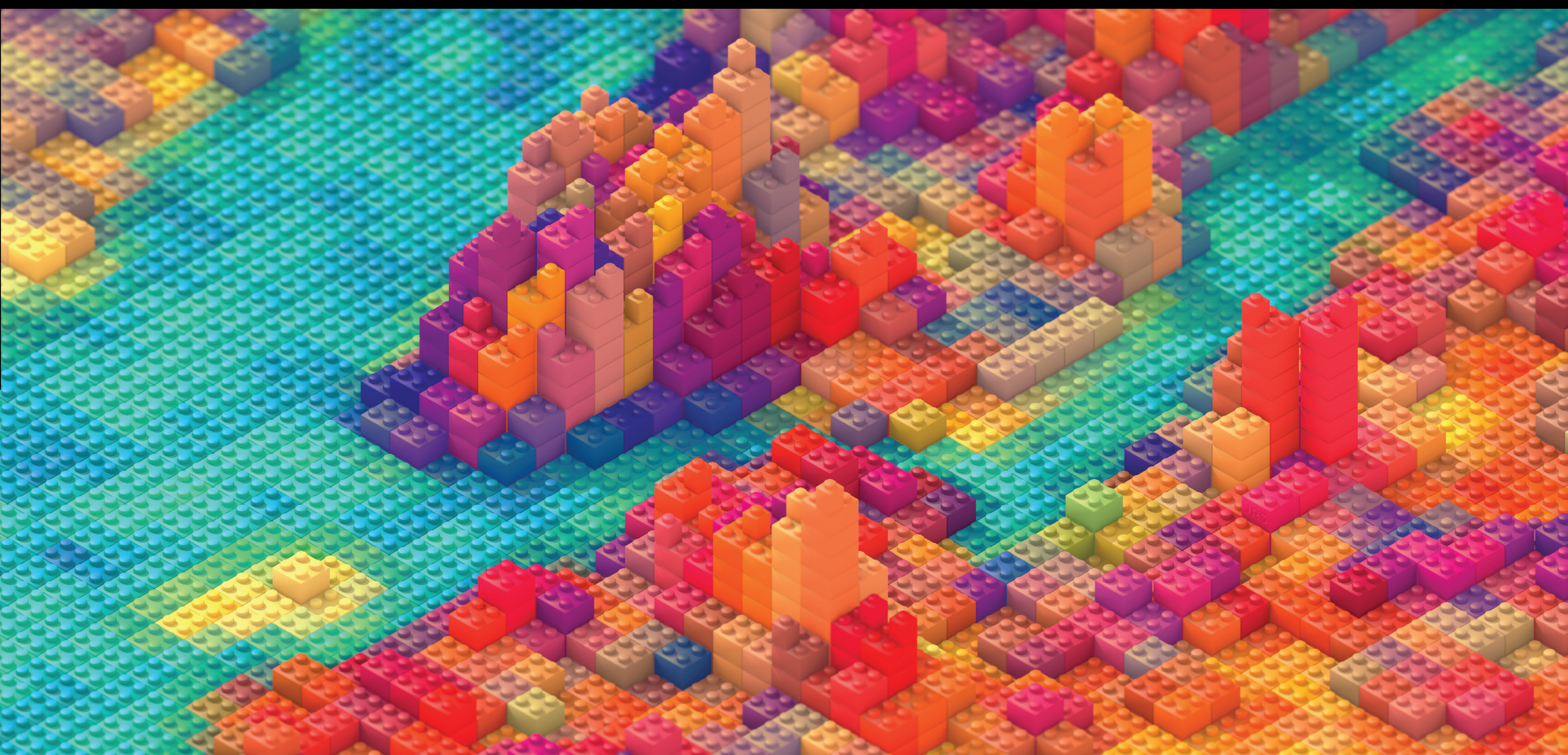
Atlas of Knowledge

Anyone Can Map

Katy Börner



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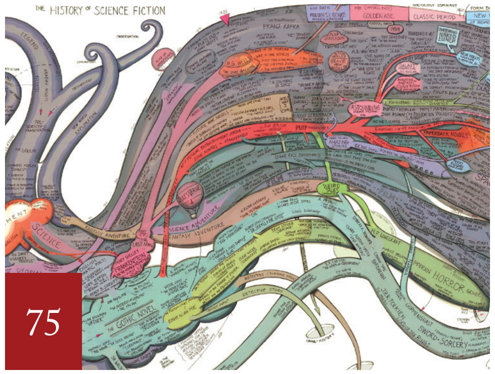

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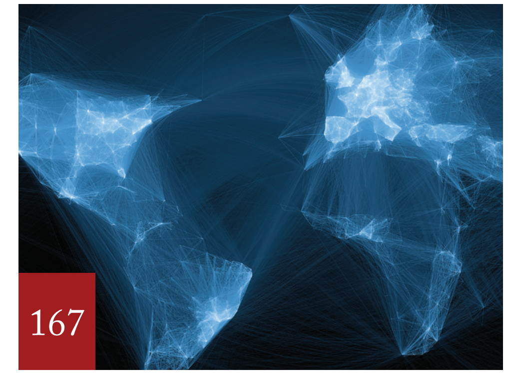
Part 3: Science Maps in Action



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Part 4: Outlook

Foreword

You could say it was Marco Polo who started it all when he returned from China and reported the distance he'd travelled east from Europe as a lot farther than it really was. So when the Italian hotshot mathematician Paolo Toscanelli used Polo's data to finalize a new map of the world and then Columbus got hold of a copy, the distance to China going the other way (west, straight across an empty ocean) looked quick and easy. Then, oops, America!

With the discovery of a new continent, there went the neighborhood. The definitive map of the world at the time was that crafted by Aristotle, who hadn't included America. What was the place doing there? And what about all the amazing stuff that began to pour in from the newfound world: new species, new minerals, new races, none of which were in Aristotle either.

In 1533, Dutch mathematician Gemma Frisius complicated matters with his idea for fixing a location by triangulation, thus making it easier for explorers to sail off into the blue; now at any point en route explorers could use the position of the last headland and the position of the next one to pinpoint where they were. Headland by headland, the more they advanced, turning the unknown into the known, the more unknown there was to explore. Discovery bred discovery, which left the other problem: What to do about their returning cargoes—that new stuff Aristotle hadn't mentioned—all of which seriously upset the comfortable medieval view of the world and everything in it.

Panic set in. If Aristotle could be that wrong, then which way was up? As contemporary worrier John Donne put it: "The new philosophy (aka the new discoveries) calls all in doubt." In the growing intellectual confusion, the search was on to generate data one could trust.

So thank you, René Descartes. In 1637, his methodical doubt and reductionism (double-check everything, down to the smallest detail) took the risk out of risk, and the West threw itself into intellectual and geographical exploration with all the abandon of an alcoholic in a brewery. The new mantra was "find useful knowledge." Armed with the sword of reductionism and protected by the shield of method, we boldly took scientific thinking where no minds had gone before. The aim: to learn more and more about less and less.

Faster than you could say "epistemology," the knowledge disciplines proliferated, generating niche studies (let's hear it for the PhD!) that in turn became disciplines generating their own niche studies. Silo-thinking was here to stay. And (to mix metaphors), inside every intellectual silo, blinkered specialists worked away, blissfully unaware of what might be going on in other silos.

Then the fun began. As products and ideas began to emerge from specialist silos, they would bump into each other with results that were more than the sum of the parts. One and one began to make three. Maybach brought together the perfume spray with gasoline and invented the carburetor. Electricity and magnetism made possible the telegraph. The discovery of the bacillus plus the invention of aniline dye added up to chemotherapy. As I have shown in my own work, innovation comes when ideas are linked in new ways. On the great web of knowledge, ultimately everything is linked to everything else. Innovation is the rule, not the exception.

As the specialists multiplied and communications technology made it easier for them to interact, the pace of innovation quickened, with unexpected results. Ripple effects could be unpredictable: The typewriter took women out of the kitchen into the office and boosted the divorce rate, refrigerators chilled food and punched a hole in the ozone layer, and X-rays bouncing off coal-crystal structures triggered the genetics industry. The sciences began to take on double, bump-together names: neurophysiology, molecular biology, astrophysics, and more. Gobbledygook was here to stay.

Then came the Internet, and suddenly it was Columbus and Frisius all over again. Today, we find ourselves in a vast, chaotic, interactive, constantly innovative, exponentially expanding world of data in which change is happening so fast that without the means to triangulate from one set of data to another, to see how the data relate, and what kind of innovation they may trigger we don't know where we are, where we're going, and, especially, what we're likely to find when we get there.

Accurate prediction is now more essential than ever, given above all the unimaginable potential social consequences of developments in different science and technology fields. Take, for example, nanotechnology: We have perhaps fifty years before the first nanofabricator, powered by photovoltaics, is able to manipulate material at the atomic level to create molecules and then turn those molecules into stuff and use that stuff to manufacture gold, food, bricks, water, and so on from primarily dirt, water, and air, making almost anything, almost free.

The first thing the first fabricator might do is make a copy of itself: one for everyone on the planet in a matter of months. Then live wherever your fancy takes you, entirely self-sufficient, with the means electronically to transmit yourself across the world as a three-dimensional hologram, a world not of 196 nations but of nine billion autonomous individuals with the freedom to do, and be, whatever they choose.

Chaos may follow. The free provision of every material need and behavior unfettered by community constraint may call into question every social institution from government to belief systems to the cultural values that unite us to the entire market economy.

Since leaving the caves, we have focused our full attention on dealing with scarcity. The finely honed skills we have developed in order to handle that millennial problem have left us totally unprepared for the radical abundance that lies down the road.

The journey from here to there is fraught with difficulties and perhaps even danger. We need to be able to identify when required that (as they would have said in medieval cartography) "Here there be dragons." We need maps to guide us, to show us where *not* to go, what innovations and new ideas *not* to espouse, to reveal the unknown unknowns so as to enable us to predict the outcome of our choices along the way.

This extraordinary *Atlas* is the first step on that road.

James Burke
Science historian, author, and television producer
London, United Kingdom

Preface

The *Atlas of Knowledge: Anyone Can Map* was written with the deep belief that just as "anyone can cook," it is also true that "anyone can map"—or at least learn to do either. The *Atlas* series is being written at a time when data literacy is becoming almost as important as language literacy. While the first of the series, *Atlas of Science: Visualizing What We Know*, provided a gentle introduction to the power of maps for the navigation, management, and utilization of knowledge spaces, the *Atlas of Knowledge* intends to empower anyone to map and make sense of science and technology (S&T) data to improve daily decision making.

Part 1 argues for a systems science approach in the study of S&T structure and dynamics. Drawing on research and teaching in data mining, information visualization, and science of science studies, it explains and exemplifies different levels and types of analysis and also reviews key facts at different levels of the S&T system.

Part 2 introduces a theoretical framework meant to guide readers through user and task analysis; data preparation, analysis, and visualization; visualization deployment; and the interpretation of S&T maps. It benefits from more than 10 years of tool development and feedback from many of the more than 150,000 tool users in academia, industry, and government.

Just like the *Atlas of Science*, this book accompanies the *Places & Spaces: Mapping Science* exhibit (**http://scimaps.org**). **Part 3** features maps from the fourth to the seventh iterations, designed for economic decision makers, science policy makers, and scholars as well as librarians and library users. The 40 large-scale, full-page maps are meant to exemplify data analysis workflows and visualization metaphors and to communicate key insights. The final 30 maps of this 10-year exhibit effort, comprising the eighth to the tenth iterations, will be included in the third volume of this series, the *Atlas of Forecasts: Predicting and Broadcasting Science, Technology, and Innovation*.

Part 4 examines S&T trends and discusses the possible impact of real-time data visualizations on practicing and steering S&T. It concludes with an outlook of expected developments that focus strongly on democratizing knowledge and participation as well as promoting the evolution of standards—in terminology, data sets, data mining and visualization algorithms, workflows, and interface design—toward higher replicability and utility.

To ease navigation and consumption, each major topic is presented solely on one double-page spread. References to other parts of the book interlink the different topics and sections, resulting in a whole that extends beyond the sum of its parts. The decision was made to compile the extensive number of references in the back matter of the *Atlas*, including more than 1,500 references, 350 image credits, 30 data credits, and 20 software credits on a page-by-page basis.

Although textbooks such as Nathan Yau's *Visualize This* or the IVMOOC book entitled *Visual Insights: A Practical Guide to Making Sense of Data* teach timely knowledge about tools and workflows, this *Atlas* series aims to present "timeless knowledge" that may still hold true many years from now—akin to Edward R. Tufte's notion of "forever knowledge" that involves information design principles that are indifferent to culture, gender, nationality, or history.

Analysis and visualization design require the many varied skills involved in data management, data analysis, design, communication, and technology. Depending on your background and expertise, different reading trajectories are proposed:

- If you are familiar with the science of science studies but not as well versed in science mapping, begin by perusing the maps in **Part 3**, then follow up by reading the **Part 2** text on how to design insightful visualizations.
- If you are a visualization expert interested in design principles and guides, go directly to **Part 2**.
- If you are a designer but not familiar with science visualizations, read **Part 1** and explore the maps in **Part 3** before consuming other parts.
- If you are a programmer interested in building tools for avid users, start by reading **Part 2**—which explains how to systematically render data into insights using algorithms and approaches from statistics, cartography, linguistics, network theory, and other areas of science. Then move on to **Parts 1** and **4** to learn about current and future user needs and applications.
- If you wish only to see the future of S&T mapping, go directly to **Part 4**.

Additional materials can be found at **http://scimaps.org/atlas2**, including high-resolution images that are available for closer examination; digital files of the more than 1,000 citations and source credits; access to data sets and tutorials on how to run specific workflows; and updates of essential materials in preparation for future editions.

I feel lucky to have had the luxury of being able to develop this *Atlas*—an attempt to organize and make accessible to many research on the analysis and visualization of S&T structure and dynamics. It is my hope that the knowledge and techniques presented in these books will not only live between the covers, online, or in the mind of each reader, but also will be applied to further our understanding and to improve both our personal and collective decision making.

Katy Börner
Cyberinfrastructure for Network Science Center
School of Informatics and Computing
Indiana University

August 11, 2014

Acknowledgments

It may seem unwise to devote a major part of one's research time to writing a series of books for readers who are unlikely to write papers or otherwise cite these books in academic circles. And yet it seems quite on target to enable those who finance science via tax dollars to benefit from the research results—forfeiting the maximization of citation counts via the production of research papers. Many others have taken this route, including the following luminaries who have inspired my own journey: Jacques-Yves Cousteau, the French explorer and researcher of the sea; David Attenborough, especially with his *Life on Earth* and *Living Planet* series; Paul Otlet, with his *Universal Atlas* or *Encyclopedia Universalis Mundaneum*; Stuart Brand, author of *The Whole World Catalog*; Richard Dawkins, famed for his "Growing Up in the Universe" lectures; Al Gore for his environmental efforts, as featured in the *An Inconvenient Truth* documentary; and Hans Rosling, whose Gapminder effort gave rise to the motto, "Let my dataset change your mindset."

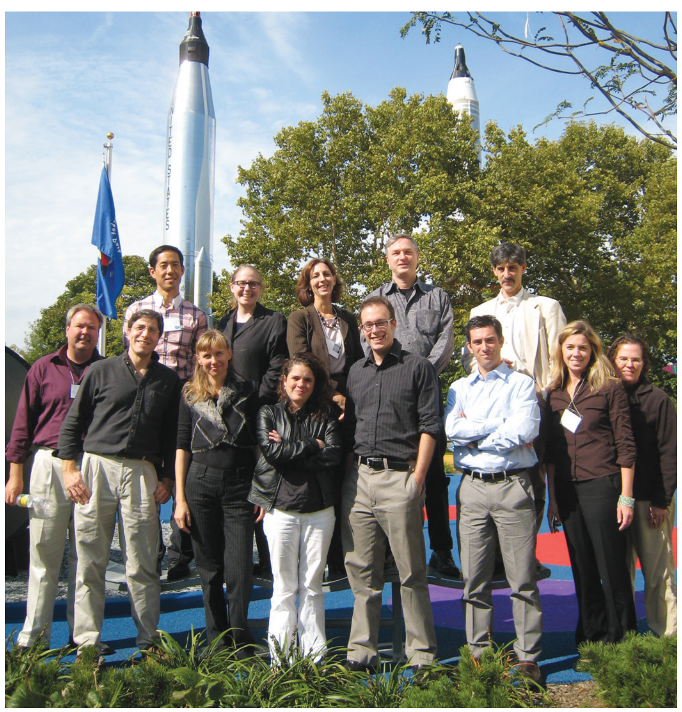
It is my hope that this *Atlas* series joins in giving both inspiration and encouragement to future science communicators.

I am deeply grateful to all those who helped to make possible this *Atlas* and the exhibit maps it features.

Part 2, Envisioning Science and Technology, benefited deeply from my teaching of relevant courses at Indiana University over the last 14 years, including teaching the Information Visualization MOOC (IVMOOC) to students from more than 100 countries in the spring of 2013.

The *Places & Spaces: Mapping Science* exhibit would not have been possible without the expertise and professional excellence of the more than 236 mapmakers and the 43 exhibit ambassadors around the globe. Exhibit advisers for the maps featured in this book include: Deborah MacPherson (Accuracy&Aesthetics), Kevin W. Boyack (SciTech Strategies, Inc.), Sara Irina Fabrikant (Geography Department, University of Zürich, Switzerland), Peter A. Hook (Law Librarian, Indiana University), André Skupin (Geography, San Diego State University), Bonnie DeVarco (BorderLink), and Dawn Wright (Geography and Oceanography, Oregon State University). External experts that reviewed iterations 4 through 7 included: John R. Hébert (Chief of the Geography and Map Division, Library of Congress), Thomas B. Hickey (OCLC), Michael Kurtz (Harvard-Smithsonian Center for Astrophysics), Denise A. Bedford (World Bank), William Ying (CIO ArtSTOR), Michael Krot (JSTOR), Carl Lagoze (Cornell University), Richard Furuta (Texas A&M University), Vincent Larivière (Université du Québec à Montréal, Canada), Adam Bly (CEO of SEED), Alex Wright (author of *Glut: Mastering Information Through The Ages*), and Mills Davis (Project10x.com).

