

Knowledge, networks and nations

Global scientific collaboration in the 21st century

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Knowledge, Networks and Nations: Global scientific collaboration in the 21st century

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Cover photo: Strain in graphene opens up a pseudomagnetic gap. Generated by the Condensed Matter Physics Group at the University of Manchester, this image is a representation of the work at Manchester lead by Professor Andre Geim FRS, a Royal Society Research Professor, and Professor Konstantin Novoselov, a Royal Society University Research Fellow. Professors Geim and Novoselov were awarded the Nobel Prize for Physics in 2010 for their groundbreaking experiments regarding graphene, a form of carbon, which is the thinnest and strongest material ever isolated. Both men have been cited since their award as 'global scientists'; both were born and studied in Russia, spent time in the Netherlands, and are now based here in the UK, attracting funding and accolades from UK, European, and international sources.
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Designs of vases and teapots that would be found in a house of a merchant in Canton, from *Designs of Chinese buildings*, by William Chambers, 1757. From the Royal Society library and archive.

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Map of China, from *An embassy from the East-India Company of the United Provinces to the Grand Tartar Cham*, by John Nieuhoff, 1669. From the Royal Society library and archive.



Executive summary

Science is a global enterprise. Today there are over 7 million researchers around the world, drawing on a combined international R&D spend of over US\$1000 billion (a 45% increase since 2002), and reading and publishing in around 25,000 separate scientific journals per year. These researchers collaborate with each other, motivated by wishing to work with the very best people and facilities in the world, and by curiosity, seeking new knowledge to advance their field or to tackle specific problems.

Knowledge, Networks and Nations reviews, based on available data, the changing patterns of science, and scientific collaboration, in order to provide a basis for understanding such ongoing changes. It aims to identify the opportunities and benefits of international collaboration, to consider how they can best be realised, and to initiate a debate on how international scientific collaboration can be harnessed to tackle global problems more effectively.

From Singapore to South Africa, new researchers and research communities are reshaping the landscape for science and innovation, so long dominated by the USA, Japan and Europe. This report explores this changing geography of science and innovation. In Part 1, it maps and investigates where and how science is being carried out around the world and the ways in which this picture is changing.

- **Science in 2011 is increasingly global,** occurring in more and more places than ever before. Science is addressing questions of global significance. It is supported by governments, business, philanthropists and charities.

- There are particular countries where this increased activity is especially striking, with investment and scientific productivity outstripping general trends of growth. The rise of **China** has been especially notable, overtaking Japan and Europe in terms of its publication output in recent years. Beyond China, rapid developments have also taken place in **India, Brazil** and **new emergent scientific nations** in the Middle East, South-East Asia and North Africa, as well as a strengthening of the smaller European nations.
- However, **the traditional 'scientific superpowers' still lead the field.** The USA, Western Europe and Japan all invest heavily in research and receive a substantial return in terms of performance, with large numbers of research articles, the lion's share of citations on those articles, and successful translation, as seen through the rates of patent registration.
- The continued strength of the traditional centres of scientific excellence and the emergence of new players and leaders point towards an **increasingly multipolar scientific world**, in which the distribution of scientific activity is concentrated in a number of widely dispersed hubs.
- **Beyond these hubs, science is also flourishing.** The recognition of the role that science can play in driving economic development, and in addressing local and global issues of sustainability, has led to increased research activity and the application of scientific method and results within less developed countries.



Part 2 reveals the shifting patterns of international collaboration. International science is largely conducted through bottom-up, informal connections, as scientists become more mobile and as large and often complex data are shared at the click of a button. But top-down, solutions-oriented initiatives are also helping to shape the research landscape, as scientists organise themselves, or are being organised, to tackle shared concerns.

- **The scientific world is becoming increasingly interconnected, with international collaboration on the rise.** Today over 35% of articles published in international journals are internationally collaborative, up from 25% 15 years ago.
- **Collaboration is growing for a variety of reasons.** Developments in communication technologies and cheaper travel make it easier than ever before for researchers to work together; the scale of research questions, and the equipment required to study demands that researchers are mobile and responsive. Collaboration **enhances the quality** of scientific research, **improves the efficiency and effectiveness** of that research, and is **increasingly necessary**, as the scale of both budgets and research challenges grow.
- However, **the primary driver of most collaboration is the scientists themselves.** In developing their research and finding answers, scientists are seeking to work with the best people, institutions and equipment which complement their research, wherever they may be.
- The connections of people, through formal and informal channels, diaspora communities, virtual global networks and professional communities of shared interests are important drivers of international collaboration. **These networks span the globe. Motivated by the bottom-up exchange of scientific insight, knowledge and skills, they are changing the focus of science from the national to the global level.** Yet little is understood about the dynamics of networking and the mobility of scientists, how these affect global science and how best to harness these networks to catalyse international collaboration.
- **Collaboration brings significant benefits**, both measurable (such as increased citation impact and access to new markets), and less easily quantifiable outputs, such as broadening research horizons. The facilitation of collaboration, therefore, has a positive impact not only on the science conducted, but on the broader objectives for any science system (be that enhancing domestic prosperity or addressing specific challenges).

Part 3 of this report explores the role of international scientific collaboration in addressing some of the most pressing global challenges of our time. The report concentrates on five case studies, and considers the strengths and shortcomings of existing mechanisms which bring scientific communities together to address global challenges. **IPCC, CGIAR, the Gates Foundation, ITER and efforts to deploy carbon capture and storage technology** demonstrate how science is already being used to respond to these challenges, and provide models and lessons for how it might be better deployed in the future.

- The global scientific community is increasingly charged with or driven by the need to find solutions to a range of issues that threaten sustainability. **These ‘global challenges’ have received much attention in recent years, and are now a key component of national and multinational science strategies and many funding mechanisms.**
- **Global challenges are interdependent and interrelated:** climate change, water, food and energy security, population change, and loss of biodiversity are all interconnected. The dynamic between these issues is complex, yet many global assessment and research programmes are managed separately, often reflecting a lack of co-ordination in the policy sphere. Governments, civil society and the private sector need to take a broader perspective on global challenges in order to appreciate how they are interrelated.

- Global challenges are being addressed via a number of different organisational mechanisms: through intergovernmental or international bodies, through national systems, and by private individuals and corporations. These mechanisms often deploy novel and innovative forms of partnership, some of which work well, others less so. **Valuable lessons can be drawn from existing models in designing, participating in and benefiting from global challenge research.**
- **Science is essential for addressing global challenges, but it cannot do so in isolation.** A wide range of approaches will be required, including the appropriate use of financial incentives, incorporating non-traditional forms of knowledge, and working with the social sciences and wider disciplines. Science is crucial but it is unlikely to produce all the answers by itself: the science infrastructure works best when it is supported by, and enables, other systems.
- **All countries have a role in the global effort to tackle these challenges,** both in defining and prioritising them and in using global research output to inform local, national and regional responses. This need is increasingly being acknowledged for inclusivity and capacity building across regions and continents, in helping to meet (national) needs, and in developing a global infrastructure that is resilient to new challenges.

Knowledge, Networks and Nations concludes with a set of recommendations to further strengthen global science. This report calls for more creative, flexible and better-resourced mechanisms to co-ordinate research across international networks and to ensure that scientists and science can fulfil their potential. It also calls for more comprehensive and inclusive ways of measuring and evaluating the science which is delivered and applied in all its forms around the world. Finally, the report highlights the importance of science—and the wider evidence base—in underpinning robust policy making, especially around shared global challenges.

Understanding global science systems, their mechanisms and motivations, is essential if we are to harness the very best science to address global challenges and to secure the future of our species and our planet.

Recommendations

1. Support for international science should be maintained and strengthened

- Even in difficult economic times, **national governments need to maintain investment in their science base** to secure economic prosperity, tap into new sources of innovation and growth, and sustain vital connections across the global research landscape. Sustained investment builds a nation's capacity to assimilate excellent science, wherever it may have been conducted, for that country's benefit.
- **International activities and collaboration should be embedded in national science and innovation strategies** so that the domestic science base is best placed to benefit from the intellectual and financial leverage of international partnerships.

- **Commitments to multinational research efforts and infrastructures should not be seen as easy targets for cuts during a period of economic turbulence.** To cut subscriptions to joint research endeavours, without due diligence and assessment, is a false economy. By disengaging from these efforts, countries run the risk of isolating their national science and losing relevance, quality and impact.

2. Internationally collaborative science should be encouraged, supported and facilitated

- **Research funders should provide greater support for international research collaboration** through research and mobility grants, and other mechanisms that support research networks.
- **National border agencies should minimise barriers to the flow of talented people,** ensuring that migration and visa regulations are not too bureaucratic, and do not impede access for researchers to the best science and research across the world.
- **National research policies should be flexible and adaptive** in order to ensure that international collaboration between talented scientists is not stifled by bureaucracy.

3. National and international strategies for science are required to address global challenges

- Recognising the interconnectedness of global challenges, **funders of global challenge programmes should devise ways to better co-ordinate their efforts, share good practice, minimise duplication and maximise impact.** Where possible, these should draw on existing infrastructure or shared technology.

- **National research funding should be adaptive and responsive to global challenges**, supporting the interdisciplinary and collaborative nature of the science required to address these issues.
- **In devising responses to global challenges, governments worldwide need to rely on robust evidence-based policy making**, and bring excellent scientists into the policy advisory process.

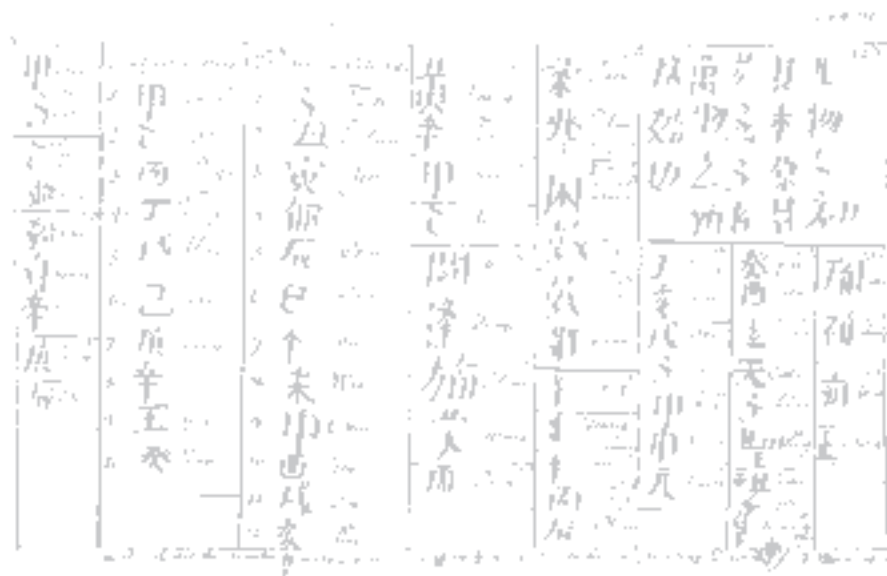
4. International capacity building is crucial to ensure that the impacts of scientific research are shared globally

- **Researchers and funders should commit to building scientific capacity in less developed countries** to help improve their ability to conduct, access, verify and use the best science, and to ensure that they can contribute to global scientific debates and develop local solutions to global problems.
- **Scientific capacity building must involve financial support for authors in developing countries to publish in open access journals.** Open access publishing has made a wealth of scientific literature available to the developing world, but conversely has made it harder for their scientists to publish under the ‘author pays’ model.
- **National academies, learned societies and other similar institutions should actively promote public and wider stakeholder dialogue to help identify, shape and respond to global challenges and their local manifestations.**

5. Better indicators are required in order to properly evaluate global science

- **UNESCO (and other agencies such as the OECD) should investigate new ways in which trends in global science can be captured, quantified and benchmarked**, in order to help improve the accuracy of assessments of the quality, use and wider impact of science, as well as to gauge the vitality of the research environment.
- **There is a specific lack of data on the flow and migration of talented scientists and their diaspora networks.** UNESCO, OECD and others should investigate ways of capturing this information as a priority, which would enable policy makers to better understand, nurture and oversee global science for the benefit of society as a whole.

Instructive memoire on the new chronological table of the history of China, by the Viceroy of Canton, 1724. From the Royal Society library and archive.



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The Royal Society gratefully acknowledges the contribution of the reviewers. The Review Panel was not asked to endorse the conclusions or recommendations of the report, nor did they see the final draft of the report before its release.

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Research, University of Sussex

Conduct of the study

The study leading to this report was overseen by an Advisory Group of Fellows of the Royal Society and other distinguished experts, supported by the staff of the Royal Society Science Policy Centre. Elsevier has provided financial support, and full access to their publication databases and analytical services throughout the study. The drafting of the report, its conclusions and recommendations are those of the Royal Society alone.

Knowledge, Networks and Nations: Global scientific collaboration in the 21st century has been approved by the Council of the Royal Society.

Advisory Group and terms of reference

The Royal Society established an Advisory Group made up of internationally renowned scientists and science policy experts from around the world, chaired by Sir Chris Llewellyn Smith FRS. The aim of the study, as outlined in the Terms of Reference, was to provide an analysis of the global scientific landscape in 2011 for a global audience of scientists, governments, business, international organisations and NGOs. Its specific goals were to:

- Provide an overview of how, where, why and by whom scientific research is being carried out across the world, and the ways in which this picture is changing.
- Compile both quantitative and qualitative evidence to offer an overview of these developments through the use of Elsevier's and other databases such as UNESCO and OECD, and by making use of the Society's extensive international networks, including its global Fellowship of over 1,400 outstanding individuals from all areas of science, mathematics and engineering.

- Identify and assess illustrative examples of opportunities and challenges these changes present for policy makers, scientists, intergovernmental agencies and business.
- Examine and discuss how international scientific collaboration can be better utilised to address global problems such as climate change, food and water security, and infectious diseases.
- Draw conclusions about the collaborative nature of research in the 21st century, and consider the potential implications for policy makers.

The study was formally launched in January 2010.

Collection of evidence

Evidence gathering for the project took place in five ways:

- a formal process, through a detailed Call for Evidence;
- a special discussion session for members of the InterAcademy Panel, held to coincide with its General Assembly at the Royal Society in January 2010;
- face-to-face and telephone interviews with key figures in international science and science policy from around the world;
- extensive desk research;
- data analysis, including work with Elsevier.

Call for evidence

The Call for Evidence was sent out on 27 April 2010 to Fellows of the Royal Society, Royal Society Research Fellows and the world's science academies, through the InterAcademy Panel (IAP), the Academy of Sciences for the Developing World (TWAS), and the UK Government's Science and Innovation Network (SIN).

We received 80 responses from individuals, academies, research institutions, government departments and other organisations from around the world. These are listed at the end of the report.

Elsevier methodology

Unless otherwise indicated, all of the data relating to publication output and impact in this report have been provided by Elsevier. We would like to acknowledge the analysis and insights provided by the following individuals:

- Dr Andrew Plume, Associate Director, Scientometrics & Market Analysis—Research & Academic Relations
- Mayur Amin, Senior Vice President—Research & Academic Relations
- Dr Henk Moed, Senior Scientific Advisor—Academic & Government Markets
- Niels Weertman, Vice President, SciVal—Academic & Government Markets

Publication data are derived from Scopus, the world's largest abstract and citation database of peer-reviewed literature. Scopus contains over 41 million records across 18,000 journals and covers regional as well as international literature. Publication outputs in this report are defined as articles, reviews and conference papers published in these journals. Where we consider overall totals of publications, these include outputs in all disciplines.

Defining global science

The Royal Society defines 'science' as 'natural knowledge'. In practice, this includes the natural sciences, mathematics and engineering. For the purposes of this report, where we discuss overall totals of publications, these include social sciences, the arts and humanities (in practice, these represent a very small proportion of publication output—8.9%); this coverage is used to match the 'input' statistics, which all register 'research' and 'researchers', which are discipline neutral. However, our examples, case studies and observations are drawn from the scientific community.

Throughout this report, we use a number of sources to characterise and quantify what is happening globally in science. In this we are constrained, to certain extents, by the available data. In order to achieve the widest international coverage, we have made use of UNESCO data on the numbers of researchers,¹ and the expenditure on research and development as indicators of expenditure and manpower in science (although a large proportion of 'research and development' is spent on D rather than R and, as such, reaches beyond strict 'science spending').

Introduction: going global

When Henry Oldenberg founded the world's first scientific publication in 1665,² it drew on emerging ideas from Germany, Italy, Hungary, France and even the Bermudas. It enjoyed a wide international readership. Oldenburg, and the other founding fellows of the Royal Society, dedicated this first edition of 'Philosophical Transactions' to sharing 'the Happy inventions of obliging Men all over the world, to the General Benefit of Mankind'.

But Oldenberg could never have imagined how many 'obliging men' and women would be contributing to scientific knowledge across the world in 2011. Science has transformed our lives in ways which would have been inconceivable in 1665. Just how it will evolve over the coming century is equally inconceivable. Yet one thing seems certain: science is inherently international and will only become more so.

As Louis Pasteur once put it, 'Knowledge belongs to humanity, and thus science knows no country and is the torch that illuminates the world.' Largely funded at a national level and conducted primarily in national institutions, science is still more determined by place than Pasteur's declaration would suggest. And yet, it is a worldwide endeavour. In 2008, 218 countries produced over 1.5 million research papers, from Tuvalu's one paper, to the UK's 98,000, China's 163,000, and the USA's 320,000.³ In 2007, Sweden spent nearly 3.7% of its gross domestic product (GDP) on research and development (R&D), Canada spent 2%, 'emerging' India spent 0.8%, and oil rich Saudi Arabia 0.04%.⁴ Research investment and output are far from evenly spread across the world,

but there are few places which are not in some way part of the scientific landscape.

Science is conducted in more places than ever before, but it is also more interlinked. Over one-third of research papers are the direct result of international collaboration, with authors' addresses from more than one country.⁵ The number of internationally co-authored papers has more than doubled since 1990.⁶ Researchers are increasingly mobile, travelling long distances to work with the best colleagues in their field, to access resources and share ideas and facilities. And they are being supported internationally through cross-border funding from international organisations (charities, philanthropic funding and business), multilateral initiatives between governments and research councils, multinational funding bodies and shared scientific infrastructure.

The scientific community is influenced by globalisation, and is also driven by its own dynamics. Scientists have been both motivated and enabled to work across disciplinary and international borders by technological advances and shifts in geopolitics. But science has always pushed boundaries, be they technological or national and political. Global science is increasing, but it is also nothing new. The founding members of the Royal Society 350 years ago looked beyond national borders to extend the frontiers of natural knowledge. Today's scientific pioneers will need to know how to navigate the changing global scientific landscape if they are to keep extending those frontiers. This report is intended to help them understand the dynamics of this complex and fast-evolving phenomenon.

2 On 6 March 1665, the first issue of [Philosophical Transactions](#) was published under the editorship of Henry Oldenburg, who was also the Secretary of the Society.

3 Data from Elsevier's Scopus.

4 Data from the [UNESCO Institute for Statistics Data Centre](#), Montréal, Canada.

5 Data from Elsevier's Scopus.

6 Leydesdorff L & Wagner C (2005).

[Mapping global science using international co-authorships: a comparison of 1990 and 2000.](#)

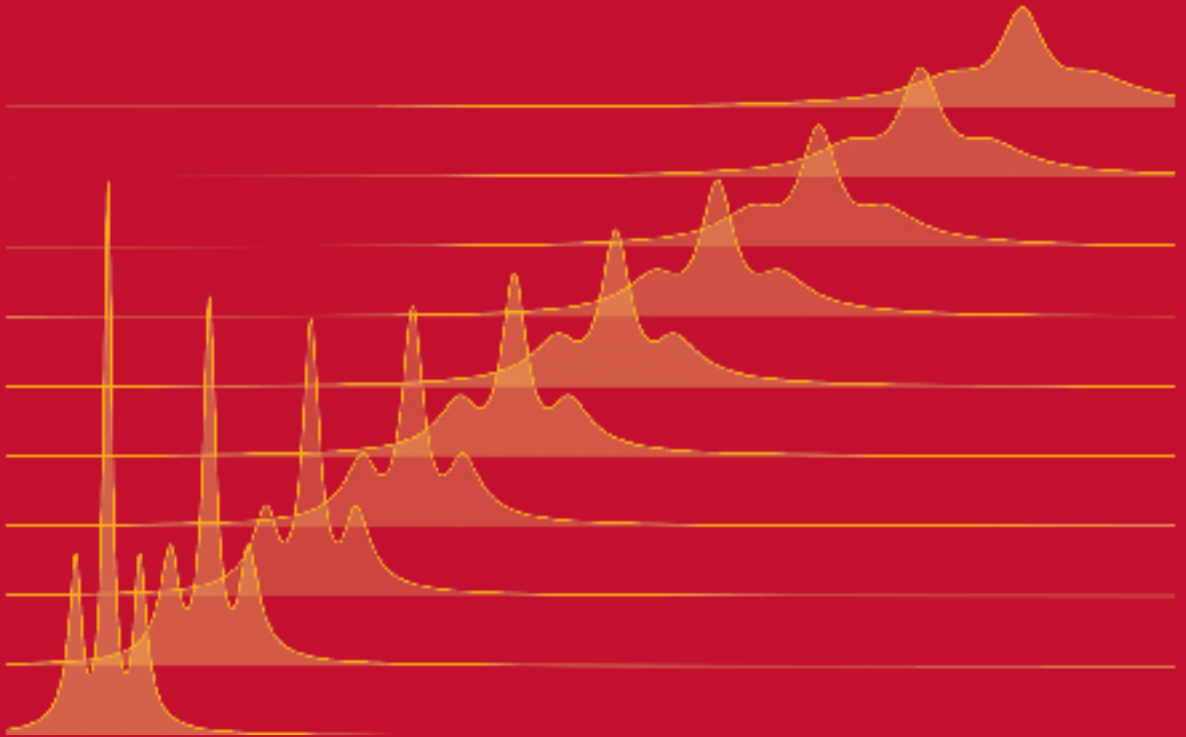
International Journal of Technology and Globalization **3**. For a discussion of how international

collaboration has grown overall and at the regional level, see Wagner C & Leydesdorff L (2005). [Network structure, self-organization and the growth of international collaboration in science.](#) Research Policy **34**, 10, 1608–1618.

PART 1

Scientific landscape in 2011

A new manifestation of the celebrated "Mollow triplet", one of the fundamental spectral shapes of light-matter interaction, from Dr Elena del Valle, Royal Society Newton International Fellow, School of Physics and Astronomy, University of Southampton. The triplet as found by Mollow emerges in the light emitted by an atom when excited by a laser. The depicted triplet is the counterpart emission from an atom when excited incoherently inside a cavity. © Dr Elena del Valle, 2010.



Science is growing globally. Since the beginning of the 21st century, the global spend on research and development has nearly doubled, publications have grown by a third, and the number of researchers continues to rise (see Table 1.1). North America, Japan, Europe and Australasia have all witnessed growth, with each increasing spending by around one-third between 2002 and 2007. In the same period, 'developing countries',⁷ including the emerging economies of China, India and Brazil, more than doubled their expenditure on R&D, increasing their contribution to world R&D spending by 7 percentage points from 17% to 24%.⁸

Table 1.1. Global science by numbers.⁹

	Spend on research and development		Numbers of researchers	Number of publications
	US\$	% GDP		
2007	1145.7bn	1.7	7.1m	1.58m
2002	790.3bn	1.7	5.7m	1.09m

The architecture of world science is also changing, with the expansion of global networks. These involve networks of individuals, mostly self-organised but sometimes orchestrated (as in the Human Genome Project). Some networks are based on collaborations at international organisations (such as CERN); others are funded internationally, by multinational businesses (which fund their own laboratories and work in universities across the globe), by major foundations (such as Gates), or by cross-national structures such as the EU. These global networks increasingly exert a significant influence on the conduct of science across the world.

1.1 Trends and developments in global science

The USA leads the world in research, producing 20% of the world's authorship of research papers,¹⁰ dominating world university league tables,¹¹ and investing nearly US\$400 billion per year in public and private research and development.¹² The UK, Japan, Germany and France each also command strong positions in the global league tables, producing high quality publications and attracting researchers to their world class universities and research institutes. These five countries alone are responsible for 59% of all spending on science globally.¹³

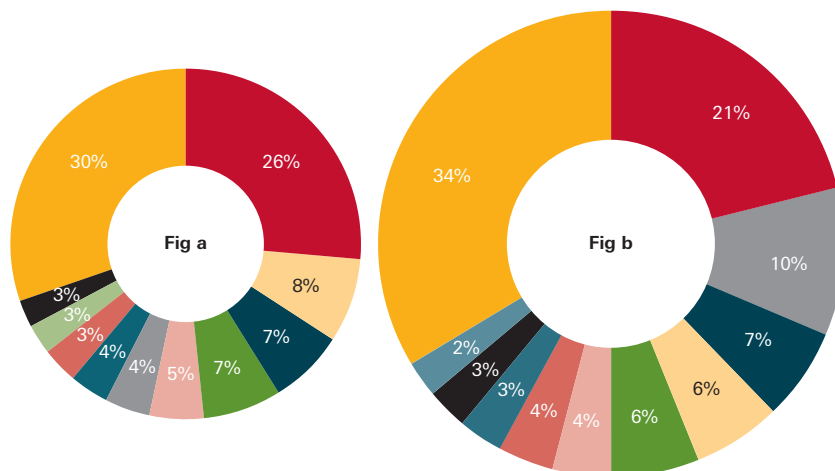
However, these countries do not completely dominate global science. Between 1996 and 2008 the USA lost one-fifth of its share of the world's article authorship, Japan lost 22% and Russia 24%. The UK, Germany and France also fell back in relative terms.¹⁴ Figure 1.1 shows how the number of articles has grown and how their distribution across the world has changed in recent years, between the periods 1999 to 2003 (Figure 1.1a) and 2004 to 2008 (Figure 1.1b).

The traditional scientific leaders have gradually lost their 'share' of published articles. Meanwhile, China has increased its publications to the extent that it is now the second highest producer of research output in the world. India has replaced the Russian Federation in the top ten, climbing from 13th in 1996 to tenth between 2004 and 2008. Further down the list South Korea, Brazil, Turkey, South East Asian nations such as Singapore, Thailand, and Malaysia, and European nations such as Austria, Greece and Portugal have all improved their standings in the global scientific league tables.¹⁵

Changes in the ranking of nations within the league tables are shifting at the same time as total output is increasing. For example, Italy maintained a steady share of publications between 1996 and 2008 (3.5% of world production in both years, fluctuating between 3% and 4% over the whole period); but in order to hold this position it increased its number of articles by 32%. All over the world, some countries are running to stand still¹⁶ while others are breaking into a sprint.

Figure 1.1. Proportion of global publication authorship by country¹⁷

The top ten producing countries in each period are shown. **Fig a.** 1999-2003. **Fig b.** 2004-2008



- 7 Based on the standard United Nations Statistics Division classification (composition of macro geographical (continental) regions, geographical sub-regions, and selected economic and other groupings).
- 8 UNESCO (2010). *UNESCO science report 2010*. Data from UNESCO Institute for Statistics, published in UNESCO Science Report 2010 (p 2, Table 1). UNESCO Publishing: Paris, France. Data are provided in US\$ pegged at current prices (2007 prices in 2007, 2002 prices in 2002) and reflect purchasing power parity.
- 9 Spend on research and development: data from UNESCO Institute for Statistics, published in UNESCO Science Report 2010 (p 2, Table 1). Number of researchers: data from UNESCO Institute for Statistics Data Centre, UNESCO Institute for Statistics: Montréal, Canada. Number of publications: data from Elsevier's Scopus.

- 10 Data from Elsevier's Scopus. If an author on a paper gives a country as his or her address, that paper is assigned to that country. So a paper which has been written by authors in the UK, Spain and Germany would be assigned as a single paper in each country (that paper therefore being accounted for three times as a 'national' paper). Figure 1.1 shows the total number of individual papers without any multiple counting. The total number of 'national' papers (ie. with papers counted multiple times if there are authors based in more than one country) in 2007 was 1,580,501; in 2002 this was 1,093,564. The USA produced 316,317 'national' papers in 2008 (221,707 with the USA as the sole authors, and 94,610 in collaboration internationally); this represents 19.97% of all 'national' papers globally.
- 11 The QS rankings have six US universities in the top 10

(Cambridge in the UK is ranked first, and the other three are also in the UK). In the Times Higher Education World University Rankings the USA holds the top five positions, seven of the top 10 places and 27 of the top 50 (the remaining three in the top ten are in the UK). In the ARWU Rankings the four top positions and 17 of the top 20 are US universities (the remaining three in the top 20 are the Universities of Cambridge, Oxford and Tokyo). Source: Academic Ranking of World Universities (2010) available online at <http://www.arwu.org/ARWU2010.jsp>; QS Top University Rankings (2010) at <http://www.topuniversities.com/university-rankings/world-university-rankings/home>; Times Higher Education World University Rankings (2010) at <http://www.timeshighereducation.co.uk/world-university-rankings/index.html>, accessed 29 September 2010.

- 12 National Science Board (2010). *Science and engineering indicators 2010*. National Science Foundation: Arlington, VA, USA.
- 13 Data from UNESCO Institute for Statistics, published in UNESCO Science Report 2010 (p 2, Table 1).
- 14 Data from Elsevier's Scopus.
- 15 Data from Elsevier's Scopus.
- 16 Royal Society (2010). *The scientific century: securing our future prosperity*. Royal Society: London, UK.
- 17 Data from Elsevier's Scopus. These charts show the top 10 countries by number of publications, with all other countries included in the 'other' segment. The pie charts are scaled to represent the increased volume of publications in the two time periods. In 1999-2003 there were 5,493,483 publications globally, and in 2004-2008 there were 7,330,334.

Key

- United States
- Japan
- United Kingdom
- Germany
- France
- China
- Italy
- Canada
- Russian Federation
- India
- Spain
- Other

Box 1.1.
A note on the data

Expenditure on research and development (R&D) is used throughout this report as a proxy for spending on science. Gross expenditure on research and development (GERD), as collated by the OECD and UNESCO, and used in this report, includes investment by government and business enterprise, funding from overseas sources, and 'other' sources, which can include funding by private foundations and charities. In areas of the report we distinguish between the proportion of this gross expenditure spent by business enterprise (BERD), and that spent by government (GOVERD). This is a commonly used, yet largely unsatisfactory proxy for science (and/or research) spending. A large proportion of 'research and development' is spent on D rather than R (with the largest proportion spent on product development). As such, this figure goes beyond the actual amount of money dedicated to funding research,

in whichever sector, but it is assumed that this has some relationship to the upstream investment in science that precedes it.

Unless otherwise stated, where changes in expenditure over time are discussed in the report, the figures used are based on current US\$ prices (2004 dollars in 2004, 2008 dollars in 2008) and purchasing power parity,¹⁸ as calculated by either the OECD or UNESCO.

When we refer to 'papers' in the report, this refers to peer-reviewed articles which have appeared in international journals. These data have been drawn, unless otherwise noted, from Elsevier's Scopus database.¹⁹ Where we discuss overall totals of publications, these include social sciences, the arts and humanities (in practice, these represent a very small proportion of publication output—8.9%); this coverage is used so as to match the 'input' statistics, which all register 'research' and 'researchers', which are discipline neutral.

¹⁸ Article: 'Croonian Lecture: On the anatomical structure of the eye', by Everard Home, drawings by Franz Bauer. PT vol 112, 1822, pp76-85. From the Royal Society library and archive.



1.1.1 Emerging scientific nations

China's rise up the rankings has been especially striking. China has heavily increased its investment in R&D, with spending growing by 20% per year since 1999 to reach over US\$100 billion a year today (or 1.44% of GDP in 2007),²⁰ in pursuit of its goal of spending 2.5% of GDP on R&D in 2020.²¹ China is also turning out huge numbers of science and engineering graduates, with 1.5 million leaving its universities in 2006.²²

China, India, South Korea and Brazil are often cited as rising powers in science.²³ India produces roughly 2.5 million science and engineering graduates each year.²⁴ In 2008, India, the world's second most

populous country, succeeded in sending its first unmanned flight to the moon, becoming only the fourth country to land a craft on the lunar surface. Brazil, in line with its aspiration to be a 'natural knowledge economy', building on its natural and environmental resources, is working to increase research spending to 2.5% of GDP by 2022²⁵ (from just over 1.4% in 2007).²⁶ South Korea has pledged that R&D spending, (3.2% of GDP in 2007), will reach 5% of GDP by 2012.²⁷

These countries are not alone in rapidly growing their science bases. Over the last 15 years, each of the G20 countries has been increasing its research production and most have scaled up the proportion

18 Purchasing power parity (PPP) measures the amount of a given currency needed to buy the same basket of goods and services as one unit of the reference currency—in this report, the US dollar. It is helpful when comparing living standards in different countries, as it indicates the appropriate exchange rate to use when expressing incomes and prices in different countries in a common currency.

19 For further information on the methodology used by Elsevier, please see the Conduct of the Study on page 11.

20 OECD (2006). *China will become world's second highest investor in R&D by end of 2006, finds OECD*. Press release, 4 December 2006. Office for Economic Co-operation and Development: Paris, France.

21 The State Council of the People's Republic of China (2006). *The national medium- and long-term program for science and technology development (2006–2020): an outline*. Beijing, China.

22 Ministry of Science and Technology of the People's Republic of China (2007). *S&T statistics data book 2007*. Beijing, China. This is the equivalent of

0.66% of the Chinese population aged between 15 and 24, which was projected to be 228,663,000 in 2010 according to the United Nations Population Division. UNESCO statistics indicate that the most recent figures of total science, engineering, manufacturing and construction graduates, expressed as a percentage of their projected population of 15–24-year-olds for 2010 (as per the UN statistics above), would equal 0.95% in the USA (428,256 graduates in these disciplines in 2008 against a projected population aged 15–24 of 44,880,000 in 2010), and 1.73% in the UK (140,575 graduates in these disciplines in 2007 against a projected population of 8,147,000 in 2010). These are not perfect comparisons, as the most recent year for which we have graduate data available varies by country, and it does not take into account graduates above this age range, or the proportion of people in the lower end of this age range who are unlikely to graduate at their age. Sources: Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat (2008). *World population prospects: the 2008 revision*. Available online at <http://esa.un.org/unpp>, accessed 7

January 2011; UNESCO Institute for Statistics website: <http://www.uis.unesco.org/>, accessed 13 January 2011.

23 See Bound K (2007). *India: the uneven innovator*; Webb M (2007). *South Korea: mass innovation comes of age*; Wilsdon J & Keeley J. *China: the next science superpower?*; Bound K (2008). *Brazil: the natural knowledge economy*. Demos: London, UK; Adams J & Wilsdon J (2006). *The new geography of science: UK research and international collaboration*; Adams J & King C (2009). *Global research report: Brazil*; Adams J, King C & Singh V (2009). *Global research report: India*; Adams J, King C & Ma N (2009). *Global research report: China*. Evidence, a Thomson Reuters business: Leeds, UK. Battelle (2009). *2010 global R&D fund-ing forecast*. Battelle: Columbus, OH, USA. Wilsdon J (2008). *The new geography of science*. Physics World, October 2008. Gilman D (2010). *The new geography of global innovation*. Goldman Sachs Global Markets Institute: New York, NY, USA.

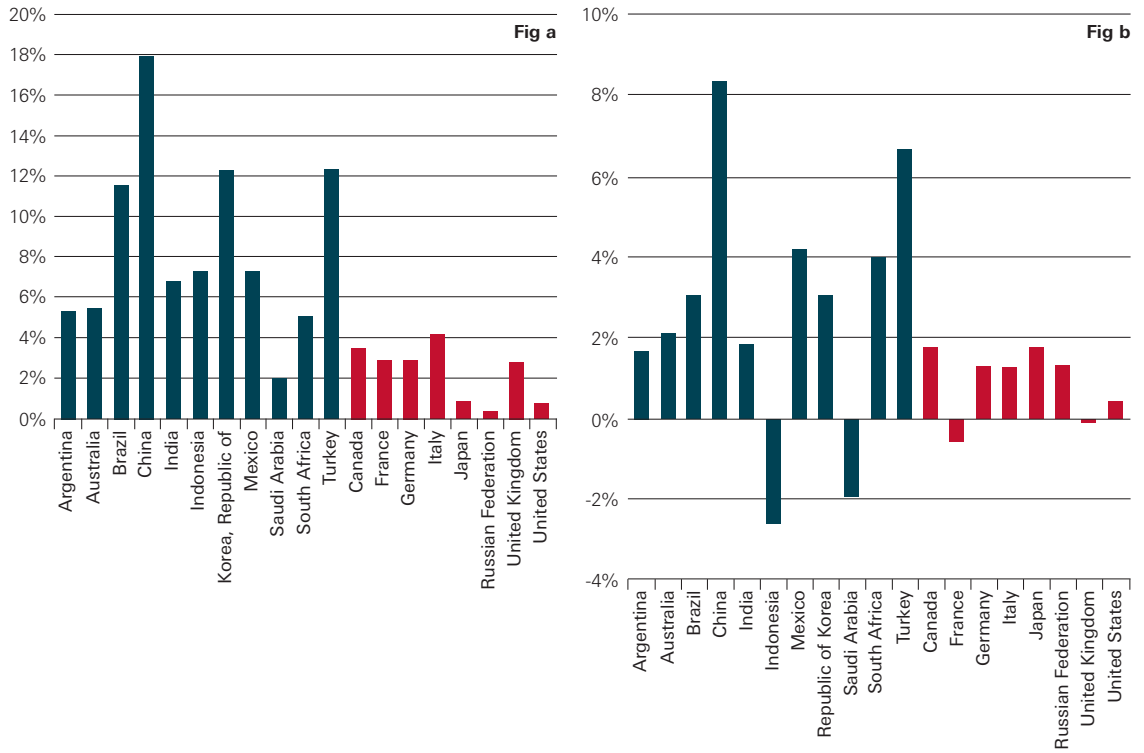
24 Bound K (2007). *India: the uneven innovator*. Demos: London, UK. India's population aged between

15 and 24 was projected to be just under 234 million according to the UN. If all those 2.5 million graduates were within that age range, they would represent 1.07% of the population in that age range. Source: United Nations website. *World population prospects: the 2008 revision*. Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat. Available online at <http://esa.un.org/unpp>, accessed 7 January 2011.

25 Kugler H (2011). *Brazil releases science blueprint*. SciDev.Net, 7 January 2011. Available online at <http://www.scidev.net/en/news/brazil-releases-science-blueprint.html>, accessed 17 January 2011.

26 Petherick A (2010). *Science safe in Brazil elections*. Nature online, 29 September 2010. Available online at <http://www.nature.com/news/2010/100929/full/467511b.html>, accessed 17 January 2011.

27 Stone R (2008). *South Korea aims to boost status as science and technology powerhouse*. Science Insider, 23 December 2008. Available at <http://news.sciencemag.org/scienceinsider/2008/12/south-korea-aim.html>.

Figure 1.2. Science in the G20*G8 labelled in red. Fig a. Annual growth in publications 1996-2008.²⁸**Fig b. Annual growth in GDP spending on R&D 1996-2007.²⁹*

of their GDP spent on R&D (see Figure 1.2). Increased investment and increased publications have taken place in tandem. The growth of commitment to science in a number of the non-G8 nations is especially striking.

