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Diana M Hicks, Sylvan Katz

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Where Is Science Going?

Diana M. Hicks and J. Sylvan Katz
Science Policy Research Unit, University of Sussex

Do researchers produce scientific and technical knowledge differently than they did ten years ago? What will scientific research look like ten years from now? Addressing such questions means looking at science from a dynamic systems perspective. Two recent books about the social system of science, by Ziman and by Gibbons, Limoges, Nowotny, Schwartzman, Scott, and Trow, accept this challenge and argue that the research enterprise is changing. This article uses bibliometric data to examine the extent and nature of changes identified by these authors, taking as an example British research. We use their theoretical frameworks to investigate five characteristics of research said to be increasingly pervasive—namely, application, interdisciplinarity, networking, internationalization, and concentration of resources. Results indicate that research may be becoming more interdisciplinary and that research is increasingly conducted more in networks, both domestic and international; but the data are more ambiguous regarding application and concentration.

Introduction

In *Prometheus Bound: Science in a Dynamic Steady State*, John Ziman examines science facing a future "within a fixed or slowly growing envelope of resources" (Ziman 1994, 10). For 300 years, science expanded very quickly—at an exponential rate. Exponential growth came to be seen as the norm by scientists, but its continuance was absurd; eventually, it would have led to every man, woman, and child spending all their time writing scientific papers (Ziman 1994, 9-10). As the demands of science on resources began to conflict with other priorities, provision of resources slowed and approached a steady state; painful adjustments were needed in a system that evolved

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under conditions of exponential growth. Ziman traces the consequences for researchers, primarily academic, and for the advance of knowledge.

Michael Gibbons, Camille Limoges, Helga Nowotny, Simon Schwartzman, Peter Scott, and Martin Trow, authors of *The New Production of Knowledge* (1994), argue that the internal dynamics of science have generated a new way of producing knowledge. The post-World War II expansion of the research and education systems, coupled with the inexorable logic of entrepreneurial fund-raising, brought into being a method of performing research qualitatively different from the discipline-based academic activity that has dominated science and our thinking about science. They call this new form of research "mode 2."

The two analyses synthesize disparate strands running through comment on the research enterprise, describing the interplay among many factors. They conclude that internal dynamics are bringing about a transition to a different type of science system, and they focus our attention on science as an evolving system of interacting institutions. In so doing, they suggest that examining systemic-level data about science could be important, and they provide a theoretical framework to help interpret such data. In this article, we use system-wide bibliometric data to examine several characteristics of the changing research system described by Ziman and Gibbons et al.

Ideally, systemic data about science would be comprehensive, covering all research institutions in a nation, and would include the links between institutions, enabling us to track their evolution over time. Bibliometric analysis can generate such data because the *Science Citation Index* (*SCI*), the basis for most bibliometric analyses, approaches comprehensive coverage of high-quality, international, published research output; it contains citation and coauthorship links; and it goes back some forty years. But does the scientometric literature contain systemic analyses as defined above? Not really. Bibliometric analyses usually examine nations as a whole or output from particular programs or in certain fields or from a small group of institutions—the top twenty, for example. In large part, this is because analysts have been limited by the techniques available for handling large text databases at a reasonable price. However, technical advances have permitted us to attempt such an analysis on a medium-sized scientific country—the United Kingdom, with 8 percent of the world's output. Our analysis of the U.K. science system is a longitudinal, comprehensive, institutional-level profile of U.K. research output. With these data, we are able to address some aspects of the evolution of science systems discussed by Ziman and Gibbons et al.

Hypotheses

Both books argue that the research enterprise is undergoing a transition, analyzing many facets of an integrated system to support this thesis. Of necessity, our analysis approaches the material slightly differently. We can look for changes in the science system empirically, but we can do this only by examining in turn each facet of the overall argument. Therefore, we first isolate the characteristics of the science system the authors believe to be changing and list these as "hypotheses." These lists are not meant to reproduce the essence of the authors' theses, as the lists are a simplification and reduction of their arguments; rather, the lists are meant to act as a bridge between their analyses and our data.

In *Prometheus Bound*, Ziman argues that modern science is characterized by the following:

1. more management
2. more evaluation
3. career structures with less permanence
4. sophisticated instrumentation
5. more emphasis on application
6. greater interdisciplinarity
7. more networking and collaboration
8. more internationalization
9. more specialization and concentration of resources

We cannot examine all these points using bibliometric data, so we will focus on the last five: emphasizing application, interdisciplinarity, networking and collaboration, internationalization, and concentration of resources. Ziman believes these features have increasingly characterized science over the last fifteen to twenty years.

They are also some of the features said to distinguish mode 2 research from its predecessor. Gibbons et al. argue that in the new mode of knowledge production,

1. quality control is no longer simply a matter of peer review;
2. more knowledge is produced in the context of application;
3. consensus on solutions to scientific problems is formed outside disciplinary boundaries, generating transdisciplinary knowledge;
4. research is performed by intellectually and organizationally heterogeneous groups often brought together only for the duration of the project; and
5. research outcomes are influenced by social accountability, and researchers are sensitive to the broader implications of their work, becoming more reflexive.

Again, we cannot examine all of these hypotheses using bibliometric data; instead, we will focus on three of them—context of application, transdisciplinarity, and the nature of the groups that perform research. Under the fourth heading, the authors put forward three more hypotheses:

1. An increase in the number of potential sites where knowledge can be created; no longer only universities and colleges, but nonuniversity institutes, research centres, government agencies, industrial laboratories, think-tanks, consultancies, in their interaction.
2. The linking together of sites in a variety of ways—electronically, organizationally, socially, informally—through functioning networks of communication.
3. The simultaneous differentiation, at these sites, of fields and areas of study into finer and finer specialities. The recombination and reconfiguration of these subfields form the bases for new forms of useful knowledge. Over time, knowledge production moves increasingly away from traditional disciplinary activity into new societal contexts. (Gibbons et al. 1994, 6)

These hypotheses overlap with those of Ziman, and we believe they can be addressed using systemic-level bibliometric data of the sort we have developed. We can investigate research in the context of application by comparing growth in publishing in more applied fields with growth in more basic fields, and by comparing growth in publishing by institutions that both produce and apply research with growth in publishing by those that just produce research. We can judge the extent to which publishing might be moving beyond disciplinary boundaries by examining the growth of publishing in cross-disciplinary journals. We can uncover the variety among publishing institutions by counting the number of institutions of various types that publish. We can assess whether publication is becoming more or less concentrated by investigating the distribution of articles across institutions. And finally, our data permit us to glimpse domestic and international scientific networks using as an indicator collaborative articles. We take each hypothesis in turn, examining the bibliometric evidence from the United Kingdom over the 1980s to assess the magnitude of any changes.

