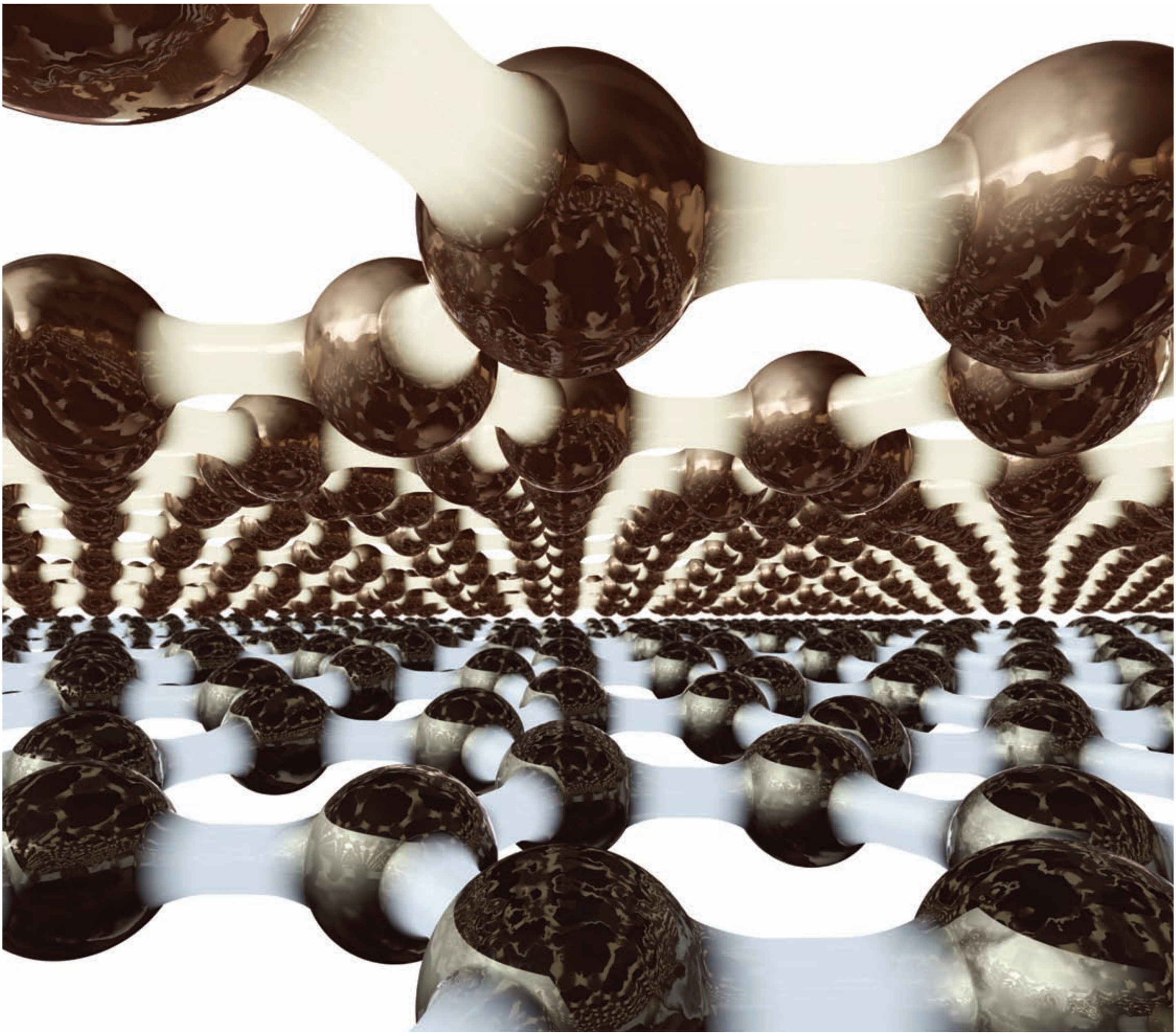

GLOBAL RESEARCH REPORT

MATERIALS SCIENCE AND TECHNOLOGY

JUNE 2011

JONATHAN ADAMS
DAVID PENDLEBURY

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THE AUTHORS

Jonathan Adams is Director, Research Evaluation. He was a founding Director of Evidence Ltd, the UK specialist on research performance analysis and interpretation.

David Pendlebury, formerly Manager of Contract Research Services for Thomson Reuters, now serves as a Consultant on bibliometric analysis. He also writes a weekly column on research metrics for the Times Higher Education magazine.

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T/ +44 113 384 5680
F/ +44 113 384 5874
E/ scientific.enquiries.evidence@thomson.com

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GLOBAL RESEARCH REPORT
MATERIALS SCIENCE AND TECHNOLOGY

"Looking back over the last ten years, we can see just how far materials science and the applied technologies derived from its discoveries have advanced, and it is emboldening to see how the niches for research have multiplied exponentially over this period. It should also give us great pleasure to note that researchers from the Asia-Pacific region have risen to the challenge and are now, more than ever, contributing to global progress in the field at the highest level. The future of materials research, and particularly in our region, looks very bright indeed." — "A Bright Future for Materials Research," NPG Asia Materials, January 21, 2010 [1]

INTRODUCTION

This is the first Thomson Reuters Global Research Report to have a topical focus rather than a geographical one. The report reviews materials science and technology, a core area of research of profound interest in most economies because of its potential contribution to manufacturing processes and innovative products. Also, 2011 is the UNESCO International Year of Chemistry, with which materials science is intimately linked. In addition, our mid-year publication coincides with the sixth biennial International Conference on Materials for Advanced Technologies, to be held in Singapore. The list of eminent researchers, including Nobel laureates, among the speakers at the conference provides powerful confirmation of the field's stature and significance. The location is significant, too: this report notes the contribution to materials science that now derives from Asia. This is corroborative evidence of the region's increasing presence on the world science map, highlighted in several earlier country-specific Global Research Reports.[2]

Fundamental discoveries in physics dominated the first half of the 20th century, whereas discoveries in molecular biology, such as the structure of DNA, dominated the second half. The 21st century may well bring forth a new era, one of revolutionary discoveries in materials research that result in far-reaching changes for society and how we live.