Turkey has improved its scientific performance at a rate almost rivalling that of China. Having declared research a public priority in the 1990s, the Turkish Government increased its spending on R&D nearly six-fold between 1995 and 2007, and now spends more annually in cash terms than either Denmark, Finland or Norway.³⁰ Over this period, the proportion of Turkey's GDP spent on R&D rose from 0.28% to 0.72%, and the number of researchers increased by 43%.³¹ Four times as many papers were published in 2008 as in 1996.³²

The number of publications from **Iran** has grown from just 736 in 1996 to 13,238 in 2008—making it the fastest growing country in terms of numbers of scientific publications in the world.³³ In August 2009, Iran announced a 'comprehensive plan for science' focused on higher education and stronger links between industry and academia. The establishment of a US\$2.5 million centre for nanotechnology research is one of the products of this plan. Other commitments include boosting R&D investment to

4% of GDP (0.59% of GDP in 2006), and increasing education to 7% of GDP by 2030 (5.49% of GDP in 2007).³⁴

Since 1996, R&D as a percentage of GDP in **Tunisia** has grown from 0.03% to 1.25% in 2009.³⁵ During the same period, a substantial restructuring of the national R&D system saw the creation of 624 research units and 139 research laboratories, of which 72 are directed towards life and biotechnological sciences.³⁶ Life sciences and pharmaceuticals remain a top priority for the country, with the government announcing in January 2010 that it wanted to increase pharmaceutical exports five-fold in the next five years while also aiming to have 60% of local medicine needs covered by the country's own production.³⁷

In 1996, Singapore invested 1.37% of GDP in R&D. By 2007 this had reached 2.61% of GDP.³⁸ The number of scientific publications has grown from 2,620 in 1996 to 8,506 in 2008, almost half of which were co-authored internationally.³⁹ The Agency for Science, Technology and Research (A*STAR) is central to the government's commitment to investment in world class research and infrastructure, and oversees Singapore's 14 research institutes and associated centres within flagship developments such as Biopolis and Fusionopolis.⁴⁰ At a cost of over US\$370 million,

28 Data from Elsevier's Scopus.

29 Data from [UNESCO Institute for Statistics Data Centre](http://www.unesco.org/education/en/files/55545/11998913265Tunisia.pdf), Montréal, Canada. Note that statistics for some countries across the period are incomplete. The closest accountable years in the period are used where complete statistics are not available.

30 OECD (2010). *Main science and technology indicators (MSTI): 2010 edition, version 1*. Organisation for Economic Co-operation and Development: Paris, France.

31 OECD (2009). *Main science and technology indicators (MSTI): 2009*

edition. Organisation for Economic Co-operation and Development: Paris, France.

32 Data from Elsevier's Scopus.

33 Science-Metrix, *Thirty years of science*. Montreal: <http://www.Science-Metrix.com>, accessed November 2010.

34 Sawahel W (2009). *Iran: 20-year plan for knowledge-based economy*. University World News.

35 Madikizela M (2005). *The science and technology system of the Republic of Tunisia*. From 'Country Studies: Arab States', UNESCO

website. Available online at <http://portal.unesco.org/education/en/files/55545/11998913265Tunisia.pdf/Tunisia.pdf>.

36 Madikizela M (2005). *The science and technology system of the Republic of Tunisia*. From 'Country Studies: Arab States', UNESCO website. Available online at <http://portal.unesco.org/education/en/files/55545/11998913265Tunisia.pdf/Tunisia.pdf>.

37 Global Arab Network (2010). *Tunisia to boost pharmaceutical & biotechnological industry*. Global Arab Network, 13 January 2010.

Available online at <http://www.english.globalarabnetwork.com/201001134357/Science-Health/tunisia-to-boost-pharmaceutical-a-biotechnological-industry.html>.

38 Data from the [UNESCO Institute for Statistics Data Centre](http://www.unesco.org/education/en/files/55545/11998913265Tunisia.pdf), Montréal, Canada.

39 Data from Elsevier's Scopus.

40 See <http://www.a-star.edu.sg/AboutASTAR/Overview/tabid/140/Default.aspx>, accessed 29 September 2010.

PART 1

Scientific landscape in 2011

Biopolis is a high-tech biomedical park which the government launched in 2003. Since then, the country's biotech expertise has continued to expand and is attracting some big players such as Novartis, GlaxoSmithKline and Roche.⁴¹

The picture of scientific research is also starting to change across the Middle East, where there are a number of significant new commitments to science. Gas-rich **Qatar** aims to spend 2.8% of GDP on research by 2015. With a population of just over 1.4 million (of which around 85% are foreign workers) and a current GDP of US\$128 billion, this target, if realised, would combine to give GERD per capita of US\$2,474.⁴² Since the mid-1990s, the Qatari Government has introduced a number of education reforms and has invested around US\$133 billion in infrastructure and projects designed to create a knowledge-based economy.⁴³ The **United Arab Emirates** is attempting to create the world's first fully sustainable city and innovation hub—the Masdar Initiative. Due to open in 2011, Masdar will eventually

house 50,000 people and 1,500 businesses focused on renewable energy and sustainable technologies.⁴⁴ GE, BP, Shell, Mitsubishi and Rolls-Royce are among those who have joined as strategic partners.⁴⁵

Elsewhere, many of the world's poorest countries have placed science behind more immediate priorities, such as healthcare and primary education. This is not to say that science and research are not having an impact in the less developed world at all, or that there are no signs of growth. Cambodia produced only seven articles in 1996, but increased this to 114 by 2008. Both Uganda and Peru, in the same period, increased their outputs four-fold, albeit from low bases (Uganda from 116 to 477 papers, Peru from 153 to 600).⁴⁶ In these countries, as elsewhere, there is often also a wealth of informal innovation carried out by farmers,⁴⁷ local health practitioners and small firms—frequently drawing on local knowledge and largely unacknowledged in formal metrics, let alone published in research papers.⁴⁸

The King of Tonkin and retinue on their way to a ceremonial blessing of the ground. An illustration for Samuel Baron's *A description of the kingdom of Tonqueen*, 1685. From the Royal Society library and archive.



Box 1.2. Measuring global science through publications

Traditionally, global scientific output has been measured through the analysis of published papers in peer-reviewed journals. Peer review means that the science that is published has been subjected to independent scrutiny and approved by qualified scientists, and thereby assures its quality and credibility. The volume of scientific literature in peer-reviewed journals is vast. Individual articles are abstracted and collected onto databases which are then searchable by their users, usually through subscription. The most comprehensive of these services are Scopus (maintained by Elsevier) and Web of Science (maintained by Thomson Reuters). These services provide access to information about titles, authors, abstracts, key words and references for thousands of journal articles each year. These data are used to assess the quality of research and, through its use as measured by citations, its impact.

There are, however, notable gaps in the coverage of the bibliometric databases. In some cases this may mean that the official publication figures under-represent the true extent of scientific activity. For example, there are many peer-reviewed journals which do not appear in

the indexing services. Regional, national and local journals in the non-English-speaking parts of the world are often not recognised and, as a consequence, journals, conferences and scientific papers from some countries are not well represented by abstracting services.

Much scientific literature is also produced for non-peer-reviewed publications (and hence not covered by Scopus or Web of Science). Often referred to as 'grey' literature, this can include: technical reports from government agencies and NGOs; working papers from research groups or committees; government white papers; conference proceedings and symposia; and a growing level of publication on internet sites. All of these are potentially valuable contributions to the global stock of knowledge, but they are not accounted for in traditional assessments of research output.

In its analyses of global science through bibliometric data, this report draws exclusively on these peer-reviewed sources of research, and specifically on Elsevier data. It is clear that bibliometric data alone do not fully capture the dynamics of the changing scientific landscape. However, they presently offer the only recognised and most robust methodology for doing so.

41 Singapore Economic Development Board (2010). *Pharmaceutical and biotech companies partner Singapore to accelerate innovation in Asia*. Press release, 4 May 2010. Singapore Economic Development Board: Singapore.

42 Authors' calculations. Qatar's population is 1,448,446 and it has a GDP of US\$128 billion. Source: US State Department website.

See <http://www.state.gov/r/pa/ei/bgn/5437.htm>, accessed 8 February 2011. 2.8% of 128 billion is 3,584 million, which when divided by the population gives us a figure of 2,474.38.

43 Source: Qatar Foundation website. See <http://www.qstp.org.qa/output/page559.asp>, accessed 30 September 2010.

44 Source: Masdar (2008). See <http://www.masdar.ae/en/mediaCenter/newsDesc.aspx?NewsID=40&MenuID=0>, accessed 29 September 2010. Masdar (the Abu Dhabi Future Energy Company): Abu Dhabi, United Arab Emirates.

45 England A (2007). *Abu Dhabi eyes renewable energy future*. Financial Times, 4 April 2007.

46 Data from Elsevier's Scopus.

47 Scoones I & Thompson J (2009). *Farmer first revisited: innovation for agricultural research and development*. Institute of Development Studies at the University of Sussex: Brighton, UK.

48 STEPS Centre (2010) *Innovation, sustainability, development: a new manifesto*. STEPS Centre: Brighton, UK.

Some governments and development partners are embracing the fact that science is not a luxury which is the preserve of developed countries. They recognise that technology and innovation are key to achieving long-term economic and social development,⁴⁹ and that science and scientific advice are vital assets in governance.⁵⁰ Paul Kagame, President of Rwanda, has been a strong advocate for science for development, saying 'We in Africa must either begin to build our scientific and technological training capabilities or remain an impoverished appendage to the global economy.'⁵¹ African science ministers resolved in March 2010 that 2011 would be the start of an African decade for science, promising increased research budgets and attempts to use science and technology to drive development.⁵² Although encouraging, political commitments to invest in science are greeted cautiously by many scientists across Africa and in other poor countries. It was in 1980 that African presidents agreed to increase research spending to 1% of GDP, as part of the Lagos Plan of Action,⁵³ but by 2007 Sub-Saharan African countries still spent an average of just 0.5% of their GDP on science and technology.⁵⁴ African leaders reiterated their 1% target, this time agreeing to reach it by 2010,⁵⁵ but South Africa is the only sub-Saharan country that is close, spending 0.92% in the 2008 to 2009 financial year.⁵⁶

1.1.2 Assessing research quality and impact

As research output has grown, so have the levels at which researchers cite one another's work. Citations are often used as a means of evaluating the quality of publications—recognition by an author's peers indicates that the scientific community values the work that has been published. They are, however, a lagging indicator, as well as a sometimes crude one.

Looking at the global picture in recent years, we can see that citations are increasing at a greater rate

than publications—between the periods 1999 to 2003 and 2004 to 2008 publications grew by 33% and citations by 55% (see Figure 1.3).⁵⁷ However, when examining citation patterns, the movement in national performance has not been as dramatic as with publication numbers. Switzerland and Australia fell down the rankings, to be replaced by China and Spain in the latter period, but the performance of China, for example, does not mirror that nation's growth in investment or publication output. Citations continue to be much more concentrated than the journal articles themselves.

It will take some time for the absolute output of emerging nations to challenge the rate at which this research is referenced by the international scientific community. There is also diversification with some countries showing leadership in specific fields, such as China in nanotechnology,⁵⁸ and Brazil in biofuels,⁵⁹ but the scientifically advanced nations continue to dominate the citation counts.

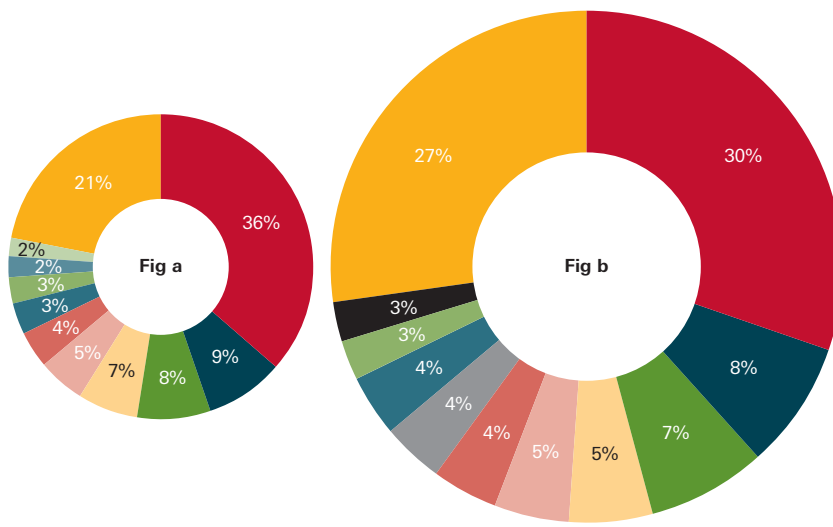
Citations are, however, only one means of benchmarking the excellence of research output. With over US\$1,000 billion each year being spent on R&D, it is unsurprising that funders and governments want to know what value they are getting for their money.

In the UK, the impact and excellence agenda has developed rapidly in recent years. The Research Assessment Exercise, a peer review based benchmarking exercise which measured the relative research strengths of university departments,⁶⁰ is due to be replaced with a new Research Excellence Framework, which will be completed in 2014.⁶¹ The UK Research Councils now (somewhat controversially) ask all applicants to describe the potential economic and societal impacts of their research. The Excellence in Research for Australia (ERA) initiative assesses research quality within Australia's higher education institutions using a

combination of indicators and expert review by committees comprising experienced, internationally recognised experts.

The impact agenda is increasingly important for national and international science (in Europe, the Commissioner for Research, Innovation and Science has spoken about the need for a Europe-wide ‘innovation indicator’).⁶³ The challenge of measuring the value of science in a number of ways faces all of the scientific community. Achieving this will offer new insights into how we appraise the quality of science, and the impacts of its globalisation.

Figure 1.3. Comparative proportion of global citations by country⁶²
The top ten cited countries in each period are shown.
Fig a. 1999-2003. Fig b. 2004-2008



Key

- United States
- United Kingdom
- Germany
- Japan
- France
- Canada
- Italy
- Netherlands
- Australia
- Switzerland
- China
- Spain
- Other

49 Conway G & Waage J (2010). *Science and innovation for development*. UK Collaborative on Development Sciences: London, UK.

50 Royal Society (2010). *Science: an undervalued asset in governance for development*. Royal Society: London, UK.

51 Kagame P (2006). Speech by Rwandan President, Paul Kagame, at the Royal Society on 18 September 2006.

52 Nordling L (2010). *African nations: way to support science*. Nature **465**, 994–995.

53 Organization of African Unity (1980). *Lagos plan of action for the economic development of Africa*.

1980–2000. The Organization of African Unity was disbanded in 2002 and replaced by the African Union.

54 Data from UNESCO Institute for Statistics, published in UNESCO Science Report 2010 (p 2, Table 1).

55 African Union (2007). *Assembly of the African Union, eighth ordinary session, 29–30 January 2007, Addis Ababa, Ethiopia: decisions and declarations*. Assembly/AU/Dec.161 (VIII). African Union: Addis Ababa, Ethiopia.

56 Department of Science and Technology, *South Africa (2010). South Africa maintains steady growth in R and D expenditure*. Press release, 9 September 2010. Department of Science and

Technology: Cape Town, South Africa.

57 Data from Elsevier’s Scopus.

58 Royal Society (2010). *The scientific century: securing our future prosperity*. Royal Society: London, UK.

59 Bound K (2008). *Brazil, the natural knowledge economy*. Demos: London, UK.

60 See <http://www.delni.gov.uk/index/further-and-higher-education/higher-education/role-structure-he-division/he-research-policy/research-assessment-exercise.htm>.

61 See <http://www.hefce.ac.uk/research/ref/>, accessed 7 January 2011.

62 Data from Elsevier’s Scopus. These charts show the top ten countries by number of citations, with all other countries included in the ‘other’ segment. The pie charts are scaled to represent the increased volume of publications in the two time periods. In 1999–2003 there were 23,639,885 citations globally, and in 2004–2008 there were 36,562,135.

63 Finnegan G (2010). *Geoghegan-Quinn: we must communicate our R&D*. Euractiv.com (European Union Information Website), 5 May 2010. Available online at <http://www.euractiv.com/en/innovation/geoghegan-quinn-we-must-communicate-our-rd-interview-493702>.

1.1.3 Global scientists

Recent decades have seen significant increases in the global competition for talent, with the workforce in places like Silicon Valley highlighting the role that skilled migrants can play in innovation and wealth creation. Countries like the UK, Australia, Canada and the USA have grappled with contentious policy decisions, aiming to strike the right balance between encouraging the highly skilled on the one hand, and discouraging 'unskilled' potential migrants on the other.

With inaccurate data and inconsistent definitions of 'highly skilled' across the world, it is difficult to measure highly skilled migration, particularly among scientists. There is no internationally agreed definition of 'highly skilled workers', although the OECD's Canberra Manual provides one useful basis for the measurement of 'human resources in science and technology' (HRST). Their definition includes those who have 'completed education at the third level in a S&T field of study and/or those not formally qualified but employed in a S&T occupation where such qualifications would normally be required'.⁶⁴ According to OECD analysis the USA, Canada, Australia and the UK attracted the largest numbers of highly skilled expatriates from OECD countries in 2001, followed by France and Germany.⁶⁵ Of the UK's 4.5 million foreign-born adult population, 34.8% had a university-level education. Approximately 19.5% of these migrants had a scientific background, many of whom hailed from emerging economies such as China and India.⁶⁶ However, we are far from understanding what factors influence these individuals' choice of location. How long do they intend to stay? And how do they connect back to their research networks from their new home?

The career paths of recent Nobel prizewinners demonstrate the international outlook of many of the world's most successful scientists. Professor

Andre Geim FRS, along with Konstantin Novoselov, was awarded the Nobel prize for Physics in 2010. Professor Geim obtained his PhD at the Russian Academy of Sciences in Chernogolovka, moved to the UK for postdoctoral positions at Nottingham and Bath, before then moving on to Copenhagen and Nijmegen, and returning to the UK in 2001 to the University of Manchester. Now a Royal Society Research Professor, Professor Geim maintains links with colleagues in Russia, and is still a professor in the Netherlands. The 2009 winner for Physics, Sir Charles Kao FRS, was born in China. He obtained his PhD from the University of London, worked at the Standard Telecommunications Laboratory in the UK, and in both the USA and Germany. Ada Yonath (the first woman from Israel to win a Nobel Prize, and currently based at the Weizmann Institute in Rehovot) held postdoctoral positions in the USA and worked in Germany before she won the 2009 Chemistry prize. Her co-winner Venkatraman Ramakrishnan FRS was born in Tamil Nadu, India, undertook graduate degrees in the USA, and now works in Cambridge, England.

1.1.4 Brain gain, drain and circulation

The Nobel Prize examples show the attractive force of the strong scientific nations, in particular the USA and Western Europe. Today issues of 'brain drain' are usually associated with developing countries, but the original phrase was coined by the Royal Society in 1963. At the time, the UK was struggling to stem the exodus of its top brains to the USA. The Society found itself at the centre of a fierce debate as to how to counter this phenomenon,⁶⁷ with the then Minister of Science, Lord Hailsham, lamenting the 'parasitising of British brains'.⁶⁸

Today, the focus of discussion has moved from preventing 'brain drain' to making the most of 'brain circulation'. It has been argued that old patterns of

one-way flows of technology and capital from the core to the periphery are slowly breaking down, creating far more complex and decentralised two-way flows of skills, capital and technology, with scientists following the best science and the best resources.⁶⁹ Some governments appreciate the value of ‘brain circulation’ and allocate resources for attracting national talent back home to start a new business or take up a senior position in academia, while maintaining useful links back to the USA or Europe.

Of the 1.06 million Chinese who studied abroad between 1978 and 2006, over 70% did not return.⁷⁰ It has been a policy priority for the Chinese Government to attract this diaspora back. The Thousand Talents Program, established in 2008, has brought more than 600 overseas Chinese and foreign academics back to China. Launching further measures in May 2010, Premier Wen Jiabao announced that, ‘We will increase spending on talent projects and launch a series of initiatives to offer talent-favourable policies in households, medical care and the education of children.’⁷¹ A range of facilities, both personal and professional, is essential to ensure that returning home is an attractive option.

India, meanwhile, has created a specific government ministry—the Ministry of Overseas

Indians—to organise policy relating to remittances and investment flows, as well as relaxing previously stringent citizenship requirements to make it easier for potential returnees. Other initiatives to connect India with its diaspora have also proven fruitful. The Indus Entrepreneurs (TiE), for example, was originally founded by Indian entrepreneurs based in Silicon Valley and it now has a global membership of 12,000 people within 11 countries, and has assisted in the creation of businesses worth over US\$200 billion in India.⁷²

Elsewhere, Malaysia recently established a new ‘Talent Corporation’ which will be charged with connecting with diaspora communities. Ecuador’s President also announced a US\$1.7 million ‘Prometheus Old Wiseman’ plan to attract senior scientists who see Ecuador as ‘the retirement destination of brilliant minds’.⁷³

Yet attracting back the diaspora is only one part of the equation. Finding new ways to connect with diaspora and other communities, and their associated global networks, is also critical. Nomadic scientists are often keen to maintain scientific and informal links with their home countries. Many are eager to contribute but are unsure where to start. In supporting international collaboration, these diaspora communities are an untapped resource.

64 OECD (1995). *The measurement of scientific and technological activities: manual on the measurement of human resources devoted to S&T: ‘Canberra manual’*. Organisation for Economic Co-operation and Development: Paris, France.

65 OECD (2002). *The global competition for talent: mobility of the highly skilled*. Organisation for Economic Co-operation and Development: Paris, France.

66 OECD (2008). *A profile of immigrant populations in the 21st century: data from OECD countries*. Organisation for Economic Co-operation and Development: Paris, France.

67 Royal Society (1963). *The emigration of scientists*. The Royal Society: London, UK.

68 Balmer B, Godwin M & Gregory J (2009). *The Royal Society and the ‘brain drain’: natural scientists meet*

social science. Notes & Records of the Royal Society **63**, 4, 339–353.

69 Saxenian A (2006). *The new Argonauts: regional advantage in a global economy*. Harvard University Press: Cambridge, MA, USA.

70 Source: <http://www.gov.cn> (Chinese Government’s official web portal). See http://www.gov.cn/english/2010-06/07/content_1622015.htm, accessed 13 October 2010.

71 Chen J (2010). *Nation aims to increase talent pool*. China Daily, 6 June 2010.

72 Bound K (2007). *India: the uneven innovator*. Demos: London, UK.

73 Hirschfeld D (2010). *Ecuador opens its doors to senior scientists*. SciDev. Net, 16 August 2010. Available online at <http://www.scidev.net/en/news/ecuador-opens-its-doors-to-senior-scientists.html>.

In reality, brain drain is still a major problem. At a recent event at the Royal Society, Princess Sumaya of Jordan reflected on the success of Jordanian graduates in the region and the wider world. 'Human capital is our greatest natural resource,' she said, 'yet it has been exported for many years. It is said that the French keep the best champagne for themselves. Perhaps we should learn from them.' Depending on the level of scientific capacity at home, migrating scientists from developing countries are generally more likely to stay permanently in their new homes than return to where there are fewer opportunities and poorer infrastructure. This is a significant problem for Africa, a continent which arguably needs its skilled workers most, but offers the least to keep them or attract them back. The challenge for governments in emerging centres of science is how to reward talented scientists and enable them to foster global networks, while still using them to build national capacity.

1.1.5 Disciplinary shifts?

With the growth in science globally, it is interesting to ask whether the large rise in the number of scientific publications in recent decades has varied greatly across the disciplines. Indeed, the use of bibliometric data across the whole of research can mask very different patterns in publication activity across disciplines with, for example, life scientists displaying a greater propensity to publish than engineers.

Available headline data suggest that there has not been a dramatic shift in the broad disciplinary breakdown of research. Between 1996 and 2008 the total number of academic publications rose by 43%; looking at the number of articles in specific disciplines (as defined by the disciplinary focus of the journal),⁷⁴ the overall share by subject area has not altered dramatically over the same period. Energy

and computer sciences have seen the highest growth, both increasing their output by over 100%, but the share of papers in 'energy' publications among scientific output has grown from only 0.73% to just 1.03%; in computer sciences this share has grown from 2.47% to 3.42%. This substantial growth in absolute output has not translated into dramatic leaps in market share.

Looking more closely at the data we can, however, see some trends in particular fields which reflect emerging or pressing research areas. Keyword searches in the Elsevier database on specific terms highlight some trends. 'Climate change', for example, has seen a six-fold increase in usage in research publications between 1996 and 2008. Such analyses can only be partial—they pick up on 'buzz words' which reflect trends in language as much, perhaps, as they do scientific content. That these areas are growing rapidly, though, is undeniable.

The geographic changes in global science do not themselves appear to have had a direct impact on the types of research being conducted. The domestic conditions of a country, such as government priorities and the availability of natural, human and economic resources have a distinct bearing on scientific output. Considering again the disciplinary spread of research as identified through journal classification, the 'developed' G7 countries have similar research profiles, which are balanced between broad research disciplines. By contrast, the BRIC grouping of major emerging economies—Brazil, Russia, India and China—are weighted towards specific fields; in the case of China, India and Russia towards engineering, and in Brazil, agriculture and biosciences. In Africa, the focus is on agriculture and medicine. However, the emergence of these areas has not to date changed the global balance of research.

Research challenges and interests are changing

as global science grows, but these changes reflect more the different types of questions being posed, rather than the nationality of the people posing the questions.

1.1.6 Reading the research

The world's research papers are produced to be read by peers in the scientific community, and for the ideas and conclusions to be put to use. So where the science is being picked up and exploited is just as important as where in the world it is being written up. The spread of access to academic journals across the world is a key factor in the globalisation of research.

Publishers have actively pursued new reader markets. Nature launched its China website in 2007, highlighting research from the Chinese mainland and Hong Kong. Nature India followed in February 2008. The Royal Society now has specific portals for those interested in research from Brazil, China, India, Malaysia, Russia and Turkey, and provides information on the website in Chinese, Farsi, Korean, Russian, Portuguese, Arabic and Spanish.⁷⁵

The pattern of downloads from Elsevier's journals show that, unsurprisingly, the largest consumers of their publications are based in the USA, Japan and Western Europe. China and South Korea have witnessed a surge in readership over the

last decade.⁷⁶ The Royal Society's own journals follow a similar trend. In the year from June 2009 to June 2010, US and UK audiences accounted for nearly 51% of the readership for the Society's seven journals. China now accounts for the third highest number of downloads and subscribers to the journals; the four BRIC countries make up 12% of the total readership.⁷⁷

Readership has been far from universal. A World Health Organisation (WHO) study in 2000 identified that 56% of institutions in countries with annual incomes of US\$1,000 and less per person had no current subscriptions to international journals, thereby cutting off their scientists from recent developments in their fields.⁷⁸

A number of initiatives such as Research4Life (R4L)⁷⁹—set up in direct response to these findings—and the International Network for the Availability of Research Publications Programme for the Enhancement of Research Information (INASP PERii)⁸⁰ have been established to explicitly improve access to research journals in the developing world, allowing free or low-cost access to universities and research institutes which had previously been unable to afford subscription fees. Take-up of R4L has been impressive. Bringing together three strands—one for biomedical and health literature, a second for

74 This will result in duplication across fields, as a journal such as the *Royal Society Philosophical Transactions A* will cover each of the mathematical, physical and engineering sciences. There will also be fluctuation between years, as journal subject areas are redefined. This, therefore, provides an imperfect indication of the disciplinary breadth of publication output, but it does indicate the general rate of output. A similar outcome can be seen in the *UNESCO Science Report 2010*, which uses data from another

indexing service—Thomson Reuters (Scientific) Inc. Web of Science. UNESCO (2010). *UNESCO Science Report 2010* (pp 10–11). UNESCO Publishing: Paris, France.

75 See <http://royalsocietypublishing.org/librarians>, accessed 29 September 2010.

76 Data from the Elsevier Science Direct database.

77 Data from Royal Society publications, July 2009–June 2010.

78 UK National Commission for UNESCO (2008). *Improving access to scientific information for developing countries: UK learned societies and journal access programmes*. UK National Commission for UNESCO Secretariat: London, UK.

79 Research4Life is a public–private partnership of the WHO, FAO, UNEP, Cornell and Yale Universities and the International Association of Scientific, Technical & Medical Publishers. Working together with technology partner

Microsoft, the partnership's goal is to help attain six of the UN's eight Millennium Development Goals by 2015, reducing the scientific knowledge gap between industrialised countries and the developing world. See <http://www.research4life.org/>, accessed 30 September 2010.

80 See <http://www.inasp.info/file/5f65fc9017860338882881402dc594e4/perii.html>, accessed 29 September 2010.

agricultural publications, and a third for environmental sciences—the platform allows access to material of particular practical interest to developing nations. Since its introduction in 2002, the biomedical and health platform 'HINARI' alone has provided 2 million downloads per year of Elsevier's output. Individual publishers are also instigating their own initiatives. The Proceedings of the National Academy of Sciences in the USA has been free online since 1997 to the developing world. In 2006 the UK's Royal Society of Chemistry (RSC) made all of its journal output free through its Archives for Africa project.

Professor Shem O. Wadinga, Director of the Centre for Science Technology Innovations in Nairobi, and Chair of the Pan Africa Chemistry Network Kenya hub, is a keen advocate of the RSC's scheme. '*Archives for Africa* has opened up a rare window for African researchers and libraries in keeping up to date with the latest scientific information. It has become the point of free access to a wealth of scientific information for African scientists through their libraries.'⁸¹ It will take some years to identify any direct, long-term impact that these schemes may have on scientific output. An early study suggests that there has been a significant increase in research output in countries eligible for R4L access, which outstrips the rate of growth seen in non-R4L countries, over the period in which the initiative has been introduced.⁸²

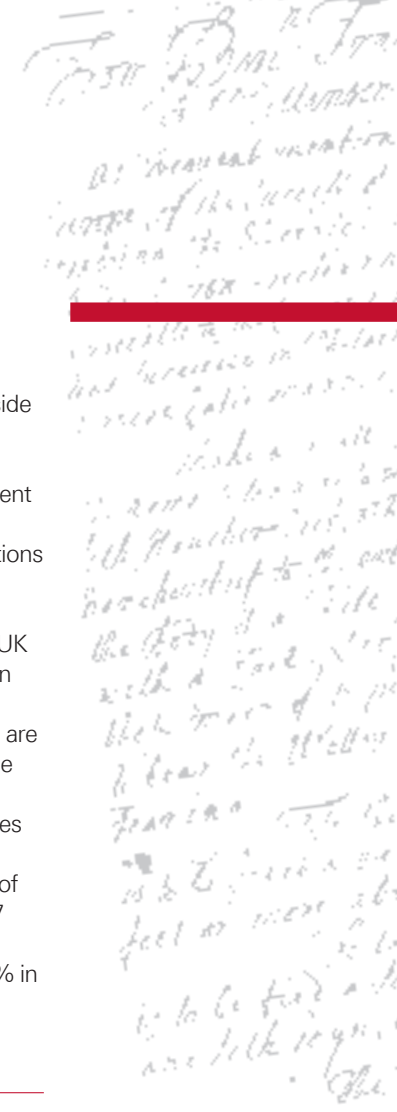
1.1.7 Opening access

In the mid-1990s, the advent of the online availability of scientific journals had two highly significant effects on the scholarly communications process. The first was a result of the dramatic fall in the costs of dissemination of published content (which no longer relied solely on physical shipping of printed copies). This led to the growth of the so-called 'big deal' whereby publishers were able to offer online editions

of their entire catalogue to institutional libraries that previously had only subscribed to specific journals. These deals were done at greatly reduced prices and most large institutions now have such arrangements in place, meaning that readers have access to vastly more research outputs than ever before. The second was the enormous increase in the capacity to search for and access published research, initially via specialist search engines such as PubMed, and later by more general tools, most notably Google (which now accounts for almost 60% of all referrals).⁸³ The ability to search for articles simply and rapidly using subject keywords, authors or abstract text has opened up much wider access to the entire breadth of research outputs.

Also highly significant has been the birth of the Open Access movement. Recognising that a great deal of published research was funded by the public purse (via research councils and universities), demands arose from various quarters for the resulting publications to be made freely available to the public who funded them, rather than being limited to subscribers. Publishers, some initially resistant to this notion, have now largely embraced open access, not least because most funding bodies now make it a requirement for their grantees. The overwhelming majority of the traditional publishers now operate an open access option (in exchange for an article processing charge secured from authors or their institutions) and a number of newer publishers have emerged who operate an exclusively open access model.

The demand for access to published scientific knowledge is set to grow as global science continues to expand. The 'author pays' model of Open Access and the subsidised subscription schemes of Research4Life and INASP cater for this demand in different ways. The latter have considerably improved access to research literature in the developing world,



but there is not yet a corresponding scheme in place to assist authors with open access charges in these very countries. However, the demand for more access is not only coming from the developing world. A variety of economic models will be required to ensure that access is maximised across a range of different markets.

1.2 Applying science

A wealth of economic literature describes the impact of knowledge on economic performance.⁸⁴ For example, studies have shown that technological change drives up income levels,⁸⁵ the relationship between high levels of patenting and GDP growth,⁸⁶ and the positive impact of innovation on business productivity and performance.⁸⁷ This body of evidence has underpinned the efforts of governments the world over to stimulate economic performance by investing in science and technology—from undirected academic science to research of strategic national importance conducted in government laboratories, to support for near-to-market technologies in the private sector.

1.2.1 Business R&D

Science is not restricted to academia, nor does it necessarily result in the publication of research papers. It takes place in many different areas outside universities and research institutes, and is funded by a range of different sources. The proportion of investment in research as compared to development varies significantly across the different industrial sectors. For example, in the UK's telecommunications sector, companies invest roughly four and a half times more money in experimental development than they do in research, while companies in the UK aerospace sector spend roughly twice as much on research as they do on development.⁸⁸

In most of the developed world, R&D activities are primarily funded by private enterprise, whereas the public sector plays a more significant role in most developing countries.⁸⁹ However, the balance varies considerably between nations. In some countries business investments in R&D far outweigh those of government, universities or other funders. In 2007 the proportion of total R&D which was funded by business was 84% in Malaysia, 70% in China, 66% in

81 Interview with Professor Shem O. Wadinga. Quote courtesy of the Royal Society of Chemistry.

82 See http://www.elsevier.com/wps/find/authored_newsitem.cws_home/companynews05_01269, accessed 13 October 2010.

83 Figure based on analysis of access to Royal Society Publishing journal content. See Rees M (2010). Speech by Lord Rees, President of the Royal Society, at Science Online, British Library, 3 September 2010. Available online at http://royalsocietypublishing.org/site/include/files/Keynote_speech.pdf.

84 See Romer D (1990). *Endogenous technical change*. Journal of Political Economy **98**, 5, S71–102; Mokyr J (1992). *The lever of riches: technological creativity and economic progress*. Oxford University Press: Oxford, UK; Lipsey R, Carlaw K & Bekar C (2005). *Economic transformations: general-purpose technologies and long-term growth*. Oxford University Press: Oxford, UK; Hall B & Rosenberg N (eds) (2010). *Handbook of the economics of innovation*. Elsevier: Amsterdam, The Netherlands.

85 Freeman C (2002). *Continental, national and sub-national innovation systems—complementarity and*

economic growth. Research Policy **31**, 2, 191–211.

86 See Chen D & Dahlman C (2004). *Knowledge and development: a cross-section approach*. World Bank Policy Research Working Paper No. 3366. This paper argued that between 1960 and 2000, a 20% annual increase in the number of patents granted in the USA—whether the technologies originated locally or overseas—produced an increase in economic growth of 3.8 percentage points. World Bank: Washington, DC, USA.

87 NESTA (2009). *The innovation index*. This report showed that two-thirds of the productivity growth

in the UK's private sector between 2000 and 2007 was attributable to innovation including technological advances. National Endowment for Science, Technology and the Arts: London, UK.

88 Source: UK National Statistics (2009). *Research and development in UK businesses 2009—datasets* (Table 5). Available online at http://www.statistics.gov.uk/downloads/theme_commerce/berd-2009/2009-dataset-links.pdf, accessed 17 January 2011.

89 UNESCO (2009). *A global perspective on research and development*. UNESCO Institute for Statistics Fact Sheet No 2, October 2009 (pp 9–11).

the USA, and 57% in Australia. In the UK, business enterprise funded 47% of all expenditure on R&D. By contrast, business was responsible for only 29% of total R&D spending in Argentina and the Russian Federation, 19% in Sri Lanka and 14% in Tunisia.⁹⁰

The role of business in science has grown in recent years, with the proportion of R&D funded by the private sector increasing steadily. In 1981, 52% of the OECD countries' spending on research and development was funded by industry; by 2008 this had reached nearly 65%.⁹¹

Is business R&D recession proof?

In the aftermath of the global economic crisis in 2008, private sector R&D investors have struggled to maintain their levels of investment in R&D. After four years of 5% growth in investment year on year, in 2009 R&D spending by the world's leading 1,400 business R&D investors fell by 1.9% on the previous year.⁹²

The EU Industrial R&D Investment Scoreboard 2010 shows that in 2009 the leading companies in Europe had decreased their R&D investment by 2.6% since 2008, and in the USA this fell by 5.1%. However, there was an increase of 40% in China and 27.3% in India. Within Europe there was considerable fluctuation too: French private R&D investment fell by 4.5%, but in Spain it grew by 15.4% on the previous year. Individual sectors have also experienced differing fortunes; pharmaceutical companies increased investment in R&D by over 5%, while the automobile industry's spend fell by 11.6%. The impact of global recession has not had a uniform effect on the patterns of corporate R&D investment.

Recent survey evidence from the European Commission shows that leading EU-based investors expect their R&D spending to continue growing between 2010 and 2011, albeit at lower rates than in

previous years. The surveyed companies expect R&D investment to continue growing strongly outside the EU, especially in India and China.⁹³

Location of business R&D

Business R&D has become increasingly mobile since the mid-1980s, following the internationalisation of manufacturing during the 1970s.⁹⁴ There are now many more large businesses with global research operations, many of whom have located laboratories in different parts of the world for strategic reasons. A case in point is Microsoft Research who have set up a number of laboratories and businesses not only in their core expertise of software, but also in other fields such as healthcare, energy, environment and robotics. Many companies have followed similar models, such as Sanofi-Aventis (who have R&D operations in China, Japan, South Korea, India, the USA, France, UK and Denmark) and Shell (which has technical centres in the USA, the Netherlands, UK, Canada, France, Germany, India, Norway, Oman, Qatar and Singapore). In the period from 1993 to 2002, R&D spending by foreign investors grew from 10% to 16% of global business R&D (from an estimated US\$30 billion to US\$67 billion).⁹⁵

Developed economies are still the favoured locations for foreign R&D investors,⁹⁶ but the growth in the amount of R&D investment flowing to developing countries has been pronounced; the share of foreign-owned business R&D in the developing world grew from 2% to 18% between 1996 and 2002.⁹⁷

The increasingly international profile of business R&D investment is, in part, a reflection of intensifying global competition for leadership and talent in the most important and fastest growing markets. Companies that site their R&D activities close to new and emerging markets gain valuable insights into

how best to meet the needs of those markets.