Methodological Background

The bibliometric method used adhered to de facto standards in the bibliometric community (Katz et al. 1995; Katz and Hicks 1995a). The difference between this and previous work is that every U.K. address on the 376,226 articles we processed was assigned to one of approximately 5,000 unified institutional names. Thus, for every article produced in the United

Table 1. List of Sectors and Notes on Their Definitions

Sector Name	*Notes on Definitions*
University	"Old" universities, polytechnics were a separate sector in the 1980s, see below
Hospital	No hospitals were counted as part of universities
Research council	Intramural laboratories, excluding "groups" at universities but including "units" at universities
Industry	Including all laboratories privatized during the decade
SHA and BPG	Special Health Authority and British postgraduate medical research institutes[a]
Government	Departmental laboratories and local government
Nonprofit	Does not include research funded by grants from charities, in universities, for example
Polytechnics	Sector became universities in the 1990s
Other	Comprising other educational, other medical, and unknown, each of which produces less than 2 percent of U.K. output

a. These are special research hospitals, and so the hospital sector is effectively split into two parts, for reasons of policy relevance.

Kingdom during the 1980s and indexed in the *SCI*, we know with which institutions its authors were affiliated. Each of the institutions was assigned to a sector, and the analysis presented here is at the sectoral level.

The data were derived from the *SCI*. Information on all published works indexed in the *SCI* and listing a U.K. address from 1981 to 1991 was bought from the Institute for Scientific Information (ISI) on tape. From the tapes, three document types were extracted—articles, notes, and reviews (collectively referred to as "articles" herein), as these tend to report original research results. Each publication was then processed to unify the institutional addresses and assign each institution to a sector. The following sectors were used: university, hospital, research council, industry, Special Health Authority (SHA) and British postgraduate medical institutes (BPG), government, nonprofit, polytechnics, and other. The definition of each sector is explained in Table 1.

Application

The first hypothesis about the changing nature of research is that more research is being performed within the context of "a need to be application relevant." We propose to examine this hypothesis in two ways. First, we will compare the growth in publication by institutions that apply research and those that do not. Second, we will compare the growth of fields closer to and farther from application.

To perform the institutional comparison, we have identified industry and hospitals as the two sectors in which research is both performed and applied. If research increasingly is performed in the context of application, we might expect that the number of articles listing either a company or hospital address would be growing faster than the number of articles listing addresses of institutions in other sectors.[1] Table 2 reports the growth in each sector's share of publications. The table displays the following for each sector: the total number of articles published from 1981 to 1991, the share of the U.K. total this represents, the average yearly growth in share (which is the slope of the linear regression through the yearly share data), and the ratio between the yearly growth and the sector's average share of U.K. articles over the decade (multiplied by 100). Since the sectors differ in size quite a bit, the last figure is presented to normalize the yearly growth rate for the size of each sector. The sectors are sorted by this ratio, with the largest at the top of the list.

Table 2 indicates that publishing by hospitals grew the fastest, with their share of U.K. output increasing by 0.43 percent per year.[2] When adjusted for the size of sector, publishing by nonprofit institutions, SHA and BPG institutes and hospitals grew the fastest. Publishing by industry grew respectably, placing it in the middle of the list. Growth rates in the other sectors were lower. To the extent that research performed in the context of application is indicated by articles listing a hospital or company address, the share of publications produced in the context of application is clearly increasing, and this stands in contrast to the share of publications produced by universities, polytechnics, research councils, government, and other small educational and medical publishers. Such research does not appear to be increasing the fastest, however. The data suggest that biomedical publishing is increasing more strongly than publishing connected directly with application.

However, research performed by hospitals and industry is not the only research oriented toward application. Therefore, we examine the same issue by looking at the growth in publishing in fields that are closer to application. We have classified articles into scientific fields based on the journal in which they appeared. Our scheme is derived from that of ISI, which classified journals using journal-journal citation patterns, expert assessment, and feedback from users of specialty products. We have aggregated the 154 subfields of the ISI scheme into 11 fields in a manner similar though not identical to that of ISI. However, ISI could not classify every journal uniquely into one subfield; some journals have more than one subfield assignment. In certain cases, a journal's subfields will fall into different fields. Instead of fraction-

Table 2. Publication Growth by Sector

Sector	*Articles*	*Share*	*Average Yearly Growth in Share*	*Yearly Growth/ Average Share (× 100)*
Nonprofit	8,878	2.4	0.05 ± 0.01	2.3
SHA and BPG	17,448	4.6	0.10 ± 0.01	2.2
Hospital	81,719	21.7	0.43 ± 0.04	2.0
Industry	28,088	7.5	0.08 ± 0.03	1.1
Other	9,832	2.6	0.01 ± 0.01	0.3
University	217,441	57.8	0.12 ± 0.06	0.2
Polytechnic	8,008	2.1	–0.01 ± 0.01	–0.5
Research council	42,814	11.4	–0.10 ± 0.05	–0.9
Government	15,597	4.1	–0.11 ± 0.01	–2.7

ating such journals across different fields, we chose to create special "interfield" categories to contain them.[3]

Our classification scheme contains seventeen disciplinary and cross-disciplinary fields (Katz and Hicks 1995a). The fields are further classified into four disciplinary groups: life science, natural science, engineering and materials science, and interdisciplinary. Life science fields are medicine, biology, agriculture, and interfield life sciences (containing journals that span two of the other life science fields). Natural science fields are chemistry, physics, earth and space sciences, mathematics, and interfield natural science. Engineering and material science fields are engineering, materials, information and communication technologies, and interfield engineering and materials science. Interdisciplinary categories are multidisciplinary (containing environmental sciences as well as *Nature*, *Science*, *Proceedings of the National Academy*, etc.) and three fields containing journals that span two disciplines.

For the purposes of this analysis, we take fields closer to application to be agriculture, medical, engineering, information, materials, and interfield engineering and materials science. Table 3 reports the growth in publishing by fields. As in Table 2, the columns report the following: the total number of articles in each field, the share this represents of U.K. output, the yearly change in share obtained from the slope of a linear regression through the yearly share data, and the ratio between the slope and the average share (multiplied by 100). As above, the columns are sorted by this ratio. The table indicates that medicine and material science are two of the fastest growing subfields but also that agriculture, information, and engineering accounted for a smaller share of U.K. output at the beginning of the 1990s than they had

Table 3. Growth in Publishing in Fields Closer to Application

Field	*Articles*	*Share (%)*	*Yearly Change in Share (%)*	*Yearly Change/ Average Share (× 100)*
Interfield natural sciences	2,590	1	0.07 ± 0.02	10.5
Material sciences	5,503	1	0.04 ± 0.01	2.4
Natural sciences—engineering and materials science	10,063	3	0.04 ± 0.02	1.6
Medicine	140,012	37	0.49 ± 0.06	1.3
Interfield life sciences	26,931	7	0.09 ± 0.03	1.2
Life sciences—engineering and material science	1,081	0	0.00 ± 0.01	0.7
Physics	33,702	9	0.04 ± 0.05	0.4
Earth and space sciences	9,105	2	–0.01 ± 0.01	–0.5
Interfield engineering and material science	4,788	1	–0.01 ± 0.01	–0.6
Biology	46,533	12	–0.11 ± 0.04	–0.9
Life sciences—natural sciences	7,985	2	–0.02 ± 0.01	–1.1
Multidisciplinary	16,545	4	–0.05 ± 0.02	–1.1
Engineering	9,919	3	–0.04 ± 0.02	–1.7
Chemistry	38,474	10	–0.20 ± 0.04	–2.0
Agriculture	13,635	4	–0.13 ± 0.02	–3.7
Mathematics	6,918	2	–0.07 ± 0.01	–4.0
Information and communication technologies	1,464	0	–0.05 ± 0.01	–12.1

at the beginning of the 1980s. Thus the data on growth of fields does not support the hypothesis that applied research is growing more quickly than basic research. Overall, the results are somewhat ambiguous. The institutional analysis indicates that research in the context of application is increasing, in contrast with research produced by other sectors, but it is not increasing the fastest. The field analysis does not support a simple hypothesis that more research is being performed in the context of application. Of course, both indicators are crude. There are application-oriented research institutions and groups in sectors other than hospital and industry, and there are applied journals of chemistry and more basic journals of engineering.[4] A finer grained analysis might reduce some of the ambiguity. Nevertheless, this analysis does warn against simplistic statements about the growth of applied research.