The Global Research Report series is intended to inform policymakers about the changing landscape of the global research base. This report will examine the origin and nature of the field, then review its growth globally and identify some key players, and finally look selectively at some of its current diversity in "hot" topics such as graphene, metal-organic frameworks, and nanofibrous scaffolds used for tissue engineering.

MATERIALS RESEARCH: WHAT IS IT?

*Web of Science*SM from *Thomson Reuters Web of Knowledge*SM aggregates the 11,500 journals that it tracks across some 250 subfield categories on the basis of their stated focus and their cited and citing relationships. Eight of those categories are associated directly — and at least a dozen more are linked tangentially — with what is generally recognized as materials science. Such categories provide a detailed basis for analysis but are too detailed for a survey of the whole field. Instead, we will use the 22 broad field categories of *Essential Science Indicators*™ from *Thomson Reuters Web of Knowledge*SM, one of which is materials science. It should be noted that papers published in multidisciplinary journals such as Nature and Science are selectively assigned to their appropriate fields within *Essential Science Indicators*.[3]

Materials science is a field of relatively recent vintage, as currently conceived. Many past researchers who focused on materials such as metals or ceramics might have been members of university departments of metallurgy or perhaps engineering. Other researchers who now hold appointments in departments of materials science would, in the previous era, have held positions in physics, chemistry or biochemistry departments.

Materials science remains intrinsically interdisciplinary despite the rise of departments, journals, and societies that now identify the field explicitly. We therefore report from contested ground. On the one hand we have research outputs identified as articles from journals linked to materials science. On the other hand we have researchers identified as materials scientists whose outputs also appear in a diversity of other journals. For the sake of simplicity, we focus on papers published in the journals we classify as materials science, according to its definition in *Essential Science Indicators*. We recognize at the outset that this may fail to capture some seminal individual contributions.[4]

INCREASING WORLD SHARE

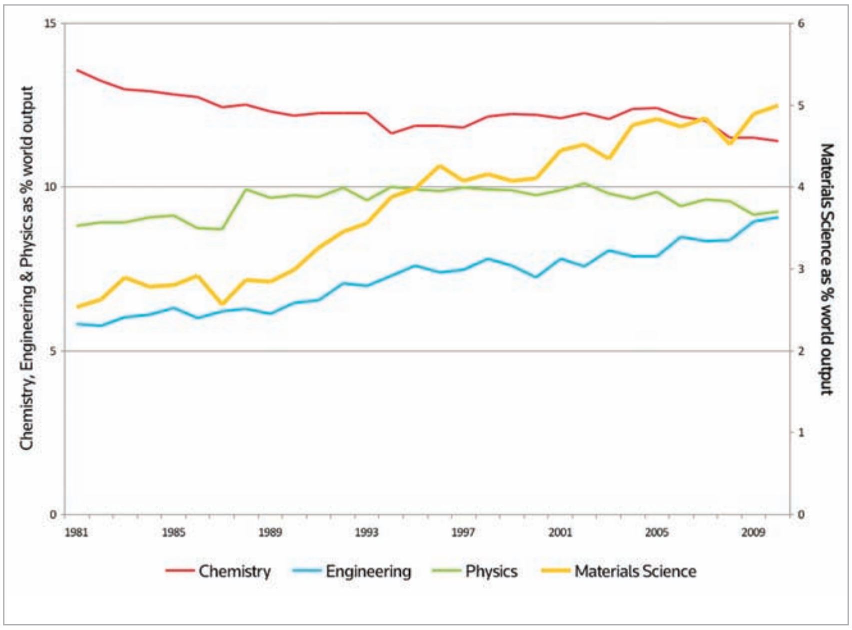
We tracked the growth of materials science research outputs — substantive articles and reviews — over three decades from 1981. During that period the number of articles and reviews covered annually by Thomson Reuters has increased more than two-fold to more than 1.1 million items per year. So, to get some idea of relative growth we need to index the number of items for any field as a share of the world total.

Figure 1 tracks world output share for chemistry, engineering, and physics, the key 'parent' fields, and for materials science. Of the four, materials science has been — and still is — the smallest by output during the last three decades but grew almost four-fold since 1981 (while average output doubled across all fields). During the same interval, chemistry grew in line with the overall average, engineering grew rather faster and physics had roughly trebled in volume until recently. Materials science now accounts for nearly 60,000 articles and reviews per year, representing some 5% of all such papers in the sciences indexed in *Web of Science*. By comparison, chemistry currently represents 11.5%, engineering 9%, and physics 9%, of such papers.

Materials research output growth is, of course, reflected in input. R&D expenditure data from Battelle's 2011 Global R&D Funding Forecast suggests a 10% rise in the last three years from 2008 despite the overall global recession. Battelle's report emphasizes sustained investment in nanotechnology in the US public sector, as well as commercial R&D allocations in chemicals and advanced materials which have been maintained in cash if not in real terms.[5]

FIGURE 1

World share of papers (articles and reviews) indexed in *Web of Science* for materials science, compared with chemistry, engineering and physics, since 1981. Note the separate axis for materials science.



Source: *Thomson Reuters Web of Knowledge*SM

NOTE: Where an '*' is used in a search term, this denotes a generic character to enable the same search to apply to e.g. singular and plural terms

REGIONS AND COUNTRIES

The increase of research output in materials science is now being driven by spectacular growth in Asia. China has grown from a barely detectable presence with fewer than 50 papers in the field in 1981 to become the largest single country producer and to overtake not only Japan and then the USA but now also to challenge the combined output of the EU-15 group of well-established European research economies (Figure 2).

