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The UK's performance in physics research

National and international perspectives

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Acknowledgement
Founded in 2002, Science-Metrix is an independent research evaluation company specialising in the assessment of science and technology using bibliometric methods and in the evaluation of science-based programmes and initiatives.

Contents

Executive summary

[1] A three-year citation window (publication year + following two years) was used to compute the ARC, which allows for scores to be computed up to 2009 only, given that citation windows for more recent publications were not complete at the time of writing the report.

This report, prepared by Science-Metrix for the Institute of Physics (IOP), the Engineering and Physical Sciences Research Council (EPSRC), and the Science and Technology Facilities Council (STFC), uses bibliometrics and case studies to examine patterns of performance in physics research in the UK. The bibliometric indicators presented here (e.g. specialisation index [SI], average of relative citations [ARC], international collaborations) are based on counts of scientific papers and citations to papers indexed in the Web of Science database produced by Thomson Reuters.

Key findings

Scientific production in physics

- The number of UK papers published in physics increased on average by 1.2% a year between 2002 and 2011. Nevertheless, this annual growth rate is lower than the 2.1% observed for UK peer-reviewed papers in all research areas combined (i.e. sciences, social sciences, and arts and humanities).
- The UK's share of world papers in physics fell from 5.1% in 2002 to 4.0% by 2012, which is in line with the decreases in share of other established scientific leading countries (e.g. the US, France and Germany). Additionally, emerging scientific countries in physics gained ground, particularly China, India and the Republic of Korea.
- Compared with established scientifically leading countries (e.g. France and Germany), but also emerging scientific countries (e.g. China, India and the Republic of Korea), the UK is placing significantly less emphasis on physics than on other fields of research, such as the life sciences and space science. In fact, in 2011, among the 25 leading countries, the UK was one of those with the lowest proportion of papers in physics.

Scientific impact in physics

- Despite the decline of its world share in physics research, the UK had the highest scientific impact in physics among the 10 largest publishing countries in 2009[1].
- The UK's scientific impact in physics has been growing in terms of both average citation rate and the proportion of highly cited papers. Between 2002 and 2009, scientific impact increased on average by 1.0% a year, which is a trend also observed in UK science as a whole.
- The leading countries with the most substantial growth in world share achieved this growth while also maintaining (and in some cases improving) their scientific impact. In particular, the steady growth observed in China and India was not detrimental to these countries' scientific impact; in fact, these countries managed to increase both their output and their scientific impact simultaneously.
- Although the scientific impact of China and India is currently below world average, it is increasing steadily in both countries.

International scientific collaborations

- The UK's rate of international scientific collaboration in physics has grown steadily, increasing on average by 1.8% a year between 2002 and 2011. This has translated into clear gains in terms of scientific impact, as measured by citations.
- Between 2002 and 2011, the UK's most important scientific partners were the US, Germany, France, Italy and China.
- Clear gains in scientific impact were noted for the UK and all of its principal partners – including the emerging countries in physics, such as China, India and the Republic of Korea – in these international scientific collaborations. Additionally, the Netherlands has a strong, reciprocal scientific affinity with the UK, meaning that both countries collaborate more with each other than expected by the size of their respective scientific production in physics.

Impacts arising from physics research

To supplement the analysis of the bibliometrics data, UK case studies of four physics clusters (i.e. applied superconductivity and materials science; astrophysics and space science; cosmology, quantum field theory and particle physics; and imaging techniques and algorithms) known for their high level of scientific excellence, as determined by citation analysis and topic modelling, were undertaken. Analysis of the case studies indicated that:

- Research in these clusters has contributed to the development of new scientific instrumentation or techniques and to the provision of highly skilled graduates.
- Research in these clusters is relevant to several UK science and technology priorities ("the eight Great Technologies"), including "big data" and "advanced materials".
- Programmes that encourage personnel exchanges or industry secondments are one of the most useful conduits for knowledge flow.

In the applied superconductivity and materials science cluster, partnerships with electricity generation and supply companies, as well as materials instrumentation companies, have led to several start-ups or spin-out companies.

In the astrophysics and space science cluster, the capacity for scientific and technological problem-solving is exemplified not only in the aerospace industry, but also by sensor systems developed for medical research and security purposes.

Within the cosmology, quantum-field theory and particle physics cluster, newly created scientific instrumentation and techniques include: improved cooling and vapour technology used in a variety of industrial applications; and precision detection equipment developed for space systems but now used by large computing companies such as Dell and IBM.

In the imaging techniques and algorithms cluster, research results have been widely used by international engineering companies (e.g. Rolls-Royce), aerospace companies (e.g. BAE Systems and Airbus) and a suite of medical-imaging businesses. Other research in this cluster applies to the power-generation industry, both nuclear and non-nuclear, where research results have been used by a UK-based power company and a German electric utilities company.

1

Introduction

[2] See, for instance, *The Importance of Physics to the UK Economy*, London: Institute of Physics, 2012.

[3] *The Importance of Physics to the Economies of Europe*, Mulhouse, France: The European Physical Society, 2013.

[4] See, for instance, *The Economic Impact of Physics Research in the UK: Magnetic Resonance Imaging (MRI) Scanners Case Study*, London: Oxford Economics, 2012; and *The Economic Impact of Physics Research in the UK: Satellite Navigation Case Study*, London: Oxford Economics, 2012.

[5] *The Career Paths of Physics Graduates*, London: Institute of Physics, 2012.

[6] The Republic of Ireland was included following a special request by the Institute of Physics at contract initiation based on the country's close ties and proximity with the UK.

Through the development and application of novel knowledge and instruments, as well as the skills and abilities of physics-trained people, physics research plays a pivotal role in the world economy. Several studies have demonstrated the direct, indirect and induced economic impacts of physics in the UK[2] and other European countries[3]. Others have provided evidence of the economic effects of specific technologies generated by physics research[4]. The contribution made by physics-trained individuals to the UK economy has also been revealed in surveys showing the wide distribution of highly skilled people with an academic background in physics across economic sectors[5].

To strengthen the economic benefits from physics research and expand the boundaries of physics knowledge, the UK must secure a strong scientific and technological base in physics and ensure that there are efficient knowledge flows between the public and private sectors. These two imperatives are particularly important because emerging scientific countries in physics – such as China, India and the Republic of Korea – are changing not only the international division of labour in physics, but also the locus of physics research activities, thus placing increasingly competitive pressure on countries with more established physics research, such as the UK.

Using bibliometric methods, this report describes the key characteristics of the state of physics research in the UK and other countries (leading countries in terms of output, the BRICK countries [Brazil, Russia, India, China and the Republic of Korea] and the Republic of Ireland[6]). The UK's performance in other scientific fields selected as comparators also highlights the position of physics research in the UK and its importance at the national level.

Finally, to supplement the analysis of the bibliometrics data, case studies were undertaken based on interviews with UK researchers active in the following four physics-based clusters, in which UK research was found to have a comparatively strong emphasis and impact (based on a topic-modelling approach).

- Applied superconductivity and materials science
- Astrophysics and space science
- Cosmology, quantum field theory and particle physics
- Imaging techniques and algorithms

These case studies emphasise the contribution of physics research to society and describe the dynamics associated with this broad field of research. For example, it was found that physics funding sources range widely, from targeted government funding to in-kind industry support. Interdisciplinary and multidisciplinary research is conducted, facilitating national, European and international collaborations. The case studies also illustrate, with a number of examples, that physics research leads to many important industrial benefits, such as developing prototypes, creating new scientific instrumentation, training of skilled graduates and the creation of new companies.

2

The UK's research performance in an international context

In the past few decades, new scientific powers have been emerging. At the same time, traditionally dominant scientific countries in the West have experienced a decrease in their share of world output in all research areas combined (i.e. sciences, social sciences, and arts and humanities), because of the maturity of their research systems and the resulting slow growth. Before examining the research performance of the UK and other countries in physics research, this section describes some of the major changes in research that have occurred internationally in all areas of scholarly knowledge production indexed in Thomson Reuters' Web of Science.

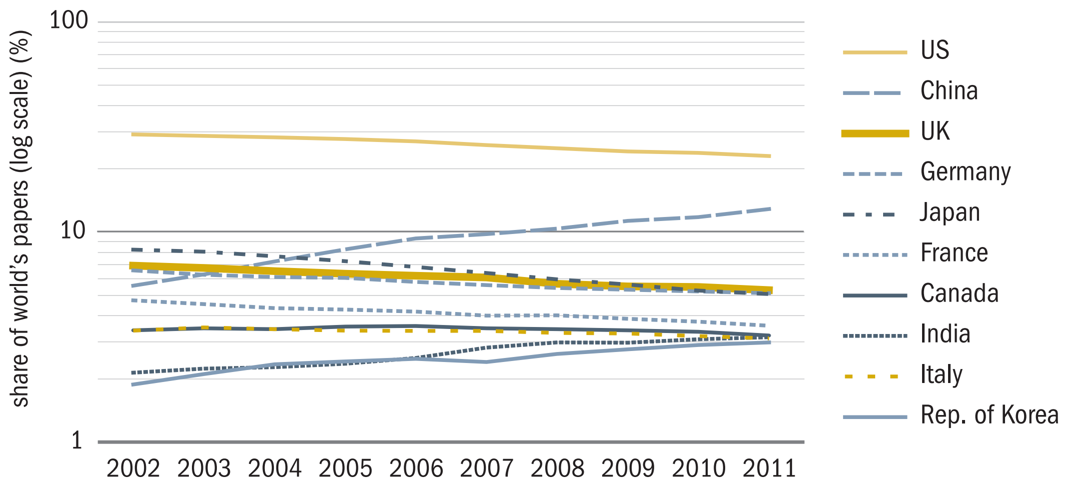
2.1. International trends in research output

The past few decades have been characterised by a rapid advancement of several countries, particularly in Asia, to the standards of living experienced in Western countries. The progress of these countries towards the world technology frontier has been accompanied by a concomitant change in the international research landscape. In particular, China, India and the Republic of Korea are growing steadily, and their growth has been accompanied by a steep increase in R&D expenditures, while, in contrast, many Western countries are struggling to increase or even to maintain their R&D expenditures, particularly because some of them have been severely hit by financial and economic downturns.

