 1994; DORE, 1996; GEOERGHIOS, 1998; GLANZEL, 2001; WAGNER & LEYDDESORFF, 2004 forthcoming). Research shows that international collaboration is increasingly collaborative (GIBBONS et al., 1994), the network is growing (WAGNER & LEYDDESORFF, 2004 forthcoming), and the global system is becoming more integrated (PERSSON & MELIN, 2002). Despite this body of evidence, it remains unclear why this class of research is growing so quickly. Indeed, it has been observed that a theoretically satisfying explanation of the phenomenon has yet to be offered (KATZ & HICKS, 1997; WAGNER-DOBNER, 2001).

The theoretically satisfying explanation may be elusive in part because we have an incomplete understanding of the dynamics of collaboration at the global level and how it differs from nationally or institutionally based research or localized collaboration.
This paper examines networks of collaboration among countries at the disciplinary level to add information about the structure and nature of international collaboration. This article complements similar analysis conducted at the global level (WAGNER & LEYDESDORFF, 2004 forthcoming). Forthcoming research will address the theoretical aspects of international collaboration between countries, while this article focuses on dynamics of collaboration within fields of science.

Focus of this article

This article examines international collaboration at the subfield level by exposing a cluster of related journals and counting co-authorships within them to add to understanding of dynamics of international collaboration at this level. The questions asked are: What is the nature of the collaborative network within the subfield at the global level and how is it different from the collective global network? Do the networks exhibit different dynamics based upon the scientific inquiry being pursued? Which dynamic is more influential on the organization of collaboration: the global dynamic or the intellectual organization of the field itself? For comparative purposes, and as a way to approximate the dynamics of change, data is examined for two years, 1990 and 2000.

GLANZEL & DE LANGE (2002) found that the extent of multinational collaboration was strongly field specific. EGGHE (1999) found that the distribution of partner countries over the international co-publications proved much more flexible and less skewed than the geometric model. MELIN (2000) suggested that collaborations take different forms based on the field that the collaborators belong to. These observations suggest that there may be field-specific motivations for collaborative patterns that cannot be seen by looking at the highest-level data.

The expectation explored here is that the motivation of practitioners to collaborate with geographically remote colleagues will vary by field of science based on the drivers for collaboration. In other words, the intellectual organisation of the field is expected to exert more influence on the willingness of practitioners to cooperate with each other than will the overall trend towards international collaboration. As a result, the expectation is that the extent of growth in international linkages will differ across subfields.

Scientific collaborations – where practitioners work together on a specific research project with a common goal – take many forms. The willingness of practitioners to collaborate is influenced by the goals of those providing the funding (e.g., government agency or philanthropic foundation), the needs of researchers for access to knowledge and research tools, the availability of these resources, and the opportunities of practitioners to link together (e.g., conferences, Internet connection) (WAGNER, 1997; BEAVER, 2001; LAUDEL, 2001). Within a subfield of science, practitioners interact, or cooperate, with other scientists in a variety of ways, including face-to-face meetings,
sharing papers and data, attending seminars and workshops, sharing equipment; the most intense being collaboration in research experimentation. MELIN (2000) and BEAVER (2001), using an interview approach, found the practitioners collaborate in order to access methods, equipment, special competence or data. Co-authored papers represent some subset of collaborative activities\(^1\) (MELIN, 2000).

It is widely acknowledged that scientific researchers seek to share ideas (cooperate) (PRICE, 1964; BEAVER & ROSEN, 1978; WHITLEY, 1984). The cooperative community within open science is complemented by the interests of a subset of practitioners within science to collaborate – to jointly conduct research experimentation that has a common research goal. However, since collaboration has higher transaction and opportunity costs than simply cooperating, we expect that the drivers motivating collaboration will be related more to structural items such as equipment (such as a telescope) and or resources (such as access to soil samples). Indeed, one might expect to find that equipment and resource sharing offer more compelling reasons to collaborate at a distance than will be the sharing of ideas alone. (For example, NEWMAN (2000) found that the average number of collaborators is markedly lower in the purely theoretical disciplines than in the experimental ones.) The underlying assumption is that explicit knowledge embodied in data and theoretical ideas are more easily shared at a distance without collaborating, while new knowledge that emerges from equipment or resource-based research requires more physical interaction, and therefore are more tacit in nature.