Focused brainstorming workshops, organized with colleagues between 2008 and 2014, contributed greatly to the discussion of research and development work that is contained in these pages. A total of 25 such workshops were held on a range of topics, including "How to Measure, Map, and



October 1-2, 2009: NSF/JSMF Workshop on How to Measure, Map, and Dramatize Science, New York Hall of Science, NY

March 4-5, 2010: NSF/JSMF Workshop on Mapping of Science and Semantic Web, Indiana University, Bloomington, Indiana

October 9-10, 2010: Modeling Knowledge Dynamics, The Virtual Knowledge Studio, Amsterdam, The Netherlands

Dramatize Science," "Mapping the History and Philosophy of Science," "Modeling Knowledge Dynamics," "Artists Envision Science & Technology," and "Plug-and-Play Macroscopes" (see group photos).

A substantial part of the source review and initial writing was completed while I was a visiting professor at the Royal Netherlands Academy of Arts and Sciences (KNAW) in the spring of 2012. I would like to thank Paul Wouters of CWTS and Andrea Scharnhorst and Peter Doorn of DANS for their support.

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Copyediting of the *Atlas* was performed by Gordana Jelisijevic, Melinda Rankin, and Todd N. Theriault; *Atlas* layout and design by Tracey Theriault, with many of the images specifically created for this book by Perla Mateo-Lujan; reference checks and formatting by Todd N. Theriault; indexing by Amy Murphy; and copyright acquisition by Samantha Hale, Brianna Marshall, Joseph Shankweiler, David K. Kloster, and Michael P. Ginda.

Yong-Yeol Ahn, Kevin W. Boyack, Alberto Cairo, David Chavalarias, Joseph Cottam, Blaise Cronin, Vincent Delvaux, Scott Emmons, Yves Gingras, Daniel A. K. M. Halsey, Andrew J. Hanson, Peter A. Hook, Ketan K. Mane, Staša Milojević, Abel L. Packer, Roberto de Pinho, Bahador Saket, Ben Shneiderman, André Skupin, and Stephen M. Uzzo reviewed a penultimate draft of the book and their expert comments were instrumental in finalizing the *Atlas*. Other valued contributions are acknowledged in the **References & Credits (page 178)**.

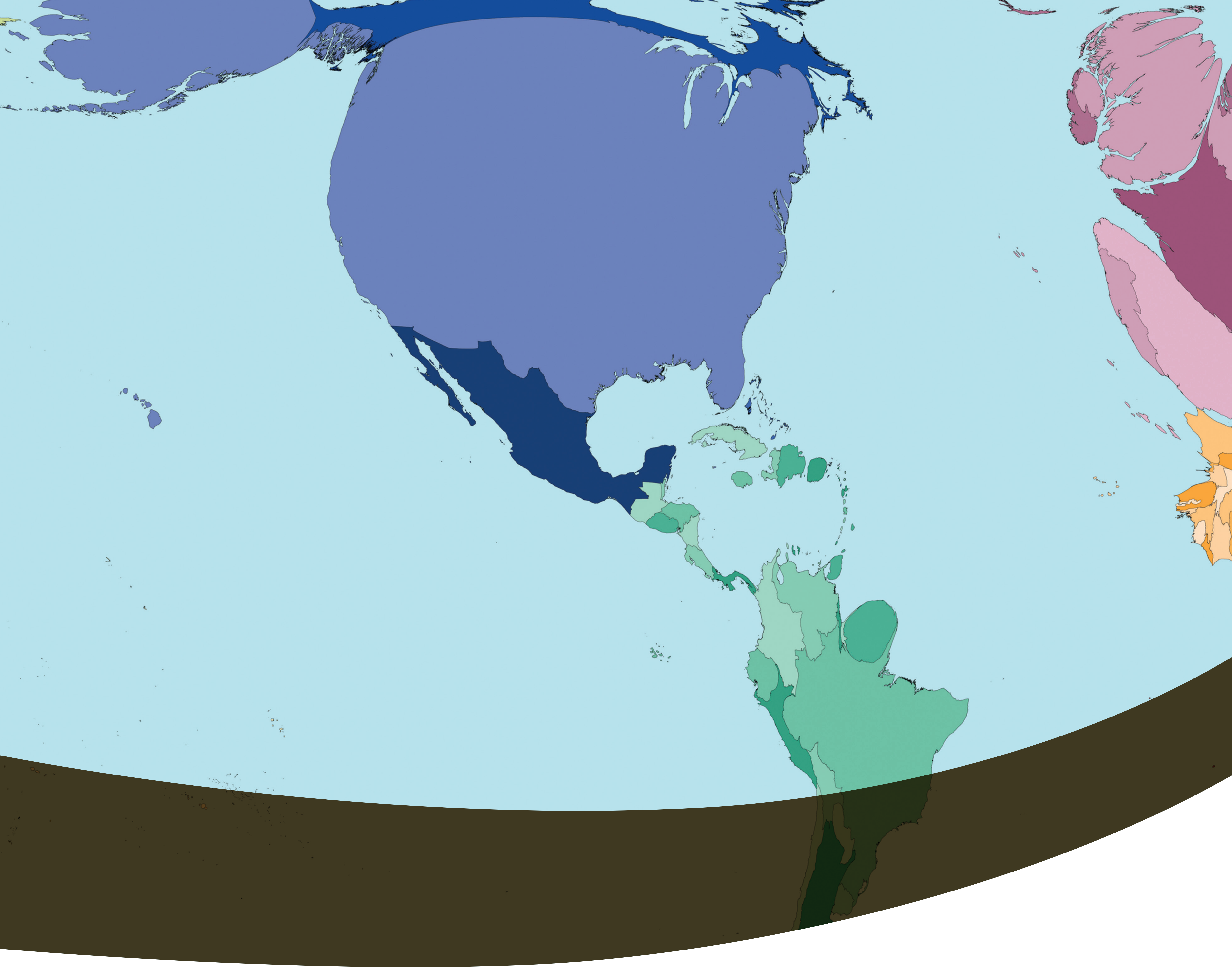
My sincere thanks go to Marguerite B. Avery, Katie Persons, and Katie Helke at MIT Press who ingeniously mastered the many complexities involved in publishing this *Atlas* series.

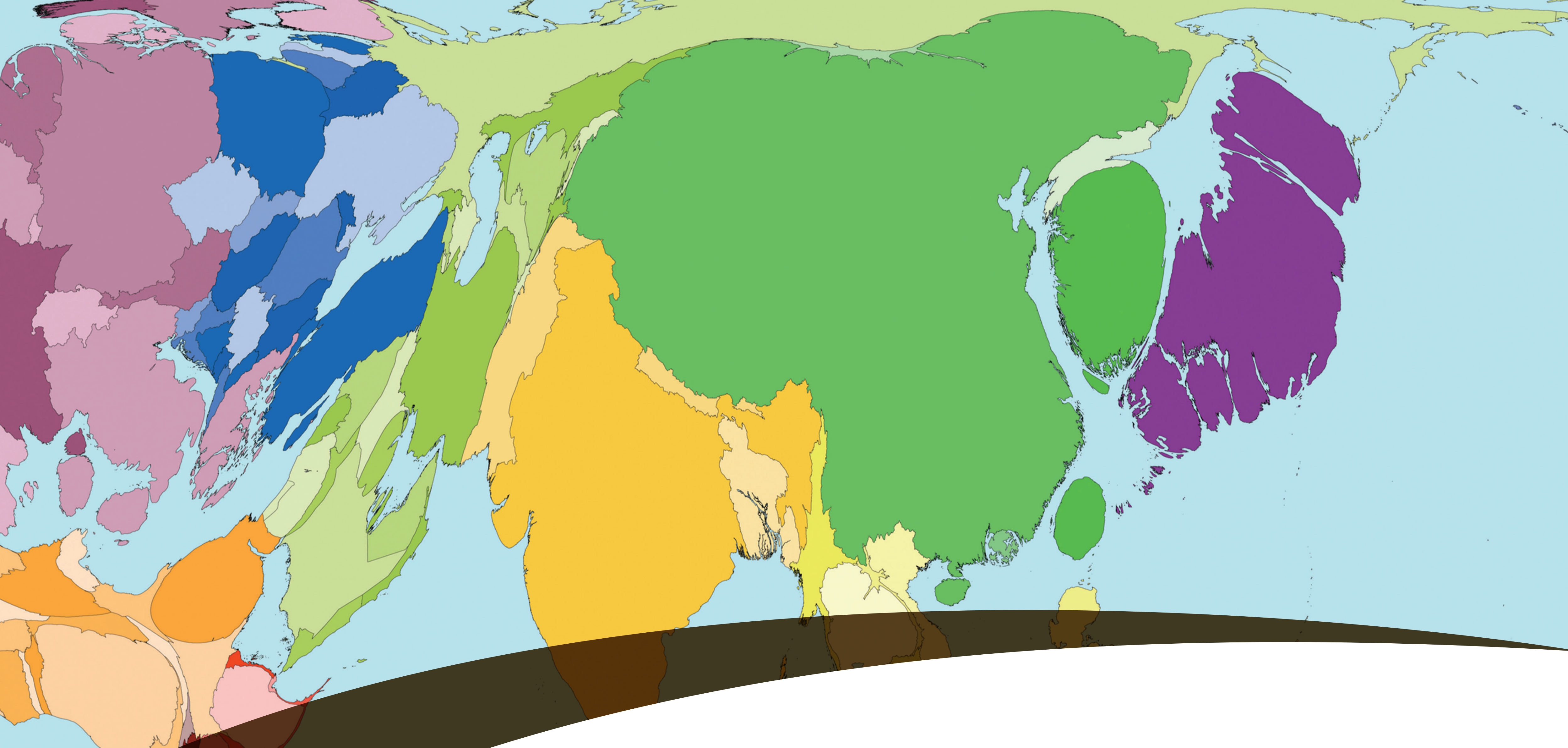
I am indebted to family and friends for providing much inspiration, energy, and loving support. This book benefited deeply from nurturing and thought-provoking family dinner discussions and empowering girls' nights out. My gratitude also rests with our cat, Jiji, who kept me company through the many long periods of writing.

August 11-12, 2011: JSMF Workshop on Standards for Science Metrics, Classifications, and Mapping, Indiana University, Bloomington, Indiana

March 25-26, 2013: Exploiting Big Data Semantics for Translational Medicine, Indiana University, Bloomington, Indiana

May 5, 2014: Researchers and Staff at the Cyberinfrastructure for Network Science Center, Indiana University, Bloomington, Indiana





Part 2: Envisioning Science and Technology

We thrive in information-thick worlds because of our marvelous and everyday capacity to select, edit, single out, structure, highlight, group, pair, merge, harmonize, synthesize, focus, organize, condense, reduce, boil down, choose, categorize, catalog, classify, list, abstract, scan, look into, idealize, isolate, discriminate, distinguish, screen, pigeonhole, pick over, sort, integrate, blend, inspect, filter, lump, skip, smooth, chunk, average, approximate, cluster, aggregate, outline, summarize, itemize, review, dip into, flip through, browse, glance into, leaf through, skim, refine, enumerate, glean, synopsize, winnow the wheat from the chaff and separate the sheep from the goats.

Edward R. Tufte

Motivation

Framework

Acquire

Analyze & Visualize

Deploy

Interpret

Foundations and Aspirations

Part 2 of this book introduces general data analysis and visualization techniques commonly used to study science and technology (S&T). Data analysis is an iterative process that cleans, filters, interlinks, mines, and augments data. Data visualization corresponds to an optimization of many different design decisions that relate not only to the layout and visual encoding of data but also to the interactivity and deployment of visualization. In this spread, foundations and aspirations for this *Atlas* are discussed, and the importance of empowering anyone to read and make visualizations is explained.

Maps, like speeches and paintings, are authored collections of information and also are subject to distortions arising from ignorance, greed, ideological blindness, or malice.
Mark Monmonier

Foundations

The structure and content of this part was inspired by scholarly works written over the last 250 years. Among them are William Playfair's *The Commercial and Political Atlas*; Jacques Bertin's *Semiology of Graphics*; John Tukey's practical epistemology; William Cleveland's combination of statistical and experimental evidence; Howard Wainer's work on history, statistics, and graphics; Edward Tufte's many examples of good design in *Beautiful Evidence*; Leland Wilkinson's codification of the structure of graphics in *The Grammar of Graphics*; and additional works from psychology, cartography, statistics, and other sciences that use data analysis and visualization, graphic design, and illustration to support decision making.

The process of creating insightful visualizations calls for the synergism of several disciplines: technology, to ensure that certain analyses can be run and designs produced; science, to provide correct and rigorous results; and art and design, to deliver aesthetically pleasing results that will attract and retain the attention of viewers so they may engage and gain valuable insights from those visualizations.

Setting Up Successful Projects

The design of insightful visualizations requires access to three essential ingredients: expertise, data, and resources. Expertise is traditionally provided by domain experts or clients that have specific insight needs (see **page 40**, **User Needs Acquisition**), are available to help with identifying and gaining access to relevant data sources (see **page 42**, **Data Acquisition**), and can interpret and evaluate results (see **page 72**, **Validation and Interpretation**). High quality and coverage of data is important. If faulty or incomplete data are used, visualizations, in turn, will also be faulty or incomplete. The problem of "garbage in, garbage out" could potentially escalate, as professionally rendered visualizations of incomplete or false data can easily lead to inappropriate decisions or the transmission of unverified information. Finally, resources include time and monetary investment or access to tools when performing the planned work. If any of these ingredients is not available, the visualization project is likely to fail.

Embracing the Power

Visualizations give form to either visible or invisible entities, making them tangible, understandable, and actionable. By thoughtfully representing high-quality, comprehensive data in an easy-to-read format, insightful renderings can change our view of the world. An example is Charles Darwin's 1837 *Tree of Life* drawing (see opposite page, top-left), which shows how species are purportedly related through evolutionary history and thereby reveals what may be life's common ancestry.

Visualizations have been instrumental in saving people's lives. One case in point is John Snow's *Cholera Map* of 1854 (see opposite page, lower-left), regarded as a key factor in the founding of the science of epidemiology. In the map, bars represent deaths caused by the 1854 London cholera epidemic. By showing them clustered around the water pump on Broad Street, the map enabled the recognition of cholera as a waterborne disease. Subsequent removal of the pump's handle led to the decreased incidence of cholera.

Another example is the "coxcomb" or polar-area diagram, first developed by Florence Nightingale. Her 1858 graphic on the *Causes of Mortality in the British Military during the Crimean War* (see opposite page, top-right) was critical in documenting that most soldiers had died of preventable or mitigable infectious diseases (blue) rather than of wounds sustained in battle (red) or other causes (black). The diagram presented vital statistical data in a way that persuaded Queen Victoria and others of the need to improve sanitary conditions in military hospitals, which substantially helped reduce death rates, profoundly influencing the subsequent course of the British military medical system.

David McCandless's *The Antibiotic Abacus: Adding up Drug Resistance* (opposite page, lower-right) uses data from the Centers for Disease Control and Prevention and the World Health Organization to communicate the increasing resistance of bacteria to antibiotics. Bacteria names are listed vertically on the left. Antibiotics and antibiotic families are plotted horizontally by date of introduction. Circles indicate the resistance of bacteria to different antibiotics (pink) and antibiotic families (purple): the larger the circle size, the higher the resistance. Note that many bacteria are "superbugs" that are resistant to multiple antibiotics. No major new antibiotics have been developed for the last 20 years—indicating a potentially fatal drug-development gap.

Visualizations have the power to help translate and cross-fertilize vital concepts across disciplinary boundaries—as did the discovery of the DNA structure by James D. Watson and Francis H.C. Crick in 1953 (see *Atlas of Science*, **page 121**). Visualizations may also serve to inspire and support future discoveries (see *The Visual Elements Periodic Table* in *Atlas of Science*, **page 115**).

Other visualizations raise our awareness of both human unity and fragility, such as the *Earthrise* picture, taken by astronaut William Anders during the *Apollo 8* mission in 1968.

In general, most people have a deep respect for facts and arguments expressed as numbers or visualizations. However, they often don't understand just how many different decisions need to be made in order to render data into insights. Information visualization designers play a key role in making that process more transparent. In addition to revealing data, analysis, and visualization details, they must provide pointers to supplemental information, as such details are vital for the proper interpretation of visualization results.

Doing It Yourself

Just as anybody can learn to cook, anybody can learn to analyze and visualize data. In a data-driven world, this is not only possible but also necessary for high productivity and intelligent decision making. This *Atlas* aims to teach general approaches and techniques that are independent of specific implementations and tools. Specifically, the subsequent double-page spread introduces a general workflow and a visualization framework that aim to guide the design of effective visualizations. As a new view of data will often also expose new data issues or inspire new questions, being able to rapidly generate and interpret results is an extremely powerful skill. As many data sets cannot be shared freely and the expertise of practitioners is invaluable for data selection and interpretation, it is desirable that as many individuals as possible acquire basic data visualization literacy. Those who master the basics can begin to find data visualization both fun and empowering while quickly advancing their skills.