In this context, the contribution of Asian countries, particularly China, to the world research output is growing rapidly, while that of several Western countries is falling. This is not surprising because, proportionally, any growth in one country's share is accompanied by a commensurate reduction in the shares of other countries (figure 1).

Figure 1: Share of world papers of the 10 countries making the largest contribution to research, fractional-paper counting, 2002–2011

Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)



China's net contribution to science has increased from 5.6% of the authorship in 2002 to 12.9% in 2011, which is an annual average increase of 9.4% of its contribution (i.e. an increase of 9.4% each year relative to the percentage of the previous year).

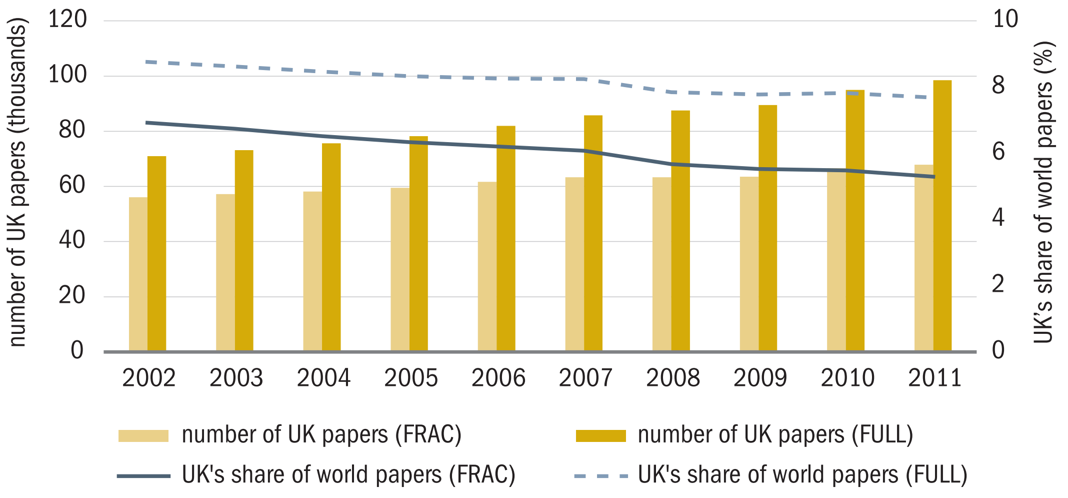
Meanwhile, the research contributions of France, the UK, Germany and the US decreased on average by between 2.6% and 3.1% per year in terms of shares of output, and Japan's relative decline was even more marked, averaging 5.4% per year. Japan's faster decline means that the UK has retained third place among countries that make the greatest contribution to science because its share of world publications decreased on average by only 3.0% per year. In 2011, the UK's share of world research output was 5.3%. France has slowed its pace, in line with a group of countries that make more modest contributions, which includes Canada and Italy. India and the Republic of Korea are currently also in this group, but have the potential to surpass their current contribution levels in the next few years if their research production continues to grow.

Although the UK and other established scientific leaders have proportionately decreased their contribution to the world scientific output, research output in the UK has increased in absolute terms (figure 2). The number of papers with at least one author with a UK address (based on full-paper counting[7]) increased from approximately 71,000 to 98,500, representing an average annual growth rate of 3.6%.

In contrast, the number of UK papers based on fractional-paper counting increased from approximately 56,100 to 67,800, representing an average growth rate per year of only 2.1%. With a negative growth rate of 1.5% per year, the UK's share of world papers decreased at a slower pace when based on full counting than compared with fractional counting. The UK's share of world papers was also higher in 2011, standing at 7.7% when based on full counting. This slower decrease in the share of full counts of publications compared with fractional counts tends to indicate that the UK increased its level of

[7] Fractional- and full-paper counting are common techniques in bibliometrics. In fractional counting, credit for co-authored papers is divided among the collaborating institutions or countries based on the proportion of their participating institution. According to this technique, when authors from three countries collaborate, for example, a third of a paper is attributed to each country. In full counting, each institution or country receives one credit for its participation in the paper. This technique is highly influenced by the collaboration rate because if the researchers of a country increase their collaboration substantially, the counting technique will show a commensurate growth in output.

Figure 2: Trend in UK-published papers and share of world papers, fractional-paper counting (FRAC) and full-paper counting (FULL), 2002–2011



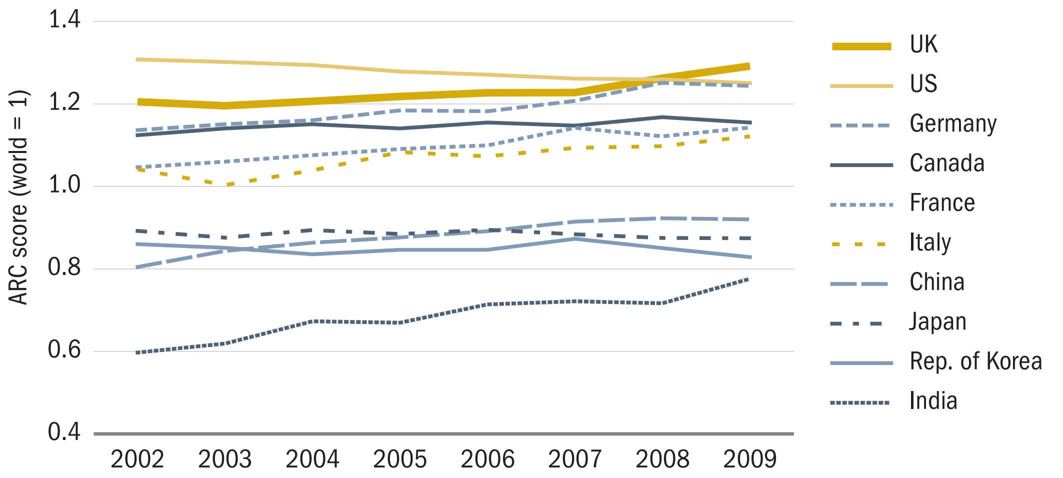
Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

collaboration at the international level over the last decade and the UK's share in fractional counting is decreasing faster because its papers are becoming more collaborative at the international level.

2.2. International trends in scientific impact

The research papers published by the UK in 2009 topped the rankings for scientific impact (figure 3), having had the highest citation rate in the subsequent two years following the year of publication (1.29), while Germany (1.24) was very close to reaching parity with the US (1.25). Canada, France and Italy had similar, fairly high impact scores in 2009. Despite their increasing contribution to the world scientific output in all research areas combined, the fastest growing countries, such as China, India and the Republic of Korea, are still lagging behind the Western countries in terms of scientific impact. In 2009, the scientific impact scores of these fastest-growing countries remained below the world average (i.e. an average of relative citations [ARC] score of 1), albeit this score increased relatively steadily in the cases of China and the Republic of Korea.

Figure 3: Scientific impact (average of relative citations [ARC]) of the 10 countries making the largest contribution to scientific authorship, 2002–2009



Publications based on full-paper counting, i.e. each collaborating country credited one count. Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

3

Scientific performance in physics in international and UK contexts

As shown in section 2, the UK has performed well in research overall during the last decade in the context of a changing international landscape. Not only has the UK successfully maintained its position in terms of scientific impact among the 10 countries that make the largest contribution to scientific authorship, its position has actually improved and it overtook the US in 2008. Moreover, the UK has been increasingly open to international scientific collaboration despite rising competition at the world level.

Against this background, this section compares the performance for a selection of leading countries in physics research to verify the extent to which the general patterns in scientific production and impact (see section 2) are observed in physics. It then compares the performance of the UK in physics research with its performance in other research fields.

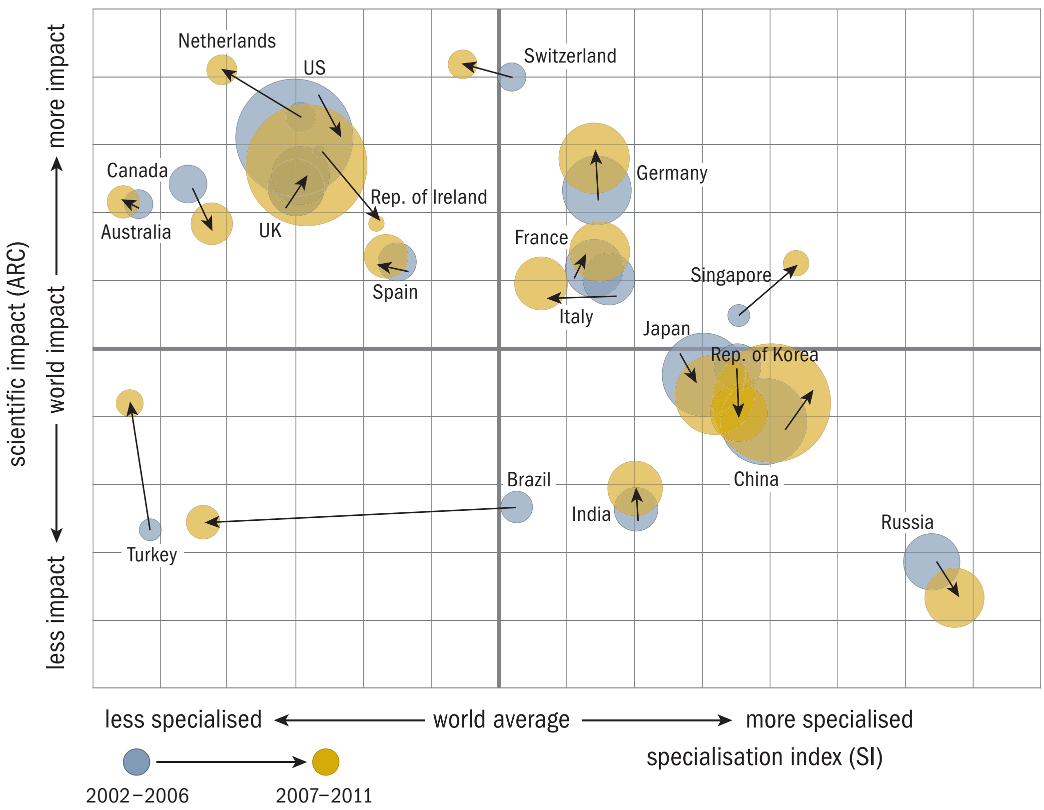
3.1. Scientific positioning of countries

The positional analysis in figure 4 highlights the most prominent features of the scientific performance of the UK (and the Republic of Ireland) and a selection of leading countries in physics research between 2002–2006 and 2007–2011. Countries are positioned in the figure based on their ARC and specialisation index (SI) scores, and the area of the circles is proportional to the number of publications. The direction of the arrows reflects the countries' changing positions from 2002–2006 to 2007–2011.

