

The Scientific Wealth of Nations

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The United States took much pleasure last summer from its performance in the Olympic Games, where it was the most successful country. But was this the right measure of performance? Counting four points for gold, two for silver, and one for bronze, and calculating the score relative to population size, a different picture emerges. Tiny Tonga was among the larger economies, and overall the United States ranked 37th, well behind most of the European countries (the United Kingdom, a lamentable 48th).

Similar questions arise when we ask about the quality of the scientific research output of countries. For purposes, most notably overall advance in our understanding of nature, it is total output that matters. For other purposes--for example, in producing trained people or for underpinning industrial advances--output per person or per size [measured by population, gross domestic product (GDP), or other things] is more relevant. In this paper I offer comparisons, from a variety of viewpoints, of scientific research outputs and their quality. I derive my analysis from a recent United Kingdom benchmarking study (1), which in turn draws on the work of others (2-4), particularly an analysis of Australian research (5). These studies are all based on the large Citation Index (SCI), established by the Institute for Scientific Information (ISI). This database covers research publications from 79 countries and more than 4000 journals since 1981. The database has some shortcomings and biases (6), but overall it gives a wide coverage of most fields. We studied the database from 1981 to 1994, in which the ISI database totaled 8.4 million papers and 72 million citations.

Publications and Citations

The top 15 countries, ranked by the contribution of their scientists to the world's total number of publications in science, engineering, and medicine, from 1981 to 1994 (7, 8) accounted for 81.3% of the world's papers (Table 1). Ten of these were the world's seven largest economies, the so-called G7 countries. The United States was dominant, producing 25% of the world's science. The United Kingdom was second, ahead of more populous countries like Germany, France, and Japan. The 15 countries that constitute the European Union (EU) rivaled the United States and produced ~32% of all

Table 1. The world's top countries, ranked by their share of the world's papers in science, medicine, and engineering (6). The table also shows citation shares, RCI (9), expenditure on R&D (22), and R&D effectiveness: citations per unit of government expenditure on R&D in G7 countries (in boldface). Boldface figures are for the yearly average for the period from 1981 to 1984; expenditures are in £million and %GDP spent on R&D are for 1994, except for 1993 for Netherlands, Denmark, and Sweden and 1992 for Switzerland.

Country	Abbr.	Share of papers	Share of citations	RCI (rank)	GDP spent on R&D
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United States	US	34.6%	49.0%	1.42 (1)	2.5%
United Kingdom	UK	8.0	9.1	1.14 (5)	2.2
Japan	JP	7.3	5.7	0.78 (18)	2.9
Germany	GE	7.0	6.0	0.86 (15)	2.3
France	FR	5.2	4.5	0.87 (14)	2.4
Canada	CA	4.5	4.5	1.00 (7)	1.6
Italy	IT	2.7	2.1	0.75 (19)	1.2
India	IN	2.4	0.7	0.27 (66)	0.7
Australia	AU	2.1	2.1	0.97 (8)	1.6
Netherlands	NE	2.0	2.2	1.10 (6)	1.9
Sweden	SE	1.7	2.1	1.24 (3)	3.3
Switzerland	SW	1.4	1.9	1.37 (2)	2.7
P.R. China	PR	0.9	0.3	0.27 (65)	0.5
Denmark	DE	0.8	1.0	1.16 (4)	1.8
Finland	FN	0.7	0.6	0.9 (12)	2.4

In terms of these countries' percentage shares of all citations, the rankings are similar except for relative citation impact, RCI [citations divided by publications (6, 9)], gives some measure of the paper. In terms of the RCI, the United States still ranks first (10), and the top 15 countries by publication include the top 8 by RCI, although significantly reshuffled. Only three of the G7 countries (United Kingdom, and Canada) rank in the top 10 by RCI; the fourth is France, at 14th.

The top five countries by publication shares, which are also the five largest economies, invest more in research and development (R&D) than do most other countries (Table). The smaller countries notably Switzerland and Sweden (second and third by RCI), are relatively high investors in R&D relative to low R&D investment and also have a low RCI.