Terminology

The following pages draw from many different areas of science, each with its own specific history, culture, and language. An algorithm cited in this section may have been originally developed in mathematics, physics, or biology; or a chart that appears here may be one used by engineers, economists, and statisticians alike, though each group will call it by a different name. This *Atlas* aims to introduce and exemplify an internally consistent approach and language for the design of insightful visualizations, which builds on and uses terminology from existing lines of research. Selecting key concepts and the best names for them posed a key challenge in the writing of this book. The ultimate choices were guided by the need for consistency within and universality across different conceptualizations and terminologies. References to original works as well as alternative names are given whenever new concepts and terminology are introduced (see **page 178**, **References & Credits**).

Disclaimer

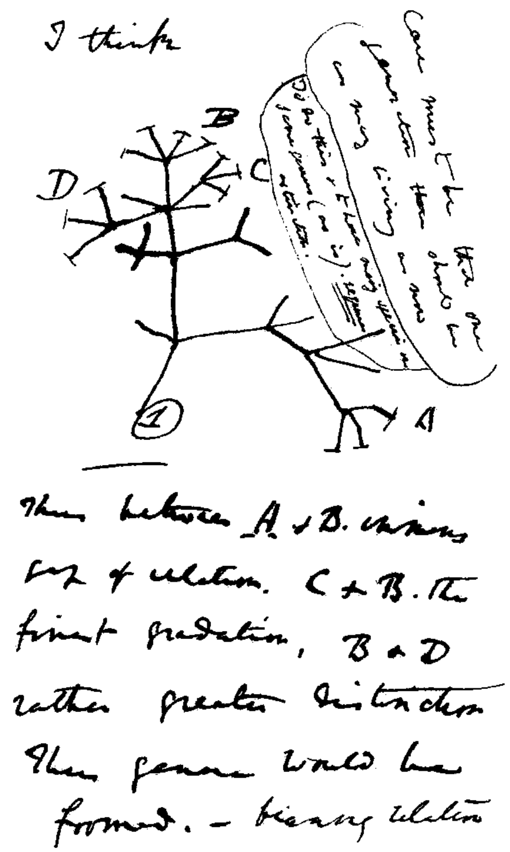
Part 2 reviews general "timeless" approaches and design principles. For "timely" step-by-step tutorials and practical design tips or reviews of specific tools, please see Katy Börner and David E. Polley's *Visual Insights*, Nathan Yau's *Visualize This*, Derek Hansen et al.'s *Analyzing Social Media Networks with NodeXL*, or Felice Frankel's *Visual Strategies*.

Visualizations are used to illustrate key concepts. See also **Part 3** (**page 75**) for detailed explanations of 40 large-scale maps; books by Edward R. Tufte for expert descriptions of hand-drawn visualizations; and recent books by David McCandless, Manuel Lima, and Sandra Rendgen for a rich assortment of highly innovative and colorful charts, graphs, and infographics.

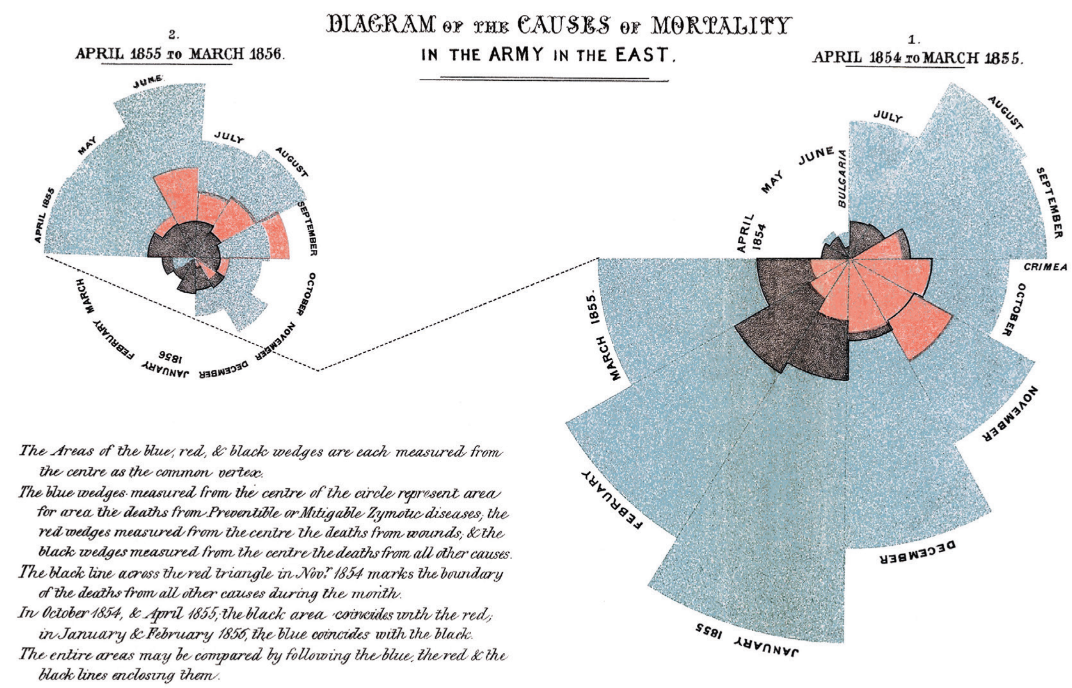
The *Atlas of Knowledge* focuses on the design and use of computer-generated (rather than hand-drawn) visualizations, which have the potential to empower anyone to make sense of big data. Toward that end, simple yet effective and validated visualizations are favored over complex visualizations designed primarily for experts.

Tree of Life

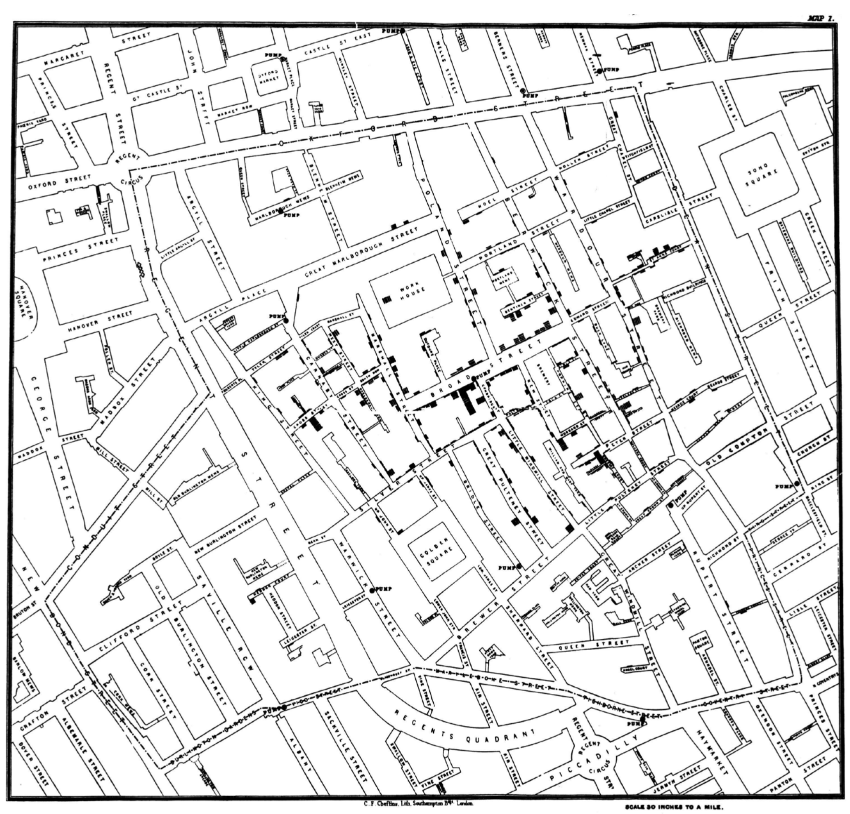
In this first sketch of an evolutionary tree (or branching diagram), Charles Darwin shows the tree's main trunk, labeled 1, as it divides and ends in leaf nodes, indicated by cross strokes. Major branches, labeled A through D, indicate living species. Twigs terminating abruptly and emerging at lower points along branches represent extinct species.



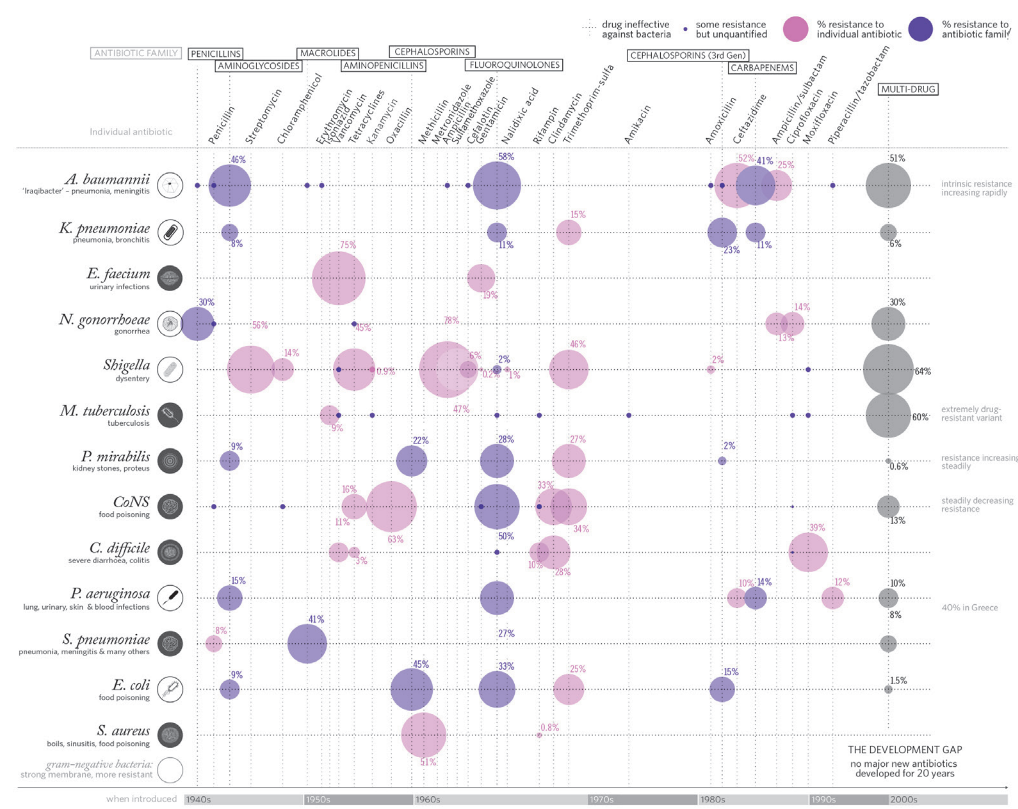
Causes of Mortality in the British Military during the Crimean War



Spot Map of the Golden Square Cholera Outbreak



The Antibiotic Abacus: Adding Up Drug Resistance



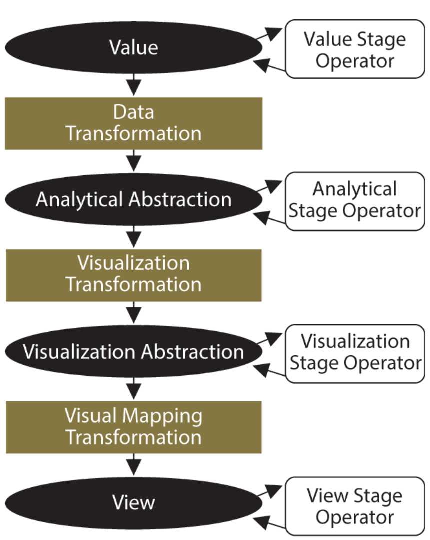
Needs-Driven Workflow Design

This double-page spread discusses the iterative design of data analysis and visualization workflows. The proposed workflow underscores the importance of having a deep understanding of user needs, expertise, and work environment. It groups and labels key processes in the data analysis and visualization workflow; emphasizes the sequential process of data reading and analysis as well as the parallel optimization of different visualization layers and deployment options; and stresses the importance of expert interpretation and validation. In addition, this spread introduces a theoretically grounded yet practically useful visualization framework that supports the design of effective visualizations.

Tell me, I forget. Show me, I remember. Involve me, I understand.
Benjamin Franklin

Visualization Taxonomies and Frameworks

Many visualization taxonomies and frameworks have been proposed (for key works, see **page 178**, **References & Credits**). Ed Chi's information visualization data-state reference model is exemplarily shown below. It identifies three transformations that convert the raw data values into a visualization view: The **Data Transformation** reads the raw data values and generates an analytical abstraction of the data, also called metadata. The **Visualization Transformation** takes that analytical data abstraction and reduces it to a visualization abstraction that can be visualized. The **Visual Mapping Transformation** reads that visualization abstraction and generates a static or interactive graphical view of the data.



Although Chi's model looks rather linear the overall process is typically very iterative and circular. Ideally, users are able to flexibly select the data that is used, the analytical abstraction that is run, and the visual mappings that are applied.

This *Atlas* series promotes (1) a needs-driven, highly iterative workflow design that combines sequential data analysis and parallel visualization design optimization; (2) argues for a clear separation of reference systems (also called base maps) and data overlays to ease the interpretation and generation of visualizations; and (3) introduces a visualization framework that distinguishes different types of insight needs (**page 26**), data scales (**page 28**), visualizations (**page 30**), graphic symbols (**page 32**), and graphic variables (**page 34**) in support of effective visualization design and transfer of visualization solutions across disciplinary boundaries. All three elements are discussed below.

Workflow Design

The *Atlas of Science* (**page 51**) discussed data acquisition, preprocessing, analysis, modeling, and visualization layout as the basic building blocks in data analysis workflows. The figure on the right shows the key elements and processes involved in the design of workflows. Starting with stakeholders in the top-left corner of the figure, workflow design involves four major tasks: **Acquire**, **Analyze & Visualize**, **Deploy**, and **Interpret**. Acquire comprises user needs analysis as well as data acquisition and preparation. **Analyze & Visualize** reads data and applies computational algorithms to convert data into visual insights. Deploy refers to the selection of output devices (e.g., paper printouts, online interactive interfaces) and the design of interactive user interfaces that might be interactive or feature combinations of multiple data views. The interpretation and validation of visualizations tend to inspire new hypotheses, insight needs, and future studies making the workflow design process highly iterative. The four tasks are used to organize Part 2—see section titles and page numbers given next to each task—effectively serving as a visual index to specific content. Subsequently, the importance of a detailed user and task analysis, access to high quality data, the sequential versus parallel nature of data acquisition, analysis, and visualization, and expert validation are discussed.

Users Are Central

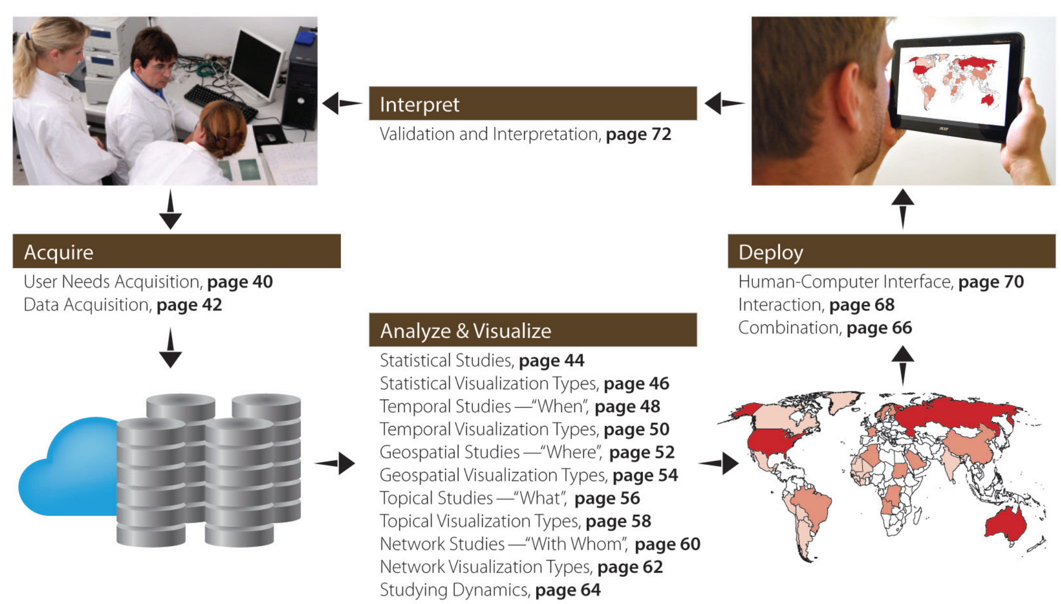
Detailed knowledge of user needs, expertise, and work environment is key for the design of successful visualizations. It is important to understand the type and level of analysis that users need (**see page 4, Systems Science Approach**); the insight needs they have (e.g., search versus comparison); the hardware-software combinations they use, as that affects deployment; and the level of data visualization literacy they currently have (e.g., what visualization types they can read and create). Involving users in data compilation, analysis, and visualization is the *only* way to ensure accuracy and relevance of results (see **page 40, User Needs Acquisition**).

Data Quality and Coverage

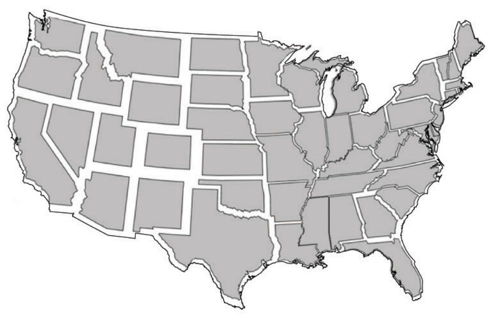
Data quality and coverage affect the type and level of analysis that can be performed. Answering "when" questions requires that data records have time stamps. Individual and global studies require data at the individual and global levels, respectively. Comparison tasks can only be supported if equivalent data on the entities to be compared is available. Data variables may be qualitative or quantitative (see **page 28**, **Data Scale Types**), influencing which visual encodings can be used (see **pages 30–39**). Data size will affect download speed and the display space that is required (see **pages 66–71** on deployment).