The ever more global footprint of business R&D is also the result of 'distributed' or 'open' innovation.⁹⁸ Companies using these business models innovate by looking outward for new knowledge (eg. collaborating or buying/licensing new processes or inventions from other companies or locating their activities in close proximity to scientific and technological centres of excellence) as well as inward (eg. through their own research). In these cases, firms respond to science and technology that they see being developed elsewhere, for example in other companies, universities or overseas. They promote collaborations and coalitions with others, such as suppliers, customers or academics, to solve their problems in innovative, competitive ways. Recruitment of the most talented individuals also occurs on an international basis.⁹⁹

At the same time, governments are doing more to exert an influence on the investment decisions of high-spending and increasingly mobile companies. Policies designed to attract foreign investment include incentives such as tax credits, direct support for capital facilities and R&D expenditure, and indirect

support through defence and other government expenditure.¹⁰⁰ Just as business is competitive, so policies to attract foreign investment are competitive too. Singapore has become a magnet for pharmaceutical companies, drawn by infrastructure such as A*Star's Biopolis. More recently, some countries (notably South Korea) have targeted new economic stimulus investments in low-carbon technologies to attract researchers and companies investing in R&D.¹⁰¹

1.2.2 Patent growth

The application of scientific knowledge can be measured to some extent by the registration of overseas patents. Patents are granted for original, non-obvious ideas, processes or products. The registration of patents by individuals and companies not resident in a territory indicates a clear desire to commercialise the research in that region. Registrations in the world's biggest single market, the USA, are a good indicator for this, reflecting also the size of the US market and the growing integration of R&D. Approximately 50% of patents now registered in the US Patent and Trademark Office are from

90 Data from the [UNESCO Institute for Statistics Data Centre](#), Montréal, Canada; 2007 figures used, or last available year.

91 These averages are of course over figures which vary considerably between different members of the OECD.

92 European Commission (2010). [Monitoring industrial research: the 2010 EU industrial R&D investment scoreboard](#). European Commission: Brussels, Belgium.

93 Tuebke A (2009). [The 2008 EU survey on R and D investment business trends](#). European Commission: Brussels, Belgium.

94 Karlsson M (ed) (2006). [The internationalization of corporate R&D: leveraging the changing geography of innovation](#). ITPS (Swedish Institute for Growth Policy Studies): Stockholm, Sweden.

95 UNCTAD (2005). [World investment report 2005: transnational corporations and the internationalization of R&D](#). United Nations Conference on Trade and Development: Geneva, Switzerland.

96 Karlsson M (ed) (2006). [The internationalization of corporate R&D: leveraging the changing geography of innovation](#). ITPS

(Swedish Institute for Growth Policy Studies): Stockholm, Sweden.

97 UNCTAD (2005). [World investment report 2005: transnational corporations and the internationalization of R&D](#). United Nations Conference on Trade and Development: Geneva, Switzerland.

98 Chesbrough H (2003). [Open innovation: the new imperative for creating and profiting from technology](#). Harvard Business School Press: Boston, MA, USA; Dodgson M, Gann D & Salter A (2008). [The management of technological innovation: strategy](#)

[and practice](#). Oxford University Press: Oxford, UK.

99 Little A (2005). [Internationalisation of R&D in the UK: a review of the evidence](#). Office of Science and Technology (now Government Office for Science): London, UK.

100 UNCTAD (2005). [Globalisation of R&D and developing countries: proceedings of the expert meeting, Geneva, 24–26 January 2005](#). United Nations Conference on Trade and Development: Geneva, Switzerland.

101 Royal Society (2010). [The scientific century: securing our future prosperity](#). Royal Society: London, UK.

PART 1

Scientific landscape in 2011

outside the USA—a figure that has remained largely constant since 1989.¹⁰²

There are a number of countries, especially on the western edge of the Pacific, that have registered a dramatic increase in the volume of patents they are registering in the USA (see Table 1.2). The volumes involved, relative to world-leading countries like Japan, are still very small: China registered 1,655 patents in the USA in 2009 (up from only 52 in 1989, and 90 in 1999); Japan registered 35,501. South Korea, having leapt from only 159 registered patents in the USA in 1989, is now the third highest patenting overseas country in the USA, with 8,762 patents registered in 2009.

If these countries maintain this rate of patenting growth, the impact will be dramatic. Extrapolating recent trends, China will overtake Japan in annual US patents by 2028, and South Korea by 2018. Of course, this simple extrapolation is subject to very

great uncertainties, but it helps illustrate the shifts in the commercialisation of science now taking place.

1.3 Drivers of research

The story of 21st-century science so far is one of dramatic growth and broadening horizons. There are more people conducting research, spending more money, publishing and accessing science than ever before.

The 2009 Turkish Academy of Sciences Science Report describes the motivation of researchers as ‘a burning curiosity, a tormenting need to know.’¹⁰⁴ This curiosity is unending. Science is growing because people are still trying to answer all types of questions and solve problems. Today’s scientists are the heirs to the natural philosophers who established the scientific societies of the 17th century. They are seeking to ‘shape out a new philosophy or perfect the old’,¹⁰⁵ to satisfy their curiosity, and to provide solutions to the questions of the day.

Table 1.2. Top 11 overseas patent registrations at the US Patent Office.¹⁰³

1989		1999		2009	
Japan	20,169	Japan	31,104	Japan	35,501
Germany	8,352	Germany	9,337	Germany	9,000
France	3,140	France	3,820	South Korea	8,762
UK	3,100	Chinese Taipei	3,693	Chinese Taipei	6,642
Canada	1,960	UK	3,576	Spain	6,472
Switzerland	1,362	South Korea	3,562	Canada	3,655
Italy	1,297	Canada	3,226	UK	3,175
Netherlands	1,061	Italy	1,492	France	3,140
Sweden	837	Sweden	1,401	China	1,655
Chinese Taipei	591	Switzerland	1,279	Israel	1,404
Australia	501	Netherlands	1,247	Italy	1,346
USA	50,184	USA	83,905	USA	82,382
Global total	95,537	Global total	153,485	Global total	167,349

Source: US Trademark and Patent Office

1.3.1 Securing prosperity and staying competitive

Science and innovation are recognised the world over as crucial to economic competitiveness. The European Commission has a formal target to spend 3% GDP on R&D across the Union, and research policy is a key component of the Union's strategy for jobs and growth.¹⁰⁶ In a speech to the Royal Society in April 2010, German Chancellor Dr Angela Merkel explained that 'the prosperity of a country such as Germany [...] must be sought through investment in research, education and science, and this to a disproportionate degree'.¹⁰⁷

The rapidly emerging economies have all prioritised science and innovation, and have steadily increased their investment in research to drive development. In China, where many members of the government are themselves trained scientists and engineers,¹⁰⁸ the long-term plan for science and technology (2006 to 2020) states 'we need to depend even more heavily on S&T progress and innovation in order to achieve substantial gains in

productivity and advance the overall economic and social development in a co-ordinated and sustainable manner.¹⁰⁹

As the world responded to the global financial crisis in 2008 and 2009, many governments outlined economic stimulus packages—short-term injections of money combined with other policy measures designed to kick-start their domestic economies. Science and innovation featured prominently in these strategies¹¹⁰; investment in green technologies was a priority in South Korea and Australia,¹¹¹ and the USA pledged 'the largest commitments to scientific research and innovation in American history'.¹¹² The recognition that science can drive economic growth is by no means new. In 1945, Vannevar Bush outlined the role that science and technology could play in preserving the health and wealth of post-war USA.¹¹³ Models of economic growth have increasingly recognised the role of science and new technology in promoting productivity increases.¹¹⁴

The Royal Society and other UK scientific bodies recently examined the contribution of science to

102 US Patent and Trademark Office (2010). [Patent counts by country/ state and by year: utility patents. January 1, 1963–December 31, 2009](#). US Patent and Trademark Office: Alexandria, VA, USA.

103 US Patent and Trademark Office (2010). [Patent counts by country/ state and by year: utility patents. January 1, 1963–December 31, 2009](#). US Patent and Trademark Office: Alexandria, VA, USA.

104 TUBA (2010). *Turkish Academy of Sciences 2009 science report*. Turkish Academy of Sciences: Ankara, Turkey. Evidence provided by the Turkish Academy of Sciences in response to the Royal Society Global Science Report call for evidence, February 2010.

105 Royal Society (1662). *First charter*. See <http://royalsociety.org/about-us/history/royal-charters/>, accessed 30 September 2010.

106 European Commission (2010). *Europe 2020: a European strategy for smart, sustainable and inclusive growth*. European Commission: Brussels, Belgium.

107 Merkel A (2010). Speech by German Chancellor Angela Merkel on being awarded the King Charles II medal at the Royal Society on 1 April 2010. Transcript available online at <http://royalsociety.org/chancellor-merkel-speech/>, accessed 30 September 2010.

108 President Hu Jintao is a hydraulic engineer, Prime Minister Wen Jiabao is a geologist, and five of

the other seven members of the political bureau of the central committee of the Communist Party of China are engineers or scientists (the other two being a lawyer and an economist).

109 The State Council of The People's Republic of China (2006). *The national medium- and long-term program for science and technology development (2006–2020): an outline*. The State Council of The People's Republic of China: Beijing, PR China.

110 Royal Society (2010). *The scientific century: securing our future prosperity*. Royal Society: London, UK.

111 OECD (2009). *Policy responses to the economic crisis: stimulus*

packages, innovation and long term growth. Organisation for Economic Co-operation and Development: Paris, France.

112 Obama B (2009). Speech by US President Barack Obama at the 146th Annual Meeting of the US National Academy of Sciences.

113 Bush V (1945). *Science the endless frontier. A report to the President by Vannevar Bush, Director of the Office of Scientific Research and Development, July 1945*. United States Government Printing Office: Washington, DC, USA.

114 Solow R (1956). *A contribution to the theory of economic growth*. Quarterly Journal of Economics **70**, 1, 65–94.

the economic prosperity of the UK.¹¹⁵ Each of these studies drew on economic history, recent academic studies, and domestic and international examples,¹¹⁶ to illustrate the strong relationship between investment in science, scientific productivity, innovation and economic growth. By creating new ideas, new industries and new technologies, and training skilled people, science is crucial to economies at all stages of development, whether they are manufacturing strongholds or dominated by service industries.¹¹⁷

1.3.2 Addressing global challenges

Science, technology and innovation are more than simply tools for advancing the cause of one nation. Recent meetings of global networks such as the G8 and the G20, or regional meetings of the European Commission, the Association of Southeast Asian Nations (ASEAN), and the African Union demonstrate the contribution of science in addressing cross-border issues. Global challenges such as climate change, food, water and energy security all feature highly on the agenda, and require politicians to engage with science globally and locally in order to identify sustainable solutions. There is also an important role for science in addressing concerns such as poverty alleviation, sustainability and diversity.¹¹⁸

The contribution that science can make to combating these issues—both in identifying problems and risks, and in providing technical solutions—will be investigated further in Part 3.

1.3.3 National science in a global age

The global science landscape is underpinned by national infrastructures, which reflect the research priorities, capacity and strengths of individual countries. Science is a cross-border enterprise, but these activities are still strongly connected to, and in some cases anchored in, national systems, either through funding, governance arrangements or simply because of location.

Levels of research investment and activity vary considerably between nations. Among the G7 economies alone the differences are striking. The proportion of GDP spent on R&D varies from 1.14% (Italy),¹¹⁹ to 3.45% (Japan).¹²⁰ In Italy, research is funded primarily by government (49% GOVERD). In Japan, the lion's share of R&D investment comes from business (78% BERD).

Comparisons of scientific architecture also reveal important differences between countries. In the UK, the majority of 'academic' research takes place in universities, with non-university labs representing only a small proportion of research activity. In Germany, university research is complemented by *Gesellschaften* and *Gemeinschaften*—the Max-Planck and Fraunhofer Societies and the Helmholtz and Leibniz Associations—non-profit, legally independent research organisations, which between them run over 200 institutes, and employ over 65,000 people.¹²¹ In China and Russia, the national academies are leading research organisations, running their own institutes (the Chinese Academy of Sciences is the world's most prolific publishing research organisation,

Red chalk drawing of sand, Antoni Van Leeuwenhoek, 1704. From the Royal Society library and archive.



with over 50,000 papers coming from its institutes in the period 2004 to 2008). In the US, specialised national laboratories (run by the government or the private sector) are commonplace. The US Department of Energy has 21 National Laboratories and Technology Centers, employing over 30,000 scientists and engineers between them, while the US Department of Agriculture's chief scientific research agency, the Agricultural Research Service, employs over 2,000 scientists in more than 100 laboratories.¹²²

A feature of almost all national science and innovation strategies is an acknowledgement of the importance of international collaboration. By being international in outlook, a nation can enhance the quality of its domestic science, absorb expertise and ideas from partners and competitors around the world, share risk and pool resources. The Science and Technology Policy Council of Finland has clearly articulated the importance of a strong international strategy. 'Through internationalisation, competition and co-operation, Finland can improve the quality of research, reduce overlapping knowledge production, pool existing resources into larger entities and deploy them to important targets.'¹²³ Other countries have also adopted a similar outlook; in its most recent S&T Development Strategy, the Vietnamese Ministry of

Science and Technology has set out as a key goal 'actively expanding co-operation and international integration in S&T.'¹²⁴

1.4 Centres for science

Scientific activities are not only unevenly distributed between nations, but also within them (see Figure 1.4). In the USA in 2004, more than three-fifths of R&D spending was concentrated in ten states—with California alone accounting for more than one-fifth.¹²⁵ In most countries there is a degree of concentration of research activity in particular places. Moscow accounts for 50% of Russian research articles; Tehran, Prague, Budapest and Buenos Aires each top 40% of their national outputs, and London, Beijing, Paris and Sao Paulo are each responsible for over 20%.

Among the most prolific publishing cities, Nanjing has leapt 66 places into the top 20 since 1996 to 2000. One of the Four Great Capitals of China, Nanjing has long been a centre for education. Today, the city is home to seven national universities, the People's Liberation Army University of Science and Technology, several other national colleges and provincial universities, and numerous industrial parks.

115 Royal Society (2010). *The scientific century: securing our future, prosperity*. Royal Society: London, UK.

116 Lipsey R, Carlaw K & Bekar C (2005). *Economic transformations: general purpose technologies and long-term economic growth*. Oxford University Press: Oxford, UK.

117 Royal Society (2009). *Hidden wealth: the contribution of science to service sector innovation*. Royal Society: London, UK.

118 STEPS Centre (2010) *Innovation, sustainability, development, a*

new manifesto. STEPS Centre: Brighton, UK; Conway G & Waage J (2010). *Science and innovation for development*. UK Collaborative on Development Sciences: London, UK.

119 Data from the *UNESCO Institute for Statistics Data Centre*, Montréal, Canada; 2006 figures used (last available year).

120 Data from the *UNESCO Institute for Statistics Data Centre*, Montréal, Canada; 2007 figures used (last available year).

121 Federal Ministry of Education and Research, Germany (2008).

German research institutions at a glance. Bundesministerium für Bildung und Forschung (BMBF): Bonn, Germany.

122 USDA (2010). *2010 performance and accountability report* (p 186). US Department of Agriculture: Washington, DC, USA. See also <http://www.ars.usda.gov/AboutUs/AboutUs.htm>, accessed 14 January 2011.

123 Science and Technology Policy Council of Finland (2003). *Knowledge, innovation and internationalisation*. Science and

Technology Policy Council of Finland: Helsinki, Finland.

124 See http://www.most.gov.vn/Desktop.aspx/Details-Article/News/The_Conference_on_Implementing_Vietnam_ST_Development_Strategy_for_the_2001-2010_period_reviewing_ST_results_for_the_2006-2010_period_task_directions/, accessed 10 January 2011.

125 Source: US National Science Foundation (2007). *Science and engineering indicators 2008* (ch 4, p 5). National Science Foundation: Arlington, VA, USA.

Figure 1.4. Top 20 publishing cities 2004–2008, and their growth since 1996–2000.¹²⁶

Key City with highest publication output in the period 2004–2008;
growth is since period 1996–2000.

- Decreased or stayed constant
- Increased 5–10 places
- Increased 10–20 places
- Increased 20+ places

São Paulo's rise of 21 places in the list of top publishing cities in the last decade reflects the rapid growth of Brazilian scientific activity, and the city's role as the capital of the state with the strongest scientific tradition. The State of São Paulo's 1947 constitution includes an article which ensures that 1% of all state revenue goes towards research. According to Carlos Henrique de Brito Cruz, the scientific director of FAPESP (Fundação de Amparo à Pesquisa do Estado de São Paulo—the Research Council for the State of São Paulo), 'no other science funding agency in possibly the whole world has that kind of security and autonomy [from the federal government].'¹²⁷

In today's competitive quest for corporate R&D investment, scientific facilities or global talent, it is increasingly regions and cities rather than countries that are the relevant units and sites.¹²⁸ Leading scientific cities and their regions are successful because they facilitate knowledge exchange between clustered institutions and organisations. They usually offer a higher concentration of diverse talent, capable of fostering a more knowledge-intensive economy. And the region or city itself provides an attractive location in which to work, invest and research.¹²⁹

1.4.1 Centres of research and infrastructure

Within these cities, individual research organisations and universities are also major hubs of scientific activity. Harvard University has dominated university league tables for the past decade as a beacon of

educational and research excellence.¹³⁰ Its publication output in 2004 to 2008 was greater than that of the whole of Argentina. The University of Cambridge (whose output in 2004 to 2008 was equivalent to more than the Ukraine) is a Nobel hothouse with 88 affiliated scientists having been awarded the accolade since the inception of the prize in 1904.¹³¹

Established research centres are no longer necessarily confined to their geographic location. Universities and research organisations are not merely national institutions, they are global brands—which exert a pull of their own on mobile students, researchers and investment. Some European and US universities have established outposts in Asia: the Chinese campuses of the Universities of Nottingham and Liverpool are two examples. Nor are research funders restricted to their national borders. The UK-based Wellcome Trust supports institutions in South East Asia, India and across Africa, including a network of 50 research centres through its African Institutions Initiative.¹³²

The importance of strong institutional infrastructure is recognised in countries with developing scientific ambitions. Over the last 15 years, Chile has created a programme of establishing and funding 'Centres of Excellence' and 'Millennium Institutes' in fields as diverse as mathematical modelling, oceanography, astronomy and systems biology.¹³³ In India, the government's 11th Five Year Plan (2007–2012) commits to the establishment of 30 new Central Universities, 20 Institutes of Information

126 Analysis by Elsevier based on data from Scopus.

127 Petherick A (2010). *High hopes for Brazilian Science*. Nature **465**, 674–675.

128 Athey G *et al.* (2007). *Innovation and the city: how innovation has developed in five city-regions*.

National Endowment for Science, Technology and the Arts (NESTA): London, UK.

129 Florida R (2008). *Who's your city?: how the creative economy is making where to live the most important decision of your life*. Basic Books: New York, NY, USA.

130 Harvard University and Harvard Medical School.

131 Source: University of Cambridge website. See <http://www.cam.ac.uk/univ/nobelprize.html>, accessed 5 October 2010.

132 Evidence provided by the Wellcome Trust in response to

the Royal Society Global Science Report call for evidence, February 2010.

133 Evidence provided by the Chilean Academy of Sciences in response to the Royal Society Global Science Report call for evidence, February 2010.

Technology (IIITs), eight Institutes of Technology (IITs), seven Institutes of Management (IIMs), and five Institutes of Science Education and Research (IISERs), each intended to foster future excellence in research.¹³⁴

Developments in the Middle East are equally striking. Saudi Arabia has recently opened its new King Abdullah University for Science and Technology (KAUST). With an endowment of around US\$20 billion, KAUST is attracting faculty and postgraduate students from across the world. As a graduate-only institution, it aims to rival the California Institute of Technology for prestige within 20 years.¹³⁵ The university has also successfully established partnerships with leading international universities, including Cambridge, Oxford and Imperial College, and expects these links to yield many new collaborative projects over the next decade.

Some of these research institutes are home to large pieces of scientific equipment. KAUST has become the latest university to host a supercomputer. Some of the top 25 most powerful computing facilities in the world are hosted at the Universities of Edinburgh, Texas, Moscow State and Tennessee, and the Chinese Academy of Sciences.¹³⁶ These supercomputers can be a draw for researchers in particular fields such as climate modelling and astrophysics, where this capacity is essential.

It is not only universities that are acting as institutional hubs. The need for large, state-of-the-art equipment, and the cost of building and maintaining these facilities has influenced research locations for many years. The European Organization for Nuclear Research (CERN) was established in 1954 on the Franco–Swiss border at Geneva. As Isidor

Rabi, the Nobel prizewinning physicist,¹³⁷ explained to UNESCO, the aim of this facility was to assist in ‘the search for new knowledge in fields where the effort of any one country in the region is insufficient for the task.’¹³⁸ Today, through core funding from 20 European member states and contributions from other observers, CERN’s powerful particle accelerators and detectors are used by physicists hailing from nearly 600 institutes and 85 countries.¹³⁹

The competition to host such facilities is fierce, as they can impact directly on the national science system and community which is hosting the facility. The dark skies above the Atacama desert in Chile made it an ideal location for the European Space Observatory (ESO)’s ‘Very Large Telescope’. But as well as drawing European researchers to the country, the telescope has provided a boon to Chilean astronomy domestically. Chilean researchers are entitled to up to 10% of the total observing time on ESO telescopes, which has made these researchers very popular as potential collaborative partners.¹⁴⁰

There are two bids to host the proposed Square Kilometre Array (SKA—an international effort to build the world’s largest radio telescope), one a consortium from Australia and New Zealand, and the other from South Africa. In Australia, as part of the bid, the International Centre for Radio Astronomy Research (ICRAR) was opened in Perth in 2009,¹⁴¹ and the Australian Square Kilometre Array Pathfinder (ASKAP) is due for completion in 2013¹⁴²—both major domestic infrastructure projects financed, in part, to demonstrate their commitment to the SKA project. The South African bid has received support from the African Union,¹⁴³ and the MeerKAT telescope will also be commissioned in 2013.

1.5 A new world order?

Changes in the scientific league tables have concerned policy makers and observers in the 'leading' scientific nations for some time. In 'Rising above the Gathering Storm', the US National Academies warned that 'the world is changing rapidly, and our advantages are no longer unique', and called for a 'renewed effort to bolster our competitiveness'.¹⁴⁴ More recently, Congress has asked the National Academies in the USA to investigate the competitive position of the USA's research universities in the global community.¹⁴⁵ In March 2010, the Royal Society warned that '[the UK's] scientific leadership, which has taken decades to build, can be quickly lost'.¹⁴⁶ The scientific league tables are not just about prestige—they are a barometer of a country's ability to compete on the world stage.

There is no doubt that the leading scientific nations of the late 20th century face increasing competition from around the world, but to say that they are in decline would be premature. While the USA, Japan, Germany, the UK and others may be

decreasing their proportion of global spend and output on R&D, they are still growing in absolute terms. The USA may rank low in terms of its annual growth rate for publications, but this is on the basis of an increase of 23,804 publications over the period 1996 to 2008, or an average increase of 1,831 papers year on year—more than the total 2008 production of Algeria. China may 'add an Israel' each year, but this is in the context of a relatively small base, with a rapidly growing scientific workforce.

Science is happening in more places but it remains concentrated. There continue to be major hubs of scientific production—flagship universities and institutes clustered in leading cities. What is changing is that the number of these hubs is increasing and they are becoming more interconnected. The scientific superpowers of the 20th century remain strong, and are being joined by relative newcomers—China, India, Brazil, South Korea and others—who are changing the dynamic of the global science community. The emergence of these new hubs is creating opportunities for researchers to work with new people in new places.

134 Planning Commission, Government of India (2008). [Eleventh five year plan 2007–12: volume I: inclusive growth](#), Oxford University Press: New Delhi, India.

135 Corbyn Z (2009). [Oasis in the desert](#). Times Higher Education, 5 November 2009.

136 Source: Top 500 Supercomputer Sites (2010). See <http://www.top500.org/list/2010/06/100>, accessed 30 September 2010.

137 Isidor Rabi won the Nobel Prize in Physics in 1944 'for his resonance method for recording the magnetic properties of atomic nuclei'. See http://nobelprize.org/nobel_prizes/physics/laureates/1944/, accessed 7 January 2011.

138 Royal Society (1986). [John Bertram Adams. 24 May 1920–3 March 1984](#). Biographical Memoirs of Fellows of the Royal Society **32**, 6. Royal Society: London, UK. Sir John Adams FRS spent much of his career at CERN, and was instrumental in building the giant particle accelerators there. See also <http://sl-div.web.cern.ch/sl-div/history/sirjohn.html>, accessed 17 January 2011.

139 Source: CERN website. See <http://public.web.cern.ch/public/en/About/Global-en.html>, accessed 30 September 2010.

140 Interview with Dr Ken Rice, Royal Observatory Edinburgh, August 2010. See also The Messenger (2006). [ESO–Chile](#)

[fund for astronomy: 10 years of productive scientific collaboration](#). The European Space Observatory (ESO) Messenger **125**, 56.

141 Pockley P (2009). [New labs boost Australian array bid](#). Physics World October 2009.

142 Westmeier T & Johnston S (2010). [The Australian square kilometre array pathfinder](#). Proceedings of Science (ISKAF2010), 056.

143 African Union (2010). [Assembly of the African Union, fifteenth ordinary session, 25–27 July 2010, Kampala, Uganda](#). Assembly/AU/Dec.303(XV) (p 1). African Union: Addis Ababa, Ethiopia.

144 US National Academy of Sciences, National Academy of Engineering

and Institute of Medicine (2005). [Rising above the gathering storm: energizing and employing America for a brighter economic future](#). National Academies Press: Washington, DC, USA.

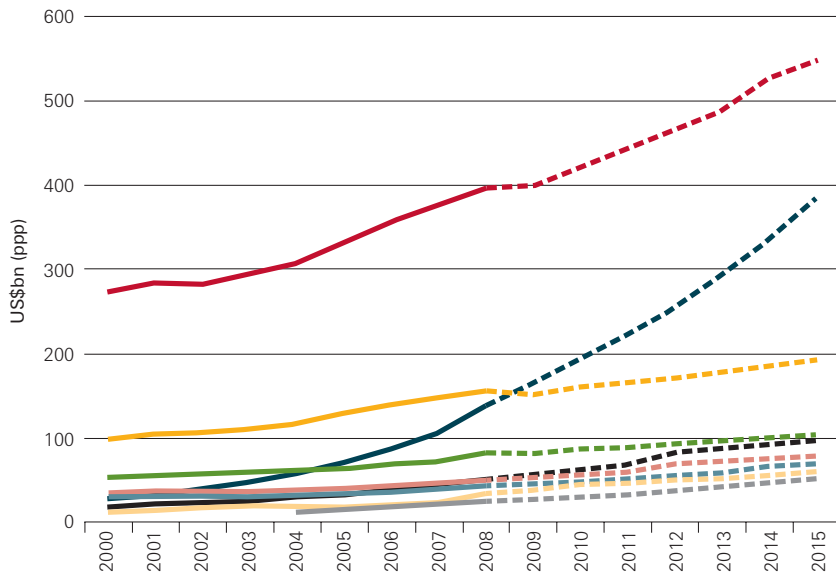
145 US House Committee on Science, Space and Technology (2009). [Four congressional leaders ask National Academies to assess condition of research universities](#). Press release, 22 June 2009. US House of Representatives: Washington, DC, USA.

146 Royal Society (2010). [The scientific century: securing our future prosperity](#). Royal Society: London, UK.

1.6 The world beyond 2011

The balance of funding for science across the globe is likely to change over the coming years as new scientific hubs and leaders emerge. In most cases, these emerging hubs are supported by explicit government policy to support R&D: China,

Figure 1.5. R&D spending, selected countries 2000–2015;
*the dotted lines indicate projections, based on announced targets.*¹⁵¹



Key

- United States
- China
- Japan
- Germany
- Korea, Republic of
- France
- United Kingdom
- Russia
- Brazil

South Korea and Brazil all maintain targets for R&D spending alongside other policies designed to boost inputs into their national science system. China intends to increase its spending on R&D to 2.5% of GDP by 2020 from its value of less than 2% at present,¹⁴⁷ South Korea 5% by 2022,¹⁴⁸ and Brazil 2.5% by 2022.¹⁴⁹ Many longer established scientific nations also maintain targets for R&D spending, such as the USA's new target of over 3% of GDP,¹⁵⁰ and the EU's similar Lisbon goal of 3% of member countries' GDP.

It is difficult to predict the course of R&D spending over future years (for example, recent significant reductions in the 2011 science budget in Brazil have raised concerns about progress towards its 2022 target). However, by extrapolating current trends to forecast the way in which the global league table of spending might change if each country meets their current spending targets for R&D, we can suggest what the scientific world might look like within the next decade.

Figure 1.5 shows the effects of countries meeting, or being on course to meet, their respective R&D targets.¹⁵¹ It can be seen that while the USA should maintain its current dominance of global R&D spending, China is set to leap above Japan in spending terms, and to chase the USA. Similarly, South Korea is highly likely to overtake the UK in coming years. Assuming these targets are met,

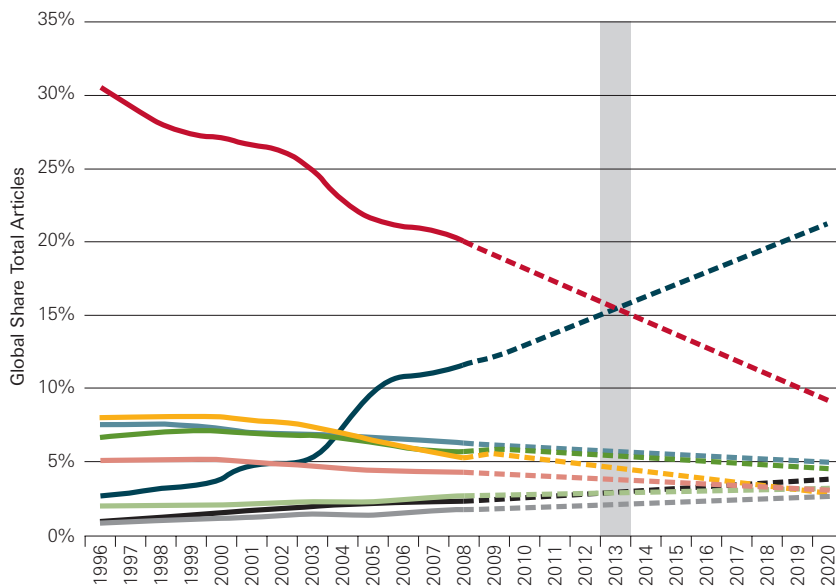
Russia and Brazil will also catch up rapidly with longer established research spenders, from very low bases at the start of the decade.

These projections suggest that the global science system is breaking away from its earlier pattern, at least as measured by the supply of inputs in the form of R&D spending. China and South Korea meet their own ambitious R&D spending targets, driving huge new expenditures into their respective science systems, while economies like Brazil and Russia also promise substantially greater resources for R&D spending.¹⁵²

In terms of publications, the landscape is set to change even more dramatically if current trends continue, as can be seen in Figure 1.6. China has already overtaken the UK as the second leading producer of research publications, but some time before 2020 it is expected to surpass the USA.¹⁵³ Projections vary, but a simple linear interpretation of Elsevier's publishing data suggests that this could take place as early as 2013.¹⁵⁴ Of course, in practice, this will not follow a linear progression (we do not expect that the USA will decrease their share of global

Figure 1.6. Linear extrapolation of future publication trends.¹⁵⁵

The dotted lines indicate projections



147 The State Council of the People's Republic of China (2006). *The national medium- and long-term program for science and technology development (2006-2020): an outline*. The State Council of the People's Republic of China: Beijing, China.

148 Ministry of Education, Science and Technology (2009). *Major policies and plans for 2010* (p 20). Ministry of Education, Science and Technology: Seoul, South Korea.

149 Kugler H (2011). Brazil releases science blueprint. SciDev.Net, 7 January 2011. Available online at <http://www.sciDev.net/en/news/brazil-releases-science-blueprint.html>, accessed 17 January 2011

150 Obama B (2009). *Speech delivered by President Barack Obama at*

[the US National Academies of Science](#), 27 April 2009.

151 GDP figures from the IMF World Economic Outlook, forecasts from 2008 to 2009. R&D targets are generally expressed as a fraction of GDP to be achieved by a set date. A simple linear growth from current GDP to target provided the path towards the target. Exceptions are: the USA, which has not provided a date for the 3% target established by President Obama to be met; we have assumed 2014. Japan has set a target of 1% of GDP for public expenditure only, to be achieved by 2010. We have assumed that private expenditure continued to grow with GDP over the remainder of the forecast period. OECD MSTI figures used for existing R&D

spending until 2007, forecasts from that date. Some discrepancies will occur between the forecast for R&D spending as a percentage of GDP, and the forecasts for GDP growth in the period 2007 to 2009. OECD Science, Technology and Industry Outlook 2008. Table 2.2 summarises R&D spending targets.

152 See also Gilman D (2010). *The new geography of global innovation*. Goldman Sachs Global Markets Institute: New York, NY, USA. This suggests China will overtake Japanese R&D expenditure by as early as 2012, compared to the more conservative forecast presented here.

153 Adams J (2010). *Get ready for China's domination of science*. New Scientist **2742**, 6 January 2010.

154 See also Shelton R & Foland P (2009). *The race for world leadership of science and technology: status and forecasts*. Proceedings of the 12th International Conference on Scientometrics and Informetrics, Rio de Janeiro, 14-17 July 2009 (pp 369-380). Shelton and Foland forecast, based on present trends, that China will near parity with the USA and EU in scientific publications in less than 10 years from this writing, when using a more complex model using GERD share forecasts as further input into the model.

155 Analysis by Elsevier based on data from Scopus. This indicates a simple linear projection of the data.

Key

- China
- United States
- United Kingdom
- Germany
- Korea, Republic of
- India
- France
- Japan
- Brazil

PART 1

Scientific landscape in 2011

publications to nothing in the next 50 years), but the potential for China to match US output in terms of sheer numbers in the near to medium term is clear.

China's rise is undoubtedly the most striking, but Brazil, India and South Korea are following fast behind, and are set (on the basis of this simple extrapolation of existing trends) to surpass the output of France and Japan by the start of the next decade. In many respects this should not come as a great surprise. Brazil and India host two of the world's largest populations, and both have committed to increasing their spending on science as their economies grow. South Korea is home to globally successful R&D-intensive industries such as Samsung; it is noted as a technology leader, and has been called the 'most wired' nation on earth.¹⁵⁶

These are, of course, publication statistics taken in isolation, and any number of external factors could impact on the projected course for increased output.

How will, for example, France and Japan respond to the impending competition? Japanese policy makers are already considering how to reverse their decline, introducing a 'Global 30' initiative to improve the international standing of their top universities,¹⁵⁷ and the French Government has committed substantial investment to research and higher education in order to strengthen its global position.¹⁵⁸

We have seen that there continue to be leading hubs for science—both those which are well established and a number which have emerged rapidly. Hubs will continue to operate, since much of science requires a critical mass of people and equipment to produce at world class level. At the same time, more science is also being produced away from these centres, on a smaller scale. How these hubs interact with each other, and with the rest of the scientific world, will help determine the shape of the scientific landscape in 2020.



Map showing the route of H.M.S. Challenger during its oceanographic voyage, 1873. From the Royal Society library and archive.

156 McCurry J (2010). [South Korea counts the cost of being the most wired nation on earth](#). The Age, 18 July 2010; Ash L (2008). [South Korea's 'e-sports' stars](#). BBC

News Online, 3 January 2008. Available online at http://news.bbc.co.uk/1/hi/programmes/crossing_continents/7167890.stm.

157 See <http://www.jsps.go.jp/english/e-kokusaika/index.html>, accessed 30 September 2010.

158 Royal Society (2010). [The scientific century: securing our future prosperity](#). Royal Society: London, UK.

PART 2

International collaboration

Figure demonstrating the methods used by Dr Tamar Makin, Royal Society Newton International Fellow, FMRIB Centre, University of Oxford, and colleagues to construct functional maps in the human brain, using Magnetic Resonance Imaging (MRI). This image was published in Orlov T, Makin T, Zohary E (2010). Topographic Representation of the Human Body in the Occipitotemporal Cortex. *Neuron* 68, pp 586-600, 4 November 2010. Authors: Tanya Orlov, Tamar R Makin, Ehud Zohary. ©Elsevier 2010.



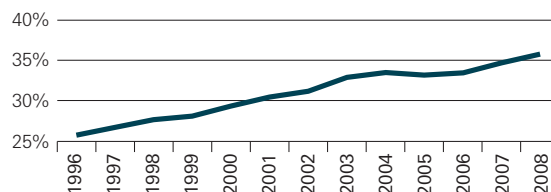
The second charter of the Royal Society in 1663 granted the right to its members ‘to enjoy mutual intelligence and affairs with all and all manner of strangers and foreigners, without any disturbance whatsoever in matters or things philosophical, mathematical or mechanical.’¹⁵⁹

There was good reason to look beyond 17th-century England for scientific inspiration. The foundations for the European scientific renaissance had been laid by scholars from all over the world. Algebra was introduced by a 9th-century Baghdad scholar, Musa al-Khwarizmi, following study of Indian number systems developed by Aryabhata. China, in the same century, saw the first reference in a Taoist text to ‘fire medicine’, or gunpowder. Each continent has its own rich history of scientific and innovative achievements, inspired not only by curiosity, but necessity—Mesoamerican and Egyptian agriculturalists would read the stars to know when to cultivate their crops.

As science has expanded in the late 20th and into the 21st century, it has become increasingly interconnected. Today, less than 26% of papers are the product of one institution alone, and over a third have multiple nationalities sharing authorship (see Figure 2.1).¹⁶⁰ Collaboration can enhance the impact of research and bring together a diversity of experience, funding and expertise to bear on a large range of research questions.

One of the fundamental tensions at the heart of today’s science is between the motives of national governments and the choices of individual researchers. National governments often fund scientific research to boost national prestige, to stimulate economic growth and to gain competitive

Figure 2.1. Increase in the proportion of the world’s papers produced with more than one international author, 1996–2008.¹⁶¹



advantage over other nations. Academic researchers rarely have nationalist motivations for their work, instead being driven by curiosity and competition. These individuals often move and collaborate to access funds, resources and data, and to ally with the most talented researchers.¹⁶²

Scientific research funded by national governments is increasingly a joint venture and the benefits are spread more and more beyond national borders. Governments have to consider how best to ensure that their scientists are ‘tapped into’ the networked system of global science so as to derive as much benefit from the networks as possible.

2.1 Patterns of collaboration

In March 2010, *Physics Letters B* published the most multi-authored research paper to date, when 3,222 researchers from 32 different countries contributed to a study of ‘charged-particle multiplicities’ measured with the ATLAS detector at the Large Hadron Collider in Geneva.¹⁶³ Similarly, the Human Genome Project,¹⁶⁴ a government-sponsored consortium of 20 institutions in six countries engaged thousands

of scientists to successfully sequence the human genome in just 13 years.¹⁶⁵ These large-scale collaborations demonstrate the extent to which science can draw in a multitude of actors to address research problems.¹⁶⁶ Few research collaborations occur on this scale or anything approaching it. Most collaborations are much smaller scale affairs, involving just a few authors.