### Choosing fields of science for analysis

Six fields of science were chosen for analysis, each representing a different possible intellectual organization for collaborative research and each expected to be of interest to researchers from different countries. Acknowledging that there may be overlaps, and that categorisation requires some subjective judgment, scientific inquiry is categorised principally into one of four areas, making up a typology of the sciences: 1) data driven, 2) resource driven, 3) equipment driven, and 4) idea or theory driven. These categories help identify the factors affecting the organisation of research, and they are expected to affect interest in collaboration. These categories are useful for discussing collaboration because they represent the factors (data, equipment, resources, and ideas) that are often cited in literature (particularly normative literature) by practitioners seeking or participating in collaborative ventures (SCHOTT, 1998; BEAVER, 2001).

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\(^1\) Some discussion in the literature has questioned the extent to which co-authorships reflect actual collaboration. According to KATZ & MARTIN (1997) and LAUDEL (2002), collaboration at the individual level is only in part reflected by co-authorship. The literature further suggests that an under-representation of collaboration applies most closely to intramural collaboration. Extramural collaboration at the international level, however, may still understimate the intramural component of the work, but is less likely to under-represent international links (MELIN & PERSSON, 2002).
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Table 1 provides a notional concept of this typology, showing some fields of science as they would be classified within this scheme.

<table>
<thead>
<tr>
<th>Data-driven collaboration</th>
<th>Resource-driven collaboration</th>
<th>Equipment-driven collaboration</th>
<th>Idea, theory-driven collaboration</th>
</tr>
</thead>
<tbody>
<tr>
<td>biomedical</td>
<td>oceanography</td>
<td>high energy physics</td>
<td>mathematics</td>
</tr>
<tr>
<td>genetics</td>
<td>geology</td>
<td>astronomy</td>
<td>economics</td>
</tr>
<tr>
<td>demography</td>
<td>seismology</td>
<td>energy</td>
<td>sociology</td>
</tr>
<tr>
<td>computer</td>
<td>zoology</td>
<td>avionics</td>
<td>anthropology</td>
</tr>
<tr>
<td>epidemiology</td>
<td>soil science</td>
<td>polymers</td>
<td>science studies</td>
</tr>
<tr>
<td>virology</td>
<td>anthropology</td>
<td>manufacturing</td>
<td>philosophy</td>
</tr>
</tbody>
</table>

Scientific or technical researchers report that geographically-remote collaborations are motivated by one or a combination of several factors: 1) sharing data that each partner may have (or be able to create), or providing complementary data analysis capabilities; 2) sharing the costs of creating and maintaining large-scale equipment or high cost, long-term research; 3) accessing scarce or unique resources; 4) seeking to enhance creativity of research by exposing ideas to a broad audience (WAGNER et al., 1997; WAGNER et al., 2001). The expectation is that international collaboration is motivated more by the need to share costs and access resources (motivations 2 and 3) than it is to share the collection or analysis of data or to expose theory to critique (motivations 1 and 4).

To explore this assertion, and to test the characterization of fields of science, six cases have been examined. To support a more in-depth look at resources and equipment as the motivating factors for collaboration, two cases each are conducted for these features. The fields analysed are:

1. Virology (data-driven scientific inquiry)
2. Geophysics, and 3) Soil Science (resource-driven scientific inquiry)
3. Astrophysics, and 5) Polymers (equipment-driven scientific inquiry)

This process creates a number of different data; these are listed in Figure 1 as products of steps 3 and 4. They are explained and presented below.

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2 I am grateful to Cooper Langford for suggesting this case study as fitting well within the requirements of the study.

3 The choice of mathematical logic as a field draws from earlier research by Wagner-Döbler (1993, 1997, and 2001) into collaboration within this field. I am grateful to Andrea Scharnhorst for bringing this literature to my attention.
Data sources and data processing

In order to explore the structure of the fields and the extent of international collaborations in each case, a series of cascading analyses are applied. The first part identifies the citing relationships within the fields to uncover the cluster of journals that scientists identify when citing other published work relevant to their field. Secondly, for the years 1990 to 2000, all addresses of the articles in the relevant journal clusters were collected and the international set was isolated. In the third step, networks of linkages among scientists at the international level are created. In the fourth step, the percentage of articles being internationally co-authored within these years was analysed to view the extent to which the fields had grown as international disciplines. Finally, the outcomes of these analyses are compared to the global level. Each step is described in more detail below.