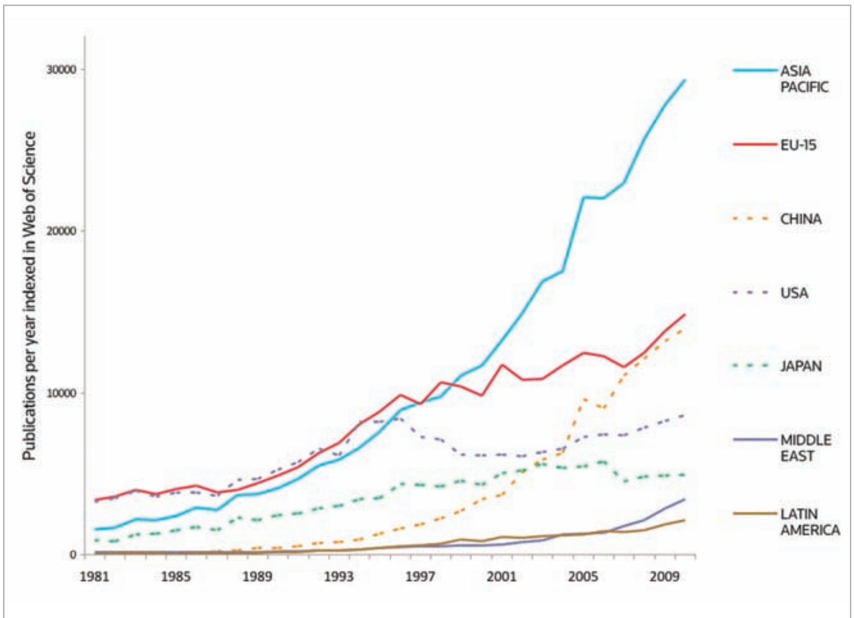
The USA moved from a clear lead in the field in the 1980s, only to stall in the mid-1990s and then actually to decline in output. Since the early 1980s, its world share of materials science papers has fallen by nearly half — from some 28% to 15%.

The EU experienced a rise in world share during the 1990s, but has since seen some fall back to a level close to that it held in the middle-1980s. Unlike the USA, the absolute output for the EU group has not declined for any extended period. Meanwhile, the Asia-Pacific region now accounts for almost half the world's papers in this field, and China alone is responsible for about half of Asia.

More than 30 countries, listed in Table 1, each produced over 1,000 articles and reviews in materials science in the last five-year period. Their distribution is worldwide, but the predominance of Asia-Pacific nations is evident.

FIGURE 2

Growth of materials science research output indexed in *Web of Science* for major regions and the most prolific countries since 1981.



Source: *Thomson Reuters Web of Knowledge*SM

Quantity does not assure quality. Dynamic output growth in Asia is balanced by greater citations per paper for the publications of the more established economies. While citation counts are not a guarantee of quality, they are a reasonable indicator of influence and significance: one that correlates well with assessments such as peer review. An index of average citation counts is also referred to by analysts as "citation impact."

There will undoubtedly be an "impact" gap for some time to come. The size of that gap — at least between Asia and Europe — no longer seems insuperable. Nonetheless, despite the USA's dwindling share, its materials science publications are on average cited twice as often as those from China (Table 2).

TABLE 1

National output of materials science research papers indexed in *Web of Science* for those producing more than 1,000 articles and reviews in the most recent five-year period, ranked by number of papers

Country	Papers	Country	Papers	Country	Papers
China	55,003	Italy	5,990	Portugal	2,503
USA	38,189	Poland	5,168	Belgium	2,299
Japan	25,473	Australia	4,642	Czech Republic	2,217
Germany	16,832	Turkey	4,142	Austria	2,044
South Korea	15,261	Romania	3,958	Mexico	1,961
India	12,693	Brazil	3,891	Greece	1,663
France	12,344	Ukraine	3,714	Egypt	1,628
UK	11,611	Sweden	3,176	Finland	1,408
Russia	7,927	Singapore	2,958	Israel	1,323
Taiwan	7,410	Iran	2,942	Slovenia	1,099
Canada	6,593	Switzerland	2,807	Malaysia	1,006
Spain	6,429	The Netherlands	2,785		

RESEARCH INSTITUTES AND UNIVERSITIES

We can look at the leading institutions for materials science research in three ways: those that publish the most papers; those that get cited most frequently; and those that have the highest citation impact. We reviewed the data for the ten-year period from early 2001 to the beginning of the current year (2011). In Table 3, the top 20 institutions are ranked by output, by citations and by impact. The number of publications tends to drive the number of citations. For example, the Chinese Academy of Sciences has both published the greatest number of papers and attracted the greatest number of citations. In fact, just over half of the institutions in the top 20 by publication output are also in the top 20 by citation counts.

The Papers and Citation columns are dominated by Asian institutions, spread across China and Japan but also including Singapore and South Korea. The impact column features a global set of institutes and universities that published at least 500 articles or reviews during the period.

Several organizations appear in the top 20 on two variables. Only the Max Planck Society, Germany, makes it into all three columns. The impact ranking is dominated by leading US institutions although these are far from dominant on capacity (the Papers column). Indeed, eight of the top 10 by Impact published fewer than 1,000 papers over the decade. Only the University of California Berkeley (with 1,259 papers — not in the top 20 by Papers) broke even that lower threshold.

The highest-impact Asian institutions were the Japan Science & Technology Agency (JST), which published 1,444 papers with an Impact of 13.98, for a rank of 24th, and the National University of Singapore (listed in the Citations column), which published 2,309 papers with an Impact of 13.75, for a rank of 27th.

A significant part of the research output capacity indicated by the Papers column in Table 3 comes from institutes outside the higher education sector, whereas high Impact seems to be associated with universities. This may reflect their very different missions and activity portfolios. We suggest that it may be that the more fundamental research of universities is more likely to achieve academic impact and be cited whereas the more application-oriented research of national laboratories achieves impact in other ways: through economic innovation and social goods.

TABLE 2

Publication counts, citation counts and citations per paper (impact) scores of materials science research indexed in *Web of Science* for leading countries in the Asia-Pacific region and two key comparators, ranked by impact (2005-2009).

