Atlas of Science

Visualizing What We Know

Katy Börner

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The MIT Press
Cambridge, Massachusetts
London, England

For information about special quantity discounts, please e-mail special_sales@mitpress.mit.edu

This book was set in Adobe Caslon Pro by Elisha F. Hardy (graphic design and layout), Tracey Theriault (design advice), and Katy Börner (concept), Cyberinfrastructure for Network Science Center, School of Library and Information Science, Indiana University. Printed and bound in Malaysia.

Library of Congress Cataloging-in-Publication Data

Börner, Katy.
Atlas of science : visualizing what we know / Katy Börner.
p. cm.
Includes bibliographical references and indexes.
ISBN 978-0-262-01445-8 (hardcover : alk. paper) 1. Classification of sciences—Atlases. 2. Science—Atlases. 3. Communication in science—Data processing. 4. Digital mapping. I. Title.
Q177.B67 2010
501.2—dc22

2009048451

10 9 8 7 6 5 4 3

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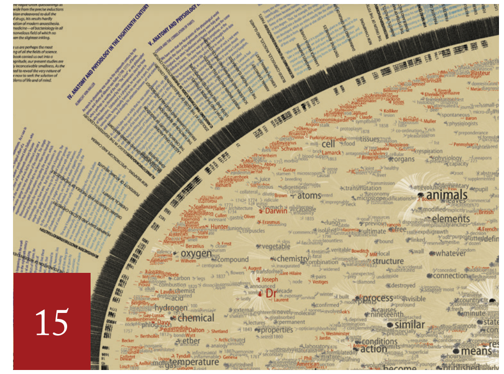

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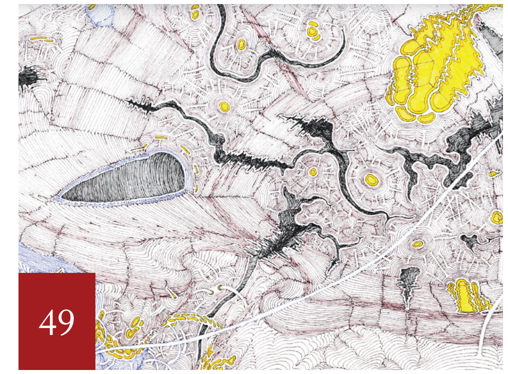

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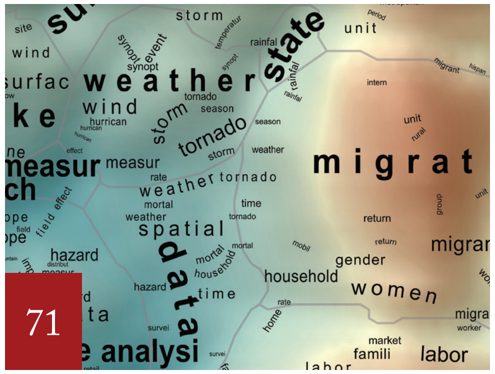

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Foreword

Those of us who make maps for a living like to think we face difficult challenges in our ongoing efforts to represent the world. To depict a complex, constantly changing, three-dimensional world on a two-dimensional page or computer screen, we simplify and symbolize by following well-established cartographic traditions, many of which date back centuries. We strive to accurately reflect the spatial alignments and interrelationships that for the most part reflect undeniable facts in the "real" world.

The explorers whose work is represented in the pages of this rich and fascinating volume face challenges far more daunting. First, the world they strive to represent is an abstract and intellectual one, not a physical reality that can be imaged from space, surveyed on the ground, and depicted in miniature on a map. The interrelationships among the landmarks of this abstract world are real, but they are not easily represented in the simple, straightforward ways that one can convey the distances between, say, three cities.

Second, there is no equivalent in the cartography of science to the standards and conventions upon which we mappers of the physical world comfortably depend. There's no agreed-upon notion of north-as-up, of systems of latitude and longitude, of symbols, scale, and projection. Mapping the world of science requires the invention of a brand-new geography. Not only that, but the new geography then needs to be represented visually using colors, lines, and symbols for which no conventions exist. Science mapmaking is a rather young human endeavor. Although many visual renderings of science have been created over the last hundred years, it was only in 1999 that a map of all sciences was rendered by automatic means. Since then, a variety of efforts have used very different data sets, resulting in a rich variety of maps. Clearly, however, no consensus yet exists on how to best represent the world of science. We can only hope and assume that the process will evolve more quickly than did the ancient conventions on which we traditional cartographers rely.

Third, the world that is being mapped in this book is changing at a dizzying rate. It's a fact of twenty-first-century science that whole realms of inquiry bloom into existence almost overnight, creating new places and spaces in ways that are alien to "normal" cartography. It is as if entire continents and archipelagoes were to constantly erupt on the roiling surface of a map even as that map was being drawn for the first time.

So it is with wonder and admiration that I peruse this important and groundbreaking (pun intended) book. This detailed review of past work, evolving conventions, and possible futures will likely facilitate the diffusion, adoption, and development of data analysis and mapping techniques that will inform the design of useful and insightful science maps. These maps of science are doing the hard work that all good maps do: They're documenting a landscape in ways that will serve as a useful historical record, which is especially important when the landscape is changing rapidly. They're showing us interesting patterns and interrelationships, revealing a surprising, even revelatory, new geography of science. They're helping us navigate a realm that for many of us has been terra incognita. They're allowing us to explore, to imagine, to understand. Which, come to think of it, is precisely why we cartographers love our work.

Allen Caroll
Chief Cartographer
National Geographic Society

Preface

This atlas attempts to introduce maps of science to a global audience. Through maps of science, we can begin to see all that we know as landscape—viewed as if from above or from a great distance. Science maps provide guidance for navigating, understanding, and communicating the dynamic and changing structure of science and technology. The career trajectories of individual researchers and their professional networks, the intellectual footprint of any given institution or country, and emerging research frontiers or bursts of activity can be projected onto science maps and animated over time. Science maps complement local fact retrieval via search engines by providing information used to determine context and relevance. They serve as visual interfaces to immense amounts of data—depicting perhaps millions of data records that we can perceive rapidly to effectively discern apparent outliers, clusters, and trends.

The *Atlas of Science* is designed to accompany the *Places & Spaces: Mapping Science* exhibit, which introduces large-scale maps of science to the public. All 30 maps from the first three (of what will be ten) exhibit iterations are included. It also features a history of the exhibit—with its curators and advisory board—as well as biographies of the mapmakers (current as of the date of map creation). Many more maps continue to be created, and milestone works are featured in the exhibit as well as online at **http://scimaps.org**.

The atlas is organized into five parts. The 200+ pages contain more than 35 full-page maps of science, 50 data charts, and 500 full-color images, including portraits of renowned mapmakers. Part 1 discusses the growth and dynamics of our collective scholarly knowledge and the utility of science maps in navigating and managing this flood of information. Part 2 situates the development of science studies and science maps in the complex network of visionary thinkers and their inventions. It also includes a 22-page comprehensive timeline of milestone algorithm, visualization, tool, and book contributions that helped to advance the state of mapping science. Part 3 reviews major techniques used to map science on an individual, local, or global scale in a temporal, geographic, semantic, or network fashion. Part 4—the heart of this atlas—presents a visual feast of science maps, the stories behind them, and the biographies of their makers. In Part 5, we conclude with a forecast of the future of science mapping. Every part consists of spreads, each with a synergistic combination of text and imagery to communicate a specific topic or theme. Neither the text nor the imagery can stand alone—they complement each other.

Meant to serve as a visual index to the rich scholarly work that exists on the mapping of science and its practical applications, the atlas contains acknowledgments of contributions for every spread—more than 80 in some instances. With a total of more than 1,650 citation references, such information could not be furnished alongside each page layout. Instead, the **References and Credits** (**page 212**) section lists references by section for each spread, followed by a subject **Index** (**page 247**). Besides citation references, the **References and Credits** section also provides image credits, data credits, software credits, and acknowledgments of the contributions of scholars with extensive expertise in bibliometrics, scientometrics, webometrics, informetrics, information science, library science, history of science, communication sciences, social sciences, geography, cartography, Internet research, economics, physics, and related areas.

The Web site **http://scimaps.org/atlas** serves as a complement to this atlas, enabling access to sources, EndNote and BibTeX files for all references, and extended search functionality. The site also provides links to high-resolution maps, particularly those included in the *Places & Spaces: Mapping Science* exhibit.

Just as an atlas of the world needs to be continually updated, an atlas of science must incorporate new developments as they emerge. It is a "living document," amended to reflect comments, corrections, and recommendations, as well as new science. As such, the supporting Web site invites comments and offers frequent updates of all materials in preparation for future editions.

More than four years in the making, the *Atlas of Science* constitutes a unique collaboration of the Cyberinfrastructure for Network Science Center team at the School of Library and Information Science, Indiana University; many of our colleagues around the globe; ESRI Press initially; and the MIT Press subsequently. It is our hope that this atlas provides actionable information and insight for many levels of application in study, work, and life.

Katy Börner
Cyberinfrastructure for Network Science Center
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Indiana University

April 16, 2010

Acknowledgments

The atlas and the exhibit from which it was born would not have been possible without the financial support of National Science Foundation awards IIS-0238261, IIS-0513650, IIS-0534909, IIS-0715303, IIS-0724282, IIS-0750993, CBET-0831636, CHE-0524661, CHE-0723989, SCI-0533892, and SBE-0738111; National Institutes of Health awards R21DA024259 and U24RR029822; two James S. McDonnell Foundation grants; the Cyberinfrastructure for Network Science Center, the School of Library and Information Science, and University Information Technology Services all three at Indiana University. Additional financial support was provided by the Indiana 21st Century Research and Technology Fund.

Generous support for the *Places & Spaces: Mapping Science* exhibit was also provided by Thomson Reuters (formerly Thomson Scientific or The Thomson Corporation); the Science, Industry and Business Library at the New York Public Library; infoUSA; Discovery Logic; Gale; Blair; and Elsevier. Thomson Reuters also provided much of the data used to create the science maps.

Scientific meetings, workshops, and conferences were instrumental to recent advances in mapping science research and the design of this atlas. These included two workshops on Visual Interfaces to Digital Libraries and six symposia on Knowledge Domain Visualizations, both organized by Chaomei Chen and Katy Börner, and a Sackler Symposium on Mapping Knowledge Domains, organized by Richard Shiffrin and Katy Börner.

Five focused workshops on the topics of scholarly databases and data integration, science mapping, and forecasting science in 2005 and 2006 were of special importance. It is the expertise and courage of the attendees (pictured below) who freely shared their knowledge across disciplinary and cultural boundaries that helped to bring both the exhibit and this atlas into being.

The mapping of science draws from a rich body of cartographic mapmaking. Rebecca C. Cape served as a living index to the amazing holdings of the Lilly Library at Indiana University. Jim Flatness and Mike Klein at the Library of Congress provided expert advice and support. Anne J. Haynes and Collette Mak were instrumental in gaining access to WorldCat.

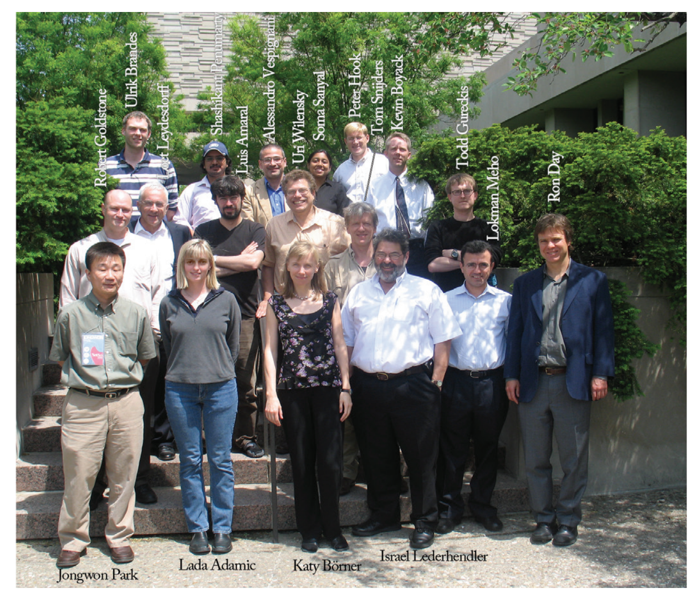
For the design of the atlas, I drew inspiration from children's books, such as *Millions to Measure*, the *Big Book of Time*, and *Zoom City*; books by Scott McCloud on understanding, reinventing, and making comics; science publications from Usborne and DK; and scholarly works such as Heinrich Berghaus's *Physikalischer Atlas*, works by Edward R. Tufte, and maps by National Geographic.

Beyond the contributions listed in the **References and Credits (pages 212–246)**, I would like to thank the many students, friends, colleagues, and bloggers who provided informal feedback over the last six years. Their honest feedback and expert advice helped to improve the readability and utility of the science maps as well as the communication of the techniques involved in their creation.

The atlas "dream team"—at the Cyberinfrastructure for Network Science Center within the School of Library and Information Science at Indiana University—included Elisha F. Hardy, who designed many of the images and nearly 1,000 layout mockups needed to ensure the synergistic interplay of imagery and text; Russell J. Duhon, who did much of the custom data analysis and visualization for the atlas; Qizheng (Stanley) Bao, Angela M. Zoss, Jennifer Coffey, and Mark A. Price, who formatted the more than 1,000 references and cred-

December 1 and 2, 2005: Mapping Science Workshop
Thomson Scientific, Philadelphia, Pennsylvania

April 4, 2006: Mapping Science Workshop
New York Academy of Science, New York City, New York



May 21, 2006: Modeling Science Workshop
Indiana University, Bloomington, Indiana

its and prepared them for the Web site; and Kristin Reed, Roxana Cazan, Richard S. Pinapati, Benjamin Ray Gonzalez Jr., Marla Fry, Bryan Hook, and Mark A. Price, who managed to secure the more than 1,100 copyright permissions. Our team benefited enormously from the supportive research environment at Indiana University, particularly at the School of Library and Information Science, directed by Blaise Cronin.

Gordana Jelisijevic was instrumental in shaping and fine-tuning the language of the atlas. Her writing mastery and editing expertise brought eloquence as well as clarity to this material. Teresa Elsey performed the final proofread of the atlas on behalf of the MIT Press.

Elisha F. Hardy designed many of the images in the atlas as well as the layout of all text and imagery in close collaboration with Katy Börner. This atlas attests to her diligence, stamina, and design skills. Tracey Theriault contributed her professional expertise to the final design of the atlas.

Four colleagues provided detailed feedback on penultimate draft of the atlas: André Skupin, Peter A. Hook, Deborah MacPherson, and Alex Soojung-Kim Pang. Their comments combined with feedback from anonymous reviewers provided by the MIT Press were instrumental in finalizing the atlas.

The *Atlas of Science* was originally designed for publication as an 11-inch x 13-inch (28 centimeter x 33 centimeter) full-color book in landscape format by ESRI Press. ESRI applied common standards of geography: for each map, piece of data and software, and image, credits need to be provided; all text on a map needs to be legible; and the accompanying text must fully support the interpretation of the map. Ideally, all science maps published hereafter would adhere to these standards for improving replicability, readability, and rigor. Shortly after I submitted the complete manuscript in August 2008, I learned that ESRI needed data and software copyrights for each of the more than 400 science maps—in addition to copyrights for the final maps. Due to the lack of formal standards for the data sets and tools used to generate science maps, it proved impossible to acquire all of these copyright levels. ESRI was thus unable to publish the atlas and reverted all rights back to me.