For the period 2007–2011, this positional analysis revealed four groups of countries whose composition remained relatively stable from the previous five-year period.

The specialisation index (SI) score is based on fractional-paper counting, whereas the average of relative citations (ARC) score is based on full-paper counting. The direction of the arrows and colour of the circles reflect the changing positions of countries from 2002–2006 to 2007–2011. The latest available year for the ARC scores was 2009 at the time of writing the report. (The area of the circles is proportional to the number of publications.)
Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

Figure 4: Positional analysis of selected countries in physics, 2002–2006 and 2007–2011



- **High scientific impact/strong emphasis on physics research.** Four countries are positioned in the top-right quadrant of figure 4, indicating an emphasis on physics research (i.e. specialisation) and scientific impact above the world average. These are France, Germany, Italy and Singapore. Among these countries, Germany had the highest ARC score (1.33) and Singapore placed the most emphasis on physics research with an SI score of 1.60.
- **High scientific impact/low emphasis.** A second group of countries comprises the UK, the Netherlands, Switzerland, the US, Canada, the Republic of Ireland, Australia and Spain. These are positioned in the top-left quadrant of figure 4. These countries all place comparatively little emphasis on physics research, but have a scientific impact above the world average. Among these countries, Switzerland (ARC score of 1.56) ranked first in terms of scientific impact. Australia showed the lowest level of specialisation in physics research, with an SI score of 0.54. As was observed with UK research in general (section 2), there was a noticeable increase in scientific impact between 2002 and 2009 with the UK attaining first place in 2009 among the 10 countries with the largest outputs in physics. Although the UK ranked fifth in ARC over the period 2007–2011, this was not sufficient to pull it ahead of the leaders in this group of countries for the whole of the same period.
- **Low scientific impact/strong emphasis.** A third group of countries comprising China, India, Japan, the Republic of Korea and Russia is characterised by an emphasis on physics research, but a lower scientific impact than the world average. With an SI score of 2.26, Russia was the most specialised country in this group in physics research, but lagged behind other countries in terms of scientific impact.
- **Low scientific impact/low emphasis.** A final group of countries (Brazil and Turkey) placed low emphasis on physics and had a lower scientific impact than the world average.

The positional analysis demonstrates that, unlike the UK, many emerging scientific leaders (e.g. China, India and the Republic of Korea) and some of the more established research leaders (e.g. Germany and France) are placing more emphasis on physics than on the world average. Additionally, all of these countries, with the exception of the Republic of Korea, increased their scientific impact between 2002–2006 and 2007–2011.

3.2. International trends in scientific output

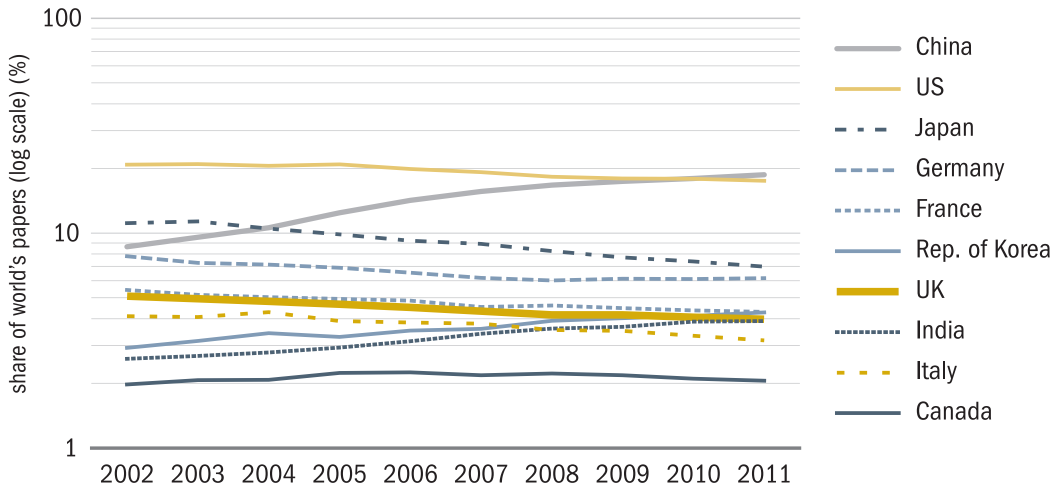
Echoing the downward trend observed in all research areas combined, physics has been affected by emergent scientific leaders alongside the UK's traditional scientific competitors. In 2010, China overtook the US as the country with the highest number of authors on physics papers and the gap between these two countries is widening (figure 5). The other significant countries that are well established in physics – Japan, Germany, France and the UK – are currently showing a slower rate of growth and the Republic of Korea has overtaken the UK, with India close to achieving the same status. Given current trends, the UK is likely to rank eighth at the world level in the near future for its contribution to physics knowledge in terms of the volume of papers published.

For the UK in particular, scientific output in physics grew on average by 2.7% a year (from 2002 to 2011) according to the full-paper-counting method and by 1.2% according to the fractional-counting method (figure 6). These growth rates are lower than those observed at the level of all research areas combined.

Despite an increase in the absolute number of UK papers in physics research between 2002 and 2011, compared with the world's total output, the UK's importance as a producer of physics knowledge dropped on average by 1.2% a year based on full-paper counting and by 2.8% a year on average when the share of world papers is based on

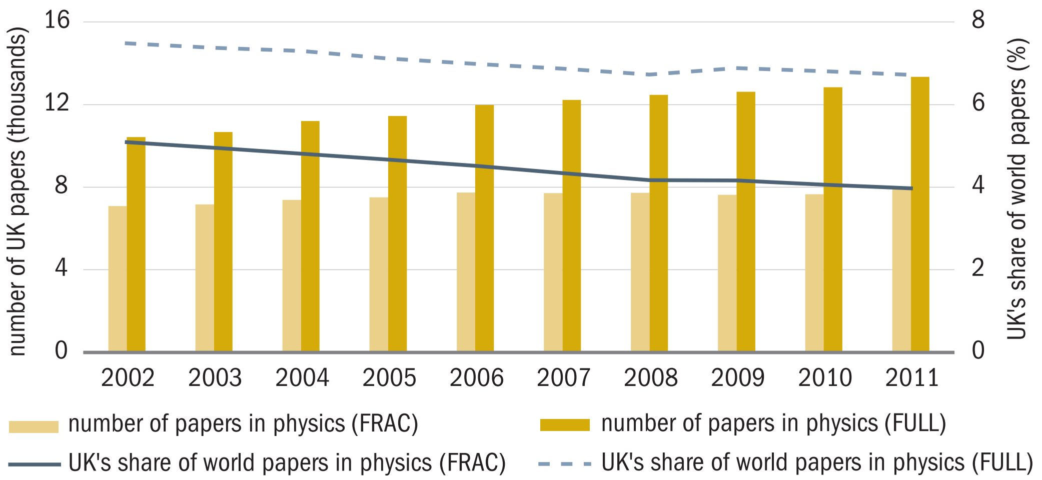
Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

Figure 5: Share of world physics papers of the 10 countries with the largest contribution to scientific authorship, fractional-paper counting, 2002–2011



Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

Figure 6: UK papers in physics and share of world papers in physics, fractional-paper counting (FRAC) and full-paper counting (FULL), 2002–2011



fractional counting. Nevertheless, these falls in percentage output are slightly lower than those observed (see section 2) for all research areas combined.

As in other research areas, the difference in the growth rates of UK papers based on full and fractional counting indicates an increasing propensity to collaborate internationally. However, the difference in levels partially reflects the contribution of large-scale, high-energy physics projects, where papers are authored by hundreds of researchers from tens of countries. These papers present challenges in the measurement of scientific output in physics. Indeed, physics is a field with large variations in authorship, ranging from few authors in theoretical physics to large teams of researchers in "big science" projects using multi-billion-pound equipment. To alleviate the distortions created by a large number of authors in physics, it is preferable to rely on fractional counting for output indicators, while retaining full counting for indicators of collaboration.

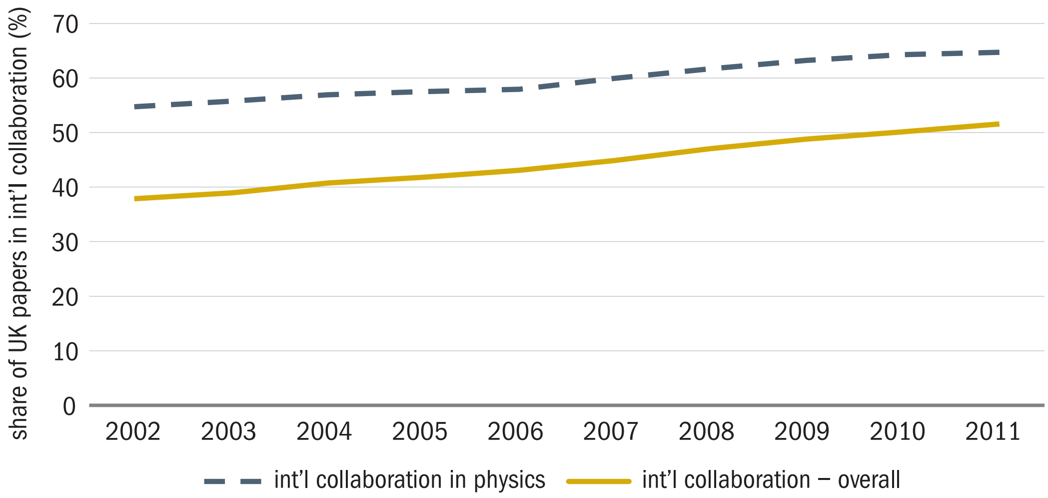
Based on the fractional-counting technique, the UK's net contribution to the production of new knowledge in physics decreased to 4.0% in 2011 (compared with slightly more than 5.1% in 2002), which is 1.3 percentage points below its net contribution in all research areas combined.

