Research Fronts: In Search of Structure of Science
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WEB OF KNOWLEDGE

RESEARCH FRONTS 2013

100 Top-Ranked Specialties in the Sciences and Social Sciences

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RESEARCH FRONT DATA REVEAL LINKS AMONG RESEARCHERS WORKING ON RELATED THREADS OF SCIENTIFIC INQUIRY, BUT WHOSE BACKGROUND MIGHT NOT SUGGEST THAT THEY BELONG TO THE SAME "INVISIBLE COLLEGE."

BACKGROUND

The world of scientific research presents a sprawling, ever-changing landscape. The ability to identify where the action is and, in particular, to track emerging specialty areas, provides a distinct advantage for administrators, policy makers, and others who need to monitor, support, and advance the conduct of research in the face of finite resources.

To that end, Thomson Reuters generates data on "research fronts." These specialties are defined when scientists undertake the fundamental scholarly act of citing one another's work, reflecting a specific commonality in their research—sometimes experimental data, sometimes a method, or perhaps a concept or hypothesis.

As part of its ongoing mission to track the world's most significant scientific and scholarly literature, Thomson Reuters surveys patterns and groupings of how papers are cited—in particular, clusters of papers that are frequently cited together. When such a grouping attains a certain level of activity and coherence (detected by quantitative analysis), a research front is formed, with the co-cited papers serving as the front's foundational "core."

Research front data reveal links among researchers working on related threads of scientific inquiry, but whose backgrounds might not suggest that they belong to the same "invisible college." For example, within this report, you'll read about how one of the highlighted research fronts, representing the combined fields of mathematics, computer science, and engineering, came together because of its underlying problem set, which required interdisciplinary input.

In all, research fronts afford a unique vantage point from which to watch science unfold—not relying on the possibly subjective judgments of an indexer or cataloguer, but hinging instead on the cognitive and social connections that scientists themselves forge when citing one another's work. The fronts provide an ongoing chronicle of how discrete fields of activity emerge, coalesce, grow (or, possibly, shrink and dissipate), and branch off from one another as they self-organize into even newer nodes of activity. Throughout this evolution, the foundations of each core—the main papers, authors, and institutions in each area—can be ascertained and monitored.

Research front analysis represents decades of bibliometric innovation dating back to the founding of citation indexing pioneered by Eugene Garfield and advanced by Henry Small. Today, Thomson Reuters is building on and furthering this methodology for observing and charting the course of science. The history of research fronts and their evolution is summarized in "Research Fronts: In Search of the Structure of Science," included as an addendum to this report.

TOP 100 RESEARCH FRONTS

This Thomson Reuters report is the first in a series to describe research fronts and their application in research management and science policy making. In this first report, we present 100 top-ranked fronts for 2013 across 10 broad areas in the sciences and social sciences. These fronts represent areas of current focus and are key fields to watch in 2013. They point to hot areas that may not otherwise be readily identified, even by some of the research institutions at the center of the action for a given front.

Each reader of this report will find his or her own points of interest in the research fronts and additional data presented here. Some prominent themes, however, may be mentioned: climate change; cell signaling; quantum behavior; energy research; computing for analysis, visualization, and modeling; and the importance of technology in the form of powerful instrumentation as a driver of scientific discovery and, ultimately, of innovations that can transform our world.

As mentioned, identifying emerging trends in science research is especially important to managers of research-intensive universities, government and industrial laboratories, as well as to national policy makers. Administrators and government officials can identify emerging fields within scientific disciplines central to their institutional or national agendas, thereby gaining an ability to invest strategically in both talent and facilities, to encourage global collaborations with institutions and authors doing the most important work in these fronts, and to benchmark their position and performance against peers.

The IP & Science division of Thomson Reuters partners with organizations around the world to promote world-class research and innovation, and the top 100 fronts—and research fronts in general—offer a unique perspective for monitoring trends and identifying opportunities for strategic investment.

METHODOLOGY AND PRESENTATION OF DATA

This report presents 100 specialties of current interest and intensive investigation in the sciences and social sciences. Our selection procedure was designed to identify the most active research fronts and, among them, those in which new knowledge is accumulating most rapidly. To this end, beginning with the nearly 8,000 research fronts currently found in Thomson Reuters Essential Science Indicators (ESI) database, we chose research fronts exhibiting the largest number of citations to their core papers. We then re-ranked the selected fronts in favor of those with the youngest foundation literature, measured by the mean year of the core papers. A research front with many core papers of recent vintage often indicates a fast-moving or hot specialty. Therefore, the research fronts highlighted in this report—10 fronts selected for each of 10 highly aggregated, main areas of science—are the hottest of the largest, not necessarily the hottest research fronts across the database, many of which are much smaller in terms of number of core and citing papers.

The specific selection procedure for the 100 research fronts listed in this report was as follows: research fronts in each of the 21 ESI fields were ranked by total citations and the top 10 percent of the fronts were extracted. These research fronts were then re-ranked according to mean year of their core papers to produce a top 10 in each area. In the tables that follow, the number of core papers, number of citations to the core papers, and mean year of the core papers are given for each research front. Since the foundation papers date from 2007 to 2012, the mean year of the core papers in a front can range from 2007 to 2012 or, typically, something in between, such as 2009.6, meaning roughly August 2009.

For each of the 10 areas in this report, a table lists the 10 top-ranked research fronts. One of the fronts in each table receives special attention: a synopsis of the research topic appears as well as supplementary data and analysis of the core papers, the citing paper group, or both, as well as other types of data meant to illustrate the analytical possibilities in exploring research fronts.

KEY

Rank: Fronts ranked by mean year of core papers, i.e., by fronts with youngest foundation literature

Research Fronts: Name of research front in each area

Core Papers: Number of core papers in the given front

Citations: Number of citations to the core papers, an indication of the front's size

Mean Year of Core Papers: Average age of the front's core literature

Shaded Row: Selected front from each category, chosen for expanded discussion and additional data

AGRICULTURAL, PLANT AND ANIMAL SCIENCES

RANK	RESEARCH FRONTS	CORE PAPERS	CITATIONS	MEAN YEAR OF CORE PAPERS
1	Impact of climate change on food crops	32	1,537	2010.0
2	Comprehensive classification of fungi based on molecular evolutionary analysis	18	1,374	2010.0
3	Arabidopsis chloroplast RNA editing	46	2,578	2009.9
4	Jasmonate biosynthesis and signaling	33	2,548	2009.9
5	Oomycete RXLR effectors and suppression of plant immunity	47	2,340	2009.7
6	Angiosperm phylogeny group classification	34	2,259	2009.7
7	Methicillin-resistant *Staphylococcus aureus* (MRSA) in livestock	17	1,071	2009.7
8	Genomic selection and estimated breeding values	39	2,281	2009.6
9	Honey bee colony collapse disorder and *Nosema ceranae*	30	1,718	2009.6
10	Insect resistance to transgenic crops producing Bt (*Bacillus thuringiensis*) toxins for pest control	22	1,134	2009.6

Source: Thomson Reuters Essential Science Indicators

JASMONATE BIOSYNTHESIS AND SIGNALING—ADVANCING CANCER RESEARCH

This research front centers on a family of plant signaling compounds known as jasmonates, which regulate the expression of plant genes in response to stress and damage, while also mediating such routine developmental processes as root growth, tuber formation, and flower development. Jasmonate signaling, for example, initiates plant-defense responses in reaction to pathogens, or to damage from herbivores.

In some instances, airborne forms of jasmonates actually afford communication from plant to plant about impending threats. Recent research has also determined that jasmonates display toxicity toward mammalian cancer cells, inducing such cells to undergo programmed death. These findings have prompted increased investigation into jasmonates as potential therapeutic anti-cancer agents.

NATIONAL AND INSTITUTIONAL ACTIVITY:
Output and uptake of highly cited core papers

Research fronts consist of a group of highly cited core papers, the foundation literature of the specialty, and a set of citing papers that frequently co-cite the core papers. The core papers all rank in the top 1 percent by citations when compared to papers of the same year in the same field. Thus, we recognize the core papers as influential, and their authors, institutions, and nations as having left a mark in the area. On the other hand, the citing papers reveal the uptake of data, techniques, and concepts reported in the core papers, even if individual papers in the citing group are not themselves highly cited or yet highly cited. The table below summarizes the nations and institutions that produced the influential foundation literature in this specialty (on the left) and then does the same with the leading edge of the research front, represented by the more recently published citing papers (on the right). As may be expected, there are similarities and differences to be noted: Michigan State University is prominent on both sides of the ledger, whereas the United Kingdom is a significant consumer of research in this area but not a highly ranked producer.