Sequential Data Acquisition and Analysis

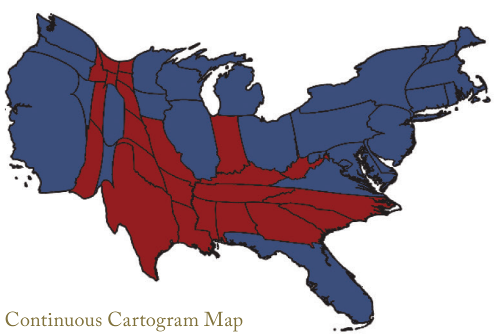
The acquisition, cleaning, and analysis of data are commonly done using a sequence of steps that build on each other. For example, a data preprocessing step might delete existing data variables (e.g., by eliminating duplicates), merge them (e.g., by linking publication and funding data based on unique scholar names), or split them (e.g., by distinguishing male from female authors). Alternatively, a processing step can add new data variables (such as latitude and longitude information for postal addresses) or introduce linkages between data records (e.g., coauthor information on publication records can be used to extract coauthor networks). That is, the result of each processing step is a data set that may have different numbers and types of records and data variables. Similarly, different types of analysis might be applied to extract existing or calculate new data variables. For instance, publication year and title information might be used to identify topic trends and coauthor networks might be analyzed to identify backbones or clusters. Sequential application of different analyses ensures that all computed values are ready for use when generating the visualization—there is no need to combine the results from different parallel analyses.



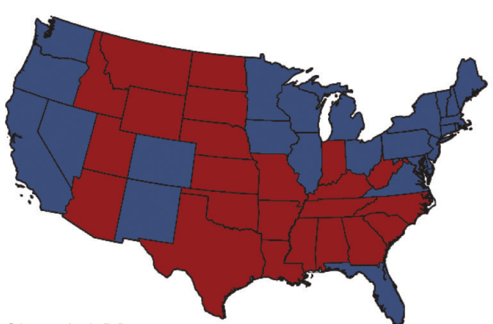
U.S. Map of Contiguous States



Disjoint Cartogram Map



Continuous Cartogram Map



Choropleth Map

Proportional Symbol Map with Line Overlays

Parallel Visualization Optimization

The *Atlas of Science* (**page 51**) introduced nine visualization layers, all of which can be grouped into visualization and deployment. Basically, visualization design comprises the selection of a base map reference system and the design of data overlays (see subsequent section). Deployment requires selecting an output medium and designing appropriate visual combinations and interactivity. Each of these subtasks or selections impacts all others. For example, selecting a small handheld device as preferred output medium considerably restricts the detail of the reference system (e.g., when using a world map, only general country outlines and few labels can be shown) and the number of data records that can be visualized; it also increases the need for effective interactivity design.

Expert Validation

It is absolutely mandatory to involve key stakeholders not only during user and task analysis, data acquisition, analysis, visualization, and deployment but also during the interpretation and validation of results. As data complexity and size increase and problems become more interdisciplinary in nature it might be necessary to involve experts with different knowledge and expertise. Different validation criteria and validation methods exist and can be applied to ensure visualizations are correct, readable, and actionable (see **page 72**, **Validation and Interpretation**).

Reference System versus Data Overlay

The *Atlas* series argues for a clear separation of reference systems (also called base maps) and data overlays. This separation makes it possible to cleanly separate reference systems (such as a Cartesian coordinate system, geospatial map, or anchoring background image of a brain) that are used in different scientific disciplines; it helps understand differences in how data is projected onto the different reference systems; and teach commonalities and differences in the design of data overlays for different visualization types.

In this *Atlas* series, a reference system defines the space onto which all data is projected. In order for users to read a visualization properly, the reference system must be well-defined and easy to understand. Data overlays are defined as a mapping of data record variables to proper **graphic symbol types** (e.g., circles or squares; see **page 32**) and **graphic variable types** (e.g., position, color or shape; see **page 34**). To give an example, a set of five maps is shown on the left. *The U.S. Map of Contiguous States* on the top is the reference system, or the base map. Below it, four data overlays are given. The *Disjoint Cartogram Map* plots data onto the size of each state by rescaling each state around its centroid, which preserves local shape but not topography. *The Continuous Cartogram Map* and the *Choropleth Map* both display 2012 U.S. presidential election results. States in red represent a majority vote for the Republican candidate, Mitt Romney; those in blue reflect a majority vote for the Democratic candidate, Barack Obama. The continuous cartogram sizes states according to their population size: the red areas are considerably reduced while blue areas are expanded providing a different view of the election results. The last map, entitled *Proportional Symbol Map with Line Overlays* shows a combination of data overlays: major U.S. airports are denoted by circles, which are size-coded by traffic data; atop are flights out of Chicago O'Hare International Airport, each represented by a line.

Reference system and data overlay together determine the resulting visualization type. For example, data variables (e.g., population counts, election results, or flight connections between geolocations) might be visualized by (1) distorting the size and/or shape of the base map, to produce what is called a cartogram; (2) visually encoding base map areas (e.g., color-coding them) in what is called a choropleth map; (3) modifying the Z dimension in a stepped relief map (see **page 53**, *In the Shadow of Foreclosures*); (4) visually encoding nodes in a proportional symbol map; or (5) visually encoding links in a linkage map.

Visualization Framework

The problem-solving space that needs to be traversed to arrive at a successful visualization solution is high-dimensional and inherently complex. Many different proposals exist on how to structure this space to make it easier to navigate and manage. The visualization framework proposed in this Atlas draws on work developed in different disciplines of science. Specifically, it distinguishes insight need types (**page 26**): sorting, trends, geospatial locations, relationships, etc.; data scale types (**page 28**): nominal, ordinal, interval, and ratio data; types of analysis (**page 4, Systems Science Approach**): temporal (when), geospatial (where), topical (what), and trees and networks (with whom); levels of analysis (**page 4, Systems Science Approach**): micro, meso, and macro; visualization types (**page 30**): table, chart, graph, map, and network layout; graphic symbol types (**page 32**): geometric symbols, linguistic symbols, and pictorial symbols; graphic variable types (**page 34**): position, form, color, texture, etc.; and, last but not least, interaction types (**page 26**): zoom, search, filter, etc., see below listing of all types discussed in Part 2. The framework creates a "periodic table" of reference systems and data overlays, which can help to identify promising visualization combinations. It is then applied to discuss data acquisition (**pages 40–43**); analysis and visualization of different types of data using approaches ranging from statistics to network science (**pages 44–65**); deployment (**pages 66–71**); and interpretation and validation (**pages 72–73**).

Visualization Framework

Insight Need Types page 26	Data Scale Types page 28	Visualization Types page 30	Graphic Symbol Types page 32	Graphic Variable Types page 34	Interaction Types page 26
• categorize/cluster • order/rank/sort • distributions (also outliers, gaps) • comparisons • trends (process and time) • geospatial • compositions (also of text) • correlations/relationships	• nominal • ordinal • interval • ratio	• table • chart • graph • map • network layout	• geometric symbols point line area surface volume • linguistic symbols text numerals punctuation marks • pictorial symbols images icons statistical glyphs	• spatial position • retinal form color optics motion	• overview • zoom • search and locate • filter • details-on-demand • history • extract • link and brush • projection • distortion

Insight Need Types

Visualizations commonly support either communication or exploration. While the former visualizations are mostly polished and static, the latter are less polished yet interactive. Jacques Bertin argues that a graphic representation might fulfill three functions: recording of information, communicating information, and processing information. Robert L. Harris distinguishes graphs for analyzing and planning; monitoring and controlling; and communicating, informing, and instructing. This spread reviews basic task and interactivity types and proposes a unifying naming scheme with descriptions and examples.

For a person to become deeply involved in any activity it is essential that he knows precisely what tasks he must accomplish, moment by moment.
Mihaly Csikszentmihalyi

Framework

This section defines a set of basic task types and a set of interactivity types. The former help guide the selection of visualization types (**page 30**), graphic symbol types (**page 32**), and graphic variable types (**page 34**). The latter guide interaction (**page 68**) and human–computer interface design (**page 70**).

For both types, i.e., basic task types (see table below) and interactivity types (see table in top-right), key approaches are discussed and a unified naming schema is proposed. Note that alignment in approaches is extremely difficult to attain and most likely imperfect, as most authors and tool developers do not provide a definition of the terms they use. Plus, the approaches were developed for very different purposes—from organizing materials in a book to helping users select appropriate visualizations.

Basic Task Types

A table of basic task types, identified by different scholars and tool developers, is shown below. Columns are sorted by time, left to right.

Jacques Bertin aims to identify tasks that can be mapped to graphic variable types, which he calls visual variable types (see **page 34**). Bertin identifies selection (whereby marks are perceived as different, forming families), order (whereby marks are perceived as ordered), association (or similarity, whereby marks are perceived as similar), and quantity (whereby marks are perceived as proportional to each other). While the first three task types are used to encode qualitative data, the last is relevant for quantitative data. Stephen Wehrend and Clayton Lewis distinguish ten general retrieval tasks, such as locate (search for a known object), identify (object is not necessarily known), distinguish, categorize, cluster, see distribution, rank, compare (within entities and between relations), associate, and correlate. Six of these ten tasks are relevant for data analysis and visualization and are given in the table. Stephen Few's Graph Selection Matrix was designed to help identify what graph type (point, line, bar, or box plot) is best for what task. It distinguishes different featured relationships, such as ranking, distribution, nominal comparison and deviation, time series, geospatial, part-to-whole, and correlation. Nathan Yau distinguishes five visualization types: patterns over time, proportions, relationships, differences, and spatial relations. Sandra Rendgen and Julius Wiedemann organize more than 400 visual graphics by location, time, category, and hierarchy. Felice Frankel distinguishes three major purposes of a visual graphic—form and structure, process and time, compare and contrast—and uses them to teach important visual design strategies. Diverse tools and online services exist that aim to empower users to generate different types of visualizations: IBM's Many Eyes site supports visualizations that reveal relationships among data points, compare data values, track rises and falls over time, see parts of a whole, analyze text, and generate maps. Chart Chooser helps users select the right graph by grouping the visuals via comparison, distribution, composition, trend, relationship, and table. The last column of the table shows the set of types that are used in this *Atlas* (see descriptions and examples on opposite page).

Basic Task Types

Bertin, 1967	Wehrend & Lewis, 1996	Few, 2004	Yau, 2011	Rendgen & Wiedemann, 2012	Frankel, 2012	Tool: Many Eyes	Tool: Chart Chooser	Börner, 2014
selection	categorize			category				categorize/ cluster
order	rank	ranking					table	order/rank/ sort
	distribution	distribution					distribution	distributions (also outliers, gaps)
	compare	nominal comparison & deviation	differences		compare and contrast	compare data values	comparison	comparisons
		time series	patterns over time	time	process and time	track rises and falls over time	trend	trends (process and time)
		geospatial	spatial relations	location		generate maps		geospatial
quantity		part-to-whole	proportions		form and structure	see parts of whole, analyze text	composition	compositions (also of text)
association	correlate	correlation	relationships	hierarchy		relations between data points	relationship	correlations/ relationships

Interaction Types

Other scholars have identified interactivity types (see top-right table). For interactive data exploration, Ben Shneiderman cites overview (seeing the entire collection), zoom (zooming in on items of interest), filter (selecting interesting items), details-on-demand (selecting one or a group of items and getting details when needed), relate (viewing relationships among items; see basic task types in lower-left table), history (keeping a log of actions to support undo, replay, and progressive refinement), and extract (access subcollections and query parameters). Daniel Keim distinguishes major interaction techniques such as zoom, filter, and link and brush. The latter technique interlinks multiple visualizations of the same data—users can select data records via brushing in one view to highlight these records in all other views. Keim also lists projection and distortion techniques (e.g., hyperbolic and spherical spaces) as a means to provide focus and context. For additional reference, please see the discussion in **Interaction (page 68)**.

Interactivity Types

Shneiderman, 1996	Keim, 2001	Börner, 2014
overview		overview
zoom	zoom	zoom
		search and locate
filter	filter	filter
details-on-demand		details-on-demand
history		history
extract		extract
	link and brush	link and brush
	projection	projection
	distortion	distortion

Naming Conventions

In this and all subsequent spreads, the following terminology will be used. Physical or virtual items will be called objects. Objects can be represented by a data record (also called a data point). A data record is an N-tuple (or vector) of data variables. Data variables (also called data properties, feature attributes, or parameters) may be qualitative or quantitative. The value of data variables may change over time. A data set (also called a data series) comprises one or more data records.

The example below shows the records of two scholars, each represented by a 6-tuple. Three data variables are qualitative (**ID**, **Name**, **Country**); all others are quantitative. The **Age** value will increase by one each year.

ID	Name	Age	Country	#Papers	#Citations
1	J. Smith	53	U.S.	101	367
2	J. Chen	45	China	59	150

In order to represent relationships between objects (e.g., scholars), a so-called linkage table can be used. Each link is represented by an M-tuple of data variables. The first two columns commonly represent the IDs of the objects that are linked. Other columns may represent additional attribute values. The table below exemplarily represents the coauthor links between the two scholars above, with **Weight** indicating the number of papers they authored together and **Begin** and **End** denoting the first and last years when a given joint paper was published.

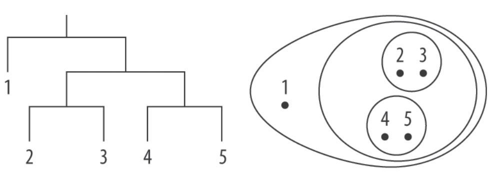
ID1	ID2	Type	Weight	Begin	End
1	2	Coauthor	3	1999	2005

Categorizing and Clustering

Categorization is the assignment of data records to a category (also called cluster, class, or group) of similar data records. Categories might be manually defined or computed using clustering techniques.

Clustering is the task of assigning a set of data records to groups (also called classes or categories) so that objects in the same cluster are more similar to each other than to those in other clusters. Cluster-defining properties may exist in the original raw data (e.g., publication year) or can be computed (e.g., the similarity of papers based on similar word usage. The result of clustering may be a hierarchy (below) or partition with disjoint or overlapping clusters.

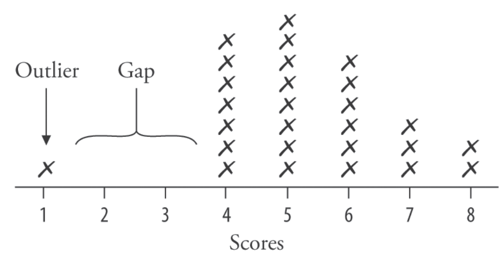
In addition, users may be able to manually explore clusters (see **page 68**, **Interaction**) and group data records. Clustering is frequently applied to make data patterns easier to see and to reduce visual complexity. For further reference, see **Clustering** (**pages 52** and **60**).



Distribution (also Outliers and Gaps)

Distributions capture how objects are dispersed in space. A statistical distribution is an arrangement of the values of a variable that shows their observed or theoretical frequency of occurrence. It supports the detection of outliers and gaps that are important for understanding data quality (uncertainty and missing or erroneous data) and data coverage (pedigree and scale).

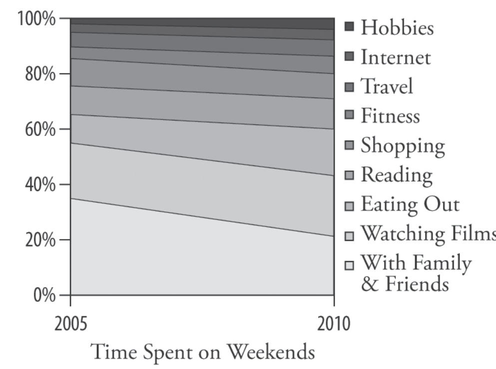
The example below shows the distribution of **Scores** for an imaginary exam. Each ✗ represents the score of one student, with most students achieving a score of 4 to 6. Five students scored higher, at 7 or 8. The single student who scored 1 is considered an **Outlier**; a **Gap** is shown between that student and the others. For further reference, see **Statistical Studies** (**page 44**).



Trends

A pattern of gradual change in the average or general tendency of data variables in a series of data records is called a trend. Trends can vary in length (from short-term, to intermediate, to long-term) and strength (in terms of the amount of change and the number of data variables and data records involved); see examples in **Temporal Studies—"When"** (**page 48**). Trends are commonly represented using a graph or map.

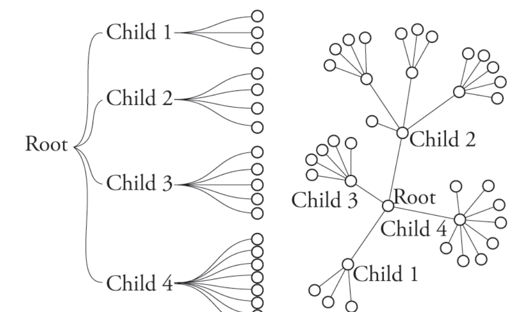
The comparison below of how people spent their weekend time in 2010 versus in 2005 shows a significant decreasing trend for spending time overall **With Family and Friends** and a milder increasing trend for specific activities such as **Eating Out**.