3.3. UK trends in international scientific collaboration

The increasing trend of international collaboration in scientific production in physics research can be demonstrated by using the international collaboration rate, which measures the share of internationally co-authored papers in all papers in the field. The UK's rate of international collaboration increased on average by 1.8% per year between 2002 and 2011 (figure 7). Currently, nearly two out of three UK papers in physics have at least one author with an address in a country other than the UK, compared with half of the UK papers in all research areas combined.

The trend of increasing international scientific collaboration has been reinforced over recent years by emergent leaders on the international scene in physics. Not only has the UK increasingly collaborated with other well established scientific leaders, but it has

Figure 7: UK papers with at least one international co-author, 2002–2011



Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)

also engaged in collaboration with emerging countries.

Table 1 lists some of the most important scientific partners of the UK in physics research between 2002 and 2011 based on the share of total UK collaborative papers at the international level. The US was clearly the UK's largest collaborator, being present in 24% of the UK's internationally co-authored publications in physics. Other well established scientific leaders – such as Germany, France and Italy – were also among the most important UK collaborators in physics. At the same time, UK researchers co-authored papers in physics with researchers from China, India and the Republic of Korea.

It is also interesting to note the countries with which the UK had a greater than expected propensity to collaborate in physics research. An affinity index was used to examine this, which considers the size of a country's scientific output and indicates whether they collaborated more than expected given their output size (score >1.0 for positive affinity).

The UK showed a strong affinity towards the Netherlands (2.34), Switzerland (1.89), Italy (1.58), France (1.54), Canada (1.47) and Germany (1.41), but it collaborated less than expected with China (0.34), India (0.45), the Republic of Korea (0.46) and Japan (0.51), even though these are all relatively important collaborators in terms of absolute numbers of collaborations (all in the top 20 most important UK collaborators). The Netherlands showed a strong, reciprocal affinity for the UK (2.34), as did Canada (1.83). The US also showed a strong affinity for the UK (1.74), which is a high level of affinity not shared by the UK (1.00).

3.4. International trends in scientific impact

Despite the decline of its world share in physics, the UK continually improved its scientific impact (figure 8). Although the US had the highest ARC score among the 10 leading countries from 2002 to 2008 (as also observed in research overall – see section 2),

Table 1: Selection of important countries for UK collaboration in physics, 2002–2011

Country	Share of the UK's international collaboration (%)	Affinity of the UK for this country	Increase in ARC for the UK (%)	UK share of the country's international collaboration (%)	Affinity of this country for the UK	Increase in ARC for the country (%)
US	23.6	1.00	46.4	11.5	1.74	38.5
Germany	10.1	1.41	44.5	7.0	1.05	43.4
France	8.1	1.54	36.5	7.7	1.36	54.1
Italy	7.2	1.58	37.2	11.3	1.52	59.2
China	4.5	0.34	36.6	6.4	1.04	92.7
Japan	4.2	0.51	48.0	6.7	1.09	99.3
The Netherlands	3.1	2.34	40.2	9.0	2.34	22.3
Russia	3.0	0.84	47.5	4.6	0.72	167.1
Canada	2.8	1.47	74.6	6.7	1.83	79.3
Switzerland	2.2	1.89	77.9	5.7	0.95	48.1
Republic of Korea	1.2	0.46	82.2	4.1	0.73	147.4
India	1.2	0.45	89.3	5.1	0.85	204.7

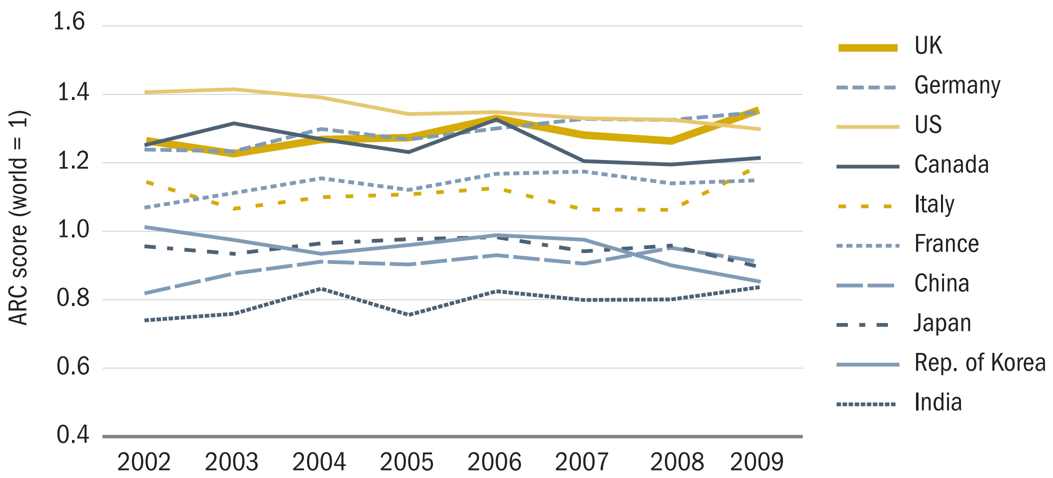
Publications based on fractional-paper counting, i.e. for publications with collaborating institutions from multiple countries, each country receives fractional credit on the basis of proportion of its participating institutions. Colour coding for the affinity index ranges from light yellow (weak affinity) to dark yellow (high affinity), with mid-yellow as the intermediate level (i.e. the level of expected affinity). Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters) it was overtaken by the UK in 2009. In 2009, the UK ranked first in terms of scientific impact in physics, with an ARC score of 1.35, which was only slightly above that of Germany and the US, but was noticeably above that of Canada, with which the UK was mostly level between 2002 and 2006.

Part of the UK's high ARC score in physics derives from internationally co-authored papers. Indeed, an important aspect of international collaboration is that it frequently leads to the production of more highly cited publications. Table 1 identifies the UK's most important collaborators in physics and demonstrates the gains made in terms of scientific impact through these collaborations. Available data confirm that internationally co-authored publications in physics produce clear gains in scientific impact. The UK and all of its principal partners experienced an increase in their ARC scores in these collaborations. For instance, publications co-authored with the US resulted in increases of 46% and 38% for the UK's ARC score and the US's ARC score in physics, respectively. China's ARC score was 93% above its base level and, in turn, the UK co-authored papers had an average score 37% above the UK's score in physics. The UK increased its scientific impact the most when it collaborated with India, the Republic of Korea, Switzerland, Canada, Japan, Russia, the US and Germany.

In a context in which the relative output of Western countries is diminishing to the benefit of emerging countries, it is important for Western countries to maintain a lead in quality, and endeavour to increase quality and scientific impact. In this regard, the UK has been able to perform well during the last decade. Not only has it maintained its position among the 10 countries that make the largest contribution to scientific authorship in physics, but it has also improved its impact. In the next decade, this will become a greater challenge as both emerging and more established leaders strive to increase the quality of their scientific production and as competition to publish in the best journals intensifies.

Figure 8: Scientific impact (average of relative citations [ARC]) in physics of the 10 countries making the largest contribution to scientific authorship, 2002–2009

Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)



4

Comparison of the UK's scientific performance in physics and other research fields

As shown in section 3, the UK's performance in physics has followed a similar pattern to its performance in all research areas combined. In particular, the UK's share of world papers in physics research has been falling, in line with its well established competitors, following the rapid growth of emerging scientific leaders in physics, mainly from Asia. However, the decrease of its world share in physics has been slightly less marked than that in all research areas combined. Moreover, although the UK is placing less emphasis on physics than its leading competitors, it has succeeded in achieving the highest scientific impact among the 10 largest publishing countries in physics.

This section goes further in the analysis of the UK's scientific performance in physics research by comparing it with that in other fields of the natural and applied sciences.

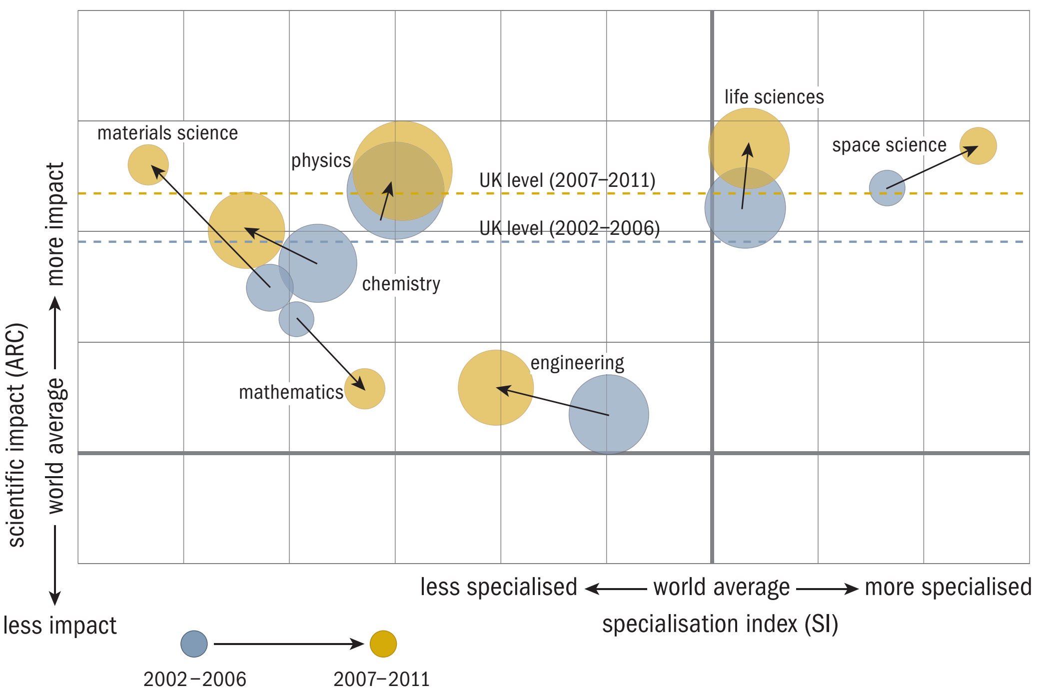
4.1. Scientific positioning of physics and other research fields in the UK

As noted in sections 2 and 3, in 2009 the UK led the world in terms of scientific impact both in research overall and in physics. The following positional analysis examines how the UK's research output in physics compares with that in fields with which physics sometimes overlaps, such as chemistry, engineering, materials science, mathematics and space science[9].