RANK	NATIONS, CORE PAPERS	%	INSTITUTIONS, CORE PAPERS	%	NATIONS, CITING PAPERS	%	INSTITUTIONS, CITING PAPERS	%
1	USA (15)	45.5	Michigan State University (8)	24.2	USA (314)	28.3	Max Planck Institute for Chemical Ecology (57)	5.1
2	China (8)	24.2	Washington State University (7)	21.2	Germany (220)	19.9	Chinese Academy of Sciences (45)	4.1
3	Japan (4) Spain (4)	12.1	Tsinghua University (4)	12.1	China (158)	14.3	Michigan State University (37)	3.3
4	Australia (3) Belgium (3) Germany (3)	9.1	Chinese Academy of Sciences (3); CSIC Spain (3); Duke University (3); Leibniz Institute of Plant Biochemistry (3); University of Ghent (3); University of Washington (3)	9.1	Japan (131)	11.8	Leibniz Institute of Plant Biochemistry (29)	2.6
5	South Korea (2) Switzerland (2)	6.1	Hunan Agricultural University (2); Konkuk University (2); Riken Plant Science Center (2); University of Antwerp (2); University of Lausanne (2); University of Nebraska (2); Washington University (2)	6.1	UK (80)	7.2	University of Gottingen (28)	2.5

Source: Thomson Reuters Essential Science Indicators

ECOLOGY AND ENVIRONMENTAL SCIENCES

RANK	RESEARCH FRONTS	CORE PAPERS	CITATIONS	MEAN YEAR OF CORE PAPERS
1	Ocean acidification and marine ecosystems	45	3,653	2009.6
2	Biodiversity and functional ecosystems	43	3,139	2009.5
3	Mangrove forests and climate change	16	1,121	2009.5
4	Models and impacts of land-use change	18	2,318	2009.4
5	Biochar amendment techniques and effects	41	2,300	2009.4
6	Adaptive evolution in invasive species and approximate Bayesian computation	19	1,255	2009.4
7	Chytridiomycosis and large-scale amphibian population extinctions	13	1,003	2009.3
8	Pharmaceutical residues in environmental water and wastewater	50	3,815	2009.1
9	Community ecology and phylogenetic comparative biology	20	1,799	2009.1
10	Climate warming, altered thermal niches, and species impact	14	1,244	2009.1

Source: Thomson Reuters Essential Science Indicators

OCEAN ACIDIFICATION AND MARINE ECOSYSTEMS

Activity in this research front examines chemical changes in seawater caused by increased levels of atmospheric carbon dioxide—the result of human fossil-fuel burning—and how these changes are affecting fragile marine ecosystems and the broad spectrum of oceanic life. The dissolving of atmospheric carbon dioxide into the ocean causes, among other effects, greater acidity in the water. This, in turn, affects ocean species whose shells and skeletons depend on calcification, threatening their presence in the deeply interconnected web of marine life. In all, this research seeks to evaluate the consequences of human-generated climate change on the oceans.

CORAL REEF SYSTEM: Australia's leadership role

Of the 45 core papers in our research front on ocean acidification and marine ecosystems, nine were produced by Australian scientists. That 20 percent representation is about four times greater than expected considering that Australia's contribution of papers to ecology and environmental sciences during the last five years was 5.5 percent. Moreover, Australia's world share of papers in all subjects surveyed in the internationally influential journals indexed by Thomson Reuters during the same period was only 3.3 percent. Therefore, it is plain that ecology and environmental sciences is a focus area for the nation and, in particular, ocean acidification, marine habitats, and specifically coral reef studies are domains in which Australia plays a global leadership role. The Australian Research Council's Centre of Excellence in Coral Reef Studies, headquartered at James Cook University in Townsville, is one explanation of the nation's research impact in the field. The Centre is a partnership of James Cook University, University of Queensland, Australian Institute of Marine Studies, Australian National University, University of Western Australia, and the Great Barrier Reef Marine Park Authority. Listed below are the nine Australian core papers in this front, along with their total citations to date, the names of the Australian authors listed on the papers, and their affiliations.

CITES	AUSTRALIAN AUTHORS	TITLE / SOURCE	AUSTRALIAN AFFILIATIONS
736	O. Hoegh-Guldberg, P. Greenfield, R.H. Bradbury	"Coral reefs under rapid climate change and ocean acidification," *Science*, 318 (5857): 1737-1742. December 14, 2007	University of Queensland, Centre for Marine Studies, St. Lucia, and Australian National University, Resource Management in Asia-Pacific Program, Canberra
176	K.R.N. Anthony, D.I. Kline, G. Diaz-Pulido, S. Dove, O. Hoegh-Guldberg	"Ocean acidification causes bleaching and productivity loss in coral reef builders," *PNAS*, 105 (45): 17442-17446, November 11, 2008	University of Queensland, Centre for Marine Studies, and University of Queensland, ARC Centre of Excellence for Coral Reef Studies, St. Lucia
141	G. De'ath, J.M. Lough, K.E. Fabricius	"Declining coral calcification on the great barrier reef," *Science*, 323 (5910): 116-119, January 2, 2009	Australian Institute of Marine Science, Townsville
85	P.L. Munday, D.L. Dixson, J.M. Donelson, G.P. Jones, M.S. Pratchett	"Ocean acidification impairs olfactory discrimination and homing ability of a marine fish," *PNAS*, 106 (6): 1848-1852, February 10, 2009	James Cook University, ARC Centre of Excellence for Coral Reef Studies, Townsville, and James Cook University, School of Marine and Tropical Biology, Townsville
55	J.M. Pandolfi, S.R. Connolly, D.J. Marshall	"Projecting coral reef futures under global warming and ocean acidification," *Science*, 333 (6041): 418-422, July 22, 2011	University of Queensland, ARC Centre of Excellence for Coral Reef Studies, St. Lucia; University of Queensland, School of Biological Sciences, St. Lucia; James Cook University, ARC Centre of Excellence for Coral Reef Studies, Townsville; and James Cook University, School of Marine and Tropical Biology, Townsville
52	K.E. Fabricius, S. Uthicke, C. Humphrey, S. Noonan, G. De'ath, J.M. Lough	"Losers and winners in coral reefs acclimatized to elevated carbon dioxide concentrations," *Nature Climate Change*, 1 (3): 165-169, June 2011	Australian Institute of Marine Science, Townsville
48	D.L. Dixson, P.L. Munday, G.P. Jones	"Ocean acidification disrupts the innate ability of fish to detect predator olfactory cues," *Ecology Letters*, 13 (1): 68-75, January 2010	James Cook University, ARC Centre of Excellence for Coral Reef Studies, Townsville, and James Cook University, School of Marine and Tropical Biology, Townsville
28	M. Byrne	"Impact of ocean warming and ocean acidification on marine invertebrate life history stages: Vulnerabilities and potential for persistence in a changing ocean," *Oceanography and Marine Biology: An Annual Review*, 49: 1-42, 2011	University of Sydney, School of Medicine and School of Biological Sciences, Sydney
10	D.L. Dixson, M.I. McCormick, S.A. Watson, P.L. Munday	"Near-future carbon dioxide levels alter fish behaviour by interfering with neurotransmitter function," *Nature Climate Change*, 2 (3): 201-204, March 2012	James Cook University, ARC Centre of Excellence for Coral Reef Studies, Townsville, and James Cook University, School of Marine and Tropical Biology, Townsville

Source: Thomson Reuters Essential Science Indicators

GEOSCIENCES

RANK	RESEARCH FRONTS	CORE PAPERS	CITATIONS	MEAN YEAR OF CORE PAPERS
1	Tectonic evolution of the southern central Asian orogenic belt	24	1,176	2010.1
2	Global terrestrial isoprene emissions and climate	25	1,300	2009.8
3	U-Pb zircon ages and geochronology of southern Tibet	45	2,521	2009.7
4	Greenland ice core chronology and the Middle to Upper Paleolithic transition	28	2,490	2009.6
5	Nucleation and growth of nanoparticles in the atmosphere	33	1,835	2009.6
6	Climate change and precipitation extremes	30	2,098	2009.5
7	Greenland ice sheet mass, melt, and motion	25	1,627	2009.4
8	Studies of the 2008 Wenchuan earthquake	38	2,326	2009.1
9	Black carbon emissions and Arctic air pollution	17	1,090	2009.1
10	Ground motion prediction equations and the 2009 L'Aquila earthquake in central Italy	31	2,196	2009.0

Source: Thomson Reuters Essential Science Indicators

STUDIES OF THE 2008 WENCHUAN EARTHQUAKE

This front chiefly concerns a major earthquake that struck the Sichuan province of China on May 12, 2008. Registering at magnitude 7.9, the quake caused catastrophic damage in four counties, killing upwards of 90,000 people and rendering more than 4 million homeless. Ironically, this earthquake—China's most devastating in more than three decades—occurred in a region not known to be at high seismic risk. Subsequent research has clarified the specifics of surface rupture and other seismological aspects of the quake, while related papers have examined similar phenomena in such locations as India and the western United States.