Country	Papers	Citations	Impact
USA	38,189	222,552	5.83
EU-15	53,283	216,712	4.07
Japan	25,473	85,866	3.37
Taiwan	7,410	23,303	3.14
South Korea	15,261	47,334	3.10
China	55,003	143,665	2.61
India	12,693	32,411	2.55

TABLE 3

Ranking of institutes and universities by papers (articles and reviews), citations, and citation impact for materials science research indexed in *Web of Science*, 2001-2011.

Institution	Papers	Rank	Institution	Citations	Rank	Institution	Impact
Chinese Academy of Sciences	14,019	1	Chinese Academy of Sciences	104,104	1	University of Washington	30.41
Russian Academy of Sciences	6,769	2	Max Planck Society, Germany	56,720	2	University of California Santa Barbara	27.41
Tohoku University	5,511	3	Tohoku University	40,135	3	University of California Berkeley	26.58
Tsinghua University	5,129	4	NIMS, Japan	36,578	4	University of Groningen	25.07
Indian Institute of Technology	4,522	5	MIT, USA	35,329	5	Harvard University	24.46
Harbin Institute of Technology	4,059	6	AIST, Japan	33,868	6	MIT	21.61
AIST, Japan	4,052	7	University of California Berkeley	33,460	7	University of Southern California	21.11
NIMS, Japan	3,952	8	National University of Singapore	31,740	8	University of California Los Angeles	19.23
Osaka University	3,618	9	Tsinghua University	31,698	9	Stanford University	18.34
Central South University	3,464	10	University of Cambridge	27,909	10	University of Minnesota	17.35
Shanghai Jiao Tong University	3,380	11	CSIC, Spain	27,285	11	Max Planck Society, Germany	17.31
Max Planck Society, Germany	3,277	12	Georgia Institute of Technology	27,201	12	Georgia Institute of Technology	17.02
CSIC, Spain	3,191	13	Osaka University	26,217	13	Northwestern University, USA	16.39
University of Science and Technology Beijing	3,065	14	Seoul National University	25,564	14	Cornell University	16.06
University of Tokyo	2,960	15	CNRS, France	25,132	15	University of Michigan	15.70
CNRS, France	2,953	16	University of California Santa Barbara	24,343	16	University of Massachusetts	15.62
Zhejiang University	2,721	17	University of Washington	24,240	17	Drexel University	15.53
Seoul National University	2,560	18	Pennsylvania State University	24,086	18	Eindhoven University of Technology	15.29
Kyoto University	2,541	19	University of Tokyo	24,080	19	University Pierre & Marie Curie	14.96
Tokyo Institute of Technology	2,520	20	Indian Institute of Technology	22,297	20	Rensselaer Polytechnic Institute	14.71

RESEARCH FRONTS IN MATERIALS SCIENCE

Bibliometric analysis can describe much more than simply research performance in terms of publication output and citation impact. It can also reveal the structure of a research field and the relationships between specific areas of investigation. Thus, publication and citation data enable us to locate materials sciences and technology in the global map of science. Materials science in the Global Map (Figure 3) appears around the nanoscience front, which serves as the bridging area between physics and chemistry, with a weaker link to biology.

Other major research fronts in the materials sciences region or close to it are solar cells, fuel cells, and polymerization. Some of the smaller, unlabeled circles represent ductile bulk metallic glasses, negative index materials, superhydrophobic surfaces, and bone-like materials for tissue engineering.

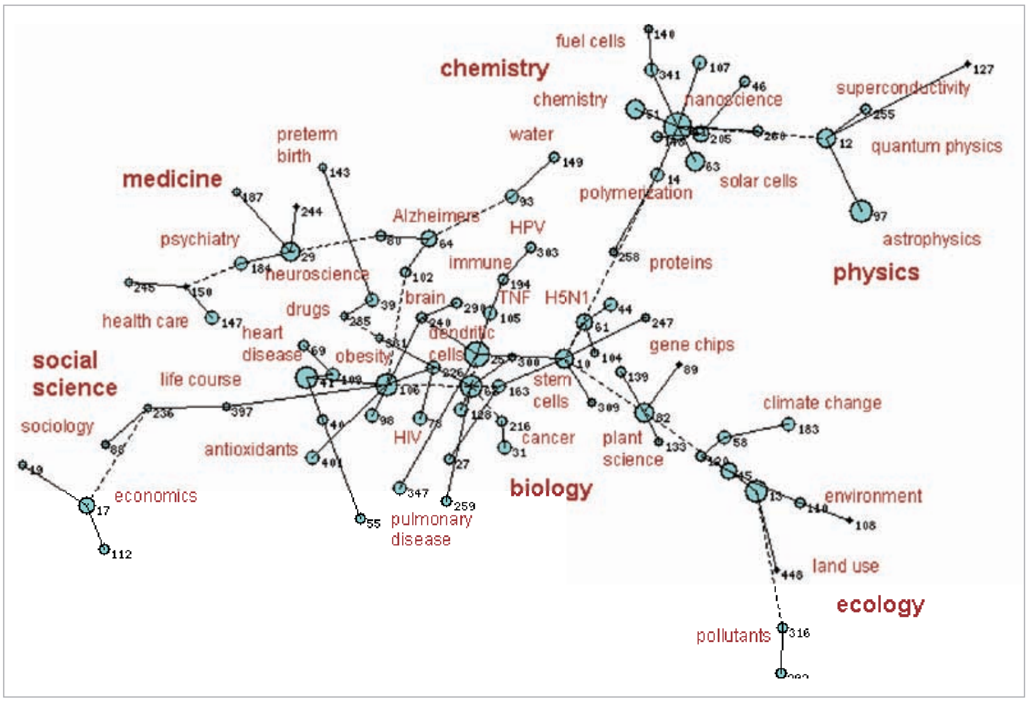
Figure 4 provides a detailed view of the nanoscience region and its constituent and closely related research fronts.[8] One branch in the map shows activity in the study of solar cells: not only dye-sensitized solar cells but also organic solar cells, an alternative approach of increasing interest. Nanotube films and graphene are logically linked. Nanomaterials also appear in other regions, including in the fuel cell region and the solar cell region. Other very active research specialties are mesoporous carbon, molecular logic gates, electrochemical sensors, metamaterials, and a large area at the center of the map concerned with the magnetic properties of various materials.