Figure 9 shows the UK's scientific output in physics and these other fields over the 2002–2006 and 2007–2011 periods. The direction of the arrows reflects the changing positions of the UK from the earlier period to the more recent period. Over these two periods, the UK published the largest number of papers in physics (approximately 75,500), followed by the life sciences (50,900),

[9] These comparator fields were selected in consultation with IOP, EPSRC and STFC. Several of these fields (i.e. chemistry, engineering, mathematics and space science) were also used as comparator fields in a bibliometric analysis undertaken for IOP (*Bibliometric Evaluation and International Benchmarking of the UK's Physics Research: Physics and Sub-Disciplines*, report prepared by Evidence for the Institute of Physics, London: Thomson Reuters, 2012). For the purposes of the bibliometric analysis, space science should be considered to refer to the more applied/engineering aspects of the field (i.e. the development of satellites/hardware, as opposed to the study of astronomy/cosmology).

Figure 9: Positional analysis of UK papers in selected fields, 2002–2006 and 2007–2011



The specialisation index (SI) score is based on fractional-paper counting, whereas the average of relative citations (ARC) score is based on full-paper counting. The direction of the arrows and colour of the circles reflect the changing positions of countries from 2002–2006 to 2007–2011. The latest available year for the ARC scores was 2009 at the time of writing the report. (The area of the circles is proportional to the number of publications.) Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters) engineering (46,900), chemistry (46,700), materials science (16,800), mathematics (11,100) and space science (10,200). The number of UK papers published in each field did not fluctuate substantially between the two periods.

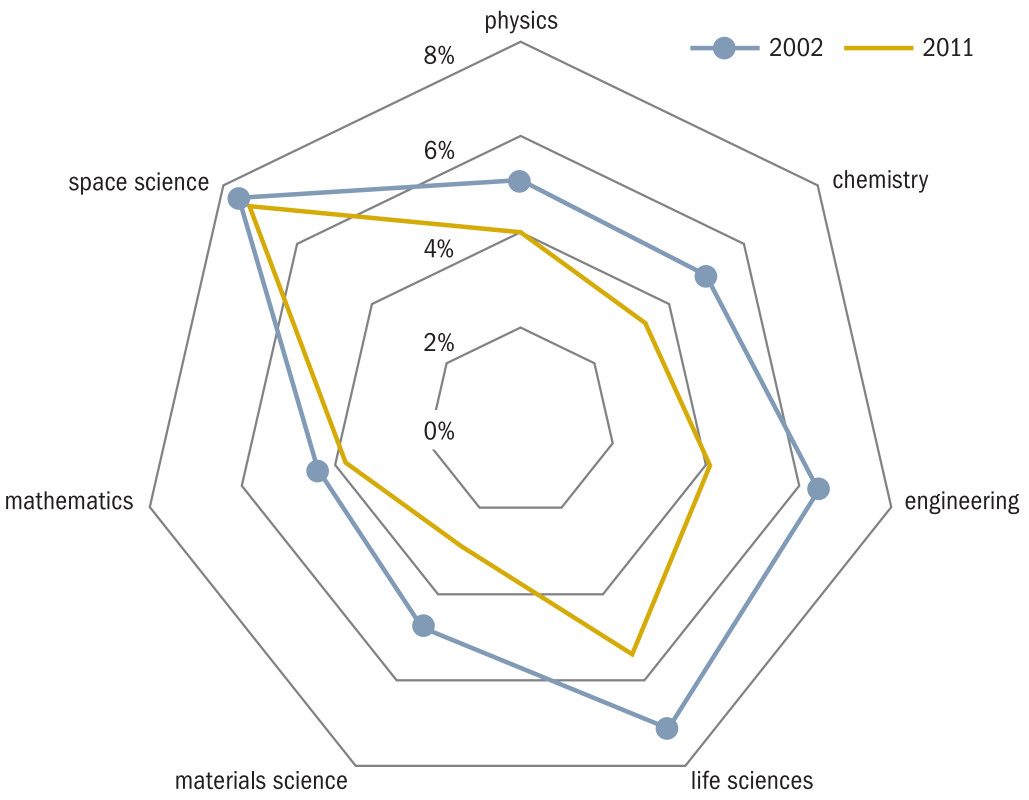
During 2007–2011, greatest emphasis (SI) and greatest scientific impact (ARC) were the hallmarks of the life sciences and space science (top-right quadrant of figure 9). The UK's ARC scores in these fields were both 1.33, while its SI scores were 1.04 and 1.29, respectively. However, physics was similar to the life sciences and space science in that it had a high scientific impact (ARC 1.30).

The remaining fields – physics, chemistry, materials science, mathematics and engineering – are in the top-left quadrant. This indicates that the UK's scientific impact was above the world average in all of these fields over the 2002–2006 and 2007–2011 periods, but that the UK did not specialise in them (i.e. its share of all UK papers in these fields was lower than that observed at the world level). For instance, the UK's SI in physics was 0.75. Nevertheless, among the fields in the top-left quadrant, physics showed the highest impact over both the 2002–2006 (1.27) and 2007–2011 (1.30) periods, which is above the UK's scientific impact of 1.21 (2002–2006) and 1.26 (2007–2011) for the whole of Web of Science in the corresponding periods. Coming back to the 2007–2011 period, physics' impact is equal to that in materials science (1.30) and slightly below that in the life (1.33) and space sciences (1.33). In contrast, the UK's ARC scores in chemistry (1.23), engineering (1.06) and mathematics (1.06) were all lower than its ARC score in all research areas combined, and lower than its score in physics research.

Improved ARC scores from 2002–2006 to 2007–2011 were observed for physics and all of the comparator fields, with the exception of mathematics. However, only space science and mathematics and, to a lesser extent, the

Figure 10: The UK's share of world publications in physics and comparator fields, 2002 and 2011

Source: Computed by Science-Metrix using the Web of Science (Thomson Reuters)



life sciences and physics, experienced an increase in emphasis.

4.2. Trends in the UK's share of world scientific research output

The observed downward trend in the UK's contribution to world publications in physics between 2002 and 2011 can also be observed in other selected scientific research fields (figure 10), echoing the general decrease of the UK's contribution to world publications in all research areas combined. However, the decline of the UK's share of world publications was less marked in physics than in the other selected scientific research fields. The decrease of the UK's share of world publications was much stronger in materials science (−5.6% per year on average) and engineering (−5.0%) than in physics (−2.8%). Moreover, the UK's share of world publications fell on average by 3.1% per year in the life sciences, but the shrinkage of the UK's contribution to world publications was less substantial in space science (−0.4%) and in mathematics (−1.6%).

Nevertheless, by 2011 the UK's contribution to world publications was lower in physics than in a number of other scientific research fields. For example, the UK's share of world publications was higher in space science (7.3%), the life sciences (5.4%) and, to a lesser extent, engineering (4.1%). However, it was lower in materials science (2.9%), chemistry (3.3%) and mathematics (3.8%).

5

Impacts arising from physics research

Despite the major changes that have occurred over the last few decades in the international scientific landscape (e.g. the emergence of new large scientific leaders), this report has illustrated the UK's scientific excellence in physics research. These changes have placed mounting pressures on the UK to maintain a strong and world-leading scientific base in physics research, while also reaping the benefits from international scientific collaborations with both its traditional competitors and the emerging countries in physics.

In a context of increasing demand for public funding accountability, maintaining a strong and excellent scientific base in physics research may not be an end in itself. The UK can seek to maximise the benefits from this scientific base to increase its contribution to the economy and society. Several recent studies have underlined the large direct, indirect and induced effects of physics research for the UK economy and other countries, in terms of increases in gross value added and in employment[10].

To examine these effects further, qualitative interviews were conducted with UK researchers in four physics-based research clusters (applied superconductivity and materials science; astrophysics and space science; cosmology, quantum field theory and particle physics; and imaging techniques and algorithms)[11]. The information gathered through the interviews, presented here in the form of case studies, sheds light on the pathways leading to such wider social and economic impact. A total of 50 clusters (i.e. subsets of articles highly relevant to a specific topic) were selected using topic-modelling techniques on all physics publications and were whittled down to four clusters where UK research displayed excellence, as indicated by high levels of scientific impact, specialisation and growth[12]. Consequently, even if these clusters do not represent all of physics research, they are to an extent representative across the physics community in the UK.

5.1. Physics clusters – case analysis

Comparing results across the four selected clusters, several interesting findings emerged. All four clusters provided clear examples of industrial benefits, as researchers worked with both large multinational companies and local UK service providers to develop new scientific instrumentation or techniques. In each cluster there were also examples of licences, spin-outs or joint ventures. Interviewees from all four clusters also placed a strong emphasis on the training of skilled graduates, with students moving on to jobs ranging from health to media and nuclear power. Not only does this enhance knowledge flow from academia to industrial sectors, it can also be the stimulus for further interactions between sectors.