EVENT-DRIVEN RESEARCH FRONTS: Researchers respond to 3-11-11

When a significant earthquake occurs, a new research front may emerge almost instantly as seismologists and other geophysical researchers collect, analyze, and publish data and interpretations of the event. As the table on the facing page shows, the 2008 Wenchuan and the 2009 L'Aquila earthquakes each produced a significant and cohesive collection of studies. So, too, for the devastating 2011 Tohoku earthquake of magnitude 9.0 on March 11, 2011. Two research fronts related to that event and its aftermath appear in our data, although neither one yet exhibits a sufficient number of citations to rank it in the top 10 percent of research fronts in the field. In terms of immediacy, or currency of the foundation literature in the front calculated as the average age of its core papers, both fronts can, however, be designated as hot.

- 2011 Tohoku and 2010 Maule earthquakes
- Radionuclide release and dispersion from the Fukushima Daiichi nuclear plant accident

The first research front includes 41 core papers cited a total of 1,003 times so far. In their citation patterns, researchers linked the Japanese event to one in Chile the year before. Both were great subduction zone earthquakes and both exhibited similar stress axes. The second research front includes 18 core papers and 253 citations of these papers to date. The average age of the core papers in this front is about July-August 2011, mere months after the catastrophe. Many of the core papers report the detection of the isotopes cesium-137, iodine-131, and xenon-133 in soil, water, and in the atmosphere.

A search of Thomson Reuters Web of Science database for papers dealing with the Tohoku-Oki earthquake, Fukushima nuclear plant accident, and its aftermath produced 882 items, 284 from 2011 and 598 from 2012. The table below lists the nations, institutions, as well as fields most frequently represented in the papers identified.

RANK	NATION	%	RANK	INSTITUTIONS	%	RANK	FIELD	%
1	Japan (388)	44.0	1	University of Tokyo (76)	8.6	1	Geosciences, Multidisciplinary (198)	22.4
2	USA (222)	25.2	2	Kyoto University (56)	6.3	2	Environmental Sciences (157)	17.8
3	China (52)	5.9	3	Tohoku University (54)	6.1	3	Nuclear Science and Technology (125)	14.2
4	Germany (51)	5.8	4	Caltech (29); Hokkaido University (29)	3.3	4	Geochemistry and Geophysics (117)	13.3
5	France (48)	5.4	5	Japan Atomic Energy Agency (24)	2.7	5	Public, Environmental and Occupational Health (62)	7.0

Source: Thomson Reuters Essential Science Indicators

As mentioned, behind the numbers given above was a real event—a terrible event—that with suddenness killed more than 15,000 persons, injured some 6,000, and left another nearly 3,000 unaccounted for. A shared humanity compels us to honor the memory of those lost and to consider the sufferings of the hundreds of thousands who were uprooted, and the even larger number indirectly, but significantly, affected by the quake, tsunami, and nuclear accident. In the aftermath, scientific professionals responded to this crisis, and not only by publishing articles in science journals. Medical and public health workers, nuclear engineers, structural engineers, geophysicists, chemists, and many others immediately provided their expertise and analysis, often under difficult circumstances and great pressure, to aid Japan's national and local authorities.

CLINICAL MEDICINE

RANK	RESEARCH FRONTS	CORE PAPERS	CITATIONS	MEAN YEAR OF CORE PAPERS
1	Transcatheter aortic valve implantation	50	2,818	2011.0
2	Atypical hemolytic uremic syndrome and complement activation	36	1,939	2010.6
3	Acquired BRAF inhibitor resistance in metastatic melanoma	36	4,777	2010.5
4	Idiopathic pulmonary fibrosis and randomized placebo-controlled drug trials	38	2,269	2010.5
5	Pathology and treatment of nonalcoholic fatty liver disease	34	1,978	2010.5
6	Chemotherapy with and without bevacizumab for HER2-negative breast cancer	14	1,909	2010.5
7	Brentuximab vedotin for refractory and relapsed Hodgkin's lymphoma	23	2,001	2010.4
8	IL28B polymorphisms and treatment response in hepatitis C patients	47	5,172	2010.3
9	Anaplastic lymphoma kinase (ALK) inhibition in non-small cell lung cancer	46	3,716	2010.3
10	Global, national, and regional assessments of maternal, newborn, and child health	42	2,640	2010.3

Source: Thomson Reuters Essential Science Indicators

ACQUIRED BRAF-INHIBITOR RESISTANCE

Roughly half of melanomas are associated with a mutation in a gene that codes for an enzyme known as BRAF, as the consequent over activation of BRAF leads to the proliferation of cancerous cells. Within the last few years, clinicians have achieved marked success in prolonging life in cases of metastatic melanoma via the use of new compounds, such as vemurafenib, which inhibit BRAF, although subsequent rates of relapse within a year or so indicate that tumors acquire resistance to the BRAF inhibitors. Activity in this research front covers general aspects of BRAF-mutated melanoma and its treatment, and focuses on the mechanisms of resistance as well as means by which additional therapies can be brought to bear to maintain BRAF inhibition.

UNITED STATES – AND GLOBAL PHARMACEUTICAL FIRMS – PURSUE THE PROMISE OF, AND PROBLEMS WITH, BRAF INHIBITORS

YEAR	PAPERS
2003	125
2004	218
2005	346
2006	378
2007	408
2008	480
2009	566
2010	757
2011	860
2012	1,252

Total papers n=5,390

The publication years of the core papers in this research front reveal the increasing pace of discovery in this specialty: 7 of the 36 core papers date from 2007-2009, while the other 29 appeared in 2010-2012. The accompanying table (left) takes a longer and deeper view of research on the BRAF gene and its mutations. From 2003 to 2012, Thomson Reuters indexed a total of 5,390 articles on BRAF in its Web of Science database. Over this decade, the annual output of such papers increased tenfold. The table below summarizes the main actors in the front, both in terms of the origins of the core papers as well as of the citing papers that represent more recent work. The United States is strongly represented. This dominant position is also reflected in the ranking of institutions by core papers and by citing papers. With the exception of the Peter MacCallum Cancer Centre in Melbourne, Australia, and Bristol Myers Squibb (a global enterprise), all those listed are US institutions. Memorial Sloan Kettering Cancer Center and Massachusetts General Hospital are clearly key institutional players.

RANK	NATIONS, CORE PAPERS	%	INSTITUTIONS, CORE PAPERS	%	NATIONS, CITING PAPERS	%	INSTITUTIONS, CITING PAPERS	%
1	USA (33)	91.7	Memorial Sloan Kettering Cancer Center (13)	36.1	USA (1,444)	61.5	Harvard University (148)	6.3
2	Australia (12)	33.3	University of South Florida (11)	30.6	Germany (202)	8.6	Memorial Sloan Kettering Cancer Center (135)	5.7
3	France (7) Germany (7)	19.4	University of California Los Angeles (10)	27.8	UK (197)	8.4	University of Texas M.D. Anderson Cancer Center (121)	5.1
4	UK (6) Switzerland (6)	16.7	Angeles Clinical Research Institute (9); Massachusetts General Hospital (9); Vanderbilt University (9)	25.0	Italy (172)	7.3	National Cancer Institute (91)	3.9
5	Canada (5) Italy (5)	13.9	Peter MacCallum Cancer Center (8); Melbourne (8); Bristol Myers Squibb	22.2	France (153)	6.5	Massachusetts General Hospital (89)	3.8

Source: Thomson Reuters Essential Science Indicators

The table below looks at activity by pharmaceutical firms in this specialty, in terms of the institutional addresses on the core papers and the citing papers. Data drawn from funding acknowledgements are also listed, providing another, and an often revealing, window on the activities and interests of industry.