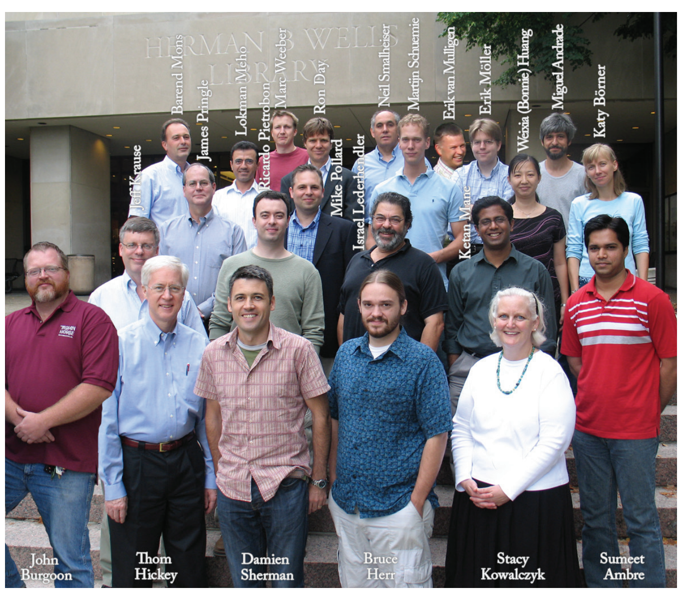
I am thankful to the MIT Press for taking on this demanding project. Transferring the material generated by our team to the MIT Press constituted an impressive challenge on both sides. The ambition to make maps of science understandable to a general audience; the complexity of the atlas in terms of synergistic text and image placement; and the sheer number of images, references, and credits all posed major challenges. Marguerite Avery, Erin K. Shoudy, Abby Roake, and Mel Goldsipe at the MIT Press played an important role in this process. They were instrumental in translating my vision for the atlas to the MIT Press, as well as their production needs to my team, while omitting irrelevant complexities.

The MIT Press also supported a larger than originally agreed upon page size for the atlas that considerably improved the legibility of many featured maps. However, all exhibit maps are sized 30 inches x 24 inches (about 76 centimeters x 61 centimeters) and several have a very high information density that cannot be reproduced in a book. I invite interested readers to visit the Web site for the atlas (**http://scimaps.org/atlas**) to explore full resolution versions of all maps.

The atlas would not have been possible without the support of my colleagues, who accepted my apologies for not reviewing papers and proposals and for not serving on committees; my students, who read and commented on many parts of the atlas while needing to schedule meetings instead of simply visiting impromptu; the authors of the more than 10,000 e-mails that were never read nor processed as I worked full-time on the atlas; and last but not least, my friends, who saw much of my husband and kids but very little of me.

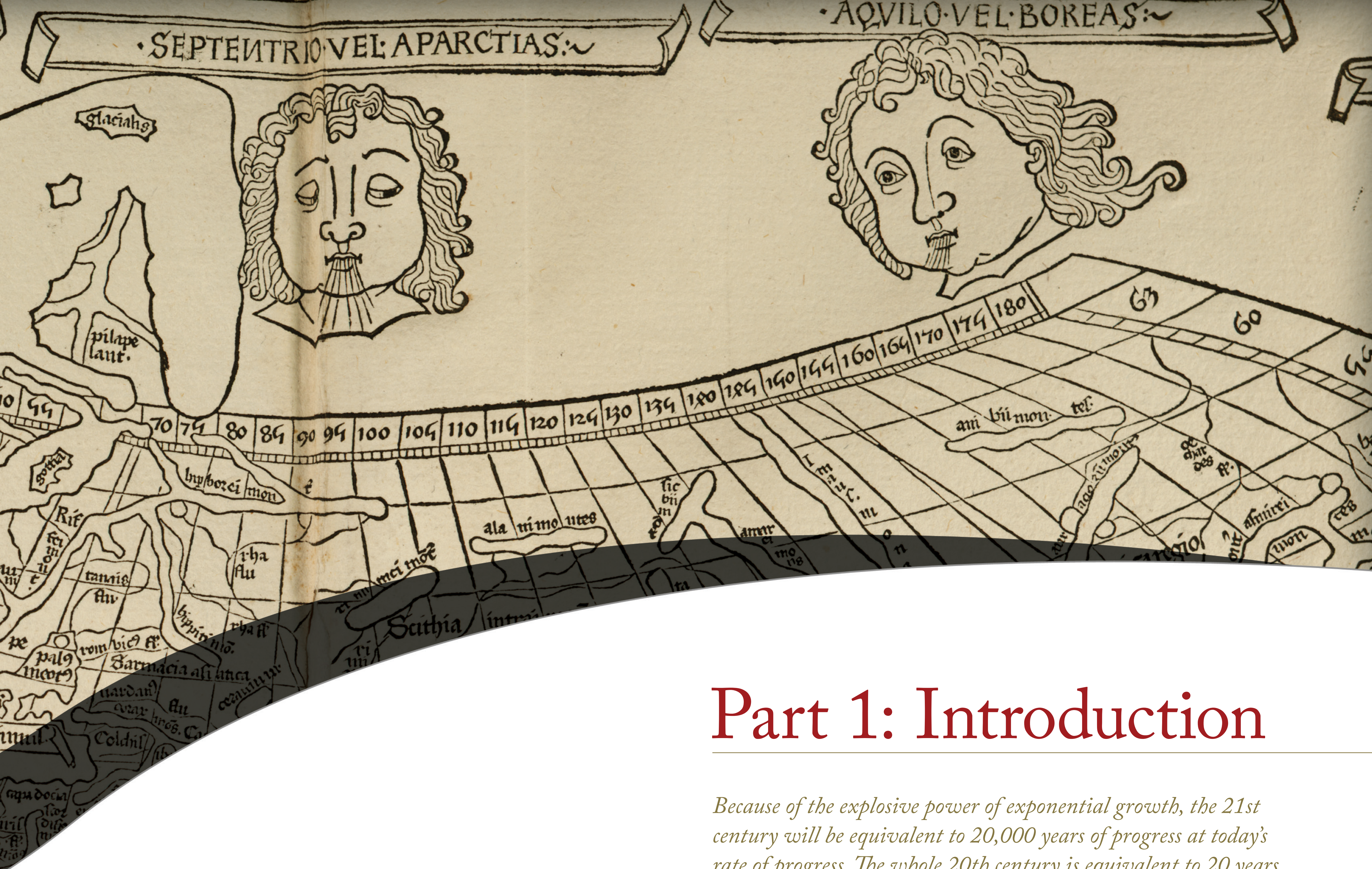
Extraordinary women—like Monika Börner, Bonnie DeVarco, Monika Herzig, Janice M. Hicks, Deborah MacPherson, Weixia (Bonnie) Huang, Anne Prieto, Andrea Scharnhorst, Maria Zemankova, and many others—empowered my thinking and provided the physical and moral support needed for this undertaking.

Last but not least, I would like to thank Melanie B. Goldstone, Eleanor B. Goldstone, and Robert L. Goldstone for their love and support.



August 10 and 11, 2006: Scholarly Data and Data Integration Workshop
Indiana University, Bloomington, Indiana

May 26, 2007: Forecasting Science Workshop
New York Hall of Science, Queens, New York



Part 1: Introduction

Because of the explosive power of exponential growth, the 21st century will be equivalent to 20,000 years of progress at today's rate of progress. The whole 20th century is equivalent to 20 years of progress at today's rate of progress. Organizations have to be able to redefine themselves at a faster and faster pace.

Ray Kurzweil

Knowledge Equals Power

Access to high-quality data, knowledge, and expertise tends to lend one authority and power. Yet there is so much to learn in so little time—tough deadlines abound. This spread discusses the dramatic increase in human population together with a history of the type and quantity of information that we have managed to produce. It also illustrates the uneven distribution of population density, urbanization, scientific productivity, and technological development on our planet. The next two pages focus on the accelerated growth of science and technology and the impact of tool development. The remainder of this introduction reviews the knowledge needs of diverse stakeholders and the evolution of geographic and science maps as guides to the navigation and exploration of physical places and abstract spaces.

Population Growth

The timeline below plots the dramatic increase in human population—estimated, recorded, and predicted—from 1,000,000 BC to AD 2200. According to United Nations estimates, the world population reached the 6 billion mark in 1999 and the 7 billion mark in 2011. It is expected to cross the 8 billion mark in 2028 and the 9 billion mark in 2054; it will nearly stabilize, at just above 10 billion, after 2200.

Significant events that have positively influenced our species, such as tool development and technological revolutions–as well as events that have negatively influenced it, such as epidemics and wars (in bold)–are listed below the population timeline. Major ages are indicated.

Knowledge and Technology Overload

The number of currently active researchers exceeds the number of researchers who ever lived previously. Researchers publish or perish. Some areas of science produce more than 40,000 papers a month. We are expected to know more works than one can possibly read in a lifetime. We receive many more e-mails per day than can be processed in 24 hours. We are supposed to be intimately familiar with data sets, tools, and techniques that are continually changing and increasing in number and complexity—all this while being reachable 24 hours per day, 7 days per week.

Libraries and storage facilities are being filled more quickly than they are being built. Scientific data sets, algorithms, and tools need to be mastered to advance science. The figure on the right depicts just how much information exists. No single man or machine can process and make sense of such an enormous stream of data, information, knowledge, and expertise.

All this leads to a quickly increasing specialization of researchers, practitioners, and other knowledge workers; a disconcerting fragmentation of science; a world of missed opportunities for collaboration; and a nightmarish feeling that we are doomed to keep reinventing the wheel for eternity.

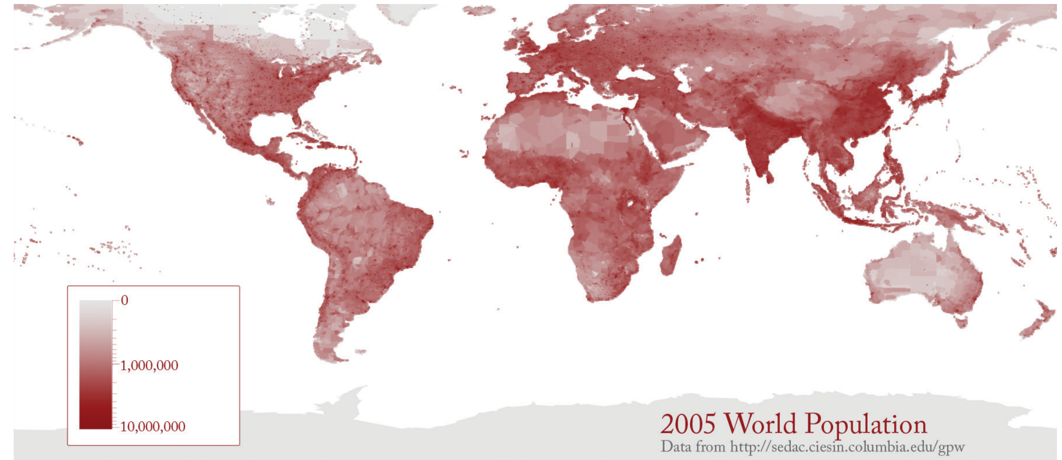
Us from Above

The four maps on the right depict the **2005 World Population** (top left), city lights in **Earth at Night** as a proxy for urbanization (top right), **2003 Scientific Productivity** (bottom left), and **2007 IP Address Ownership** as a proxy for technological development (bottom right). All four use the same equidistant cylindrical projection. World population correlates strongly with urbanization (see Earth at Night) scientific productivity, and IP address ownership in economically developed countries. In other areas of the world, there exist major contrasts: many densely populated areas are black in the Earth at Night map, and scientific productivity and Internet access are scarce and often limited to urban areas.

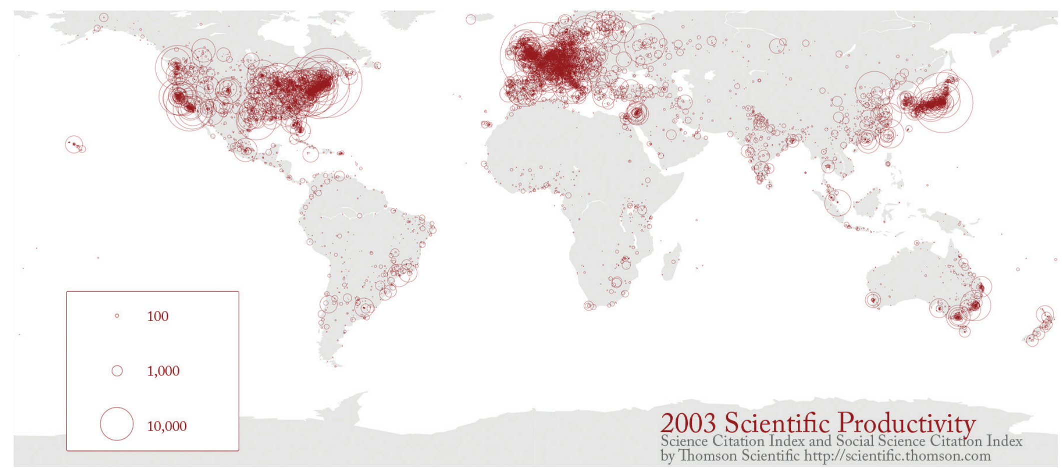
The Web of Knowledge

Over the last few centuries, our collective knowledge has been preserved and communicated via scholarly works such as papers and books. Works might herald a novel algorithm or approach, report experimental results, or review one area of research among others. Some report several small results; others proclaim a single large result, like the decoding of the human genome. Some confirm results; others disprove them. Different areas of science vary greatly in their publishing formats and quality standards. The description of a single set of results, such as the development of a novel algorithm, could be published in a computer science journal, a biology journal, or a physics journal—and would look different in each publication.

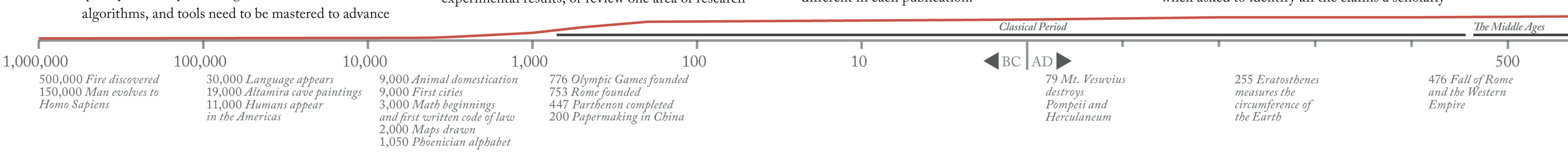
Citation references came into existence in 1850. Citation networks show who consumes, elucidates, or cites whose work. Networks of coauthors can be extracted by counting how often two authors have collaborated. The quality of a paper and the reputation of its author are commonly estimated via citation and download counts. Acknowledgments provide links to experts, data sets, equipment, and funding information. Experts may be challenged when asked to identify all the claims a scholarly

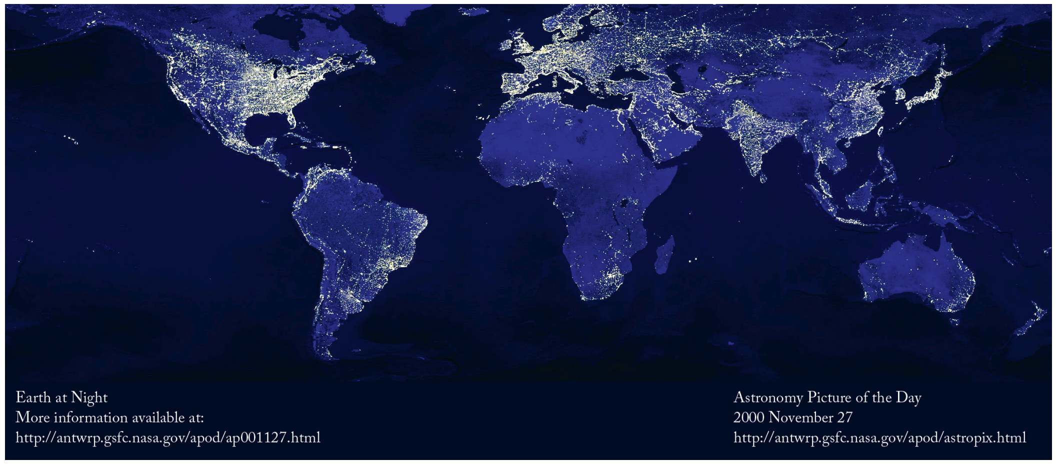


The population map uses a quarter-degree box resolution. White boxes represent a count of zero people. Darker shades of red indicate higher population counts per box, using a logarithmic interpolation. The highest density boxes appear in Mumbai (Bombay), with 11,687,850 people in the quarter-degree block; Kolkata (Calcutta), 10,816,010; and Shanghai, 8,628,088. China and India are the only two countries to have more than 1 billion inhabitants.