Three types of data are collected and analysed in this study: 1) journal-journal citations to enable subfield identification; 2) publications and international co-authorships within the identified journals at the subfield level; 3) the network of collaborations at the international level, using co-authorships, within the subfields for 2 years, 1990 and 2000. The methodology of each data set is discussed here.
1. Research shows that aggregated scientific journal-journal citations can be exploited to expose patterns of interrelationships within and among fields of science. (CARPENTER & NARIN, 1975; DOREIAN & FARARO, 1985; TUSSEN et al., 1987). LEYDESDORFF & COZZENS (1993) show that journal-journal citations can be used to define the disciplinary structure of science. The environment for these cases was determined by conducting an analysis of the citing relationships among journals based on factor or eigenvector analysis, identifying a central tendency journal, and then finding the journals with citing relationships to it. The resulting list of journals constitutes a journal cluster (WOUTERS, 1999; MULLINS, 1988; LUUKONEN et al., 1993).

LEYDESDORFF (2002) has argued that the journal set used to delineate a changing situation cannot be chosen ahead of time, but must be selected with hindsight, that is, after the change has occurred. He suggests that the analysis seeking to shed light on the current shape of the discipline should choose the content of the journal set according to a posteriori standards, and then the analysis should backtrack from the present to the past. Thus, the outlines of the disciplines in 2000, revealed by the citation relationships, become the boundaries of the field for purposes of comparison with journals in 1990. This method has the advantage of identifying the sub-field from the bottom-up: discerning how scientists themselves identify their field by identifying the journals they cite, rather than imposing a pre-conceived structure on the field. The year 2000 is the base year: the journal set identified in 2000 is also used in 1990, held constant for comparative purposes (Figure 1, step 1). The method has the disadvantage that the journal set for 1990 is almost always smaller than the set in 2000.

2. For each of the cluster of journals created for the cases, all the related records were collected for the years 1990 and 2000 from the Science Citation Index-Extended available through the Web of Science. Co-author names and affiliations were then obtained from the resulting data files. These data were separated by a) authors and b) addresses to allow identification of linkages among authors by country (Figure 1, step 2). Using custom computer programs written for these purposes, the data were analysed to reveal the number and extent of internationally co-authored articles by field, the number and percentage of co-authorships.

3. Attaching addresses to the co-author links identified in the step described above, the co-authorship data were further analyzed as relational data, representing communication links among authors at the level of nations (SCOTT, 2000). This is visualized first as a co-occurrence matrix in SPSS and then as a network in Ucinet to reveal both an observed network (containing all links created by co-authoring relationships) and a weighted network based on the cosine between variables.

4 The data presented here are drawn from the databases of the Institute for Scientific Information SCI and JCR CD-ROM data. The JCR CD-ROM data consist of listings of all journals processed and included for 1994-2001.

5 This includes articles, reviews, proceedings, notes, signed editorials, letters, and book reviews.

6 The data were collected between May 2002 and July 2003.
Both the observed data and the cosine analysis were exported to Pajek for illustration (Figure 1, step 4) (BORGATTI et al., 2002). A k-core analysis conducted on these cases reveals networks showing the most intense relationships among authors from different countries. The cosine matrix was used as a similarity criterion because, in related analysis, it was found to be most illustrative of the relationships we were researching (WAGNER & LEYDESDORFF, 2004 forthcoming; AHLGREN et al., 2003). Thus, in keeping with GLÄNZEL (2001), we have used the cosine similarity measure to view the networked relatedness of countries and as the basis for network drawings presented here.

These data were then compared across the six cases. (Figure 1, step 3.)

Findings

An analysis of collaboration at the disciplinary level shows that international collaboration as evidenced by co-authorships has grown significantly over the 10 years examined. The fields examined for the case studies grew at a rate higher than the world rate of growth for collaboration reported in WAGNER & LEYDESDORFF (2004 forthcoming).