RANK	COMPANY	CORE PAPERS	COMPANY	FUNDING OF CORE PAPERS	COMPANY	CITING PAPERS	COMPANY	FUNDING OF CITING PAPERS
1	Bristol Myers Squibb	8	Bristol Myers Squibb	10	Bristol Myers Squibb	46	Bristol Myers Squibb	89
2	Plexxikon	7	Novartis	7	Genentech	33	Pfizer	61
3	Hoffmann La Roche Medarex	5	Hoffmann La Roche	6	Hoffman La Roche, Novartis	22	GlaxoSmithKline	53
4	GlaxoSmithKline	3	Genentech, Merck, Pfizer, Plexxikon	3	Plexxikon	18	Hoffman La Roche, Novartis	47
5	Genentech, Novartis	2	Millennium	2	GlaxoSmithKline	15	Merck, Sharp, Dohme	38

Core papers n=36 and citing papers n=2,350
Source: Thomson Reuters Essential Science Indicators

BIOLOGICAL SCIENCES

RANK	RESEARCH FRONTS	CORE PAPERS	CITATIONS	MEAN YEAR OF CORE PAPERS
1	DNA methylation analysis and missing heritability	25	3,153	2011.0
2	Toxicity of amyloid beta (Aβ) oligomers in Alzheimer's disease	45	2,588	2010.6
3	Differentiation and function of follicular helper CD4 T cells (TFH)	38	2,760	2010.5
4	Human beta(2) adrenergic G-protein-coupled receptors (GPCRs)	44	6,261	2010.4
5	Linear ubiquitin chain assembly complex and activation of nuclear factor-κB (NF-κB)	43	3,749	2010.4
6	Lgr5 receptor-expressing intestinal stem cells	23	2,699	2010.3
7	TET mutations, reduction of 5-hydroxymethylcytosine (5hmC), and malignancy	45	6,112	2010.2
8	Inhibition of TOR (Target Of Rapamycin) signaling, increased lifespan, and diseases of aging	30	3,152	2010.1
9	HIV-1 Vpu and Vpx proteins and restriction factors SAMHD1 and BST-2/Tetherin	48	3,760	2009.9
10	Mitochondrial sirtuins and regulation of metabolism	32	3,395	2009.9

Source: Thomson Reuters Essential Science Indicators

BETA(2) ADRENERGIC GPCRS

In cellular communication, few players are as essential as the G-protein-coupled receptors (GPCRs). Modulating molecular signals across the cell membrane and initiating various cellular responses, GPCRs are involved in the biochemical workings underlying the senses of taste, smell, and sight, as well as responses to a host of hormones and neurotransmitters. Not coincidentally, they serve as ideal drug targets and are therefore of enormous interest to the pharmaceutical industry. Activity in this front principally consists of structural and functional studies of the GPCR family, whose members currently number upwards of 800. One GPCR complex in particular, the β2 adrenergic receptor, has undergone detailed scrutiny by X-ray crystallography and other means to determine its precise molecular structure, with the aim of improving drug design for a variety of diseases.

STIMULATING RESEARCH WINS NOBEL PRIZE

YEAR	CORE PAPERS	HOT PAPERS
2007	3	NA
2008	7	NA
2009	2	NA
2010	4	2
2011	13	5
2012	15	7

Last October, the Royal Swedish Academy of Sciences announced that the 2012 Nobel Prize in Chemistry would be awarded to Brian K. Kobilka of Stanford University and Robert J. Lefkowitz of Duke University for their biochemical studies of G-protein-coupled receptors, also known as seven-transmembrane (7TM) receptors. Typically, a Nobel Prize recognizes fundamental discoveries published two or three decades in the past. Lefkowitz, in fact, made his first significant contribution to this subject in 1970. In 1984, Kobilka joined the laboratory of Lefkowitz at Duke as a post-doc and was part of the team that cloned the β2 adrenergic receptor in 1986. Kobilka formed his own laboratory at Stanford in 1989. But the work that won this pair the Nobel Prize is anything but old news.

What is notable about the research front highlighted here is its great size and currency. It exhibits 44 core papers that have been cited more than 6,000 times by nearly 2,500 papers. Moreover, of the 44 core papers, 32 were published in just the last three years. This shows a specialty whose foundational literature is turning over rapidly. And of the 30 core papers in the front that appeared since November 1, 2010, 17 of these are classified as hot, meaning that they not only rank in the top 1 percent by citations, (as all core papers do), but also in the top .1 percent of the citation frequency distribution for papers in the same field and of the same age. The table at left shows that nearly half of the 2012 core papers in this front are hot papers (by definition, hot papers are all two years old or younger, and the period surveyed for these was November 1, 2010 through October 31, 2012, which explains the presence of "NA" for the years 2007, 2008, and 2009). One of these hot papers, published in *Nature* in September 2011, provided the three-dimensional structure of the moment of activation of the β2-adrenergic receptor. This high-resolution image of what is known as an active ternary complex was described by Nobel committee member Sara Snogerup Linse as the equivalent of finding the Holy Grail.

It is no surprise that Kobilka is author of 14 of the 44 core papers in this front (Lefkowitz is author of two). Another leading investigator in this specialty, with 13 core papers, is Raymond C. Stevens of the Scripps Research Institute in La Jolla, California. Papers by Kobilka and by Stevens account for 25, or more than half, of the foundation papers in this research front (two of these were coauthored). The table below summarizes the leading nations and institutions in this specialty, both in terms of number of core papers and papers citing the core papers.

RANK	NATIONS, CORE PAPERS	%	INSTITUTIONS, CORE PAPERS	%	NATIONS, CITING PAPERS	%	INSTITUTIONS, CITING PAPERS	%
1	USA (31)	70.5	Stanford University (14)	31.8	USA (1,106)	44.9	Scripps Research Institute (69)	2.8
2	UK (11)	25.0	Scripps Research Institute (13)	29.5	Germany (340)	13.8	Kyoto University (58)	2.4
3	Germany (7)	15.9	MRC Laboratory of Molecular Biology (7)	15.9	UK (282)	11.4	University of Copenhagen (57)	2.3
4	Denmark (4) France (4) South Korea (4)	9.1	University of California San Diego (6)	13.6	France (191)	7.8	CNRS (46) Monash University (46) Stanford University (46)	1.9
5	Australia (3) Japan (3)	6.8	University of Michigan (5)	11.4	Japan (141)	5.7	University of North Carolina (40)	1.6

Source: Thomson Reuters Essential Science Indicators

CHEMISTRY AND MATERIALS SCIENCE

RANK	RESEARCH FRONTS	CORE PAPERS	CITATIONS	MEAN YEAR OF CORE PAPERS
1	Enhanced visible-light photocatalytic hydrogen production	43	1,620	2011.2
2	Ruthenium- or rhodium-catalyzed oxidative C-H bond activation	46	1,900	2011.0
3	Aggregation-induced emission characteristics and compounds	47	1,989	2010.9
4	Photoredox catalysis in organic synthesis	32	1,945	2010.5
5	Enantioselective phosphine organocatalysis	35	1,927	2010.5
6	Nanopore DNA sequencing	33	1,914	2010.5
7	Small-molecule solution-processed bulk heterojunction solar cells	31	1,841	2010.5
8	Nitrogen-doped graphene	26	2,364	2010.4
9	Roll-to-roll processed polymer solar cells	35	3,969	2010.3
10	Silicon nanowires for lithium-ion battery anodes	50	2,896	2010.3

Source: Thomson Reuters Essential Science Indicators

POLYMER SOLAR CELL PROCESSING

Considerable recent research has focused on the development of solar cells that convert sunlight to electricity by means of organic polymers, as opposed to the more-established technology employing cells based on silicon. Due to their potentially low cost and environmentally friendly properties, polymer solar cells are extremely promising, although their photovoltaic efficiency and durability still require improvement.

Research in this front discusses methods of roll-to-roll processing for polymer solar cells —actually printing such cells on a thin sheet. Ultimately, this step will afford mass production, thereby fulfilling the technology's promise of lightweight, flexible solar panels whose applications will include powering mobile devices and bringing electricity to remote regions in the developing world.

RESEARCHER ON A ROLL:
Frederik C. Krebs of the Technical University of Denmark

Krebs, Professor in the Department of Energy Conversion and Storage at the Risø National Laboratory for Sustainable Energy/Technical University of Denmark, Roskilde, is the author of a remarkable 31 of 35 core papers in this highlighted research front. Lest anyone think that such a monopoly reflects the work of one researcher focusing on a narrow subject of concern only to himself, 95 percent of the 4,525 citations to the core papers in this front derive from others, not from the publications of Krebs and his team members. These data clearly demonstrate the central position of Krebs in research on roll-to-roll processing of polymer solar cells. Listed below are the five most-cited core papers in this area, all by Krebs and his colleagues, and the last in collaboration with researchers at the Danish firm Mekoprint A/S.