The above analysis can be broken down by field (Table) (7). As expected, the United States ranks first in all 20 fields we discriminated; percentages ranged from 70% (in psychology) to 37% (in physics). United Kingdom was second in 15 of the 20 fields, and placed lowest (fifth) in physics. The rankings when the quality measure of RCI is used, although the United States still showed strongly, followed by Sweden, United Kingdom, and others.

Table 2. Comparative advantage in citations, RCA (11), and a measure of absolute quality, F 20 fields of science defined by the ISI (6, 7, 23), for the United Kingdom. Also shown are the top five countries ranked by share of the world's citations and by RCI in each of the 20 fields. Abbreviations are Fig. 1. BE, Belgium.

Field	RCA	RCI	Top five countries	
			By total citations	
Agriculture	1.05	1.56	US,JP,UK,CA,GE	SE,UK,DE,CA,N
Astrophysics	1.06	1.13	US,UK,GE,FR,CA	US,SW,NE,CH,U
Biol. & biochem.	0.96	1.05	US,UK,JP,GE,CA	US,SW,SE,UK,C
Chemistry	0.87	1.22	US,JP,GE,UK,FR	US,SW,IS,NE,SI
Clinical medicine	1.22	1.10	US,UK,CA,GE,FR	US,CA,UK,SE,D
Computer sci.	0.65	0.69	US,UK,CA,GE,FR	IS,US,SW,CA,D
Ecol. & environ.	0.79	1.04	US,CA,UK,AU,GE	SE,NO,US,SW,A
Engineering	0.92	0.98	US,UK,JP,GE,CA	DE,SE,US,SW,A
Geosciences	1.05	1.13	US,UK,CA,FR,AU	US,AU,UK,SW,I
Immunology	0.96	0.96	US,UK,FR,JP,GE	SW,US,BE,UK,S
Materials sci.	0.80	1.13	US,JP,GE,UK,FR	US,DE,NE,IS,SV
Mathematics	0.87	1.26	US,UK,FR,GE,CA	DE,NO,UK,US,N
Microbiology	1.09	1.02	US,UK,GE,JP,FR	US,SW,UK,NE,I
Molec. biol. & genetics	1.03	1.05	US,UK,GE,FR,JP	SW,US,GE,UK,I
Multidisciplinary	1.07	1.44	US,UK,USSR,FR,GE	US,SW,DE,SE,C
Neuroscience	1.12	1.13	US,UK,CA,GE,FR	SE,US,SW,UK,I
Pharmacology	1.27	1.37	US,UK,JP,GE,FR	SW,NZ,UK,US,S
Physics	0.67	1.09	US,GE,JP,FR,UK	SW,DE,US,NE,I
Plant & animal sci.	1.18	1.39	US,UK,CA,GE,AU	UK,SE,DE,US,A
Psychology	0.99	1.11	US,UK,CA,AU,GE	US,SE,DE,UK,C

Bibliometric analysis can also uncover patterns of relative investment or relative advantage of subject, compared with the world average. The Australian study (5) defined a country's "revealed advantage" (RCA) in a specified scientific field as the fraction of all that country's citations (or p particular field, relative to the fraction of the world's citations that are in that field (11). Thus, if t 1, a comparative advantage is revealed, and vice versa. As shown in Table , on the basis of th

Kingdom has a strong comparative advantage in pharmacology, clinical medicine, plant and animal science, and neuroscience. In view of both the RCI and RCA, it appears that the United Kingdom is strong in biomedical research, and has absolute strength across a broad range of scientific disciplines. This is supported with a separate recent review of the U.K. science base (12).

Similar analyses for other countries (5) suggest that some smaller European countries (Denmark, Switzerland) have prominence in biomedical research. The Asian economies have prominence in certain industries (such as engineering, computing, chemistry, and materials). Some countries (New Zealand, and South Africa) have prominence on research based on natural resources; for the scientifically strong United States, Japan, France, and Germany, and the scientifically weak Pacific Rim countries (Thailand) no particular pattern of specialization emerges.

A measure of evenness of a country's scientific effort is given by the variance of the distribution of papers or citations) for the 20 fields specified by the ISI (13). The United Kingdom has the lowest variance (papers) or greatest evenness in its patterns of scientific capability among the 20 fields. The United States is followed by Germany, United States, Netherlands, Switzerland, and France (14). It is not surprising that larger economies show such relative evenness, but the presence of small countries such as Switzerland (where many would expect preponderant investment in pharmacologically related research) is surprising. Most of the Asian countries that are emerging as scientific powers, in contrast, have high variance (for example, Philippines, China, Indonesia, Singapore, Thailand, and South Korea).