<table>
<thead>
<tr>
<th>Case study</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of journals in the cluster</td>
<td>2000</td>
<td>1990 2000 % increase</td>
<td>1990 2000 % increase</td>
<td>1990 2000 % increase</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Astrophysics</td>
<td>14</td>
<td>4472 6547 46</td>
<td>1301 3097 138.0</td>
<td>29 47.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mathematical Logic</td>
<td>6</td>
<td>131 309 136</td>
<td>27 117 333.3</td>
<td>21 37.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polymers</td>
<td>13</td>
<td>3469 5242 51</td>
<td>269 1046 288.8</td>
<td>7.8 20.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geophysics</td>
<td>13</td>
<td>1654 2789 69</td>
<td>237 921 288.6</td>
<td>14.5 34.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil Science</td>
<td>10</td>
<td>968 1382 43</td>
<td>107 453 323.4</td>
<td>11 32.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Virology</td>
<td>9</td>
<td>2331 2878 25</td>
<td>327 676 106.7</td>
<td>14 23.5</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

7 The program Pajek is freely available for non-commercial use at http://vlado.fmf.uni-lj.si/pub/networks/pajek

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This supports the assumption that these fields are of interest to researchers from different countries. Table 2 summarizes the data created and presents the quantitative outcomes of collaboration within the cases.

Table 2, column B shows the number of journals that are included in the cluster of the citing environment for the respective discipline in the year 2000. Columns C and D show the total number of journal articles that were downloaded for that cluster in 1990 and in 2000. The aggregates differ considerably among the journal clusters, with the discipline with the fewest articles being Mathematical Logic with a total number of 440, and the field with the highest number being Astrophysics with 11,019 articles (Also see HUBER & WAGNER-DÖBLER (2001) on mathematical logic.).

Table 2, column E shows the percentage change in the number of articles appearing in each cluster in the two years examined. In each case, the number of papers published in total (by a singleton or joint authorship) increased by at least 20 percent in the 10 years studied. As shown in column E, the percent increase for all publications (not just collaborative publications) was highest for Mathematical Logic at 136 percent, and lowest was for Virology with 25 percent increase. As noted above, the increase may, in part, be an artefact of the methodology. (The list of related journals revealed through the citation analysis, defining the field in 2000, is also the list used in 1990.) The field is not redefined in 1990, the field definition for 2000 is used, and so no new journals are included in the analysis in 1990. Because of this procedure, the list of journals used in 1990 cannot be larger than the list used for 2000, and they are almost surely smaller than the 2000 sets.

The percentage of articles within each case that are internationally co-authored is also presented in Table 2. Columns F and G show the number of internationally co-authored articles identified within each of the fields in 1990 and 2000. Column H shows the percentage increase in 2000 over 1990. The largest percentage increase in internationally co-authored articles is in Mathematical Logic, with a 333 percent increase over ten years, admittedly from a low base. The smallest increase is in Virology, with 107 percent increase.

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8 Seismology and geophysics are considered as one field of science for the purpose of this chapter and the discussion of the cases. A separate study finds that seismology emerges from within geophysics in the time period studied, but, since it did not exist in 1990 as a separate field, the two fields are treated as one in this article (see WAGNER & LEYDESDORFF, 2003).

9 It is interesting to note that the data at the subfield level shows significantly higher percentages of growth in collaboration than at the global level. For example the National Science Board Science & Engineering Indicators 2000 (Appendix Tables) show that, for all fields of science in 1988 and 1997, the average number of papers was 459,175 and 515,708 respectively, an 11 percent increase. In related research, Loet Leydesdorff and I found that the global rate of growth was 15.6 percent between 1990 and 2000 (WAGNER & LEYDESDORFF, 2004 forthcoming). In forthcoming research, Persson et al. find that, between 1980 and 1998, international co-authorships increased by 45 percent, while national co-authorships increased by 26 percent.

10 For example in the field of geophysics, in 2000, 13 journals are identified in 2000. Of these, 7 were being published in 1990. This field had the greatest number of journal entrants over the 10 years examined.
Table 2 Columns I and J show the percentage of all articles that are internationally co-authored. The field with the highest percentage of internationally co-authored articles is Astrophysics, with 47.3 percent of all articles in 2000 co-authored at the international level; this field also had the highest percentage of international co-authorship in 1990. Behind Astrophysics, Mathematical Logic is the next most highly connected at the international level, with 37.9 percent of all articles published. The least internationally interconnected field in 2000 is polymers with 20 percent co-authored; it was also the least interconnected field in 1990. Table 3 shows the rank order of six case studies (in descending order from most to least internationalized) by the percent of co-authorships at the international level: the rank order changes little from 1990 to 2000.