CITATIONS	AUTHORS	TITLE / SOURCE	AFFILIATIONS
630	M. Jorgensen, K. Norrman, F.C. Krebs	"Stability/degradation of polymer solar cells," *Solar Energy Materials and Solar Cells*, 92 (7): 686-714, July 2008	Technical University of Denmark
593	F.C. Krebs	"Fabrication and processing of polymer solar cells: A review of printing and coating techniques," *Solar Energy Materials and Solar Cells*, 93 (4): 394-412, April 2009	Technical University of Denmark
414	F.C. Krebs, S.A. Gevorgyan, J. Alstrup	"A roll-to-roll process to flexible polymer solar cells: Model studies, manufacture and operational stability studies," *Journal of Materials Chemistry*, 19 (30): 5442-5451, 2009	Technical University of Denmark
289	F.C. Krebs, T. Tromholt, M. Jorgensen	"Upscaling of polymer solar cell fabrication using full roll-to-roll processing," *Nanoscale*, 2 (6): 873-886, 2010	Technical University of Denmark
287	F.C. Krebs, M. Jorgensen, K. Norrman, O. Hagemann, J. Alstrup, T.D. Nielsen, J. Fyenbo, K. Larsen, J. Kristensen	"A complete process for production of flexible large area polymer solar cells entirely using screen printing-First public demonstration," *Solar Energy Materials and Solar Cells*, 93 (4): 422-441, April 2009	Technical University of Denmark, and Mekoprint A/S, Støvring, Denmark (Fyenbo, Larsen, and Kristensen)

Source: Thomson Reuters Essential Science Indicators

In April 2011, Thomson Reuters interviewed Krebs for its online resource *ScienceWatch* regarding a fast-breaking paper in which he described a real-world use of his laboratory invention (F.C. Krebs, T.D. Nielsen, J. Fyenbo, M. Wadstrom, and M.S. Pedersen, "Manufacture, integration and demonstration of polymer solar cells in a lamp for the 'Lighting Africa' initiative," *Energy & Environmental Science*, 3 (5): 512-525, 2010). The Lighting Africa Initiative is a joint program of the International Finance Corporation and World Bank that "supports the global lighting industry in developing affordable, clean, and efficient modern lighting and energy solutions for millions of Sub-Saharan Africans who currently live without access to the electricity grid" (World Resources Institute, "A Compilation of Green Economy Policies, Programs, and Initiatives from Around the World. The Green Economy in Practice: Interactive Workshop 1, February 11th, 2011," page 5; available at http://pdf.wri.org/green_economy_compilation_2011-02.pdf).

"The general idea of demonstrating your research to everyone interested and not simply describing it in scientific articles (while keeping it secret from the rest of the world) is in my view necessary to achieve credibility of the research," Krebs told *ScienceWatch*. "It is naïve to think that you can develop something in the laboratory, patent it, and then think that there will be widespread usage of the invention. Any development has to be adapted to the real world, and making the laboratory development in its final form represents only 10-20 percent of the way to real usage and benefit to society."

(http://archive.sciencewatch.com/dr/fbp/2011/11aprfbp/11aprfbpKreb/)

PHYSICS

RANK	RESEARCH FRONTS	CORE PAPERS	CITATIONS	MEAN YEAR OF CORE PAPERS
1	Alkali-doped iron selenide superconductors	49	2,000	2011.2
2	Spin-orbit coupled Bose-Einstein condensates	48	1,752	2011.1
3	Dark matter direct detection experiments	48	3,285	2010.6
4	Evidence of majorana fermions	44	2,887	2010.6
5	Top quark forward-backward asymmetry	48	2,213	2010.6
6	Quantum simulations with trapped ions	36	2,017	2010.5
7	Nodal gap structure in iron-based superconductors	36	1,863	2010.4
8	Holographic Fermi surfaces and entanglement entropy	37	2,643	2010.1
9	Interpreting quantum discord	41	3,650	2010.0
10	Topological insulators	45	8,957	2009.9

Source: Thomson Reuters Essential Science Indicators

ALKALI-DOPED IRON SELENIDE SUPERCONDUCTORS

It has been a long and winding road from the discovery of high-temperature superconductivity in cuprates in 1986 (for which J. Georg Bednorz and K. Alex Müller won the Nobel Prize in Physics in 1987) through a succession of other compounds exhibiting high T_c. More recently, in 2006 and 2008, iron-based compounds with superconducting properties were identified. In 2010, selenium was substituted for arsenic in the iron pnictide compounds, with intercalation of potassium, rubidium, cesium, or thalium between the iron and selenium layers. This group is known as the iron chalcogenide family of superconductors.

Superconductivity—the state in which materials can conduct current with absolutely no electrical resistance—promises a wide variety of applications. The powerful electromagnets used in magnetic resonance imaging (MRI) and nuclear magnetic resonance (NMR) machines constitute just one example of existing technology. Future applications are expected to include transmission lines that can carry electricity over long distances with little or no loss of power, and the further development of propulsion systems such as those already seen in some "maglev" (for "magnetic elevation") trains that employ electromagnets to attain high speed.

CHINESE SCIENTISTS AT THE FOREFRONT

Thomson Reuters analysts are frequently asked: "When will China have its first home-grown Nobel laureate in the sciences?" It is a question impossible to answer because no one knows what remarkable discoveries will be made in the future or how the Nobel committees decide on their specific honorees for research published in the past. Nonetheless, the rise of China in the internationally influential journal literature indexed by Thomson Reuters—in terms of share of world output—is the most significant event in the structure of scientific research in the past 30 years. In 1983, China produced just .6 percent of articles surveyed by Thomson Reuters in the Science Citation Index (Web of Science). Now, China produces some 13 percent of the literature, second only to the United States at 29 percent. Output, or world share, does not necessarily align with research impact as measured by citations, but there is typically some correspondence between capacity and quality, eventually.

The research front ranked first in the table on page 18 focuses on a new class of superconducting materials. The analysis below of the national and institutional affiliations of the authors on the front's 49 highly cited core papers reveals China's dominant position in this cutting-edge area of condensed matter physics. Also listed are the researchers with the greatest number of core papers in the front – and all are affiliated with Chinese institutions.

RANK	NATION	%	INSTITUTIONS	%	SCIENTISTS	%
1	China (30)	61.2	Chinese Academy of Sciences (15)	30.6	Gen-Fu Chen, Renmin University (9)	18.4
2	USA (15)	30.6	Renmin University of China (13)	26.5	Xian-Hui Chen, USTC (8)	16.3
3	Germany (7)	14.3	University of Science and Technology of China (8)	16.3	Jun-Bao He, Renmin Univ (7); Du-Ming Wang, Renmin Univ (7); Jian-Jun Ying, USTC (7)	14.3
4	Japan (5) Moldova (5) Switzerland (5)	10.2	Zhejiang University (7)	14.3	Xiang-Feng Wang, USTC (6)	12.2
5	France (4)	8.2	University of Augsberg (6)	12.2	Chi-Heng Dong, Zhejiang Univ (5); Ming-Hu Fang, Zhejiang Univ (5); Jiang-Ping Hu, CAS (5); Ai-Feng Wang, USTC (5); Hang-Dong Wang, Zhejiang Univ (5); Meng Zhang, USTC (5)	10.2

Source: Thomson Reuters Essential Science Indicators

What about the search for the Higgs boson?

A research front on the search for the Higgs boson is, in fact, the hottest current research front in our database. A grouping of 38 core papers—all published in 2012—define this front along with their citing papers. The citation count for this front puts it at the 78th percentile among those for physics—astonishing given that all the papers of the foundation literature were published only last year and had relatively little time to be cited by year-end. Since the selection method in this report surveyed only those fronts that ranked in the 90th percentile in terms of total citations and then re-ranked these by immediacy of their core papers (this in order to capture the largest areas of focus within a field that had the greatest currency), we did not select this specialty. However, had we reversed our method and chosen currency of the foundation literature first and considered total citations afterwards—an approach that would identify the hottest, though not necessarily the largest, research fronts—the research front would have floated to the top, not only in physics but in all fields of the sciences and social sciences. A future Thomson Reuters report on research fronts will focus on the characteristics and identification of both hot and emerging specialties.

ASTRONOMY AND ASTROPHYSICS

RANK	RESEARCH FRONTS	CORE PAPERS	CITATIONS	MEAN YEAR OF CORE PAPERS
1	Galileon cosmology	34	1,584	2010.7
2	Probing extreme redshift galaxies in the Hubble Ultra Deep Field	31	2,415	2010.3
3	Sterile neutrinos at the eV scale	41	2,472	2010.2
4	Herschel Space Observatory and initial performance	9	1,456	2010.2
5	Kepler Mission and the search for extra-solar planets	47	4,211	2010.0
6	Neutron star observations and nuclear symmetry energy	18	1,536	2009.9
7	Evolution of massive early-type galaxies	18	1,724	2009.6
8	Gamma-ray sources detected by the Fermi Large Area Telescope	8	1,531	2009.5
9	Data from Hinode (Solar-B) Solar Optical Telescope and Solar Dynamics Observatory (SDO)	24	3,023	2009.4
10	Supernova Type Ia light curves and dark energy	19	5,920	2009.2

Source: Thomson Reuters Essential Science Indicators

KEPLER MISSION AND THE SEARCH FOR EXTRA-SOLAR PLANETS

Launched in 2009 by NASA, the Kepler observatory, named for the 17th-century German astronomer Johannes Kepler, has been orbiting the Sun, its sensors trained on upwards of 150,000 stars in the Milky Way galaxy. Its mission: scan for evidence of Earth-like planets in the "habitable zone" near parent stars—a zone in which atmospheric conditions might permit the existence of water. A candidate planet betrays its presence by transiting in front of its parent star, causing a momentary dimming of the star's light. This dimming is captured and recorded by Kepler's instruments. Three such transits are required before a candidate planet can be confirmed. Thus far, Kepler has identified more than 1,200 Earth-like planet candidates. Reports in this research front discuss general aspects of the Kepler mission as well as others such as the CoRoT space telescope, a joint venture of France and Brazil that was launched in 2006 before the Kepler Mission. The 47 core papers in the highlighted research front discuss data collection procedures, as well as the specific characteristics of several observed planets.