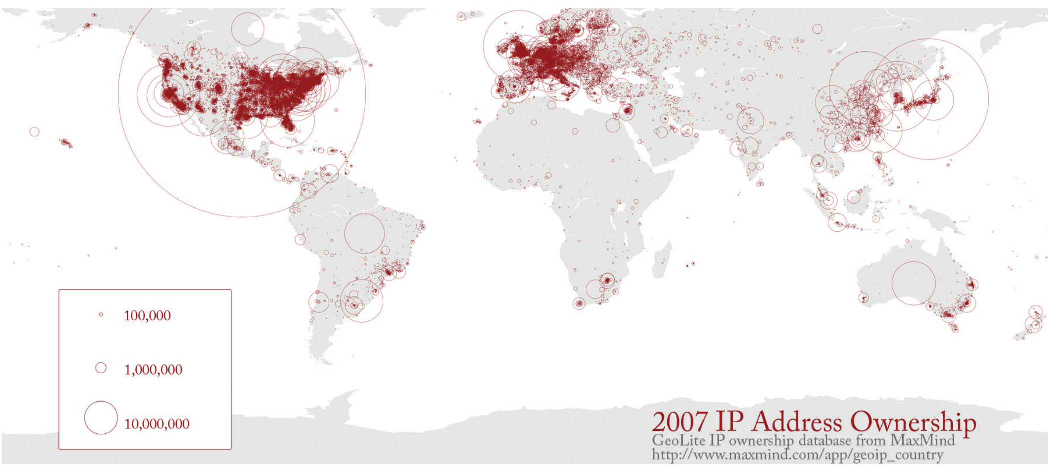


This figure shows where science research is performed. Each circle indicates a geographic location where scholarly papers are published—the larger the circle, the more papers produced. The top three paper-production areas are Boston, Massachusetts; London, United Kingdom; and New York, New York. Note how this map compares to the ***Earth at Night*** and ***2007 IP Address Ownership*** maps, while contrasting with the ***2005 World Population*** map.





This image shows city lights at night. It was composed from hundreds of pictures made by orbiting satellites. The coasts of Europe, the eastern United States, and Japan are particularly well lit. Many cities exist near rivers or oceans so that goods can be exchanged at less expense by boat. The central parts of South America, Africa, and Asia are rather dark despite their high population densities (see map to left).

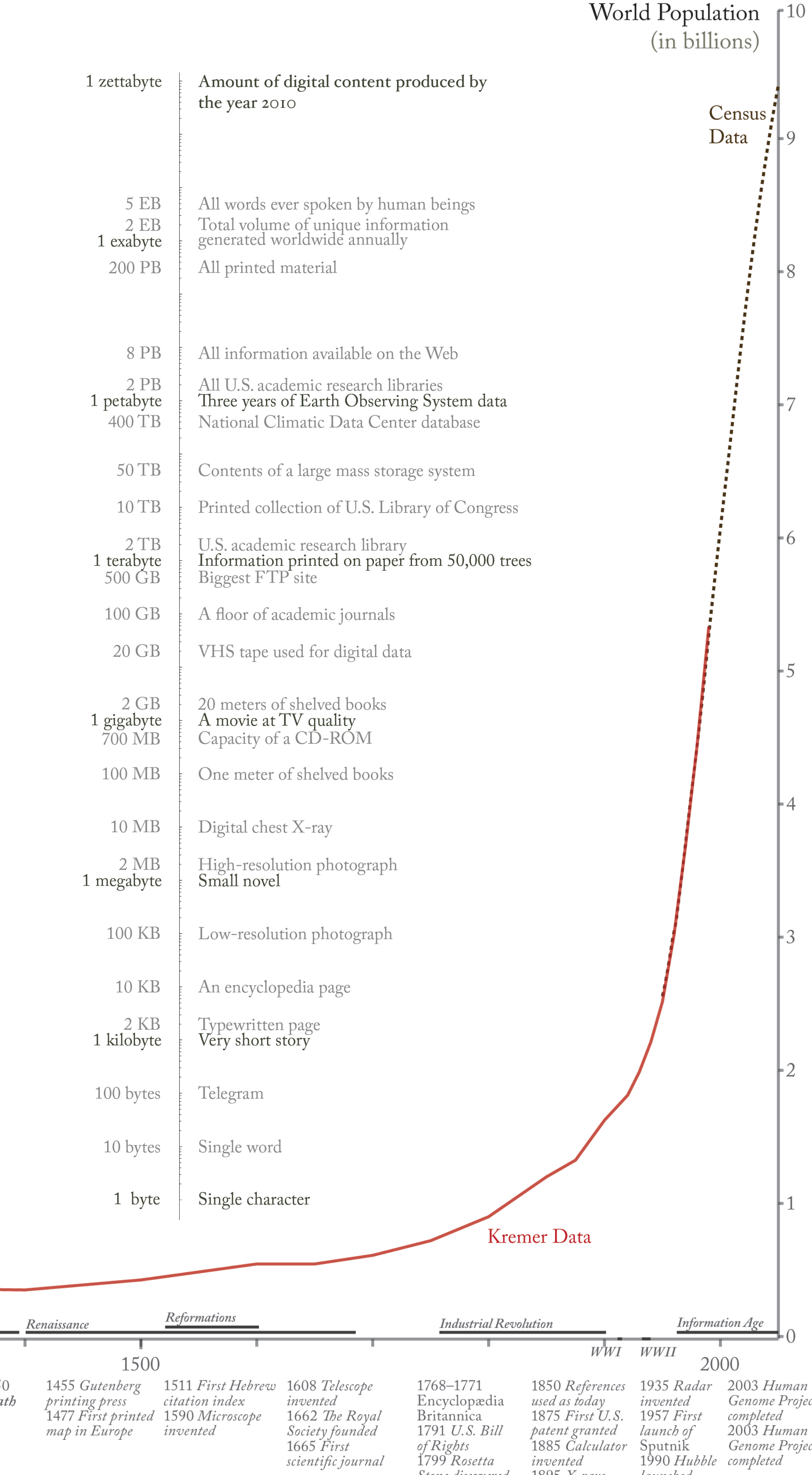


This map shows IP address ownership by location. Each owner is represented by a circle, and each circle's size corresponds to the number of IP addresses owned. The largest circle denotes MIT's holdings of an entire class-A subnet, which equates to 16,581,375 IP addresses. The countries that own the most IP addresses are the United States (560 million), Japan (130 million), and Great Britain (47 million).

work makes. In some cases it is simply not known how important today's discovery will be for tomorrow's society. It is an even harder task to determine how discoveries are interlinked with the complex network of prior (supporting and contradicting) results manifested in papers, books, patents, data sets, software, and tools.

Consequently, it is difficult for researchers, educators, and practitioners to keep up with the increasing quantity and the accelerating speed of our knowledge production. This is a major concern, as scientific results are needed to enable all human beings to live healthy, productive, and fulfilling lives. We need better tools to access, track, manage, and utilize our collective scholarly knowledge and expertise. Maps of science that guide our scholarly endeavors may well make a difference.

1 zettabyte	Amount of digital content produced by the year 2010
5 EB	All words ever spoken by human beings
2 EB	Total volume of unique information generated worldwide annually
1 exabyte	
200 PB	All printed material
8 PB	All information available on the Web
2 PB	All U.S. academic research libraries
1 petabyte	Three years of Earth Observing System data
400 TB	National Climatic Data Center database
50 TB	Contents of a large mass storage system
10 TB	Printed collection of U.S. Library of Congress
2 TB	U.S. academic research library
1 terabyte	Information printed on paper from 50,000 trees
500 GB	Biggest FTP site
100 GB	A floor of academic journals
20 GB	VHS tape used for digital data
2 GB	20 meters of shelved books
1 gigabyte	A movie at TV quality
700 MB	Capacity of a CD-ROM
100 MB	One meter of shelved books
10 MB	Digital chest X-ray
2 MB	High-resolution photograph
1 megabyte	Small novel
100 KB	Low-resolution photograph
10 KB	An encyclopedia page
2 KB	Typewritten page
1 kilobyte	Very short story
100 bytes	Telegram
10 bytes	Single word
1 byte	Single character



The Rise of Science and Technology

The data and graphics presented here document the tremendous increase observed in the number of books, journals, papers, and patents produced, as well as in the numbers of researchers and engineers. They also reveal the impact of funding, policy decisions, and historical events on the developments of science. We conclude with a discussion of science and society in equilibrium.

The Rise of the Creative Class

In the agricultural age, value was created from land and physical labor. In the industrial age, it was the product of raw materials and again of labor. In the information age, value is the result of these but even more so of creativity, imagination, and intelligence. Knowledge-based professionals, or members of the "creative class," include architects, artists, designers, engineers, musicians, and scientists, among others.

In the United States around 1900, there were 38,000 professional engineers, 9,000 chemists, and 12,000 other scientists, constituting 0.26 percent of the labor force. In 1970, there were a total of 2 million scientists and engineers, making up 2.5 percent of the labor force. That is a tenfold increase in only 70 years. The steady increase in engineers, physical scientists, mathematicians and information technologists, social scientists, and life scientists in relation to the total U.S. population is shown in the **People** graph below. Note the 500-fold increase in mathematicians and information technologists over the 50-year time span.

In 2008, knowledge-based professionals made up 20 to 30 percent of the labor force in developed countries—yet their salaries accounted for 50 percent of all recorded earnings. In the United States, on average, a high school diploma will lead to lifetime earnings of $1,100,000; a bachelor's degree, $2,100,000; a master's degree, $2,500,000; and a doctorate, $4,400,000.

Enormous amounts of effort and money are spent on gaining access to the brightest minds of our population. For example, a ticket to the TED (Technology, Entertainment, Design) conference—featuring "inspired talks by the world's greatest thinkers and doers"—costs about $6,000. The tickets for TED2008 sold out more than a year in advance, and more than 3,000 people were on the TED2009 waiting list when tickets were sold out.

Growth of Science

Since the early 1800s, there have been numerous studies on the progress of scientific research and development, including the quantity of results produced. Here, we consider the history of scientific publications, including books, journals, and scholarly papers, as well as Wikipedia entries.

Books

Records indicate that 8 million books were published prior to the 19th century, while 1 million books were published in 2008 alone. Since the invention of movable type, an estimated 100 million books have been printed. The **Books** graph below shows the number of books indexed per publication year by providers such as WorldCat, Bookman/Publishers Weekly/Bowker, and Chemical Abstracts Service (CAS).

Various efforts to scan all existing books and make them freely available online as e-text books (e-books) are underway. Two projects are discussed here and included in the **Books** graph. The Million Book Project, launched by several professors from Carnegie Mellon University, offers scans of 10,850 books. Project Gutenberg, the first producer of free e-books (see **page 18, Knowledge Collection**) featured more than 22,000 e-books in November 2007 and plans to offer an additional 1 million e-books by 2015. The chart shows the number of books digitized (not published) per year. Both projects use the Internet Archive (see **page 18, Knowledge Collection**) as a backup distribution site. At the rate of less than one thousand books per year, however, it will take 100,000 years to digitize all existing books. To that end, it would be necessary to capture born-digital publications at the time of creation and to scan books at a rate of 1 million books per year, or 3,000 each day.

Papers and Journals

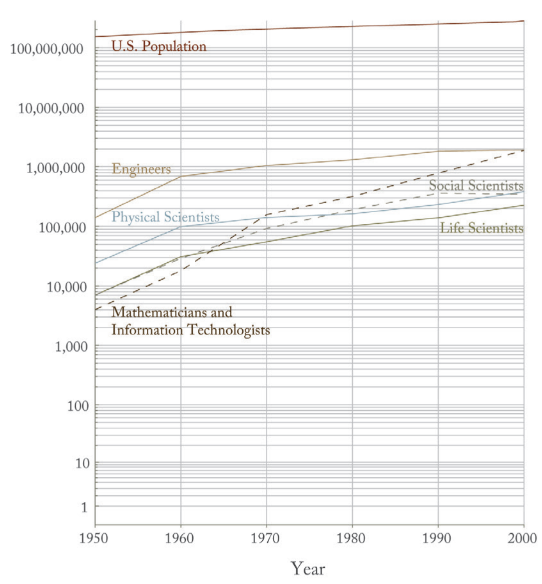
The growth of science as a whole is often estimated by counting the number of scientific journals in existence. If we begin in 1750 with a count of 10 journals and end in 1950 with a count of 100,000, we find a steady doubling time of 15 years. The graph on the right, by Derek John de Solla Price, shows the total number of scientific journals and abstract journals as a function of date. It was originally published in de Solla Price's *Science Since Babylon* (1962).

In *Science: Growth and Change* (1971), Henry W. Menard reported the growth rates for different types of scientific records. He identified a tenfold increase in the number of papers every 50 years, abstracts every 30 years, and computer indexes every 10 years.

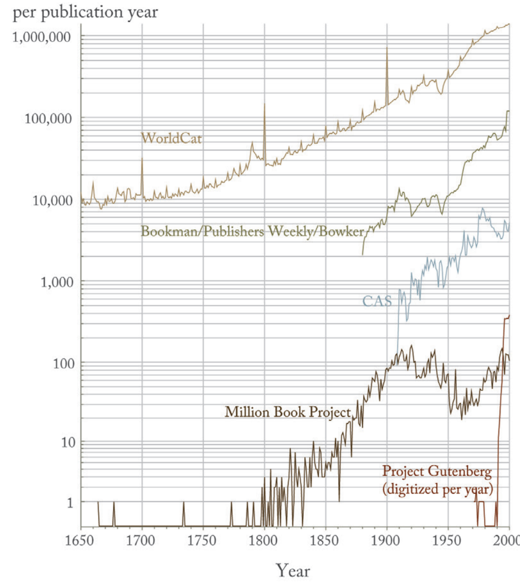
The **Papers and Wikipedia Entries** graph below shows the number of papers—or abstracts in the case of the National Federation of Advanced Information Services (NFAIS) abstracting service—served by different databases per publication year. The highest numbers belong to NFAIS. Data provided by Thomson Reuters includes the Science Citation Index Expanded (1900–present; 6,126 journals), Social Sciences Citation Index (1956–present; 1,802 journals), and Arts and Humanities Citation Index (1975–present; 1,136 journals), among others. Thomson Reuters's Web of Science (WoS; established 1981), includes all three data sets. The third-highest number of holdings belongs to Elsevier's Scopus, which indexes 15,000 peer-reviewed journals from more than 4,000 publishers. Google Scholar is missing from this graph, as detailed data was not available.