Composition (of Objects and of Text)

Composition refers to the way distinct parts or objects are arranged to form a whole. Part-to-whole relationships are important, as is the individual form and structure of the parts and the whole. Composition also refers to the process of putting words and sentences together to create text; see **Topical Studies—"What"** (**page 56**).

The two visualizations below show the number of directories and subdirectories in a file hierarchy as a tree view (left) and a force-directed layout (right); see **Network Studies—"With Whom"** (**page 60**).



Ordering, Ranking, and Sorting

Ordering (also called sorting) refers to the arrangement of objects in relation to one another according to a particular sequence, pattern, or method. The position in a sorted arrangement of objects is called a ranking.

Shown below-left is an alphabetically sorted list of subsection titles, with the title in the fifth rank highlighted. Given on the right is a numerically sorted list of numbers. Items may also be sorted by size, speed, or other data properties.

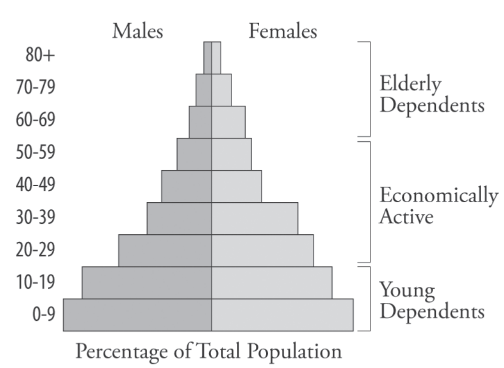
Subsection Titles
Categorizing and Clustering
Comparison
Composition (of Objects and of Text)
Correlations and Relationships
Distribution (also Outliers and Gaps)
Geospatial Location
Ordering, Ranking, and Sorting
Trends

Numbers
3
5
19
220
23
29
101
1,000

Comparison

A comparison refers to the process of examining two or more objects to establish similarities and dissimilarities. Single data values, objects with many data values, object groups, or object interlinkages can be compared. Visual comparisons become easier if visualizations are shown side by side.

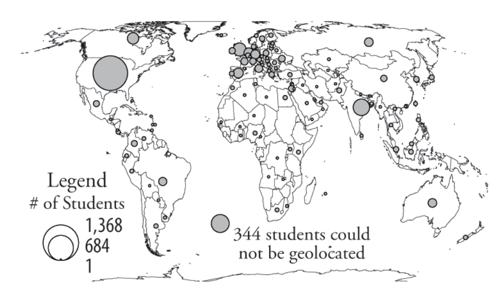
An example is the population pyramid below, which shows the number of male (left) and female (right) citizens per age group. Numbers decrease as age increases, with women shown to live slightly longer than men.



Geospatial Location

Geospatial location refers to a particular place or position. Two geometric objects can have diverse spatial relationships, defined by such "predicate" terms as equal, disjoint, intersects, touch, overlap, cross, within, or contain. A map is commonly used to show the locations, forms, sizes, and spatial relationships of objects; see description in **Geospatial Studies—"Where"** (**page 52**).

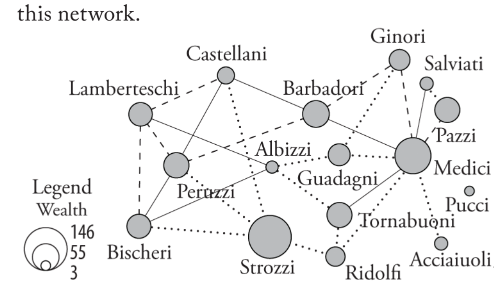
Shown here is a map of the world with a proportional symbol overlay that reveals the origin and number of students who registered for the spring 2014 Information Visualization MOOC course at Indiana University by the end of May 2014. Although 1,368 of the more than 3,600 students were based in the United States, students came from more than 200 countries.



Correlations and Relationships

Correlations express the relationship between two or more objects or attribute values. Relationships can have different cardinality: One-to-one relationships (e.g., position rank vs. income) are commonly represented by scatter plots and other graphs (see **page 44** and **47**, **Correlations**). One-to-many or many-to-many relationships are typically communicated using network visualization types; see **page 60**. Networks might have one or more node types and one or more link types. Links might be undirected or directed, unweighted or weighted.

The network below shows 16 nodes representing Italian families, size coded by wealth, and interlinked by marriage (dotted) and business (dashed) relationships, or both (solid). See **page 62**, **Radial Tree** for an alternative layout and a discussion of this network.



Data Scale Types

Data can be qualitative or quantitative. Qualitative data take on only specific values with no values in between and are frequently determined by counting. Examples are names or job types. Quantitative data may take on any value within a finite or infinite interval and are commonly acquired via measurement. Examples are time or counts. In 1946, Harvard psychologist Stanley S. Stevens coined the terms "nominal," "ordinal," "interval," and "ratio" to describe a hierarchy of data scales. This spread reviews existing works for the classification of data scale types. Specifically, it describes and exemplifies Stevens's data scale types and discusses their utility and limitations.

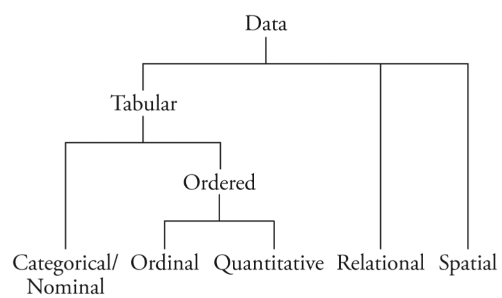
Not everything that counts can be counted, and not everything that can be counted counts.
Albert Einstein

Framework

Many different definitions exist for data scale types. Key works are shown in the table below. In his 1946 paper "On the Theory of Scales of Measurement," Stanley S. Stevens distinguished nominal, ordinal, interval, and ratio data based on the type of logical mathematical operations that are permissible (see section **Mathematical Operations** and table top-right). That is, the type of scale used depends on the mathematical transformations that can be performed on the data.

In 1967, Jacques Bertin argued for three data scale types: qualitative, ordered, and quantitative—which roughly corresponds to nominal, ordinal, and quantitative (also called numerical). His terminology was adopted by geographer Alan MacEachren, and many other cartographers and information visualization researchers. Robert Harris's *Classification of Scales* distinguishes the same three types as Bertin but calls them category, sequence, and quantitative.

Visualization researcher Tamara Munzner distinguishes tabular, relational, and spatial data; then further divides tabular into categorical/nominal and ordered; and finally subdivides ordered into ordinal and quantitative (see *Data Hierarchy* above). Using this classification, tabular visualizations such as GRIDL (**page 69**) or Gapminder (**pages 65** and **71**) may have categorical/nominal or ordered axes. Relational data refer to linkages between data records, which may be categorical (e.g., "marriage," "business"; see **page 27, Correlations and Relationships**) or weighted (quantitative), and are commonly represented using network visualizations (see **page 62, Network Visualization Types**). Spatial data (e.g., latitude and longitude information) is needed to geolocate records (see **page 54, Geospatial Visualization Types**).



Data Hierarchy

Stevens's approach has been adopted here and is shown in the right-most column of the below table. The title was revised to *Data Scale Types* to match other terminology in the visualization framework. Descriptions and examples of the different data scale types can be found on the opposite page.

Data Scale Types

Stevens, 1946 *Scales of Measurement*	Bertin, 1967 *Level of Organization of the Components*	Harris, 1996 *Classification of Scales*	Munzner, 2011 *Visualization Principles*	Börner, 2014 *Data Scale Types*	
nominal	quantitative	category	categorical/nominal	nominal	More Qualitative
ordinal	ordered	sequence	ordinal	ordinal	
interval	quantitative	quantitative	quantitative	interval	More Quantitative
ratio	quantitative	quantitative	quantitative	ratio	

Conversions

Simple transformations can make real-world data more amenable to analyses and visualizations that truly satisfy users' needs. For example, quantitative data scale types can be converted into qualitative data scale types, or thresholds can be applied to convert interval data into ordinal data. Rankings (ordinal) are commonly converted to yes/no categorical decisions (e.g., with hiring or funding decisions). Typically, this is done in such a manner that equal groups result, and different approaches may be appropriate for different types of distributions (see **page 44, Statistical Studies**).

The reverse is possible as well: more qualitative data scale types can be converted into more quantitative data scale types. For example, Robert P. Abelson and John W. Tukey mapped ordinal scales onto interval scales and estimated the amount of error that resulted. Tukey also discussed situations in which interval scales (e.g., measurements from a miscalibrated scale) should be converted to a ratio scale that behaves more simply. Roger N. Shepard, Joseph B. Kruskal, and others developed multidimensional scaling methods to convert ordinal into ratio scales. See **page 178, References & Credits,** for details.

Mathematical Operations

Stevens distinguished types of scale based on the type of logical mathematical operations that are permissible. Major operations for all four types are given in the top-right table. Check marks indicate permitted operations, whereas cross-outs indicate that particular operations cannot be performed with the given data type. All types support determining equality and inequality (such as by identifying and categorizing the members of a numerical series). All but nominal types can be ordered (e.g., alphabetically or numerically). Only interval and ratio types support determining if differences are equal (e.g., $2 - 0 = 4 - 2$). Ratio types also support operations that determine if aspects of objects (or numbers) are equal (e.g., $4/2 = 8/4$). The bottom row shows the operations used to measure central tendency for the different data types (see also **page 44, Statistical Studies**).

Limitations

The four scale types do not account for all the data that one may encounter or measure. For example, percentages (which are bounded at both ends and cannot tolerate even arbitrary scale shifts) cannot be classified in this system. In his seminal paper, Stevens argued for using the four data scale types for classifying and selecting permissible statistical procedures. A number of textbooks and analysis tools implemented his recommendation. However, given the fact that the four scale types are not able to capture all possible data and that scale types can be converted into other types, these automatic permissibility rules restrict the possible set of valuable analyses and could even lead to the selection of inaccurate analyses.

Data Scale Types		Nominal	Ordinal	Interval	Ratio
Logical Mathematical Operations	x ÷	×	×	×	√
	+ -	×	×	√	√
	< >	×	√	√	√
	= ≠	√	√	√	√
Measure of Central Tendency		mode	median	arithmetic mean	geometric mean

Applications

Data should never prescribe analyses or visualizations. Instead, user needs (translated into the questions asked of the data) should influence what data is collected and how it is used. For example, if a ranking of scholars is desired then nominal data variables are inappropriate but ordinal, interval, or ratio data variables are necessary (see example in section **Nominal Scale** on opposite page). If calculating the arithmetic mean of a variable is important then interval or ratio scale data has to be acquired.

Documentation

Psychologists emphasize the importance of documenting exactly what data scale has been used to acquire any given data, why that scale was developed (e.g., for intelligence tests), who should complete the scale, how the scale should be used and scored (including sample items and values), and the scale's characteristics. Without this information, data collected for specific purposes runs the risk of being inappropriately used in psychology and other fields of science.

Nominal Scale

A nominal scale (also called a categorical or category scale) is qualitative. Categories are assumed to be nonoverlapping in that each data variable is assigned to one category and no two variables are assigned to the same category.

Examples include dichotomous and nondichotomous data. A dichotomous (or dichotomized) example is an attribute that can be either “true” or “false.” Nondichotomous examples (comprising multiple categories) are words or numbers constituting the names and descriptions of people, places, things, or events. Each word or number defines a distinct category that contains one or more entities. It is possible to have multiple assignments within a nominal category (e.g., a person can be bi-racial or have multiple nationalities or jobs).

Nominal data can be counted (e.g., the number of male/female scholars in an institution or the number of scholars per country). The results may then be displayed in frequency tables and graphs. Shown below is a fictive set of faculty members who work on an interdisciplinary research topic at a U.S. university and the counts of their departments, courses, books, and funding awards.

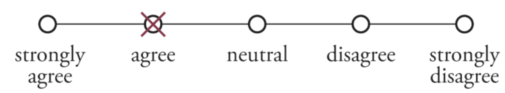
Entity Type	Count
Books	205
Courses	27
Departments	53
Faculty	55
Funding Awards	501

Mathematical qualitative operations such as equal and not equal can be performed (see the table on the opposite page, top-right). Although words and numbers that label or describe categories can be sorted alphabetically, they cannot be ranked or mathematically manipulated. No quantitative distinction can be drawn among them, as there is no intrinsic ranking or order. The mode, or the most common item, is allowed as the measure of central tendency for the nominal type. The median, or the middle-ranked item, makes no sense for the nominal type of data, because ranking is not allowed. Similarly, taking the mean on a nominal variable has no meaning.

Ordinal Scale

An ordinal scale (also called a sequence or ordered scale) is qualitative. It sorts or rank-orders values representing categories that are based on some intrinsic ranking but not at measurable intervals. That is, there is no information as to how close or distant values are from one another.

Examples include dichotomous and nondichotomous data. Dichotomous examples include “sick” versus “healthy” or “guilty” versus “innocent.” Nondichotomous examples include days of the week or months in a year; job ranks within a workplace; degrees of satisfaction and preference rating scores (as with a Likert scale, offering **strongly agree**, **agree**, **neutral**, **disagree**, and **strongly disagree** choices that users can check; see below); or rankings such as low, medium, and high.



For ordinal string variables, alphabetical sorting might be applied (e.g., when listing index terms). However, that understanding cannot be applied when data follow a nonalphabetical order, as do the days of the week (see below; note that in the United States the week starts on a Sunday).

Days of the Week	Alphabetical Sorting
Sunday	Friday
Monday	Monday
Tuesday	Saturday
Wednesday	Sunday
Thursday	Thursday
Friday	Tuesday
Saturday	Wednesday

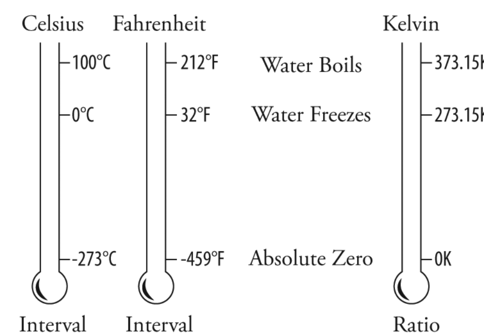
Mathematical qualitative operations, such as determining when figures are equal or not equal, can be performed; the mode and median (or middle-ranked item) but not the mean (or average) can be calculated (see **page 44, Statistical Studies**).

Note that most psychological measurements, such as of opinions or IQ scores, are ordinal. That is, the mean and standard deviations have no validity; only comparisons are valid. There exists no absolute zero, and a ten-point difference may carry different meanings at different points of the scale.

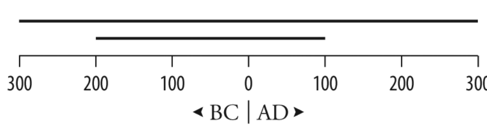
Interval Scale

An interval scale (also called a value or discrete scale) is a quantitative numerical scale of measurement, whereby the distance between any two adjacent values (or intervals) is equal, but the zero point is arbitrary. Interval-type variables are also called scaled variables or affine lines (in mathematics).

Examples are the Celsius and Fahrenheit temperature scales, which have an arbitrarily defined zero point; see the below comparison of both scales with the Kelvin ratio scale. Similarly, an interval scale is used to measure the distance between calendar dates within an arbitrary epoch (such as the AD year numbering system).



Scores on an interval scale can be added and subtracted; for example, the time interval between the first days of the years 1981 and 1982 is the same as that between 1983 and 1984—namely, 365 days. Interval scale values cannot be meaningfully multiplied or divided; for example, 20°C cannot be said to be “twice as hot” as 10°C. However, ratios of value differences can be expressed; for example, one difference can be twice another (see the bars for 600- and 300-year time durations in the figure below).

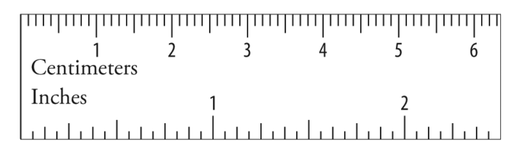


The mode, median, and arithmetic mean can be calculated to measure the central tendency of interval variables, whereas measures of statistical dispersion include range and standard deviation.

Ratio Scale

A ratio scale (also called a proportional or continuous scale) is a quantitative numerical scale. It represents values organized as an ordered sequence, with meaningful uniform spacing, and has a unique and nonarbitrary zero point.

Most physical measurements—including length (see ruler below), weight, height, mass, (reaction) time, energy, and intensity of light—are made on ratio scales. Periods of time can be measured on a ratio scale, and one period may be correctly defined as double another. The Kelvin temperature scale (see image at left) is a ratio scale because it has a unique, nonarbitrary zero point called absolute zero—even if that point is purely theoretical. Other examples of measurements would be the counts of any published papers, coauthors, or citations.



In physics, two types of ratio scales are distinguished: fundamental (e.g., length or weight) and derived (e.g., density or force). Examples are population counts (e.g., per city) and population density counts (i.e., population per unit area or unit volume), respectively. The former may be represented by proportional symbol maps that use size-coded geometric objects to represent the number of inhabitants per city. Population density is commonly represented by choropleth maps (see **page 54, Geospatial Visualization Types**).

A value of zero has special meaning; for example, with respect to age the actual zero point allows one to say that a ten-year-old is twice the age of a five-year-old. Qualitative operations such as addition, subtraction, multiplication, and division can be performed (e.g., length measurements can be converted from inches to feet or from feet to meters via multiplication with a constant). Statistical dispersion, standard deviation, and the interquartile range can all be calculated. In fact, all statistical measures are allowed because all necessary mathematical operations are defined for the ratio scale.

Visualization Types

Many different types of visualizations have been developed by scientists, engineers, designers, artists, and other scholars. Diverse proposals have also been made on how best to organize visualizations into different types—for instance, based on user task, data shown, reference system employed, data overlay provided, deployment used (hand-drawn versus computer-generated), or key insights gleaned. A pragmatic solution is presented here that uses the type of reference system employed as the main criterion. The final set of types selected comprises tables, charts, graphs, maps, and network graphs, as explained and exemplified in this double-page spread.