IDENTIFYING EXOPLANETS:
A growth industry

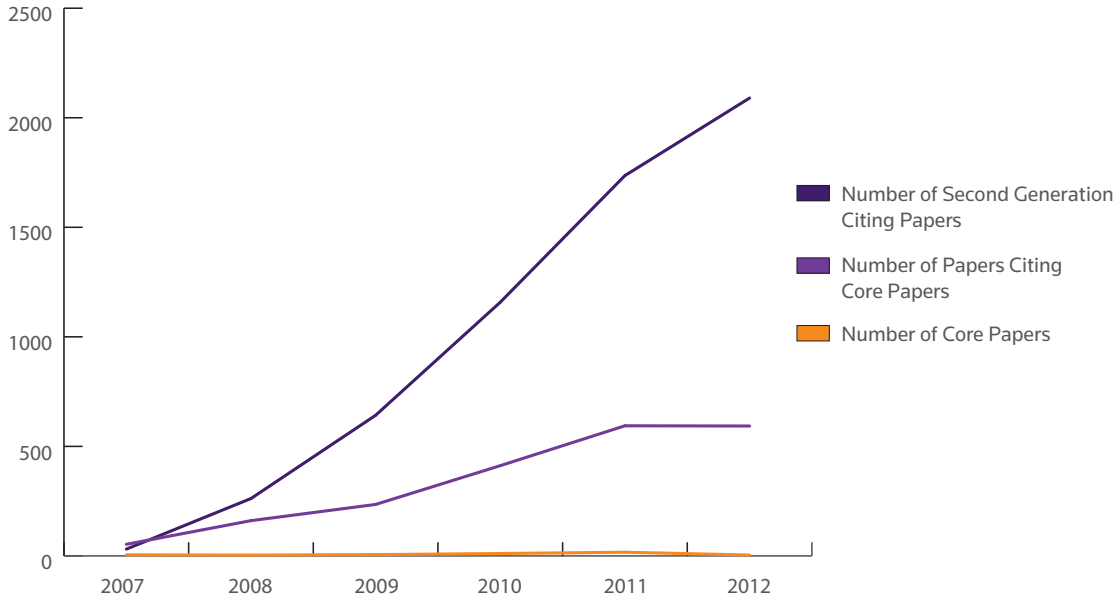
The table below lists the number of articles indexed by Thomson Reuters each year from 2007 through 2012 that were identified as 1) core papers in the highlighted research front, 2) papers that cited the core papers, and 3) papers that cited the papers that cited the core papers, or second generation citing papers (the graph below illustrates the sharp expansion of activity deriving from a comparatively small core). It is evident that the search for exoplanets is a growth industry, and this is also reflected in a rapidly increasing catalogue of verified extra-solar planets.

PUBLICATION YEARS	NUMBER OF CORE PAPERS	NUMBER OF PAPERS CITING CORE PAPERS	NUMBER OF SECOND GENERATION CITING PAPERS
2007	5	53	31
2008	4	161	262
2009	6	235	642
2010	11	412	1158
2011	17	594	1736
2012*	4	593	2090
Total	47	2048	5919

*includes papers published in 2013 journals received in 2012

Source: Thomson Reuters Essential Science Indicators

EXOPLANETARY RESEARCH: THE NEXT GENERATION(S)
How a small core of foundational papers can initiate an expanding sphere of subsequent reports and citations



Source: Thomson Reuters Essential Science Indicators

MATHEMATICS, COMPUTER SCIENCE AND ENGINEERING

RANK	RESEARCH FRONTS	CORE PAPERS	CITATIONS	MEAN YEAR OF CORE PAPERS
1	High-energy rechargeable lithium-air batteries	49	2,006	2010.8
2	Boundary value problems of nonlinear fractional differential equations	47	1,172	2010.2
3	Chemical kinetic reaction mechanism for combustion of biodiesel fuels	49	1,555	2010.0
4	Nonlocal Timoshenko beam theory and carbon nanotubes	39	1,480	2009.8
5	Constrained total-variation image de-noising and restoration	49	2,741	2009.7
6	Graphene transistors	16	2,270	2009.7
7	Analyzing next-generation DNA sequencing data	6	2,025	2009.6
8	Heat transfer in nanofluids	40	1,928	2009.6
9	Calcium looping process for carbon dioxide capture	36	1,562	2009.6
10	Differential evolution algorithm and memetic computation	30	1,351	2009.6

Source: Thomson Reuters Essential Science Indicators

CONSTRAINED TOTAL-VARIATION IMAGE DE-NOISING AND RESTORATION

The core papers for this research front present several methods and algorithms designed for the recovery or restoration of signals, images, and videos in instances in which the data source might be sparse, or where noise or blur must be corrected, or missing data filled in. Such measures find application in medical imaging and intelligence gathering. Specific examples include tracking moving objects in noise-filled videos, locating objects on the ground from satellite observation, directing unmanned aerial vehicles, and minimizing radiation exposure from CT scans.

KEY PLAYERS:
Authors of multiple core papers

This research front in mathematics, computer science, and engineering was chosen precisely for its interdisciplinarity. Whether the core papers are examined in terms of traditional classification of journals to fields or on the basis of the departmental affiliations of the authors of the papers, about half the foundation literature in this specialty derives from mathematics or mathematicians, and the other half about evenly split between computer science and engineering or computer scientists and engineers. It is a strength of the co-citation clustering method to reveal the links among researchers working on a common problem but whose backgrounds might not suggest that they belong to the same "invisible college." Below are prominent members of that college, who are the authors of the highest number of core papers in this research front.

CORE PAPERS	RESEARCHER	TITLE	INSTITUTION
7	Stanley Osher	Professor of Mathematics and Director of Applied Mathematics; also, Director of Special Projects, Institute for Pure and Applied Mathematics	University of California Los Angeles
5	Jian-Feng Cai	Assistant Professor of Mathematics	University of Iowa
5	Emmanuel J. Candès	Simons Chair in Mathematics and Statistics, Professor of Mathematics and of Statistics, and Professor of Electrical Engineering	Stanford University
5	Mário A.T. Figueiredo	Professor of Electrical and Computer Engineering	Instituto Superior Técnico, Lisbon
5	Zuowei Shen	Tan Chin Tuan Centennial Professor	National University of Singapore

Source: Thomson Reuters Essential Science Indicators

ECONOMICS, PSYCHOLOGY AND OTHER SOCIAL SCIENCES

RANK	RESEARCH FRONTS	CORE PAPERS	CITATIONS	MEAN YEAR OF CORE PAPERS
1	Urban policy mobilities and global governance issues	42	898	2010.4
2	Entrepreneurism and performance of family firms	30	1,051	2009.9
3	Training and plasticity of working memory	21	1,177	2009.8
4	Accrual-based earnings management and accounting irregularities	17	1,148	2009.8
5	Patient-centered medicine, primary care, and accountability measures	32	1,240	2009.7
6	Social learning strategies and decision making	39	3,642	2009.6
7	Input-output analysis of carbon dioxide emissions	49	1,630	2009.6
8	Recognition heuristic research	28	1,280	2009.6
9	Online consumer reviews, social networks, and online display advertising	37	1,609	2009.5
10	Financial crisis, liquidity, and corporate governance	37	1,595	2009.4

Source: Thomson Reuters Essential Science Indicators

SUBPRIME MORTGAGE CRISIS, LIQUIDITY AND CREDIT, AND CORPORATE GOVERNANCE

Research in the highlighted front examines the complex array of institutional practices and financial mechanisms that determine liquidity and credit—and, in particular, how concurrent stresses on these elements precipitated the worldwide financial crisis of 2008. From analysis of the contraction in available bank credit following the collapse of subprime mortgages, to general examinations of corporate governance in such matters as cash holdings and the assumption of risk, this front crystallizes the complicated dynamics that led to the global recession whose effects are still being felt.

ALONG THE LEADING EDGE OF RESEARCH ON THE 2008 FINANCIAL CRISIS

This specialty comprises some 37 core papers, the majority of which were published in 2009 or thereafter. In many ways this is another example of an event-driven research front, like those seen in Geosciences (page 10). Certainly the events of 2008 were the financial equivalent of an earthquake, tsunami, and nuclear meltdown all in one. By focusing on the 833 papers in the front that have cited the 28 core papers published after the crisis of 2008, a summary can be obtained of the nations, institutions, and individuals now working at the leading edge of research on this event. The distribution by publication year of these citing papers is: 45 in 2009, 132 in 2010, 285 in 2011, and 356 in 2012 (as well as 15 so far in 2013).