Papers from the Royal Society (established 1665) and Physical Review (established 1887) journals record the scholarly history of their respective research communities in a very comprehensive and longitudinal fashion. JSTOR, with its strong archi-

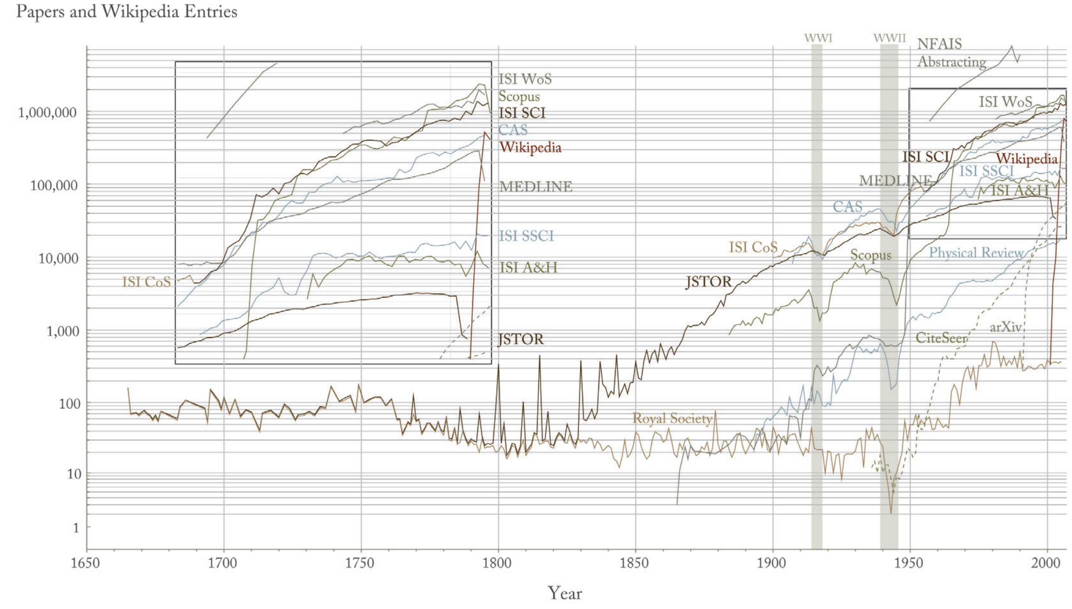
People

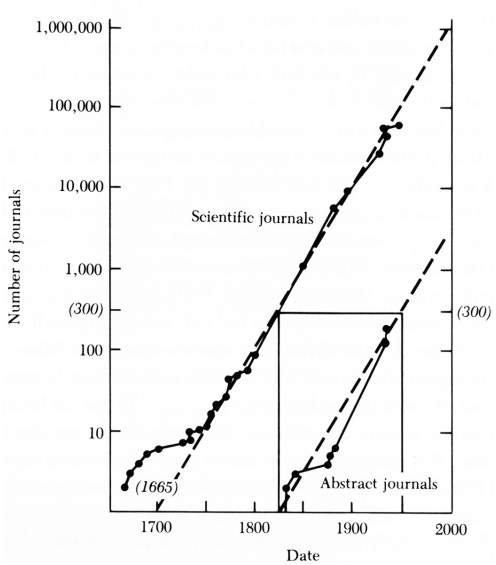


Books
per publication year



Papers and Wikipedia Entries





val mission, includes the Royal Society papers and offers broad coverage of the arts and humanities. Note the effect of external events on scholarly publication activity, for example, the decrease in papers printed during World War I and World War II.

MEDLINE, CiteSeer, and arXiv provide free access to full-text articles. MEDLINE (established 1971) is sponsored by the National Library of Medicine. It currently offers more than 19 million records—mostly biomedical—and in 2008 offered more records than Scopus for the years 1949–1965. ArXiv and CiteSeer are grassroots efforts of the physics and computer science communities, respectively. Paul Ginsparg created arXiv in 1991. Steve Lawrence, C. Lee Giles, and Kurt Bollacker at NEC Research made CiteSeer available internally in 1997 and started serving it to the world in 1998.

Data from Jimmy Wales's Wikipedia (see **page 19, Jimmy Wales**) was included to hint at the possibility of a different grain size for recording scholarly results (see **page 20, Paul Otlet**) and the power of the "million minds" approach (see **page 24, Global Brain**). An encyclopedia entry cannot be directly compared to a research paper, and the editing process Wikipedia uses is clearly different from the peer-review process that scholarly papers undergo. Nevertheless, the number and quality of entries written by volunteers around the globe for the English version of Wikipedia is impressive (see also **page 166, Science-Related Wikipedian Activity**).

Patents

Intellectual property rights have been claimed and protected since 500 BC. Lawful patent protection came into existence in the Republic of Venice as early as 1474. The total number of patents granted by main patent offices between 1883 and 2005 is shown in the **Patents** graph. Between 1883 and 1959, patenting activity was concentrated in the United States, Germany, the United Kingdom, and France. The average annual growth rate was about 2 percent. Starting in 1960, new states and nations, such as Japan and the Soviet Union, increased the number of filings. The European Patent Convention came into existence in 1977 and led to a decline in filings at national offices in Germany, France, and the United Kingdom. Since 1980, the patent offices of the United States, Europe, and China have all experienced significant growth in filings, at a rate of around 3.35 percent per year. The Patents graph shows the vast and sharp increase in the number of applications filed, particularly by the United States and Japan. In 2005, the European and Chinese patent offices filed nearly the same number of patents.

Highly cited patents are assumed to have higher technological impact. Patent citations indicate connections between companies and technological areas, as well as between industry and academia. Patent filings are used to compute indicators of activity, association, and impact, then applied to competitor assessment, merger/acquisition targeting, and investment strategy decisions.

Investing in the Future

Nations and regions fund research and education to improve their scientific wealth and economic power. In 2002, the public and private sector investment in research and development (R&D) as a percentage of the gross domestic product (GDP) was 1.86 percent in the United Kingdom, 2.20 percent in France, 2.51 percent in Germany, and 2.67 percent in the United States.

United States R&D expenditures by funding source since 1953, in constant 2000 dollars, are shown to the left in the **U.S. R&D Expenditures** graph. Note the crossing of federal government and industry funding in 1980 and the decline of industry funding in 2002 after the technology stock bubble burst.

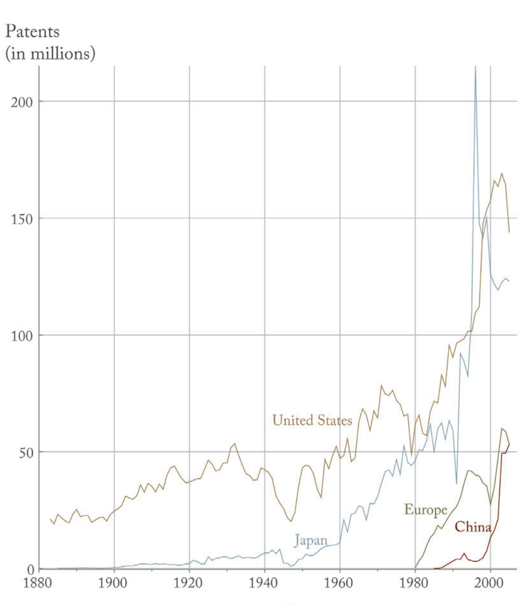
In 2006, the Wellcome Trust spent $800 million on funding, with an average project cost of about $375,000. A typical project produces three major papers, so the price of one paper can be estimated at $125,000.

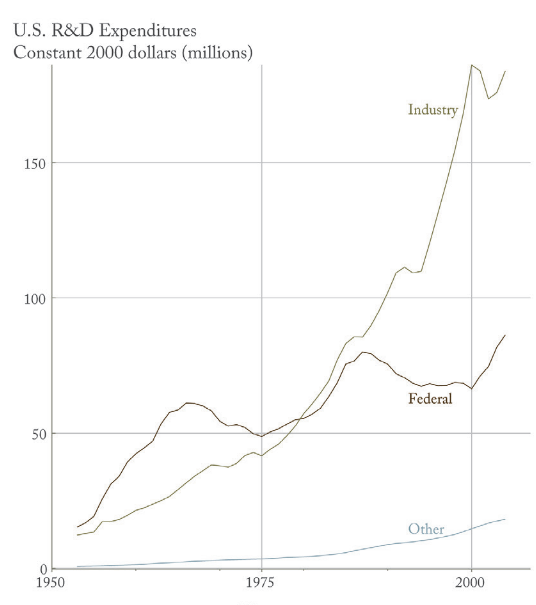
The amount of money required to perform cutting-edge R&D continues to increase. In 1970, the cost of one scientist—including salary, office, and laboratory support—was calculated to be $41,000 per year. Since then, science has become ever more interdisciplinary and dependent on technology. In 2010, the Large Hadron Collider and the Hubble Space Telescope, and similar such socio-technical infrastructures are vital sources of information and inspiration in our quest to expand our knowledge of the world.

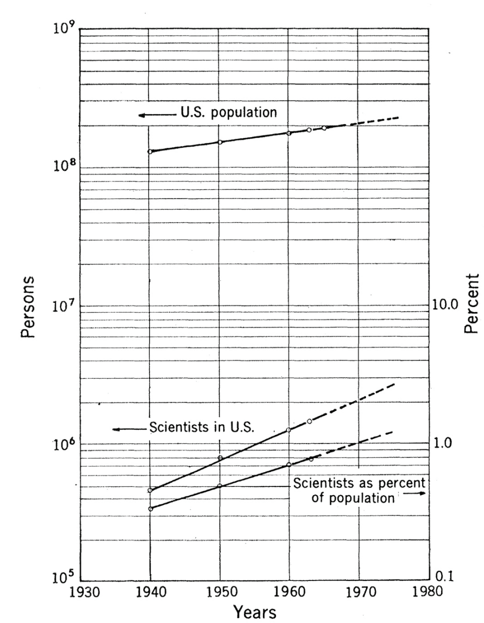
Science and Society in Equilibrium

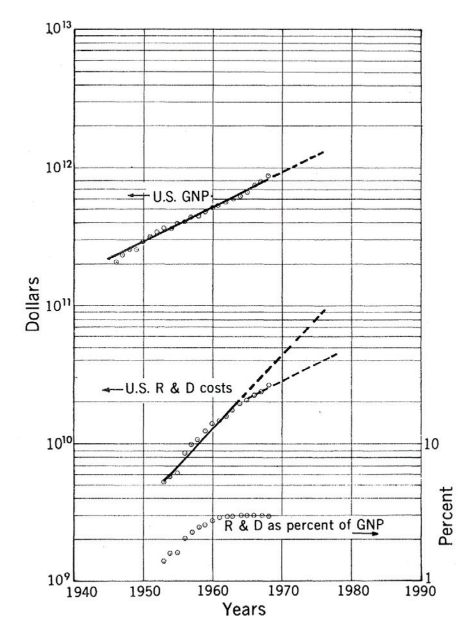
In *Little Science, Big Science* (1963), de Solla Price predicted that the growth of science would eventually decelerate, as the number of scientists could not possibly exceed the population count and the dollars devoted to R&D could not exceed the gross national product (GNP). He calculated that the number of scientists doubles every 15 years, while the U.S. population doubles every 40 to 50 years.

The pair of graphs below are derived from Joseph P. Martino's *Science and Society in Equilibrium* (1969). The left graph compares the number of U.S. scientists to the U.S. population between 1940 and 1969. During those nearly 30 years, the proportion of scientists in society increased from less than 0.5 percent to 1.0 percent. In 2008, of the 300 million U.S. residents, scientists numbered 5 million or 1.7 percent of the population (see **page 4, The Rise of the Creative Class**). The right graph shows the increase in U.S. GNP since 1946 and the dollar resources expended on R&D since 1953. As shown below, the U.S. GNP devoted to R&D had doubled from slightly less than 1.5 percent to 3 percent. Of the $13 trillion GNP in recent years, 2.3 percent, or $0.3 trillion, has been devoted to R&D (see previous section, **Investing in the Future**). While the number of scientists steadily increases in society, the increase in funding parallels the increase in GNP.









Addictive Intelligence Amplifiers

In a knowledge- and innovation-driven world, survival of the fittest is determined by one's inventiveness, expertise, and powers of influence. Creativity and innovation tend to be stimulated by the sociotechnical environment enjoyed by an individual or community. Tools that amplify our intelligence and allow us to engage in symbiotic relationships with other experts and technology play an important role here. Given the limitations of human perception and cognition, these tools improve our fitness.

Shrinking Planet

Increases in travel and communication speeds reduce the relative size of our world. This is made tangible in the chart by Buckminster Fuller (bottom right; see also **page 25, Buckminster Fuller**) which shows transportation times from 500,000 BC to AD 1965. The shaded area represents population growth; the solid line, transportation speed; and the dashed line, communication speed. The entire time span is divided into 9 epochs. For each epoch, the travel times, means of transportation, distance traveled per day, state size, and means of communication are given. Four Dymaxion maps—a projection of the World map onto the surface of a polyhedron then unfolded in two dimensions—show the relative size of the world as transportation and communication technology advance.

An extended population graph, covering 1,000,000 BC to AD 2005, can be found on **page 2, Knowledge Equals Power**. Extensions of Fuller's chart are shown in the **U.S. Transportation** graph (opposite page), which shows passenger miles for national railroad, intercity automobile, and domestic airline travel in the United States. Note the rise and fall of railroad and car traffic around 1945 and the impact of the oil crises in 1973 and 1979.

The **U.S. Communication** graph (opposite page) shows tremendous increases in communication, first by telegraph, then by radio and television, and most recently by cell phones and the Internet. Since the World Wide Web came into existence in 1989 (see **page 20, Tim Berners-Lee**) it has been growing at a phenomenal rate. Due to the Web's decentralized nature, the existing number of static Web pages is difficult to compute. Plus, many Web pages are generated on the fly using databases; the size of these dynamically generated Web pages, the so-called deep Web, is much more extensive. Even larger than the stock of Web pages is the number of blog posts and e-mails sent. In 2008 alone, 210 billion e-mails were sent each day by 1.3 billion users worldwide and 900,000 news blogs were posted.

From Little Boxes to Big Boxes

According to Barry Wellman, communities evolved from "little boxes" (clusters of tightly knit "door-to-door" neighbors) to "glocalized" networks (with dense local and weak global links) to sparse groups with "networked individualism" (dynamically changing links, regardless of locality).

The developed world is in the midst of a paradigm shift both in the ways in which people and institutions are actually connected. It is a shift from being bound up in homogenous "little boxes" to surfing life through diffuse, variegated social networks. Although the transformation began in the pre-Internet 1960s, the proliferation of the Internet both reflects and facilitates the shift.
Barry Wellman

This evolution is driven by the complexity and dynamics of our activities and the capabilities of our tools. Teams form, storm, norm, and perform at a high pace. While we might be happier and more productive offline, many of us spend a considerable amount of time online, weaving our increasingly larger and more dynamic networks.

Accelerating the Rate of Change

The tools we build work to accelerate the rate of change. The more knowledge we generate, the more we have to manage. The more efficiently we can link to others, the larger the networks we need to operate, navigate, and maintain.