Transdisciplinary Publishing

The second hypothesis about the changing nature of the research enterprise concerns interdisciplinary research. Many observers of science believe that such research is increasingly pervasive and significant. However, few if any attempts have been made to measure the relative extent of interdisciplinary versus disciplinary research activity and the rates of change. This is not surprising given the apparent impossibility of even agreeing on a definition of interdisciplinary research.

Nevertheless, in the face of these difficulties, we have somewhat boldly proposed to measure the increase in interdisciplinary publishing using articles published in cross-disciplinary journals as an indicator. We conjecture that journals that cannot be classified into a single field or even a single discipline cross field boundaries in some way, perhaps by addressing multiple audiences, or by taking submissions from several research communities, or by publishing articles that tend to require a broader range of skills than is customary in a traditional discipline. We label such journals and the articles published in them "transdisciplinary." We suggest that this transdisciplinary publishing bears some relation to the much discussed concept of interdisciplinary research.

We will assess the growth in transdisciplinary publishing by examining whether the share of articles published in single-field journals (those classified as medicine, biology, chemistry, or physics, for example) has decreased and the share of articles in cross-field journals (those classified as, for example, interfield life sciences, life sciences/natural sciences, or multidisciplinary) increased. The second and third columns of Table 4 report the number of articles and share of U.K. output accounted for by each category of journal. The fourth column lists the yearly change in percentage share of U.K. output calculated from the slope of the regression line through the yearly data.

The table indicates that the share of U.K. output published in journals that were assigned to single fields such as medicine or physics decreased slightly, while the share of U.K. output published in journals that could not be classified into single fields increased slightly. The share of articles in single-discipline journals decreased by 0.11 percent per year on average, while the share in transdisciplinary journals increased by 0.11 percent per year. Transdisciplinary publishing has several components. The share of publishing that crosses field boundaries (for example, medicine and agriculture, physics and chemistry) but remains within the same discipline (life sciences, natural sciences, or engineering and materials sciences) increased by 0.14

Table 4. Growth in Share of Interdisciplinary Articles

Category	*Number of Articles*	*Share of U.K. Output (%)*	*Yearly Change in Share (%)*
Single-field journals	305,265	81.4 ± 0.6	–0.11 ± 0.05
Cross-field journals	69,983	18.6 ± 0.6	0.11 ± 0.05
Interfield	34,309	9.1 ± 0.6	0.14 ± 0.03
Interdisciplinary	19,129	5.1 ± 0.3	0.02 ± 0.03
Multidisciplinary	16,545	4.4 ± 0.2	–0.05 ± 0.02
Total	375,248[a]	100	

a. Excludes articles in journals classified as "unknown," which represent only 0.3 percent of all U.K. articles.

percent per year, the largest increase. The share of articles in journals that span disciplinary boundaries (i.e., life sciences/natural sciences, life sciences/engineering and material science, or natural sciences/engineering and materials science) remained stable. Articles in multidisciplinary journals such as *Nature* or *Science* are not themselves multidisciplinary. These journals cannot be classified into a single discipline, however, because they accept articles from many disciplines. The share of U.K. articles in this "multidisciplinary" category (which includes also environmental journals) decreased slightly. The data support the hypothesis that publishing in transdisciplinary journals is playing a larger role in U.K. science. However, there has been no dramatic shift in the percentage of U.K. output in each category. Roughly four-fifths of U.K. output is in single-discipline journals, and roughly one-fifth is in transdisciplinary journals.[5]

The data support the idea that research crossing the boundaries of traditional disciplines increased more quickly than disciplinary research in the United Kingdom during the 1980s. However, the differences in growth rates were not large enough to create a large increase in the share of U.K. publications in cross-disciplinary journals at the expense of publications in traditional journals. Therefore, these data indicate that disciplinary research still accounts for by far the bulk of U.K. scientific output and will apparently continue to do so for some time to come. However, the measure is imperfect. Certain fields, such as agriculture or materials science, are considered "disciplinary" in our scheme, but this designation could be questioned. Refined journal classification might produce more intuitively satisfying results. Even so, a journal-based classification will always be less satisfactory than an article-by-article classification, however impractical such a scheme may be to implement.[6]

Collaboration

Disciplinary and interdisciplinary research differ in part in the diversity of skills and knowledge brought to bear on research problems. A wider range of capability is combined to produce an interdisciplinary article than a disciplinary article. A greater breadth of skills and knowledge may be demanded by research in the fastest growing areas of science—or so the last section suggests. The extent to which skills and competencies are combined to produce scientific articles can be assessed in other ways. In particular, we can examine the extent to which authors and institutions work together to produce and publish research by examining collaborative articles. Because complementary assets such as knowledge, equipment, and materials are brought together by collaborating scientists, increases in collaboration indicate more combining of knowledge and equipment to produce scientific articles.

Both Ziman and Gibbons et al. point to increasing networking, collaboration, and communication in the scientific community, arguing that networking is in part necessitated by the increasing interdisciplinarity of research and in itself facilitates interdisciplinarity. As with interdisciplinarity, many observers of science have commented upon growth in collaboration. In addition, analysts have produced bibliometric evidence of increasing research collaboration. De Solla Price (1986) noted increasing collaborative publishing as long ago as 1963. More recently, the bibliometric community has focused on increases in international collaboration (European Commission 1994; Leclerc et al. 1992; Luukkonen, Persson, and Sivertsen 1992; Narin and Whitlow 1990). Our data permit the first detailed assessment of the rate of collaboration among institutions *within* a national science system and its growth over time.

We begin our examination of collaboration and the extent to which institutional resources are combined in research by calculating the average number of authors, institutions, and countries involved in the production of an article. We find that by the end of the decade, an average number of authors for a U.K. article was 3.4, and the average number of domestic institutions was 1.3. The average number of foreign countries for an article that listed a foreign address was 1.3. The increase in these averages is analyzed using linear regression, and the results are displayed in Table 5. This table indicates that the extent to which resources were combined to produce scientific articles gradually increased during the 1980s.