Similarly, evenness in quality can be estimated by calculating the variance in the appropriately weighted RCI of a country's RCIs among the 20 fields (15). The greatest evenness in quality, by this measure, is followed by the United Kingdom, Netherlands, France, Finland, Canada, and United States (16). The data above and in Table indicate that the distribution of the data for the 20 fields for the United Kingdom is more clustered than for any other country. Whether this is a good thing is another question.

Consideration of a country's share of the world's total papers or citations tends to focus attention on the smaller economies. As in the opening analogy with the Olympic Games, we ask about performance in terms of medals, size, or money spent on basic research. On this basis (Table), the top 12 countries ranked according to papers per person are smaller, mainly northern European countries; the top G7 country is Canada, at fifth place, followed by the United Kingdom at eighth and United States at ninth. A similar pattern holds in terms of citations per person. Germany, Italy, and Japan come low in the rankings. Unlike the case for Olympic medals, there is no performance by a very small country. This is understandable; science has thresholds of critical

Table 3. Measures of relative performance (1, 5). Top 12 countries are listed first for each indicator.

Country	Paps. per person	Country
Switz.	167	Switz.
Israel	152	Sweden

Israel	152	Sweden
Sweden	147	Israel
Denmark	127	Denmark
Canada	127	U.S.
Neth.	109	Neth.
Finland	107	Canada
U.K.	104	U.K.
U.S.	100	Finland
N. Zealand	99	Iceland
Norway	96	Norway
Australia	93	Australia
France (15)	72	France (15)
Germany (17)	67	Germany (16)
Japan (19)	49	Japan (19)
Italy (21)	41	Italy (20)

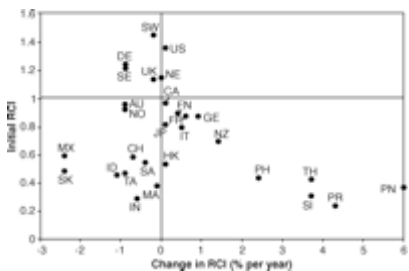
Comparison of scientific output relative to government money spent on research and development (and excluding defense funds) is arguably the best measure of the cost-effectiveness of spending on strategic research (Table , last columns). There is a marked gap--by a factor of 3 or more--measured in citations per unit of civil expenditure, of the top three G7 countries (United Kingdom, Canada) and the other four. The United Kingdom does particularly well in these performance rankings because the number of citations of papers by U.K. scientists is relatively high and partly because R&D is relatively low. A similar, although slightly smaller, gap is also seen if total government expenditure as the scaling factor [and similar patterns are seen if papers, rather than citations, are rescaled

Patterns of Change

From 1981 to 1994, the world's output of scientific papers increased by 3.7% per year. This rate corresponds to an average of 19 years. The greatest growth rates, >10% per year, were exhibited by the scientifically emerging countries: China, Singapore, South Korea, and Taiwan. The scientifically established countries had lower, though still high, average growth in publications: United States, 2.7%; United Kingdom, 3.0%; Germany, 3.3%; and France, 3.5%. In terms of publications relative to population size (Table), the countries that were already the leaders in 1981 continued to lead in 1994.

Such increases in output from newer players have meant that the United States, United Kingdom, and other scientifically developed Western countries have seen their share of the world's papers decrease from 1981 to 1994. The United States' share of world papers decreased by 1.0% per year from 1981 to 1994. The United Kingdom's share by 0.9%, and Germany's by 0.4%, whereas France's share increased by 0.7%. Japan's share increased by 2.1%. Overall, however, absolute rankings have not changed much. In terms of s

total papers, the United States ranked first, United Kingdom second, Japan third, and Germany beginning and at the end of the 1981-1994 interval. In terms of papers per population, the top were top at both the beginning and end of the 14-year span, with the exception of the Netherlands



Germany from the top 12) and also with minor reordering in the ranks. We note that the United States was ahead of the United Kingdom at the end). The U.S. decrease in world share of citations was about 1.1% per year. The United Kingdom's share decreased 1.1% per year.