RANK	NATION	%	INSTITUTION	%	RANK	RESEARCHER (INSTITUTION)	CITING PAPERS
1	USA (493)	59.2	National Bureau of Economic Research (86)	10.3	1	Viral V. Acharya (NYU, NBER, London Business School)	9
2	UK (93)	11.2	Harvard University (35)	4.2	2	Hyun Song Shin (Princeton Univ.)	8
3	China (64)	7.7	New York University (31)	3.7	3	Chen Lin (Chinese Univ. Hong Kong)	7
4	Germany (50)	6.0	University of Chicago (29)	3.5	4=	Murillo Campello (Cornell Univ. NBER)	6
5	France (43) Netherlands (43)	5.2	University of Pennsylvania (24)	2.9	4=	Victoria Ivanshina (Harvard Univ.)	6
6	Italy (36)	4.3	International Monetary Fund (20)	2.4	4=	Arvind Krishnamurthy (Northwestern Univ., NBER)	6
7	Canada (34)	4.1	Federal Reserve Bank of New York (19)	2.3	4=	Luc Laeven (International Monetary Fund)	6
8	Switzerland (31)	3.7	Massachusetts Institute of Technology (17)	2.1	4=	Yue Ma (Lingnan Univ. Hong Kong)	6
9	Australia (24)	2.9	Cornell Univ. (16); Princeton Univ. (16)	1.9	4=	Phillip E. Strahan (Boston College, NBER)	6

Source: Thomson Reuters Essential Science Indicators

RESEARCH FRONTS: IN SEARCH OF THE STRUCTURE OF SCIENCE

ADDENDUM BY DAVID A. PENDLEBURY

When Eugene Garfield introduced the concept of a citation index for the sciences in 1955, he emphasized its several advantages over traditional subject indexing.[1] Since a citation index records the references in each article indexed, a search can proceed from a known work of interest to more recently published items that cited that work. Moreover, a search in a citation index, either forward in time or backward through cited references, is both highly efficient and productive because it relies upon the informed judgments of researchers themselves, reflected in the references appended to their papers, rather than the choices of indexing terms by cataloguers who are less familiar with the content of each publication than are the authors. Garfield called these authors "an army of indexers" and his invention "an association-of-ideas index." He recognized citations as emblematic of specific topics, concepts, and methods: "the citation is a precise, unambiguous representation of a subject that requires no interpretation and is immune to changes in terminology."[2] In addition, a citation index is inherently cross-disciplinary and breaks through limitations imposed by source coverage. The connections represented by citations are not confined to one field or several – they naturally roam throughout the entire landscape of research. That is a particular strength of a citation index for science since interdisciplinary territory is well recognized as fertile ground for discovery. An early supporter of Garfield's idea, Nobel laureate Joshua Lederberg, saw this specific benefit of a citation index in his own field of genetics, which interacted with biochemistry, statistics, agriculture, and medicine. Although it took many years before the *Science Citation Index* (now the Web of Science) was fully accepted by librarians and the researcher community, the power of the idea and the utility of its implementation could not be denied. This year marks the 50th anniversary of the appearance of the *Genetics Citation Index*, a prototype for the *Science Citation Index* that became commercially available the following year.[3]

While the intended and primary use of the *Science Citation Index* was for information retrieval, Garfield knew almost from the start that his data could be exploited for the analysis of scientific research itself. First, he recognized that citation frequency was a method for identifying significant papers—ones with "impact"—and that such papers could be associated with specific specialties. Beyond this, he understood that there was a meaningful, if complex, structure represented in this vast database of papers and their associations through citations. In "Citation indexes for sociological and historical research," published in 1963, he stated that citation indexing provided an objective method for defining a field of inquiry.[4] That assertion rested on the same logical foundation that made information retrieval in a citation index effective: citations revealed the expert decisions and self-organizing behavior of researchers, their intellectual as well as their social associations. In 1964, with colleagues Irving H. Sher and Richard J. Torpie, Garfield produced his first historiograph, a linear mapping through time of influences and dependencies, illustrated by citation links, concerning the discovery of DNA and its structure.[5] Citation data, Garfield saw, provided some of the best material available for building out a picture of the structure of scientific research as it really was, even for sketching its terrain. Aside from making historiographs of specific sets of papers, however, a comprehensive map of science could not yet be charted.

Garfield was not alone in his vision. During the same era, the physicist and historian of science, Derek J. de Solla Price, was exploring the characteristic features and structures of the scientific research enterprise. The Yale University professor used the measuring tools of science on scientific activity, and he demonstrated in two influential books, of 1961 and 1963, how science had grown exponentially since the late 17th century, both in terms of number of researchers and publications.[6, 7] There was hardly a statistic about the activity of scientific research that his restless mind was not eager to obtain, interrogate, and play with. Price and Garfield

became acquainted at this time, and Price, the son of a tailor, was soon receiving data, as he said, "from the cutting-room floor of ISI's computer room."[8] In 1965, Price published "Networks of scientific papers," which used citation data to describe the nature of what he termed "the scientific research front."[9] Previously, he had used the term "research front" in a generic way, meaning the leading edge of research and including the most knowledgeable scientists working at the coalface. But in this paper, and using the short-lived field of research on N-rays as his example, he described the research front more specifically in terms of its density of publications and time dynamics as revealed by a network of papers arrayed chronologically and their inter-citation patterns. Price observed that a research front builds upon recently published work and that it displays a tight network of relationships.

"The total research front of science has never... been a single row of knitting. It is, instead, divided by dropped stitches into quite small segments and strips.... Such strips represent objectively defined subjects whose description may vary materially from year to year but which remain otherwise an intellectual whole. If one would work out the nature of such strips, it might lead to a method for delineating the topography of current scientific literature. With such a topography established, one could perhaps indicate the overlap and relative importance of journals and, indeed, of countries, authors, or individual papers by the place they occupied within the map, and by their degree of strategic centralness within a given strip."[10] (page 515)

The year is 1972. Enter Henry Small, a young historian of science previously working at the American Institute of Physics in New York City who now joined the Institute for Scientific Information in Philadelphia hoping to make use of the *Science Citation Index* data and its wealth of title and key words. After his arrival, Small quickly changed allegiance from words to citations for the same reasons that had captivated and motivated Garfield and Price: their power and potential. In 1973, Small published a paper that was as groundbreaking in its own way as Garfield's 1955 paper introducing citation indexing for science. This paper, "Co-citation in the scientific literature: a new measure of relationship between two documents," introduced a new era in describing the specialty structure of science.[11] Small measured the similarity of two documents in terms of the number of times they were cited together, in other words their co-citation frequency. He illustrated his method of analysis with an example from recent papers in the literature of particle physics. Having found that such co-citation patterns indicated "the notion of subject similarity" and "the association or co-occurrence of ideas," he suggested that frequently cited papers, reflecting key concepts, methods, or experiments, could be used as a starting point for a co-citation analysis as an objective way to reveal the social and intellectual, or the socio-cognitive, structure of a specialty area. Like Price's research fronts, consisting of a relatively small group of recent papers tightly knit together, so too Small found co-citation analysis pointed to the specialty as the natural organizational unit of research, rather than traditionally defined and larger fields. Small also saw the potential for co-citation analysis to make, by analogy, movies and not merely snapshots. "The pattern of linkages among key papers establishes a structure or map for the specialty which may then be observed to change through time," he stated. "Through the study of these changing structures, co-citation provides a tool for monitoring the development of scientific fields, and for assessing the degree of interrelationship among specialties."