2.1.1 Collaboration in a national context

As a proportion of national output, the rapidly growing scientific nations are collaborating less than most of their 'developed' counterparts. China, Turkey, Taiwan, India, South Korea and Brazil produce over 70% of their publications from national researchers alone. By contrast, small nations and less developed countries are collaborating at a much higher rate. Over half of the research published from Belgium, the Netherlands and Denmark in 2004-8 was the product of multinational authorship. In parts of Africa and South-East Asia this is closer to 100%.

The research output of the established scientific nations is also increasingly collaborative. Figure 2.2 (on page 48) shows how collaboration has grown in absolute terms in a selection of countries, and also how this relates to their total publication output. The

growth of international collaboration is common to all countries. However, while the USA, Europe and Japan are demonstrating a growing propensity to collaborate with global partners, China, Turkey and Iran are proportionally decreasing their collaborations. Furthermore, ambitious scientific nations such as Saudi Arabia and South Africa are increasing their relative collaboration.

These differences are not surprising. They reflect the strength of research, the availability of resources, and the scale of the research community in each country. In China, the overall numbers of international collaborations are growing significantly, but this is simply not keeping pace with the even more dramatic rise in its overall publication productivity. Established scientific nations such as the leading European nations are increasing their proportional collaboration, by contrast; this is, in part, a direct response to the increased and improved performance of the newly emerging powers. The growth in overall collaboration globally indicates that the scientific landscape is increasingly interlinked. The level of collaboration may differ proportionately between countries, but it is clear that it is intrinsic to science on both a national and global level.

159 Royal Society (1663). *Second charter*. See <http://royalsociety.org/about-us/history/royal-charters/>, accessed 30 September 2010.

160 Data from Elsevier's Scopus.

161 Analysis by Elsevier based on data from Scopus. Data in some subject fields in 2000, 2001 and 2002 lacked complete author affiliation

data; the data for these years shown have been interpolated accordingly.

162 Wagner C (2008). *The new invisible college: science for development*. Brookings Institution: Washington, DC, USA.

163 Aad G *et al.* (2010). *Charged-particle multiplicities in pp*

interactions at $\sqrt{s} = 900$ GeV measured with the ATLAS detector at the LHC. Physics Letters B **688**, 21–42.

164 See http://www.ornl.gov/sci/techresources/Human_Genome/project/about.shtml, accessed 30 September 2010.

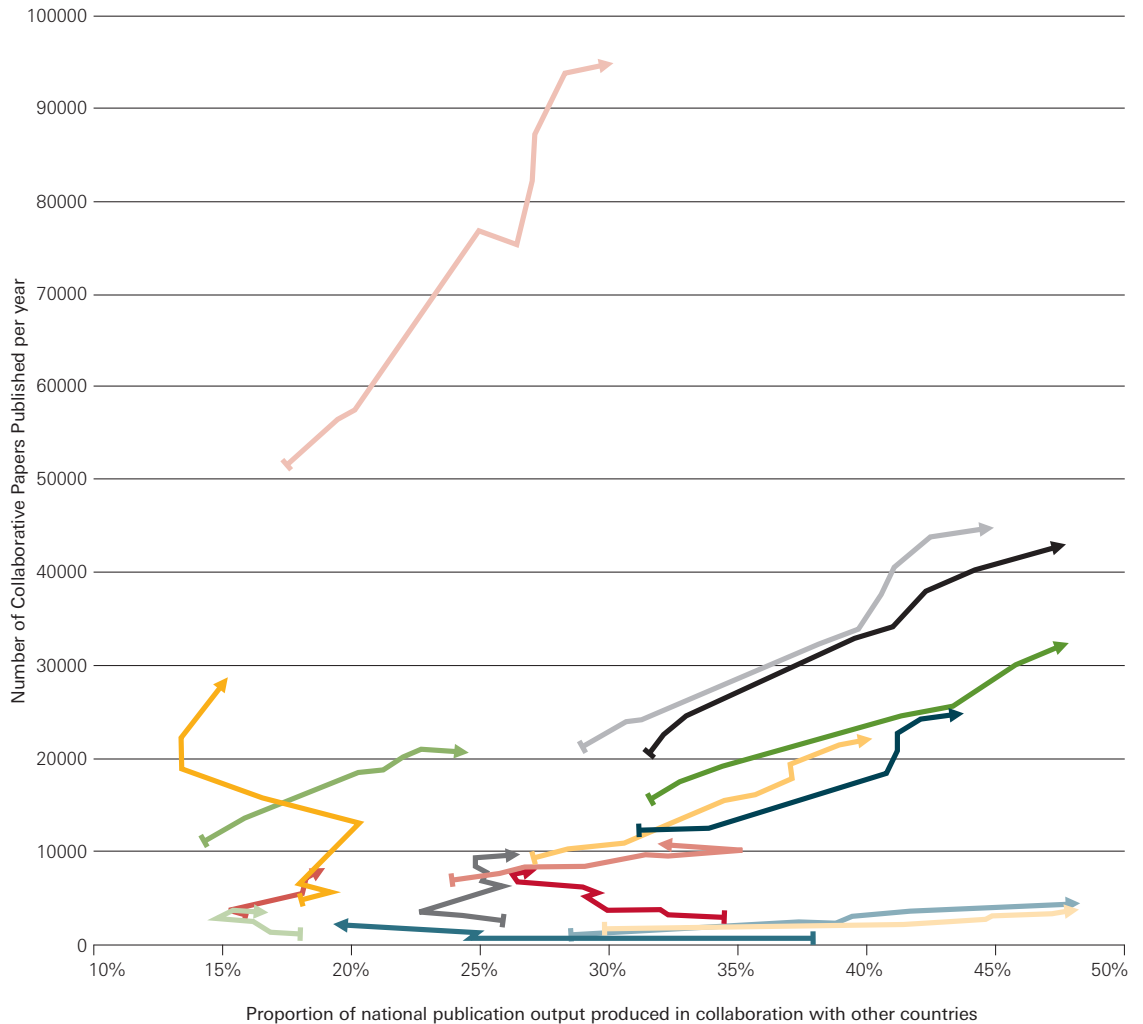
165 The institutions were based in Canada, China, France, Germany, India, Japan, New Zealand, the UK and the USA.

166 Wagner C *et al.* (2002). *Linking effectively: learning lessons from successful collaboration in science and technology*. Science and Technology Policy Institute, RAND Corporation: Arlington, VA, USA.

PART 2

International
collaboration

Figure 2.2. Growth in international collaboration for selected countries and the proportion of national output that this represents 1996–2008.¹⁶⁷



Key

1996 figures are shown with a dash, and 2008 figures with an arrow, indicating progression over time.

- Brazil
- Canada
- China
- France
- Germany
- India
- Iran
- Italy
- Japan
- South Korea
- Russia
- Singapore
- South Africa
- Turkey
- United Kingdom
- United States

2.1.2 Who is collaborating with whom?

Figure 2.3 (on pages 50-51) shows the spread of collaboration globally, and its intensification over time, between 1996 and 2008. The dominant role of the USA is striking. Only 29% of research output from the USA is internationally collaborative, yet international collaborations involving the USA account for 17% of all internationally collaborative papers.

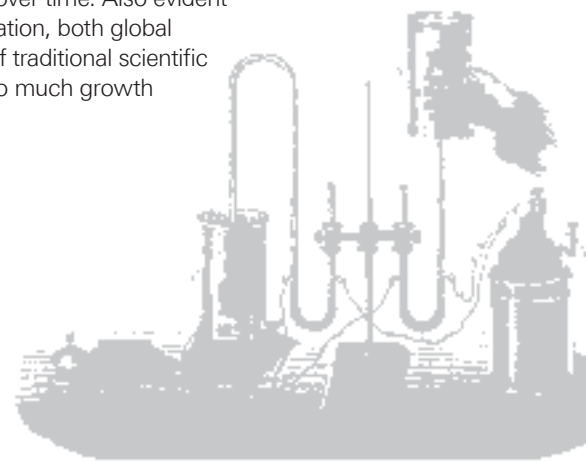
Other global and regional hubs for collaboration also stand out. The central role of traditional scientific nations is clear, but there is substantial growth elsewhere. Interesting trends can be identified, including the linguistic and historical ties which bind countries together. A striking example is the enduring influence that France has as a major collaborative partner with its former colonies and the rest of the French-speaking world.

These network maps represent patterns of collaborations between countries, based on numbers of jointly authored research papers. Connections are shown when the collaboration between two

countries represents between 5% and 50% of the overall publication output of one of the partners. A line is shown running clockwise from country A to country B; its thickness is relative to the proportion of nation A's output that the collaboration represents. So, we see lines running clockwise from many countries into the USA, which is a significant partner for many countries (but no lines that run clockwise from the USA, for which collaboration with no one country represents more than 5% of its total output). When collaboration constitutes over 5% for both partners, they are joined by two lines (one clockwise from A to B, representing the relative importance of the collaboration for A; the other clockwise from B to A, representing the importance for B).¹⁶⁸

The two maps, covering the periods 1996 to 2000 and 2004 to 2008 show the spread of collaboration globally, and its intensification over time. Also evident are particular hubs for collaboration, both global and regional. The central role of traditional scientific nations is clear, but there is also much growth elsewhere.

Apparatus used to illustrate the law of diffusion. Fig 12, 'A Treatise on Chemistry', Vol 1, H.E Roscoe & C. Schorlemmer. From the Royal Society library and archive.



¹⁶⁷ Analysis by Elsevier based on data from Scopus.

¹⁶⁸ Visualisation is by the Force Atlas algorithm, which treats the network of lines as a system of interconnected springs with the result that countries sharing a

collaborative relationship tend to group together, while those that do not are placed further apart. The map is created by taking into account all collaborations between countries over a threshold of 0.0002% of global collaborations—so at least 25 collaborations

between countries in the 2004–2008 period, and at least 15 in the period 1996–2000. The final visualisation then eliminates the lines of any relationships which constitute less than 5% or more than 50% of an individual nation's total output (if any country's

total output is dominated by one other country to the extent that it represents over half, this would suggest that the domestic science base is particularly weak). Analysis by Elsevier based on data from Scopus.

Figure 2.3. **Global collaboration** see footnote 168
Fig a. 1996-2000

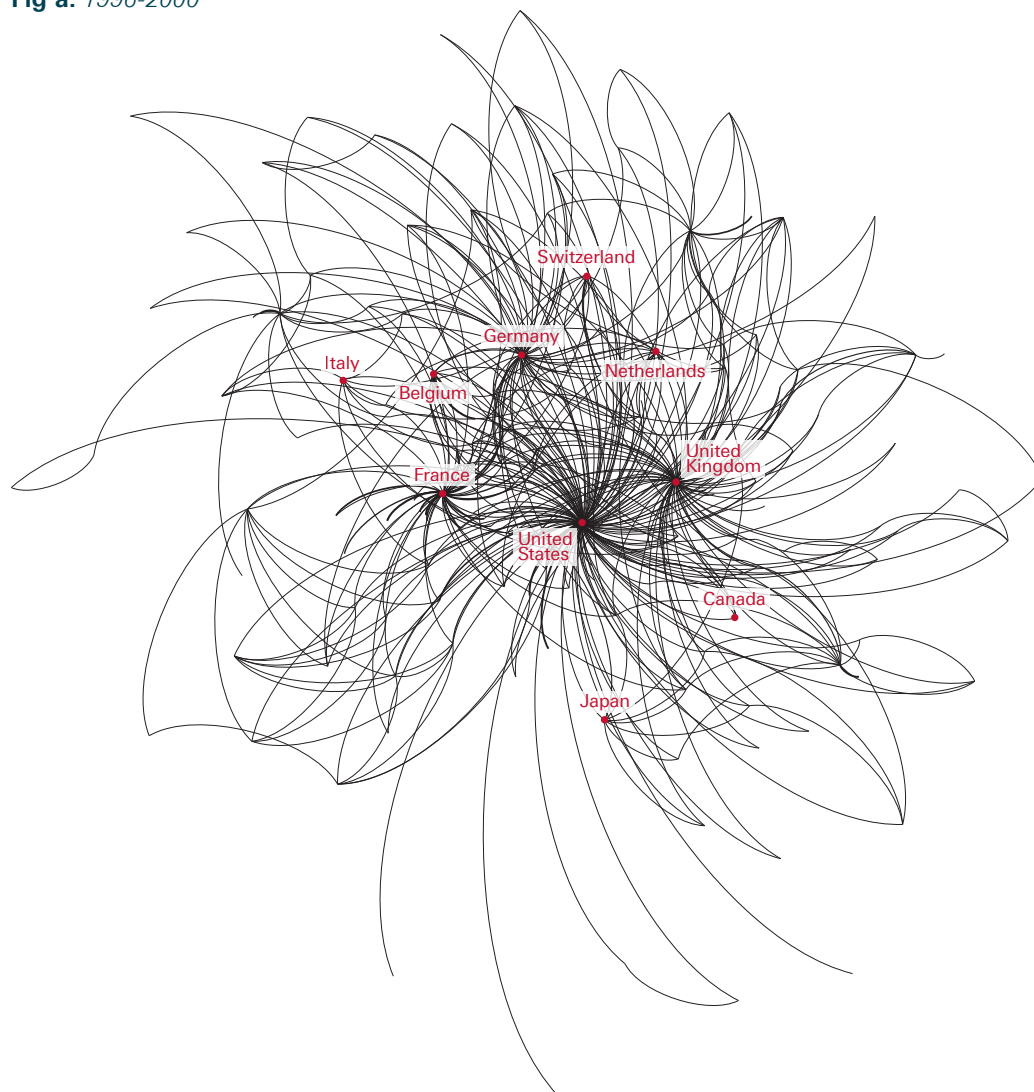


Fig b. 2004-2008

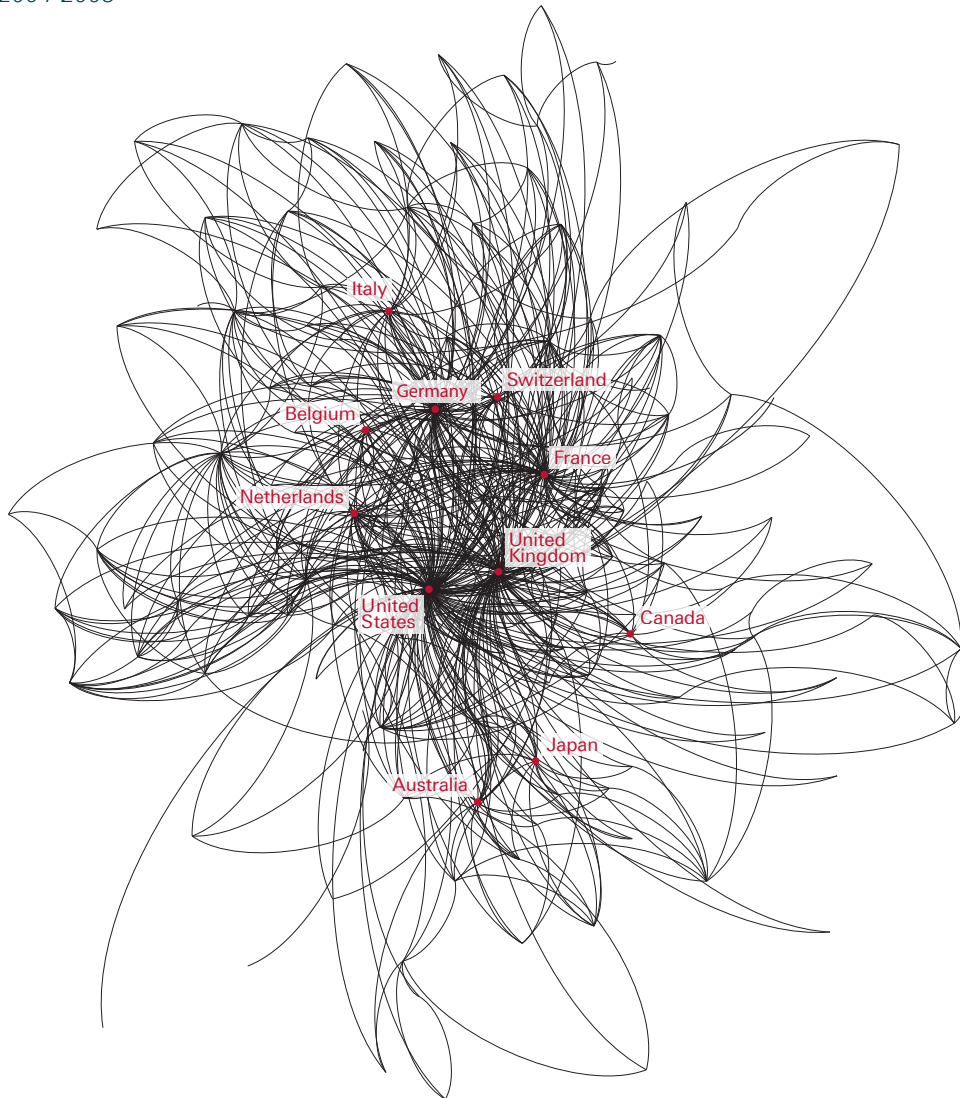


Figure 2.4. **Collaboration between African countries**¹⁶⁹
Fig a. 1996-2000

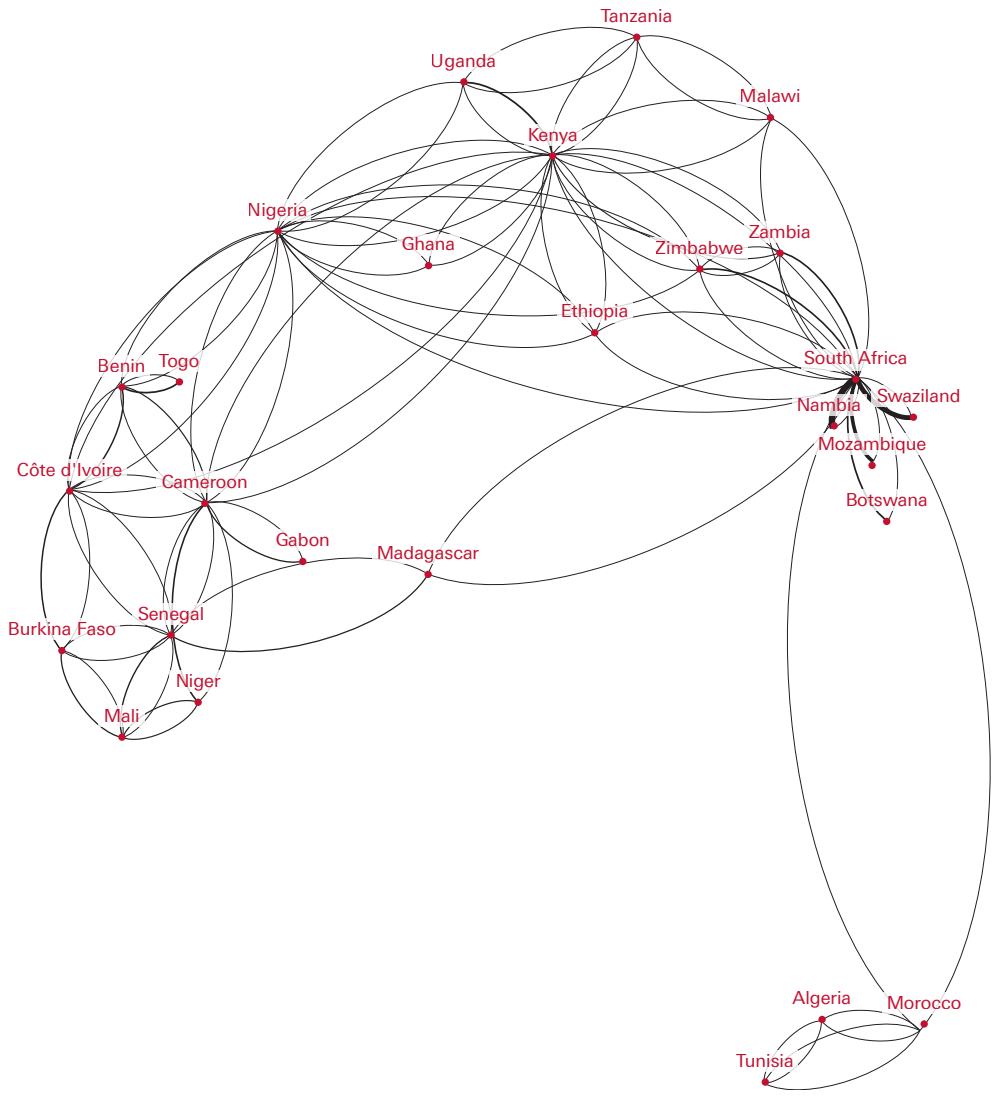
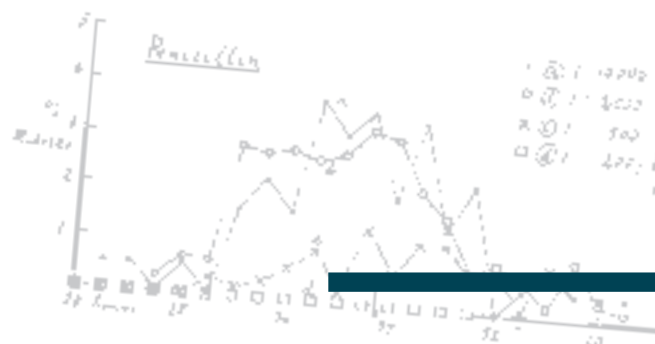
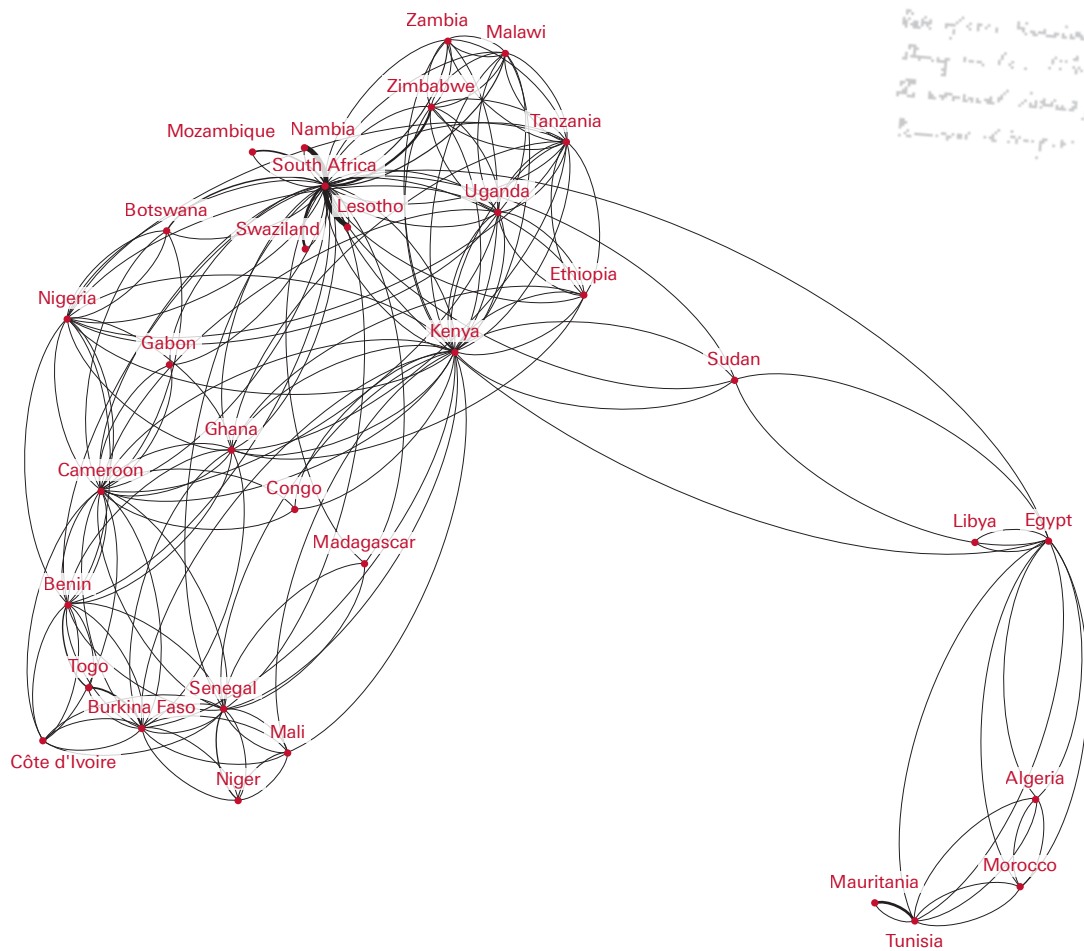


Fig b. 2004-2008



Rate of 100% ...
 Penicillin was applied at 2000 hours
 The normal ...
 Removal of ...

Penicillin graph, c.1940. From the Royal Society library and archive.

169 The methodology on producing these maps is the same as the global maps (see footnote [165]). The threshold for collaborations to be included is a minimum of 0.02% of collaborative output

from the region—at least 13 collaborative papers between two countries in 1996–2000, and 25 papers in 2004–2008. Analysis by Elsevier based on data from Scopus.

2.2 Regional collaboration

Collaboration is not driven solely by geographical proximity, although there are notable examples of regions which form important units for researchers coming together to share resources and expertise. They may be addressing issues borne out of similar environmental conditions, sharing hardware and physical resources or simply speaking the same language. These patterns have been underpinned by political support; the European Union (EU), African Union (AU), and the Association of South-east Asian Nations (ASEAN) each have research strategies, and can help to co-ordinate scientific efforts within their regions and broader spheres of influence.

Emerging regional ties reflect the growing influence of certain nations as they develop on the international science scene. Before 2000 South Africa was an influential centre for collaboration between African nations, but was one of many, with Senegal, Cameroon, Nigeria, Uganda and Morocco, also key focal points in intra-African research (see Figure 2.4). By 2008 the network had grown substantially, with more countries producing many more research papers, and South Africa had become more clearly the linchpin of the continent's collaborative efforts. Egypt and Sudan have emerged as bridges between north and Sub-Saharan Africa, neither having been drawn into the network in the earlier period.

The strengthening of these countries in the network coincided with increased overall domestic production (South Africa and Egypt both growing by 43% and Sudan by 89% between the periods 1999 to 2003 and 2004 to 2008), and, in the cases of South Africa and Egypt, substantial intensification of investment by government and business. In Egypt, overall investment in science jumped from US\$403 million in 1996 to \$911 million in 2007, and in South Africa investment more than doubled over the same period.¹⁷⁰ In Sudan, curiously, spending has declined

over this period; patterns of collaboration do not always necessarily follow the money.

Intra-regional collaboration is not, however, the dominant form of international co-operation. European collaborations have increased since the 1990s (in part as a result of EU funding initiatives), but the USA continues to be a major partner for most European countries. In South-east Asia, regional networks have strengthened over this decade but, as the Vietnam example shows (Figure 2.5), the connections with partners beyond the region are more plentiful.

2.2.1 South–South collaboration: a growing trend

Beyond regional collaboration, there is also increasing 'south–south' collaboration—links between developing countries to build capacity and share knowledge.¹⁷² India, Brazil and South Africa recently joined forces to promote South–South co-operation through the 'IBSA initiative'. Science and research are key components of this agreement and meetings have been held on issues such as nanotechnology, oceanography and Antarctic research.¹⁷³ With support from UNESCO and the Malaysian Government, the International Science, Technology and Innovation Centre for South–South Co-operation (ISTIC) was established in 2008. Based in Kuala Lumpur, ISTIC aims to be an international platform for countries of the G77 and the OIC to collaborate on science, technology and innovation, and is already facilitating discussions in areas such as water, energy, health and agriculture.¹⁷⁴

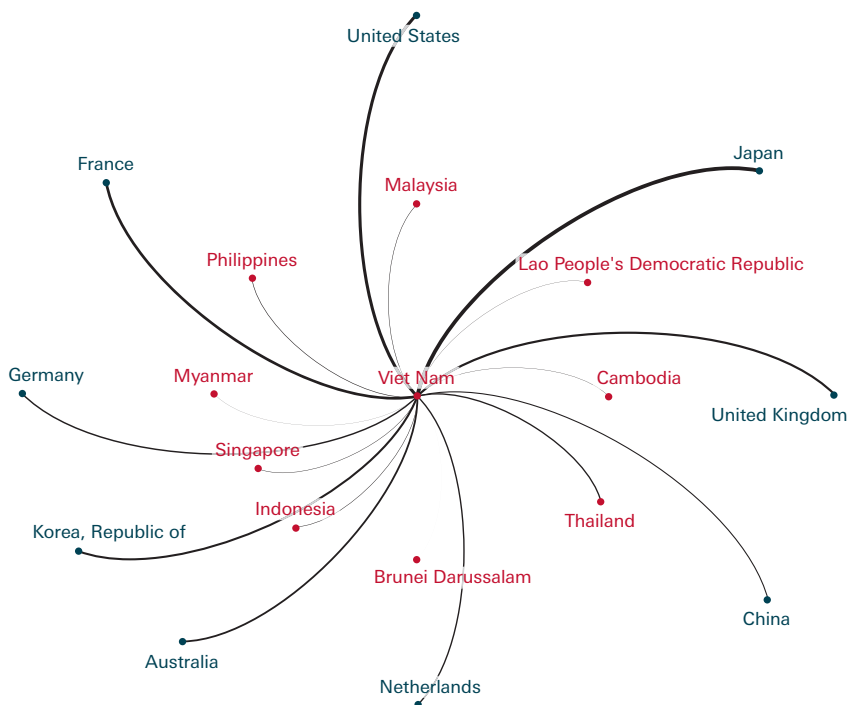
In some instances, multi-party North–South arrangements (where a developed country works with developing countries, providing funding or facilitation) have provided the basis for successful collaborations. One such example is the Brazil–UK–Southern Africa biofuels taskforce, which the Stern Review on the economics of climate change suggested would build

capacity to address agricultural and energy security in Southern Africa, and facilitate technology transfer between the partners.¹⁷⁵

Individual countries are increasingly taking a leading role in South–South partnerships. ‘Developing countries’ or the ‘global South’ are very heterogeneous groups, comprising countries of vastly differing economic, natural resource and human capital wealth. Within the group, there are different hierarchies and an emerging class of leaders—China, India, Brazil and South Africa among them. The China–Africa science and technology partnership programme (CASTEP) was launched in 2009, with the Chinese partners providing funding for African scientists to study in China, and for research equipment on their return home.¹⁷⁶

Collaboration between developing countries is, however, still minimal. A recent study revealed that, between 2004 and 2008, while 77% of African biomedical research papers are produced with international partners, just 5% were the result of collaborations with another African country.¹⁷⁷ Figure 2.7 shows that, while links between the BRIC countries (Brazil, Russia, India and China) have grown in recent years, they pale in comparison to the volume of collaboration between these individual countries and their partners in the G7 (each leading economies, and leading scientific nations). However, these partnerships are a trend to watch, as they may prove to be a significant factor in the dynamics of global science in the future.

Figure 2.5. Vietnamese collaborative papers as a proportion of total output (2004–2008).¹⁷¹



The inner circle shows the collaborations with other South-east Asian neighbours, and the outer with the countries where the proportion of collaboration is highest. The thickness of the line indicates the volume of output.

170 Data from the *UNESCO Institute for Statistics Data Centre*, Montréal, Canada. Figures in current US\$ and at PPP.

171 Analysis by Elsevier based on data from Scopus.

172 UN Millennium Project (2005). *Innovation: applying knowledge*.

in development. Task Force on Science, Technology, and Innovation. United Nations Development Programme: Geneva, Switzerland.

173 See <http://www.ibsa-trilateral.org/> and <http://www.forumibsa.org/interna.php?ln=en&id=45>, accessed 30 September 2010.

174 See <http://istic-unesco.org/programs.htm>, accessed 30 September 2010.

175 Stern N (2006). *The economics of climate change: the Stern review*. Cambridge University Press: Cambridge, UK.

176 See http://www.cistc.gov.cn/englishversion/News_Events/News_Events4.asp?column=114&id=72159, accessed 13 October 2010.

177 Nwaka S et al. (2010). *Developing ANDI: a novel approach to health product R&D in Africa*. *PLoS Medicine* 7, 6, June 2010.

Figure 2.6a. **Collaboration between Brazil, Russia, India and China 1996–2000.**

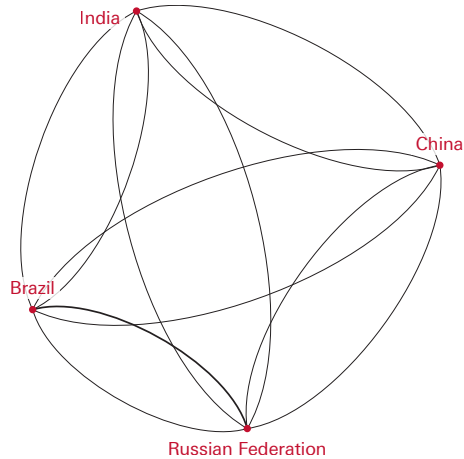


Figure 2.6b. **Collaboration between Brazil, Russia, India and China 2004–2008.**¹⁷⁸

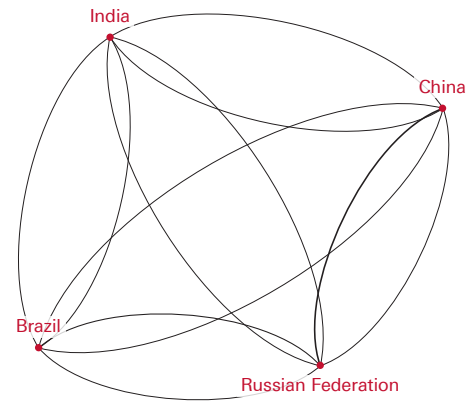


Figure 2.6c. **Collaboration between Brazil, Russia, India and China and the G7 1996–2000.**

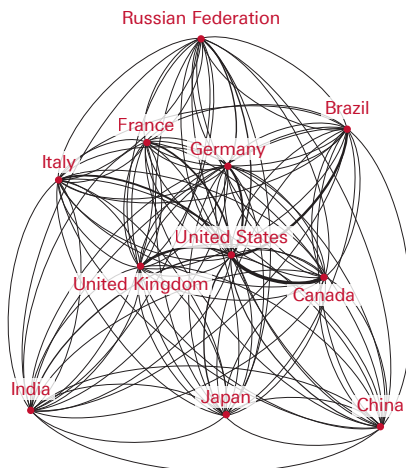
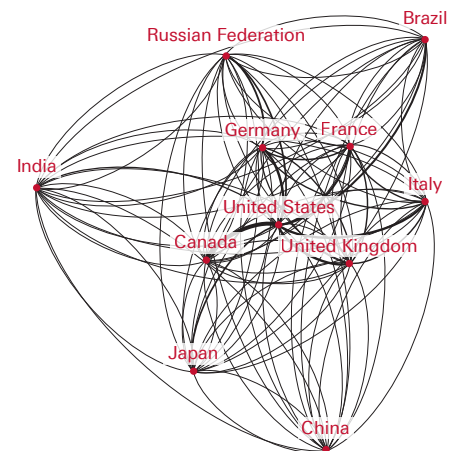


Figure 2.6d. **Collaboration between Brazil, Russia, India and China and the G7 2004–2008.**¹⁷⁹



2.3 Why collaborate?

There are various motivating factors that underpin global collaboration.¹⁸⁰ It is important to understand why researchers collaborate, what drives them, what enables that collaboration, and what the benefits of this joint working might be. By better understanding the dynamics of collaboration, we can better understand the dynamics of emerging global scientific networks and systems.

2.3.1 Seeking excellence

There are a number of reasons why collaboration is important in science. By working with partners, scientists can enhance the quality of their work, increase the effectiveness of their research, and overcome logistical obstacles by sharing costs, tasks and expertise.

Scientists seek to work with the most outstanding scientists in their field. According to one scientist at Imperial College, ‘if you are the best, geography doesn’t exist.’¹⁸¹ Most scientists look for partnerships with researchers in their field, or indeed other fields, in order to access complementary skills and knowledge, with a view to stimulating new ideas. These collaborations between individual scientists are mutually beneficial, and allow the partners to develop their expertise with resources that they would have otherwise lacked. Such partnerships can broaden the dissemination (and subsequent impact) of the work of

all partners involved. Scientists can also use personal ties to shape research agendas, or to gain access to other knowledge networks. Such advantages are likely to be particularly pronounced for scientists from less developed economies, where access to high-quality equipment and knowledge networks may be more limited.¹⁸²

Collaboration enables scientists to draw on wider stocks of knowledge or to apply learning in new geographical settings. For example, experienced botanists at the Royal Botanic Gardens, Kew, in the UK, have joined up with colleagues in the University of Addis Ababa to catalogue Ethiopia’s fauna and flora—sharing expertise and collaborating on this task. This enables the UK scientists to apply their cataloguing expertise which is no longer required to the same extent in the UK, as that task has been completed.

Collaboration brings with it the obvious benefit of scale. The International Space Station and the Large Hadron Collider are instances where the scale or scope of research is too great for a single nation, even if that nation is scientifically advanced.¹⁸³

Sharing the burden of research activity, breaking down complex tasks into manageable pieces, can be invaluable. The Human Genome Project is an obvious example. Another is the recently released First Census of Marine Life, which brought together 2,700 researchers from 670 laboratories

178 The methodology on producing these maps is the same as the global maps (see footnote [165]). No threshold for the number of collaborations was applied. Analysis by Elsevier based on data from Scopus.

of collaborations was applied. Analysis by Elsevier based on data from Scopus.

180 See Wagner C et al. (2002). [Linking effectively: learning lessons from successful collaboration in science and technology](#). Science and Technology Policy Institute, RAND Corporation: Arlington, VA, USA. This documented briefing, prepared for the White House

Office of Science and Technology Policy, offers a framework for considering why scientists collaborate, along with four case studies, each of which represents one of four types of collaboration.

181 Day N & Stilgoe J (2009). [Knowledge nomads: why science needs migration](#). Demos: London, UK.

182 Conway G & Waage J (2010). [Science and Innovation for development](#). UK Collaborative on Development Sciences: London, UK.

183 Leydesdorff L & Wagner C (2008). [International collaboration in science and the formation of a core group](#). Journal of Informetrics 2, 4, 317–325.