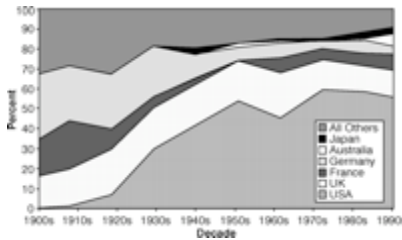
Change in the inherent quality of a country's science from 1981 to 1985 is indicated by changes in the RCI. As shown in Fig. 1, the emerging countries mentioned above tended to show large increases in RCI over the period, starting from a relatively low base. Other countries started the period with high RCI and tended to show little change. The countries that rank highest in average RCI (Table 1), or in citations or papers per population, tended to show little change. The greatest gain among the top 12 countries in Table 1 was by New Zealand, which showed an average annual growth in RCI of 1.4% per year. The greatest declines were for Australia, Norway, and Sweden, all of about 0.9% per year. RCI increased at 0.1% per year in the United States and at 0.2% per year in the United Kingdom. In general, there is thus little suggestion of any marked decline in the scientific output of the top-ranking countries in Table 1.

Fig. 1. Change in the quality of scientific output, measured as average percentage change in RCI (9) versus average RCI (average 1981-1985), for the larger scientifically developed, and developing, countries. Abbreviations are: CH, Chile; HK, Hong Kong; ID, Indonesia; MA, Malaysia; MX, Mexico; NZ, New Zealand; NO, Norway; PH, Philippines; SI, Singapore; SA, South Africa, SK, South Korea; TA, Taiwan; TH, Thailand. [\[View Image \(14K GIF file\)\]](#)

Corresponding analyses of trends in citations need to be interpreted with care, because citation counts are not strictly comparable over time (17). Thus, all else being equal, papers published in the early 1980s (or earlier) should contribute more to the citation count than those published in the early 1990s. But such considerations seem to us unlikely to introduce a bias greater than a couple of years [a supposition supported by the average half-life of citations (17)]. A difference in the age of researchers who did this work were trained 10, 20, or more years earlier. Today's performance is likely to be better than in the past, as well the new generations of scientists are being nurtured [see (1) for further discussion].

Another way of assessing a country's science base is to look at its success in winning major international awards. It is often asserted, for example, that the relative paucity of Nobel prizes won by U.K. scientists over the past century is evidence of declining scientific strength. Although still the best known and richest, the Nobel Prize has seen a growing number of notable awards. Its scope is, moreover, restricted: among the sciences, only physics, chemistry, and medicine (broadly construed as the biomedical end of the life sciences) are recognized.

We thus counted all internationally recognized scientific prizes worth more than \$200,000 (United States' Fields Medal (18), by decade through the 20th century (Fig. 2). Up to the past few



essentially solely of Nobels. German scientists won most of the awards in the 1930s and 1940s, and scientists in the United States began to win many awards in the decades around World War II, proportionally fewer German awards while U.S. scientists established a continuing command of around 30% of prizes. Scientists in the United Kingdom have maintained a steady share of all awards throughout the century. If this total is rescaled for population, the United Kingdom has been the leader throughout the century. One bias in this analysis is that one recent award, the Australia Prize, has been won largely by Australians. Japan and United States each give two large prizes. United Kingdom, Germany, and France none.

Fig. 2. The figure shows the fraction of the world's major international science prizes (18) won by each of the G5 countries and Australia, by decade, over the 20th century (1). Order of curves is as listed in the 1 Version of this Image (28K GIF file)

Analysis of prizes gives a time-delayed measure of performance. This consideration may explain why the G5 countries have continued to win about 80% of the awards over the past three decades, despite the rising performance of new players and the G5 countries' diminishing share of the world's papers and citations.

Discussion

The above comparisons are to a degree confounded because a large and growing fraction of scientific work involves international collaborations [see discussion in (8)]. In 1994, for example, 26% of papers with first authors in the United Kingdom were the product of transnational collaborations (4). Another concern is that there is an English language bias in the ISI database, both in the journals included and in patterns of citation. Could this explain why the United States, United Kingdom, and Canada do so much better than France, Germany, Italy, and Japan (Table , last columns)? But the same broad patterns of performance among the G7 countries are also seen in the analysis in Table , where the four leaders are not the English-speaking countries.