We can examine these trends in greater detail by looking at the frequency distribution of authors, institutions, and countries per article (see Figure 1). The graphs display these distributions in 1981 and 1991.[7] The first graph

Table 5. Average Number of Authors, Institutions, and Countries per Article

	1981	*1991*	*Linear Yearly Increase*
Authors	2.63	3.34	0.08 ± 0.01
Institutions	1.19	1.28	0.01 ± 0.00
Countries	1.17	1.25	0.01 ± 0.00

reveals that during this decade, the share of articles with one and two authors decreased, while the share of articles with three authors increased slightly and the share of articles with four or more authors increased quite appreciably. De Solla Price (1986) examined similar data from 1900 to 1960, and Figure 2 compares his data with ours. In de Solla Price's data, the proportion of articles with two authors grew and the proportion with three authors increased rapidly. Between 1960 and 1980, the system seems to have made a transition. Now, the proportion of articles with two authors is declining, and soon the proportion with three authors will probably begin to decline. In the future, only the proportion of articles with four or more authors will continue to grow, gradually replacing articles with three or fewer authors.[8]

De Solla Price's (1986) data indicate that the need to combine skills and labor in scientific work grew throughout this century. By 1950, the lone investigator was the exception in chemistry, accounting for less than 50 percent of published articles. Our data indicate that more recently, a second transition occurred, a transition in the breadth required to produce a piece of knowledge. Today, two people and three people are less and less likely to have all the skills, equipment, and material required in modern scientific research. By the turn of the century, the current trends suggest that four or more authors will be needed to produce published research.

The second graph in Figure 1 displays the frequency distribution of the number of domestic institutions per article. We can see that the share of articles produced by one institution is declining, while the share produced by two or more institutions is on the rise. The final graph displays the frequency distribution of foreign countries per article. The share of articles listing one foreign country increased by about 10 percent over the decade. The shares of articles with two or more countries increased by 2 percent. Both trends suggest that producing research increasingly demands not just that individuals pool resources but that they do so across institutional and even national boundaries.

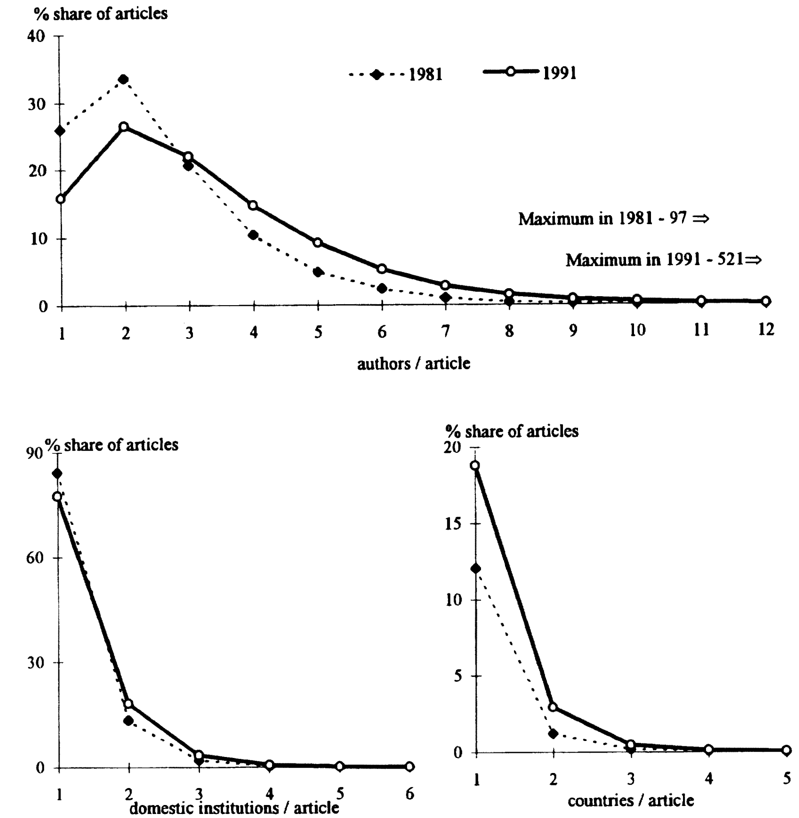

Figure 1. Frequency distributions of authors, domestic institutions, and countries per article, 1981 and 1991.

NOTE: Lines plotting the data in the intervening years proceed smoothly from the 1981 to the 1991 position. The values plotted add to 100 in the case of authors and domestic institutions because every article has at least one author and one domestic institution. However, not every article has a foreign coauthor. The shares of countries per article add to 14 percent in 1981 and 23 percent in 1991. The share of single-author, single-institution, and single-country articles are decreasing. The share of multiple-author, multiple-institution, and multiple-country articles is increasing. The exception is the share of articles with two authors, which is decreasing.

The resources of different institutions can sometimes be combined by a single individual. This happens when a researcher moves and puts on the article the name of the institution at which the work was begun and at which it was finished or written up. It also happens when individuals hold joint appointments (Katz and Martin in press). In most instances, these data do not allow us to detect this activity. However, on 2.1 percent of U.K. articles, the

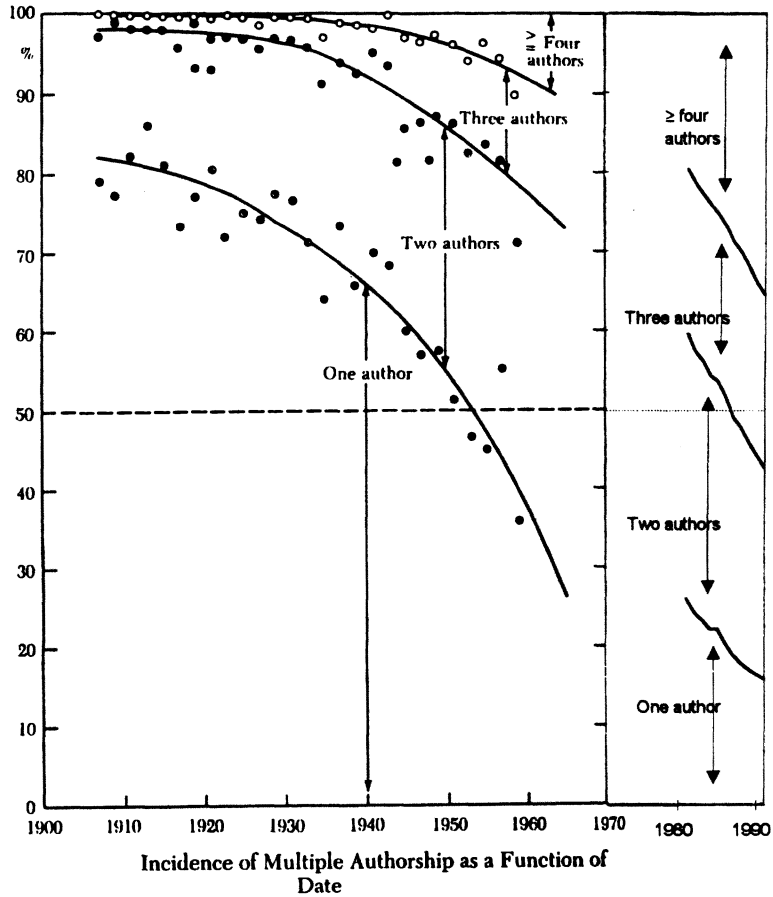

Figure 2. Comparison of de Solla Price and Science Policy Research Unit data on number of authors per article.

SOURCE: Figure for 1900 to 1960 from *Little Science, Big Science and Beyond* by Derek de Solla Price. © 1986 by Columbia University Press. Reprinted with permission of the publisher. (p. 78)

number of institutions listed on an article exceeds the number of authors, revealing either mobility or joint appointment. The percentage was steady over the decade, although in 1991 it rose to 2.5 percent. Although we cannot measure this activity precisely using these indicators, we should not forget its existence. Temporary and enduring links between institutions are forged both through collaborations between their employees and through joint appointments and job mobility.