The best way to learn about visualizations is to make them.
Martin Wattenberg

Framework

The table below lists and compares major approaches to grouping and naming different types of visualizations. Jacques Bertin's *Semiology of Graphics* distinguishes diagrams, maps, and networks. Robert L. Harris distinguishes tables, charts (e.g., pie charts), graphs (e.g., scatter plots), maps, and diagrams (e.g., block diagrams, networks, Voronoi diagrams). Yuri Engelhardt distinguishes proportionally divided space, space with categorical or metric axes, map space, and text space. Ben Shneiderman's taxonomy organizes visualizations according to data types: linear (1D), planar (2D), volumetric (3D), multidimensional (nD), temporal, tree, network, and workspace. Microsoft Excel, a tool widely used, supports the creation of tables and diverse charts, including pie and doughnut charts as well as line and bar graphs. The set of visualization types adopted in this *Atlas* covers five types: table, chart, graph, map, and network graph (see descriptions and examples on right).

Conversions

Simple modifications can transform one visualization type into another. For example, changing the quantitative axes of a graph into categorical axes results in a table (see the *GRIDL* visualization on **page 69**). Interpolating discrete area topic maps as continuous, smooth-surface elevation maps makes them look like geospatial maps (see *In Terms of Geography* in *Atlas of Science*, **page 103** and **page 58, Isoline Map**).

Combinations

Most data sets can be visualized in a variety of ways (see examples on right and **page 66, Combination**). In some cases, the different views may be coupled to support data exploration (see **page 68, Interaction**). For example, human migration data may be depicted using a table of top-N migration flows and a world map with flow overlays; selecting a flow value in the table highlights the corresponding link in the map. That is, each visualization reveals a different aspect of the data set, which in turn leads to different insights (see **page 72, Validation and Interpretation**).

Visualization Types

Bertin, 1967	Harris, 1996	Shneiderman, 1996	Engelhardt, 2002	Tool: MS Excel	Börner, 2014
	table			tables	table
diagram	chart		proportionally divided space, random space	pie, doughnut	chart
diagram	graph	linear (1D), planar (2D), temporal, volumetric (3D), multidimensional (nD)	timeline (metric or ordered), metric axis, ordering axis, categorization axis	column, line, bar, area, surface, scatter, bubble, radar, stock	graph
map	map		map space (metric or ordered)		map
			text space		
network	diagram	tree, network			network layout (tree or network)
		workspace			

Descriptions and Examples

Tables

A table is an ordered arrangement of rows and columns in a grid. The space at which one row and column intersect is called a cell. Data values are stored in cells and can be indexed by the respective rows and columns. In most cases, each row holds one data record (see **page 26, Naming Conventions**). Columns are typically used to store data values for different data variables. The first row may be used as a header row, with column names consisting of a word, phrase, or numerical index. Meaningful header names help infer meaning about a dataset. Table elements can be color-coded or size-coded. They can also be sorted, grouped, and segmented in many different ways.

Score	Count
96-100	5
91-95	34
86-90	50
81-85	23
76-80	11
Below 75	1

Alternating Rows Table

Score	Count
96-100	5
91-95	34
86-90	50
81-85	23
76-80	11
Below 75	1

Groupings Table

Table types include frequency, percentage, summary, and quartile tables (see Robert Harris's *Information Graphics: A Comprehensive Illustrated Reference* for more types). Pivot tables are a data summarization that can be used to sort, count, total, average, or cross-tabulate data stored in one table.

Score	Count		Relative Count, %	Cumulative Count
96-100	5		3.85	5
91-95	34		26.15	39
86-90	50		38.46	89
81-85	23		17.69	112
76-80	11		8.46	123
Below 75	1		0.77	124

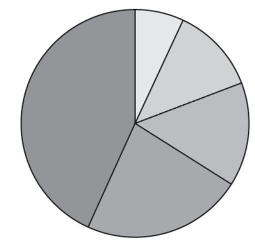
Frequency, Percentage, and Summary Table

Some tables support interactive selection and sorting of rows and columns as well as visual encoding. Cells may contain proportional symbols or small charts/graphs (see example on **page 66** in top-right). Line overlays can be used to show relations between table cells.

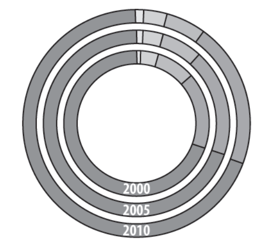
Charts

Charts visually depict quantitative and qualitative data without using a well-defined reference system. They are supported by many spreadsheet programs and are widely used in information graphics.

Examples are pie charts or doughnut charts. The sequence of "pie slices" and the overall size of a "pie" are arbitrary; the pie-slice angles and area sizes represent a percentage of the whole (i.e., the sum of all slices should be meaningful). Examples of a pie chart and doughnut chart with values for three years are shown below. Note that human comparisons made using angles or areas are less accurate than comparisons made using length (see **page 34, Graphic Variable Types**).

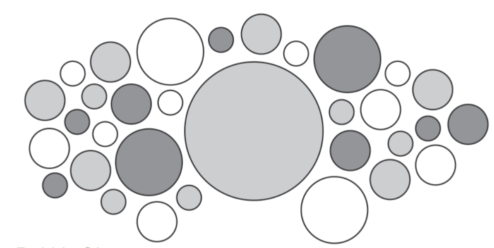


Pie Chart



Doughnut Chart

Bubble charts and tag clouds (also called word clouds) represent each data record with a randomly positioned geometric object or word (see below examples). However, to achieve the most effective use of space or to establish some discernible pattern, position may be specified. For instance, larger items (objects or words) may be set closer to the center, and/or words may be arranged to follow an alphabetical sequence.



Bubble Chart

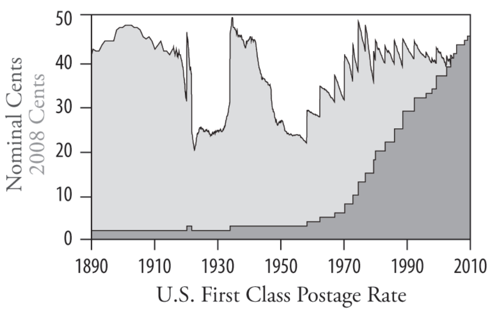
In these and other charts, graphic variable types such as area size, font size, and color may be used to encode additional properties (see **page 34**). Typically, quantitative data variables are used to size-code, whereas qualitative data variables are used to color- or shape-code.

Tag Cloud

Graphs

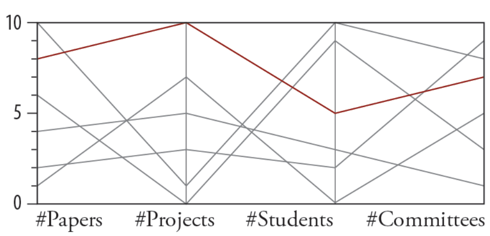
A graph plots quantitative and/or qualitative data variables using a well-defined reference system, such as coordinates on a horizontal or vertical axis. Binning, extrapolation, and smoothing can be applied to aggregate data so that larger data amounts can be more easily understood (see **page 44, Statistical Studies**, and **page 48, Temporal Studies—"When"**). Relationships between data records can be overlaid as links.

Many different graph types exist (see **page 46, Statistical Visualization Types**). Among them are line graphs (see below and discussion on **page 50**), bar graphs, and the stacked versions of each. Scatter plots and bubble graphs (see Gapminder visualizations on **pages 56** and **71**) are widely used.



Line Graph

Parallel coordinate graphs plot multiple data values per record using multiple axes. Links interconnect all values per record (see discussion of this graph on **page 47**).



Parallel Coordinate Graph

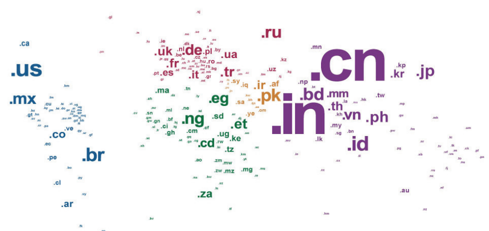
Crossmaps (**page 58, Topical Visualization Types**, and *Atlas of Science*, **page 94**) use a combination of quantitative and qualitative axes (e.g., topics versus time). Geometric symbols may be overlaid (e.g., circles might represent papers on different topics published in different years) and be sized according to some numerical property (e.g., the number of citations per paper). Symbols may also be hue-coded to indicate additional attribute values (e.g., red for review paper, green for research paper). Finally, linkages may be used to denote relations (e.g., citations between papers).

Maps

Maps display data records visually according to their physical (spatial) relationships and show how data are distributed geographically. They are used to show the location, proximity, and distribution of data records. The geolocation of a data record requires the existence of a data variable that defines a location, such as a postal address or a latitude/longitude data pair. Additional data variables can be visualized using graphic variable types (**page 34**) such as area size, font size, and color. Relationships between data records are commonly displayed using links.

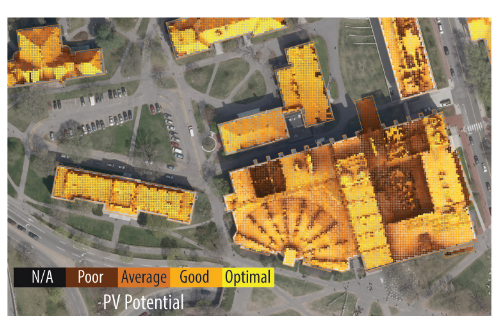
Major map types include cartograms, choropleth maps, relief maps, and proportional symbol maps (see **page 24, Needs-Driven Workflow Design**, and **page 54, Geospatial Visualization Types**).

The *Country Codes of the World* map below shows 245 country codes—the top-level domain codes or extensions used at the end of any internationally based URL or email address. Each two-digit country code is mapped according to the location of the country or territory it represents and color-coded by continent. It is also sized relative to the population of that region (with the exception of China and India, whose codes have been scaled at only 30 percent of their population size in order to fit the layout).



Proportional Symbol Map Showing Country Codes of the World

Data overlays may be either continuous or discrete and may display data for all areas or for selected areas only. Shown below is a choropleth map (**page 54**) that visualizes the potential of rooftop surface areas for solar energy generation. Dark brown denotes low potential; yellow indicates optimal potential.



Choropleth Map Using Roof Top Grid Layout

Network Layouts

Network layouts use nodes to represent sets of data records, and links connecting nodes to represent relationships. Different representations exist for tree and network structures.

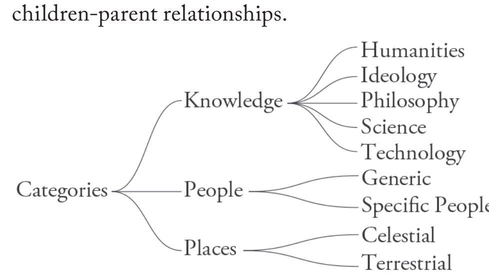
Nodes may be positioned in space according to their attribute values (e.g., publication year or geolocation), the relationships between records in terms of similarity or distance between attribute values (e.g., number of shared words), or a combination of both. Many different network layout algorithms exist (see **page 58, Network Visualization Types**). Node size or color value is used to encode additional quantitative variables, whereas shape, color hue, or pattern commonly represent qualitative data variables.

Edges may be weighted or unweighted, directed or undirected, symmetric (reciprocated), or asymmetric. They may be of different types and can have additional qualitative or quantitative variables. Edge shape, color hue, and pattern (e.g., dotted or dashed) may be used to encode qualitative data variables and directedness; size (line width) and color value are used to encode quantitative variables. In some cases, record relations are used exclusively to compute the position of nodes, though they are not directly visualized.

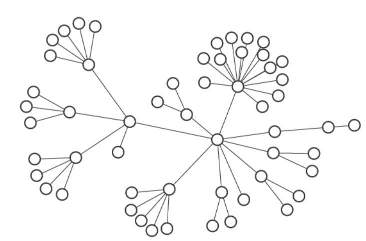
Trees

Tree layouts are used to display file directories, family trees, tournament trees, or classification hierarchies.

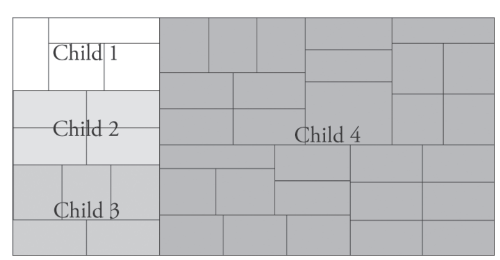
Trees may be represented as indented lists, dendrograms, node-link trees (see the tree view below and beneath that a force-directed layout of a different tree), circle packings (see **page 62, Enclosure Trees**), or treemaps (see below and **page 62**). The latter two use spatial nesting to represent children-parent relationships.



Tree View



Force-Directed Layout



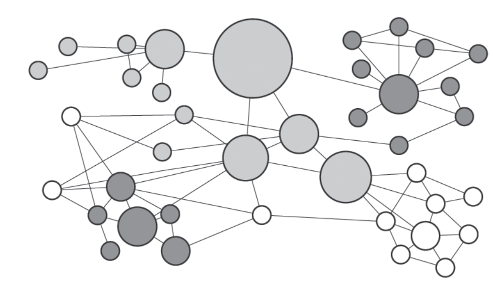
Treemap

Networks

Networks may depict social networks, concept or topic maps, food webs, or the interconnectivity of Internet servers, among others.

Networks may be represented by one-dimensional arc graphs (see below), tabular matrix diagrams, bimodal network visualizations, axis-based linear network layouts (see **page 63, Hive Graph**), or force-directed layouts (see below). The first four types use well-defined reference systems (e.g., nodes may be sorted by a node attribute), which means the axes are labeled and their value range is known. Force-directed layouts have no axes. In fact, the layout is unaffected by mirroring or rotation; only the distances between pairs of nodes matter (see also **page 62, Network Visualization Types**).

Arc Graph



Force-Directed Layout

Graphic Symbol Types

Cartographers, semioticians, statisticians, and others have worked to enumerate the basic, primary graphic symbols used to convey information on a map or visualization. The key types discussed here comprise geometric symbols (e.g., point, line, area equaling a bounded polygon, surface, volume), linguistic symbols (e.g., text and numerals), and pictorial symbols (e.g., images and statistical glyphs). They can designate location, convey qualitative and quantitative information, highlight specific information, help to identify and differentiate, depict form, represent multiple data variables via miniature graphs, or serve as enclosures. Each symbol has different graphic variables that can be used to encode additional quantitative and qualitative data; see the subsequent spreads in **Graphic Variable Types** (**page 34**) and the examples in the *Graphic Variable Types versus Graphic Symbol Types* table (**pages 36–39**).

In the final analysis, a drawing simply is no longer a drawing, no matter how self-sufficient its execution may be. It is a symbol, and the more profoundly the imaginary lines of projection meet higher dimensions, the better.
Paul Klee

Framework

Graphic symbols (also called geometric elements or geometric forms) are small graphic representations that are used to represent data records in a visualization. They encode different data variables via graphic variable types (**page 34**) such as spatial position, size, or color.

Different approaches to identifying and naming graphic symbol types are shown in the table below. The original titles are given in italics. Jacques Bertin's pioneering *Semiology of Graphics* identified and used three "Geometric Elements:" point, line, and area. Cartographer Alan MacEachren adopted Bertin's framework and successfully used it to explain how geospatial maps work.

Robert Harris expanded the set by adding volume and pictorial graphic symbol types to what he called "Symbol Types," of which his book *Information Graphics: A Comprehensive Illustrated Reference* provides detailed descriptions and numerous examples. He cleanly distinguishes two types of points: geometric and pictorial.

As part of his *Morphological Elements of Visual Language*, Robert E. Horn distinguishes three general types of graphic symbols: shapes, words, and images. He further lists different subtypes for each, as words can be "single words, phrases, sentences, [or] blocks of text." Horn distinguishes four types of shapes: point, line, abstract shape, and space between shapes. The latter type is not shown in the table below as it appears to be redundant when designing data visualizations—given the spatial position and visual encoding (e.g., size, of two graphic symbols, their distance can be computed).

Yuri Engelhardt—in his comparison and "translation" of numerous, discipline-specific approaches by key authors ranging from Edward Tufte, Jacques Bertin, and Stuart Card to Alan MacEachren and George Lakoff—identified what he called the "universal 'ingredients' of visual representations," consisting of (1) meaningful spaces—roughly equivalent with visualization types (**page 30**), (2) 'Visual Objects,' listed in the table below, and (3) visual properties (see **page 34**, **Graphic Variable Types**). Three of his visual objects were omitted from the table below, as they do not encode data variables: container—referring to the outer boundaries of a visualization; grid—used to improve readability of data values; and mark—used to highlight specific values.

In *The Grammar of Graphics*, Leland Wilkinson argued for the five "Geometric Forms" that include surface symbols but not linguistic and pictorial graphic symbol types.

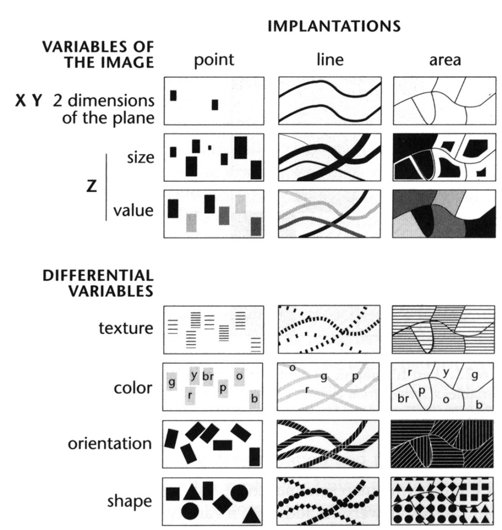
The final set of graphic symbol types that are used in this *Atlas* is given in the rightmost column of the table. Three general types of graphic symbols are distinguished: geometric, linguistic, and pictorial. Descriptions and examples are given on the opposite page. For more examples, see the *Graphic Variable Types versus Graphic Symbol Types* table (**pages 36–39**).