179 The methodology on producing these maps is the same as the global maps (see footnote [165]). No threshold for the number

in 80 countries to assess and explain the diversity, distribution and abundance of marine life.¹⁸⁴

Remote locations such as the Antarctic also tend to necessitate international collaboration, as do cross-country research where large datasets across regions are required.¹⁸⁵

There is also the push of external factors, not related to the science itself. In 2002 and 2003, Severe Acute Respiratory Syndrome (SARS), presented a very real and immediate epidemic threat. Over 8,000 people were infected, with over 770 deaths.¹⁸⁶ The World Health Organisation (WHO) was charged with unravelling the fundamental questions behind the cause, transmission, treatment and containment of this dangerous disease. Fortunately, the existing infrastructure proved up to the task. In 1996, the WHO had set up FluNet, a global tool for influenza virological surveillance, which brings together data from a number of national influenza laboratories in order to track epidemiological data on a global scale.¹⁸⁷ FluNet identified the new coronavirus agent of SARS, rather than influenza, as the cause of an outbreak of severe febrile respiratory illness in Hong Kong in 2003.¹⁸⁸ Within a very short period, clinicians, epidemiologists, microbiologists and many others had joined the international effort. This was a global public health emergency, for which large scale global commitment and collaborative research were essential, to ensure a rapid and effective response. The global challenges of the 21st century look to be drawing researchers together to combat broad issues, which require a collaborative approach.

Box 2.1. The language of research?

Although English is the 'lingua franca' of research, there still remain significant language barriers to global research. The Brazilian Academy of Sciences has difficulty in fully evaluating science in Latin America, because a significant amount of research output from the region is produced in Spanish and Portuguese (according to Latindex, there are 13,446 Spanish language journals and 5,297 Portuguese language journals produced in the 30 countries of Latin America),¹⁸⁹ and not captured in global metrics. A similar issue arises with Chinese language journals, and indeed most non-English publications. This also has an impact on collaboration; a representative of the Brazilian Academy explained that collaboration was 'blurred by the fact that the language spoken [in Brazil] is relatively difficult'.¹⁹⁰

Language barriers are not insurmountable. In Brazil, FAPESP is trying to overcome them by offering two-year fellowships to overseas scientists which include Portuguese lessons.¹⁹¹ There are initiatives in place to assist non-English speakers to improve their language skills so as to be able to publish in English language journals such as *SciEdit* and *AuthorAID*.¹⁹² English looks set to continue to be the dominant language for research, and the global research community are, by and large, prepared to adapt to this.

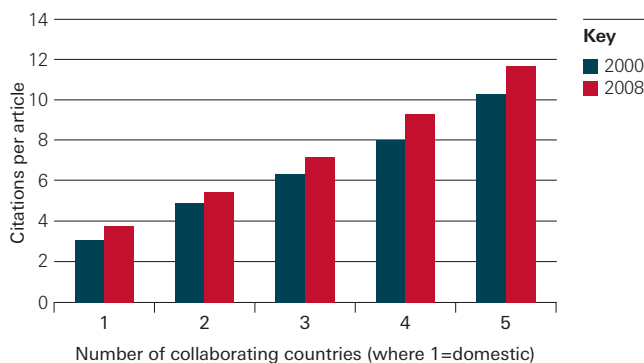
2.3.2 The benefits of joint authorship

In citation terms, research collaboration is beneficial. For each international author on an article, there is a corresponding increase in the impact of that paper (see Figure 2.7), up to a tipping point of around 10 authors, after which the relative impact of extra country authors is less clear (in part, due to the smaller numbers of articles which are produced with this quantity of countries involved).¹⁹³

The increase in citation rate has attracted attention. For example the UK Government annually commissions a report on the comparative performance of the UK research base, citing the strong impact gained from collaborations particularly with Switzerland, Denmark and Belgium, as well as Brazil, the USA, France and Germany.¹⁹⁴

Citation impact is not a direct measure of quality. A multi-authored piece may provide a 'network effect' in that it is seen by more people (perhaps as a result of having multiple international authors) and therefore becomes more cited. This does not necessarily mean it is of higher quality than one which is cited less. However, citation is a commonly used indicator for quality and how well 'used' a piece of research may be.

Figure 2.7. Citations per article versus number of collaborating countries.¹⁹⁵



Certain country 'pairings' deliver significant benefit to the partners involved as Figure 2.8 demonstrates. Using Elsevier data, this table reveals country collaborations which have resulted in a three-fold increase on the publication's impact compared to a standard domestic publication. This highlights some interesting examples of high-impact collaboration. Mexico, for example, achieved its strongest impact

184 First Census of Marine Life 2010. Highlights of a Decade of Discovery. October 2010.

185 National Research Council (2008). *International collaborations in behavioral and social sciences: research: report of a workshop*. Board on International Scientific Organizations, National Research Council. National Academies Press: Washington, DC, USA.

186 World Health Organisation (2003). *Summary of probable SARS cases with onset of illness from 1 November 2002 to 31 July 2003 (based on data as of the 31 December 2003)*. World Health Organisation website. Available

online at http://www.who.int/csr/sars/country/table2004_04_21/en/index.html, accessed 29 September 2010.

187 See <http://www.who.int/csr/disease/influenza/influenzanetwork/fluinet/en/>, accessed 13 December 2010.

188 Nelson K & Williams C (2007). *Infectious disease epidemiology: theory and practice* (2nd edn, p 595). Jones and Bartlett Publishers: Sudbury, MA, USA.

189 Latindex (the regional co-operative online information system for scholarly journals from Latin America, the Caribbean, Spain and

Portugal) offers a comprehensive bibliographic account of Ibero-American scholarly journals worldwide. See <http://www.latinindex.unam.mx/>, accessed 26 January 2011. See also Cetto A & Alonso-Gamboa J (2010). *Ibero-American Systems for the Dissemination of Scholarly Journals: A Contribution to Public Knowledge Worldwide*. Scholarly and Research Communication **1**, 1.

190 Evidence provided by the Brazilian Academy of Sciences in response to the Royal Society Global Science Report call for evidence, February 2010.

191 The Economist (2011). *Go south, young scientist*. The Economist, 6 January 2011.

192 See <http://www.sci-edit.com> and <http://www.authoraid.info>, accessed 29 September 2010.

193 Data from Elsevier's Scopus.

194 Evidence Ltd (2009). *International comparative performance of the UK research base*. Department for Business, Innovation and Skills: London, UK.

195 Analysis by Elsevier based on data from Scopus.

Figure 2.8. Those countries (country y) in 2008 which achieved a three-fold increase on their standard domestic publication impact, through collaboration with 'country x'. Minimum of 1,000 papers published by each country in 2008.¹⁹⁶

Impact accrued by... (country y)	By collaborating with... (country x)																						
	Australia	Austria	Belgium	Canada	China	Czech Republic	Finland	France	Germany	India	Israel	Italy	Japan	South Korea	Netherlands	Norway	Russia	Spain	Sweden	Switzerland	United Kingdom	United States	
Argentina																						3.2	
Australia																		3.2					
Brazil	4.5			3.1								3.7			3.9								
China			3.8					3.6	3.5	4		5			3.9		4.1	4.8	3.5	4.2	3.1	3.2	
Czech Republic															3.9						3.1	3.2	
India								3.8				3.7											
Japan																		3.3		3.1			
South Korea								3.8	3														
Mexico									3.1			3.4											
Poland		3.2	3.8	3.6								3.3			4.1			3.3	3	3.9	3.5	3.1	
Russia				4.7	3.4	3.4	3.4	3.2	3.1		4.8	3.7	3.6	4.5	4.4	3.6		4.2	4	4.2	4	3.6	
Slovakia																							3
Spain	3.5												3.2										
Taiwan									3.2														

factors when collaborating with Germany and Italy. When working with Russia, Chinese authors quadrupled the standard impact of their papers; Russian authors tripled the impact of their output when working with China. Russian publications also 'gain' significantly from being produced in collaboration with each of the country's G8 partners.

That the leading collaboration 'hubs' such as the

USA, UK, France and Germany have an impact on citation rates is perhaps not surprising, particularly given the size of the scientific communities and the citation rates generated within these countries. However, not unexpectedly in light of Figure 2.8, these countries each benefit from working together, and in turn with other partners. It is rare to find a collaborating country which is solely a 'donor' in

terms of impact—scientists and funders are likely to be motivated more by reciprocity than by altruism alone.

Other collaboration pairs bring a noticeable increase in citation impact. Australia's collaborations with Spain and China benefit from the strength of research in those countries in medicine (mostly clinical drug studies) and genetics/genomics respectively. Others, such as those between China and Russia or Spain and Japan, are underpinned by high-quality physics and astronomy in the partner countries.

2.3.3 Capacity building through collaboration

For scientists in developing countries, the need to collaborate can be acute. Collaborating with other nations enables access to facilities, funding, equipment and networks that are often limited in their own countries. The economic realities of many developing countries mean that equipment is often badly maintained or out of date. It is therefore common for a scientist from a developing country to perform fieldwork locally, but then carry out data analysis in labs overseas, due to the lack of up-to-date facilities. In return, partners from overseas often get access to unique geographical resources (like the fossils of the Afar region, or Malaysia's rainforest biodiversity) as well as being able to draw on local knowledge and understanding. Similarly, due to the disparity in information access, many scientists must work with international partners in order to access

the latest developments in their field.¹⁹⁷

Access to funding is an important factor. Many governments' science budgets barely cover salaries and institutional running costs, let alone providing research grants. For example, the Kenya Medical Research Institute (KEMRI) depended on international partners for two-thirds of its income in 2006–2007.¹⁹⁸ The Ifakara Health Institute in Tanzania expects to receive 3.72 billion shillings (US\$2.53 million) from international development partners in 2010–2011, compared with just over 150 million shillings from the country's government.¹⁹⁹ While there are some arguments that international funding deters domestic governments from making their own investments,²⁰⁰ international collaboration remains a highly effective tool through which to complement (rather than replace) the limited budgets available in poorer countries.

It is clear that science and research, and particularly collaboration in science, build capacity in all areas of the world. Strong domestic support for science and a flexibility which allows that science base to absorb experience and expertise from outside provide the basis on which to build the capacity to become both an intelligent customer and a responsible contributor on the global stage. This holds true regardless of a nation's stage of development. This is particularly clear, as we shall see in Part 3, when nations and individuals are drawn together to address global problems which have both local and global consequences.

196 Data from Elsevier's Scopus.

197 For a detailed discussion of capacity building and the role of developing countries in science, see Wagner C *et al.* (2001). [Science and technology collaboration](#).

[building capacity in developing countries?](#); C Wagner, E Horlings & A Dutta (2002). *Can science and technology capacity be measured?* Rand Corporation: Santa Monica, CA, USA.

198 Nordling L (2010). [African nations vow to support science](#). Nature **465**, 994–995.

199 Nordling L (2010). [African nations vow to support science](#). Nature **465**, 994–995.

200 IAC (2004). *InterAcademy Council realizing the promise and potential of African agriculture*. InterAcademy Council. Amsterdam, The Netherlands.

2.3.4 The geopolitical potential of scientific collaboration

When considering the motivations and benefits of international collaboration, the political and diplomatic dimensions also warrant reflection.²⁰¹ As Part 3 will explore in greater detail, many of the major global challenges of the 21st century have scientific dimensions. The tools, techniques and tactics of foreign policy need to adapt to a world of increasing scientific and technical complexity. Over the past 18 months, the Royal Society has continued to grapple with the potential of science diplomacy.²⁰²

Throughout the Cold War, scientific organisations were an important conduit for informal discussion of nuclear issues between the USA and the Soviet Union. The Royal Society itself became an important facilitator of scientific collaboration, and was party to numerous agreements with many of the newly established academies within the Soviet Union in the late 1950s and 1960s. Such agreements proved extremely important for eastern European academies and scientists as they provided the legal framework to enable collaboration to take place, despite sensitivities and often paranoia at government levels.²⁰³

Today, science continues to offer alternative channels of engagement with countries where relations may be strained at political levels. In President Obama's landmark speech to the Islamic world at Cairo's Al-Azhar University in June 2009, he identified science as a tool with which to strengthen relationships, and he stressed the importance of educational exchanges, scholarships and investments in research collaboration.

Despite political tensions between the USA and Iran, scientific collaboration has proven surprisingly resilient. Between the periods 1996 to 2002 to 2004 to 2008, co-authored papers between these two countries increased from just 388 papers to 1,831

papers, an increase of 472%.²⁰⁴ Following the Iranian elections in June 2009, Iranian scientists called out to the international research community to 'do everything possible to promote continued contact with colleagues in Iran, if only to promote détente between Iran and the West when relations are contentious.'²⁰⁵

Such pleas reflect the potential of international collaboration to help repair fractious relations, or at least to maintain channels of communication. A distinct benefit of scientific collaboration is that it can act as a bridge to communities where political ties are weaker.

One example of this bridge-building is the Synchrotron-light for Experimental Science and Applications in the Middle East (SESAME) under construction in Jordan. Modelled on CERN in Europe, SESAME is a partnership between Bahrain, Cyprus, Egypt, Israel, Iran, Jordan, Pakistan, the Palestinian Authority and Turkey. Synchrotrons are large and relatively expensive facilities, so pooling regional resources is the obvious way to construct SESAME, which has the potential not only to build scientific capacity in the region but also to foster collaboration.

2.4 Underlying networks

It has been suggested that today's scientific world is characterised by self-organising networks, bringing together scientists who collaborate not because they are told to but because they want to.²⁰⁶ These networks, motivated by the bottom-up exchange of scientific insight, knowledge and skills, span the globe, and are changing the focus of science from the national to the global level. Policy makers have not always recognised the importance of these linkages to quality and to the direction of science, tending to emphasise research investment to the detriment of developing policies that support and foster such networks. Knowledge is being developed

Different species of *Hexastylus*, magnified up to 400x, from *Report on the scientific results of the voyage of H.M.S. Challenger*, by Sir C. Wyville Thomson, 1880. From the Royal Society library and archive.



in more places around the world; redundant capabilities may not always be the most efficient use of resources.

The connections of people, through formal and informal channels, diaspora communities, virtual global networks and professional communities of shared interests are important drivers of international collaboration. Yet little is understood about the movements and networks of scientists and what they mean for global science.

2.4.1 Tapping into the global networks of science

Within the global networks of science, many good scientists move about physically and virtually, looking for new ideas, complementarities, and new connections (as discussed in Section 1.1.4) which will enhance the efficiency of their work. Where they travel to or where their networks are strongest is often determined by where they can find the best minds, the best equipment and the best science. Scientists can be ruthlessly meritocratic—wanting to work with the best people and facilities in their fields, wherever they may be.

Scientists should be enabled to build these global networks. While there are some prestigious schemes and scholarships to encourage scientific exchange, the number of awards is small and competition is fierce. Examples include the

Humboldt Research Fellowship for postdoctoral researchers, which is awarded to approximately 600 researchers annually to study for between six and 24 months in Germany,²⁰⁷ and Marie Curie Fellowships which provide European placements for pre- and post-doctoral researchers in any scientific discipline that contributes to the objectives of the European Commission's Framework Programme.²⁰⁸ Over 15,000 researchers have received Marie Curie Fellowships since they were introduced in 1990,²⁰⁹ which equates to approximately 750 per year. Another 750 fellowships and scholarships are awarded to individuals of member countries through the Commonwealth Scholarship Commission in the UK. The UK Academies run Newton International Fellowships which bring early-career researchers across the sciences, engineering, humanities and social sciences to the UK each year, building links between the UK and the future global leaders of science.

These schemes are important in facilitating collaboration, particularly at the earlier stages of researchers' careers, but more could be done. Only a tiny fraction of the global budget for scientific research is directed towards international mobility. The challenge for policy makers is how to ensure that the fluid networks of science are able to flourish and grow, and then how to tap the knowledge emerging from them.

201 For a discussion of the relationship between geopolitical factors and scientific activity, based on publication data from a 30 year period (1980 to 2009), see Archambault E (2010). [30 years in science: secular movements in knowledge creation](#). Science-Metrix: Montréal, Canada.

202 Royal Society (2010). [New frontiers in science diplomacy: navigating the changing balance of power](#). Royal Society: London, UK.

203 Cox S (2010). [The Royal Society in cold war Europe](#). Notes and Records of the Royal Society. Published online 14 July 2010.

204 Data from Elsevier's Scopus.

205 Nature (2009). [We are all Iranians](#). Nature **460**, 11–12; [An appeal to President Ahmadinejad](#). Nature **457**, 511; Butler D (2007) [Academic freedom under threat in Iran](#). Nature **447**, 890–891.

206 Wagner C (2008). [The new invisible college: science for development](#). Brookings Institution: Washington, DC, USA.

207 Source: Alexander von Humboldt Foundation website. See <http://www.humboldt-foundation.de/web/humboldt-fellowship-postdoc.html>, accessed 30 September 2010.

208 See <http://cordis.europa.eu/improving/fellowships/home.htm>, accessed 11 January 2011.

209 Source: Euroalert.net (2010). [Record number of applications for Marie Curie research grants](#). Euroalert.net, 13 September 2010. Available online at <http://euroalert.net/en/news.aspx?idn=10490>. Euroalert.net is a website providing news and information from the EU.

PART 2

International collaboration

Box 2.2. Access denied?

After the 9/11 attacks, US scientists complained that the country became a 'closed shop' to the international research community, with students being deterred from travelling to the USA to study.²¹⁰ The situation in the USA has now improved dramatically, but researchers still experience difficulties. In 2007 Microsoft opened a software centre in Vancouver, citing explicitly the more 'welcoming' immigration regulations in Canada in comparison to the States.²¹¹

In the UK, universities and businesses have joined forces to campaign against immigration caps imposed in 2010 which have meant that non-EU overseas scientists are finding it increasingly difficult to visit the UK.²¹² The UK's Nobel laureates agree. In October 2010, eight of the 11 laureates based in the UK signed a letter warning of the impact of immigration caps on British science. 'The government has seen fit to introduce an exception to the rules for Premiership footballers,' they said. 'It is a sad reflection of our priorities as a nation if we cannot afford the same recognition for elite scientists and engineers.'²¹³ While some concessions have been made, there remain concerns about the impact of the proposed changes on the UK's ability to compete in the global market for scientific talent.

2.5 Enabling collaboration to promote excellent science

As the cumulative number of researchers grows, so too does the number of potential collaborators. The well documented rise of China, India and Brazil, the new found ambition in science in the Middle East and the Islamic world²¹⁴ and in other places are all providing new opportunities for the production of science, for international collaboration and for efficient sharing of resources.

Whether underpinned by historical connections, by expanding networks, by global problems or other motives, it is clear that the factors which *enable* international collaboration have also undergone significant changes in recent decades.

2.5.1 Technology

Research collaboration is usually a very personal activity, with scientists meeting face to face and working together on areas of mutual curiosity. However, one of the most obvious enablers has been rapid technological advances. Whether through email, the internet, data-sharing tools or mobile phones, technology has made it easier to collaborate with colleagues beyond one's own country. As one Fellow of the Royal Society explained, 'I can co-author papers with others in widely dispersed parts of the world at the push of a button.'²¹⁵

The internet is a big factor. It has changed almost every aspect of modern life, contributing hugely to globalisation. Quantifying its specific effect on science is almost impossible, but a wealth of anecdotal evidence supports its role in making collaboration easier. Indeed, the development of the World Wide Web technology at CERN was motivated by the need to facilitate international collaboration at its Large Electron-Positron Collider (LEP).²¹⁶



Observations on duckweed. Antoni Van Leeuwenhoek to The Royal Society, 25 December 1702. From the Royal Society library and archive.

The countries showing the fastest rate of growth in publication output and those rising up the global league tables as collaborative hubs show strong trends of growth in mobile phone usage and in internet penetration. Internet growth in Iran, for example, has grown 13,000% since the turn of the century (albeit from a starting point of only 250,000 users). Internet use in China has grown over 1,800% in the same period (from 22.5 million users to 420 million) and in Tunisia, penetration has grown 3,600% (from 100,000 users to 3.6 million).²¹⁷

Email provides a free, near instant method for communicating with multiple individuals around the world. This allows for rapid and effective sharing of information, and a forum for posing questions and ideas. Free telephone calls over the internet (VOIP) and video conferencing offer augmented communication possibilities, providing another medium for effective communication. Applications such as Skype have made this kind of face-to-face remote communication both accessible and affordable.

The possibilities heralded by the internet continue to evolve. Scientific conferences often now include a Twitter hashtag: in this way anyone can follow the discussion and share their ideas, whether they are sitting in the plenary session or on the other

side of the globe. The rise of cloud computing is also presenting some exciting opportunities for collaboration: different people, using different devices, can access the same documents and resources more easily and cheaply.²¹⁸

While allowing for instant communication, these developments have also provided the means by which a potential barrier has turned out also to yield a benefit. Whereas researchers previously were solely reliant on making telephone calls to collaborators at a suitable hour in both time zones, now one partner can send data and drafts from Delhi at the end of the working day, only for their colleague in Sao Paolo to continue working on the same piece of work at the start of their day, and then send it on to Vancouver for the day's work to carry on. Global collaboration, with the assistance of immediately accessible technology, need never sleep.

In addition, the rise of the social web and, in particular, social networks has the potential to dramatically change the way scientists collaborate. Could an aspiring PhD student find a supervisor through Facebook or Twitter? Will it become as normal to 'meet' online as at a conference? Although about 90% of all collaborations begin face-to-face,²¹⁹ these advances in communication reduce the dependency on physical place but do not (yet) render

210 US National Academy of Sciences, National Academy of Engineering and Institute of Medicine (2005). *Rising above the gathering storm: energizing and employing America for a brighter economic future*. National Academies Press: Washington, DC, USA.

211 Day N & Stilgoe J (2009). *Knowledge nomads: why science needs migration*. Demos: London, UK.

212 CaSE (2010). *Official estimates show migrant loss—immigration cap threatens brain drain*. Press

release, 29 June 2010. Campaign for Science and Engineering in the UK: London, UK.

213 *Letter to the Times from eight Nobel laureates*: Sir Paul Nurse FRS, Sir Martin Evans FRS, Professor Andre Geim FRS, Sir Tim Hunt FRS, Sir Harry Kroto FRS, Dr Konstantin Novoselov, Sir John Sulston FRS, Sir John Walker FRS. The Times, 7 October 2010.

214 Royal Society (2010). *A new golden age? The prospects for science and innovation in the Islamic world*. Royal Society: London, UK.

215 Evidence provided by Professor Jenny Clack FRS in response to the Royal Society Global Science Report call for evidence, February 2010.

216 Gillies J & Cailliau R (2000). *How the web was born: the story of the world wide web*. Oxford University Press: Oxford, UK.

217 Source: Internet World Stats website. See <http://www.internetworldstats.com>, accessed 29 September 2010. This website draws on data from Nielsen Online, The International

Telecommunications Union, Worldwideworx.com and the Computer Industry Almanac Inc.

218 Leadbeater C (2010). *Cloud culture—the future of global cultural relations*. Counterpoint, the think tank of the British Council: London, UK.

219 Wagner C (2008). *The new invisible college: science for development*. Brookings Institution: Washington, DC, USA.

Box 2.3. The European framework

The European Commissioner for Research, Innovation and Science, Máire Geoghegan-Quinn, has asserted that there is 'no more efficient investment in the future than research and innovation.'²²⁰ The European Commission's Framework Programme (FP) is the main tool through which Europe collectively delivers this investment.²²¹ Between 2007 and 2013 FP7 will spend €53.2 billion on a range of schemes and sub-programmes aimed at increasing the competitiveness of the EU, and encouraging collaboration and co-operation between European Member States. FP funding is equal to approximately 5% of the funding available for European research through national budgets.

The FPs have been running since 1984 and, over this period, intra-European collaboration has grown substantially (see Figure 2.9). Among the 27 countries of the EU, collaboration grew from 32% of total publication output in 1996, to 46% in 2008, outstripping the increase witnessed at a global level. In the five years to 2000, France and Germany co-authored 12,516 articles. In the five years to 2008 this had grown to 23,291—an increase of nearly 100%. It is clear that the increase in funding from the Commission's programmes has contributed to this level of growth. €32 million of current funding requires that scientists collaborate internationally.²²²

FP7 draws together a number of initiatives, from large-scale infrastructure projects (eg. some projects funded by EURATOM), to mobility funding

for individual researchers (Marie Curie) to 'frontier' research projects (the European Research Council).

The European funding mechanisms have had their critics. Some fear that the widespread requirement for collaboration has led to unbalanced and incompatible partnerships, or that excellence has been the price of increasing participation. The combined objectives of building capacity in some areas of the Union, increasing the competitiveness of all countries and Europe as a whole, and pursuing research excellence, do not always sit well together. The FP is also often labelled as being overly bureaucratic—the priority for each appraisal being 'simplification'.²²³

Yet despite these concerns, the FP is seen as a potential model for regional collaborations in Africa and elsewhere. Under its auspices, the Commission is forging scientific links with other regional groupings, such as South-East Asia and Latin America, through high-level interregional dialogues and specific networks, SEA-EU NET and EULARINET.²²⁴

The Framework Programmes have become an essential part of the European research funding landscape. As the Commission and Member States prepare to identify the future shape of this research support beyond 2013 in FP8, science and innovation has also been put at the centre of the Commission's vision for the future of Europe.²²⁵ The interplay between science and European policy more broadly looks set to be an important dynamic for the future of both European research and European politics, and engagement with the wider world in both fields.²²⁶

face-to-face communication unnecessary. Some question whether they ever will. Yet actual travel has become easier and cheaper too, with the explosion in commercial air travel and the rise of low-cost carriers.

As dramatic a change as the internet has brought, it is still not ubiquitous. In 2006 fewer than 5% of Africans used the web compared with more than 50% in the G8 countries. Even within 'richer' regions such as Europe there are huge disparities. In 2007 only one-fifth of Bulgarians and Romanians were connected to the web, compared with more than 75% in the Nordic countries. Access to the net is growing fast in some middle-income developing countries, such as South Korea (where access is almost universal) and Brazil.²²⁷ But it is rising only very slowly in low-income countries: 0.06% of the population in low-income countries had access to the web in 1997, rising to 6% 10 years later.²²⁸

In each of these areas, however, the scientists are one community who are most likely to have good access. More troublesome for researchers is internet bandwidth which may be limited, or infrastructure issues which may hinder the ability to communicate effectively. For example, power

cuts are frequent in many universities across Africa and the internet connection speed is low. Scientists at these universities are philosophical about such challenges—doing other things like marking when the computers are off.

2.5.2 Funding mechanisms

International research collaboration is inexpensive, yet despite the arrival of low-cost airlines and developments in communications technologies, it is still not cheap. Being able to travel around the world to work with colleagues or to host overseas scientists costs a significant amount of money. These simple logistical costs can make or break research projects.

International engagement has increasingly become a priority for research funders. In 2008, Germany's cabinet adopted the 'Strategy for Internationalisation of Science and Research', which specifically aims to promote an internationally co-ordinated research agenda and boost collaborative research with developing countries.²²⁹ The Chinese Ministry of Science and Technology has now signed science and technology co-operation agreements with more than 100 countries.²³⁰ National bodies are also increasingly

Continued on page 70

220 Geoghegan-Quinn M (2010). [Speech by European Commissioner for Research, Maire Geoghegan-Quinn, on the Seventh Framework programme calls for proposals](#), 19 July 2010.

221 The European Commission's Framework Programme is also the world's largest research funding programme. See Parliamentary Office of Science and Technology (2010). [EU Science & Technology Funding](#). Postnote 359, June 2010. Parliamentary Office of Science and Technology: London, UK.

222 Source: [EUBOPA \(European Commission website\)](#). See <http://ec.europa.eu/research/era/instruments/instruments/seventh>

[framework_programme_en.htm](#), accessed 30 September 2010.

223 European Commission (2010). [Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: simplifying the implementation of the Research Framework programmes](#). European Commission: Brussels, Belgium.

224 SEA-EU NET is the South-east Asia–European Union Network, and EU-LARINET is the European Union–Latin America Research and Innovation Network.

225 European Commission (2010). [Europe 2020: a European strategy](#)

[for smart, sustainable and inclusive growth](#). European Commission: Brussels, Belgium.

226 EASAC (2009) [Memorandum for incoming MEPs and Commissioners](#). European Academies Science Advisory Council: London, UK.

227 According to the World Bank, South Korea had the 54th highest gross national income *per capita* in 2009 (calculated using the Atlas method and PPP), while Brazil had the 84th. See <http://siteresources.worldbank.org/DATASTATISTICS/Resources/GNIPC.pdf>, accessed 14 December 2010.

228 Leadbeater C (2010). [Cloud culture—the future of global cultural](#)

[relations](#). Counterpoint, the think tank of the British Council: London, UK.

229 Federal Ministry of Education and Research, Germany (2008). [Strengthening Germany's role in the global knowledge society: strategy of the Federal Government for the Internationalization of Science and Research](#). Bundesministerium für Bildung und Forschung (BMBF): Bonn, Germany.

230 Technopolis Group (2008). [Drivers of international collaboration in research. Background report 4: conference report Brussels 13–14 October 2008](#). Technopolis Group: Amsterdam, The Netherlands.

Figure 2.9a. **Collaboration between EU27 countries 1996–2000.**²³¹

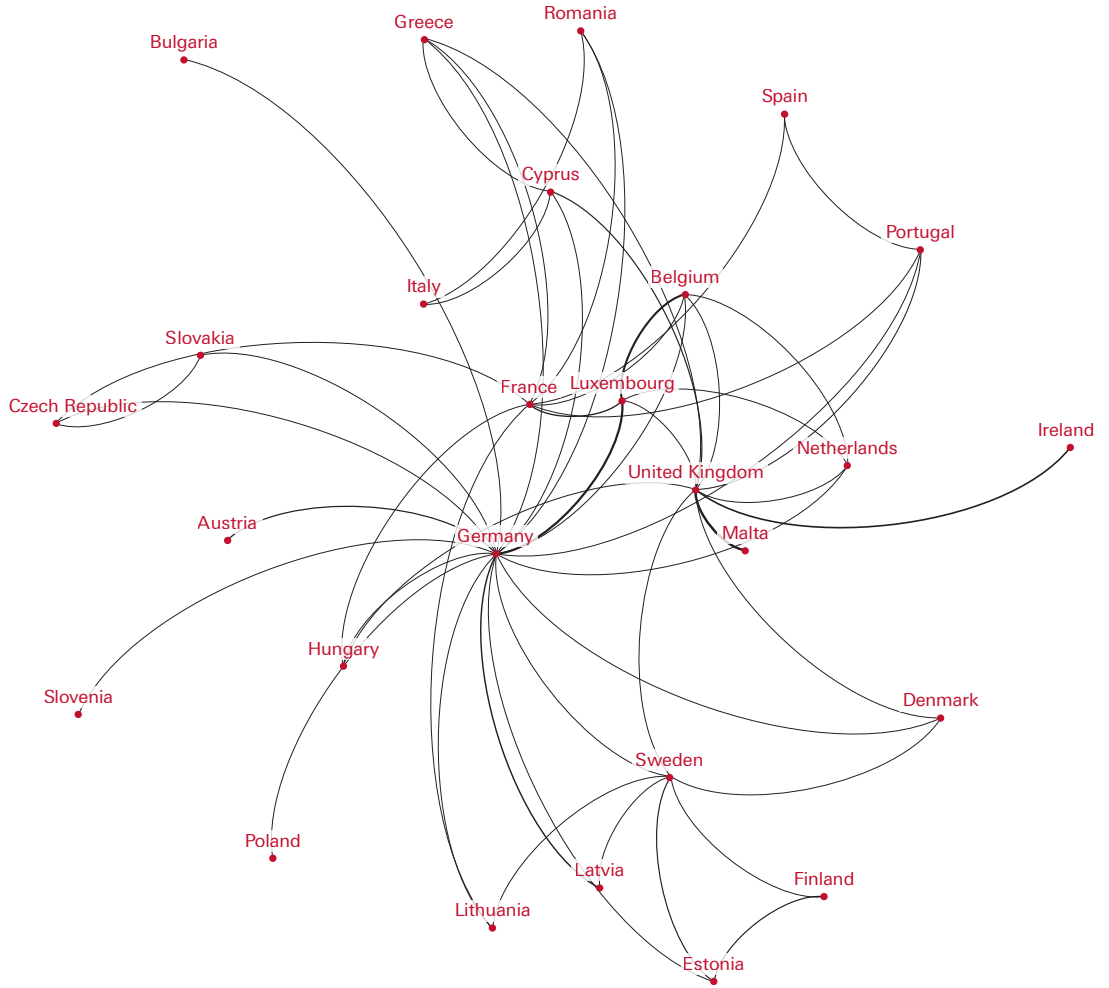
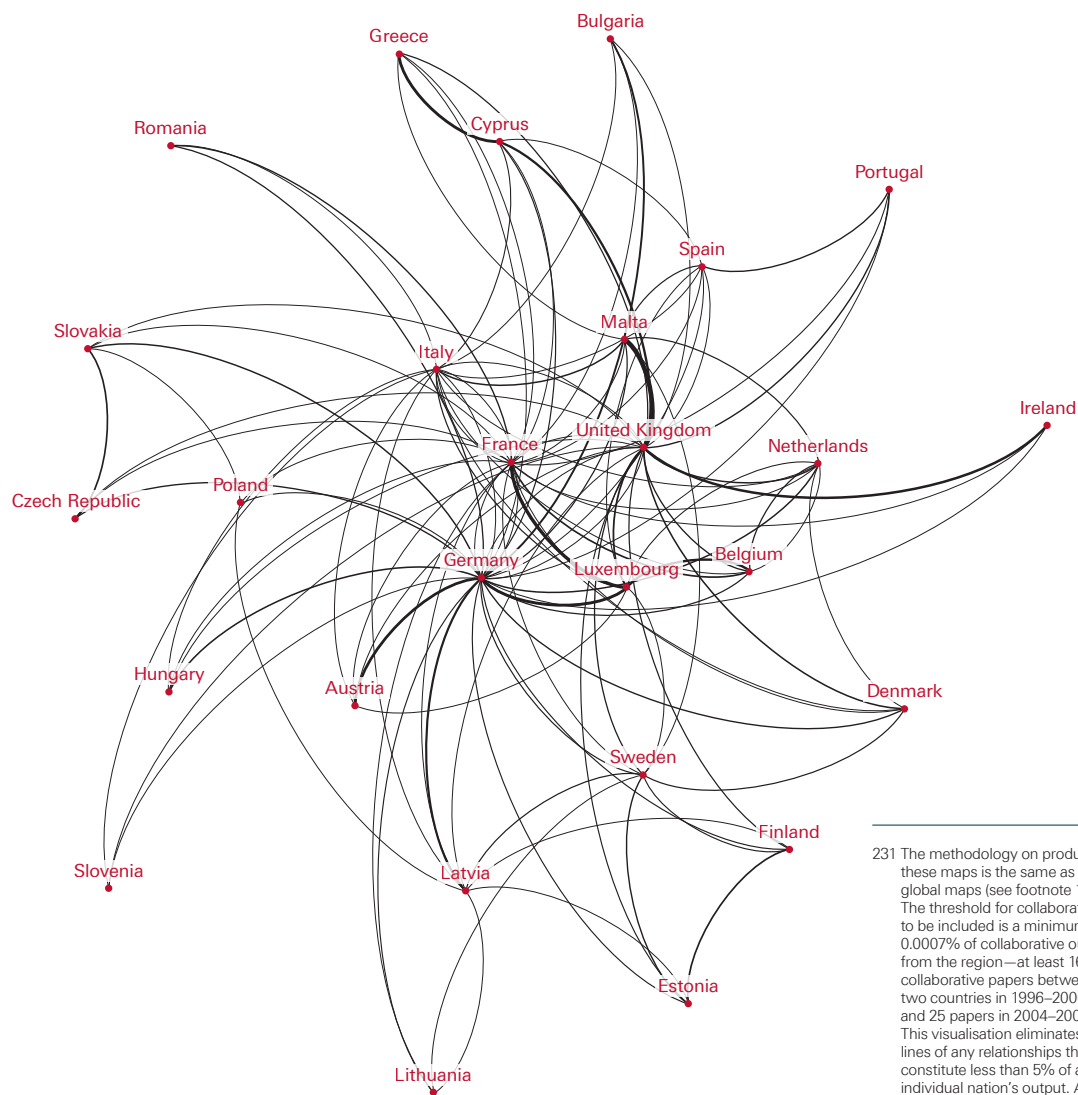


Figure 2.9b. **Collaboration between EU27 countries 2004–2008.**



231 The methodology on producing these maps is the same as the global maps (see footnote 168). The threshold for collaborations to be included is a minimum of 0.0007% of collaborative output from the region—at least 16 collaborative papers between two countries in 1996–2000, and 25 papers in 2004–2008. This visualisation eliminates the lines of any relationships that constitute less than 5% of an individual nation's output. Analysis by Elsevier based on data from Scopus.

working together. In 2010 the Research Councils of the G8 countries announced their first joint call for proposals for multilateral research projects in their participating countries.²³² The Joint Programming Initiative among the member states of the EU is intended to pool national funding related to specific calls for research activity, with a view to reducing fragmentation in European research; the pilot relates to research into neurodegenerative diseases, and further initiatives are forthcoming in the areas of health, food security and agriculture.²³³

Recent years have also seen the emergence of new regional and global funders, whether they be pan-continental bodies such as the European Framework Programme, specifically the European Research Council,²³⁴ or philanthropic organisations such as the Leverhulme Trust and Sloan Foundation, among many others.

These funding initiatives are all welcomed by scientists keen to collaborate internationally, but implementation is not always straightforward. Funders are becoming better at delivering flexible conditions for international collaboration, and are actively trying to dismantle barriers to cross-border funding (the role of the UK Research Councils overseas offices in dealing with the problem of double jeopardy in joint agency funding applications has been successful to date).²³⁵ But there is more work to be done in this area to ensure that the funders of research are meeting the requirements of an increasingly mobile research community.

2.6 Harnessing collaboration

We have described significant changes in the global scientific landscape, underpinned by an increase in international collaboration, driven by individual researchers seeking to work with the best scientists in the world, and by governments seeking to improve the quality, scope and critical mass of national science bases. This co-operation helps leverage new and existing knowledge and resources, attract incoming talent, tackle intrinsic research questions and build research capabilities. It has led to an increasing number of players emerging in the international scientific arena at the individual, regional, national and global levels, creating and disseminating knowledge around the world in ever more complex and interconnected networks.

Increasingly, a significant driver behind international scientific collaboration is the urgency of the problems facing human society in the 21st century, and the recognition that science has a role to play in their solution. These 'global challenges', such as climate change, biodiversity, food, energy and water security, and global health dominate the contemporary scientific agenda. In Part 3, we investigate how global science systems and scientists are responding to these societal challenges, how they have done so in the past, and we discuss how they can address the unidentified challenges of the future.

232 Research in Germany (2010). [Multilateral research funding](#). Research in Germany, 7, April/May. Available online at <http://www.research-in-germany.de/media-service/newsletter/>

[nl-ausgabe-7/44440/multilateral-research-funding.html](#).