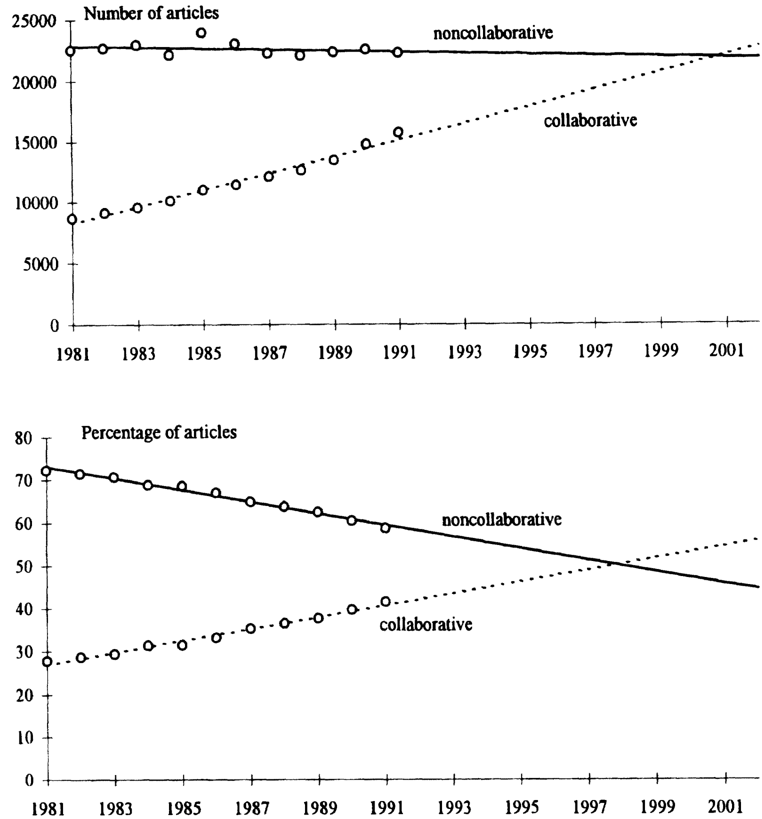

Figure 3. Collaboration.

NOTE: The number and percentage share of collaborative and noncollaborative articles in the years 1981-91 are plotted with open circles. Collaborative articles are those listing more than one institutional address. Collaborations between departments in one university or between different sites of one company are counted as noncollaborative. Linear regressions through the data are carried forward to the turn of the century when, for the first time, the number of articles produced by researchers collaborating across institutional boundaries will exceed those produced by researchers working in a single institution. Collaboration across geographical and institutional barriers will become the rule, not the exception.

We next examine collaboration more directly by analyzing trends in the numbers of collaborative and noncollaborative articles. Institutionally collaborative articles are defined as those listing addresses from different institutions. Articles listing different department names within one institution or different sites of one company are not considered to involve an institutional collaboration. The growth in collaborative publishing and the associated slight decline in noncollaborative work are displayed in Figure 3. Both numbers and shares of articles are displayed for each year, and each set of data is accompanied by a regression line that is carried forward to identify the point at which the lines will cross. During the 1980s, the number of U.K. articles published by authors located at one institution (the noncollaborative articles) declined slightly, while the number published by authors working at more than one institution rose steadily. These trends suggest that the skills and instruments located at one institution are less and less adequate to produce knowledge, and so researchers in different institutions increasingly combine resources to produce and publish research. If these trends continue, the share of collaborative articles will exceed that of noncollaborative articles sometime around the turn of the century. Thus, as Britain enters the next millennium, its research system will undergo a transition in which research collaboration among geographically separated institutions will become the normal way of conducting research—the rule, not the exception. Both Ziman and Gibbons et al. discuss the policy and management implications of this transition.

International collaboration is often singled out for special mention. It has been a concern of recent EU science policies and of bibliometric analysis (Schubert and Braun 1990). Ziman argues that the increased cost of certain instruments, the increased scope of many problems, the global reach of research-intensive multinational companies, and increased travel and communication are combining to make the scientific community even more transnational—research having always been a more international pursuit than most. Gibbons et al. also believe that increasing international collaboration arises from forces intrinsic to the research process, forces operating over a very long time scale. Both connect rising international collaboration to increased travel and communication.

In an attempt to illustrate this thesis, we examined a longer time series of collaborative data (Katz and Hicks 1995b). The first graph in Figure 4 displays the percentage of U.K. and U.S. articles with an international collaborator from 1975 to 1991. In this figure, our data are combined with those published in the U.S. National Science Board's (1993) *Science and Engineering Indicators* to provide a longer time series. International collaboration has been increasing for fifteen years, both in the United States and in the United Kingdom. Figure 4 also compares the trends in international collaboration with trends in travel and communication—specifically with number of international scheduled air passengers and number of outgoing international telephone calls. All three graphs exhibit long-term growth originating in the mid-1960s. Growth in collaboration is the most linear,

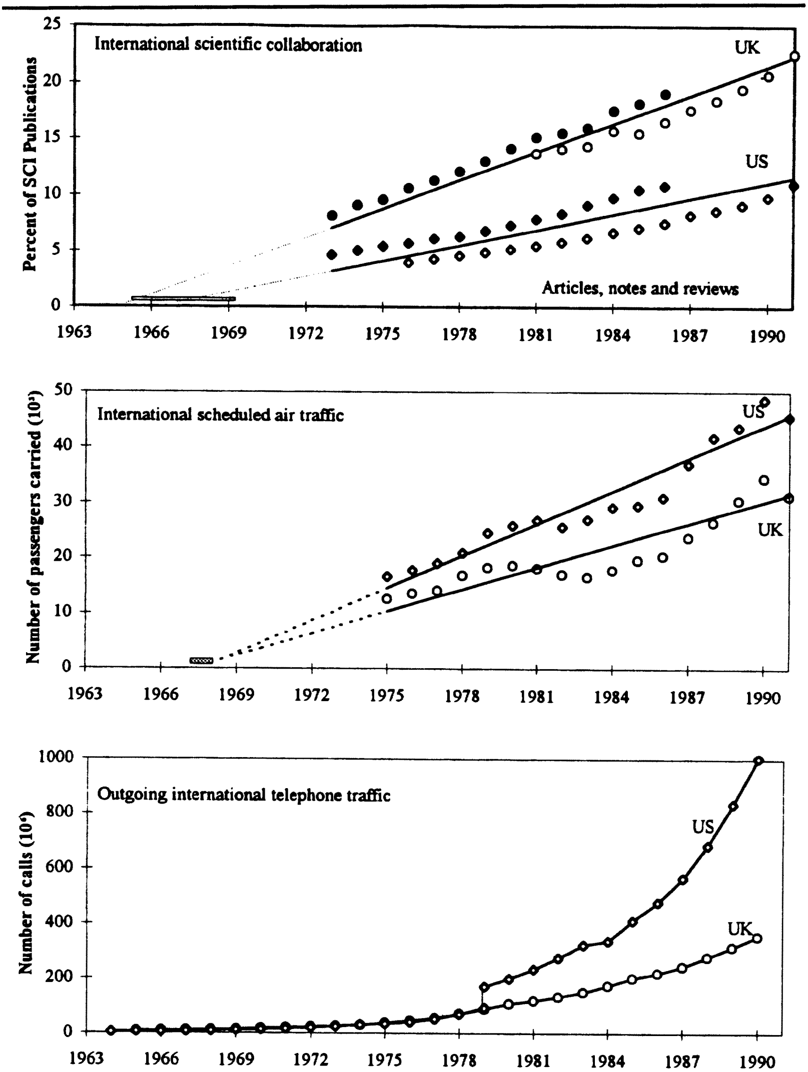

Figure 4. Growth in international scientific collaboration, international scheduled air traffic, and outgoing international telephone traffic, United States and United Kingdom.