The more tools, the faster the change—reaching a point where it is questionable whether the environment can sustain it. Major tools are atomic bomb, telephone, production-line system of manufacture, aircraft, plastics, guided rocket, television. Each has enormous potential for man's benefit or his destruction.
James Burke

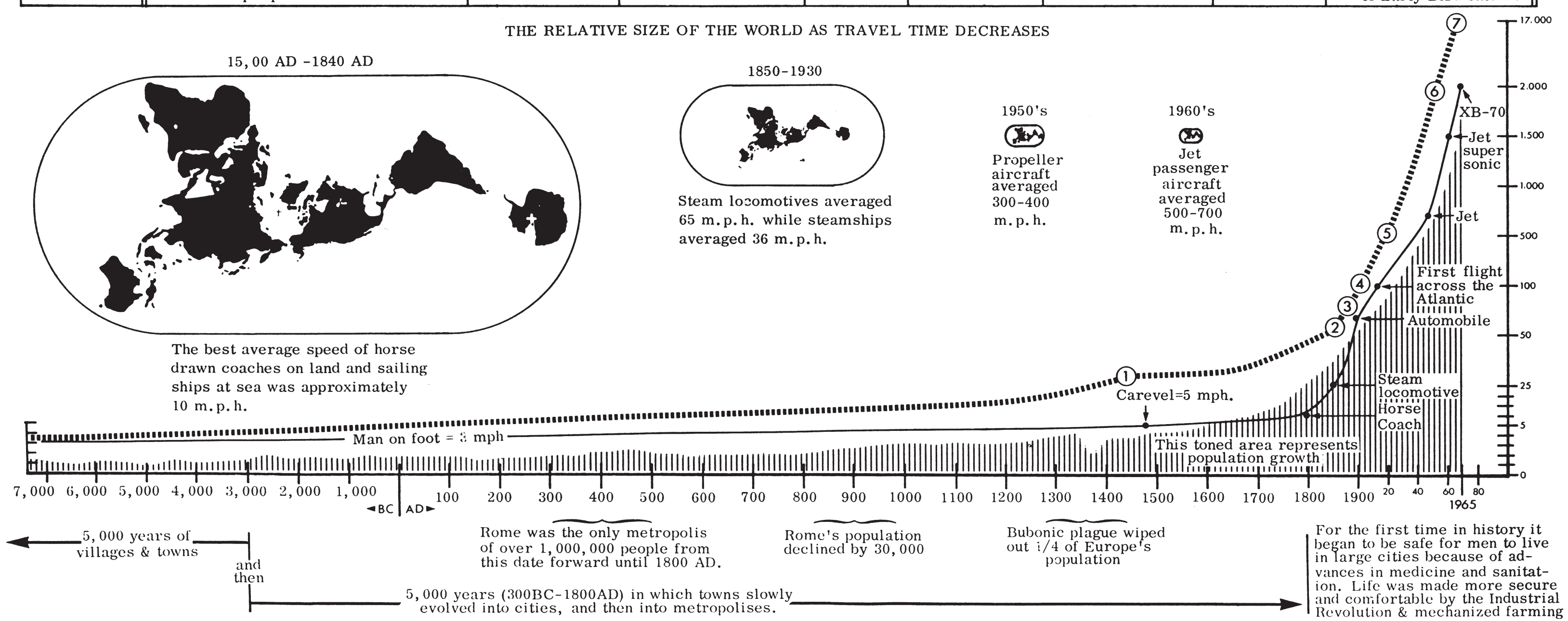
On-the-Fly Assembly

We are entering an era where units of interest are becoming reduced and less defined. Books are being replaced by e-mails, memos, and endlessly evolving wiki items. Data warehouses and cathedral-like

SHRINKING OF OUR PLANET BY MAN'S INCREASED TRAVEL AND COMMUNICATION SPEEDS AROUND THE GLOBE

YEAR	500,000 BC	20,000 BC	300 BC	500 BC	1,500 AD	1900 AD	1925	1950	1965
Required time to travel around the globe	A few hundred thousand years	A few thousand years	A few hundred years	A few tens of years	A few years	A few months	A few weeks	A few days	A few hours
Means of transportation	Human on foot (over, ice bridges)	On foot and by canoe	Canoe with small sail or paddles or relays of runners	Large sail boats with oars, pack animals, and horse chariots	Big sailing ships (with compass), horse teams, and coaches	Steam boats and railroads (Suez and Panama Canals)	Steamships, transcontinental railways, autos, and airplanes	Steamships, railways, auto jet and rocket aircraft	Atomic steamship, high speed railway auto, and rocket-jet aircraft
Distance per day(land)	15 miles	15-20 miles	20 miles	15-25 miles	20-25 miles	Rail 300-900 miles	400-900 miles	Rail 500-1,500	Rail 1000-2000
Distance per day (sea or air)		20 by sea	40 miles by sea	135 miles by sea	175 miles by sea	250 miles by sea	3,000-6000 air	6000-9500 air	408,000 air
Potential state size	None	A small valley in the vicinity of a small lake	Small part of a continent	Large area of a continent with coastal colonies	Great parts of a continent with trans-oceanic colonies	Large parts of a continent with transoceanic colonies	Full continents & Transocean Commonwealths	The Globe	The globe and more

Communications	Word of mouth, drums, smoke, relay runners, and hand printed manuscripts prior to 1441 A.D.	① The Gutenberg 1441 printing press	② The rapid print Web 1863 newspaper press	③ The Bell 1876 telephone	④ The Marconi 1895 telegraph	⑤ First commercial 1920 radio broadcast	⑥ National 1950 Television	⑦ 1965 Transcontinental T. V. with the introduction of Early Bird satellite

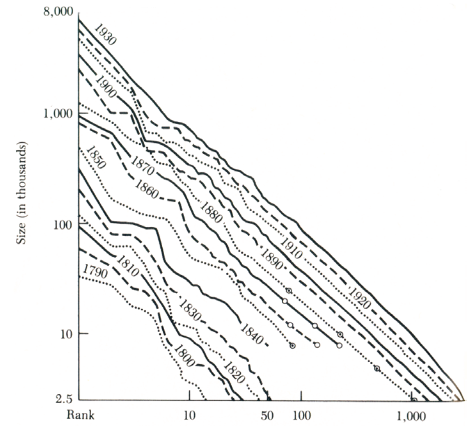


supercomputing centers are superseded by highly modular plug-and-play architectures and marketplaces of scholarly data sets, algorithms, and other resources. Project teams, and even whole companies, are assembled on the fly for a few days or a few years. There is no longer any lifelong job guarantee. Social and emotional intelligence, lifelong learning skills, and the ability to communicate across disciplinary and cultural boundaries become ever more important. Disciplined, synthesizing, creative, respectful, and ethical minds are promised the brightest futures.

Urban Species

Spatially, we are grouped into clusters called cities. About 500 years ago, there were only 5 cities with more than 100,000 people. In 2008, there were about 300 cities with populations of more than 1 million. In 1800, 50 million people lived in cities; in 2000, 3 billion did—more than half of the global population. For the first time in human history we are an urban species. In 2009, cities occupy near 3 percent of the world's land but they support more than 50 percent of the global population and use 75 percent of the world's resources.

This urban migration and population growth was discussed by George K. Zipf in *Human Behavior and the Principle of Least Effort* (1949). He ranked U.S. cities in decreasing order of population size for the years 1790 to 1930, and plotted population size versus rank in a log-to-log plot



(above). The resulting graphs follow a power law (see also **page 57, Power Laws**) as curving lines for different years move parallel to one another.

Natural-Born Cyborgs

While science and technology increase at a rapidly accelerating pace, human perception and cognition appear to stay nearly constant. Lifelong learning and training increase our knowledge and expertise, but not by several orders of magnitude. This is where tools come in—they amplify our intelligence by letting us offload tasks, such as keeping time, doing routine jobs (for example, calculations), and connecting to people (for example, via phone or e-mail). They augment our environments by interlinking the many everyday physical objects and bits and pieces of information that populate our homes and offices. The Internet and the World Wide Web are the beginnings of a global "world brain," as envisioned by many far-seeing thinkers (see **page 24, Global Brain**) which intimately links the unique capabilities of people and machines. To fully exploit the power of tools, we will need to

… appreciate what we already are: creatures whose minds are special precisely because they are tailor-made to mix and match neural, bodily, and technological ploys. … Cognitive technologies are best understood as deep and integral parts of the problem-solving systems that constitute human intelligence. They are best seen as proper parts of the computational apparatus that constitutes our minds.

Andy Clark

Moths to the Flame

We are drawn to technology like moths to a flame, as evidenced by our dependence on watches, cell phones, cars, and the Internet. If one of our technologies breaks down—a laptop on a business trip, for instance—our capacity and efficacy too are impaired. Handling calls and processing e-mails keeps many of us in the flow, and lets us effectively operate in a complex web of social, professional, and other networks.

One day, perhaps soon, we'll create mobile, semi-intelligent beings to do our dull, dirty, dangerous work. Soon after that, they'll become so useful and so competent that we'll keep them as pets and as companions for our children. … How we treat them, how we employ them, even whether they live or die, all will be up to us. Yet for that very reason, how we use them—these creations of our genius, these children of our minds—will determine how the future judges us.

Gregory J. E. Rawlins

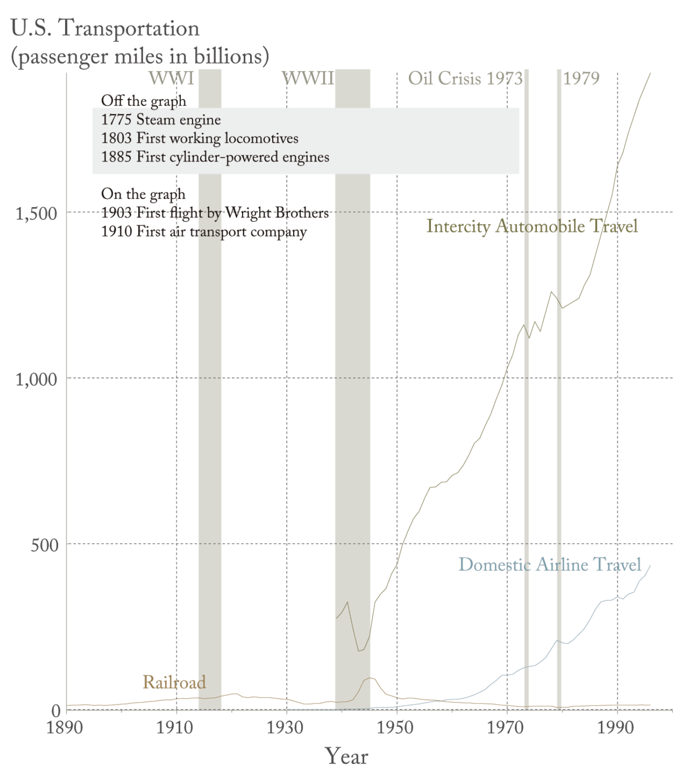
Man vs. Machine

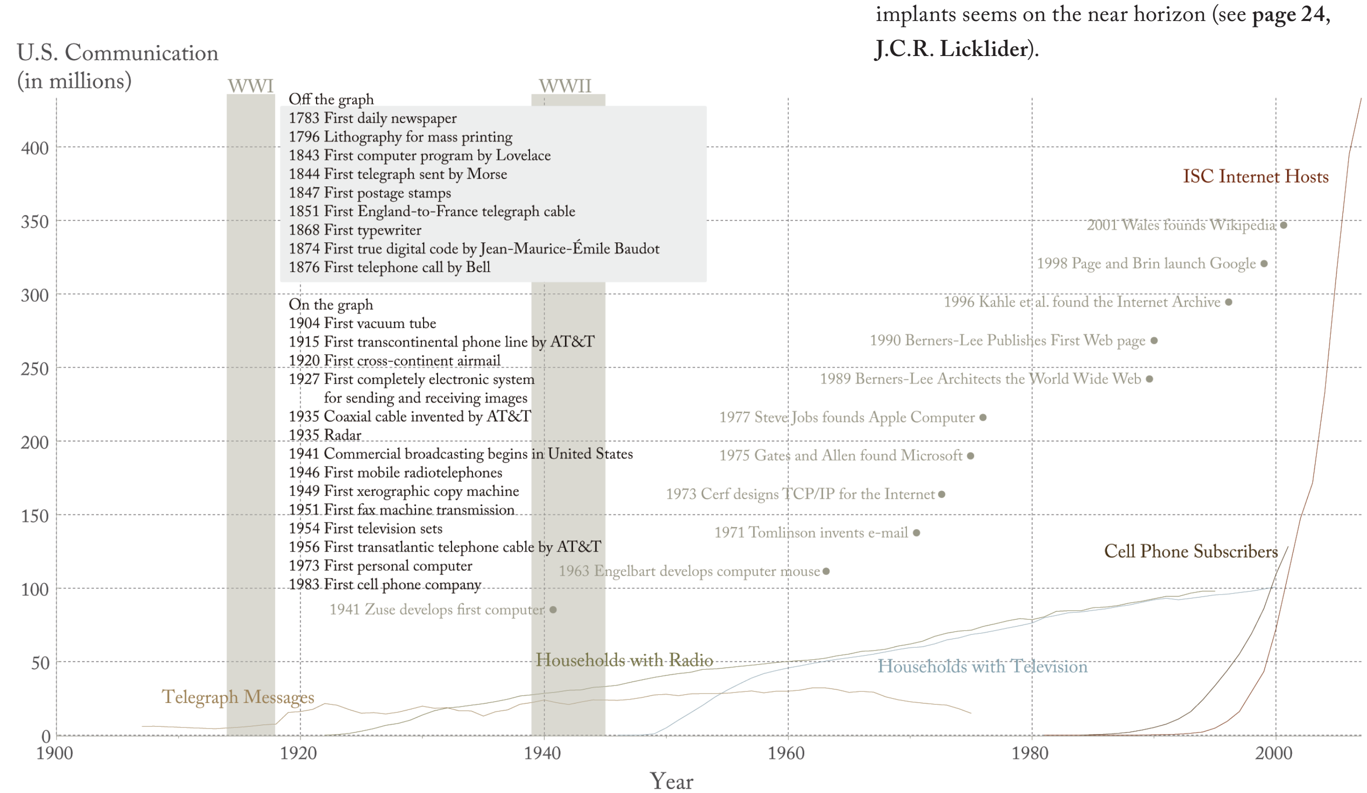
In the 1980s, microcomputers reached the consumer market. Since then, the amount of information that computers are capable of processing and the rate at which they do so has doubled about every two years, a phenomenon known as Moore's law. At this rate, some predict that computing speed will reach a limit in about 80 years. Other researchers cite physical laws and predict that this doubling rate could proceed for another 600 years.

Computers are universal machines, their potential extends uniformly over a boundless expanse of tasks. Human potentials, on the other hand, are strong in areas long important for survival, but weak in things far removed.

Hans Moravec

Machines, and particularly computers, will remain instrumental in augmenting our collective intelligence. A true symbiosis of human perception and cognition and mechanistic and computational implants seems on the near horizon (see **page 24, J.C.R. Licklider**).





Knowledge Needs and Desires

While people have highly diverse needs and priorities, many find themselves drowning in data and information. They simply cannot read all the e-mails, papers, or books they are supposed to know; explore the many new datasets and tools that become available each day; collaborate closely with relevant experts and colleagues; and devote sufficient time and attention to the many important decisions they make each day. The concrete needs and desires of six prototypical groups are reviewed here with a special emphasis on those that might be addressed by maps of science. Sample science map displays are given in the lower part of this spread, along with descriptions of how to interpret or use them. **Part 5: The Future of Science Maps (page 197)** presents approaches and tools that are specifically tailored to the user groups discussed here.

What information consumes is rather obvious. It consumes the attention of its recipients. Hence a wealth of information creates a poverty of attention.
Herbert A. Simon

Data Providers and Librarians

The mission of data providers and digital libraries is to support access to our collective knowledge. Excepting the fact that commercial providers charge for information access and public libraries are free, they share many goals. Generally, both aim for highly usable and accessible collections. They respect copyrights and help create and promote best practices, standards, and open systems to ensure the longevity of and ongoing access to their holdings. In many cases, they add value to materials by supplying contextual information or metadata. They develop tools and services to promote enhanced interpretation, context, and understanding. Both have to deal with the fact that the need for quality has by far outshadowed the need for quantity.