Graphic Symbol Types

Bertin, 1967 *Geometric Elements*	MacEachren, 1995 *Geometric Elements*	Harris, 1996 *Symbol Types*	Horn, 1998 *Morphological Elements of Visual Language*	Engelhardt, 2002 *Visual Objects*	Wilkinson, 2005 *Geometric Forms*		Börner, 2014 *Graphic Symbol Types*
point	point	point: geometric	shapes: point	node	point	geometric	point
line	line	line	shapes: line	link, line locator	line	geometric	line
area	area	area	shapes: abstract shape	bar	area	geometric	area
				surface locator	surface	geometric	surface
		volume			solid	geometric	volume
			words: single words, phrases, sentences, blocks of text	label, character		linguistic	text, numerals, punctuation marks
		point: pictorial	images: objects in world	pictorial element		pictorial	images, icons, statistical glyphs

Instantiation

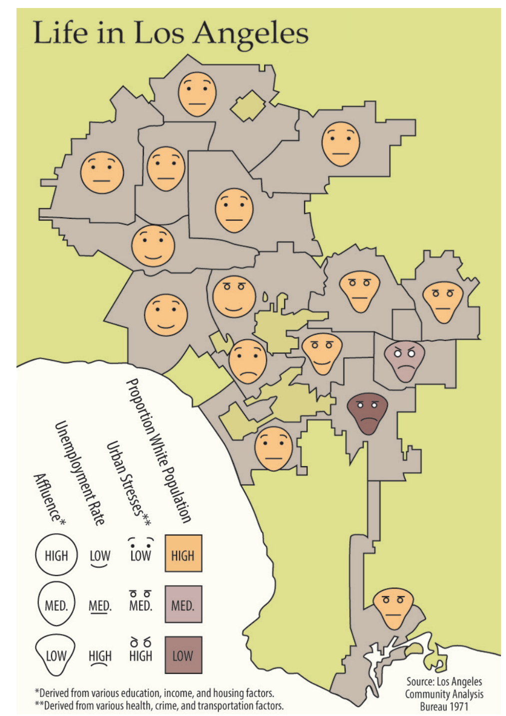
Each graphic symbol type has diverse attribute values, so-called graphic variable types (**page 34**), that can be used to encode additional data attribute values. MacEachren's instantiations (which he calls IMPLANTATIONS) of different graphic variable types for different symbol types are shown in the figure below. Columns represent the three graphic symbol types: **point**, **line**, and **area**. The rows represent different VARIABLES OF THE IMAGE such as **position**, **size**, and **value**; and DIFFERENTIAL VARIABLES such as **texture**, **color**, **orientation**, and **shape**. Instantiations of a substantially expanded set of graphic variable types and graphic symbol types can be found in the *Graphic Variable Types versus Graphic Symbol Types* table on **pages 36–39**.



Combinations

Multiple graphic symbol types can be combined. For example, a node in a network may be represented by a labeled circle—a combination of an area geometric symbol and a text linguistic symbol (see **page 53**, *The Debt Quake in the Eurozone*). Statistical glyphs such as pie charts can be combined with geometric lines to render the nodes and edges in a network graph (see **page 67**, *U.S. Healthcare Reform*). Gestalt principles such as proximity, continuity/connectedness, common region, or combinations thereof can be applied to visually interlink different graphic symbol types.

Analogously, different graphic variable types can be applied and combined. Exemplarily shown below is a geospatial map of Los Angeles with an overlay of statistical glyphs that resemble faces.



These so-called Chernoff faces (**page 33**) map different data variables onto facial expressions, such as head shape, mouth type, and eye type. Furthermore, a face can have different graphic variable types, here color hues. Each of the three facial expressions and the graphic variable type has three possible values resulting in 3 x 3 x 3 x 3 = 81 possible combinations.

Geometric Symbols

Geometric symbols are distinguished by the dimensionality they establish, involving points, lines, areas, surfaces, and volumes. They are easy to draw (to position, size, and color-code) using existing tools and easy to read and compare—even at very small sizes. Multiple symbols of the same type can be used, for example, to show data density. Disadvantages include the limited selection of symbols and the need to explain their usage in the legend.

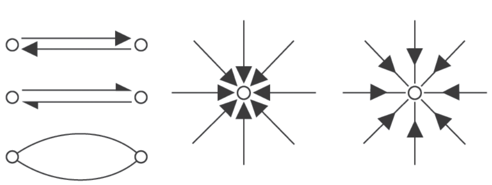
In traditional geometry, a point is nothing but a location in space, lacking size and any other visual encoding; a line has a given position and length but no width or color. In compliance with prior work that aims to define graphic symbol types and developed with the intention of using geometric symbols for encoding data variables, the framework presented here assumes that point, line, area, surface, and volume symbols can be size-, color-, and shape-coded; see examples in the *Graphic Variable Types versus Graphic Symbol Types* table (**pages 36–39**).

Points

A point symbol is commonly used to visualize data records that exist at a discrete point location, such as a postal address. Points are used to specify location and show density distribution. Additional data variables are encoded using graphic variable types (**page 34**).

Lines

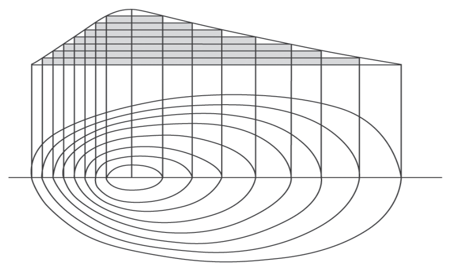
A line connects two points. Line symbols are applied to denote linear geographic objects such as streets, rivers, boundary lines, or geological faults as well as phenomena in motion, such as hurricane and tornado paths or ocean currents. Lines may be directed, as in network graph visualizations (**page 62**). This is commonly indicated through the use of arrows or line shapes, which may be read clockwise from source to target mode (see examples, below-left). When using arrowheads as line endpoints, nodes that have many incoming links may appear to have a larger size (see below-middle); this can be resolved by placing arrowheads at a distance from the destination nodes (see below-right).



Lines might be weighted and labeled and can be bundled (see **page 62**, **Network Visualization Types**).

Areas

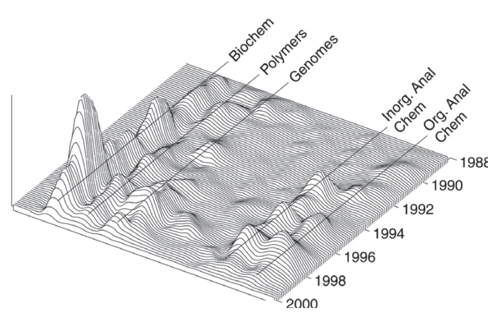
Area symbols include bounded polygons, used to represent country or state boundaries (see the *U.S. Map of Contiguous States* on **page 24**). Another type of area symbol is an isoline (also called an isopleth or isogram), which on a base map interconnects points that have the same value (e.g., places on a map registering the same amount or a given ratio of any given phenomenon, such as elevation or population density). More widely spaced lines indicate a gentle slope, whereas dense lines denote a steep slope (see below).



Areas can be qualitatively differentiated using graphic variables to show nominal differences (e.g., ethnic maps or vegetation and soil maps). Areas can be quantitatively differentiated using the choropleth, isoline, or cartogram methods (see **page 54**, **Geospatial Visualization Types**).

Surfaces

Surface symbols, such as surface plots, have a three-dimensional surface that connects a set of data points. An example is a surface plot of topics over time (see below and **page 58**, **Crossmap**).



Volumes

Volume symbols are also three-dimensional. They are used in bar graphs or **Stepped Relief Maps** (**page 54**). Examples include *In the Shadow of Foreclosures* (**page 53**) and *On Words—Concordance* (**page 57**).

Linguistic Symbols

Linguistic symbols, such as letters, numbers, or punctuation marks are widely used. One example is the use of chemical elements (i.e., symbols of the periodic table, such as Cu, Au, Zn, or Fe) or abbreviations for country names (e.g., CA, DE, FR, or US per the ISO two-letter code system), which most viewers would understand without the need of a legend (see **page 31**, *Country Codes of the World*).

The exact location and size of linguistic symbols tends to vary due to the differences in letter shapes; their proper placement can be aided by rendering linguistic symbols inside of geometric symbols (see **page 53**, *The Debt Quake in the Eurozone*).

Either serif (e.g., Cambria) or sans serif (e.g., Arial) typefaces may be used. Some type fonts (e.g., Caslon) have uppercase and lowercase numbers (see example below).

Cambria A b c d e f 0 1 2 3 4 5 6 7
Arial A b c d e f 0 1 2 3 4 5 6 7
Caslon A b c d e f 0 1 2 3 4 5 6 7 8 9

A typeface can be proportional, containing glyphs of varying widths (e.g., Garamond), or monospaced, using a single standard width for all glyphs in the font (e.g., Courier). Using all uppercase letters in labels should be avoided, as reading all capitals takes more time than reading sentence-case text.

Garamond Proportional Typeface
Courier `Monospace Typeface`

Font families refer to groups of related fonts that vary in weight, orientation, and width, but not in design. For example, Times New Roman, *Times New Roman—Italic*, and **Times New Roman—Bold** are all members of the Times font family.

Fonts can be printed in different sizes or colors; formatted with underlining, outlining, or shading; and set in superscript or subscript positions (see **page 34**, **Graphic Variable Types**).

Some type fonts render pictorial symbols that can encode additional data variables via (partially) filled shapes (see examples below).

Webdings 

Conventional Dingbats 

Text can be left or right aligned, centered, or justified. Numbers are commonly aligned vertically on the decimal point.

Pictorial Symbols

A pictorial symbol (also called an iconic symbol, sign, or pictogram) is an arbitrary or conventional mark used to represent complex notions, such as quantities, qualities, or relations. Pictorial symbols can be concrete reproductions of the objects they represent; specialized, such as statistical glyphs or the symbols used in weather maps; or abstract, composed of different geometric shapes. They can be shown from different perspectives, such as in profile or as a top view, and are typically positioned according to their centroid or mass point.

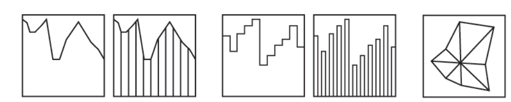
Images and Icons

Image symbols are drawn reproductions of the objects they represent. They tend to be easy to read and to understand. The larger their size and geometric complexity, the fewer that can be placed in a visualization.

Icons are specialized symbols designed to convey specific meaning. They are an efficient means of encoding information. Typically, a legend must be presented to signify what any given icon represents.

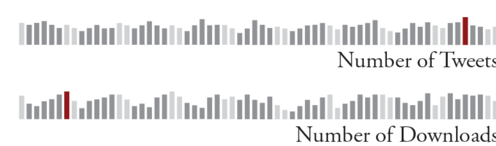
Statistical Glyphs

Statistical glyphs (also called miniature graphs) have no titles, labels, check marks, or grid lines (see **page 46**, **Statistical Visualization Types**). Examples are line graphs, profile graphs, histograms, bar graphs, and radar graphs (see below, from left to right), each of which can be used to encode 10 to 20 quantitative or qualitative variables. Glyphs are frequently used in combinations (**page 66**), small multiples (**pages 66**, **67**, and **69**), or matrix displays (**page 66**).



Two types of statistical glyphs that are more widely known and used are sparklines and Chernoff faces (see **page 46**, **Statistical Visualization Types**).

Sparklines are numerically dense, word-sized graphs that show data variation over time (see the miniature bar graph below).



Chernoff faces are pictorial symbols that map multiple data variables to facial expressions (see **page 32**, *Life in Los Angeles*). Most humans know how to read faces and can read data encoded in Chernoff faces.

Graphic Variable Types

The geometric, linguistic, and pictorial graphic symbol types discussed in the previous spread can be used to encode additional data variables using graphic variables. The key approaches to defining and grouping graphic variable types are compared here in an attempt to provide a Rosetta stone for interlinking different approaches and theories and to arrive at a set of well-defined and exemplified key types (see opposite page). Psychological results on the accuracy of graphic variable types are also discussed, as they help to guide the selection of graphic variable types that can be easily read and distinguished.

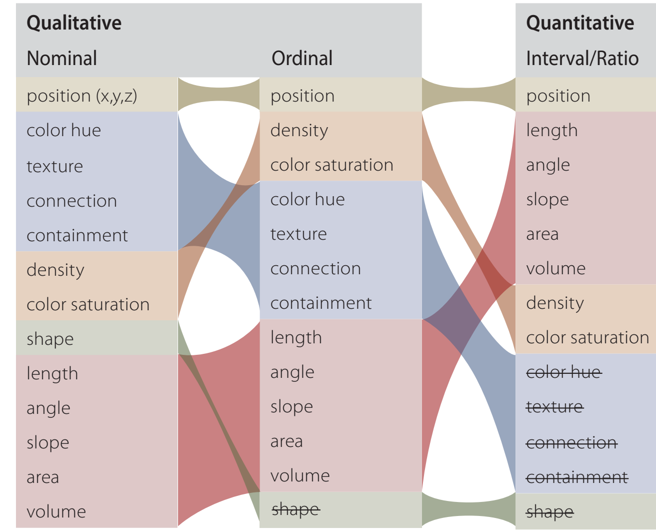
All the pieces are here—huge amounts of information, a great need to clearly and accurately display them, and the physical means for doing so. What is lacking is a deep understanding of how best to do it.
Howard Wainer

Framework

Various theories exist on how to identify and name graphic variable types. The table below lists the approaches proposed by leading experts. Cartographer and theorist Jacques Bertin conducted extensive landmark work as early as 1967 and later expanded on that research. Cartographer Alan MacEachren adopted Bertin's variable types, but also added clarity, which may be broken down into three subcomponents: crispness, resolution, and transparency. Crispness is the ability to selectively and dynamically filter for edges, fill, or both. Resolution defines how sharp or pixilated a given object appears and can be used to represent uncertainty in data. In his book *Visual Language*, political scientist Robert E. Horn added illumination and motion. In *The Grammar of Graphics*, Leland Wilkinson developed a complete grammar for the design of graphs and tables of graphs and introduced a hierarchical organizational schema for graphic variable types with superclasses form, color, texture, and optics. The rightmost column of the table shows the graphic variable types adopted in this *Atlas*. Spatial and retinal properties are distinguished. The former equate positioning in a three-dimensional space. The latter can be subdivided into form, color, texture, and optics—groupings that conform to Wilkinson's superclasses. Extending Wilkinson's schema, this table includes motion. It also adds a number of new graphic variable types, namely those that are preattentively processed even before attention is fully focused on it (e.g., curvature, angle, closure, stereoscopic depth) and those that conform to Gestalt principles (e.g., motion variables).

Graphic Variable Types

Bertin, 1967	Bertin, extended	MacEachren, 1995	Horn, 1998	Wilkinson, 2005	Börner, 2014		
location		location	location: in 2D or 3D	position	spatial	position	x y z
size (small vs. large)		size	size: area, thickness	form: size			size
shape (circle vs. triangle)		shape		form: shape			shape
orientation (up vs. down)		orientation	orientation	form: rotation		form	rotation curvature angle closure
color value (light vs. dark red)		color value	color: value	color: brightness			value
color hue (red vs. blue)		color hue	color: hue	color: hue			hue
	color intensity (saturated vs. dull)	color saturation		color: saturation		color	saturation
texture (spaced vs. dense)	pattern arrangement (striped vs. crossed)	texture	texture	texture: granularity, pattern, orientation		texture	spacing granularity pattern orientation gradient
		crispness		optics: blur			blur
		resolution					
		arrangement					
	transparency	transparency		transparency			transparency
			illumination			optics	shading stereoscopic depth
	animated: speed		motion				speed velocity
	animated: rhythm				retinal	motion	rhythm



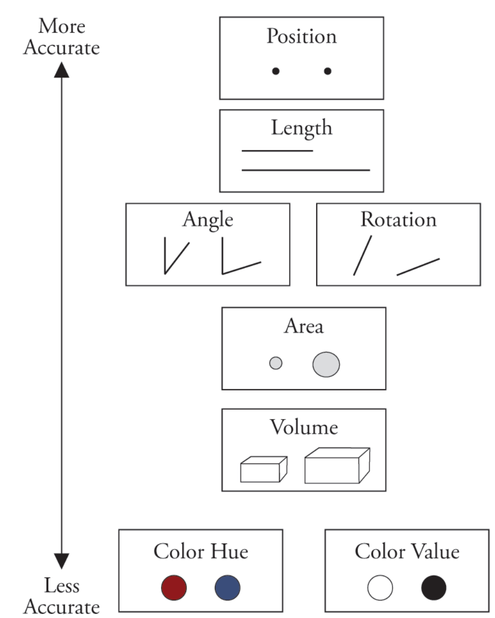
Combinations

In some cases, only one data variable is used to visually encode a graphic symbol, called a "univariate" symbol. Typically, multiple visual variables, or "multivariate" symbols, are mapped. The mapping of data variables to graphic symbols should be consistent per visualization. For instance, when data is identical, it should be consistently represented by the same chosen graphic symbol and its graphic variable encoding. Note that most attribute combinations are independent of each other (such as with shape and color hue); in some cases, combinations may be interdependent, such as when increases in symbol size conflict with position constraints (e.g., keeping all symbols on the canvas).