Despite these concerns, the large differences in performance indicated in Table , last columns, are surprising. My view--and it is no more than a guess--is that a large part of the difference in performance between the top dozen or so countries in Table and the lower ranking of the G7 countries arises from differences in the nature of the institutional settings where the scientific research is done. Germany and France have superb scientists who do outstanding work, but a large proportion do this work in dedicated research institutes: Max Planck and CNRS Institutes. By contrast, most basic research in North America, United Kingdom, the Scandinavian countries, and others among the top countries in Table , is

done in universities (19). The nonhierarchical nature of most North American and northern European universities, coupled with the pervasive presence of irreverent young undergraduate and postgraduate students, could be the best environment for productive research. The peace and quiet to focus on a mission in a research institute, undistracted by teaching or other responsibilities, may be a questionable blessing.

I thus suggest that, among the scientifically advanced countries, better value for money (in terms of papers or citations per person or per dollar spent) might be associated with performing basic research mostly in universities, rather than in research institutes. If so, there are significant implications for those countries, such as the United Kingdom, Sweden, and Australia, which recently have seen great enlargement in the number of tertiary institutions designated as universities. It seems unlikely that governments can afford to supply the previously customary level of infrastructure for research (equipment, technicians, research libraries, properly furnished laboratories, and so on) to all departments in these more numerous universities. This raises questions about how to focus such infrastructure support and indirect costs upon the best people and groups. The question is sharpened by the observation that, in the United Kingdom, by the year 2000 half of all scientific papers will have three or more authors, from two or more institutions. I think the alternative of hiving off most fundamental research into dedicated institutes could be a suboptimal solution. This issue deserves further analysis.

To end on a parochial note, I observe that the United Kingdom does well in attracting inward investment (20). It is believed that the strength, and the accessibility, of the science base is a large factor in this success. Anecdotes abound, but a convincing and objective analysis is more difficult. More generally, the acknowledged strength of the science base in the United Kingdom, although it helps create wealth around the world, is not consistently translated into strong industrial performance within the United Kingdom itself. The Technology Foresight enterprise in the United Kingdom currently seeks to remedy this, by forging new connections between the two. But this is another story (21).

REFERENCES AND NOTES

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2. J. S. Katz *et al*, *The Changing Shape of British Science* (Science Policy Research Unit, University of Sussex, Sussex, UK, October, 1995). 5. *Australian Science:*

- Performance from Published Papers* (Australian Government Publishing Service, Canberra, 1996).
3. The ISI database has many acknowledged biases and limitations. Some problems have to do with the compilation of the database. It includes citations of books and chapters in edited books, but it does not include the citations in such publications. Other publications, such as government and other agency reports and working papers, are essentially omitted. It does not cover all significant scientific journals [for example, many Australian journals are not covered (5)]. Journals from non-English-speaking countries are not as well represented as those from English-speaking countries. There are problems with shifting definitions of countries (for example, the breakup of the USSR); the ISI database preserves the 1981 list of countries through time, ignoring changes in boundaries. Other problems are associated with citation patterns. Papers that describe technical methods may attract thousands of reflexive citations, while pathbreaking papers may be cited only slightly for many years. Review articles can mask the primary papers they review. Citation patterns vary among fields (for example, average citation rates are far higher in molecular biology and genetics than in materials science). Spectacular scientific errors may attract many citations, although we think this may distort overall counts less than is sometimes suggested; interesting errors can, moreover, spark new ideas and developments in science. Self-citation (which accounts for at least 10% of all citations) may bias some of the results. For a more detailed discussion of these questions, see (2), (5), and E. Garfield, *Citation Indexing: Its Theory and Application in Science, Technology and Humanities* (Wiley, New York, 1979).
 4. The ISI database covers some additional fields of social science, but [following (5)] these are omitted from our analysis.
 5. There are several ways of counting authors of collaborative papers. Here, following (5), such papers are attributed to each of the countries represented among the authors. In order that percentage shares add up to 100, the world total of papers is defined as the sum of papers across all countries, even though this means some double counting. The EU study (2) attributes fractions of a paper among countries in proportion to authorial numbers. The United Kingdom performs even better on this basis; the 1993 world shares of papers for the G7 was the United States 35.8%, United Kingdom 8.7%, Japan 8.2%, Germany 6.3%, France 5.1%, Canada 4.5%, and Italy 3.0%. These proportions changed relatively little from 1981 to 1993 and may be compared with the corresponding figures in Table . Yet another method is simply to assign papers to first authors. A survey of different accounting methods by P. Bourke and L. Butler [*A Crisis for Australian Science?* (Australian National University Press, Canberra, 1994)] suggests that these various approaches have relatively little effect on conclusions.
 6. For country i , let total papers be P_i and citations C_i . The share of the world's papers is then $p_i = P_i/P$, where $P = \sum P_j$ is the world's total number of papers. Similarly, citation share is $c_i = C_i/C$, with $C = \sum C_j$. Hence $\text{RCI}_i = c_i/p_i = (C_i/P_i)(P/C)$. That is, for country i , the average number of citations per paper, C_i/P_i , is RCI_i multiplied by the ratio of all citations to all papers (namely 8.53).