Developing a high-quality yet affordable library on a specific topic for a scholarly community is not a trivial matter. Since the early 19th century, research librarians have systematically applied citation analysis in their collection development; the quality of a journal was determined by the number of citations it received. With the implementation of the Thomson Reuters citation indexes, it has become possible to automatically extract citation data at the journal and individual paper level to guide the search, evaluation, and use of knowledge.

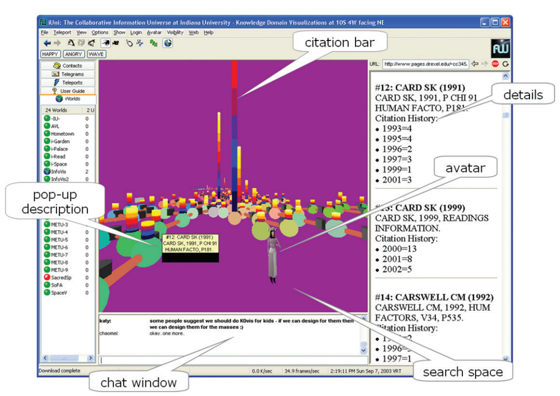
The number and variety of available databases is overwhelming. Databases vary considerably in their temporal, geographic, and topical coverage. Database quality ranges from "downloaded from the Web" to "manually curated by experts." Visual interfaces to digital libraries provide an overview of the holdings—as well as indexes to the records—of a library or publisher. They apply powerful data analysis and layout techniques to generate visualizations or maps of large document sets. Visual interfaces can be understood as a value adding service intended to help humans mentally organize, electronically access, and manage large, complex information spaces.

Industry

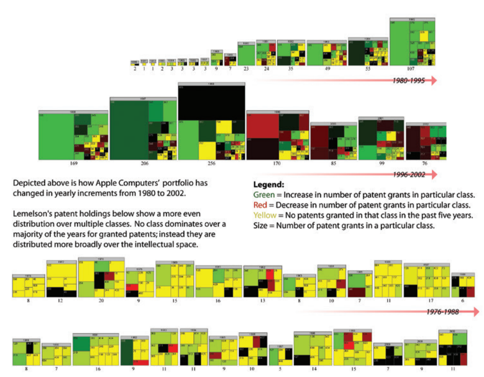
A deep understanding of technology, governmental decision-making, and societal dynamics is required to make informed economic choices that can ensure survival in highly competitive markets. Discontinuities caused by disruptive technologies have to be determined and relevant innovations detected, grasped, and used. Companies need to look beyond technical feasibility to identify the value of new technologies, predict diffusion and adoption patterns, and discover new market opportunities as well as threats.

The absorptive capacity of a company—in other words, its ability to attract the sharpest minds and "play with the best"—has a major impact on its survival. The importance of social networking tools and network visualizations increases with the demand for an understanding of the "big picture" in a rapidly changing global environment. (See **Claiming Intellectual Property Rights via Patents** below).

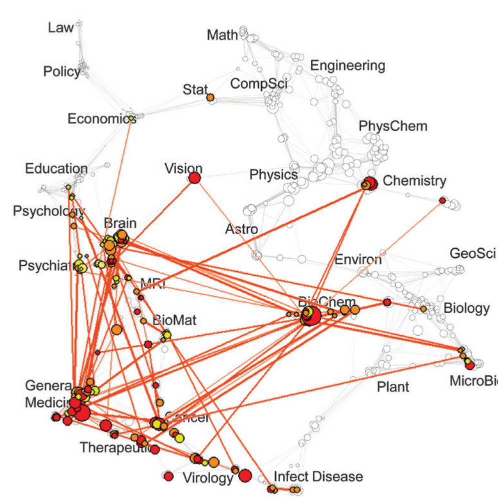
Competitive technological intelligence analyses, technology foresight studies, and technology road mappings are used to master these tasks. Easy access to the most current and cutting-edge results, data, tools, and expertise is key to success. Last, but not least, companies need to communicate their vision and goals to a diverse set of stakeholders in order to hire and cultivate experts, attract venture capital, and continue to promote their products.

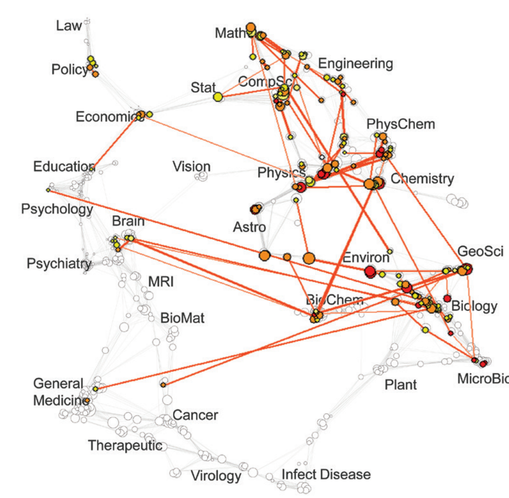


Collaborative Visual Interfaces to Digital Libraries
A three-dimensional virtual world is used to organize papers spatially. Each paper is represented as a node in a semantic network of related papers. Citation bars represent the number of citations a paper received. Users can click on a paper to retrieve details, which are displayed as a pop-up description (shown in the window at right). Multiple users can explore this space together, communicate via a chat window, and combine results.



Claiming Intellectual Property Rights via Patents
The evolving patent portfolios of Apple (1980–2002) and Jerome Lemelson (1976–2002) are shown here. The number of patents granted per year matches the size of the square. Each square is further subdivided into color-coded patent classes: green signifies an increase in the number of patents, red a decrease in the number of patents, and yellow that no patent was granted in that class over the last five years. While Apple claims more and more space in the same patent classes, Lemelson's patent holdings are distributed more broadly over the intellectual space.





Funding Profiles of NIH (left) and NSF (right)
Using a base map of science (see **page 12, Toward a Reference System for Science**), the core competency of institutes, agencies, or countries can be mapped and visually compared. Shown here are funding profiles of the National Institutes of Health (NIH) and the National Science Foundation (NSF). As the base map represents papers, funding was linked by matching the first author of a paper and the principal investigator using last name and institution information. A time lag of three years between funding of the grant and publication of the paper was assumed. While the NIH mostly funds biomedical research, the NSF focuses on math, physics, engineering, computer science, environmental and geo sciences, and education. Overlaps exist in chemistry, neuroscience, and brain research (see **page106, The Structure of Science** for details).

Science Policy Makers

Increasing demands for accountability require decision makers to assess outcomes and impacts of science and technology policy. There is an urgent need to evaluate the impact of funding and research on scientific progress: to monitor long-term money flow and research developments, to evaluate funding strategies for different programs, and to determine project durations and funding patterns. Should science be supported by an approach that is "Newtonian" (curiosity-driven), "Baconian" (application-driven), or a "Jeffersonian" compromise? Should small grants be distributed to many scholars, or should large-scale funding be concentrated in a small number of centers?

In addition, professional science managers are keen to identify areas for future development, to stimulate new research areas, and to increase the flow of ideas into products. Hence, they need to detect emerging research areas; understand how various science fields are interlinked; examine multidisciplinary areas; measure collaborations and knowledge flows at the personal, institutional, national, and global levels; identify and compare core competencies of economically competing institutions and countries; and identify and fund central, rather than peripheral, research centers.

Researchers

Most researchers wear multiple hats: they are authors, editors, reviewers, teachers, mentors, and science administrators to varying degrees.

As researchers and authors, they need to strategically tap their expertise and resources to enhance their reputations. Expertise refers both to the knowledge they already have or can quickly obtain, as well as the expertise that can be acquired via collaborations. Resources refer to data sets, software, and tools, as well as to people supervised or paid.

Researchers and authors also need to keep up with novel research results; examine potential collaborators, competitors, and related projects; weave a strong network of collaborations; ensure access to high-quality resources; and monitor funding programs and their success rates. Last but not least, they need to review and incorporate findings and produce and disseminate superior research results in pursuit of citation counts, download activity, and press coverage.

As editors and reviewers, researchers act as gatekeepers of science. They need detailed expertise in their own domains and in related domains of research to ensure that only the most valuable and unique works are added to the growing mountain of scholarship.

As teachers and mentors, they provide students with a deep understanding of the structure and evolution of their fields as well as the peculiarities of a domain of research and practice. They might give an initial overview of the material to be covered, then highlight prominent scientists, important papers, and key events. They provide pathways to help students discover, understand, and interrelate details.

As science administrators, they are responsible for decisions regarding hiring and retention, promotion and tenure, internal funding allocations, budget allocation, and outreach. Toward this end, a global overview of the major entities and processes in their areas, as well as their temporal, spatial, and topical dynamics is vital.

Children

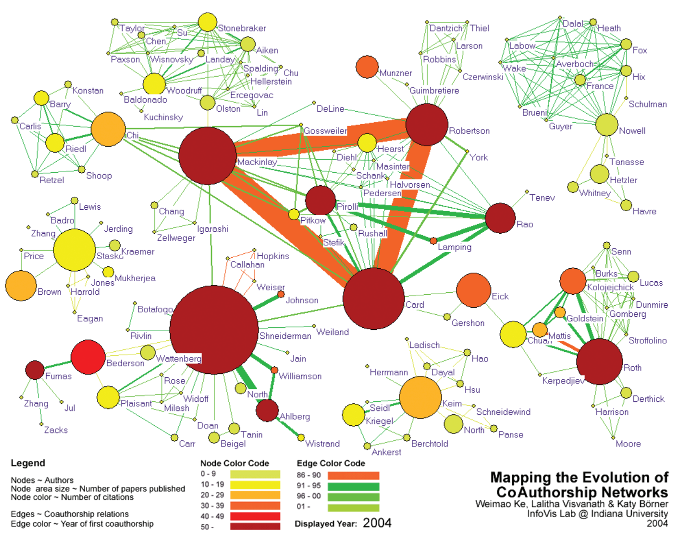
In school, children learn about many different sciences. However, they never get to see them as landscape or topography "from above." Hence, they have a limited understanding of the breadth and the complex interrelations of these many sciences.

How will they be able to answer these fundamental questions: What intellectual travels did prominent inventors undertake? Why is mathematics necessary to succeed in almost all sciences? How do the different sciences build upon one another? And how do I find my own place in science?

Imagine a map of our collective scholarly knowledge hangs beside the map of the world in each classroom. Imagine students can not only travel our planet online, but also explore the web of knowledge. How might this change the way we learn, understand, and create? **Hands-On Science Maps for Kids (page 186)** introduces physical renderings of science maps and world maps that invite children, and adults alike, to learn where major inventors and scientists pursued their work and where inventions and discoveries came into existence.

Society

Science is public rather than private knowledge—yet scientific publications are rarely accessed or understood by the general public. Placing all existing knowledge into a format that is easy to navigate has the potential to dramatically improve access to scientific knowledge and expertise. Ubiquitous, free, and simple access to information would thus advance the circulation and application of knowledge. Imagine a daily broadcast—like a weather forecast—that communicates breakthrough results and discoveries in science and technology to a wider audience.



Mapping the Evolution of Coauthorship Networks

This is the last frame of an animation sequence that shows the evolution of authors (nodes) and their coauthorship relations (links) in the domain of information visualization. Coding of node area size reflects the number of papers an author has published; color denotes the number of citations these papers received. Link width equals the number of coauthorships, and link color denotes the year of the first collaboration. Large dark nodes are preferable. Large light nodes indicate papers that have not (yet) been cited. Ben Shneiderman, working in a student-dominated academic setting, experienced a different collaborative environment than did Stuart K. Card, Jock Mackinlay, and George G. Robertson, who worked at Xerox Parc for most of the time captured here.

Hands-On Science Maps for Kids

The **Hands-On Science Maps for Kids** discussed and shown on **page 186** invite children to see, explore, and understand science "from above." This map shows our world and the places where science is practiced or researched. A complementary map shows the major areas of science and their complex interrelationships. Children and adults alike are invited to help solve the puzzle by placing the images of prominent scientists, inventors, and inventions in their proper places. Children are encouraged to look for the many hints hidden in the drawings to find the perfect place for each puzzle piece. What other inventors and inventions exist? Where would a favorite science teacher and science experiment go? What area of science to explore next?

Places & Spaces: Mapping Science Exhibit

This exhibit is a 10-year effort to introduce science maps to the general public. It aims to demonstrate the power of maps to help us navigate and make sense of physical places and abstract topic spaces. In 2007, the exhibit featured the first three of 10 mapping iterations—The Power of Maps, The Power of Reference Systems, and The Power of Forecasts—as well as an Illuminated Diagram display, WorldProcessor globes, and Hands-On Science Maps for Kids. The Web site **http://scimaps.org** features many more maps, together with references, the schedule of showings, and information on how to host the exhibit.

The Power of Maps

Cartographic maps have guided our explorations for centuries. They have enabled the discovery of new worlds even while marking territories inhabited by legendary sea creatures. Convenient to use (flat and small for easy handling), they are credible tools (made by established mapmakers and institutions) that simplify our world (showing key points) with clear, direct, and lasting visual impact. Only after millennia of observation and charting did we begin to arrive at a scientifically accurate map of the world. Much later, the first thematic maps, statistical graphics, and data visualizations came into existence. Fortunately, the mapmakers of science can learn and benefit from prior work to arrive at visual depictions of scientific networks and semantic spaces that help us navigate and make sense of the world of science.

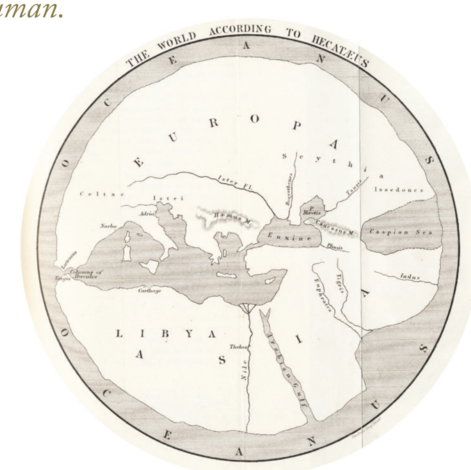
I sense that humans have an urge to map—and that this mapping instinct, like our opposable thumbs, is what makes us human.
Katharine Harmon

The Power of Stories

For thousands of years, stories were the primary means of imparting wisdom from one generation to another. With the invention of writing, these stories began to be recorded on smooth and enduring surfaces, from stone and vellum to papyrus and paper—all of which could be preserved, enabling continued communication of their contents. Many stories were accompanied by imagery. One example is the 20-inch x 230-foot (approximately 50 centimeters x 70 meters) Bayeux Tapestry (portion shown below)—an embroidered cloth providing, in part, a visual narrative of events surrounding the 1066 Norman Conquest of England.

Early Mapmaking

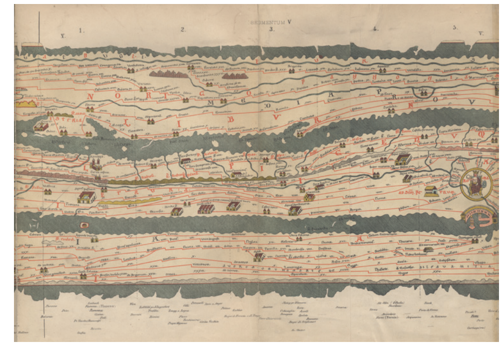
Maps of real and imagined worlds helped our ancestors to externalize, navigate, and comprehend the world and their place in it. The first maps were more descriptive than scientific, with neither reference systems nor standard symbols and formats.