Table 4 lists the top 20 research fronts in materials science, based on the number of citations to the core papers in each front. A ranking of research fronts by total citations reveals specialties of exceptional current activity. The average citation impact for these fronts is relatively high compared with, for example, the organizational averages in Table 3. The score for the average year of the core papers in each front indicates whether the foundation literature of the front is new or turning-over quickly. A very recent average year suggest that the area is an emerging or hot topic.

The broad fields represented by these 20 research fronts include chemistry, physics, engineering, and biological sciences. Their scope shows how materials research extends its influence in many directions. Some major specialties appear twice in different forms: graphene (1 and 6), solar cells

RESEARCH FRONTS are currently dynamic specialty areas of research. Research fronts are created by first identifying highly cited papers — those that rank by their citations in the top 1% of their field according to their year of publication — published during the last five years. The papers that have cited these highly cited papers are collected and a co-citation analysis of the cited papers is performed. Co-citation analysis is an iterative process. When two papers are frequently co-cited, it is possible to begin to form a cluster of related research. This is a research front. Some research fronts are built around just two or a handful of papers whereas others, because of frequent co-citation, can have up to 50 related co-cited papers. These are the core papers within the front. In the end, the research front consists of a number of core papers and many more citing papers that link the core papers together.[7]

Research fronts are not chosen or defined by information analysts. They are created by researchers themselves through the references they add to their papers. As such, research fronts reflect the informed judgment of experts. The research fronts are constantly changing in size and in content, according to progress in research. With each Thomson Reuters data update, some die away while others emerge. These research fronts therefore represent a contemporary commentary by the global research community on the structure of science.



Source: *Thomson Reuters Web of Knowledge*SM

FIGURE 3

Global Map of Science based on research front data presented in *Essential Science Indicators*. Research fronts are clusters of related highly cited papers that rank within the top 1% by citations for their field and year. The Map reveals both fields and specialty topics, and their relationships according to citation linkages.[6] Each circle represents one research front or a cluster of fronts on a broad topic within that field. The size of each circle is proportional to the number of papers within the specialty and the lines between circles convey how closely one area is associated to another. Labels identify broad fields and subfields.

(2 and 4), and mesoporous materials (14 and 18). Biomedical topics appear in three fronts (10, 14 and 17). The highest citation impact scores are linked to graphene and polymer solar cells. The youngest core literature is associated with molecular logic circuits (20), upconversion fluorescent rare-earth nanocrystals (19), and self-assembling supramolecular nanostructed gel-phase materials (13).

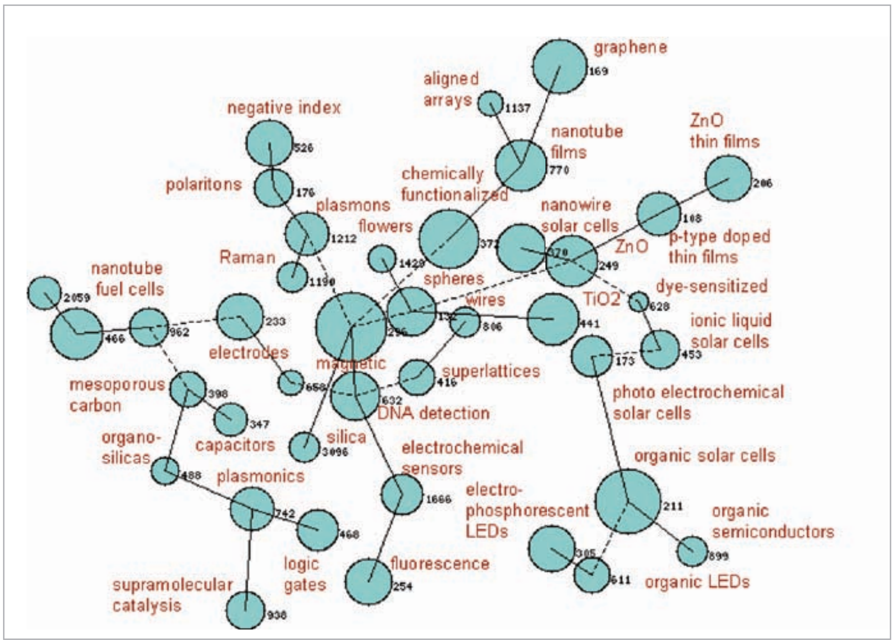


FIGURE 4

Map of Nanoscience based on research-front data presented in *Essential Science Indicators*.

TABLE 4

Top 20 research fronts in materials science, 2006-2010, ranked by total citations, from *Essential Science Indicators* database, 2006-2010. These were selected from 438 research fronts in materials science, which represent 6.6% of the 6,641 research fronts in all fields of the sciences and social sciences.

Rank	Field description within materials science	Core papers	Citations	Citation impact	Average year of core
1	Electronic properties of graphene	6	9,524	1587.3	2005
2	Polymer solar cells	15	6,656	443.7	2007
3	Multiferroic and magnetoelectric materials	31	6,509	210.0	2006
4	Titanium dioxide nanotube arrays in dye-sensitized solar cells	47	5,645	120.1	2007
5	ATRP and click chemistry in polymer synthesis	34	5,129	150.85	2006
6	Graphene oxide sheets	16	4,815	300.9	2007
7	Superhydrophobic surfaces	47	4,732	100.7	2007
8	High-Tc ferromagnetism in zinc oxide diluted magnetic semiconductors	48	4,667	97.2	2006
9	Highly selective fluorescent chemosensors	46	4,581	99.6	2007
10	Electrospun nanofibrous scaffolds for tissue engineering	45	4,577	101.7	2006
11	Ductile bulk metallic glasses	41	4,267	104.1	2006
12	Single-molecule magnets	47	4,013	85.4	2007
13	Self-assembling supramolecular nanostructured gel-phase materials	33	3,810	115.4	2007
14	Mesoporous silica nanoparticles for drug delivery and biosensing applications	34	3,693	108.6	2007
15	Mechanical properties of nanocrystalline metals	45	3,682	81.8	2007
16	Discotic liquid crystals for organic semiconductors	30	3,637	121.2	2006
17	Gold nanorods for imaging and plasmonic photothermal therapy of tumor cells	21	3,506	166.9	2006
18	Highly ordered mesoporous polymer and carbon frameworks	25	3,362	134.5	2006
19	Upconversion fluorescent rare-earth nanocrystals	49	3,351	68.4	2007
20	Molecular logic circuits	47	3,315	70.5	2008

SPECIAL TOPICS

Next in the report, we focus on three important and active areas: graphene; metal-organic frameworks; and electrospun nanofibrous scaffolds for tissue engineering applications. These represent large-, medium-, and small-sized specialties, respectively. The three topics are also significant because of their implications for global and national economies, offering potential revolutions in electronics, energy storage, and biomedical engineering.