Regarding the eight Great Technologies for the UK set out by the Chancellor of the Exchequer in 2012[13], "big data" and "advanced materials" were cited by interviewees working in three of the four clusters as areas where research in these clusters would have the most impact. Additionally, although publications and reports were still considered the most important conduits for knowledge within the academic community, interviewees also noted other useful avenues of knowledge flow. For example, the majority of the interviewees encouraged personnel exchanges or secondments as one of the most successful ways to facilitate the passage of new information and ideas between organisations.

The following sections present more details on salient findings per cluster. Note that these are based on a small number of qualitative interviews and are intended to present a complementary perspective to the quantitative results presented earlier in this report, as opposed to a set of generalisable statistically significant observations.

[10] *The Importance of Physics to the UK Economy*, London: Institute of Physics, 2012; *The Importance of Physics to the Economies of Europe*, Mulhouse, France: The European Physical Society, 2013.

[11] For the cluster analysis, physics publications were aggregated by topics using a topic-modelling approach (latent Dirichlet allocation) based on semantic proximity. Although space science is viewed as distinct from physics because it was defined for the bibliometric analysis by means of the Essential Science Indicator classification, some of the physics publications are close to the field of space science. These publications were thus aggregated by the topic-modelling algorithm in a cluster entitled "Astrophysics and space science".

[12] The final selection of clusters was made by IOP, EPSRC and STFC.

[13] Willetts D 2013 *Eight Great Technologies*, London: Policy Exchange.

5.2. Applied superconductivity and materials science

Objectives and funding sources

This cluster lies at the border of physics, presenting close ties with engineering and materials science. Its core focus encompasses applied sciences closely related to advanced materials with fundamental properties such as superconductors and magnetic materials.

Interviewees in the applied superconductivity and materials science cluster placed high importance on the use of their research outside the realm of the public research sector. Indeed, as indicated by its name, the broader objectives of the research in this cluster are relatively more applied, from solving problems facing the mainstream microelectronics industry, to exploring applications of materials for a range of markets such as wireless communications, solar cells, water purification or energy storage, and developing engineering applications of superconductors.

In terms of funding sources, all interviewees in this cluster cited regular project funding from industry in addition to the more traditional institutional and project-based public funding (e.g. EPSRC, the Technology Strategy Board). For instance, to carry out research projects, interviewees took advantage of public–private partnerships aimed at stimulating European industry (e.g. the ENIAC Joint Undertaking, co-funded by the Technology Strategy Board), as well as contracts with local companies.

Collaborative modes of research

Interviewees stated that applied superconductivity and materials science borrows techniques from computer modelling, materials processing and manufacturing, and electrochemistry. As Prof. Maria Merlyne De Souza at the University of Sheffield explained: "I just pick up from whatever discipline I need to, sometimes even from chemistry. They talk a different language, but it ultimately boils down to the same thing. I just borrow from whatever discipline I need in order to solve the problem." Interviewees also emphasised the importance of multidisciplinary (e.g. engineering and materials science) and interdisciplinary (e.g. electroengineering and chemistry) research, although the balance between the two varies according to each interviewee's personal research agenda and background.

Interviewees also indicated that they regularly collaborate with local companies. As stated by Dr Tim Coombs at the University of Cambridge: "What tends to happen is the industrial collaborations tend to be within the UK, the academic collaborations tend to be outside the UK. But neither is mutually exclusive." This was reflected by other interviewees who noted that they work mostly with local UK companies because this is where the practical expertise lies within this cluster. Conversely, international collaborations were generally with other universities or research organisations, such as the Chinese Academy of Sciences.

Achievement of expected outcomes

The following two Great Technologies were singled out as areas that make the greatest contribution to research in this cluster.

- **Advanced materials.** Work in this area is currently focused on single- or few-layer materials such as carbon nanotubes, graphene, molybdenum disulfide and phosphorene. Researchers in this cluster both contribute to and use these research results, and as the materials are improved, the range of applications for which they can be used expands.
- **Energy storage.** Following on from the above, the development of new materials or tools in this cluster also feeds into new ways to store and convert energy for more efficient batteries that are urgently required for the smart grid.

Research in the cluster goes beyond increasing the stock of useful knowledge for industry. For instance, all interviewees highlighted the training of skilled graduates as an important benefit to industry, giving examples of former students who are now working for multinational companies. The advantage of having an outflow from academia to industry is the potential stimulus for further interactions between the sectors in the future. As noted by Prof. De Souza: “It’s our job to train people and to make sure that they have the skills to solve the problems, not just thinking in the short term, but globally as a society, we know what we need to resolve in the next 20–25 years. There are roadmaps in place and we need to develop this capacity and make sure that we deliver.”

The contribution of research in this cluster to an increased capacity for scientific and technological problem-solving is also perceived to be high, particularly for the industrial base. The main industries that use the research results of this cluster range from technology manufacturers, consumer goods, aerospace, water, electricity generation and supply companies, as well as materials-instrumentation companies both within and outside the UK. Interestingly, all interviewees indicated that the time lag between research outputs in this cluster and their application by industry varies immensely, from less than a year (e.g. incremental improvements to materials) to more than 10 years (e.g. work on cadmium telluride semiconductors, now being used for photovoltaics).

Finally, most of the interviewees in this cluster were involved in their own start-ups or spin-out companies that resulted from their research and collaborations with UK companies. For example, a strong partnership between Durham University and industrial collaborators has resulted in two successful start-ups to date. One of these companies, Bede Scientific Instruments (now Jordan Valley Semiconductors [UK]), manufactures X-ray tools for the semiconductor industry, and the second, Kromek, specialises in the fabrication of X-ray detectors based on the semiconductor cadmium telluride. Kromek employs more than 100 people in the UK and the US, and floated on the London AIM Stock Exchange in October 2013.

Channels of knowledge flow

For interviewees in this cluster, personnel exchanges and secondments were the most important source of knowledge exchange. Interviewees who had the opportunity to spend time at various industrial research laboratories around the world stated that this was a useful learning experience that “widens horizons”. Even smaller knowledge transfer programmes that enable student exchanges or short-term placements with local companies are beneficial in facilitating direct contact with industrial partners.

Similarly, joint or co-operative ventures and consulting practices were also considered to be beneficial. These avenues of knowledge flows not only encourage rapid problem-solving, but also help to orientate the research in this cluster towards boosting the overall competitiveness of the related industrial sectors.

Finally, publications and reports were considered to be a main knowledge conduit for academia, whereas conferences and presentations were considered to be a better way to engage with industry partners.

5.3. Astrophysics and space science

Objectives and funding sources

In a broad sense, the aim of the research included in the astrophysics and space science cluster is to explore physics at the extremes, from high to low densities, from strong to weak magnetic fields and from the formation to the death of stars. As such, the fundamental understanding of scientific problems is of high importance in this cluster. Theoretical aspects of the field, such as the development of models, are covered, as well as experimental aspects (e.g. radio observation). Publications in this cluster serve the purpose of describing the universe and providing an understanding of phenomena related to celestial objects in the universe.

Most astrophysics and space science work is funded through a variety of government sources, either nationally through the UK Research Councils such as STFC or internationally through the European Commission. Other funding sources are the private, not-for-profit sector, including the Royal Society and the Leverhulme Trust.

Collaborative modes of research

Although research in this cluster does borrow techniques from other disciplines such as computer science and mathematics and, to a lesser extent, biochemistry and engineering, interviewees said that their research tends to be less multidisciplinary and interdisciplinary than in the other clusters.

Importantly for this cluster, many collaborations are dictated by the physical location of the facilities (e.g. telescopes and observatories). As such, UK researchers often form collaborations with NASA, member states of the European Space Agency and the Japan Aerospace Exploration Agency. As summarised by Prof. Andy Fabian at the University of Cambridge: “If you want to use the top facilities in the world, then they are not necessarily all British. In terms of access to space using telescopes, then the major nations that have launched them are basically the US, [member states of] the European Space Agency, which includes the UK, and Japan.” However, these are not the only collaborators, and one interviewee noted that his particular sub-field of astrophysics has historically included a large effort from Germany, the Netherlands and Spain, with less involvement from the UK and the US.

Achievement of expected outcomes

Three of the eight Great Technologies are relevant to the astrophysics and space science cluster as described below.

- **Big data and energy-efficient computing.** There are multiple connections with this priority area because large optical surveys of the sky produce large data sets and require high performance and efficient computing capabilities. Now and in the future, a major challenge in this cluster will be to find ways to exploit and sufficiently analyse the big data being collected by observatories around the world.
- **Satellites and commercial applications of space.** This priority is a clear fit with this cluster because satellites are benefiting from major improvements from research in this field. Examples include new on-board sensors, superior satellite imagery apparatus and improved understanding of solar storms, which allows for better satellite protection.
- **Robotics and autonomous systems.** Autonomous systems for operating satellites in space are heavily relied on in this cluster. As noted by researchers, this is less of a priority than the above two areas, but it remains important to continue development in this area.

Research in this cluster is perceived as having a high relevance for industry through an increasing capacity for scientific and technological problem-solving. As noted by Prof. Fabian, the detectors used today in household cameras and smartphones were the result of problem-solving undertaken by astronomers: “Astronomers are extremely good at making very sensitive detectors. In most other branches of science, if you haven’t got enough light on what you want to image or study, you just turn the brightness up. Astronomers can’t do that because you can’t make a star brighter or a galaxy brighter. We just have to make the detector a lot better. So that’s a big area, I would say, that astronomy over the last 50 years has made a contribution to.” Another example stems from the way in which astronomers analyse their data and images. Prof. Paul Crowther at the University of Sheffield reported that one of his colleagues had implemented an algorithm that elegantly scans and pulls out unusual sources from astronomical data sets. The same technique has been applied to medical microscopy imaging to automate the detection of cancerous cells and other anomalies, a technique that has the potential to save lives by improving early treatment.

All interviewees also agreed that industry has greatly benefited from the production of skilled graduates. According to

Prof. Crowther: "That's really one of our main outputs, in terms of getting students through the system and learning to do problem-solving, and then they go off into industry. We have a student who just graduated last year and is now working on designing nuclear power plants for submarines."