Prehistoric maps have been found on cave walls. More than 4,000 years ago in Babylon, people drew maps on clay. Ancient Egyptians made maps from papyrus and developed ways of surveying the land.

Ancient maps were primarily based on travelers' descriptions of the lands they had seen. Maps like the one above, by Hecataeus of Miletus (circa 560–550 BC), were extremely schematic. Nevertheless, they were a great advance, as the relative positions of the continents could be communicated.

An example of the quintessential travel map is the Peutinger map (above right), a medieval copy of an ancient Roman map (circa 64–12 BC). It shows roads as jagged lines, where every node is a stopping place. Symbols depict different types of settlements, such as cities and military camps; the distance between them is also shown, as well as important features in the landscape. Most fascinating is the way this itinerary is conceived: the entire Roman Empire is compressed into a 20-foot x 1-foot (about



60 meters x 30 centimeters) scroll—ideal for the traveler to roll up and take with him on his voyages.

During the Middle Ages (400 to the late 1400s), mapmaking progressed in China and the Arab world. The Chinese printed the first map in 1155, more than 300 years before maps were printed in Europe.

The first detailed coastline maps, known as portolan charts, were developed around 1300 and have been found to be amazingly accurate. Marshall Islands stick charts, developed around 1500, represent ocean currents by stick patterns and island locations with shells and were used to aid navigation and fishing between islands.

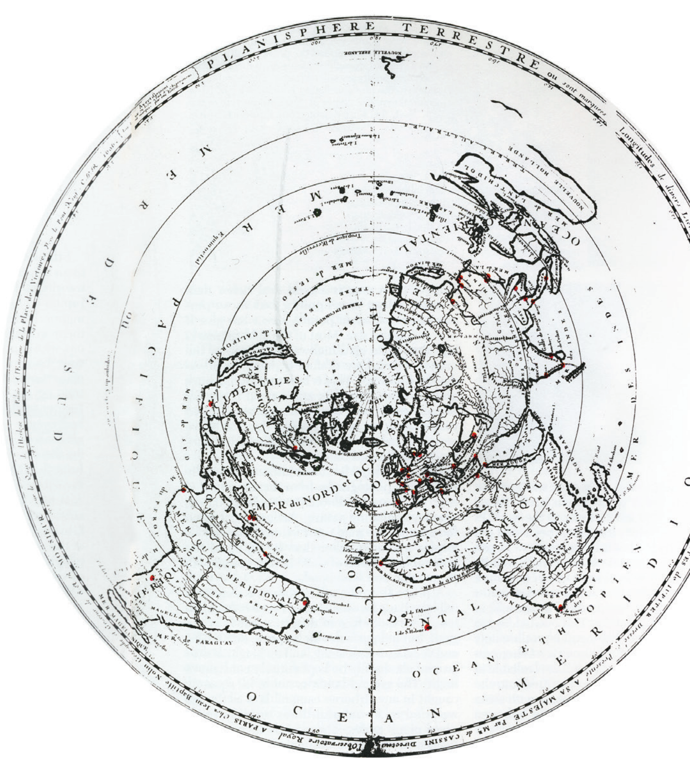
Historical maps are great reflections of what was known at the time of their creation and also of what was valued. Physical maps, for instance, show natural features such as rivers and rocks. Human maps show farms, transportation, and homes.

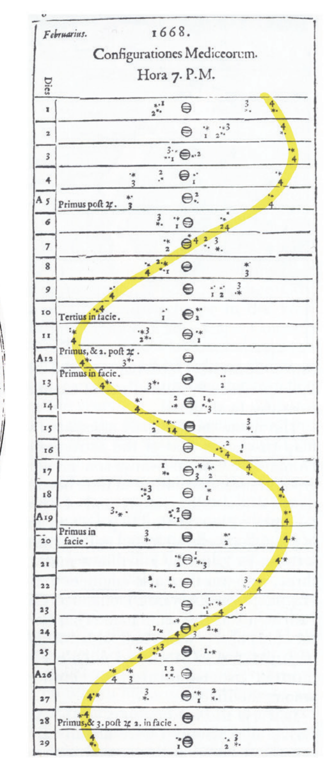
Toward a Geographic Reference System

Hundreds of years were required for the emergence of a common geographic reference system that was useful for navigation and mapping of commercial, social, political, and other entities.

The Greeks were the first to realize that the Earth is a sphere. They calculated the planetary dimensions and defined the locations of the equator and the poles. Hipparchus was the first to plot lines of latitude and longitude. Ptolemy compiled long tables of place names with their geographic features and coordinates, largely based on the descriptions of travelers. These tables, together with the Ptolemaic projection, facilitated the design of more accurate world maps in AD 160 (see example on **page 78, Cosmographia World Map**).

Nevertheless, because of errors and gaps in the data, most maps were out of proportion, inconsistent in their determination of orientation, and included mainly well-known coastal towns. As late as 1700, for instance, mapmakers did not yet have complete information about the coastlines of continents such as Australia (see **page 82, A New Map of the Whole World with the Trade Winds According to Ye Latest and Most Exact Observations**).





Scientific Mapmaking

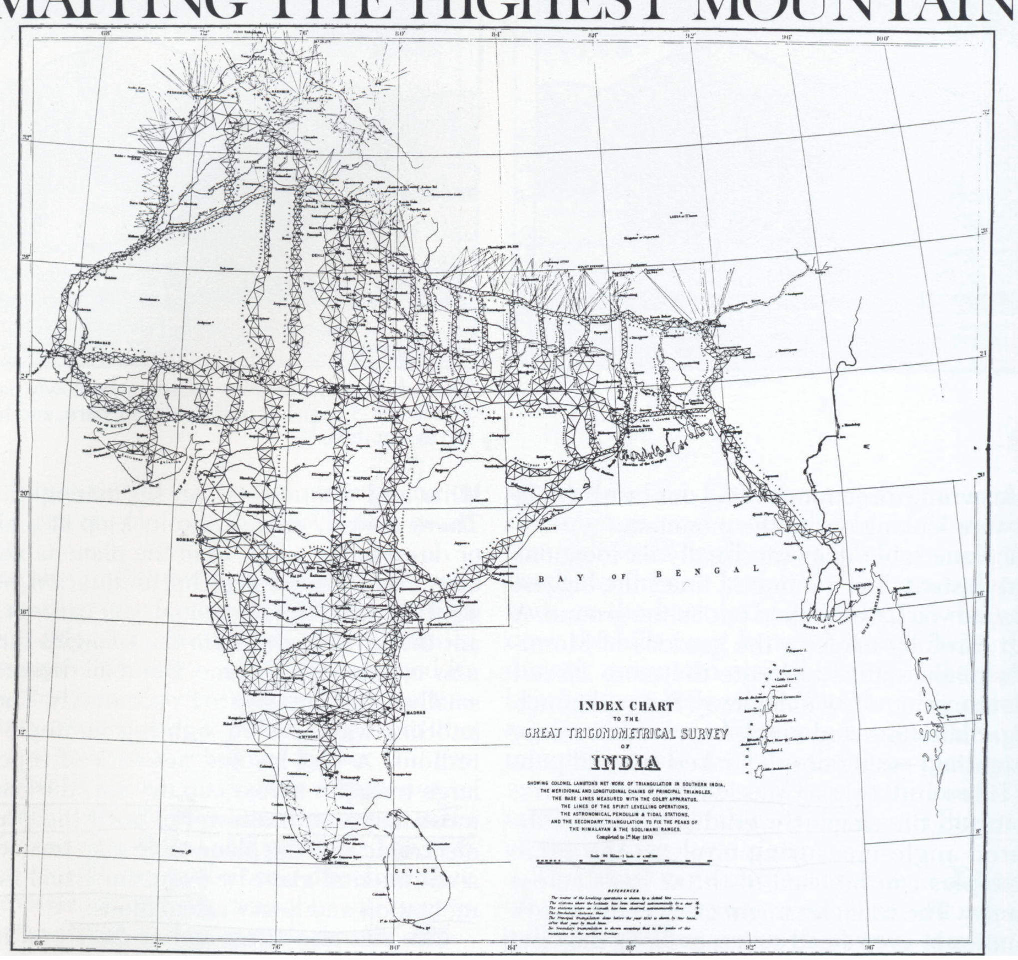
Advances in timekeeping and surface measurements (triangulation) enabled the accurate mapping of space. Between 1600 and 1700, land surveying techniques were developed.

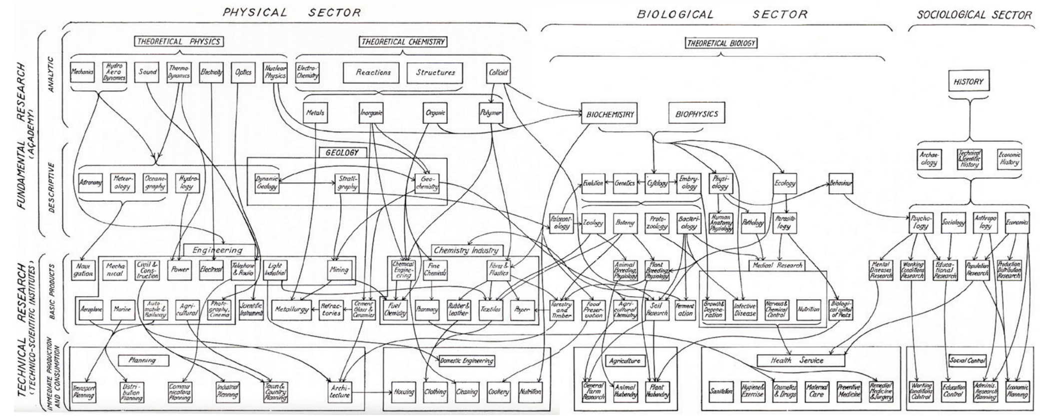
In 1696, the first accurate map of the Earth was drawn by Giovanni Domenico Cassini, based on 40 points of accurate latitude and longitude (below left; points shown in red). The north-south position (latitude) of any point on Earth could be determined via star paths. To measure east-west position (longitude), exact time measurement was essential: one minute of uncertainty implied a 10-mile margin of error in location. Inspired by Galileo Galilei's work, mapmakers used the planet Jupiter as a "clock in the sky." They carefully recorded the motions of Jupiter's moons (see Cassini's 1668 table of the eclipses of Jupiter's moons, opposite page, lower right). Based on these tables, events such as eclipses could be predicted and correctly timed to within a minute. By comparing the time at a certain location to local time in Paris, the site's longitude could be determined.

In 1744, Cassini's son César-François and his team started to map France in a rigorous fashion using triangulation. In the late 1700s, the world's first national land survey of France was completed. In 1870, Sir George Everest set out to map India by triangulation. For generations, a vast network of repeating sightline triangles was meticulously measured and recorded (see **Mapping the Highest Mountain,** below). What resembles a pattern of eyelashes on the northern border represents the sightlines to stations built above treetops. While analyzing the triangles in the calculating offices of Calcutta, the mapmakers discovered the highest peak in the world: Mount Everest.

In 2008, there were more than 20 global positioning system (GPS) satellites in orbit, each on its own track. While revolving around the planet, each transmits a radio signal to the ground. GPS receivers pick up these signals from multiple satellites and derive the exact location of the receiver. The World Geodetic System provides a standard coordinate frame for the Earth for use in cartography, geodesy, and navigation, despite continental plate movement, volcanic activity, earthquakes, tsunamis, and human activity upon the Earth's surface.

MAPPING THE HIGHEST MOUNTAIN





Thematic Mapmaking, Statistical Graphics, and Data Visualization

In the 18th century, mapmakers began to show more than just geographic locations on a map. New graphic forms such as isolines and contours were invented, allowing geologic, economic, historical, political, and medical data to be overlaid on maps. Edmond Halley's 1700 isogonic map is presumed to be the first thematic map in the modern sense. Many of the first statistical graphs had a strong geographic component. For example, John Snow's cholera map of 1854 used dashes next to each patient's home address to indicate the number and location of cholera cases in one London neighborhood—showing a high density of cholera cases near a well on Broad Street. Once the pump handle of that well was removed, the epidemic ended.

Charles Joseph Minard's 1861 map of **Napoleon's March to Moscow** (see **page 84**) combines a cartographic map and a timeline. It shows the terrible fate of Napoleon's army in Russia via six variables: line width represents the size of the army; line path shows the army's latitude and longitude; line direction is color coded for advance and retreat; and temperature on various dates during the retreat from Moscow.

Harry Beck's 1931 map of the London Underground sacrifices accuracy of both location and scale in favor of readability. In Beck's original map, and in nearly all recent subway maps, Tube lines are drawn in exclusively horizontal, vertical, or diagonal fashion and subway stations are shown to be equidistant, regardless of their actual locations.

Data Charts and Network Visualizations

Another line of mapping work involved the invention of data graphs, charts, and network visualizations without a geographic component.

In 1786, engineer and political economist William Playfair published *The Commercial and Political Atlas* in London. It contained 43 time-series plots and the first known bar chart. Playfair also invented the line graph, circle graph, and pie chart and he is also known as the inventor of statistical graphics.

In 1858, nursing pioneer Florence Nightingale designed charts that plotted the number of deaths due to preventable diseases versus the number of deaths due to wounds and other causes. These statistical comparison charts led to greater social awareness of preventable diseases and ultimately to reform in hospital sanitation methods.

In 1934, Jacob L. Moreno, known as the father of sociometry, published his first network diagram in the *New York Times.* Soon thereafter, many other social scientists and scholars began to map social and scholarly networks (see **page 26, Sociometry map**).

In 1939, John D. Bernal, a physicist, historian, and sociologist of science, designed one of the first "maps of science." This map divided science into physical, biological, and sociological sectors; it also distinguished technical and fundamental research (see above map).

Many more examples of the history and power of drawn maps have been beautifully compiled in the works of Edward R. Tufte, Howard Wainer, and Jacques Bertin and references to major books are given on **page 216, in References and Credits**.

Recent advances in computer technology and software development have made possible the algorithmic creation of maps from large-scale data sets, allowing the mapping of, for example, Web sites or cyberspace. Information visualizations support the interactive exploration of large amounts of abstract data. Knowledge visualizations focus on the creation or transfer of knowledge among people. Knowledge domain visualizations, also called science maps, are discussed next.

Science Maps and Their Makers

In 1963, Derek John de Solla Price suggested that science be studied using scientific methods. His visionary work led to the creation of the field of scientometrics. Early scientometric studies were completed by hand, as citation index databases did not yet exist and computers were not yet widely available. Today, computational scientometrics refers to the processing of terabytes of scholarly data by means of interconnected computers running advanced software. The communication of the structure and evolution of science at an individual, local, and global scale, however, is nontrivial. Tables and timelines are easy to read and understand, yet they fail to convey the complex interdependencies of scholarly entities and the feedback loops in which they are involved. The design of reference systems and visual vocabulary to depict science at different scales for different stakeholders is a major research topic.

Maps, even more than the printed word, impress people as authentic. We tend to accept the information on maps without question.
Jon A. Kimerling

Mapping Science

Science maps aim to visually encode the structure and evolution of scholarly knowledge (see **page 26-47, Milestones in Mapping Science** for more than 100 maps of science and technology). Science maps are also known as scientographs, literature maps, domain maps, and knowledge domain visualizations. The mapmakers of science are scientometricians, bibliometricians, visualization researchers, and graphic designers, among other experts. Recently, a number of cartographers and geographers have devoted their extensive talents and techniques to the mapping of nonphysical knowledge spaces.