The only change over the decade is that Soil Science appears one notch higher than it did in 1990. Otherwise, as Table 3 shows, the concentration of international activity in the fields, relative to each other, has remained unchanged.

<table>
<thead>
<tr>
<th>1990</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Astrophysics</td>
<td>Astrophysics</td>
</tr>
<tr>
<td>Mathematical Logic</td>
<td>Mathematical Logic</td>
</tr>
<tr>
<td>Geophysics</td>
<td>Geophysics</td>
</tr>
<tr>
<td>Virology</td>
<td>Soil Science</td>
</tr>
<tr>
<td>Soil Science</td>
<td>Virology</td>
</tr>
<tr>
<td>Polymers</td>
<td>Polymers</td>
</tr>
</tbody>
</table>

**Geographic participation in collaboration**

The next step in the analysis examines the relationship of co-authorships and publications by the number of countries whose authors are represented in the address lines. This enables a view into the geographic reach of participation by field, and a comparison of the spread of collaboration over the decade of the 1990s.

Table 4 shows a rank order of fields with the widest distribution of research cooperation in both years – that is, those fields with the largest number of country names in the list of addresses. The fields with the largest number of countries participating in the network are Virology, Soil Science, and Polymers. As shown in Table 4, in 2000, these three fields each have more than 80 countries in the network of co-authorships represented by the citing cluster. Virology has more than 90 different country names represented in the address lines of articles within the cluster of journals related to the field in 2000. Like the extent of international connectivity of fields, shown in Table 2, the relative relationship of the fields does not change from 1990 to 2000 – all the fields grew, but they did not change relative to each other. The rank order remains the same.
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Table 4. The number of countries whose addresses appear in the cluster of relevant journals, ranked in order of fields that have the most to the least number of countries participating in international cooperation, 1990 and 2000, and percentage increases by field

<table>
<thead>
<tr>
<th>Field of science</th>
<th>Number of countries participating in the international network</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1990</td>
</tr>
<tr>
<td>Astrophysics</td>
<td>57</td>
</tr>
<tr>
<td>Mathematical Logic</td>
<td>23</td>
</tr>
<tr>
<td>Polymers</td>
<td>58</td>
</tr>
<tr>
<td>Seismology and Geophysics</td>
<td>57</td>
</tr>
<tr>
<td>Soil Science</td>
<td>60</td>
</tr>
<tr>
<td>Virology</td>
<td>62</td>
</tr>
</tbody>
</table>

Although the ranking of countries does not change between 1990 and 2000, the percentage increase shows variation among the cases. The field with the lowest number of countries participating in the network in 1990 – Mathematical Logic – shows the greatest percent increase (39 percent) in the participation of new countries in 2000. All the other fields cluster around 25 to 32 percent increases in the number of countries participating at the global level.

It is important to note that the percentage increase in the number of countries participating at the international level (Table 4) is different from the change in the extent of internationalization of co-authorships (Table 3). The distribution of the network (Table 4) – represented by the number of countries appearing in the address lines of articles – shows a geographic representation of scientific capacity and interest of practitioners to collaborate in that field. On the other hand, the extent of internationalization of fields (Table 3) is an indication of the methods of knowledge creation, and the interest of scientists to work with colleagues whose interests, competence, or complementarities aid their research. It is possible to imagine that an increase in international collaboration (Table 3) could occur without the added dimension of a spread in the geographic distribution of the participants (Table 4). As an illustration, consider the possibility that, within the country set for a field in 1990, a greater number of practitioners are attracted to work at the international level, but this happens without adding researchers from “new” countries. This scenario would show an increase in the number of international co-authors in Table 3 without adding any new countries to the network in Table 4. It is certainly interesting that both indicators show increases across all the fields of science studied. We will be returning to this observation in the discussion of the data.
A visualization of the networks provides insights into the structure of the fields, showing that each of the fields of science has experienced growth in the number of participants and in the number of linkages over the ten years. The co-authorships at the country level within each field can be analysed to reveal the nature of the networks of researchers across international lines (WAGNER & LEYDES/DORFF, 2004 forthcoming). Networks can provide useful information about the dynamics of interconnection, interdependence, and connection among researchers working in different countries. They can show which countries can be considered the strongest partners, where regional groupings are important, and to what extent smaller or peripheral countries participate in international research. In this case, they show that the networks have grown independent of the organizing motives for different types of sciences.