Although the aerospace industry in the UK and elsewhere in Europe is recognised as the main industry to use the research outputs from this physics-based cluster, some interviewees mentioned that other industries are also likely to use their findings. These may be transformed into commercial benefits within five to 10 years. As stated by Prof. Martin Barstow at the University of Leicester: "There is also a lot of spin-out into sensor systems associated with areas like medical research, but also increasingly aspects like security, recognition of counterfeit materials and objects. So, it's anything to do with recording images or spectral information that can be applied."

Channels of knowledge flows

Interviewees highly rated the publication of articles and reports as a source of information flow, mainly to the academic community. Alternatively, conferences, seminars and other public meetings presented opportunities for the interviewees to engage more strongly with industry representatives, and also allowed for informal discussion and knowledge exchange. Interviewees in this cluster also participated in industry secondments or the Knowledge Transfer Partnerships programme run by the UK's Technology Strategy Board. Joint ventures were also useful to exchange knowledge, one example being a partnership between a university and Astrium, a large European provider of space-based services. According to Prof. James Hough at the University of Hertfordshire, this helped to create a lasting partnership for future space-science missions: "Linking with people who are driven by scientific interests, invariably involving cutting-edge technologies, is incredibly useful for space companies or satellite companies because it gives them a chance to further their own horizons."

Conversely, interviewees noted that the work in this cluster could make an effort to contribute more to patents, licensing and spin-outs than it currently does. These avenues were recognised as effective knowledge-flow mechanisms, although the general consensus was that this cluster was "slow on the uptake" in these particular areas.

Finally, interviewees were positive about public engagement and outreach as a form of wider social knowledge dissemination. They often collaborate with schools, provide continuing professional development for teachers and open their observatories or facilities for hands-on experience and tours. In this way, research in this cluster contributes to continuing education, teaching and learning opportunities.

5.4. Cosmology, quantum field theory and particle physics

Objectives and funding sources

From attempting to solve unanswered questions in particle physics to mathematically describing black holes, the overall research goals in the cosmology, quantum field theory and particle physics cluster stick closely to a fundamental understanding of the structure of the universe. There is a strong emphasis on core theoretical subjects in space science, such as string theory and general relativity[14]. Consequently, this cluster has a strong proximity with mathematics as its principal tool for developing models. However, interviewees in this cluster observed a recent shift towards research that is more focused on practical applications.

The main funding sources include the UK Research Councils, such as STFC and EPSRC, as well as the European Commission and the European Research Council, although sometimes industry provides in-kind resources such as computing hardware and software.

[14] The definition of space science used for the research cluster analysis is different from the comparator in the rest of the report, which focuses on the more applied/engineering aspects of the field.

Collaborative modes of research
Research in this cluster involves borrowing knowledge and specific techniques from mathematics and statistics. Most of the interviewees noted the importance of multidisciplinary and interdisciplinary work, not only relying on, but actually driving development in the latest computational, engineering and mathematical techniques.

Moreover, every interviewee indicated the critical importance of international collaboration. Interviewees said that 50–90% of their collaborations were with teams based outside the UK, not only because international ties are traditionally strong (e.g. based on the work of CERN) but also because the large infrastructure (e.g. Large Hadron Collider) required for this type of research cannot be built with national resources alone. In the words of Prof. Chris Sachrajda at the University of Southampton: "The research that's been done at CERN with the discovery of the Higgs [boson] can only be done on a big international scale with everyone contributing their expertise and creativity as well as their pounds or dollars or euros together," and Prof. Christine Davies at the University of Glasgow: "You have to be working at the international forefront otherwise you're not doing anything. That means you've got to engage with the international community very strongly. It also allows you to tap into funding streams in different countries."

Achievement of expected outcomes
According to the interviewees, the work conducted as part of this cluster contributes to the following of the eight Great Technologies.

- **Big data and energy-efficient computing.** Typical experiments in quantum-field theory and particle physics require high-performance computing and data analysis. This has resulted in a highly productive feedback loop where the demand for faster and better data-processing techniques drives developments in this area. As noted by Prof. Davies: "The needs in our field for very high-performance computing have to some extent driven the development of computing. A lot of people have moved from my area into these computing companies, driven by the fact that they've been well trained in using computers as part of our work."
- **Advanced materials.** Studies in high-temperature superconductivity, superfluidity and condensed matter have contributed to new analytical techniques that in turn drive developments in the construction and characterisation of new materials.
- **Satellites and commercial applications of space.** Increasingly, research in cosmology and into black holes is being performed via satellites (rather than ground-based observatories) and the technology is continually being evolved to meet these needs.

Interviewees cited many examples of derived industrial benefits, which usually arise in the medium- to long-term. Examples of the creation of new scientific instrumentation and techniques include:

- the development of a commercial weather forecasting tool for the ionosphere;
- improved cooling and vapour technology used in a variety of industrial applications;
- precision detection equipment developed for space systems but now used by large computing companies such as Dell and IBM; and
- new computer algorithms that have been used by small software engineering companies.

Interviewees were emphatic that a key contribution of researchers in this cluster was the ability to train students and postdoctoral researchers with "mathematical, computational, problem-solving, instrumentation" and other wide-ranging skills that are transferrable to other positions. Indeed, interviewees cited instances of postdoctoral researchers who moved on not only to faculty positions, but also to industrial R&D laboratories, private equity companies and computer-related businesses. Examples also include high-ranking positions such as a board of directors, member of a national media-related company and a CEO of an insurance company.

Additionally, forming networks and stimulating social interaction is also viewed as a key contribution of research in this cluster. Although this may not lead to direct industry benefits, the researchers' ability to network, particularly internationally, has resulted in clear social benefits. As most interviewees noted, the best example is the World Wide Web, which originated from CERN in 1989 and completely revolutionised global and social interaction.

Channels of knowledge flow

Researchers in this cluster use multiple channels to disseminate and transfer knowledge from the academic world to the wider social and economic environment.

Primarily, as befits the more basic sciences, all interviewees cited peer-reviewed publications and reports as their main form of knowledge dissemination. Conferences and seminars (e.g. the European Physical Society Conference and the EuroScience Open Forum) were also mentioned as avenues to engage multiple audiences (although it was recognised that some of these were still mostly academic).

Graduates and postgraduates recently hired by sectors outside academia (as noted previously) were also a key knowledge transfer link. Although the skillset gained by working within the cluster promotes desirable employees, graduates will also transfer ideas and research capacity to the public or private organisations where they have been recently hired. As noted by Prof. Thomas Mohaupt at the University of Liverpool: "The typical pattern is that only a very tiny minority can stay for life in the kind of research we are doing. Many people in various levels have to make a change of career. And that I think is one of the most important pathways in which knowledge is transferred out of our sector." Similarly, public programmes to foster knowledge exchange (e.g. the Marie Curie Fellowships, early-career research grants) are often used by researchers in this cluster and increase knowledge mobility.

Specifically on economic or social impacts, interviewees noted, in order of importance, the following pathways of knowledge flow.

- **Joint or co-operative ventures.** For example, interviewees collaborated with computing manufacturers and software companies to build the DiRAC[15], which is an integrated supercomputing facility for theoretical modelling and research in particle physics, astronomy and cosmology. Currently, the publically funded DiRAC facility sells time for its use by industry, thus not only bringing in revenue, but also facilitating academic–industry exchange.
- **Contract research and/or consulting.** As Prof. Jon Butterworth at University College London explained: "We place contracts with industry rather than the other way around." However, this remains an effective way to transfer knowledge because as the researchers work with the companies, the companies "get up to speed" on the researchers' needs and can then go out to bid for more contracts.
- **Patents and licences.** For example, collaborators of one interviewee have patented and licensed a chip for the IBM supercomputer project Blue Gene[16].

5.5. Imaging techniques and algorithms

Objectives and funding sources

This cluster covers a wide range of physics sub-disciplines given that most research topics require the use of tools to describe and characterise their respective studied systems. However, the most frequent topics covered in this cluster are medical physics and materials engineering, both heavily relying on tools that stem from physics research. Other topics covered in this cluster include face- and speech-recognition algorithms, computer

[15] Distributed Research utilising Advanced Computing, **www.stfc.ac.uk/1263.aspx**.

[16] IBM Icons of Progress, Blue Gene, **www-03.ibm.com/ibm/history/ibm100/us/en/icons/bluegene/**.

vision and many other topics closely related to applied physics.

Support for this cluster is from a wide range of sources. The UK research councils such as EPSRC often provide grants, but work also proceeds through co-funding arrangements involving university partners and several industrial companies. Other projects are fully funded by large private enterprises or medical charities. In the last two cases, interviewees describe the process as more "top-down" in that the funder is seeking answers to a question that researchers are expected to address.

Collaborative modes of research

Research in this cluster involves, to a great extent, borrowing techniques from other disciplines such as mathematics. It is also highly interdisciplinary, involving the sharing of research approaches and/or facilities from medical imaging, seismic imaging, computational techniques and mathematical modelling while working separately on distinct aspects of a problem. However, not all interviewees viewed their work as multidisciplinary, and those who did mentioned regular interactions with biologists and clinical staff.

According to the interviewees, collaborations within this cluster tend to be mostly European-based. The majority are within the UK as well as in Germany, France, Spain and the Scandinavian countries. There are generally fewer collaborations outside Europe, simply because the existing expertise and funding opportunities within Europe are readily accessible and sufficient for the research needs of this cluster.

Achievement of expected outcomes

Work conducted as part of the imaging techniques and algorithms cluster contributes to three of the eight Great Technologies as follows.

- **Big data and energy-efficient computing.** By storing and processing massive amounts of data (e.g. time-variant 2D and 3D images), researchers working in the imaging techniques field clearly contribute to advancements in the "big data" priority.
- **Advanced materials.** Most interviewees viewed this priority as a "two-way street" contributing to, and learning from, continuing advanced-materials research.
- **Robotics and autonomous systems.** This was cited as an increasing priority for this cluster, particularly as more automated imaging techniques and robotic vision are developed.