Historically, science maps were created to navigate, understand, and communicate the structure of scientific knowledge. Recent work aims to use science maps to understand and communicate the dynamics of science. Science maps complement local fact retrieval via search engines by providing global views of large amounts of knowledge. They can be used to objectively identify premier research areas, experts, institutions, collections, grants, papers, journals, and ideas in a domain of interest.

It is important to note that science maps promote improvements in data quality and coverage. While we do not expect a search engine to retrieve every existing publication on a given subject, we do require a map of science to be accurate and complete. Fortunately, scholars want to be on the map and are therefore amenable to supplying the information necessary. Easy to use, Wiki-like interfaces empower scholars to add, organize, and interlink data items improving data quality and coverage (see also **page 68, Scholarly Marketplaces**).

The Utility of a Science Reference System

Science spaces differ from physical places in that they are abstract and cannot be touched or visited. As a result, most people find science to be alien and inaccessible. Science maps aim to make the structure and evolution of science tangible, appealing, and navigable.

Just as centuries were needed to arrive at a geographic reference system (see **page 10, The Power of Maps**) we must allow for the time and patience necessary to eventually agree upon a formally grounded and practically validated reference system for science. Certainly, having a science reference system to organize our collective scholarly knowledge is well worth the necessary disputes and battles, as it will ultimately help us settle on common terminology and standards. The envisioned reference system resembles a library classification system in that it can be used to organize all knowledge in space. However, instead of being used exclusively by librarians and classification-savvy library patrons, it would be used by the general public, both children and adults, to navigate and utilize the world of knowledge.

The design of a science reference system must take our current knowledge of science into account. It requires a conceptualization of the structure and growth of science (see **page 52-59, Conceptualizing Science**) and needs to be derived from the best and most comprehensive set of scholarly data in existence (**page 60, Data Acquisition and Preprocessing**). It must apply the most scalable and advanced algorithms (**page 62, Data Analysis, Modeling, and Layout**) and must be validated against existing classification systems and data sets in a formal and practical sense.

Different user groups and insight needs (see **page 8, Knowledge Needs and Desires** and **page 197, Part 5: The Future of Science Maps**) will demand very different maps. However, given a common reference system, the science map used in the classroom will be comparable to the maps used in financial decision-making or in library organization.

Toward a Reference System for Science

As the amount of information available increases (see **page 4, The Rise of Science and Technology**) our ability to bring order to the existing and continuous stream of new scholarly data needs to improve. Automated approaches that can analyze and map millions of scholarly records must be developed and applied. Results need to be confirmed for local and global accuracy and completeness. Manually derived classification systems have a leading role to play in the development and validation of a shared reference system.

Recent work by Kevin W. Boyack and Richard Klavans (see maps to the right) aspires to the creation of a global map of and spatial reference system for all sciences. The maps are based on a large subset of papers from the most comprehensive databases in existence: the Science Citation Index (SCI), Social Sciences Citation Index (SSCI), and Arts and Humanities Citation Index (AHCI), all by Thomson Reuters, and Scopus, provided by Elsevier (see **page 60, Data Acquisition and Preprocessing**). The four maps were generated using the following steps:

- A set of scholarly journals or papers is taken as input.
- The similarity between pairs of journals or papers is calculated based on either direct citation, cocitation (the number of times they are jointly cited by another paper), or bibliographic coupling (the number of references they share).
- The resulting similarity matrix is normalized. The network of paper/journal nodes and their linkages is analyzed to retain only the strongest links for each node. The spatial layout aims to place similar nodes close to each other and to minimize the crossing of linkages.
- Journals/papers are assigned to clusters.
- The result is interpreted and labeled manually.

This process is explained in detail in the following: **In Terms of Geography**, **Map of Scientific Paradigms**, and **Maps of Science: Forecasting Large Trends in Science** on **pages 106**, **136**, and **170** respectively. The distinguishing factor of this work is that the clustering of papers or journals is not based on the original correlation matrix but on the spatial layout, or the position of nodes in a two-dimensional space.

Alternative approaches to science mapping exist and are featured in the timeline of milestone events in **Milestones in Mapping Science, pages 26-47**.

The **Backbone of Science** map (top left) has been used in extensive studies that aim to validate and optimize the processing pipeline applied to generate this map and maps discussed later. Specifically, the regional accuracy, scalability, accuracy of different similarity algorithms, and the readability of the layouts were examined. As the map is based on journal-level data, it is understood to be a disciplinary map.

The **2002 Base Map** (top right) expands on the backbone map, in that bibliographic coupling counts have been reaggregated at the journal cluster level to calculate the (x, y) position for each journal cluster and by association the (x, y) positions for each journal. Journal names can now be used to "science locate" individuals, institutions, countries, and scientific fields based on their publication records. The map was included in the first iteration of the *Places & Spaces: Mapping Science* exhibit (see **page 106, The Structure of Science**). In 2006, it was the most comprehensive map of science ever generated. The map was also used for diverse overlays of funding amounts per science area (see **page 202, Science of Science Policy Maps for Government Agencies**).

The **Paradigm Map** (bottom left) was generated by recursively clustering the 820,000 highly cited papers referenced in 2003. The resulting map has 776 paradigms or active research areas, each of which is indicated by a circle. The map appears in the second iteration of the Mapping Science exhibit (**page 136, Map of Scientific Paradigms**). It also served as a base map for the Illuminated Diagram display (**page 180, Illuminated Diagrams**) and the Hands-On Science Maps for Kids (**page 186, Hands-On Science Maps for Kids**).

The **UCSD Map of Science** (bottom right) shows a three-dimensional layout of disciplines (groups of journals). It places those disciplines on the surface of a sphere; the spheric layout is then flattened using a Mercator projection to create a two-dimensional version of the map. Each node is labeled and has an extensive list of key phrases as metadata, which can be used to "science locate" nonjournal data, such as patents or grants. That is, key phrases from each patent or grant (titles and abstracts) are extracted; fractional assignment to map nodes proceeds by matching the associated metadata. Thus, each grant or patent is fractionally assigned to multiple nodes. Adding the fractions allows for the number of grants, dollars by agency, or patents associated with each node to be computed. Drilldowns for each of the more than 550 nodes are underway. The UCSD map is part of the third iteration of the exhibit and is shown in large form on **page 170, Maps of Science: Forecasting Large Trends in Science**.

Although different in final form when published or exhibited, the maps are represented here using the same visual encoding. In all four maps, nodes represent clusters of journals. The nodes are size-coded by the number of papers they contain. Nodes in the UCSD map are color-coded according to the major fields of science they represent. Labels are used to indicate the general positions of these fields. While different data sets—paper- or journal-level data—and similarity measures are used, the placement of major science areas and the ways they interrelate is very similar across the four maps.

The 2002 Base Map is used on **page 106, The Structure of Science** to indicate which areas of science are captured by each exhibit map.

Mapmakers of Science

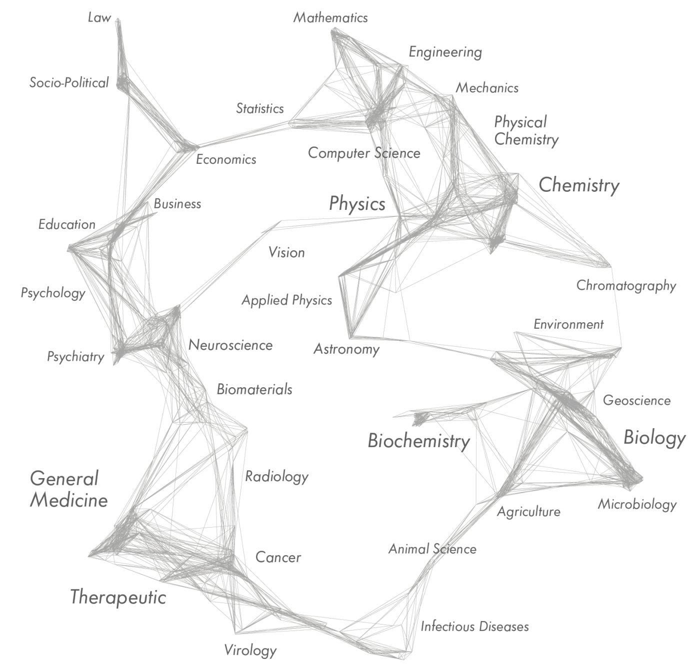
The old mapmakers are typically depicted as elderly, often bearded men, formally dressed in tweeds and gabardine, sitting at high desks with pens in hand, surrounded by stacks of books and maps, cloistered in towers of wisdom.

The new generation of computational scientometricians includes men and women with backgrounds in cartography, history (of science), psychology (perception and cognition), education, visualization, data mining, (digital) library science, scientometrics, bibliometrics, informetrics, or webometrics. They dress as they please and enjoy access to large-scale data sets, major cyberinfrastructures, and other experts around the globe. There are about 300 of them in the world, and several of them are driven to bring knowledge not only to other academic and government institutions but to every person on this planet.

Backbone of Science

Data: Combined SCI/SSCI from 2000, 7,121 journals
Similarity Metric: Cocitation
Number of Disciplines: 212

2002 Base Map

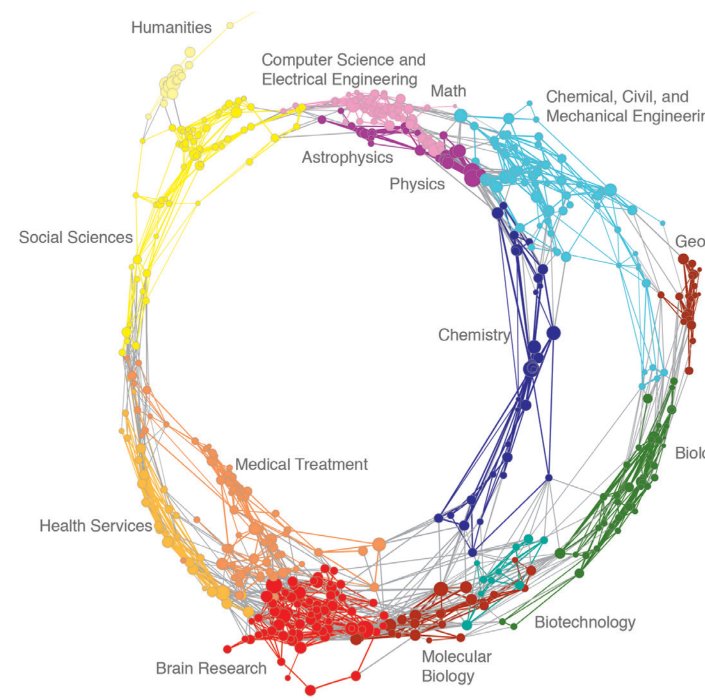


Data: Combined SCI/SSCI from 2002, about 1.07 million papers, 24.5 million references, 7,300 journals
Similarity Metric: Bibliographic Coupling
Number of Disciplines: 671

Paradigm Map

Data: Combined SCI/SSCI from 2003, about 820,000 highly cited reference papers
Similarity Metric: Cocitation
Number of Paradigms: 776

UCSD Map of Science



Data: WoS and Scopus for 2001–2005, 7.2 million papers, more than 16,000 separate journals, proceedings, and series
Similarity Metric: Combination of bibliographic coupling and keyword vectors
Number of Disciplines: 554

References & Credits

This section lists 1,650 citation references, more than 580 image credits, 80 data credits, and 60 software credits. More than 150 scholars provided input on the material presented in the atlas, and their contributions are acknowledged here.

As some spreads have up to 80 references and adding 80 parenthetical references or four-digit numbers to the page layout would considerably hurt readability, the references and credits are not given in the text. Instead, they are listed here by section. References are ordered alphabetically except for those in the **Timeline, pages 26-47,** which are ordered chronologically.

The Web site for the atlas (**http://scimaps.org/atlas**) supports pinpoint citations (that is, references and credits are associated with the specific text they support). In addition, the site will make available EndNote and bibtex files containing all the references.

vi Contents

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1 Part 1: Introduction

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2 Knowledge Equals Power

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26 Milestones in Mapping Science

All references in this section are organized in order of their appearance in the timeline. For each double page spread all algorithm, visualization, tool, and book references are listed together with image credits.

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Hands-On Science Maps for Kids, featured in *Places & Spaces: Mapping Science*, World Map featuring original artwork by Fileve Palmer, Indiana University.

Hands-On Science Maps for Kids, *Places & Spaces: Mapping Science*, Science Map by Fileve Palmer (original artwork and design) and Katy Börner (concept), Indiana University, incorporating the structural elements of the "Map of Scientific Paradigms" by Kevin W. Boyack and Richard Klavans, SciTech Strategies, Inc. **http://www.mapofscience.com** (accessed June 10, 2008).

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Discussion

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This timeline benefited from material compiled by Peter A. Hook, Kevin W. Boyack, and Loet Leydesdorff. Bryan J. Hook and Mark A. Price kindly retrieved books and papers.

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Boyack portrait courtesy of Katy Börner.

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Elements of the Exhibit

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Illuminated Diagrams: *see* Boyack 2007.

Hands-On Maps for Kids: *see* Börner 2009 and **http://scimaps.org/http://scimaps.org/flat/exhibit_info** (accessed March 23, 2010).

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Web site: design and programming by Elisha F. Hardy and Russell J. Duhon, concept by Katy Börner, *see* **http://scimaps.org.**

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Science and Geography Maps: Elisha F. Hardy (design), Katy Börner (concept), Indiana University; adapted from Boyack and Klavans 2002 Base Map, *see* Boyack et al. 2009.

Contributors

Bryan J. Hook compiled the data used in the geographic and science map of exhibit venues.

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Overview of the first iteration: Elisha F. Hardy (design), Katy Börner (concept), Indiana University.

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Deborah MacPherson and Bonnie DeVarco coauthored the original biography and description of this map.

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Henry G. Small provided feedback on the text, images, and references.

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Software Credits

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Josh Bonner and Alaa Elie Abi Haidar programmed initial TV prototypes; Shashikant Penumarthy gave expert advice; Eric Giannella helped with the selection of patent examples.

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Ingo Günther coauthored the description of the map and globes; the assistance of John Mahoney, Stephen Oh, Monika D. Zhu, and many others has been invaluable.

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Overview of the third iteration: Elisha F. Hardy (design), Katy Börner (concept), Indiana University.

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This description was coauthored by Alex Soojung-Kim Pang.

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B: "Illuminated Diagram Topic Map," based on "Map of Scientific Paradigms Research" and Node layout by Kevin W. Boyack and Richard Klavans, SciTech Strategies, Inc., **http://www.mapofscience.com**. Graphics and typography by W. Bradford Paley, Information Esthetics, **http://didi.com/brad**. Conceptualized and commissioned by Katy Börner.

C: "Relationships Among Scientific Paradigms," as displayed in *Nature*, December 21, 2006, vol. 444, p. 985: 2006 Gallery.

D: "Relationships Among Scientific Paradigms," as displayed in *SEED* magazine, March 7, 2007.

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New ID software was implemented by Jagan Lakshmipathy. Eric Wernert, Mike Boyles, Chris Eller, and Pooja Gupta contributed to the new ID setup. Kevin W. Boyack and W. Bradford Paley coauthored the text.

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Photographs courtesy of Katy Börner.

Timeline of Inventors and Inventions by Fileve Palmer (artwork) and Elisha F. Hardy (graphic design and layout).

Contributors

Base maps taken from Illuminated Diagram display by Kevin W. Boyack, Richard Klavans and W. Bradford Paley. Stephen Miles Uzzo (director of technology, New York Hall of Science) and Michael Lane (director of exhibit services, New York Hall of Science) provided expert advice and manufactured the physical maps.

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Special thanks to John Burgoon, Monika Zhu, and Stephen C. Oh. © 2006 Ingo Günther.

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