SOURCES: U.S. National Science Board (1993), International Civil Aviation Authority (1975-1993), International Telecommunication Union (1975, 1977-1979, 1990)

growth in air travel is the most subject to economic cycles, and growth in telephone calls is the closest to exponential. Between 1981-83 and 1989-91, the number of articles produced in international scientific collaboration increased by 74 percent; the number of international airline passengers carried from the United Kingdom increased by 87 percent, and the number of international telephone calls from the United Kingdom increased by 138 percent. The graphs suggest that Ziman and Gibbons et al. are right to place international collaboration in a broader context.

The increases in collaboration suggest that the competencies, skills, and material resources combined to produce an advance in knowledge are growing gradually but inexorably over time. Some types of research are already well known for being organized in large international consortia—high-energy physics, space, oceanography, polar, and other environmental sciences. If these trends continue, however, producing scientific and technological knowledge of any type will come to be seen as a matter of coordinating dispersed groups of people—though groups in most areas may never become as large as those in the aforementioned "consortia sciences."

We might then wonder what will be the end point in this evolution. Perhaps the system will asymptotically approach complete connection (i.e., every institution collaborates with every other institution). Or perhaps it will approach some point in between completely connected and completely disconnected. If we accept some of the new notions that the amount of complexity in a system is at a minimum both when the institutions have no connections (no collaborations) and when each is connected to every other institution (completely collaborative), then perhaps somewhere between the extremes the system is most complex with institutions connected yet still flexible enough to respond to external changes (Gell-Mann 1994; Crutchfield 1994). Where is that point? And is the British science system approaching it? A longer time series of data would be needed to address these questions.

Concentration or Dispersion of Research Production?

Another way of interpreting the increase in collaboration is that the production of knowledge is becoming more socially dispersed. In other words, a "piece" of knowledge will in the future be produced by more people in more locations. As the production of pieces of knowledge becomes more dispersed, will the capability to produce knowledge become more dispersed too? The authors disagree on this point. Gibbons et al. point to increasing dispersion in the system. According to their analysis, there is

> an increase in the number of potential sites where knowledge can be created; no longer only universities and colleges, but nonuniversity institutes, research

centres, government agencies, industrial laboratories, think-tanks, consultancies, in their interaction. (Gibbons et al. 1994, 6)

In contrast, Ziman sees the research system as becoming more concentrated. He points to very powerful forces of competition based on excellence that are endogenous to science and that lead to concentration of resources over time. In addition, he notes that closer management of research leads to even more concentration to achieve administrative efficiency, economies of scale, and division of labor. "Selectivity" is, in his view, increasingly part of managing steady state science: "What selectivity has come to mean in practice is a systematic policy of *concentrating* research activity into a smaller number of more *specialized* units" (Ziman 1994, 156).

We can examine bibliometrically whether the U.K. science system is becoming more dispersed, as Gibbons et al. propose, or more concentrated, as Ziman believes. Our data permit us to look at several facets of the concentration/dispersion phenomenon. We can analyze the types of institutions publishing research to see whether a more varied set of institutions are participating in the system. We can also examine the number of institutions publishing to look for increases. Finally, we can look at concentration measures used by economists to see whether research production is becoming more evenly distributed among institutions.

We begin by examining the types of U.K. institutions that publish, or rather the types of institutions that publish articles, notes, or reviews in journals included in the *SCI*. These 3,000 or so journals were selected in the first instance because they have a high international impact. Indeed, coverage of the database has been criticized because the criteria for the inclusion of second-rank journals are inconsistent and applied fields are not well covered (European Commission 1994, 33-34). In addition, we counted only articles, notes, and reviews because they are most likely to report substantial research results and be peer reviewed. Discussions, letters, editorials, and meeting abstracts have been excluded.

Therefore, the *SCI* as analyzed here represents international peer-reviewed science—the domain of academics. Why then do 60 percent of articles list the addresses of noneducational institutions? Why do hospitals and firms account for 63 percent of the institutions that averaged one or more articles per year? Why did ICI, Wellcome, SmithKline Beecham, and BT each contribute more than 1,000 articles during the 1980s? Because of collaboration, about 60 percent of articles also list the address of an educational institution.[9] Nevertheless, the fact that so much international-level, peer-reviewed, scientific knowledge in the United Kingdom is produced outside the university sector, or in collaboration with institutions other than univer-

Table 6. Selected U.K. Institutions That Published 50 to 150 Articles from 1981 to 1991

Animal Health Trust	Malaysian Rubber Producers' Research Association
Atkinson Morleys Hospital	Meat and Livestock Commission
British Ceramic Research Ltd.	National Museum of Wales
British Railway Board	Nature Conservancy Council
British Trust Ornithology	Organon Research Labs Ltd.
Forensic Science Service	Royal Botanical Gardens, Edinburgh
Forestry Commission	Royal Museum Scotland
Greenwich District Hospital	Royal Society for the Protection of Birds

sities, suggests that universities do not have a monopoly on "academic" research. Medical institutions, industrial laboratories, research council and other government laboratories, and nonprofit institutes collectively seem to be as important as universities in the modern U.K. research system. Many of these institutions, such as local councils and police forces, are not normally thought of as contributing to Britain's scientific research output. Table 6 illustrates this institutional variety by listing a selection of institutions not known for their research output (not universities, polytechnics, or research council laboratories) that published between 50 and 150 articles during the decade.

Analyses of that part of the research system publishing in international refereed scientific journals must take into account the variety in the system. An exclusive focus on research in higher education is a distortion.