In addition to the increase in the stock of useful knowledge, other relevant benefits from research conducted in this cluster for industry and for society as a whole were identified by interviewees, such as:

- the development of prototypes;
- the creation of new scientific instrumentation and techniques;
- the formation of networks and stimulation of social interaction;
- increasing the capacity for scientific and technological problem-solving; and
- training skilled graduates.

Interviewees noted that their research results have been widely used by international engineering companies (e.g. Rolls-Royce), aerospace companies (e.g. BAE Systems and Airbus) and a suite of medical-imaging businesses. For example, one interviewee who investigates novel systems to image contrast agents and biomarkers listed the international companies that regularly use and/or fund his work. The interviewee anticipated that some of this work would lead to either a licence or spin-out technology within the next year.

Prof. Paul Wilcox at the University of Bristol noted that the aerospace sector greatly benefits from research in defect analyses and advanced-materials conception because it facilitates stronger and lighter manufacturing. Other research in this cluster applies to the power-generation industry, both nuclear and non-nuclear, where interviewees' research results have been used by the UK-based power company EDF Energy and the German electric utilities company RWE. In general, interviewees said that the time lag between research outputs in this cluster and industrial application occurred more on a long-term scale (i.e. 10 years or more).

Finally, the training of skilled graduates was a highly rated industry benefit, with interviewees saying that approximately half of their students remained in academia, while the other half went on to work either in clinical medicine or for industrial companies. Most interviewees made a point of keeping in touch with these students because they may provide opportunities for collaboration in the future.

Channels of knowledge flow

Interviewees in this cluster placed a high value on networking via public meetings and informal discussions. Rather than traditional conferences targeted to a largely academic audience, interviewees cited success in organising "mini-conferences" or meetings to which key industry representatives have been invited. This facilitates communication and knowledge exchange that is focused on the needs of the individual participants or the organisations they represent. Licensing, particularly open-source software, was also often cited as a good way to encourage knowledge transfer between multiple users.

Finally, but no less importantly, publications and reports were cited as the primary channel for knowledge exchange within the academic community.

6

Conclusions

This report assesses the UK's scientific performance in physics research by using indicators based on bibliometric data, which is supplemented by case studies of four physics-based research clusters.

The results of the bibliometric assessment indicate that the UK's share of world papers in physics has been in decline over the last decade, a trend that was also observed for other well established scientific leaders such as the US, France and Germany, and which is the result of increasing competition, most notably from China, India and the Republic of Korea. Nevertheless, the UK has succeeded in maintaining its position among the leading countries in physics. From 2002 to 2011, the UK dropped only one rank (from seventh to eighth) among the 25 countries that made the largest contribution to scientific authorship in physics over this period. On a more positive note, the UK has the highest scientific impact in physics among the 10 largest publishing countries in the field. This performance in terms of scientific output and impact is all the more remarkable given that the UK is placing significantly less emphasis on physics than other leading scientific countries, and is focusing instead on research areas such as the life sciences and space sciences.

To maintain and improve its position, the UK must secure a solid scientific and technological base in physics. This includes sustained expenditure on physics research and infrastructure, and the ability to train highly skilled personnel. It also requires the pursuit of international collaborations with both established and emerging leaders in order to benefit from international knowledge flows. Currently, two out of three UK papers in physics are co-authored internationally, compared with half of UK papers overall. From 2002 to 2011, the UK's major partners were the US, Germany, France, Italy and China. Moreover, nearly all partners involved made clear gains in scientific impact from their international collaborations. The evidence from the bibliometric analysis was confirmed by that from the case studies: collaboration, particularly international, plays a central role in UK physics knowledge flow, not only between researchers within academia, but also between academia and industry.

The evidence gathered from the case studies on the four selected physics clusters clearly shows that important contributions are being made to several research priorities for the UK, in particular "big data" and "advanced materials". Additionally, the case studies point to concrete industrial benefits from the work done in these clusters, as well as the provision of highly skilled researchers to sectors outside academia.

Thus, in broad terms, this assessment presents a picture of the UK as a strong physics performer at the international level, despite a changing global research landscape marked by the emergence of scientific leaders and the UK's relatively low level of scientific specialisation in physics. However, the challenges on the scientific front are many, combined with expanding Asian economies positioned to reap the economic benefits of physics research, including the ability to employ highly qualified personnel who contribute to the development and production of high-tech, high-value-added goods.

Appendix: Methods

This section presents the source of data and classification schemes that were selected for the bibliometric study. It also includes a detailed description of the indicators used.

Choice of database

The data in this report were drawn from Thomson Reuter's Web of Science, which is composed of three databases (the Science Citation Index Expanded, the Social Sciences Citation Index and the Arts & Humanities Citation Index).

Classification scheme

The fields of science used to compare the state of physics were selected by IOP, EPSRC and STFC from the Essential Science Indicator journal classification (produced by Thomson Reuters). This classification was used to define six comparable research areas to be analysed alongside physics: chemistry, life sciences, engineering, materials science, space science and mathematics.

In the case of physics, the field was defined as a new set consisting of the union of subject categories from the Web of Science selected by IOP, EPSRC and STFC. Overall, 14 subject categories were used to define the physics data set.

- Acoustics
- Applied physics
- Astronomy and astrophysics
- Atomic, molecular and chemical physics
- Biophysics
- Condensed matter physics
- Fluids and plasma physics
- Instruments and instrumentation
- Mathematical physics
- Multidisciplinary physics
- Nuclear physics
- Optics
- Particles and field physics
- Polymer science

Selection of countries

The top 25 leading countries in physics based on fractional counts of publications from 2002 to 2011 were selected for analysis, along with the Republic of Ireland, to encompass all of the countries requested by IOP, EPSRC and STFC. Shorter selections of countries among this list are presented in the report to highlight the salient features of the study.

Number of publications

The number of publications was analysed using full-paper counting or fractional-paper counting. In the full-counting method, each paper was counted once for each entity listed in the address field. In fractional counting, publications were divided based on the number of addresses of authors of the publication and each entity (address) was attributed its share of the publication.

Growth rates

The average annual growth rate is calculated using the first and last year of a given period and by means of the following equation:

$$r = \ln(p_n/p_1)/n$$

where n = period and ln = natural logarithm operator.

The average annual growth rate is expressed as a percentage and is based on a model of continuous exponential growth between two points in time. It does not take into account the intermediate values of a series, nor does it correspond to the annual rate of change measured at a one-year interval. The average annual growth rate was computed for the main bibliometric indicators presented in the report.

[17] Katz, J S 2000 Scale-independent indicators and research assessment *Science and Public Policy* **27** 23–36.

Specialisation index (SI)

The SI is an indicator of research intensity in a given entity (e.g. a country) for a given research area or field relative to the output of a reference entity (e.g. the world) for the same research area. In other words, when a country is specialised in a research area, it places more emphasis on that area at the expense of other research areas. Specialisation is therefore said to be a zero-sum game: the more a country specialises in an area, the less it does elsewhere. To ensure that it is a real zero-sum game, the publication numbers used to compute the SI were based on fractional counting. An index value above 1 means that a given entity was specialised relative to the reference entity, whereas an index value below 1 means the contrary.

Average of relative citations (ARC)

The ARC is an indicator of the scientific impact of papers produced by a given entity (e.g. the world, a country, an institution) relative to the world average (i.e. the expected number of citations). The number of citations received by each publication was counted for the year in which it was published and for the two subsequent years, and was normalised by sub-field, year of publication and document type to obtain a relative citation score accounting for different citation patterns across these variables (e.g. there are more citations in biomedical research than in mathematics).

The ARC of a given entity is the average of the relative citation scores of the papers belonging to it. An ARC value above 1 means that a given entity was cited more frequently than the world average, whereas a value below 1 means that it was cited less frequently than the world average.

Highly cited papers (HCPs)

The HCP indicator is generally used to compute the proportion of a country's papers that are among the 10% most highly cited papers at the world level. Highly cited papers are publications that received the highest relative citation score in their respective field and year. All things being equal, a score of 10% for each country would be expected, and hence a score above 10% would denote excellence in research.

For this study, the 25% most cited publications in physics were used to examine international collaboration among leading organisations in order to identify world leaders not only based on raw output, but also according to high-impact research.

Number of co-publications

A co-publication is defined as a publication co-authored by more than one author (although in rare cases it may be the work of a single author whose research has been conducted for several organisations). When counting the number of co-publications in which the co-authors are from at least two individual countries, the number of international co-publications is obtained. This number was computed using both fractional counting and full counting. The number of co-publications of an entity can be expressed in absolute terms or as a percentage of the entity's total scientific output.

Collaboration index (CI) and affinity index (AI)

Analyses of scientific collaboration are best performed with the CI because of the presence of power-law relationships in collaborations. These non-linear relationships can be observed, for example, between an entity's (e.g. a country's) number of papers and its number of co-publications (or collaborations)[17]. When both indicators (collaborations and number of publications) are log transformed, power-law relationships can be analysed with linear regression models. Therefore, the approach used to compute the CI consisted of performing a log-log linear regression analysis between the number of co-authored publications and the number of publications at a specific aggregation level (e.g. countries) to estimate the constants (a and k) of the power-law relationship:

$$Expp(M)=aM^k$$

where Expp = the expected number of co-authored papers of an entity (e.g. a country) based on the regression model, and M = the observed number of publications of the entity (e.g. country) being measured.

The log-log linear regression analysis was performed with a reduced major axis to estimate the parameters (a and k) of the regression model. The indicator is simply the ratio of observed-to-expected co-authored publications. When the indicator is above 1, an entity produced more publications in collaboration than expected based on the size of its scientific production, whereas an index value below 1 indicates that it produced fewer publications than expected. This indicator was computed for the UK and other countries at the field level. It was also computed asymmetrically as an affinity index (AI) to identify the countries with which the UK has the strongest positive affinities and the strongest negative affinities for collaboration.

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