233 See http://ec.europa.eu/research/era/areas/programming/joint_programming_en.htm, accessed 13 December 2010.

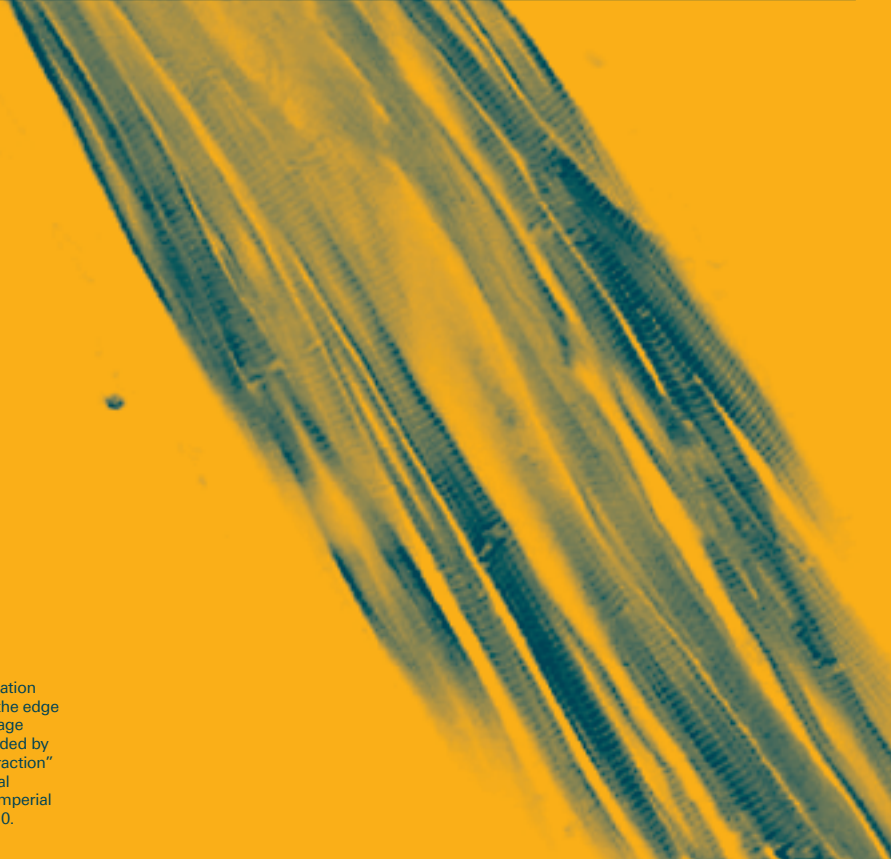
234 See <http://erc.europa.eu>, accessed 30 September 2010.

235 Double jeopardy refers to the difficulty in applying to multiple agencies for 'joint' funding of a research project—applications may

be accepted by one funder but not by the other, and the research project therefore is not viable.

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A microscopic image showing failing cardiac cells on the edge of a region that suffered degenerative damage following infarction. The image displays a dense, textured structure of blue and yellow fibers, likely representing the cellular structure of the heart tissue.

The image, acquired with two-photon excitation microscopy, shows failing cardiac cells on the edge of a region that suffered degenerative damage following infarction (rat cardiac tissue provided by Dr A. Lyon) from "Lighting up muscle contraction" by Dr Valentina Caorsi, Newton International Fellow, National Heart and Lung Institute, Imperial College London. © Dr Valentina Caorsi, 2010.

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At a meeting at the Royal Society in January 2010, members of the InterAcademy Panel on International Issues—the network of the world’s science academies—identified climate change, global health, food security, biodiversity, water security, population and energy security as humanity’s most pressing concerns.²³⁶ These are frequently referred to as ‘global challenges’ or ‘grand challenges’—those which transcend national boundaries and pose significant threats to societies and ecosystems. Science is critical to finding solutions to such challenges, although there are many other economic, social and political factors at play.²³⁷

Global challenge science looks set to increase in terms of importance, scale and impact. It requires international co-operation on a large scale because of the nature and magnitude of the potential consequences of these problems. No one country or scientific discipline will be able to offer complete solutions. This presents challenges of its own in the organisation and governance of the science, and as such requires special consideration. Policy makers around the world recognise this. US President Barack Obama has pledged ‘to harness science and technology to address the grand challenges of the 21st century’.²³⁸ The EU’s renewed research agenda places grand challenges at its core.²³⁹ In May 2010, Canada launched a ‘Grand Challenges’ fund, backed up by 225 million Canadian dollars (US\$220 million), which helps scientists from the developing world to solve health problems facing their regions.²⁴⁰ Such initiatives build on more established frameworks such as the 1992 Rio Earth Summit,²⁴¹ which defined a framework for sustainable development, and the UN’s Millennium Development Goals, which pioneered measurable objectives and targets to guide poverty eradication across the world.²⁴²

Science can help measure and predict impacts, identify solutions, evaluate pathways for adaptation and assess risks for mitigation. In recent decades, science-based innovations have eradicated or attempted to eradicate life-threatening diseases, increased agricultural productivity and pioneered low-carbon technologies.²⁴³ The challenge for governments, scientists, NGOs and others is how best to orchestrate research efforts to address such issues collectively, while combining scientific with wider social, political and economic perspectives.

In order to discuss how science can address these problems, we begin by highlighting two examples of successful global responses to global challenges: tackling the depletion of the ozone layer, and the eradication of smallpox. We then briefly survey a range of bodies that have global responsibilities and could play a crucial role in bringing scientists to bear on global problems. Some examples are then outlined of collaborative research initiatives which have been established in response to such problems. Following a brief discussion of some of the issues surrounding the governance of global challenge research initiatives, and their wider implications in terms of capacity and infrastructure, we then look at five more detailed case studies of global responses to global problems, in order to identify how the problems were brought to the attention of those in a position to take action and initiate a response, and to consider whether additional mechanisms are needed. We conclude by examining the pros and cons of the way these initiatives were organised, and discuss the lessons for the future.

3.1 Scientific solutions

On 16 September 1987, scientists, diplomats, governments, NGOs and industry representatives from 24 countries came together in Montreal to tackle one of the most pressing global environmental challenges of recent times: the depletion of the ozone layer. The link between ozone depletion and chlorofluorocarbons (CFCs) was first discovered in the 1970s by Professor Sherwood Rowland ForMemRS and Professor Mario Molina, building on earlier work by Richard Stolarki and Ralph Cicerone, now President of the US National Academy of Sciences, who had been examining the effects of chemical emissions from NASA rockets. Perhaps partly because of the link with NASA, and the greater awareness it engendered of the upper echelons of the atmosphere, the ozone depletion theory became an area of major public concern in the USA, which was reflected in the media and then taken up by members of Congress.²⁴⁴ This led to the USA banning CFCs as propellants for non-essential

aerosol sprays in 1978, and eventually to the 1985 Vienna Convention, which established a framework for the international regulation of ozone-depleting substances (a precursor to the Montreal Protocol).²⁴⁵

In the absence of the Montreal Protocol, scientific modelling has projected a world in which nearly two-thirds of the earth's ozone layer would be gone by 2065, with UV radiation up by 650% and catastrophic consequences for life on Earth.²⁴⁶ Instead, the hole in the ozone layer appears to have stopped widening in recent decades.²⁴⁷

Professor Bob Watson, whose work greatly influenced the Protocol and who was awarded the Blue Planet prize partly for his achievements, argues that the research effort was underpinned by a number of principles. 'It had to be international, transparent, open, credible and peer reviewed', he argues. 'In the end the policy options were straightforward. In order to get rid of the Antarctic ozone hole, we showed that there was a clear need to stop the industrial use of chlorine and bromine

236 Highfield R & Lawton G (2010). *Global challenges: what the world's scientists say*. New Scientist, 14 April 2010.

237 UN Millennium Development Task Force on Science, Technology, and Innovation (2005). *Innovation: applying knowledge in development*. New York: United Nations 2005. Available online at http://www.unmillenniumproject.org/reports/tf_science.htm.

238 Executive Office of the President, National Economic Council, Office of Science and Technology Policy (2009). *A strategy for American innovation: driving towards sustainable growth and quality jobs*. Executive Office of the President of the United States: Washington, DC, USA.

239 *The Lund Declaration (2009)*. On 8 July 2009, 350 researchers, research funders, business people

and politicians gathered at the 'New world—new solutions' conference in Lund to discuss the future development of European research. They agreed on a document—the Lund Declaration—which states that 'European research must focus on the Grand Challenges of our time'.

240 Campbell C (2010). *Canada launches 'unique' Grand Challenges fund*. SciDev.Net, 12 May 2010. Available online at <http://www.scidev.net/en/news/canada-launches-unique-grand-challenges-fund.html>.

241 UN (1992). *Report of the United Nations Conference on Environment and Development. Annex I: Rio Declaration on Environment and Development*. United Nations General Assembly: New York, NY, USA.

242 The eight Millennium Development Goals (MDGs)—which range from halving extreme poverty to halting the spread of HIV/AIDS and providing universal primary education, all by the target date of 2015—stem from the Millennium Declaration agreed to by 189 world leaders in September 2000. See <http://www.undp.org/publications/fast-facts/FF-mdg.pdf>, accessed 30 September 2010.

243 Dowdle W (1998). *The principles of disease elimination and eradication*. Bulletin of the World Health Organisation **76** (Suppl 2), 22–25; Royal Society (2009). *Reaping the benefits: science and the sustainable intensification of global agriculture*. Royal Society: London, UK; Omer A (2008). *Focus on low carbon technologies: the positive solution*. Renewable and Sustainable Energy Reviews **12**, 9, 2331–2357.

244 Benedick R (2007). *Science, diplomacy, and the Montreal Protocol*. In: *Encyclopedia of Earth*. Cleveland C (ed). Environmental Information Coalition, National Council for Science and the Environment: Washington, DC, USA.

245 European Commission (2007). *The Montreal Protocol*. Office for Official Publications of the European Communities: Luxembourg.

246 Newman P *et al.* (2009). *What would have happened to the ozone layer if chlorofluorocarbons (CFCs) had not been regulated?* Atmospheric Chemistry and Physics **9**, 2113–2128.

247 BBC (2006). *Ozone hole stable, say scientists*. BBC News Online, 23 August 2006. Available online at <http://news.bbc.co.uk/1/hi/sci/tech/5276994.stm>.

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compounds. But one of the things that really helped us get there was the interplay between scientific experts, the private sector, social scientists, and large funders.’ Reversing the depletion of the ozone layer may be more manageable than some of today’s global challenges, but the Montreal Protocol stands as a model of what can be achieved through international collaboration.

Another example, of a much longer standing global problem that was solved by international collaboration, is even more remarkable. For at least three millennia, smallpox has been one of the deadliest diseases known to humanity, and a common scourge which has afflicted civilisations throughout the world, killing up to 30% of those infected.²⁴⁸ Although the major breakthrough was made by Edward Jenner FRS in 1798, who demonstrated that inoculation against cowpox could protect against the disease, it was not until 1979, just 12 years after the World Health Organisation (WHO) launched an intensified plan to eradicate it, that the global eradication of smallpox was confirmed, after a multi-faceted campaign which mobilised local bureaucratic, political and civilian support for a public health programme reliant on large-scale immunisation and isolation.²⁴⁹

Other problems have been identified but not solved in time, often with catastrophic consequences. Perhaps the most devastating example of this was the 2004 tsunami, which was picked up by satellites and seismometers minutes before it hit the shore. There was no in-built warning system to alert people in sufficient time, with the resultant loss of over 220,000 lives.²⁵⁰ This was despite the fact that the disaster had been predicted, notably by Dr Smith Dharmasaroja, Director General of Thailand’s Meteorological Department in 1994, but such warnings were not heeded.²⁵¹ As Waverly Person, a geophysicist and seismologist from the

US Geological Survey noted after the event, ‘had they had tide gauges installed, many of these people that were farther away from the epicentre could have been saved’.²⁵² Eighteen months later, an Indian Ocean tsunami warning system was finally set up,²⁵³ to add to a number of other local initiatives established since the 2004 disaster, such as the UK Natural Hazards Working Group—set up by Prime Minister Tony Blair in 2005 to advise government on detecting natural hazards and providing early warnings.²⁵⁴

3.2 Global research governance

There are many models of partnerships between scientists, governments, industry, philanthropists, charities and civil society which are designed to address global challenges. There is no uniform approach. The governance structures which shape such partnerships and initiatives are diverse, and targeting specific challenges can be tough. They are often interdependent, and characterised by a diverse array of local effects. Climate change, for example, is expected to lead to flooding in some areas and drought in others.²⁵⁵ Research requires co-ordination across different disciplines and regions, working with local knowledge systems to understand such impacts and define solutions.

At the global level, there are a number of organisations with mandates in these areas, such as: UNESCO and the UN Committee on Science and Technology for Development (UN-CSTD) under the UN umbrella; the International Council for Science (ICSU), that co-ordinates programmes across its scientific members, representing 141 countries and incorporating a wide range of activities, including global sustainability research²⁵⁶; and the European Co-operation in Science and Technology programme (COST), an example of an intergovernmental framework endeavouring to co-ordinate nationally

funded research, minimise duplication, avoid fragmentation and provide a platform for regional co-operation with partners beyond Europe.²⁵⁷ Bodies such as these are not necessarily optimised to address the global problems of the 21st century, taking into account the interdependencies of global challenges.

3.2.1 Challenge-led research initiatives

Specific global challenges have inspired a range of internationally collaborative research initiatives. To meet the challenge of providing renewable energy, the Generation IV International Forum (GIF) was set up by the US Government's office of Nuclear Energy, Science and Technology in 2000, and joined by eight other governments with the aim of identifying and developing a new generation of nuclear energy systems with enhanced safety and minimal waste.²⁵⁸ This involves a partnership between various countries' energy agencies, aiming to minimise costs, share ideas and avoid duplication. It also actively involves regulators, which should speed up licensing when demonstrators get built.

Professor Tim Abram, Chair in Nuclear Fuel Technology at the University of Manchester, co-authored part of the Generation IV roadmap, and has been involved in the programme since its

inception in 2000. 'The presence of an international programme like G4, along with the credible partners that make it up, will have acted as a major factor in decisions by responsible governments to put up appropriate funding for what would usually be done by national laboratories. Without G4, it would have been difficult for the individual labs to make their cases. It clearly saves money to pool resources, and Generation IV has brought together a range of world experts, and stimulated a great deal of collaboration and positive relationships.' Although most of the work is done by national laboratories, there is also involvement of industry,²⁵⁹ which has in turn raised a number of issues surrounding intellectual property. According to Abram, "Generation IV has forced people, especially scientists in government labs and universities who might not otherwise have thought about IPR issues, to confront them early in the process and reach a clear understanding of the rights and obligations of all parties before the research begins."

In the area of environmental assessment, major international initiatives include the Group on Earth Observation (GEO), a partnership of governments and international organisations which aims to develop a global observation system to enable more effective responses to environmental challenges²⁶⁰; the

248 See <http://www.who.int/mediacentre/factsheets/smallpox/en/>, accessed 30 November 2010.

249 See <http://www.smallpoxhistory.ucl.ac.uk/>, accessed 2 December 2010.

250 See http://nasadaacs.eos.nasa.gov/articles/2005/2005_tsunami.html, accessed 2 December 2010.

251 Tima R (2010). 'Mad' scientist gets belated recognition. South-East Asian Press Alliance, 12 May 2010. Available online at [http://www.seapabkk.org/announcements/fellowship-2005-program/57-mad-](http://www.seapabkk.org/announcements/fellowship-2005-program/57-mad-scientist-gets-belated-recognition.html)

[scientist-gets-belated-recognition.html](http://www.seapabkk.org/announcements/fellowship-2005-program/57-mad-scientist-gets-belated-recognition.html).

252 Voice of America (2004). *Experts say tsunami warning system would have saved lives*. Available online at <http://www.voanews.com/english/news/a-13-2004-12-28-voa5-67486957.html>, accessed 7 January 2011.

253 See http://portal.unesco.org/en/ev.php-URL_ID=33442&URL_DO=DO_TOPIC&URL_SECTION=201.html, accessed 7 January 2011.

254 See <http://www.nerc.ac.uk/>

[research/issues/naturalhazards/](http://www.nerc.ac.uk/research/issues/naturalhazards/), accessed 7 January 2011.

255 IPCC (2007). *Climate change 2007: synthesis report*. Intergovernmental Panel on Climate Change: Geneva, Switzerland.

256 ICSU (2010). *Earth system science for global sustainability: the grand challenges*. International Council for Science: Paris, France.

257 See http://www.cost.esf.org/about_cost, accessed 30 September 2010.

258 Abram T & Ion S (2008). *Generation-IV nuclear power: a*

review of the state of the science. Energy Policy **36**, 4323–4330; The Independent (2001). [UK signs up to nuclear power pact](http://www.independent.co.uk/news/science/uk-signs-up-to-nuclear-power-pact-2001-09-16). The Independent, 16 September 2001. GIF now has 13 members which comprise 12 countries and Euratom. See <http://www.gen-4.org>, accessed 30 September 2010.

259 Interview with Sue Ion, Chair of the UK Fusion Advisory Board, 5 October 2010.

260 See http://www.earthobservations.org/documents/200904_earth_info_sheets.pdf, accessed 6 October 2010.

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Millennium Ecosystem Assessment, modelled on the Intergovernmental Panel on Climate Change (IPCC),²⁶¹ and its successor, the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES)²⁶²; and the Horn of Africa Regional Environment Network (HoA-REN), a network of environmental organisations and higher education institutions which promotes the exchange of environmental knowledge in the region.²⁶³

To tackle the challenge of sustainable food production, the International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD) was initiated by the World Bank in partnership with a multi-stakeholder group of organisations, with a mission to reduce hunger and poverty, improve rural livelihoods and facilitate sustainable development through agricultural knowledge, science and technology.²⁶⁴ In its final report in 2009,²⁶⁵ it called for a fundamental rethink of agricultural knowledge, science and technology, in order to achieve sustainable global food production.

In the field of infectious disease, the Wellcome Trust has been at the forefront of attempts to address the most pressing problems in human and animal health for 72 years.²⁶⁶ The Structural Genomics Consortium (SGC) is an international public–private partnership which aims to determine the structures of proteins involved in a wide range of diseases.²⁶⁷ An idea championed by Alan Williamson, former vice-president for worldwide research strategy at Merck, who played an important role in brokering the SNP consortium (a non-profit foundation that put single-nucleotide polymorphisms—differences in single DNA base pairs between individuals—into the public domain),²⁶⁸ the SGC began operations in 2004,²⁶⁹ and in April 2010 supported research that identified a potential treatment for sleeping sickness.²⁷⁰

Elsewhere, the European and Developing Countries Clinical Trials Partnership (EDCTP) seeks to combat

HIV/AIDS, malaria and tuberculosis through genuine partnership between European and sub-Saharan African countries,²⁷¹ and has been commended for introducing a new model of international research co-operation which promotes African ownership.²⁷² More generally, the Global Research Alliance brings together nine R&D organisations from around the world to co-ordinate large-impact projects in support of the Millennium Development Goals.²⁷³

Among the long established global research programmes in the life sciences with an outstanding track record of success are the Human Genome Project discussed earlier, and the Human Frontier Science Program (HFSP), an international intergovernmental scientific programme that funds basic research focused on the complex mechanisms of living organisms and which has funded thousands of scientists worldwide to perform cutting edge research since 1989. The HFSP has been a highly imaginative programme which has continually refined its mechanisms as it has developed. For the first 10 years of the programme, a reductionist, analytical approach prevailed, but this has now been supplanted by an emphasis on the interaction of scientists from different disciplines in investigating biological questions.²⁷⁴

Prize schemes dedicated to addressing global challenges, such as the US Congress's H-prize and the Grainger Challenges prize,²⁷⁵ provide further incentives. They can stimulate competition and offer a novel way of identifying and mobilising scientific excellence while also capturing the public imagination. A 2009 report from McKinsey and Co found that the total number of prizes offered is going up, as is the number of incentive prizes (as opposed to retrospective prizes that recognise past work, such as the Nobel Prizes).²⁷⁶ In November 2010, the US Government's Office of Management and Budget sent a memorandum to all federal agencies urging

them to use incentive prizes to stimulate innovation and to solve tough problems, following a September launch of a dedicated website to act as a clearing house for government sponsored prizes.²⁷⁷

3.2.2 Integrating challenges and maximising resources

Global research partnerships such as these do important work, but it could be asked whether further, overarching mechanisms are needed for prioritising or integrating work on challenges, reducing duplication and maximising resources (and to what extent this is actually possible in practice). Although there is unlikely to be a single, general purpose framework appropriate for such a range of endeavours—the diversity of these may be a source of strength in itself—attempts are being made to better understand how global challenge research can be orchestrated to best effect. The OECD has embarked on a study

of new approaches and governance mechanisms for multilateral scientific co-operation to address global challenges,²⁷⁸ which may offer some important insights into how best to move forward.

While the direction of basic scientific research will continue to be driven by the curiosity of individual scientists and the goals of those funding the research, it has also been argued that research agendas could benefit from being informed by a more diverse range of interests, with greater involvement of civil society and marginalised communities.²⁷⁹ This would also help ensure engagement and ‘buy-in’, and would require sufficient flexibility in governance structures to enable this. The influence of private sector research and innovation is also significant, for example in the delivery of healthcare in the developing world.²⁸⁰ Matching industrial strengths, scientific capacity and policy objectives is a priority for future governance structures.

- 261 Reid W et al. (2002). *Millennium ecosystem assessment methods*. The Millennium Ecosystem Assessment was completed in 2005.
- 262 Kinver M (2010). *‘Green light’ for global biodiversity science panel*. BBC News online, 14 June 2010. Available online at <http://www.bbc.co.uk/news/10307761>.
- 263 See <http://www.hoarec.org/index.php/about>, accessed 6 October 2010.
- 264 IAASTD (2003). *An assessment of agricultural science and technology for development: the final report of the steering committee for the consultative process on agricultural science and technology*. International Assessment of Agricultural Knowledge, Science and Technology for Development: Washington, DC, USA.
- 265 IAASTD (2009). *Agriculture at a crossroads*. International Assessment of Agricultural Knowledge, Science and Technology for Development: Washington, DC, USA.
- 266 The Lancet (2008). *The Wellcome Trust: an unsung hero in health research*. The Lancet, **371**, 9612, 531.
- 267 See <http://www.sgc.ox.ac.uk/>, accessed 6 October 2010.
- 268 Butler D (2000). *Wellcome discusses structural genomics effort with industry*. Nature **406**, 923–924.
- 269 See <http://www.wellcome.ac.uk/Funding/Biomedical-science/Funded-projects/Major-initiatives/Structural-Genomics-Consortium/index.htm>, accessed 10 January 2011.
- 270 Frearson J et al. (2010). *N-myristoyltransferase inhibitors as new leads to treat sleeping sickness*. Nature **464**, 728–732.
- 271 Interview with Professor Charles Mgone, Executive Director, EDCTP. See also <http://www.edctp.org/About-EDCTP.2.0.html>, accessed 6 October 2010.
- 272 Van Velzen W (2009). *Independent external evaluation report of the European and developing countries clinical trials partnership*. European and Developing Countries Clinical Trials Partnership: The Hague, The Netherlands.
- 273 See <http://www.research-alliance.net/aims%structure.html>, accessed 30 September 2010.
- 274 Reddington M (2010). *Funding the frontier—the Human Frontier Science Program*. Bioessays **32**, 842–844.
- 275 See <http://hydrogenprize.org/> and <http://www.nae.edu/Programs/GraingerChallenge.aspx>, accessed 30 September 2010.
- 276 McKinsey & Company (2009). *And the winner is ...: Capturing the promise of philanthropic prizes*. McKinsey & Company: Sydney, Australia.
- 277 Feder T (2010). *Incentive prizes reinvented to solve problems*. Physics Today, November 2010. See also <http://challenge.gov/>, accessed 12 January 2011.
- 278 OECD (2010). *New approaches and governance mechanisms for multilateral co-operation in science, technology and innovation to address global challenges: project rationale and relevance*. DSTI/STP(2010)7. Organisation for Economic Co-operation and Development: Paris, France.
- 279 STEPS Centre (2010). *Innovation, sustainability, development: a new manifesto*. STEPS Centre: Brighton, UK. See also Wynne B, Stigoe J & Wilsdon J (2005). *The public value of science*. Demos: London, UK.
- 280 Green A (1987). *The role of non-governmental organizations and the private sector in the provision of health care in developing countries*. International Journal of Health Planning and Management **2**, 1, 37–58.

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Greater funding for multi- or interdisciplinary research into global challenges is needed. Universities, research funders and systems of research assessment too often reinforce disciplinary borders and prohibit more creative collaborations.²⁸¹ Meanwhile, national funding structures and reporting requirements can form barriers to effective international co-operation and more coherent governance structures. International scientific organisations could take the lead in harmonising these structures, and the ethical norms and intellectual property policies that surround them.²⁸²

3.2.3 Building capacity and resilience

Research directed towards global challenges could usefully be complemented by broader initiatives to enhance access to education as well as building stronger scientific capacity and infrastructure.²⁸³ This local capacity needs to be resilient and well networked into both local and global scientific networks. As we have seen, a number of developing countries are gradually improving their scientific

capabilities from a low base through investment and collaboration. Continued investment (both domestically and multi-nationally) and international collaboration—along with support from developed countries—will help these countries to develop faster, and enhance their ability to contribute to, and benefit from, global science structures and networks.

Given the pervasive nature of global challenges, national priorities may need to align more closely with global challenge priorities and obligations. This shift is already underway in some areas. For example, the crucial role that science and innovation can play in international development has received more emphasis over the last decade. Some development agencies, such as Canada's International Development Research Centre (IDRC), have explicitly put scientific and technical research at the heart of their agenda.²⁸⁴ The UK's Department for International Development (DFID) has also scaled up research into climate change, health and agriculture through its research strategy.²⁸⁵

Kiangsi boat, from *Voyages a Peking, Manille et l'île de France*, by Chretien Louis Joseph de Guignes, 1808. From the Royal Society library and archive.



3.3 Case studies

There are many examples of ambitious projects which seek to address particular global challenges. These are based on a range of governance, co-ordination and financing mechanisms, and engage different combinations of stakeholders. They may involve the construction of large facilities and state-of-the-art infrastructure, the creation of joint research or delivery partnerships, the provision of comprehensive global assessments of the state of research in a given field, or large-scale collaboration between government and industry. Others are driven by philanthropic foundations, which have had a significant impact on research in health and agriculture.

Here we select five such high-profile international research efforts as case studies, discuss the origins of these different challenge-based models, and assess their effectiveness in more detail. The five considered here—the Intergovernmental Panel on Climate Change (IPCC), the Consultative Group on International Agricultural Research (CGIAR), the Bill and Melinda Gates Foundation, the International Tokamak Experimental Reactor (ITER), and the global efforts to develop and deploy carbon capture and storage (CCS) technology—were chosen according to the following criteria:

- to reflect a balance of global challenges (climate change, food production, infectious disease, and environmentally responsible provision of energy)
- to reflect a range of organisational mechanisms (intergovernmental forum, network of research centres, large-scale philanthropy, government–industry collaboration and large facilities/ infrastructure)
- to reflect a balance of global regions and countries (the IPCC is truly global; CCS has been largely led by the G8; CGIAR has research centres in Asia, Africa, Europe and the Americas; the Gates Foundation is based in North America and works mainly in the developing world; ITER, while based in Europe, has a global membership)
- to reflect the involvement of a range of different stakeholders (governments in the case of CCS, IPCC and ITER; research institutes in the case of CGIAR; private philanthropy in the case of the Gates Foundation; and the involvement of industry in the case of CCS, the Gates Foundation and CGIAR)
- to assess projects which are high-profile, key initiatives in the research on global challenges which they seek to address.

Of course, there are many other mechanisms and projects which address the global challenges of the 21st century, some of which have been mentioned earlier in Part 3. These five examples offer valuable lessons, as well as pointers for future efforts to design global challenge initiatives.

281 Royal Society (2009). *Hidden wealth: the contribution of science to service sector innovation*. Royal Society: London, UK.

282 Leshner A & Turekian V (2009). *Harmonizing global science*. Science **326**, 5959, 1459.

283 Discussions around this theme were held at the [STI Global Forum 2009](#).

284 IDRC (2010). *IDRC at 40: a brief history*. International Development Research Centre: Ottawa, Canada.

285 DFID (2010). *Research strategy 2008–2013*. Department for

International Development: London, UK.

3.3.1 The world's largest 'warning system': the Intergovernmental Panel on Climate Change (IPCC)

The IPCC's 2007 Nobel Peace Prize is a tribute to what is the largest and most complex orchestration of sustained international scientific co-operation the world has ever seen. It originated from proposals put forward at the World Meteorological Association (WMO) Congress in 1987 by several directors of national meteorological services, especially from developing countries, for a mechanism that would enable them to respond to increasingly frequent requests to brief their governments authoritatively on the threat of global warming.²⁸⁶ These were given added weight by an influential report in the same year by the UN World Commission on Environment and Development which increased the profile of climate change as a threat to human society and the environment.²⁸⁷ In the 22 years since its formation by the WMO and the UN Environment Programme (UNEP), the IPCC has engaged over 3,000 scientists and cited over 40,000 peer-reviewed publications. It has yielded a landmark sequence of global assessments related to climate change, and sustained the interest and support of the world's governments around a critical agenda.

Yet less than three years after receiving the prize, the IPCC has found itself under increasing scrutiny after the IPCC's Fourth Assessment report was found to contain a very small number of mistakes which were then widely reported. The difficulties that the IPCC has undergone in recent years illustrate three main points: the highly polarised nature of the debate around climate change; the political diversity of an organisation made up of 194 nations; and the difficulties involved in synthesising and managing a wide range of research data, including 'grey' literature.²⁸⁸

On any reckoning, climate change is a challenge of enormous scale and complexity. Rising global temperatures are likely to affect the world's most vulnerable people and have serious consequences for biodiversity and ecological systems. In his 2006 economic assessment of climate change, Lord Stern referred to it as 'the greatest market failure the world has ever seen'.²⁸⁹

Achievements

The successful completion of the IPCC's intergovernmental climate assessments is an extremely difficult task. It requires the co-ordination of large numbers of people all over the world with varying expertise, cultures, interests and expectations, and the synthesis of information that is extensive, multidisciplinary and international, extends across time and space, and is subject to different interpretations with a wide range of uncertainties.²⁹⁰ It is widely agreed that the IPCC, through its assessments, has been instrumental in informing national and international climate policy, climate change knowledge, and in raising public awareness of climate change.²⁹¹ It has shaped research networks around the world (there were 170 lead and contributing authors for the First Assessment report and more than 560 for the Fourth),²⁹² raised the profile of climate science in the developed and developing world, and has been instrumental in creating research and analytical capacity worldwide.

This global infrastructure is founded largely on the voluntary participation of thousands of scientists and the goodwill of hundreds of institutions. As such, the IPCC is a fascinating case study in why and how scientists work together, and with policy makers, for the global good. In its very design, it represents a 'significant social innovation'.²⁹³ Furthermore, the IPCC also directly contributes to building the capacity

of the climate science research base, through new IPCC scholarships for vulnerable and developing countries, established with Nobel Prize funds.²⁹⁴

Critically, the IPCC treads a fine line between policy relevance and policy prescription,²⁹⁵ culminating in a pressured line-by-line negotiation process with government representatives to produce intelligible summaries for policy makers. Working in this way, the IPCC has stimulated and sustained policy debate over two decades, and has served as a model for the establishment of similar assessment programmes on biodiversity, including the Millennium Ecosystem Assessment (and its successor, the Intergovernmental Panel on Biodiversity and Ecosystems Services (IPBES)). The IPCC acts as a comprehensive warning system for climate change: it lays bare the evidence that helps policy makers identify and prioritise where and when mitigation and adaptation strategies should be deployed.

Criticisms

Recent widely reported inaccuracies in parts of its last assessment report (in truth, a very small proportion of the total report) have heightened public scrutiny of the IPCC.²⁹⁶ Climate change—together

with the IPCC's assessment process—is now central to a multi-trillion dollar energy economy, further raising the stakes. So many competing interests are at play—not least the 194 UN member nations.

The annual Plenary, attended by all member nations, is presently the only decision-making body in the IPCC framework. This can impede the pace, momentum and agility of the organisation, so much so that its governance framework is now outdated. The recent review by the InterAcademy Council called for an executive committee to be formed, comprising representative IPCC members, NGOs, academics and the private sector, to improve the responsiveness of the IPCC, and to enhance its credibility and independence. Correspondingly the IPCC has set up a task group to look at governance issues.

The IPCC's critics argue that it has moved from being an impartial scientific assessment body towards policy advocacy. The involvement of governments has laid the IPCC open to criticisms of politicisation. Any perceived bias in the synthesis reports risks the complexity and nuance of the science being lost, a concern further exacerbated by cultural and linguistic diversity.

286 Zillman J (1997). *The IPCC: a view from the inside*. Australian APEC Study Centre: Melbourne, Victoria, Australia.

287 World Commission on Environment and Development (1987). *Report of the World Commission on Environment and Development: our common future*. United Nations: New York, NY, USA.

288 The term 'grey literature' covers material typically produced by OECD, the World Bank, UN agencies and the commercial/private sector. While not quality assured as robustly as conventional peer review,

this information is invaluable at regional and local levels for the development of effective adaptation strategies that are cost effective, participatory and sustainable. See Robinson J & Herbert D (2001). *Integrating climate change and sustainable development*. International Journal of Global Environmental Issues **1**, 2, 130–149.

289 Stern N (2006). *The economics of climate change: the Stern review*. Cambridge University Press: Cambridge, UK.

290 IAC (2010). *Climate change assessments: review of the processes and procedures of the*

IPCC. InterAcademy Council: Amsterdam, The Netherlands.

291 Hulme M & Mahony M (2010). *Climate change: what do we know about the IPCC?* Progress in Physical Geography, published online, 18 June 2010. Available online at <http://ppg.sagepub.com/content/early/2010/06/18/0309133310373719.abstract>.

292 Christ R (2010). *IPCC products, procedures and processes*. Presentation to IAC Review panel, 14 May 2010. Available online at <http://reviewipcc.interacademycouncil.net/>.

293 IAC (2010). *Climate change assessments: review of the*

processes and procedures of the IPCC. InterAcademy Council: Amsterdam, The Netherlands.

294 See http://www.ipcc.ch/ipcc-scholarship-programme/ipcc_scholarshipprogramme.html, accessed 30 September 2010.

295 IPCC (2006). *Principles governing IPCC work*. Intergovernmental Panel on Climate Change: Geneva, Switzerland.

296 Kintisch E (2010). *IPCC/Climategate criticism roundup*. Science Insider, 15 February 2010. Available online at <http://news.sciencemag.org/scienceinsider/2010/02/an-overview-of-ipccclimategate-criticism.html>.

Others are concerned that the consensus nature of the IPCC favours only majority views and excludes minority views. This is not helped by accusations that IPCC reports emphasise the negative in how they articulate risk and likelihood.²⁹⁷ Prejudices and criticisms are further fuelled by the lack of transparency in many of the IPCC's processes and procedures.²⁹⁸

Lessons

As the Stern Review noted, any action to address climate change will be serious and potentially life-changing,²⁹⁹ and will involve significant economic cost. In contrast to the successful international efforts to stop ozone depletion discussed earlier, solutions to climate change—whether preventive, adaptive or mitigative—will be far more expensive, and will probably involve major changes in lifestyles. This will no doubt lead to serious political and social consequences, and may help to explain why the IPCC has faced the amount of pressure and public scrutiny that it has. This pressure is now amplified by modern communication tools such as online media, blogs and social media, which were not as ubiquitous when the IPCC was set up, and with which its communications structure is now forced to contend.

Despite this, the IPCC offers some interesting pointers for the governance of global challenge initiatives in the future. First, by combining traditional peer-reviewed science with 'grey literature', it is forced to strike a balance between maintaining scientific credibility and quality control, while retaining political buy-in through the involvement of national governments.³⁰⁰ It must be inclusive and geographically representative, despite the

participation of many developing countries being constrained by poor research capacity and access to data and publications. Engendering a collective global sense of ownership and action is critically important. Knowledge that is claimed by its producers to have universal authority is interpreted very differently according to the political and cultural context.³⁰¹ In order to address global challenges, scientists and policy makers need to develop a better understanding of the diversity of local contexts for the production and use of expert knowledge. The difficulties the IPCC has faced foreshadow a wider debate about future global challenge initiatives (and specifically their scientific authority, credibility and relevance), which is likely to intensify in the years ahead.

Second, the IPCC must mobilise the voluntary dedication of thousands of scientists, yet also be completely open and accountable. Its integration of scientists, social scientists and policy makers, and its decentralised and geographically representative researcher network is a source of strength and vitality. However, it also lays the IPCC open to criticism of its governance and management, and to questions about whether the science should be entirely separate from its translation into policy.

Finally, the IPCC engages a wide range of disciplines in a large number of countries. There are contrasts, and sometimes conflicts, in the way scientists, social scientists and economists work. These differences can sometimes be difficult to reconcile, but the value of multidisciplinary approaches to global problems is increasingly recognised.

3.3.2 Centres of excellence in agriculture: the Consultative Group on International Agricultural Research (CGIAR)

The food price spikes that sparked riots in several countries in 2008, and the fears of a possible repeat as global food prices hit a record high in December 2010,³⁰² served as a stark reminder that food security is one of today's most pressing global challenges.³⁰³ Increasing food production alone cannot ensure food security for all, but it is a key part of meeting the challenge, especially in the face of pressures from climate change, changing consumption patterns and an increasing global population. Agricultural science has a key role to play in sustainable food production.³⁰⁴

The roots of the CGIAR can be traced back to a research programme funded by the Mexico-Rockefeller Foundation in the 1940s. This programme led to varieties of wheat with yields three times higher than traditional varieties, resulting in Mexican self-sufficiency in wheat and a Nobel Peace Prize for research champion Norman Borlaug ForMemRS.³⁰⁵

The success of this research initiative and other efforts by the Rockefeller and Ford Foundations,³⁰⁶

combined with dire predictions of a global food shortage,³⁰⁷ paved the way for a series of independent 'centres' of agricultural research, funded and driven by the donor community. However, the foundations were not able to continue support in perpetuity on their own.³⁰⁸ Eventually, following a series of policy consultations in 1969–1971, led by the World Bank, UN Food and Agriculture Organisation (FAO), United Nations Development Programme (UNDP) and the Rockefeller and Ford foundations,³⁰⁹ the donors agreed to establish the CGIAR in May 1971, with its own Executive and Scientific Councils, supported by a small secretariat at the World Bank.

Agriculture and rural development were central to the World Bank's poverty reduction mission.³¹⁰ Its President Robert McNamara's support and influence were instrumental in helping to set up and shape the CGIAR to reduce poverty and hunger through high-quality research in some of the world's poorest regions.³¹¹ CGIAR was the first global programme to receive grants from the World Bank's net income,³¹² and its expansion continued with 15 autonomous centres in countries as diverse as Malaysia, Peru,

297 Von Storch H (2010). [Presentation to IAC review panel](#), 15 June 2010. Available online at <http://reviewipcc.interacademycouncil.net>.

298 IAC (2010). [Climate change assessments: review of the processes and procedures of the IPCC](#). InterAcademy Council: Amsterdam, The Netherlands.

299 Stern N (2006). [The economics of climate change: the Stern review](#). Cambridge University Press: Cambridge, UK. 300 Hulme M & Mahony M (2010). [Climate change: what do we know about the IPCC?](#) Progress in Physical Geography, published online, 18 June 2010. Available online at <http://ppg.sagepub.com/content/early/2010/06/18/03091333/10373719.abstract>.