It should be noted that the Russian information scientist Irena V. Marshakova-Shaikevich also introduced the idea of co-citation analysis in 1973.[12] Since neither Small nor Marshakova-Shaikevich knew of each other's work, this was an instance of simultaneous and independent discovery. The sociologist of science Robert K. Merton designated the phenomenon "multiple discovery" and demonstrated that it is more common in the history of science than most recognize.[13,14] Both Small and Marshakova-Shaikevich contrasted co-citation with bibliographic coupling, which had been described by Myer Kessler in 1963.[15] Bibliographic coupling measures subject similarity between documents based on the frequency of shared cited references: if two works often cite the same literature, there

is a probability they are related in their subject content. Co-citation analysis inverts this idea: instead of the similarity relation being established by what the publications cited, co-citation brings publications together by what cites them. With bibliographic coupling, the similarity relationships are static because their cited references are fixed, whereas similarity between documents determined by co-citation can change as new citing papers are published. Small has noted that he preferred co-citation to bibliographic coupling because he "sought a measure that reflected scientists' active and changing perceptions."[16]

The next year, 1974, Small and Belver C. Griffith of Drexel University in Philadelphia published a pair of landmark articles that laid the foundations for defining specialties using co-citation analysis and mapping them according to their similarity.[17, 18] Although there have since been significant adjustments to the methodology used by Small and Griffith, the general approach and underlying principles remain the same. A selection is made of highly cited papers as the seeds for a co-citation analysis. The restriction to a small number of publications is justified because it is assumed that the citation histories of these publications mark them as influential and likely representative of key concepts in specific specialties, or research fronts. (The characteristic hyperbolic distribution of papers by citation frequency also suggests that this selection will be robust and representative.) Once these highly cited papers are harvested, they are analyzed for co-citation occurrence, and, of course, there are many zero matches. The co-cited pairs that are found are then connected to others through single-link clustering, meaning only one co-citation link is needed to bring a co-cited pair in association with another co-cited pair (the co-cited pair A and B is linked to the co-cited pair C and D because B and C are also co-cited). By raising or lowering a measure of co-citation strength for pairs of co-cited papers, it is possible to obtain clusters, or groupings, of various sizes. The lower the threshold, the more papers group together in large sets and setting the threshold too low can result in considerable chaining. Setting a higher threshold produces discrete specialty areas, but if the similarity threshold is set too high, there is too much disaggregation and many "isolates" form. The method of measuring co-citation similarity and the threshold of co-citation strength employed in creating research fronts has varied over the years. Today, we use cosine similarity, calculated as the co-citation frequency count divided by the square root of the product of the citation counts for the two papers. The minimum threshold for co-citation strength is a cosine similarity measure of .1, but this can be raised incrementally to break apart large clusters if the front exceeds a maximum number of core papers, which is set at 50. Trial and error has shown this procedure yields consistently meaningful research fronts.

To summarize, a research front consists of a group of highly cited papers that have been co-cited above a set threshold of similarity strength and their associated citing papers. In fact, the research front should be understood as both the co-cited core papers, representing a foundation for the specialty, and the citing papers that represent the more recent work and the leading edge of the research front. The name of the research front is derived from a summarization of the titles of the citing papers. Just as it is the citing authors who determine in their co-citations the pairing of important papers, it is also the citing authors who confer meaning on the content of the resulting research front. It is not a wholly algorithmic process, however. A careful, manual review of the citing papers sharpens accuracy in naming a research front.

In the second of their two papers in 1974,[19] Small and Griffith showed that individual research fronts could be measured for their similarity with one another. Since co-citation defined core papers forming the nucleus of a specialty based on their similarity, co-citation could also define research fronts with close relationships to others. In their mapping of research fronts, Small and Griffith used multidimensional scaling and plotted similarity as proximity in two dimensions.

Price hailed the work of Small and Griffith, remarking that while co-citation analysis of the scientific literature into clusters that map on a two-dimensional plane "may seem a rather abstruse

finding," it was "revolutionary in its implications." He asserted: "The finding suggests that there is some type of natural order in science crying out to be recognized and diagnosed. Our method of indexing papers by descriptors or other terms is almost certainly at variance with this natural order. If we can successfully define the natural order, we will have created a sort of giant atlas of the corpus of scientific papers that can be maintained in real time for classifying and monitoring developments as they occur."[20] Garfield remarked that "the work by Small and Griffith was the last theoretical rivet needed to get our flying machine off the ground."[21] Garfield, ever the man of action, transformed the basic research findings into an information product offering benefits of both retrieval and analysis. The flying machine took off in 1981 as the *ISI Atlas of Science: Biochemistry and Molecular Biology, 1978/80*.[22] This book presented 102 research fronts, each including a map of the core papers and their relationships laid out by multidimensional scaling. A list of the core papers was provided with their citation counts, as well as a list of key citing documents, including a relevance weight for each that was the number of core documents cited. A short review, written by an expert in the specialty, accompanied these data. Finally, a large, fold-out map showed all 102 research fronts plotted according to their similarities. It was a bold, cutting-edge effort and a real gamble in the marketplace, but of a type wholly characteristic of Garfield.

The *ISI Atlas of Science* in its successive forms—another in book format and then a series of review journals[23,24]—did not survive beyond the 1980s, owing to business decisions at the time in which other products and pursuits held greater priority. But Garfield and Small both continued their research and experiments in science mapping over the decade and thereafter. In two papers published in 1985, Small introduced an important modification to his method for defining research fronts: fractional co-citation clustering.[25] By counting citation frequency fractionally, based on the length of the reference list in the citing papers, he was able to adjust for differences in the average rate of citation among fields and therefore remove the bias that whole counting gave to biomedical and other "high citing" fields. As a consequence, mathematics, for example, emerged more strongly, having been underrepresented by integer counting. He also showed that research fronts could be clustered for similarity at levels higher than groupings of individual fronts.[26] The same year, he and Garfield summarized these advances in "The geography of science: disciplinary and national mappings," which included a global map of science based on a combination of data in the *Science Citation Index* and the *Social Sciences Citation Index*, as well as lower level maps that were nested below the areas depicted on the global map.[27] "The reasons for the links between the macro-clusters are as important as their specific contents," the authors noted. "These links are the threads which hold the fabric of science together."

In the following years, Garfield focused on the development of historiographs and, with the assistance of Alexander I. Pudovkin and Vladimir S. Istomin, introduced the software tool HistCite. Not only does the HistCite program automatically generate chronological drawings of the citation relationships of a set of papers, thereby offering in thumbnail a progression of antecedent and descendant papers on a particular research topic, it also identifies related papers that may not have been considered in the original search and extraction. It is, therefore, also a tool for information retrieval and not only for historical analysis and science mapping.[28,29]

Small continued to refine his co-citation clustering methods and to analyze in detail and in context the cognitive connections found between fronts in the specialty maps.[30,31] A persistent interest was the unity of the sciences. To demonstrate this unity, Small showed how one could identify strong co-citation relationships leading from one topic to another and travel along these pathways across disciplinary boundaries, even from economics to astrophysics.[32,33] In this, he shared the perspective of E. O. Wilson, expressed in the 1998 book *Consilience: The Unity of Knowledge*.[34] Early in the 1990s, Small developed SCI-MAP, a PC based system for interactively mapping the literature.[35] Later in the decade, he introduced research front data into the new database

Essential Science Indicators (ESI), intended mainly for research performance analysis. The research fronts presented in ESI had the advantage of being updated every two months, along with the rest of the data and rankings in this product. It was at this time, too, that Small became interested in virtual reality software for its ability to create immersive, three-dimensional visualizations and to handle large datasets in real time.[36,37] For example, in the late 1990s, Small played a leading role in a project to visualize and explore the scientific literature through co-citation analysis that was undertaken with Sandia National Laboratories using its virtual reality software tool called VxInsight.[38,39] This effort, with farsighted support of Sandia's senior research manager Charles E. Meyers, was an important step forward in exploiting rapidly developing technology that provided detailed and dynamic views of the literature as a geographic space with, for example, dense and prominent features depicted as mountains. Zooming into and out of the landscape allowed the user to travel from the specific to the general and back. Answers to queries made against the underlying data could be highlighted for visual understanding.

In fact, this moment—the late 1990s—was a turning point for science mapping, after which interest in and research about defining specialties and visualizing their relationships exploded. There are now a dozen academic centers across the globe focusing on science mapping, using a wide variety of techniques and tools. Developments over the last decade are summarized and illustrated in Indiana University professor Katy Börner's 2010 book, which carries a familiar-sounding title: *Atlas of Science – Visualizing What We Know*.[40]

The long interval between the advent of co-citation clustering for science mapping and the blossoming of the field, a period of about 25 years, is curiously about the same time it took from the introduction of citation indexing for science to the commercial success of the *Science Citation Index*. In retrospect, both were clearly ideas ahead of their time. While the adoption of the *Science Citation Index* faced ingrained perceptions and practice in the library world (and by extension among researchers whose patterns of information seeking were traditional), delayed enthusiasm for science mapping—a wholly new domain and activity—can probably be attributed to a lack of access to the amount of data required for the work as well as technological limitations that were not overcome until computing storage, speed, and software advanced substantially in the 1990s. Data are now more available and in larger quantity than in the past and personal computers and software adequate to the task. Today, the use of the Web of Science for information retrieval and research analysis and the use of research front data for mapping and analyzing scientific activity have found not only their audiences but also their advocates.

What Garfield and Small planted many seasons ago has firmly taken root and is growing with vigor in many directions. A great life, according to one definition, is "a thought conceived in youth and realized in later life." This adage applies to both men. Thomson Reuters is committed to continuing and advancing the pioneering contributions of these two living legends of information science.

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