Gibbons et al. not only point to this variety in the research system but also claim that it has been increasing. To investigate this, we can ask whether the number of participants in the research system has been increasing. Figure 5 displays for each sector three-year moving averages of the number of institutions publishing for each year 1983 to 1991. In the graph, publishing institutions are classified into four categories according to whether they published on average 1 article per year, 2 to 10 articles, 11 to 100 articles, or more than 100. (Only Oxford and Cambridge published more than 1,000 articles per year.) The graph reveals that in this area, sectors have very different characteristics. For example, many hospitals or companies published just 1 article or less per year, while most universities published more than 100 articles per year.[10]

The graph shows that the number of institutions at which publications originate increased during the 1980s in all sectors but one. The numbers at the beginning and end of each sector's graph report the number of institutions in the first and last years. If we take the difference between these numbers as

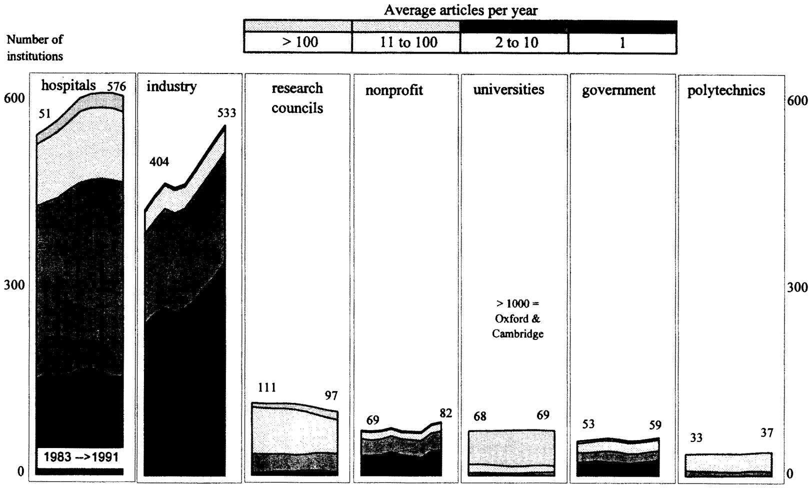

Figure 5. Number of publishing institutions.

NOTE: Three-year moving averages of the number of institutions publishing. Institutions are classified by average number of articles per year. Only Oxford and Cambridge published more than 1,000 articles per year. The numbers indicate the total number of institutions in the sector publishing in the first and last three-year periods. The number of institutions increased in all sectors except research councils. The university sector consists mostly of large publishers; research councils, of medium-sized publishers; hospitals, of small publishers; and industry, of companies publishing only one article per year on average.

a measure of the size of the change, the number of firms increased by 32 percent,[11] and the number of hospitals increased by 11 percent. The number of nonprofit institutions, level through most of the decade, increased in the last two years by 19 percent.[12] The number of polytechnics increased also by 12 percent, though this corresponds to just four institutions. The number of government institutions varied over the decade, though the number in the final year was 11 percent higher than in the first year.[13] The number of universities remained essentially constant. The exception to the increase is the research council sector in which numbers decreased by 13 percent due in large part to consolidation by the Agriculture and Food Research Council. The increase in the number of research council laboratories producing more than 100 articles per year (the top band) is consistent with concentration.

The increasing number of institutions housing authors of journal articles lends support to the idea that research production is becoming more dispersed. Only the decline in number of research council laboratories lends support to the idea that more management of research is leading to consolidation and concentration. The weight of evidence favoring dispersion reinforces the point that academic research accounts for only half of the research system in the United Kingdom today. In fact, it forms the static half. The number of institutions of other types that produce journal articles, such as companies and hospitals, has grown.

The number of institutions is not by itself an adequate measure of concentration, however. Concentration has two dimensions: both number of organizations and the inequality of size among them play a role. The distribution of research production across institutions has always been uneven, with a few institutions producing a great deal and a large number producing little. Whereas Ziman points to the forces (traditional and internal—new and external) that produce this distribution, the analysis by Gibbons et al. suggests that the distribution might be becoming more even.

Figure 5 displays the number of institutions housing authors of scientific articles, qualitatively conveying differences in how much they publish. To analyze concentration more quantitatively and to examine whether there were any changes over the decade, we will examine measures of concentration (see Table 7). As there are various measures of concentration, none ideal in all circumstances, we present two such measures here, both of which reflect the two dimensions of concentration (Davies et al. 1988, 79-86). The first measure is the number of firms publishing 25 percent, 50 percent, 75 percent, and 100 percent of the articles, which is easy to understand and conveys the nature of the tail in the distribution for each sector. The second measure is the Herfindahl index, which, being a single number, makes it possible to assess change in concentration over time. This index is calculated by summing the squares of each institution's share of the sector's publication (its maximum value is 1). For example, if there were two institutions in a sector producing 95 percent and 5 percent of the articles, respectively, the Herfindahl index would be $0.95^2 + 0.05^2 = 0.905$. In a sector of size n, concentration reaches a minimum when all institutions publish the same number of articles. At this minimum, the Herfindahl index would equal $1/n$, where n is the number of institutions. By reversing this logic, each sector can be seen to be as concentrated as a sector of 1/Herfindahl index number of equal-sized institutions. This number of institutions is reported in the last line of the tables. There are three panels in the table. The first two report a three-year average, in 1981-83 and 1989-91, respectively. The final panel reports the difference between the figures in the first two panels. The columns are ordered by how concentrated the sectors were in the 1989-91 period.

The tables indicate that the sectors vary somewhat in their degree of concentration. In the first part of the decade, government was the most concentrated; in the latter part, the nonprofit sector was the most concen-

Table 7. Concentration Measures

	Nonprofit	*SHA & BPG*	*Government*	*Industry*	*Research Polytechnic*	*Universities*	*Councils*	*Hospitals*
1981-83								
Percentage of articles								
25	1	2	2	3	3	5	5	5
50	3	4	3	12	8	12	16	18
75	10	7	7	52	17	25	38	60
100	109	17	86	723	35	70	122	602
Herfindahl index	0.115	0.108	0.121	0.033	0.049	0.031	0.025	0.021
Sector size equivalent	9	9	8	30	20	32	40	48
1989-91								
Percentage of articles								
25	1	2	2	3	4	4	4	5
50	2	4	4	11	11	12	11	17
75	9	8	8	62	20	24	26	57
100	149	18	91	992	37	69	109	639
Herfindahl index	0.151	0.098	0.095	0.036	0.036	0.033	0.030	0.022
Sector size equivalent	7	10	11	28	28	30	33	45
Difference between 1989-91 and 1981-83								
Percentage of articles								
25	0	0	0	0	1	−1	−1	0
50	−1	0	1	−1	3	0	−5	−1
75	−1	1	1	10	3	−1	−12	−3
100	40	1	5	269	2	−1	−13	37
Herfindahl index	0.036	−0.010	−0.026	0.003	−0.013	0.002	0.005	0
Sector size equivalent	−2	1	2	−3	7	−2	−7	−2

trated. Hospitals are the least concentrated sector. Sector concentrations changed somewhat over the decade. Five sectors became more concentrated: research councils, industry, nonprofit, university, and hospital; three became less concentrated: polytechnics, government, and SHA and BPG. Thus there is no uniform trend toward concentration or dispersion. Some changes are clearly related to government policy, those in the polytechnics and research councils in particular. However, even government policy did not have a uniform effect, producing dispersion among the polytechnics and concentration among research council laboratories.

Conclusion

As the economy becomes more knowledge based, workers, firms, and governments are adapting. It is hardly surprising then that the knowledge-producing scientific system is changing as well. The proportion of research that is interdisciplinary is increasing, collaboration—domestic and international—is rising steadily, and more institutions are producing research articles. Research projects combine an ever broader range of skills and resources, indicated by increasing interdisciplinarity and collaboration between individuals, institutions, and countries. By the turn of the century, one-half of all articles will probably be produced by four or more authors collaborating across institutional boundaries.