Each of these areas has been characterized by exceptionally rapid growth from the point of first announcement in the research literature. Figure 5 summarizes the growth patterns for the three fields together, for comparison.

TOPIC 1: GRAPHENE

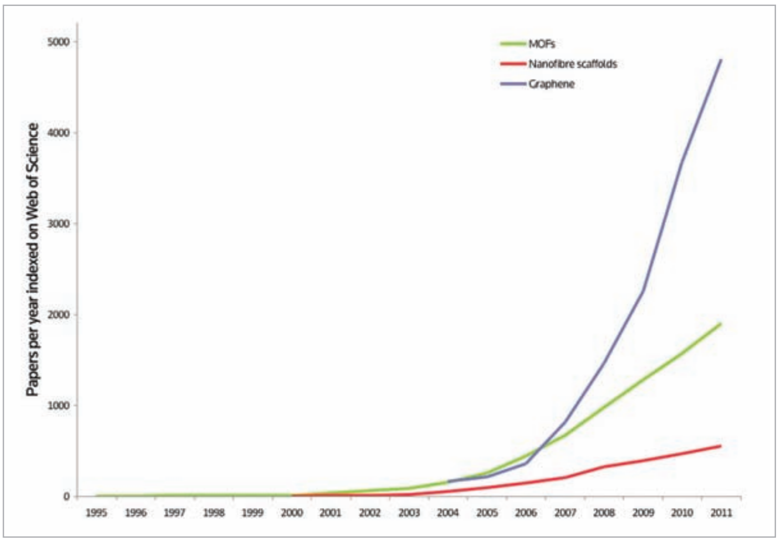
Any review of significant developments in materials research during the last decade must certainly include graphene, a one-atom-thick carbon film with remarkable electronic, mechanical, thermal, and optical properties. Since the 2004 breakthrough discovery account by Andre K. Geim, Konstantin S. Novoselov, and colleagues at the University of Manchester, UK, and the Institute for Microelectronics Technology, Chernogolovka, Russia,[9] articles dealing with graphene have increased dramatically in a manner similar to those on fullerenes after 1985 and on high-temperature superconductivity in cuprate-perovskite materials after 1986.

According to *Web of Science* database, there were 164 papers published in 2004 with the word "graphene" in their titles, abstracts or list of keywords. By 2010, there were 3,671 such articles recorded. As of May 2011, the accumulated total of "graphene" articles indexed since 2004 was 10,527. We estimate that graphene-related papers will total some 4,800 for 2011 (Figure 5).

So significant was their discovery that Geim and Novoselov were awarded the Nobel Prize for Physics in 2010 "for groundbreaking experiments regarding the two-dimensional material graphene" just six years after their 2004 paper. The impact of their research was evident from citations rapidly accumulating to their 2004 account and another paper published in Nature in 2005.[10] This prompted Thomson Reuters in 2008 to predict a Nobel Prize for Geim and Novoselov.[11] Their two papers from 2004 and 2005 have now been cited more than 4,300 times and more than 3,000 times, respectively, placing them among the 20 most-cited research reports in all fields of the physical sciences during the last decade.

FIGURE 5

Number of special topic papers indexed in *Web of Science* database, 1995-2011 (count for 2011 is an estimate). Papers were selected if ["metal-organic framework*"] for the MOF line, ["electrospun or electrospin*" and "scaffold* or tissue*"] for the nanofibre scaffolds line or ["graphene"] for that line appeared in the title, abstract, or list of keywords.



Source: *Thomson Reuters Web of Knowledge*SM

TABLE 5

Summary of fields represented by graphene research, based on journal category assignments for graphene-related research publications, 2004 – May 2011. Some journals are assigned to multiple fields so paper counts may sum to more than the net total.

Rank	Fields	Papers
1	Physics, Condensed Matter	3,405
2	Materials Science, Multidisciplinary	3,144
3	Physics, Applied	2,577
4	Chemistry, Physical	2,528
5	Nanoscience & Nanotechnology	2,134
6	Chemistry, Multidisciplinary	1,644
7	Physics, Multidisciplinary	1,294
8	Physics, Atomic, Molecular & Chemical	464
9	Engineering, Electrical and Electronic	357
10	Electrochemistry	268

TABLE 6

Ranking of countries and institutions by their output of graphene-related research papers, 2004 – May 2011.

Papers	Country	Rank	Institution	Papers
3,263	USA	1	Chinese Academy of Sciences	440
1,957	China	2	National University of Singapore	232
1,022	Japan	3	CSIC, Spain	225
846	Germany	4	Russian Academy of Sciences	190
593	UK	5	University of California Berkeley	182
543	South Korea	6	Tsinghua University	170
529	France	7	Nanyang Technological University	166
450	Spain	8	CNRS, France	155
384	Singapore	9	Massachusetts Institute of Technology, USA	150
363	Russia	10	University of Texas Austin	147

Owing to graphene's many unusual and potentially exploitable properties, researchers from several different fields have focused their attention on the new material. Table 5 provides a ranking of fields represented by graphene research, reflected by the journals in which the 10,527 graphene-related papers were published from 2004 through May 2011. These data show that graphene research is well represented in physics, chemistry, and materials and nanoscience, and somewhat less so in engineering.