Figure 2. Network of international co-authorships. Mathematical Logic, 2000 (cosine a 0.05)
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Figure 3. Network of international co-authorships, Mathematical Logic, 1990 (cosine ≥ 0.05)

Figure 4. Network of international co-authorships, Polymers, 2000 (cosine ≥ 0.05)
The networks provide a different view of the shifting nature of international collaboration than that shown by the descriptive statistics alone. Figures 2 and 3, for example, show the field of Mathematical Logic. Of the six cases examined, this field had the least populated network in 1990 (Figure 3). Although the network becomes more populated by 2000, it is still largely a star network with the United States at the center. This feature of network structure is more characteristic of networks in 1990, when the U.S. can be shown to hold a center position in a number of networks, but by 2000, most fields had become more diversified and dispersed (WAGNER & LEYDESDORFF, 2004 forthcoming). Figures 4 and 5 help to illustrate this shift from a center-periphery model to a networked model. The field of polymers in 1990 (Figure 5) shows a star network with the United States in the center. By 2000 (Figure 4), the network exhibits a number of hubs and participation by more countries.

To further explore the geographic distribution of collaborative partners, country participation is analysed using cosine analysis. The resulting data is presented in Table 5. Cosine analysis allows a normalization of the data in a way that reveals patterns of participation among the most active participants in the networks. This analysis provides a different view on geographic distribution than the observed level.
Table 5. Cosine analysis (≥ 0.01) of number of countries in the k-core of the network of collaborating countries

<table>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Astrophysics</td>
<td>57</td>
<td>76</td>
<td>18</td>
<td>32</td>
<td>33</td>
<td>43</td>
</tr>
<tr>
<td>Mathematical Logic</td>
<td>23</td>
<td>38</td>
<td>4</td>
<td>17</td>
<td>12</td>
<td>32</td>
</tr>
<tr>
<td>Polymers</td>
<td>58</td>
<td>82</td>
<td>8</td>
<td>14</td>
<td>20</td>
<td>24</td>
</tr>
<tr>
<td>Seismology and Geophysics</td>
<td>57</td>
<td>82</td>
<td>9</td>
<td>16</td>
<td>19</td>
<td>23</td>
</tr>
<tr>
<td>Soil Science</td>
<td>60</td>
<td>85</td>
<td>8</td>
<td>13</td>
<td>13</td>
<td>15</td>
</tr>
<tr>
<td>Virology</td>
<td>62</td>
<td>91</td>
<td>14</td>
<td>23</td>
<td>13</td>
<td>14</td>
</tr>
</tbody>
</table>

Table 5 adds and compares new data with that presented in Table 4. The list from Table 4 is compared to new data analyzing similarity patterns. If the fields were ranked by the percent of participating countries that are also in a k-core group\(^\text{11}\) – a highly active sub-group within the network – in the year 2000, the rank order would be different from the list resulting from an aggregate number of countries. Ranked by the k-core group, Astrophysics has the largest number of countries in the k-core, followed by Mathematical Logic, Polymers, Seismology/Geophysics, Soil Science, and Virology.

Table 5. Cosine analysis (≥ 0.01) of the number of countries in the core group of cooperating countries, 2000 and 1990, ordered by rank with the most to the least number of countries participating in the network.

This analysis suggests that the core group of researchers working within the fields of Astrophysics and Mathematical Logic are highly networked, actively linked group who frequently co-author among themselves. Virology and Soil Science, on the other hand, might be considered more "open" networks where linkages are weaker and possibly easier to make and where new entrants may find it easier to participate. Figures 6 and 7 illustrate the cosine networks at ≥0.05 for Astrophysics and Figures 8 and 9 for Soil Science to illustrate the two ends of the spectrum from closed to open networks.