Science policy must also change and, in fact, has already begun to change. Both Ziman and Gibbons et al. point to changes under way and those likely in the future. Knowing how to fund, manage, facilitate, and conduct collaborative research will become core scientific and policy competencies in the next century. Evaluation methods must adapt. Methods based on examining a unit's "own" research output in comparison with others will not work when individuals, groups, departments, or institutions do not have their "own" research output because more than 50 percent of their research is collaborative.

Knowledge-producing institutions are more heterogeneous than is perhaps commonly realized, and this variety is increasing as more nonacademic institutions begin to publish scientific articles. To the extent that articles from small, new publishers reflect in-house research (and we hope to establish this in future research), such organizations may mimic small biotechnology firms in accommodating research outside academia. Even today, academics have no monopoly on knowledge production. More flexible, focused, and context-sensitive institutions may mount an increasingly visible challenge to academia as their numbers increase.

Literature-based analysis paints a picture of gradual change that is somewhat at odds with impressions gleaned from qualitative work. Ziman in particular suggests dramatic change; Gibbons et al. do to a lesser extent. Of course, Ziman discusses managerial changes, which may well be more dramatic than the changes we examine.

Bibliometric data can reveal only so much, however, and we should not forget those aspects that are invisible to bibliometric analysis but are addressed by Ziman and Gibbons et al. Like Gibbons et al., we examine science at the systemic level. Gibbons et al. recognize the hardship suffered by individuals caught up in the ongoing changes but do not focus on this. Ziman uses the systemic changes more as the setting for a discussion of the hardship faced by scientists and the difficulties of an academic career in the 1990s. Bibliometric analysis provides no indication of the stress felt by individuals in the system. However, we would say that one cannot generalize from individual hardship to conclude that the system is falling apart. Difficult as the adjustments are for the scientists affected, there is no evidence here that the British science system is disintegrating or in decline.

The authors also make a general argument about scientific research, whereas we examine only U.K. research. Data for other countries will look different; for example, a higher percentage of articles may list academic addresses. However, if Ziman and Gibbons et al. are correct, the trends will be the same. We are working with groups in other countries to produce comparative data to generalize our empirical argument.

Any analysis of dynamic change in a system must be grounded in an understanding of the "energy" inputs to the system. In science, there are two such inputs: people and money. Ziman analyzes how the system is responding to reduced growth in the money allocated it. He has a very clear grasp of the importance of funding, while Gibbons et al. give much less weight to this factor. This may also explain the difference between their predictions about research concentration. The increasing degree of concentration among research council institutions indicates that funding must be given prominence in any systemic analysis of science. On the other hand, Gibbons et al. emphasize the huge post-World War II growth in the number of college-educated and Ph.D.-trained people in Organization for Economic Cooperation and Development (OECD) countries. They realized that this growth has led to research competence being distributed much more widely through society, no longer confined to universities. Our analysis confirms the significance of this trend.

Our data do not deal with instrumentation. Gibbons et al. discuss it briefly and in a somewhat abstract way. Ziman gives it a prominent place in his analysis. We believe that the scientific community and scientific instrumentation are coevolving systems. If comprehensive data about the performance, cost, and scale of instruments and the connections between them were available, they might explain some of the trends we have found.

Finally, we should not forget the invisible years; although a decade of data seemed like a lot at the beginning of this project, it now seems like just the beginning. To some extent, the conflicting ideas of Ziman and Gibbons et al. can be put in perspective by considering the time periods they cover. Ziman focuses on changes over the past decade or so, the period for which we have bibliometric data. Gibbons et al. analyze the longer term, approximately the last fifty years. Over this longer period, we would certainly see entry into publishing of large numbers of institutions in each sector. The postwar period was a time of institution building, before the steady state was reached. New universities were established during this period, for example. We might hypothesize that as the institution-building, expansive phase ended in the late 1960s, networking and collaboration began to increase. Only extended time series bibliometric data going back thirty years or so would allow us to investigate and to understand fully the complexity and order in the U.K. science system.

Notes

1. The reasons why companies publish articles are analyzed in Hicks (1995).

2. "Hospital publishing" means those articles listing a hospital address. Since many articles list addresses of institutions in more than one sector, the percentage share figures add to more than 100 percent. Because the rate of collaboration is increasing (see below), the extent of what we might term "overlapping shares" is increasing, and it is conceivable that every sector's share of publications could have increased.

3. These interfield categories contain the articles we call interdisciplinary in the next section.

4. Indeed, in the early 1980s, ISI journals were classified into four categories based on how basic or applied was the research they reported. Unfortunately, this scheme has not been updated. Therefore, we could not use it here.

5. This trend, and the growth in interdisciplinarity discussed in the next section, could be caused by expanded coverage of the *SCI* if many new journals were added and they were all applied. However, during the 1980s, the coverage of the database was relatively stable. In 1981, it indexed 3,068 journals (or "source publications"); in 1991, this had become 3,213 journals (a 5 percent difference). The maximum number of journals were indexed in 1983—3,327. Thus expanded coverage of the *SCI* does not confound the trends we report. Nevertheless, the *SCI* grew. Even with a relatively stable number of source journals, the number of articles grew by 12 percent (from 387,000 to 434,000).

6. Scott Cunningham (Science Policy Research Unit, University of Sussex, D.Phil. research in progress) is developing techniques for classifying large numbers of articles on an individual basis.

7. In the intervening years, the curves move smoothly from the 1981 to the 1991 position.

8. Analysis by the ISI reveals that since 1989, the number of articles with more than 50 authors has increased sharply. Similar trends are visible in numbers of articles with more than 100, 200, and 500 authors (ISI 1995).

9. If we divide each sector's share of publications by the sum of sector shares, the resulting "normalized" shares will add to 100. In this case, educational institutions account for about 53 percent of U.K. output, and noneducational institutions account for 47 percent.

10. Those that do not are, in general, oddities, such as the London Business School, publishing a few articles in journals indexed in the *SCI*.

11. Company names were unified to the 1989 Who Owns Whom, and thus the number of parent companies are counted.

12. The following nonprofit institutions published no articles between 1981 and 1983 but published five or more articles between 1989 and 1991: British Heart Foundation, British Institute Reflect Profiling Syndicate, British Society Horticulture Research, Essential Rights, Fund for the Replacement of Animal Medical Experimentation, National Society for Epilepsy Research Group, Pain Relief Foundation, Quadrant Research Foundation, Thrombosis Research Institute, Wynn Institute of Metabolism Research.

13. Laboratories privatized during the decade were categorized as industry during the whole period. If they had been moved to industry as they were privatized, the number of government institutes would have declined noticeably and the number of companies risen even more.

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Diana M. Hicks is a senior lecturer at the Science Policy Research Unit. She has recently published examinations of the relationship between tacit and published knowledge (in Industrial and Corporate Change*), university-industry research links in Japan (in* Policy Sciences*), and Japanese-European corporate research networks (in* Research Policy*). Her current research interests include understanding the evolution of science systems, particularly the contribution of companies to them.*

J. Sylvan Katz is a research fellow at the Science Policy Research Unit. He has recently published examinations of the relationship between the evolution of science systems and government policy (in Nature*), the relationship between geographical separation and university-university collaboration within three countries (in* Scientometrics*), and the information carried by fractal distributions (in* Sports Medicine, Training, and Rehabilitation*). His current research interests include techniques for analysis of large text databases, the effect of policy on research systems, and complexity and self-organization in science systems.*