301 Jasanoff S (2010). [A new climate for society: Theory, Culture & Society](#) 27, 2–3, 233–253.

302 Kim Y (2011). [G20 to tackle food prices as countries reassure consumers](#). Reuters.com, 7 January 2011. Available online at <http://www.reuters.com/article/idUSL3E7C701120110107>.

303 Evans A (2008). [Rising food prices: drivers and implications for development](#). Available online at http://www.chathamhouse.org.uk/files/11422_bp0408food.pdf. Chatham House: London, UK.

304 Royal Society (2009). [Reaping the benefits: science and the sustainable intensification of global agriculture](#). Royal Society, London, UK.

305 See http://nobelprize.org/nobel_prizes/peace/laureates/1970/

[borlaug.html](#), accessed 5 October 2010.

306 World Bank (2003). [The CGIAR at 31: celebrating its achievements, facing its challenges](#). Précis published by World Bank's Operations Evaluation Department (OED). World Bank: Washington, DC, USA.

307 Shah M & Strong M (1999). [Food in the 21st century: from science to sustainable agriculture](#). Consultative Group on International Agricultural Research (CGIAR): Washington, DC, USA.

308 See <http://www.cgiar.org/who/history/origins.html>, accessed 11 January 2011.

309 See <http://www.cgiar.org/who/history/origins.html>, accessed 11 January 2011.

310 Shah M & Strong M (1999). [Food in the 21st century: from science to sustainable agriculture](#). Consultative Group on International Agricultural Research (CGIAR): Washington, DC, USA.

311 CGIAR (2006). [A partnership for research and development: World Bank and the CGIAR](#). Consultative Group on International Agricultural Research: Washington, DC, USA. See also <http://www.cgiar.org/who/index.html>, accessed 30 September 2010.

312 World Bank (2003). [The CGIAR at 31: celebrating its achievements, facing its challenges](#). Précis published by World Bank's Operations Evaluation Department (OED). World Bank: Washington, DC, USA.

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Mexico, Kenya and Syria. These centres continue to benefit from contributions from the World Bank and other multinational donors including the UN, and from over 60 countries.

In 2003, an independent review highlighted the CGIAR system's need for a formal legal charter, and the requirement for system-level responses to developments in biotechnology, genetic resource management, intellectual property rights and private sector research.³¹³ In response to this, and a growing mood for change within the donor community, in 2007 the CGIAR initiated radical reforms to its organisation, governance, finance and management to enhance its coherence and strategic impact. This led to the establishment of a centrally administered global fund for research, a legally constituted consortium to manage the separate centres, as well as mechanisms to monitor performance and delivery. Under the new system, the bulk of the CGIAR research agenda will be delivered through eight 'mega-programmes' which are yet to be fully defined—but it is hoped that this will ensure a more efficient and effective framework for research.³¹⁴

Achievements

The CGIAR has become a major hub for agricultural research in the developing world. Although its annual research budget of approximately US\$550 million pales in comparison to the private sector's budget,³¹⁵ it is estimated that for every \$1 invested in CGIAR research, \$9 worth of additional food is produced in developing countries.³¹⁶ A 2010 review concluded that, 'CGIAR research contributions in crop genetic improvement, pest management, natural resources management, and policy research have, in the aggregate, yielded strongly positive impacts relative to investment, and appear likely to continue doing so.'³¹⁷ An independent review in 2008 had already concluded that without CGIAR:

- world food production would be 4–5% lower;
- world grain prices would be 18–21% higher;
- some 13–15 million more children would be malnourished.³¹⁸

The success of the CGIAR lies in combining cutting-edge global research with practical local impact. The International Rice Research Institute (IRRI) in the Philippines is one of the Consultative Group (CG) Centres. Bob Zeigler is its Director General, and a firm advocate of the centres' mission, the opportunities presented by their freedom to evolve, and their critical role in engaging and mobilising local communities. Benefits flow in both directions—to the local community (through employment) and to the global research community via CG Centres themselves by harnessing local knowledge (on traditional rice varieties, soil conditions, farming practice and social and dietary preferences). This local knowledge in turn drives, enriches and broadens the scope for research and impact. In the case of IRRI, Zeigler acknowledges that the centre's research portfolio has evolved significantly from its original focus on production and yield. Education is also important in developing and maintaining local capacity: 'IRRI was founded with a clear mandate to develop, and conduct education in, the production of rice in Asia. Research and education were seen to be equally important.' As a major research hub in the developing world, it is not surprising that IRRI has developed a complex network of partners. Zeigler notes that 'the challenge now is in bringing the different partners together in a coherent way'.

Recent reforms

As the reforms that began in 2007 reach completion, their longer term impacts remain to be seen. In particular, the respective roles of the donors and consortium in shaping the direction of the CGIAR may

take some time to establish. With a second phase of reform planned and new Strategy and Results Frameworks expected every six years, there is room to monitor and review the changes.

The centres themselves may also face an uncertain future. Although the mega-programme proposals will still be driven by the CG Centres themselves, the proposals will be considered by an Independent Science Partnership Council on the basis of their delivery against applied impacts as well as donor expectations.³¹⁹ How this focus on applied results will affect the exploratory research capacity and freedoms of the CG Centres is not yet clear. The move towards a global fund, increased administrative complexity and associated decrease in direct funding may also impact on the longer term capabilities and value for money of individual centres.

In addition, agriculture and food security are areas where there is a plethora of grey literature emerging from developing countries, often founded upon local knowledge and expertise. Strategic decision-making processes will need to acknowledge the significant contribution of bottom-up networks in agriculture, including those emphasising farmer participatory research.³²⁰ Care needs to be taken to ensure that centralising trends within the CGIAR are not detrimental to such localised and targeted research

programmes which contribute to smallholder food security. Without these systems for local engagement, the essential purpose of CGIAR research in terms of reducing poverty and hunger could be lost.

Lessons

The CGIAR might not have evolved into the success it is now, had it not been for the rapid expansion of the CG Centres. Indeed, the expansion of the centres played an important role in building and enabling local capacity which is so important in the CGIAR today. To some extent, reforms were enabled by the external landscape and learnt from examples of co-operation platforms in Europe and elsewhere. While the move from direct Centre funding to more centralised structures will provide coherence across the CGIAR portfolio, the new research agenda and its focus on applied science may put pressure on core funds that permit more exploratory research. Links to significant donors (World Bank) and political forums (UN) have also done much to ensure the visibility and impact of the research. A further interesting development took place in December 2009 when it was announced that the Bill and Melinda Gates Foundation (see Section 3.3.3) will join CGIAR, to which it is already a significant donor, having allocated US\$400 million to several CGIAR centres over 2009–2013.³²¹

313 World Bank (2003). *The CGIAR at 31: an independent meta-evaluation of the Consultative Group on International Agricultural Research*. World Bank: Washington, DC, USA.

314 For more on the new structure, see CGIAR (2009). *Voices for change: the new CGIAR*. Consultative Group on International Agricultural Research: Washington, DC, USA.

315 Monsanto's annual research budget is US\$1.2 billion. See Gilbert N (2010). *Inside the hothouses of industry*. Nature **466**, 548–551.

316 Source: CGIAR website. See <http://www.cgiar.org/who/index.html>, accessed 30 September 2010.

317 Renkow M & Byerlee D (2010). *The impacts of CGIAR research: a review of recent evidence*. Food Policy, **35**, 5, 391–402.

318 Consultative Group on International Agricultural Research (2008). *Bringing together the best of science and the best of development: independent review of the CGIAR system synthesis report* (pp 119–120). CGIAR Secretariat: Washington, DC, USA.

319 For example, potential impact expectations set out for the GRiSP mega-programme on rice equate to an average of 15 additional kg per ha per year additional yield growth, which would result in a 10–23% rice price reduction in Asian countries and 7–10% reduction in major Latin American and African markets. See CGIAR (2010). *CGIAR proposed mega-program portfolio*. Consultative Group on International Agricultural Research: Washington, DC, USA.

320 Examples include prolinnova, terra preta network, farmer

first network. See Scoones I & Thompson (2009). *Farmer first revisited: innovation for agricultural research and development*. Institute of Development Studies at the University of Sussex: Brighton, UK.

321 Sharma Y (2009). *Gates Foundation joins global crop research network*. SciDev.Net, 10 December 2009. Available online at <http://www.scidev.net/en/news/gates-foundation-joins-global-crop-research-network-1.html>.



3.3.3 A transformative impact on global health: the Bill and Melinda Gates Foundation

Getting 40 billionaires together in one room is no mean feat. Yet in August 2010, Microsoft founder Bill Gates and investor Warren Buffett did just that as part of a high-profile philanthropic campaign called 'The Giving Pledge' which they had instigated.³²² Present that night were CNN founder Ted Turner and New York's mayor Michael Bloomberg, who pledged to give away at least half their fortunes to charity, estimated at nearly US\$9 billion.³²³

Such examples demonstrate the power of philanthropy and its effect on research, charity and development objectives. This is not a new phenomenon. Many of the central figures in the USA's extraordinary economic and industrial growth in the late 19th and early 20th centuries, such as Andrew Carnegie, John D Rockefeller, Andrew Mellon and Henry Ford, set up hugely influential foundations which have been major benefactors of US colleges and universities,³²⁴ and continue to give out hundreds of millions of dollars a year.³²⁵

The most high profile and largest philanthropic organisation in the world today is the Bill and Melinda Gates Foundation,³²⁶ with overall expenditure totalling US\$3 billion in 2009.³²⁷ Since its establishment in the late 1990s, it has transformed global health research. In 2007, the Foundation's spend of US\$1.2 billion on global health alone was almost as much as the WHO's annual budget of US\$1.65 billion.³²⁸ Through funding directed to fight AIDS, tuberculosis and malaria, the Foundation seeks to combat three of the world's most devastating diseases, particularly in sub-Saharan Africa. In October 2007, Bill and Melinda Gates called on global leaders to commit to 'an audacious goal—to reach a day when no human being has malaria, and no mosquito on earth is carrying it'.³²⁹

Achievements

It has been claimed that the Gates Foundation has helped to raise the profile of international health research, and to create a much higher profile for infectious diseases and vaccine development.³³⁰ In 1999, the Foundation gave a start-up grant of US\$750 million to the Global Alliance for Vaccines and Immunisation (GAVI),³³¹ a public-private global health partnership funding vaccines which has since immunised more than 200 million children and averted over 3.4 million premature deaths.³³² '[The Foundation] sees science and innovation as an important driver for solving the world's big problems', explains Laurie Lee, Deputy Director of External Affairs. 'One of our achievements has been to stimulate major growth in global R&D investment in drugs and vaccines to treat diseases which had hitherto been neglected by the pharmaceutical industry—but which kill millions of people in the developing world.' By leveraging its significant funds through the GAVI Alliance and similar programmes, as well as working closely with pharmaceutical companies to develop treatments for neglected tropical diseases, the Foundation's work has successfully corrected wider market failures.

In the area of malaria control, the size of the Gates Foundation's grants have enabled it to energise research and forge partnerships between academia, governments and industry much more effectively than other institutions, according to Professor Brian Greenwood FRS.³³³ The Medicines for Malaria Venture and the Malaria Vaccine Initiative are two successful examples of these public-private partnerships.³³⁴ The Global Fund to Fight AIDS, Tuberculosis and Malaria (GFATM), to which the Foundation is a significant donor, with total contributions of US\$650 million,³³⁵ has been lauded as a model for streamlining funding into these diseases into a single source, which lessens

the burdens on health ministries in developing countries, which can otherwise be weakened by the proliferation of actors in global health research.³³⁶

Furthermore, the call for the eradication of malaria discussed earlier has had a significant impact on the malaria research and control communities, galvanising them to take a more aggressive approach to malaria elimination, rather than accepting some degree of control of the infection as the best that could be achieved. It has led to new control and research initiatives such as the Malaria Elimination Group and the Malaria Eradication Agenda, which would not have happened without their initiative.³³⁷

It could also be argued that the efforts of the Foundation have paved the way for other wealthy and powerful individuals to pump resources into

tackling other challenges. In February 2007, Virgin CEO Richard Branson launched the US\$25 million Earth Challenge Prize, to be given to someone who proposes a method which successfully removes at least a billion tonnes of carbon per year from the atmosphere.³³⁸ In the same year, the Global Water Initiative (GWI), a new partnership of seven international NGOs, received a donation of US\$150 million for rural water and sanitation projects in 13 countries in Africa and Central America, provided by the Howard G. Buffett Foundation, a multi-million dollar private foundation controlled by Warren Buffett's eldest son.³³⁹ The motivations of these philanthropists, as with those of individual scientists working on these issues, may well be altruistic, but recognition and competition could also be factors.

322 Clark A (2010). *US billionaires club together—to give away half their fortunes to good causes*. The Guardian, 4 August 2010. Buffett's generosity is particularly remarkable, having donated US\$37bn to the Gates Foundation rather than establish his own foundation. See <http://news.bbc.co.uk/1/hi/5115920.stm>, accessed 1 December 2010.

323 Authors' calculations. According to Forbes.com, Bloomberg's net worth in 2009 was US\$16 billion and Turner's net worth was US\$1.9 billion, a total of US\$17.9 billion, of which half is US\$8.95 billion. See http://www.forbes.com/lists/2009/10/billionaires-2009-richest-people_Michael-Bloomberg_C610.html and [http://www.forbes.com/lists/2009/10/billionaires-2009-richest-people-Robert-F-\(Ted\)-Turner_ETX7.html](http://www.forbes.com/lists/2009/10/billionaires-2009-richest-people-Robert-F-(Ted)-Turner_ETX7.html), accessed 5 October 2010.

324 Smith W & Bender T (eds) (2008). *American higher education transformed 1940–2005*.

documenting the national discourse (p 423). The Johns Hopkins University Press: Baltimore, MD, USA.

325 Cannadine D (2008). *The changing art of giving*. BBC News Online, 11 January 2008. Available online at <http://news.bbc.co.uk/1/hi/magazine/7183245.stm>.

326 New York Times (2010). *Bill and Melinda Gates Foundation*. Times Topics, 29 January 2010. Available online at http://topics.nytimes.com/top/reference/timestopics/organizations/g/gates_bill_and_melinda_foundation/index.html.

327 Bill and Melinda Gates Foundation (2010). *2009 annual report* (p 13). Bill and Melinda Gates Foundation: Seattle, WA, USA.

328 McCoy D, Kembhavi G, Patel J & Luintel A (2009). *The Bill & Melinda Gates Foundation's grant-making programme for global health*. The Lancet **373**, 9675, 1645–1653. See also Bill and Melinda Gates Foundation (2008). *2007 annual*

report (p 46). Bill and Melinda Gates Foundation: Seattle, WA, USA.

329 Bill and Melinda Gates Foundation (2007). *Bill and Melinda Gates call for new global commitment to chart a course for malaria eradication*. Bill and Melinda Gates Foundation: Seattle, WA, USA.

330 Walt G & Buse K (2000). *Partnership and fragmentation in international health: threat or opportunity?* Tropical Medicine and International Health **5**, 7, 467–471.

331 Source: Gavi Alliance (2008). See http://www.gavialliance.org/media_centre/facts/index.php, accessed 30 September 2010.

332 WHO, UNICEF, World Bank (2009). *State of the world's vaccines and immunization*, 3rd edn (p 88). World Health Organisation: Geneva, Switzerland.

333 Okie S (2006). *Global health—the Gates—Buffett effect*. New England Journal of Medicine **355**, 11, 1087.

334 See <http://www.mmv.org> and <http://www.malariaivaccine.org/>, accessed 2 December 2010.

335 Okie S (2006). *Global health—the Gates—Buffett effect*. New England Journal of Medicine **355**, 11, 1086.

336 Moon S *et al.* (2010). *The global health system: lessons for a stronger institutional framework*. PLoS Medicine **7**, 1.

337 See <http://www.malariaeliminationgroup.org/> and <http://malera.tropika.net/>, accessed 2 December 2010.

338 BBC (2007). *Branson launches \$25m climate bid*. BBC News Online, 9 February 2007. Available online at <http://news.bbc.co.uk/1/hi/sci/tech/6345557.stm>.

339 IRC International Water and Sanitation Centre (2007). *Global water initiative: new NGO partnership gets US\$ 150 million*. Available online at <http://www.irc.nl/page/38048>. IRC: The Hague, The Netherlands.

Unintended consequences

Despite these successes, and the significant nature of the Foundation's contribution to global health research, its efforts are not without their critics, who argue that its largesse has unintended consequences. Its considerable resources mean that it has huge influence on the research agenda in global health, whereas previously this agenda would have been set by more open and representative bodies such as the WHO. Therefore the priorities that it defines have significant effects on the demand for scientists and clinicians in a number of different fields. It is argued that the concentration on 'high profile' diseases such as AIDS has created an internal 'brain drain' away from basic healthcare areas, such as maternal care and the treatment of common fatal illnesses like diarrhoea.³⁴⁰

In terms of governance, many perceive that the Foundation lacks transparency, with its first guiding principle being that it is 'a family foundation driven by the interests and passions of the Gates family.'³⁴¹ It has been urged to 'rethink the concept of accountability.'³⁴²

Comparisons with other models

However, others claim that the Foundation's novel approach to grant making supports high-risk and potentially transformative research.³⁴³ For example, researchers applying for grants under the Foundation's 'Grand Challenges Explorations' programme only need to submit a two-page explanation of the proposal, with no need to provide preliminary data. The proposals are then reviewed by a diverse and eclectic group composed not just of scientists, but also including engineers, business people and others with a track record of

high-risk research. Tadataka Yamada, President of the Foundation's Global Health Programme, acknowledges the risk of this approach, but argues that 'billions have already been thrown at [these problems ...] and nothing's happened—the standard approaches haven't been successful'.³⁴⁴

The Gates Foundation is, of course, a relatively new entrant into the arena of global health research; in this regard the template to follow has arguably been set by the Wellcome Trust. The world's second largest research foundation has built a hugely impressive track record of achievements in its 72 years of existence, including the development and testing of the anti-malarial artemisinin, and the sequencing of around one-third of the human genome through its Sanger Institute in Cambridge; it also contributes to capacity building in Africa by strengthening African universities and institutions.³⁴⁵

Lessons


The Gates Foundation offers a number of lessons for policy makers. As we have seen, concerns have been raised about its governance structure, but it has been praised for its fresh, risk-taking approach to grant making. Foundations can be fast and agile in response to problems when they arise, as they are free from the limitations of government policy,³⁴⁶ and can help to stimulate partnership and achieve more when they pool resources.

The Gates Foundation has had a huge impact on global health research. However, Gates funding has tended to focus on a few high-profile diseases, which has arguably had some adverse unintended effects on basic healthcare. This may offer a salutary lesson for the governance of other global challenge initiatives funded by high-income countries which

aim to address problems that disproportionately affect the developing world, or those that target funding exclusively on solving a particular 'global challenge'.

The energy, drive and ambition of wealthy individuals and foundations are crucial assets, which policy makers around the world should utilise in the effort to address global challenges. Looking to the future, it is likely that the global philanthropic landscape will change in line with the shifting balance of global wealth and power. Chinese and Indian entrepreneurs are rapidly reaching the levels of assets of the great US philanthropists of the early 20th century, and will be among the leaders of globally relevant philanthropy in the future. Tata in India and Hong Kong's Li Ka-Shing are two examples of historically influential donors to world-class science and medicine respectively.³⁴⁷

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- 340 Pillier C & Smith D (2007). *Unintended victims of Gates Foundation generosity*. Los Angeles Times, 16 December 2007. www.scidev.net/en/features/g-a-tadataka-yamada-and-wild-science-ideas.html.
- 341 See <http://www.gatesfoundation.org/about/Pages/guiding-principles.aspx> accessed 13 October 2010.
- 342 Garrett L (2007). *The Challenge of Global Health*. <http://www.foreignaffairs.com/articles/62268/laurie-garrett/the-challenge-of-global-health>. Foreign Affairs **86**, 1.
- 343 Nature (2008). *A risk worth taking*. Nature **455**, 1150.
- 344 Nightingale K (2009). *Q&A: Tadataka Yamada and wild science ideas*. SciDev.Net, 12 June 2009. Available online at [http://](http://www.scidev.net/en/features/g-a-tadataka-yamada-and-wild-science-ideas.html)
- 345 The Lancet (2008). *The Wellcome Trust: an unsung hero in health research*. The Lancet, 371, 9612, 531.
- 346 Gavaghan H (2005). *On firm foundations*. Nature **436**, 748–749.
- 347 Nichols R (2007). *Analysis of philanthropy for science and technology, part II: opportunities in funding science and technology. In: Mapping the New World of American Philanthropy: Causes and Consequences of the Transfer of Wealth*. Raymond S & Martin M (eds). John Wiley & Sons: Hoboken, NJ, USA.



Pencil sketch of volcanic clouds and ash-falls on Vesuvius by Antonio Piaggi, 1779. From the Royal Society library and archive.

3.3.4 Towards sustainable energy: the International Tokamak Experimental Reactor (ITER) Project

'There will be a day when ITER will become largely energy self-sustaining', explains Professor Steve Cowley, CEO of the UK Atomic Energy Authority. 'That will be one of those great moments in science—analogous to Fermi's achievement of nuclear fission on the 2nd of December 1942.'

ITER is one of the most ambitious scientific endeavours of the 21st century. Latin for 'the way', its goal is to demonstrate the scientific and technical feasibility of generating energy from nuclear fusion. If successful, fusion has the potential to provide sustainable, low carbon energy in a period when fossil fuels are being rapidly depleted. The decision to build ITER is a truly international response to the challenge, involving collaboration between China, the EU, Japan, India, South Korea, Russia and the USA.

International collaboration is essential for fusion development. It is relatively expensive compared to most scientific research (if not on the scale of the world's energy market), and mastering it is a huge scientific and technical challenge best met by combining expertise from around the world. Furthermore, it is sufficiently far from the market that intellectual property issues have not hindered collaboration, although they are not straightforward. With the construction of ITER just beginning, it is too early to assess the organisation of the project. It is, however, possible to identify a number of relevant issues for possible future multinational collaborative efforts of a similar nature.

The proposal to build a very large fusion experiment as a collaborative project involving major powers grew from discussions between Presidents Gorbachev, Mitterrand and Reagan in 1985, partly

motivated by a desire to instigate collaborations that might help break down the barriers of the Cold War era. The EU, Japan, Russia and the USA began design studies in 1988, under the auspices of the International Atomic Energy Authority, but some momentum was lost when the Cold War ended. The USA withdrew in 1998 on cost grounds, following which a less ambitious design was adopted. Growing anxiety about the continued use and eventual depletion of fossil fuels led to China, South Korea and the USA (re)joining in 2003; India joined in 2006. Negotiation of the Agreement governing the construction of ITER started in 2001, while negotiations concerning the site began at the end of 2003. The site in France proposed by the EU was chosen in 2005 (in preference to a site in Japan, after a long and occasionally bitter contest),³⁴⁸ and the Agreement was signed in 2006, coming into force in 2007.

The agreement between major powers to fund and work together to build ITER encourages the hope that the world's governments will be increasingly willing to make long-term commitments to pool expertise and resources in order to tackle global problems. However, while reaching agreement was a success, the ITER experience raises issues that those planning future projects will need to consider carefully.

Delays to the project

Firstly, the Agreement took a long time to negotiate. This was partly due to the novelty of the project and the nature of the collaboration, and the fact that the number of partners grew during the negotiations. There was also difficulty in choosing the site, resulting in the polarisation of the parties into two camps during the negotiating phase. Given the 'spillover' benefits of large facilities, and their

propensity to attract scientific talent to the host country, as demonstrated by CERN and the current competition to host the Square Kilometre Array (SKA) Telescope,³⁴⁹ perhaps it is unsurprising that a contest to host ITER developed, which then brought to the surface deeper diplomatic tensions and international allegiances. Furthermore, site selection over other similar projects has often involved trade-offs in totally different fields. A famous example is the decision to site the Joint European Torus (JET) project in the UK instead of Germany, following the UK's assistance to the then West German Government in preparing the successful hostage rescue operation in Mogadishu.³⁵⁰ However, in the case of ITER, the part of the European Commission involved was responsible for a much narrower range of issues, making such geopolitical trade-offs impossible.

Setting up both the ITER Organisation (which is responsible for all aspects of the project: licensing, hardware, construction, operation and eventual decommissioning)³⁵¹—and seven so-called Domestic Agencies (which were created by the seven members to act as the liaison between national governments and the ITER Organisation,³⁵² and will be responsible for most of the procurement), and the establishment of working relationships and confidence between the many different players, also took longer than expected. Once this happened, the ITER Organisation, with the collaboration of the Domestic Agencies, then

had to review and revise the cost and design used as a basis for the negotiations—during which time they were considered 'frozen'.

Spiralling costs

ITER's construction expenses have risen from around €5 billion to over €13 billion owing to a number of factors.³⁵³ One of these was the decision to split responsibility for procuring technically interesting components between several members, in response to their wish to be involved in a large range of technologies. This was deemed necessary for political reasons, but has resulted in significant cost increases, and has also complicated reaching agreement on design details. It is likely to cause problems when delays or technical difficulties are encountered. Another exacerbating factor was that the 'frozen' design had not been endorsed by the team which took on the responsibility for building ITER, or checked in detail by industry.

Politics and governance

The member countries had mostly never been involved in comparable projects. This meant that during the negotiations they were perhaps overly diligent in protecting their national positions, with the result that the agreement now requires unanimity for all serious decisions—while consensus, often relatively easy to achieve, might have been sufficient.

348 New Scientist (2005). *Biggest nuclear fusion project goes to France*. New Scientist, 28 June 2005. Available online at <http://www.newscientist.com/article/dn7593-biggest-nuclear-fusion-project-goes-to-france.html>.

349 Bohannon J (2010). *Can Africa topple Australia in the contest to build the world's biggest telescope?* Science Insider, 14 January 2010. Available online at <http://news.sciencemag.org/scienceinsider/2010/01/its-africa-vs-a.html>.

350 Herman R (1990). *Fusion: the search for endless energy* (p 124). Cambridge University Press: Cambridge, UK.

351 See http://www.efda.org/the_iter_project/organisation.htm, accessed 7 January 2011.

352 See <http://www.iter.org/org/das>, accessed 7 January 2011.

353 Cowley S (2010). *Nuclear fusion—what is it worth?* The Guardian, 16 July 2010.

PART 3

Global approaches to global problems

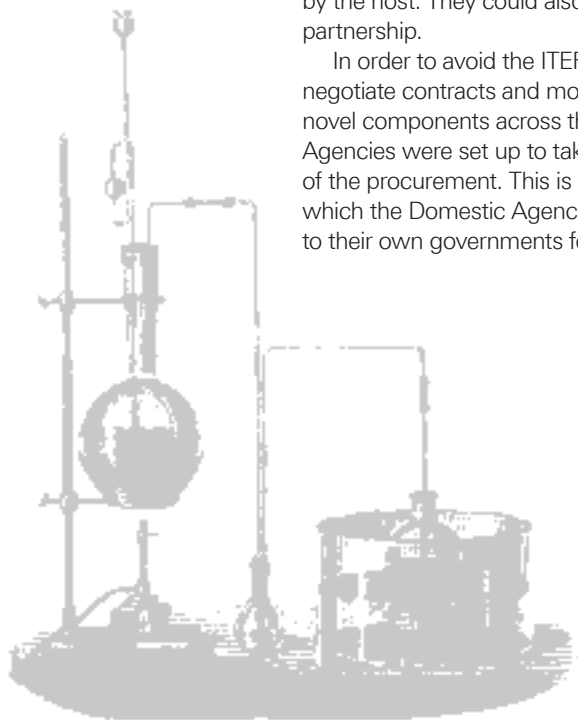
It also gave diplomatic consideration equal weight to technical factors in making the initial management appointments.

The Host Contribution made by the EU, which is 45.45% (reduced from 50% when India joined) in the construction period, and will be 34% during the operational phase, is another potential source of political friction, particularly in the current financial climate. Whether such a large Host Contribution is a good precedent is unclear. It could help create stability, but large differentials in contributions could result in cost increases putting differential strains on the members, and make the project particularly vulnerable to any financial difficulties encountered by the host. They could also unbalance the spirit of partnership.

In order to avoid the ITER Organisation having to negotiate contracts and monitor the fabrication of novel components across the world, the Domestic Agencies were set up to take responsibility for most of the procurement. This is problematic in cases in which the Domestic Agencies (which are responsible to their own governments for the use of their budgets)

are not satisfied that the specification of components (for which the ITER Organisation is responsible) is optimal from a technical or cost perspective. The ITER Council has no control over the Domestic Agencies, and until recently has had no official means of monitoring their progress.

Careful analysis of the ITER experience should help minimise such difficulties in similar projects in the future. Perhaps one of the key lessons to be drawn from ITER and from other large facilities such as CERN is that collaboration is most likely to succeed where there is a clear overriding need to collaborate, a compelling joint interest in a successful outcome, and that as far as possible decisions are technically, rather than politically driven (although this may not always be possible, eg. for procurement splitting). In setting up collaborations, sufficient time should be allowed for the different players (scientists, engineers and government representatives) to build confidence between each other. Finally, cost estimates should be treated with caution until they are endorsed by those who will carry the responsibility for construction, and checked by industry.



Apparatus used in examining solubility of hydrochloric acid. Fig 36, 'A Treatise on Chemistry', Vol 1, H.E Roscoe & C. Schorlemmer. From the Royal Society library and archive.

3.3.5 Capturing the initiative on CO₂: the global efforts to deploy carbon capture and storage (CCS) technology

'Climate change is a serious and long-term challenge that has the potential to affect every part of the globe [...] use of energy from fossil fuels, and other human activities, contribute in large part to increases in greenhouse gases associated with the warming of our Earth's surface.'³⁵⁴ The joint communiqué issued by the G8 leaders at the 2005 Gleneagles summit clearly summed up the threat of rising global temperatures, and was accompanied by a plan of action which included a pledge to accelerate the development of CCS. The UK Government prioritised climate change during its hosting of the G8 Presidency, and had begun to recognise the growing importance of CCS, which had been highlighted by a number of energy companies through their future scenario work.³⁵⁵

Most scenarios predict that fossil fuels will dominate energy supply until at least the middle of the century,³⁵⁶ and coal's global share of energy consumption recently rose to its highest level since 1970.³⁵⁷ It has been claimed that newly built coal-fired power plants, as long-term capital investments, will 'lock in' significant greenhouse gases (GHG) emissions for several decades unless they are retrofitted with CCS.³⁵⁸ Other sources of fossil fuels are becoming increasingly attractive to industry, such as natural gas (the global price of which has been

in decline), and tar sands, the use of which will also require CO₂ reduction through CCS.

CCS is therefore potentially an important component of the portfolio of technologies required to achieve substantial global emissions reductions.³⁵⁹ This was recognised by the then President of the Royal Society, Lord Rees, in a letter to the UK Energy Secretary, John Hutton, in March 2008, in which he argued 'the world is not going to stop burning coal any time soon. The UK should seize the chance to get a head start in developing the CCS technologies which will be needed worldwide.'³⁶⁰

CCS has not yet been demonstrated on a large scale,³⁶¹ and will require substantial long-term capital investment—not only because of the capital costs of demonstrators, but because of the energy it will consume, which is expected to reduce the efficiency of electricity generation by some 10% (eg. from 45% to 35%)³⁶² —the so-called 'energy penalty'. However, Stuart Haszeldine, Professor of CCS at the University of Edinburgh, argues that when the cost of CCS is debated, 'no calculation of the externality of environmental damage—the "cost" of doing nothing now—is made'. When the cost of this externality is included, it has been calculated that the cost of saving a tonne of CO₂ emissions with CCS technologies is in the same order of magnitude as doing so with many renewables (which also require the construction of infrastructure, and the creation of

354 [The Gleneagles Communiqué](#) (2005). Signed by the leaders of the UK, France, Russia, USA, Germany, Japan, Italy, Canada and the European Commission.

355 Interview with David Hone, Senior Group Climate Change Adviser, Shell, 20 October 2010.

356 IPCC (2005). [Carbon dioxide capture and storage](#) (p 3). Intergovernmental Panel on Climate Change: Geneva, Switzerland.

357 China and India's coal consumption also rose by 10% and 7% respectively in 2009. See Carr M & Gismatullin E (2010). [Coal's share of energy use rises as China, India grow](#). Bloomberg, 9 June 2010. Available online at <http://www.bloomberg.com/news/2010-06-09/coal-burning-surges-to-40-year-high-as-natural-gas-use-declines-by-record.html>.

358 See <http://www.pewclimate.org/global-warming-basics/coalfacts.cfm>, accessed 3 November 2010.

359 International Energy Agency (2009). [Technology roadmap: carbon capture and storage](#). International Energy Agency: Paris, France.

360 See <http://royalsociety.org/Letter-to-Secretary-of-State-on-Carbon-Capture-and-Storage>, accessed 14 March 2011.

361 Haszeldine S (2009). [Carbon capture and storage: how green can black be?](#) *Science* **325**, 5948, 1647–1652.

362 Swart R, Marinova N, Bakker S & van Tilburg X (2009). [Policy options to respond to rapid climate change](#) (p 68). Alterra, Wageningen University: Wageningen, Netherlands.

subsidies to make them economically viable)³⁶³ and new nuclear build (and waste disposal).³⁶⁴

CCS involves, first, separating ('capturing') CO₂ produced at coal or gas burning power plants (fossil fuel-fired power plants are responsible for around one-third of total global CO₂ emissions),³⁶⁵ or large industrial plants. The next step involves compression and transportation via pipeline or ship,³⁶⁶ prior to storage in deep geological formations, such as saline aquifers or depleted oil or gas wells.³⁶⁷ The cost of CCS lies mostly in the capture and compression phases, whereas the risk is mostly involved in the storage phase. Both need to be successful for CCS to work.³⁶⁸

CCS on power plants therefore requires a large number of demonstrator units, with three different capture technologies and a variety of geological conditions. International collaboration in constructing these demonstrators would obviously save costs and time, and sharing the results would speed up widespread deployment. It was therefore fitting that the G8 gave a fresh impetus to these efforts, now led by the International Energy Agency; the 25-member, ministerial level Carbon Sequestration Leadership Forum (CSLF), recently joined by the Global CCS Institute,³⁶⁹ established in 2009 with 226 members including national governments, industries and research organisations.³⁷⁰ In the same year the IEA published an ambitious roadmap for CCS which called for an additional investment of over US\$ 2.5–3 trillion from 2010 to 2050, which is estimated to be 6% of the overall investment needed to achieve a 50% reduction in GHG emissions by 2050. To achieve this, CCS technology must spread rapidly to the developing world, requiring greater international collaboration and financing for CCS demonstration in developing countries at an average annual level of US\$1.5–2.5 billion from 2010 to 2020.³⁷¹

Achievements

The Gleneagles communiqué has catalysed a number of successes, and has given fresh influence to national CCS groups in getting their governments to take action. By April 2010, government–industry collaboration had led to 80 large-scale power plant and industrial projects at various stages of development worldwide, over US\$ 26 billion in government support for the development of large-scale CCS projects, and government commitment to the launch of between 19 and 43 large-scale projects.³⁷² Since then, the European Commission has launched the NER 300 scheme, which hopes to raise between €4.5 billion and €9 billion to fund the operational costs of (pre) commercial CCS demonstration projects through selling emissions allowances on the carbon market; the US Government has announced nearly \$1 billion investment in three large-scale CCS projects,³⁷³ and the UK Government has committed up to £1 billion for one of the world's first commercial CCS demonstrations on an electricity generation plant, with three additional demonstration plants to follow.³⁷⁴

Some of the earlier investments are already starting to pay dividends. In January 2010, a major end-to-end CCS demonstration facility was launched in Lacq, southwestern France, which expects to capture and store around 120,000 metric tonnes of CO₂ over the next two years.³⁷⁵ In total, CCS pilot projects and test sites around the world already capture about 3 megatonnes of CO₂ per year.³⁷⁶

Given the involvement of industry, reaching a common understanding on intellectual property is essential. The Zero Emissions Platform (ZEP), a diverse coalition in Europe supporting CCS which involves industry, academia and environmental NGOs, attempts to address this via an innovative

three-tier model for sharing detailed results between the CCS demonstration projects themselves, with more limited results available to non-publicly funded CCS projects, and a further, lower level of sharing with the wider public.³⁷⁷ According to its chairman, Shell's Executive Vice President CO₂, Dr Graeme Sweeney, 'CCS will have a major role to play in tackling CO₂ emissions. A key enabler for getting these projects up and running is close collaboration between industry and government.'

Difficulties

CCS increases the cost of power generation, and can therefore only succeed through a robust financial and/or regulatory incentive framework. Otherwise, the high upfront cost and the wait for financial returns are substantial barriers to investment. As UK Minister for Energy, Charles Hendry, has admitted, the successful implementation of CCS technology will

require 'vast amounts of capital' that might not be recouped for 'many years'.³⁷⁸ Thomas Kuhn, President of the Edison Electric Institute, which represents the majority of US power generators, told a US House of Representatives Select Committee in June 2008 that commercial deployment of CCS for emissions from large coal-burning power stations would require 25 years of R&D and cost around \$20 billion.³⁷⁹

Acknowledging these financial barriers, President Obama's Interagency Task Force on CCS stressed that the establishment of a carbon price is critical, as is the development of supportive policy frameworks. It also concluded that long-term financial liabilities associated with CO₂ storage could be a barrier to deployment.³⁸⁰ These are due to issues such as uncertainty about the quantity of CO₂ which could leak from a failed site, or the ability to visualise CO₂ in the subsurface by low-cost and reliable monitoring for decades after injection. Communication and

363 For a further discussion of these issues, see Green R (2010). *Climate-change mitigation from renewable energy: its contribution and cost*. In: *The Economics and Politics of Climate Change*. Helm D & Hepburn C (eds). Oxford University Press: Oxford, UK.

364 Source: Accept website. [Fact sheet on carbon dioxide capture and storage \(CCS\)](http://www.accept.org/outputs/FactSheetonCarbonDioxideCaptureandStorage(CCS).pdf). Acceptance of CO₂ capture, storage economics, policy and technology: DNV, Rotterdam, the Netherlands. Available online at <http://www.accept.org/outputs/CCSFactsheet.pdf>, accessed 3 November 2010.

365 International Energy Agency (2003). *CO₂ capture at power stations and other major point sources* (p 5). Working Party on Fossil Fuels, International Energy Agency: Paris, France.

366 Unless a suitable storage site is available locally.

367 Injection into operating oil wells is also a possibility which can be used to enhance oil recovery.

368 Friedmann S (2007). *Carbon capture and storage*. Lawrence Livermore National Laboratory: Livermore, CA, USA.

369 See <http://www.globalccsinstitute.com>, accessed 4 October 2010.

370 International Energy Agency (2010). *IEA/CSLF report to the Muskoka 2010 G8 Summit. Carbon capture and storage: progress and next steps*. International Energy Agency: Paris, France.

371 International Energy Agency (2009). *Technology roadmap: carbon capture and storage*. International Energy Agency: Paris, France.

372 International Energy Agency (2010). *IEA/CSLF report to the Muskoka 2010 G8 summit. Carbon capture and storage: progress and*

next steps. International Energy Agency: Paris, France.