\(^\text{11}\) The list was derived within Pajek using the algorithm found in KAMADA, T. & S. KAWAI (1989), An algorithm for drawing general undirected graphs, Information Processing Letters, 31 (1): 7–15.
Figure 6. The network of international co-authorships, Astrophysics, 2000 (cosine $\alpha = 0.05$)

Figure 7. The network of international co-authorships, Astrophysics, 1990 (cosine $\alpha = 0.05$)
Figure 8. The network of international co-authorships, Soil Science, 2000 (cosine α 0.05)

Figure 9. The network of international co-authorships, Soil Science, 1990 (cosine α 0.05)
Figure 10. The network of international co-authorships. Virology, 2000 (cosine ≥ 0.05)

Figure 11. The network of international co-authorships, Virology, 1990 (cosine ≥ 0.05)
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Figure 12. The network of international co-authorships, Geophysics, 2000 (cosine = 0.05)

Figure 13. The network of international co-authorships, Geophysics, 1990 (cosine = 0.05)
The cosine analysis for Virology and Geophysics reveal networks that they are highly interconnected in 2000 (Figures 10-13). Of the two fields, however, Virology (Figures 10 and 11) appears to be a more open network than Geophysics (Figures 12 and 13); with many more countries in the core group of participants than is the case in Geophysics. This suggests that Geophysics has a pattern similar to Astrophysics in that a group of co-authors work together frequently, and new entrants find it harder to break into collaboration at the international level.12

Table 6 suggests a scheme for viewing the cases in terms of their network and geographic distribution. All the fields are networked and each show a degree of geographic distribution. Along a spectrum that could start with the networked to highly networked, and dispersed to highly dispersed, the cases would take positions relative to each other, along the lines suggested in the table.

<table>
<thead>
<tr>
<th></th>
<th>Networked</th>
<th>Highly networked</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dispersed</td>
<td>Polymers</td>
<td>Astrophysics: Math Logic</td>
</tr>
<tr>
<td>Highly dispersed</td>
<td>Virology</td>
<td>Soil Science: Geophysics</td>
</tr>
</tbody>
</table>

Discussion of the data

This research was undertaken to explore the nature of international collaboration at the disciplinary level. The analysis sought to test whether different motivations for collaboration affect the extent of and patterns of the internationalization of research evidenced by co-authorships. The patterns of collaboration within four types of sciences were exposed, illustrated, and compared. Contrary to the expectation, the drivers proposed appear to have little explanatory capacity when used with these case studies.

The expectation that resource-driven or equipment-driven sciences were more likely to show growth in international collaboration than data-driven or theory-driven science could not be shown with this data. In fact, the theory-driven science studied – Mathematical Logic – showed the greatest percentage increase in the number of internationally co-authored articles with a 333 percent increase over 10 years (Table 2). Virology, a data-driven science, showed the lowest level of growth in co-authorships, which is expected. Nevertheless, it would be difficult to draw conclusions about the relationship of the drivers to the rate of co-authorships based on this case alone, in part because Virology also showed the highest growth in the number of countries joining the international collaborative network.

12 Both of these fields are also sub-fields of physics, and the structure of the larger field may influence the subfields.
Growth in co-authorships can be seen in an equipment-driven science (Polymers) and a resource-driven science (Soil Science), as expected, but no pattern can be derived from the rate of the increases shown, since growth occurred in all the fields studied. The most internationalized field in terms of co-authorships is Astrophysics, an equipment-driven science. But, the least internationalized field in terms of co-authorships, Polymers, is also an equipment-driven science. This lack of a pattern or correspondence between the motivation and the extent of internationalization of co-authorships also disappoints the expectation. (Nevertheless, it may be that the equipment needed for astrophysics is highly centralized and thus encourages collaboration, while the equipment needed for polymer research is not as rare or difficult to access, and therefore is not a driver for collaboration).

One way in which the cases support the expectation is suggested by the resource-driven sciences: Soil Science and Geophysics. Both of these fields are shown to have a high percentage of internationally co-authored articles in widely geographically-distributed networks, and they both show significant growth in international co-authorships in the 10 years studied (Table 2). Thus, it may be that within the resource-driven sciences, the need to share access to soil samples or geophysical resources or phenomena (shake tables or fault lines), may help to explain some of the growth in international collaboration (WAGNER & LEYDES Dorff, 2003). However, since growth is shown in all the fields, it is difficult to draw a conclusion for one driver based on this data.