Table 6 lists the output of graphene-related research papers by nation and by institution since 2004. The USA is the leader in publication output, but the production of graphene papers by Asian nations is significant, represented by China and Japan, ranked 2nd and 3rd, South Korea ranked 6th, and Singapore ranked 9th. Singapore's contribution is noteworthy since its research base is relatively small compared with the other listed nations. The institutional ranking features several national research organizations that represent large networks of laboratories in different locations. The Chinese Academy of Sciences, ranked first, is an example; the others are Spain's CSIC, the Russian Academy of Sciences, and France's CNRS. In terms of universities, the USA is represented in the top 10 by the University of California Berkeley, MIT, and the University of Texas Austin. China is represented by Tsinghua University and Singapore by both NUS and NTU.

There are no signs that research on graphene is slowing: the total citations for graphene papers published since 2004 now exceed 163,000 and continue to accumulate. *Essential Science Indicators* currently lists 503 papers with graphene in their titles, published during the last decade, that are recognized as highly cited. This is a disproportionate 2.1% of the papers recognized as highly cited (the global top 1%) in materials science, chemistry, and physics. Articles with graphene in their titles account for 13 of 85 papers highly cited papers published during just the last two years in materials science (15%), 23 of 195 in chemistry (12%), and 10 of 123 papers in physics (8%). One of these is a 2009 review by Geim, on "Graphene: Status and Prospects," that already has nearly 600 citations.[12] Other recent articles also analyzed the publication history of graphene research and projected its future course.[13]

TOPIC 2: METAL-ORGANIC FRAMEWORKS

Research on metal-organic frameworks (MOFs) shows a strong association with chemistry, particularly molecular coordination chemistry, in contrast to graphene's tilt toward physics. MOFs is a good example of what Nobel laureate Sir Harry Kroto recently described as the "molecule-by-molecule assembly of more and more complex systems with advanced functions at nanoscale dimensions" and as "simply 21st-century advanced chemistry."[14]

TABLE 7

Summary of fields represented by metal-organic frameworks research based on journal category assignments for MOF-related research publications, 2004 – May 2011. Some journals are assigned to multiple fields so paper counts may sum to more than the net total.

Rank	Fields	Papers
1	Chemistry, Multidisciplinary	2,669
2	Chemistry, Inorganic & Nuclear	2,105
3	Crystallography	1,260
4	Chemistry, Physical	1,210
5	Materials Science, Multidisciplinary	1,150
6	Nanoscience & Nanotechnology	379
7	Engineering, Chemical	164
8	Physics, Condensed Matter	158
9	Physics, Atomic, Molecular & Chemical	142
10	Chemistry, Applied	132

TABLE 8

Ranking of countries and institutions by their output of research papers on metal-organic frameworks, 1995 – May 2011.

Papers	Country	Rank	Institution	Papers
2,584	China	1	Chinese Academy of Sciences	450
1,398	USA	2	Nanjing University	314
447	Germany	3	Nankai University	189
393	Japan	4	Northeast Normal University	156
388	UK	5	Jilin University	130
355	France	6	Sun Yat-sen University	120
292	India	7	Kyoto University	118
250	South Korea	8	University of Michigan	101
240	Spain	9	Northwestern University	96
160	Australia	10	Northwest University, Xian	86

MOFs are porous crystalline solids, composed of metal ions linked by organic bridging ligands, designed from the ground up using molecular "building blocks" to have a specific functionality. Omar Yaghi, now of the University of California Los Angeles, pioneered the design and synthesis of MOFs in the mid to late 1990s.[15] Since then, more than 2,000 varieties have been reported by his group and others worldwide.

Because of their record surface areas and through the careful design of architectures tailored to particular applications (which Yaghi terms "reticular synthesis"), MOFs are suitable for gas storage — hydrogen, methane, and other gases — and for gas purification and separation, as well as for catalysis. Another use of MOFs is for highly selective sensors. Their potential for energy storage has excited many within the scientific community and far beyond it.

So far this century, research publications on MOFs have skyrocketed from some dozen papers in 2000 to an estimated 1,900 that will appear in 2011 (Figure 5). We identified 6,313 papers on MOFs published from 1995 through May 2011, papers with "metal-organic framework*" in their titles, abstracts or keywords in *Web of Science* database. These papers have been cited more than 147,000 times to date: almost as much as graphene-related papers, albeit over a longer period.

Chemistry is the broad field most frequently represented by the 6,313 papers on MOFs, based on the category assignments for the journals in which these papers were published. The top ranked subfields are multidisciplinary chemistry, inorganic and nuclear chemistry, crystallography, and physical chemistry, followed by multidisciplinary materials science (Table 7).

China, ranking in first place among nations by number of papers on MOFs published since 1995, has produced nearly twice the volume output of the second-ranked USA. Europe (Germany, UK, France and Spain) and the rest of Asia-Pacific (Japan, India, South Korea, and Australia) are far behind these two in output of MOFs papers.

TABLE 9

Summary of fields represented by electrospun nanofibrous scaffolds' research. This is based on journal category assignments for related research publications, 2004 – May 2011. Some journals are assigned to multiple fields so paper counts may sum to more than the net total.

Rank	Fields	Papers
1	Engineering, Biomedical	629
2	Materials Science, Biomaterials	581
3	Polymer Science	480
4	Materials Science, Multidisciplinary	276
5	Nanoscience & Nanotechnology	223
6	Biotechnology & Applied Microbiology	193
7	Chemistry, Multidisciplinary	156
8	Physics, Applied	146
9	Cell Biology	136
10	Chemistry, Physical	114

TABLE 10

Ranking of countries and institutions by their output of research papers on electrospun nanofibrous scaffolds for tissue engineering, 2000 – May 2011.