373 US Department of Energy (2010). *Secretary Chu announces nearly \$1 billion public-private investment in industrial carbon capture and storage*. Press release, June 10, 2010. US Department of Energy: Washington, DC, USA.

374 See HM Treasury (2010). *Spending review 2010* (pp 23, 61). HM Treasury: London, UK.

375 Carbon Capture Journal (2010). *Total inaugurates Lacq project*. 12 January 2010.

376 Source: Science website. See http://sciencecareers.sciencemag.org/career_magazine/previous_issues/articles/2010_05_07/ceadit.a1000047, accessed 4 November 2010.

377 ZEP (2008). *EU demonstration programme for CO₂ capture and storage* (CCS): ZEP's proposal.

European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP): Brussels, Belgium.

378 Quoted in Stephenson M (2010). *How much are we willing to pay for CCS?* Carbon Capture Journal **17**, Sept/Oct 2010.

379 Kuhn T (2008). *Written testimony of Thomas R. Kuhn, President, Edison Electric Institute before the United States House of Representatives Committee on Energy and Commerce Subcommittee on Energy and Air Quality: "Legislative proposals to reduce green-house gas emissions: an overview"*. 19 June 2008. See also Pearce F (2008). *Let's bury coal's carbon problem*. New Scientist **197**, 2649, 36–39.

380 The White House (2010). *Report of the Interagency Task Force on Carbon Capture and Storage*. The White House: Washington, DC, USA.

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Global approaches to global problems

engagement around CCS has therefore not moved as swiftly as might be expected, given the scale of deployment envisaged, despite some notable successes.³⁸¹

Lessons

Widespread deployment of CCS remains at least a decade away (although many analyses of greenhouse gas mitigation costs require it to be ready for routine operation in the 2020s). However, a number of lessons can be drawn from the efforts to develop CCS. Firstly, a large-scale endeavour with the scope and ambition of CCS cannot succeed without high-level intergovernmental co-operation, significant investment and the creation of appropriate financial and regulatory incentives. Secondly, industries which emit CO₂ can play a crucial role in any solution, and can bring invaluable resources, expertise and influence.³⁸² Furthermore, CCS has inspired many

disparate stakeholders from across the political spectrum, including industry and environmental NGOs, to work in partnership. Public engagement, including sufficient dialogue on the timescale and viability of CCS as well as its associated risks, remains vital.

Further intergovernmental agreement will be critical. Dr Mike Farley, Director of Technology Policy Liaison at Doosan Power Systems and, until June 2010, a member of the UK Government's Advisory Committee on Carbon Abatement Technology argues, 'There are three fundamental steps that need to be taken to ensure CCS is on an equal footing with other energy technologies: regulation, including the transfer of liabilities where appropriate; the creation of appropriate financial incentives; and a clear plan for the next stage of roll-out. A specific, quantifiable global agreement on CCS would be a huge step forward.'

Mexican hieroglyphics, from *Voyage de Humboldt et Bonpland*, by Friedrich Wilhelm Heinrich Alexander von Humboldt, 1811. From the Royal Society library and archive.



3.4 Co-ordinated efforts to tackle global problems

Part 3 has provided a snapshot of several prominent international research efforts directed towards global challenges. Analysing these different research efforts in detail enables the identification of a number of recurring themes in the way that global challenges are identified, defined and addressed. These can be broken down into two stages as follows:

Initiation

Identification of the challenge. Previously unknown challenges are often identified through the serendipitous discoveries or far-sighted theorising of individual scientists or research teams, as with the depletion of the ozone layer, or Arrhenius's 19th-century prediction of climate change resulting from greenhouse gas emissions. It is therefore essential that supporting 'blue skies' research and empowering outstanding individual scientists to shape their own research agenda should remain at the heart of national and international science funding. Problems and solutions in science often come from unexpected sources.

New problems can also be brought to the attention of scientists and/or policy makers from local sources 'on the ground', which is often the case in the field of infectious disease. In other cases, such as ITER and CCS, the problem was already well defined and a possible solution needed to be identified; in the latter case, industry played a crucial role in this through scenario work.

One of the main difficulties lies in identifying problems that require a global response—some,

such as food, water and energy security, are obvious and well documented, whereas others such as the ozone hole (and climate change a few decades ago) are not. Other problems, such as SARS, arise sufficiently quickly and dangerously as to require the identification of rapid solutions which need an international response, while other potential solutions, such as CCS, benefit greatly from a systematic global approach.

Systematic, proactive horizon scanning is therefore crucial in order to bring new problems, and/or new potential responses to long-standing problems, to the attention of those in power. The IPCC's work, underpinned by a vast international network of scientists around the world, is a good example of this kind of horizon scanning in action. The combined input of stakeholders across the spectrum will be invaluable in ensuring the early identification of issues that need, or would benefit from, global responses as they emerge, in order to better prepare for future disease outbreaks, resource shortages or challenges as yet unidentified.

Identification of suitable forums for initiating action. Once the problem, or possible solution, has been identified, the next vital stage is to get the problem onto the radar screen of those with the necessary power and resources to be able to act. For example, CCS required significant funding and political will, which meant that the G8 was the most powerful and decisive body to kick-start the process, and the interplay between industry, government science advisers and the leaders themselves proved crucial. In the case of CGIAR, it was the sustained long-term support of the World Bank,

381 Hammond J & Shackley S (2010). *Towards a public communication and engagement strategy for carbon dioxide capture and storage projects in Scotland: a review of*

Research Findings, CCS project experiences, tools, resources and best practices. Scottish Carbon Capture and Storage, University of Edinburgh; Edinburgh, UK.

382 Lovell B (2009). *Challenged by carbon: the oil industry and climate change.* Cambridge University Press; Cambridge, UK.

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Table 3.1. Summary of international research efforts discussed in Part 3.

Initiative	Strengths	Weaknesses
<p>IPCC <i>Intergovernmental assessment</i></p> <p>The IPCC is the leading international body for the assessment of climate change, established by the United Nations Environment Programme (UNEP) and the World Meteorological Organisation (WMO) to provide the world with a clear scientific view of the current state of knowledge in climate change and its potential environmental and socio-economic impacts.</p>	<ul style="list-style-type: none"> • Comprehensive geographic representation and ownership • Engages governments and policymakers; clear policy impact • Extends knowledge on climate change; shaping research agenda and building research capacity • Synthesises and assesses a wide range of high quality research from around the world to improve its comprehension, relevance and accessibility to the policymaking community • Stimulates public discourse and profile of climate change 	<ul style="list-style-type: none"> • High-profile (if not critical) errors in some of its reports • Owned by all countries, but governed by none • Straying into policy advocacy • Perceived political bias <p>[The 2010 IAC review of IPCC addresses such weaknesses; the IPCC has implemented many of its recommendations already and will discuss remaining ones at its May 2011 Plenary]</p>
<p>CGIAR <i>Consortium</i></p> <p>CGIAR is a global partnership which aims to achieve sustainable food security and reduce poverty in developing countries through scientific research and research-related activities in the fields of agriculture, forestry, fisheries, livestock, policy and the environment.</p>	<ul style="list-style-type: none"> • Highly efficient investment, with every \$1 invested leading to \$9 worth of additional food produced in developing countries • Combines cutting-edge global research with practical, local impact • Readiness and capacity to undergo radical reform 	<ul style="list-style-type: none"> • Currently undergoing radical reforms which are too early to assess—more centralised structures may result in better donor co-ordination and less duplication, but may adversely affect freedom of individual centres and capacity for exploratory research
<p>Bill and Melinda Gates Foundation <i>Philanthropy</i></p> <p>The Bill & Melinda Gates Foundation is the richest private foundation in the world, dedicated to bringing innovations in health, development, and learning to the global community.</p>	<ul style="list-style-type: none"> • Drive, ambition and resources • Supports innovative, risk-taking research • Provides innovative incentives for the pharmaceutical industry to address neglected tropical diseases • Sets an example to other wealthy philanthropists • Stimulates public-private partnerships and creativity • Fast and agile 	<ul style="list-style-type: none"> • Opaque governance structure • Large investments may create perverse incentives/unintended consequences in developing countries

Initiative	Strengths	Weaknesses
ITER <i>Large facilities/infrastructure</i> ITER is an international project to design and build an experimental fusion reactor based on the 'tokamak' concept.	<ul style="list-style-type: none"> • Technical agreement was a catalyst for other agreements • Project stimulated international co-operation—huge costs meant it would not have been possible without it 	<ul style="list-style-type: none"> • Time needed to build confidence between partners working in a new configuration • Difficulty of reconciling political and technical interests, resulting (eg.) in sub-optimal procurement arrangements in terms of time and cost minimisation
Carbon capture and storage <i>Government-Industry collaboration</i> CCS is a range of technologies that have the potential to trap a significant proportion of CO ₂ emissions from power stations and large industrial plants that burn fossil fuels, given added impetus by the decision of the G8 in 2005 to accelerate its development.	<ul style="list-style-type: none"> • Brings the resources, expertise and research strengths of industry to address a major global challenge • CCS has catalysed intergovernmental co-operation at the highest level, and encouraged genuine commitment 	<ul style="list-style-type: none"> • Scale of the challenge and time required to solve it means further international agreements and funding are necessary • Collaboration between government and industry requires resolution of a number of issues relating to liability and regulation, including the establishment of a carbon price

with UN backing, that enabled it to build on the early successes of private philanthropy.

However, climate change was already apparent to governments around the world by the 1980s, and it was national meteorological services, responding to the demand for more information from their governments, that led to the creation of the IPCC through the UN mechanism, which represented a wide range of countries and brought openness and legitimacy.

Where existing institutions or forums are inappropriate or outdated, new mechanisms have arisen in some cases to fill the gaps. Since its inception in the 1990s, the Gates Foundation has saved over 3 million lives through the GAVI Alliance, and focused the agenda of malaria research towards the eradication of the disease, which arguably would not have happened under the auspices of the pre-existing global health bodies.

Implementation

Once the problem has been defined and the

need for action identified, the next stage involves the implementation of the proposed solution.

Governments must be persuaded to act. This can be through high-level, quiet diplomacy, as the links between industry and government helped to achieve in the case of CCS, or through more formal reporting mechanisms such as IPCC and CGIAR.

Sources of funding also need to be identified. Long-term projects which require large facilities, expensive technology and upfront investment, such as CCS and ITER, would not be possible without national governments making long-term funding commitments or creating appropriate incentive frameworks, in addition to pooling labour and resources where necessary, and navigating political sensitivities. Where programmes rely on multilateral consensus, buy-in and action, national financial contributions through forums such as the UN are a crucial part of maintaining accountability and inclusivity. Philanthropists such as the Gates Foundation have a vital role to play, as they can take risks and support excellent science wherever it takes

place, in ways that national governments would find difficult; the CGIAR's work was in part pioneered by the vision of foundations such as Rockefeller. In areas such as next generation nuclear technology, and where market incentives encourage it, industry plays an important part.

From our analysis of the action taken by the global challenge research programmes we have profiled, a number of overarching themes emerge:

Governance. Good governance, transparency and accountability are crucial to international collaborative frameworks. At the same time, they must be agile and flexible enough to support innovative, risk-taking research—where the philanthropic sector arguably leads the way in some areas. It is also important to ensure that models are structurally appropriate. ITER, for example, has encountered some difficulties because its main Organisation and Council are responsible for the project, but most of the budget is held by individual countries' Domestic Agencies which are accountable only to their own authorities. The IPCC, on the other hand, is owned by all UN member states but governed by none of them effectively.³⁸³ At the other extreme, the Gates Foundation's investments are largely driven by the interests of a single family and their advisers, whom critics have argued are not sufficiently responsive to local needs.

Global challenges are often interdependent and interrelated, as evident in the interplay between climate change, poverty, water, food and energy security, population change, and biodiversity loss. The dynamic between these issues is complex, yet many global assessment and research programmes are managed separately, reflecting a lack of any co-ordination in the policy sphere. Governments, civil society and the private sector need to consider how to integrate the many disparate global challenge frameworks in order to co-ordinate research efforts,

maximise coherence and minimise duplication.

Multidisciplinarity. Given this interconnectedness, a multidisciplinary approach is essential. One of the key ingredients of the Montreal Protocol's success was in bringing together scientists and social scientists from a variety of disciplines; similarly, IPCC's working groups bring together natural and social scientists. Researchers from all disciplines have a role to play in shaping future adaptation and mitigation policies, requiring the reconciliation of quite different methodologies and terminologies.

Funding and incentives. Although many efforts to address global challenges are funded directly by governments, philanthropists, industry or other actors, incentive structures can play a vital role in supporting risk-taking research and encouraging behaviour change. (This is something that is clearly being increasingly recognised, as the increase in the number of incentive prizes discussed earlier demonstrates.) Reducing CO₂ emissions through CCS will not be achieved by market forces alone, and will only be possible within an internationally agreed and effective carbon pricing framework. Pooling of resources also adds value. A fundamental achievement of the CGIAR reform has been to convince donors to move from direct funding of specific projects or centres to contributing to a global fund, capable of more strategic deployment of resources and monitoring of impact.

Involvement of industry. We have seen how senior experts within power companies are playing a key role in co-operating with governments in developing CCS technology, bringing formidable knowledge and commitment to addressing the problem. Likewise, the pharmaceutical industry has responded to the Gates Foundation's financial incentives to develop crucial drugs for saving lives in the developing world. In any collaborative project,

but particularly in those involving industry, reaching a common understanding on intellectual property will be essential; this is an issue with which ITER is having to contend and is demonstrated by the novel approaches devised by the Zero Emissions Platform. Many global challenges, and CCS is a case in point, will require substantial investment from, and the creation of an appropriate incentive structure by, government—but will rely on industry to carry out the work. Agreements should take into account the need for publicly funded research to be accountable, and the need to appropriately safeguard and reward innovation and creativity.

Capacity building. All countries have a stake in solving global challenges, both in defining and prioritising them and in using global research output to inform local, national and regional responses. However, national and local capacity to deliver and apply science is highly variable. The IPCC has attempted to develop this capacity in the field of climate science through its scholarships programme for developing countries, while many have argued that the work of the Gates Foundation could be greatly enhanced by devoting more attention to institutional capacity building. Global challenge programmes should therefore consider incorporating a capacity-building element,³⁸⁴ to help minimise these disparities and improve scientific literacy across the piece.

Addressing global problems requires an understanding of their local manifestations. In areas

where traditional scientific infrastructure is weak, this may involve drawing on local indigenous knowledge or non-peer-reviewed research, especially in the development of adaptation strategies which are cost-effective, participatory and sustainable.³⁸⁵ IPCC's use of 'grey literature' is a case in point. These sources are important, but the management of tensions between orthodox, peer-reviewed science and less formal sources of knowledge will have major implications for the governance of global challenge research in the years ahead.

Engagement. As global challenges become increasingly prominent, issues of expertise, democracy and accountability become more pressing. We have seen this with climate change, which has polarised debate in many countries, and where criticism and analysis have been greatly amplified in recent years by new media such as blogs, Facebook and Twitter. These present a formidable challenge for communications teams at bodies such as the IPCC, which were established in an earlier era. Pressures such as these will raise transparency issues around data access, and may radically change the way scientists collaborate. Likewise, the possible risks and pay-offs associated with the development of ambitious technologies such as CCS, which involve significant amounts of public funds, should be clearly communicated as they progress.

It is therefore critical to ensure continuous assessment of the design and framing of research

383 IAC (2010). *Climate change assessments: review of the processes and procedures of the IPCC*. InterAcademy Council: Amsterdam, The Netherlands.

384 For a discussion of the importance of scientific capacity in addressing global challenges, see InterAcademy Council (2004). *Inventing a better future: a strategy for building worldwide*

capacities in science and technology. InterAcademy Council: Amsterdam, The Netherlands.

385 Robinson J & Herbert D (2001). *Integrating climate change*

and sustainable development. International Journal of Global Environmental Issues **1**, 2/2001, 130–149.

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questions through to the production, diffusion, exploitation and assessment of new knowledge; this will help to ensure that the involvement of all appropriate stakeholders is encouraged as much as possible. Greater public engagement in science, for example, presents an opportunity for a more widespread assessment of some environmental challenges, as is illustrated by the rise of ‘citizen science’.³⁸⁶ However, even in cases where science seems to hold the answers, it works best when it is supported by and enables other approaches, and this is vital for implementation.

Moving forward

This chapter has discussed five high-profile and contrasting approaches to collaboration. Each of these provides an insight into how scientists organise themselves, or are encouraged by others, to address shared challenges. There is no single formula appropriate for addressing global problems. Some are best tackled through intergovernmental co-operation; some on the basis of co-ordinating existing national systems; others are driven by a variety of innovative partnerships or consortia. Governance frameworks

vary, but all offer valuable lessons for tackling future global challenges.

Policy makers now need to harness the self-organising, researcher-led and bottom-up global science system and deploy it optimally to address critical challenges facing the planet. This will involve both ‘top-down’ approaches that invoke the combined power and resources of national governments as and when necessary, orchestrating effective co-ordinated work by large interdisciplinary teams, and also recognising the pivotal role of individual researchers and small teams.

Models like those discussed here show what can be achieved—and conversely where lessons can be learnt from approaches that have not worked so well. Given the urgency of global challenges, challenge-led approaches are likely to dominate research agendas in years to come. This creates great opportunities for progress, but may also have unintended consequences as research agendas are skewed in certain directions, a risk that will need to be constantly debated and reviewed.

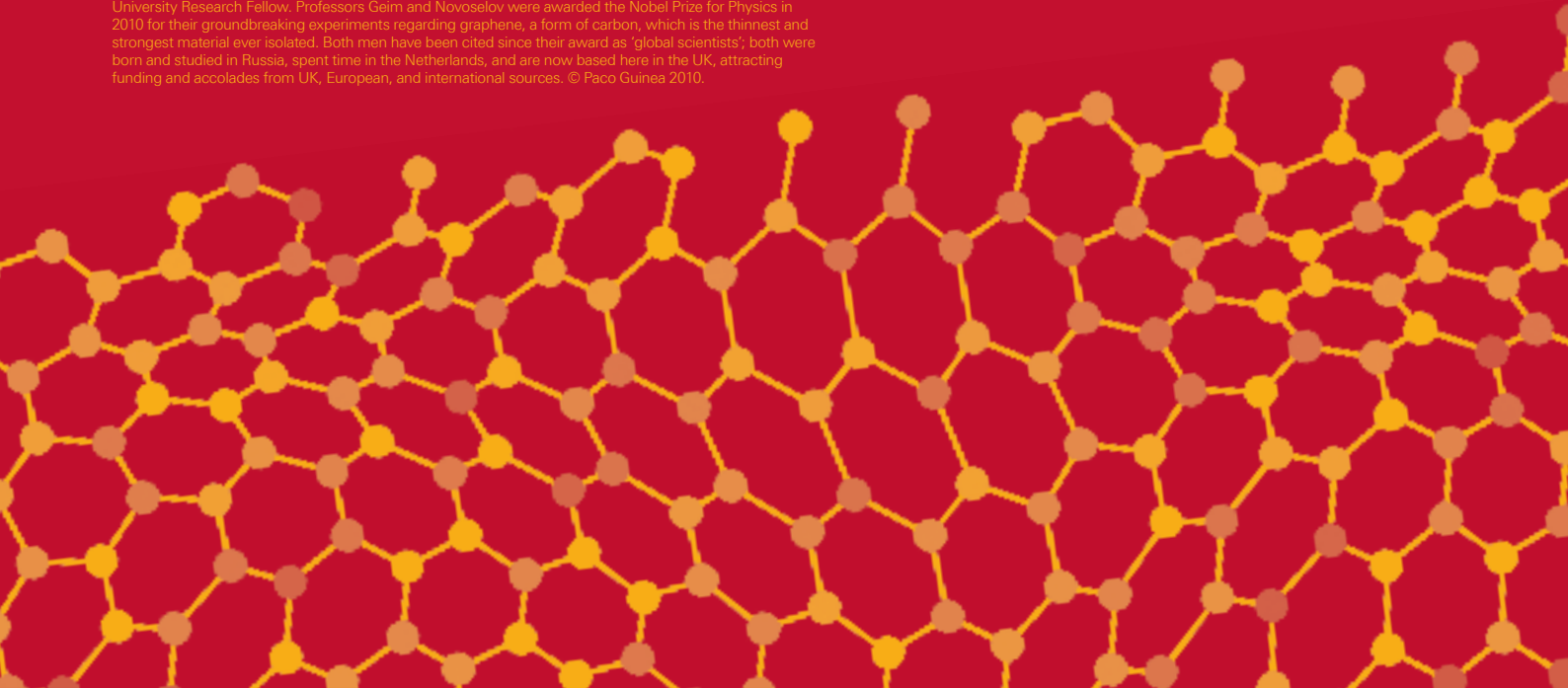
386 ECOS Magazine (2009). *Citizen science breaks new ground*. ECOS 149, 10–14. Commonwealth

Scientific and Industrial Research Organisation (CSIRO) Publishing: Collingwood, Victoria, Australia.

CONCLUSIONS AND RECOMMENDATIONS:

Cultivating the global scientific landscape

Strain in graphene opens up a pseudomagnetic gap. Generated by the Condensed Matter Physics Group at the University of Manchester, this image is a representation of the work at Manchester lead by Professor Andre Geim FRS, a Royal Society Research Professor, and Professor Konstantin Novoselov, a Royal Society University Research Fellow. Professors Geim and Novoselov were awarded the Nobel Prize for Physics in 2010 for their groundbreaking experiments regarding graphene, a form of carbon, which is the thinnest and strongest material ever isolated. Both men have been cited since their award as 'global scientists'; both were born and studied in Russia, spent time in the Netherlands, and are now based here in the UK, attracting funding and accolades from UK, European, and international sources. © Paco Guinea 2010.



CONCLUSIONS AND RECOMMENDATIONS:

Cultivating the global scientific landscape

Science is becoming increasingly global, with more scientific activity taking place in more countries, cities and institutions than ever before. At the same time, growing global collaboration is making this activity increasingly interconnected. Continued growth in worldwide research spending and the development of easier and faster ways to collaborate means that this trend looks set to continue.

The league tables of science, so long dominated by the 'scientific superpowers' such as the USA, Western Europe and Japan, are in flux. In the coming years, China, Brazil, India and South Korea are set to assert themselves even further, along with newly emergent scientific nations in the Middle East, South-east Asia, North and South Africa, and middle-ranking industrial countries such as Canada and Australia as well as some of the smaller nations of Europe. The recognition of the role that science can play in driving economic development, and in addressing local and global sustainability has led to increased research activity and the application of science within less developed countries.

International collaboration fundamentally enhances and transforms scientific research; it is driven by three main factors:

Quality: the added value gained by bringing together different skills, knowledge and perspectives (manifested in the increased citations of papers with international collaborators). Scientists search out

suitable collaborators in their field wherever they are located to progress their research, bringing together a range of relevant and complementary skills and resources.

Efficiency and effectiveness: the drive to combine intellectual, financial and infrastructural resources, to achieve more than one nation could manage alone, best exemplified by multinational projects such as the LHC and the Human Genome Project.

Necessity: to address high-level global challenges such as climate change and pandemics which do not recognise national boundaries, and which require large-scale co-operation and the mobilisation of resources to tackle them, as well as the application of global knowledge to local manifestations of these problems.

The challenge for governments, scientists, civil society, and others, is how to reap the maximum benefit of global science; how to ensure that the fruits of this science are best used to address current global issues, and to prepare for the opportunities and challenges of the future.

The recommendations that follow are intended to provide a basis for scientists, and those who support, facilitate and fund scientific activity around the world, to realise the full potential of globally collaborative research.

1. Support for international science should be maintained and strengthened

In order to best benefit from 'global science' (socially, economically and intellectually), nations need to be able to adapt their science and innovation strategies so that they can absorb the fruits of the best research, wherever it may have taken place. This means being open to collaboration, and participating in multi-partner activities where all parties can share and learn from global scientific excellence. Nations which adopt flexible science and research systems will be best placed to respond to the opportunities offered by the changing science landscape.

- Even in difficult economic times, **national governments need to maintain investment in their science base** to secure economic prosperity, tap into new sources of innovation and growth, and sustain vital connections across the global research landscape. Sustained investment builds a nation's capacity to assimilate excellent science, wherever it may have been conducted, for that country's benefit.
- **International activities and collaboration should be embedded in national science and innovation strategies** so that the domestic science base is best placed to benefit from the intellectual and financial leverage of international partnerships.
- **Commitments to multinational research efforts and infrastructures should not be seen as easy targets for cuts during a period of economic turbulence.** To cut subscriptions to joint research endeavours, without due diligence and assessment, is a false economy. By disengaging from these efforts, countries run the risk of isolating their national science and losing relevance, quality and impact.

2. Internationally collaborative science should be encouraged, supported and facilitated

Global collaboration brings significant benefits, both measurable (increased citation impact, access to markets), and less easily quantifiable, such as broadening research horizons. It is primarily driven by scientists seeking to work with the best people and access the best data and equipment wherever they are found, to develop their research and find answers to the big questions in their fields. This appetite for collaboration is further fuelled by advances in communication technologies, greater ease of international travel and the wider impact of globalisation. Collaboration is also increasingly essential for addressing the global challenges of the 21st century. The facilitation of collaboration therefore has a positive impact on national science and on national science systems.

- **Research funders should provide greater support for international research collaboration** through research and mobility grants, and other mechanisms that support research networks.
- **National border agencies should minimise barriers to the flow of talented people,** ensuring that migration and visa regulations are not too bureaucratic, and do not impede access for researchers to the best science and research across the world.
- **National research policies should be flexible and adaptive** in order to ensure that international collaboration between talented scientists is not stifled by bureaucracy.

CONCLUSIONS AND RECOMMENDATIONS:

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3. National and international strategies for science are required to address global challenges

Global challenges are social, economic and environmental in nature, engage a wide range of stakeholders, and impact on all cultures and countries. The global scientific community is increasingly concerned with finding solutions to 'global challenges'; while the challenges may be interconnected, many of the efforts to tackle them are not. Governments, civil society and the private sector need to think more systematically about frameworks for co-operation on global challenges and how they should relate to each other.

There is little natural incentive for the market to drive basic research independently in these areas. Consequently, there is a clear role for national governments to take the lead in understanding and articulating these challenges, bringing together diverse organisations, philanthropists, researchers and resources. This should allow scientists to better respond to new challenges and opportunities for research, while taking account of the broader social implications, and recognising the need for equitable access and participation across the global scientific community. By the same token, public participation and 'citizen science' will become increasingly important, as global challenges become more prominent and more public resources are spent on them.

- Recognising the interconnectedness of global challenges, **funders of global challenge programmes should devise ways to better co-ordinate their efforts, share good practice, minimise duplication and maximise impact.** Where possible, these should draw on existing infrastructure or shared technology.
- **National research funding should be adaptive and responsive to global challenges,** supporting the interdisciplinary and collaborative nature of the science required to address these issues.
- **In devising responses to global challenges, governments worldwide need to rely on robust evidence-based policy making,** and bring excellent scientists into the policy advisory process.

Red chalk drawing of sprouting beans from *Anatome plantarum*, by Marcello Malpighi, 1675. From the Royal Society library and archive.



4. International capacity building is crucial to ensure that the impacts of scientific research are shared globally

Tackling global challenges requires the very best available science: to measure and predict impacts, identify solutions, design mitigation strategies and evaluate pathways for adaptation. Countries worldwide need to be involved in the design and framing of research questions about shared challenges, and should have an underlying capacity to respond to these questions. The wide disparities between nations in their science spending and science infrastructure demonstrate that, despite global growth, there are countries and regions that are ill-equipped to play a full role in the 21st-century global landscape.

- **Researchers and funders should commit to building scientific capacity in less developed countries** to help improve their ability to conduct, access, verify and use the best science, and to ensure that they can contribute to global scientific debates and develop local solutions to global problems.
- **Scientific capacity building must involve financial support for authors in developing countries to publish in open access journals.** Open access publishing has made a wealth of scientific literature available to the developing world, but conversely it has made it harder for their scientists to publish under the 'author pays' model.
- **National academies, learned societies and other similar institutions should actively promote public and wider stakeholder dialogue to help identify, shape and respond to global challenges and their local manifestations.**

5. Better indicators are required in order to properly evaluate global science

Traditional metrics do not fully capture the dynamics of the emerging global science landscape. Levels of investment in R&D, the activities of funding bodies and the characteristics of national science and innovation strategies only tell part of the story. Global science in 2011 is increasingly characterised by bottom-up, researcher-led networks. These are founded on the architecture of national science systems but operate increasingly independently of them, often at local and regional levels, sometimes drawing on less conventional sources of science and innovation. To capture the transformative impact that these scientists and their networks are having on international science, more sophisticated impact measures are required to provide a richer understanding of the available knowledge. They must go beyond the traditional indicators of national scientific output and recognise the important informal characteristics of collaboration.

- **UNESCO (and other agencies such as the OECD) should investigate new ways in which trends in global science can be captured, quantified and benchmarked,** in order to help improve the accuracy of assessments of the quality, use and wider impact of science, as well as to gauge the vitality of the research environment.
- **There is a specific lack of data on the flow and migration of talented scientists and their diaspora networks.** UNESCO, OECD and others should investigate ways of capturing this information as a priority, which would enable policy makers to better understand, nurture and oversee global science for the benefit of society as a whole.

Glossary of acronyms

ASEAN	Association of Southeast Asian Nations	FONDAP	Fund for Advanced Research in Priority Areas
AU	African Union	FP	European Commission's Framework Programme
BERD	Business enterprise expenditure on research and development	GAVI	Global Alliance for Vaccines and Immunisation
BRIC	A grouping acronym that refers to the countries of Brazil, Russia, India, and China that are deemed to all be at a similar stage of newly advanced economic development	GERD	Gross expenditure on research and development
CAGR	Compound annual growth rate – an average growth rate over a period of several years	GEF	Global Environmental Facility
CCS	Carbon capture and storage	GDP	Gross Domestic Product – a measure of total economic activity
CERN	the European Organisation for Nuclear Research	G7	Group of seven of the world's leading industrialised nations, comprising Canada, the US, UK, France, Germany, Italy and Japan
CGIAR	Consultative Group on International Agricultural Research	G8	Group of eight which includes Russia in addition to the nations above, the leaders of which meet face-to-face at an annual summit
EC	European Commission	G20	Group of twenty finance ministers and central bank governors, established in 1999 to bring together systemically important industrialized and developing economies to discuss key issues in the global economy
ESO	European Organisation for Astronomical Research in the Southern Hemisphere	GOVERD	Government expenditure on research and development
EU	European Union	GRISP	Global Rice Science Partnership
EIARD	European Initiative for Agricultural Research for Development	GWI	Global Water Initiative
EURATOM	European Atomic Energy Community	IAASTD	International Assessment of Agricultural Knowledge, Science and Technology for Development
DAs	ITER Domestic Agencies	IAC	InterAcademy Council
DfID	Department for International Development (UK)		
FAO	Food and Agriculture Organisation of the United Nations		
FAPESP	Fundação de Amparo à Pesquisa do Estado de São Paulo (Research Foundation for the State of São Paulo, Brazil)		

ICT	Information and communication technologies	NGOs	Non-governmental Organisations
ICSU	International Council for Science, formerly International Council of Scientific Unions	OECD	Organisation for Economic Co-operation and Development
IDRC	International Development Research Centre (Canada)	R&D	Research and development
iGem	International Genetically Engineered Machine competition	R4L	Research4Life – the collective name for three public-private partnerships which seek to help achieve the UN’s Millennium Development Goals by providing the developing world with access to critical scientific research
IO ITER	Organisation	SBSTA	Subsidiary Body for Scientific and Technological Advice
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services	SESAME	Synchrotron-light for Experimental Science and Applications in the Middle East
IPCC	Intergovernmental Panel on Climate Change	SKA	Square Kilometre Array – an international effort to build the world’s largest radio telescope
IRRI	International Rice Research Institute	TWAS	Academy of Sciences for the Developing World (formerly Third World Academy of Sciences)
ISTIC	International Science, Technology and Innovation Centre for South-South Cooperation (under the auspices of UNESCO)	UN	United Nations
ITER	International Tokamak Experimental Reactor	UN-CSTD	United Nations Commission on Science and Technology for Development (CSTD)
KAUST	King Abdullah University for Science and Technology, Saudi Arabia	UNDP	United Nations Development Programme
KEMRI	Kenya Medical Research Institute	UNEP	United Nations Environment Programme
MDGs	Millennium Development Goals – eight targets which range from halving extreme poverty to halting the spread of HIV/AIDS and providing universal primary education, all by the target date of 2015 –agreed to by all UN member countries	UNESCO	United Nations Educational, Scientific and Cultural Organisation
MIT	Massachusetts Institute of Technology	UNFCCC	United Nations Framework Convention on Climate Change
MRC	Medical Research Council	WHO	World Health Organisation
		WMO	World Meteorological Organisation

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We received 80 responses to our call for evidence from individuals, academies, research institutions, government departments, and other organisations from around the world. These are listed below.

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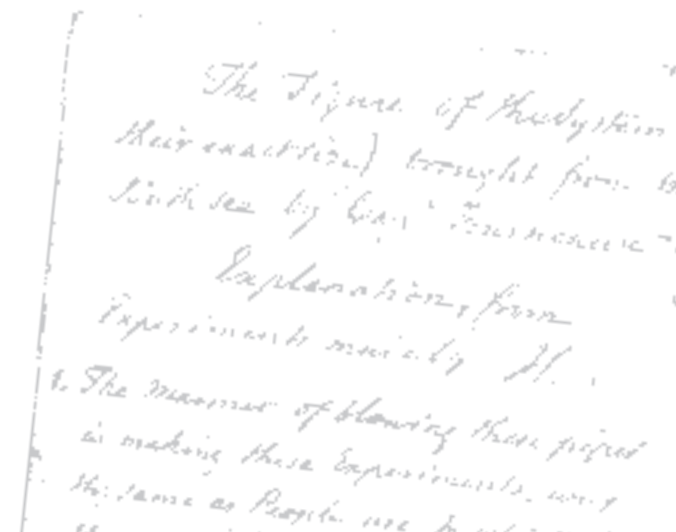
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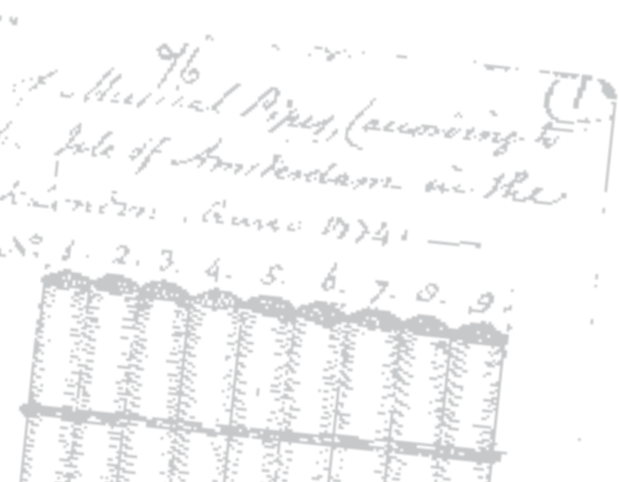
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A system of musical pipes from the Isle of Amsterdam (Tongatapu Island, Tonga), paper and drawing by Joshua Steele, 1 December 1775. From the Royal Society library and archive.



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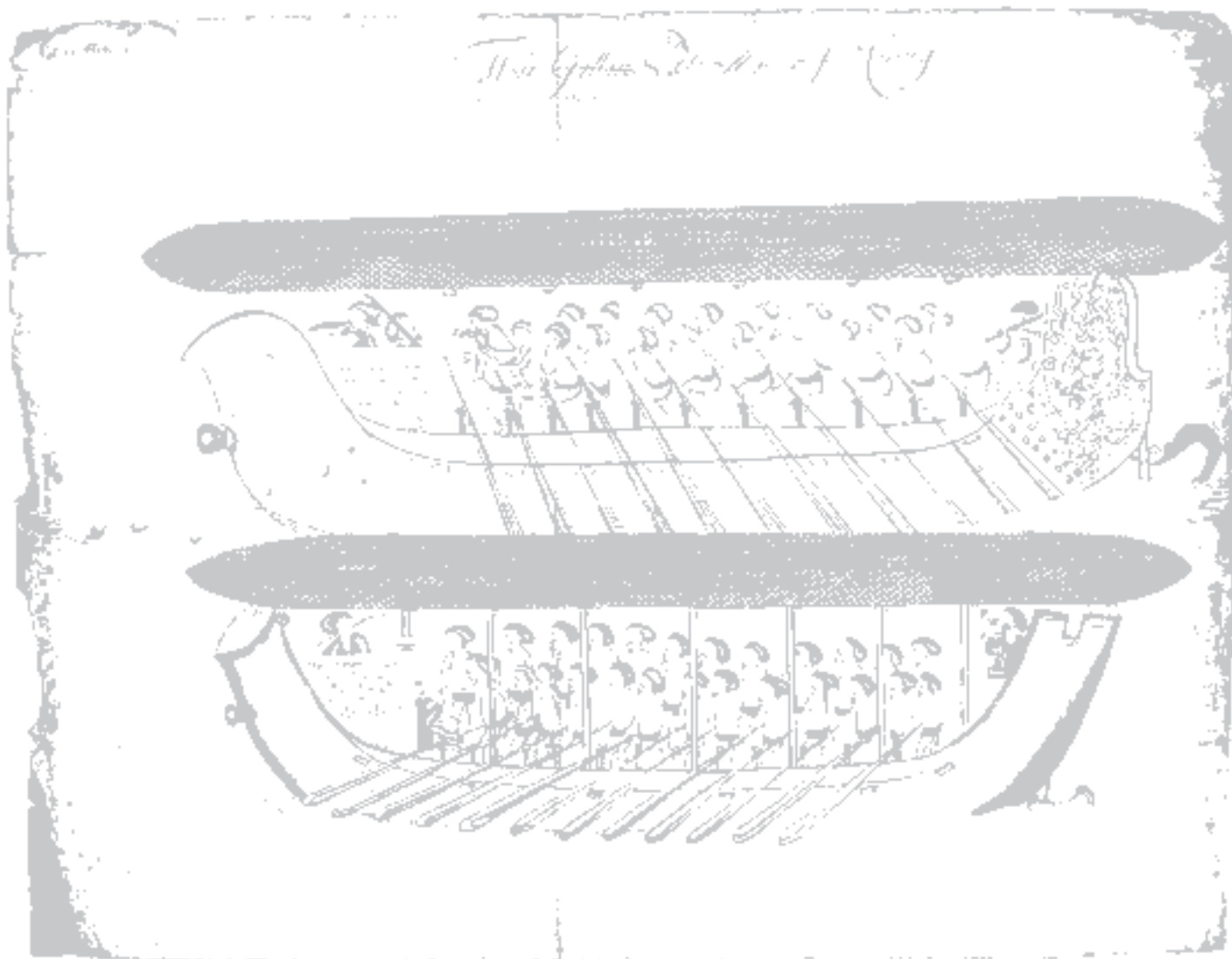
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Side elevations of an armed vessel powered by rowers. An illustration for Samuel Baron's *A description of the kingdom of Tonqueen*, 1685. From the Royal Society library and archive.



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