7. It has been suggested that U.S. scientists, on average, tend to be more insular than their European and other counterparts, tending to focus more on their own (United States) literature than is the case in other countries (5). If so, this would tend to elevate the RCI for U.S. papers.
8. Define $P_i(j)$ as the number of papers published in field j by country i . Then the quantity P_i of (9) is $P_i = \sum P_i(j)$. Following (2, 5), I define $RCA_i(j) = [P_i(j)/P_i] \div [P(j)/P]$, where $P(j) = \sum P_i(j)$ is the world's total of papers in field j , and P is the overall total of (9). It follows that $RCA_i(j) = [P_i(j)/P(j)] \div p_i(j)/p_i$. Here p_i is the overall publications share of country i , as defined in (9), and $p_i(j)$ is the corresponding publications share in field j . 12. *The Director General of Research Councils' Review of the Science Budget Portfolio* (UK Office of Science and Technology, London, May 1995).
9. Such a measure of evenness of scientific capabilities cannot sensibly be obtained simply from the variation in citation or publication shares among fields because the ISI's 20 fields are themselves of variable breadth: some, like chemistry or physics, include many subfields, while others, like astronomy, are narrow. We must use the variance of the distribution in the indices of revealed comparative advantage, $RCA_i(j)$, as defined in (11).
10. See figure 2.3b and discussion in (5).
11. We do not simply use the distribution of $RCI(j)$ by fields j , but rather $RCI(j)$ normalized by the overall citation impact of a country across all fields [in analogy to that in (13)]. Such normalization allows us to make meaningful comparisons of variances among different countries, accounting for the different values of their overall RCI.
12. See figure 2.3a and discussion in (5).
13. This bias is further complicated because the citation half-life of a paper tends to vary among disciplines, being longer in subjects like ecology (average around 7 years), and shorter in subjects like molecular biology (average around 2 years).
14. Figure 2 includes the following awards: Nobel (Sweden), Crafoord (Sweden), Wolf (Israel), Kyoto (Japan), King Faisal (Saudi Arabia), Volvo (Sweden), Japan, Draper (U.S.), Balzan (Italy), Australia, Chorofas (Switzerland), Bower (U.S.), Fields Medal.
15. About 80% of UK papers come from universities and teaching hospitals, around 11% from research council and government institutes, and 9% from industry (4).
16. The United Kingdom accounts for more than a third of all inward investment into the EU, including roughly 40% of all such investment from the United States, 40% from Japan, 50% from South Korea. Put another way, the United Kingdom receives roughly 17% of all outward investment from the United States, 7% of Japan's outward investment, and 15% of Germany's.
17. *A Strategy Taking the Foresight Programme to the Millennium* (Office of Science and Technology, UK Department of Trade and Industry, London, December 1996).
18. Data mainly from (5); see also (1) and (3).
19. Data from ISI database. The first column follows (5). For the second column, based on RCI, which is a relative measure of performance, we have excluded countries that contribute less than about 0.2% of all publications in that field.

Otherwise, one (or a few) highly cited multi-authored paper that has one author from a small country can produce a high RCI ranking for that country, which arguably is misleading; we follow (5) in assigning multi-authored papers to each country with a contributing author (8).