An unexpected finding is one showing an inverse relation between the growth of the percentage of international co-authorships and the spread of geographic networks of collaboration (countries). The fields that have the highest percentage of international co-authorships are lower on the list of those that have a wide geographic distribution of countries in the network. Several explanations may be:

1. The need to access equipment. Since the fields with higher international co-authorships are collaborating among a relatively smaller number of countries, perhaps essential equipment is needed for scientific inquiry in that field. This equipment may be available only to researchers in a small number of countries. This would hold for Astrophysics, which is highest on the list of international co-authorships, but low on the number of countries participating in that list. Nevertheless, this explanation cannot hold across all fields, because Mathematical Logic is one of the fields with a high percentage of internationally co-authored papers, but fewer numbers of countries participating, suggesting that a large number of papers are published between researchers from the same countries. Moreover, Mathematical Logicians report that they do not have any specialized equipment.

2. A second explanation might be called an elite argument: The fields with a high percentage of international co-authorships but with lower geographic distribution may be highly elite in that few new entrants are welcomed into the pool of scientists
cooperating with each other at the international level. For example, researchers in several countries may work together on a long-term basis, and they publish together, but do not welcome newcomers into their collaborations. In this case, both access to resources (characterizing Astrophysics) and lack of need for resources (Mathematical Logic) can still be consistent with this explanation.

3. Another explanation that also fits the data might be called an emphasis argument: perhaps only a few countries have advanced university research positions for scientists in specific fields. Thus, perhaps Astrophysics and Mathematical Logic are fields that have not been commonly found at universities, particularly in the universities of developing countries. Even though the field has a high number of internationally co-authored papers, they may be co-authored by a smaller pool of researchers. This explanation would suggest that there is a smaller pool of international colleagues to draw from for cooperation in this field.

Growth of networking

All the fields show a growth in the network of co-authorships over the 10 years. The fields that show a relatively active network in 1990 are the ones whose networks grew at a lower rate than others (See Figures 7 and 11 showing active networks for Astrophysics and Virology in 1990). Moreover, while some fields showed a higher rate of growth at the international level than others, relative to each other, the fields do not reveal a significant difference in the rate of growth: they remain in essentially the same rank order from 1990 to 2000 (see Table 3).

This suggests that global dynamics - the factors driving international linkages - are similarly experienced across all fields of science. The global dynamic is more determinant of the organization of collaboration than is the intellectual organization of the field or the drivers. Moreover, the analysis suggests that the growth in international co-authorships cannot be tied to specific policy directives. These could include incentives within the European Community to increase collaborations - which has happened over the time frame studied - but network growth did not occur only within that geographic region. Neither can it be tied to "big science" projects where governments seek to share costs of large-scale research: this might be the case with Astrophysics, but the same could not be said for Soil Science.

Conclusions and areas for future research

The intellectual organisation within disciplines of science appears not to be a consistent factor explaining the growth in international collaboration in science. A factor that is consistent with the data - resource sharing - can explain some but not all the growth in collaboration. Other explanations need to be explored and tested.
Although these were not part of the initial hypothesis, the data in this study is consistent with two other possible explanations. One is the suggestion by some that practitioners are seeking collaborative opportunities in order to increase their visibility within their field, and this explanation can be assumed to operate across all fields of science, since the sciences generally have a common reward structure (SCHOTT, 1998; WHITLEY, 1994). Another explanation discussed in the literature also fits the data: this is that the weak ties and shifting networks are preferable to strong ties and stable networks when the goal of an activity is to encourage new knowledge creation. The geographic distribution evidenced by the networks in each of the sciences may be encouraging innovation and new knowledge creation at a rate that is not experienced in close collaboration or stable networks (GRANOVETTER, 1974; HAWTHORNEWAITE, 2001; COWAN & JONARD, 2003). Strong ties and geographically proximate collaboration results in rich communication, but, research shows that, eventually, close collaborators begin to think alike and share a common outlook (HAYTHORNEWAITE, 2001). Stable networks are often not efficient (BALA & GOYAL, 2000). Collaborators at a distance – either across geographic or intellectual boundaries – can be assumed to have different points of view and different experiences. As a result, collaborators-with-a-difference may be more likely to challenge or perhaps complement the outlook and capabilities of others. These collaborations may be more likely to result in innovative research and intriguing outcomes. Practitioners seeking to add something new to their field may find that they gain more by seeking diverse ideas and distant partners than by collaborating within their own laboratory. The growth in international collaboration may be reflecting this motivation for linkages within science. This requires further analysis, and forthcoming research by the author will shed light on this question.

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