Papers	Country	Rank	Institution	Papers
657	USA	1	National University of Singapore	144
448	China	2	Songhua University	120
438	S. Korea	3	SUNY Stony Brook	58
161	Singapore	4	Virginia Commonwealth University	56
92	UK	5	Seoul National University	53
80	Italy	6	Chinese Academy of Sciences	42
70	Germany	7	Hungnam National University	35
66	Japan	8	Chulalongkorn University	34
49	Australia	9	Ohio State University	28
39	Thailand	10	University of Pennsylvania	27

It is therefore not surprising that the institutional ranking (Table 8) is also dominated by Chinese institutions and universities, which account for seven of the top 10 and all of the top six. These data demonstrate that research on MOFs is a priority realm of research for Chinese researchers and for the Chinese government, presumably not merely for academic interest but also for the enormous potential of MOFs for energy storage and other industrial applications.

TOPIC 3: ELECTROSPUN NANOFIBROUS SCAFFOLDS

The research front "Electrospun nanofibrous scaffolds for tissue engineering," ranked 10th by citations in the materials science specialties (Table 4), exemplifies a multidisciplinary area of investigation that links materials sciences, polymer chemistry and nanotechnology with biomedical engineering. The technique of electrospinning, which is not new, has been used recently to create continuous fibers of nanometer diameter for building scaffolds that mimic the native extracellular matrix, both structurally and functionally. The scaffold, based on a variety of biocompatible materials, can not only support seeded cells but also, owing to porosity of the fibers, encapsulate proteins that promote cell adhesion and proliferation as well as hold and release drugs such as antibiotics or anticancer drugs. Although electrospinning represents just one approach to preparing scaffolds, the results obtained to date plainly hold great promise for the regeneration of tissues and organs.

Searching *Web of Science* database for papers with "electrospun OR electrospin*"AND "scaffold* OR tissue*," in their titles, abstracts or keywords, we identified 1,899 papers dealing with nanofibrous scaffolds produced by electrospinning, published from 2000 through May 2011. These have been cited more than 31,000 times to date. The growth of papers on this topic during the last decade has been dramatic, from just a handful during the three-year period from 2000 to 2002 to an estimated 550 for 2011 (Figure 5).

The fields represented by the 1,899 identified papers on electropsun nanofibrous scaffolds published from 2000 through May 2011 testify to the interdisciplinary nature of this research, especially at the interface between materials science and biomedical sciences (Table 9).

The USA appears first among countries ranked by their output of research papers on electrospun nanofibrous scaffolds since 2000, but the next three countries represent Asia — China, South Korea and Singapore — and their combined output exceeds that of the USA by a wide margin. *Science Watch* newsletter from Thomson Reuters recently featured science in Singapore and reported that the nation produces more than twice its expected output in biomedical engineering and in cell and tissue engineering, and that its papers in these fields recently earned 67% and 25% more citations per paper, respectively, than the world average in these areas.[16]

Asia is also represented in Table 10 by Japan, ranked 8th, and by Thailand, ranked 10th. Among institutions, four of the top 10 are US universities and the other six all represent Asian universities or research institutions: NUS for Singapore, Donghua University and the Chinese Academy of Sciences for China, Seoul National University and Chungnam National University for South Korea, and Chulalongkorn University for Thailand.

Seeram Ramakrishna, a leading researcher in the field who is Professor of Mechanical Engineering and also Vice President for Research Strategy at the National University of Singapore, has recently observed that the major focus of future investigation will be how "to effectively exploit the pluripotent potential of Mesenchymal Stem Cell (MSC) differentiation on [these] composite nanofibrous scaffolds."[17]

SUMMARY

Materials science and technology may be seen as an opaque area to many outsiders. It has an extensive specialist vocabulary with noun-stacked descriptions. It covers a range of knowledge and techniques that can seem arcane, even incomprehensible. But the challenge of understanding is one that is worth meeting because it is the diversification and growth of materials science and its evident potential for translation into innovative products and processes that is making it critical to economic growth and social change.

The use and development of materials has constituted a major current in the history of mankind. The history of technology is replete with important examples of revolutionary change brought on by the discovery of new materials and new uses for materials. Bronze gave way to Iron, then to Steel and arguably now to Silicon. Will graphene replace silicon in electronics? Will cars be fueled by hydrogen stored in MOFs? Will stem cells grown on nanofibrous scaffolds make organ replacement routine? The fact that we can pose these questions says something about recent advances in materials science and technology. As suggested here, we may now be entering a distinctly new Age of Advanced Materials.

Who will be in the vanguard of this change? Asian nations and institutions are clearly focusing their research efforts on new materials. There does not appear to be a similar commitment to this research on the part of Europe and North America — especially on the part of the USA which has seen its world share of materials sciences research papers not only fall by half in the last three decades but actually decline in output in the late 1990s and in the early years of the last decade. It is only now that its output of such papers is returning to the level of 1996.

The standard of US research in the field remains excellent despite the challenge: US papers in materials science earn an average of 73% more citations per paper than the world average. In fact, the USA exhibits its highest relative citation impact scores in this field compared to all other fields. Western Europe also retains a high average impact. But, as experience creates expertise among thousands of new materials researchers in Asia, the gap in citation impact between Asia, on the one hand, and Europe and North America, on the other, is starting to close.

Global research need not be seen in competitive terms, but it can be useful to view national performance comparatively. This is the context for the observations above. However, materials research in particular is closely tied to economic growth. Therefore, US and European Commission policy makers and elected representatives may wish to consider whether it is important, even vital, to make a larger commitment to materials research for the sake of future prosperity — even beyond that provided by the US National Nanotechnology Initiative and similar funding by the European Commission. Will industrial applications deriving from materials research accrue to the benefit of other nations and leave the G7 as an importer rather than an exporter of new products based on this research? In the USA, for example, biomedical research has received handsome increases in research support compared to funding for physics, chemistry, and materials science. Perhaps a new balance should be considered, despite the fact that leading institutions in the material sciences field, when citation impact is examined, are still well represented by US universities. In Europe, the Max Planck, CNRS and CSIC organizations are also well represented but the universities are less evident in our topic tables despite the location of key innovators. More universities appear when we look at citation impact but, perhaps, strategies for research support in higher education also need some reconsideration if past intellectual capital in the established research economies is fruitfully to be built upon.

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