Perception Accuracy

In 1986, Jock D. Mackinlay published a ranking of perceptual tasks for different data scale types (**page 28**), as shown in the top-right figure. He ordered variables top-down according to how accurately humans perceive data at standard levels of measurement. The ranking was designed to help with the prioritization and matching of data scale types to graphic variable types. The six grayed-out graphical variable types are not relevant to the given data scale types. For all data scale types, **Position** is most accurately perceived. For **Nominal** data, **color hue** is second best. **Qualitative** data uses **density**; **Ordinal** data uses **length**.

Different studies have since been conducted to ascertain which graphic variable types most accurately convey quantitative data variables. William Cleveland and Robert McGill conducted a number of visual perception studies to determine what people can accurately decode. Robert Spence's visual summary of Cleveland and McGill's results is shown below. Note that only paired comparisons (e.g., **Position** versus **Length**) have been validated. Judging magnitudes differs from identifying outliers. The top of the image shows the tasks that are performed more accurately. A noticeable gap exists between the accuracy at which **Angle** or **Rotation** and **Area** can be judged. There is an even larger gap in accuracy when judging **Volume** and **Color Hue** or **Color Value**.



Descriptions and Examples

Spatial

Spatial position refers to the location of a record in a one- to three-dimensional space; see the **Spatial** rows in the *Graphic Variable Types versus Graphic Symbol Types* table (**pages 36–37**).

Retinal

Retinal variable types refer to all nonspatial properties; see the **Retinal** rows in the same table (**pages 36–39**).

Form

Form is defined as the visible shape or configuration of a graphic symbol.

Size refers to the scaling of graphic symbols and is commonly used to encode additional quantitative data variables, to attract attention, define importance, and support comparisons. Symbols can be size-coded by absolute data values, apparent magnitude values, or values that discriminate data ranges.

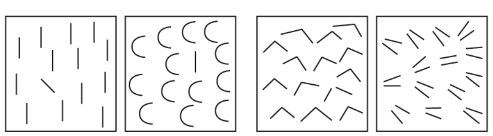
Shape comes in three basic types: geometric (e.g., triangles, squares, circles), natural (e.g., hands, trees, animals), and abstract (e.g., icons, glyphs). A legend must be provided to guide interpretation. Whenever possible, existing visual "grammar" systems should be used.

Rotation (also called angle or slope) refers to the orientation of graphical symbols (at any angle within the full rotation of 360 degrees, see below). It can be used to encode qualitative information (e.g., live, standing tree and dead, fallen tree, **page 37**) and quantitative information (e.g., clock face).

Curvature refers to the degree to which a graphic symbol is curved (see below).

Angle refers to the space between two intersecting graphic symbols at or close to the point at which they intersect. It is usually measured in degrees (see examples in the subsequent spread).

Closure is a graphic variable that indicates how much a circle or other geometric figure is closed.

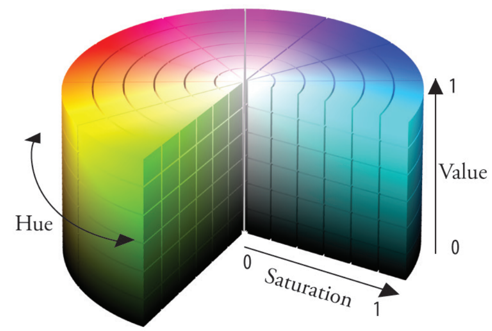


Rotation Curvature Juncture Parallelism

All these six form attributes are preattentively processed; juncture and parallelism are not (see example above).

Color

The color of an object is determined by the measure of its value, hue, and the saturation of light being reflected from or emitted by it. An HSV (hue, saturation, value) color model is shown below.



Color is often used to convey importance or attract attention to specific symbols. It can help to alter the effects of camouflage (e.g., expose red cherries in a tree), develop an understanding of material properties (e.g., the condition of food or tools), and support comparisons. It can also be used to document nature (e.g., blue lakes in maps) and to generate or invoke emotions ranging from warm and active to cold and passive. Color is less effective in displaying how objects are positioned in space, how they are moving, or what their shapes are.

Value (also referred to as brightness, shade, tone, percent value, density, intensity, and luminance) relates to the amount of light coming from a source or being reflected by an object. It indicates how dark or light a color looks (see **page 36** for an example of a gradient that ranges from white to black). The ratio between the minimum and maximum brightness values in an image is also called a contrast ratio.

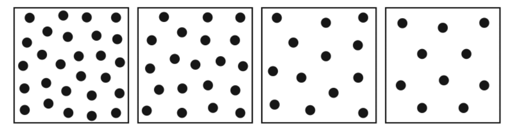
Hue (also called tint) refers to the dominant wavelength of a color stimulus. It is commonly used to represent qualitative data. However, if quantitative data (e.g., terrain heights) is being represented, the data should be carefully binned and a meaningful color sequence selected (e.g., blue lakes set against green forests or brown mountains set against the white of snow-covered mountaintops).

Saturation (also called intensity) refers to how much hue content is in the stimulus. Monochromatic hues are highly saturated. Completely desaturated colors constitute the grayscale, running from white to black, with all of the intermediate grays in between. More highly saturated (purer) colors appear in the foreground, whereas less saturated (duller) colors fade into the background.

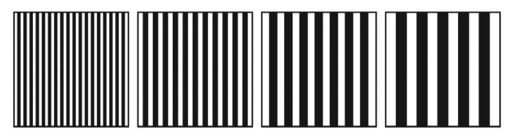
Texture

Texture relates to the surface or "look and feel" of an object. It adds depths and visual interest. Printed visualizations inherit the texture of the material on which they are printed. Those displayed onscreen have a designed texture that is made up of smaller graphic elements (lines, dots, shapes, etc.) set out in a consistent pattern. Texture properties comprise spacing, granularity, pattern, orientation, and gradient; these are explained and exemplified for different geometric symbol types on **pages 38–39**.

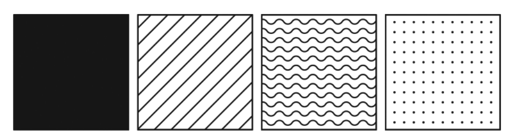
Spacing (also called density) refers to the amount of space between the graphic symbols that make up a texture (see below).



Granularity (also called coarseness) indicates the size of graphic symbols, while the ratio of figure to ground (or ratio of black symbols to white background) remains constant (see below).

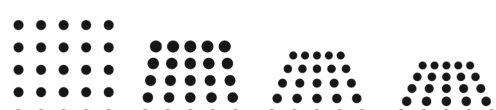


Pattern refers to the type of graphic symbols used (e.g., dots, lines, and solids as well as flags or data-generated symbols; see below). Textures with linear components (e.g., grids) are frequently used to reveal surface shapes. Background images (e.g., satellite images or aerial photographs) are used to provide context.



Orientation refers to the rotation or incline of graphic symbols. They may be perfectly horizontal or vertical, or diagonal at any angle within the full rotation of 360 degrees.

Gradient is used to indicate an increase or decrease in the magnitude of a property and also to show perspective (see below).



Optics

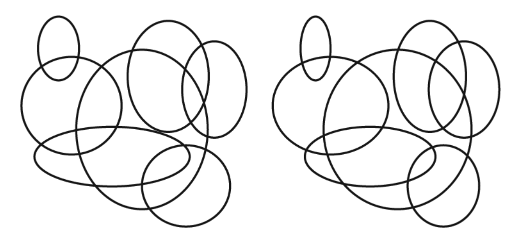
Optical properties can be used to indicate data uncertainty, deal with overlaps, emphasize structure, and attract attention.

Blur (also called crispness or resolution) is a measurement of discernable pixels. The fewer the pixels in any given visualization, the more blurred (or less clear) the image. Blur has been proposed by MacEachren as a means to depict data uncertainty.

Transparency (also called opacity or translucence) refers to the visibility of an object. Solid graphic symbols will stand out but may also overlap. Transparency can improve readability as it makes occlusions easier to detect.

Shading, related to illumination, refers to the darkened area or shape on a surface that is produced when a body comes between rays of light and that surface. It can be used to emphasize structure and to attract attention. It also helps to reinforce our perception of the location of light sources and objects. An even stronger effect is produced with motion (see discussion below). In fact, shadow motion can serve as a greater depth cue than a change in size due to perspective. Shadows are most effective when cast to a nearby surface. However, as shadows can interfere with other displayed information, they should be rendered with blurred edges.

Stereoscopic depth can be used to create or enhance the illusion of depth in a visualization. Two images are needed—one for each eye. The depth variance is encoded in the differences between the two views (see the example of intertwining rings below).



Motion

Graphic variable types that require moving objects are difficult to exemplify in print; yet they are highly effective in interactive visualizations.

Speed refers to the rate at which a set of objects moves (but not the direction of movement).

Velocity is a vector quantity that captures the speed and direction of a set of moving objects.

Rhythm (also called flicker) refers to regular, repeated pattern changes in spatial position or retinal variables. It is highly effective for attracting attention (e.g., to alert users of dangerous situations).

Motivation Framework Acquire Analyze & Visualize Deploy Interpret

Validation and Interpretation

There now exists a rich variety of algorithims, tools, and services that turn data into visualizations. While some are designed for use by experts, a growing number of easy-to-use tools is widely used by non-experts. Most datasets can be analyzed and visualized in many different ways. The majority of the possible algorithm and visualization design combinations is incorrect or imperfect; only a select few combinations result in readable, informative, and actionable visualizations. This spread reviews the criteria and methods for validating (alternative) visualizations and for estimating their value for sound decision making. Examples of good and bad visualizations are used to illustrate common problems and potential solutions (see opposite page).

Human judgment without automated data mining is blind; automated data mining without human judgment is empty.
Colin Allen

Validation Criteria

Visualizations are commonly optimized and evaluated according to three qualities: function (utility, usability, effectiveness, and scalability), aesthetics (quality and appeal), and integrity (accuracy and replicability); for details, see works by Edward Tufte, David McCandless, and Bradford W. Paley (**page 178**, **References & Credits**). Some metrics can be observed or computed (e.g., in terms of speed, accuracy, or scalability). Others (e.g., beauty or relevance) require expert evaluation.

Function

A visualization should display the most important information in clear and accessible form. Relevant questions for consideration can be broken down into function-specific categories.

Utility

Does the visualization satisfy the technological, contextual, and business insight needs of the target audience? What is the decision-making value—that is, which major insight does the visualization provide, and why does it matter? Does it inspire viewers to learn more or to act differently? Does it support asking questions, making future explorations, or generating hypotheses? How generic is the solution? What range of questions can be answered? Do people continue to use it in practice? Do they buy it or purchase upgrades? Is the creator invited to continue producing similar visualizations?

Usability

Is the visualization easy to read and use by the target audience? Is its purpose clear? Does it use a common yet sufficiently expressive reference system? Is the mapping, from data scale types to graphic variable types, easy to understand? Is the provided interactivity easy to use, and is it sufficient?

Effectiveness

For each visualization, one should clearly state the user needs and then show the rationale behind the selection of certain reference systems, metaphors, color-coding, interactivity design, etc. Questions to be addressed comprise: Is the display space used effectively? Is the number of data points and the data density appropriate? Is all relevant data visible, or are there occlusions? Are the key findings dominantly represented? Is the given story told in a consistent fashion? Does it allow easy access to additionally needed data?

Scalability

Most visualizations work well at the micro and meso levels; few scale to the macro-level, big-data studies that have millions or even billions of data points. Does the visualization degrade gracefully as the amount of data increases (e.g., are data analysis techniques used to help derive insights from dense networks that are initially illegible or visually akin to spaghetti balls)? How responsive is the visualization to user interaction?

Aesthetics

Visualizations need to attract the attention of viewers to communicate. Visual aesthetics (i.e., well-composed, high-quality data renderings) are important.

Design Quality

Visual aesthetics comprise design quality, the originality of the underlying idea, and international and/or interdisciplinary appeal. Carefully selected and easy-to-read image compositions, color palettes, shapes, and forms help to improve quality.

Appeal

Ideally, viewers will be attracted by a visualization and have fun interacting with it. The visualization will have even higher mass appeal if it has been featured in news channels, popular blogs, social media, on the cover of a major journal or magazine, or as part of a prominent museum exhibit.

Integrity

A visualization should present data in the most objective way. It should be generated using the most accurate and highest coverage data and the best methods available. All of these factors add to the creator's credibility.

Accuracy

The quality of the data, analysis, and design is key for the creation of accurate visualizations. If uncertainty exists in either the data or in the analysis and visualization workflow, then it should be stated unambiguously. Subjective choices or manual data modifications need to be clearly documented.

Replicability

Any visualization should come with sufficient documentation to recreate it. Documentation should comprise information on the original data (including source and baseline statistics); details about how data was cleaned or preprocessed; the analysis and visualization algorithms that were applied; and the parameter values that were used. One should list all authors, ideally with brief information on their expertise and specific contributions, and mention all funders, as commercial interests are likely to influence visualization design and description. A detailed documentation of work will improve consistency and ease future studies.

Validation Methods

When designing visualizations, it is beneficial to validate results early and often. Different qualitative and quantitative methods exist to (obtrusively or nonobtrusively) evaluate visualizations.

Field studies are employed to understand how users interact with a visualization or tool in the real world—with their own data and tasks. Longitudinal field studies work with users over extended periods of time. Field experiments design user tasks to simulate real analyses and recruit groups of users for one-on-one sessions that test the visualization or software (not the users), encourage thinking aloud, and record top usability issues. Both emphasize real-world context and learning through observation (not just opinion).

User Studies

User studies are commonly employed to evaluate or compare design alternatives. Evaluation metrics such as task-time completion and error counts shed light on the usability and effectiveness of visualizations. Users may be asked to think aloud so that evaluators can capture their thought processes and insights. Eye-tracking devices help researchers understand how interactive visualizations guide users' eyes as well as their navigation and processing of information spaces. Longitudinal studies (i.e., repeated observations over long periods of time) are used to study the adoption of novel visualizations among existing ones.

Human (Expert) Validation

An open-ended protocol, a qualitative insight analysis, and an emphasis on domain relevance may all benefit the identification of those visualization features that can help users achieve insight and those that may prove problematic—directly informing visualization refinement and improvement. For example, human experts may be asked to draw a domain map, and this map would then be compared to visualizations automatically constructed according to domain data. Experts may also be consulted in classification and labeling studies, in which participants are asked to freely explore given visualizations and then to identify major domains and prevalent topics (e.g., by drawing cluster boundaries around similar objects and assigning a label to each cluster). In utilization studies, participants use visualizations to make sense of data, and the results are compared to those derived by automatic means.

Controlled Experiments on Benchmark Tasks

For rigorously evaluating visualizations, many scientific communities have compiled data repositories and synthetic data sets that support the given experiments. In general, benchmark tasks must be predefined by test administrators, and users must precisely follow specific instructions during the experiments. Each task has a definitive completion time that is fairly short (typically under one minute), in support of a large number of task repetitions. Each task has definitive answers that are used to measure accuracy. Answers are often simple (e.g., multiple choice in support of objective mechanical or automated scoring).

Crowdsourcing Evaluation

Amazon's Mechanical Turk and similar platforms can be used to crowdsource evaluation (see **page 174, Democratizing Knowledge and Participation**). For example, Jeffrey Heer and Michael Bostock crowd sourced graphical perception experiments by replicating prior studies of spatial encoding and luminance contrast; conducting new experiments on rectangular area perception (as in treemaps or cartograms) and on chart size and gridline spacing; and analyzing the impact of reward (payment) levels on completion time and result quality finding that higher rewards lead to faster completion rates.

Interpretation

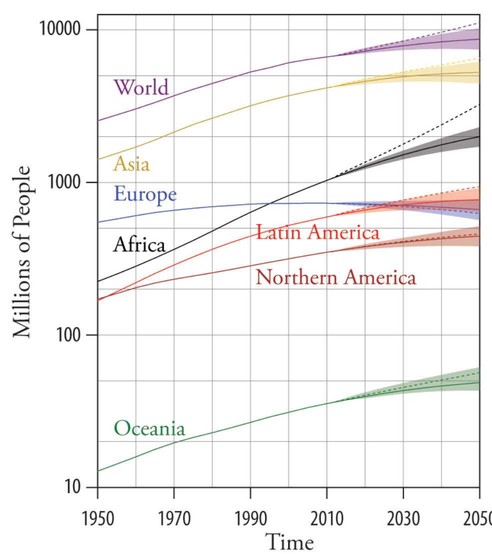
Data analysis and visualization create a "formalized representation" of data, which needs to be interpreted to inform sensemaking and actions. When reading a visualization, it is important to detect any omissions, errors, and biases.

Errors are easily made in any step of the analysis and visualization workflow. Critical data can be left out; algorithm and parameter selections can have a major impact on visualization layout and design; and visual encoding choices will affect the interpretation of results. John Brian Harley's theory of cartographic silence distinguishes two types of silences: intentional silences, which are specific acts of censorship, and unintentional silences, which are unconscious omissions. Examples of misleading visualizations are given on the right. When interpreting a visualization, it is important to understand both its power and its limitations.

When using visualizations in decision making, it is important to distinguish (1) the true question or issue from (2) the data and methods applied to answer it and (3) the potential impact of planned decisions. Frequently, decisions influence future actions and the resulting data. For example, funding a new area of research will lead to new hires; newly hired scholars will then publish or perish; and each publication will cite other papers—most likely within the funded area. That is, there is a strong correlation between the amount of funding an area of science enjoys and the number of citations papers in that area receive. If future funding is based on the number of existing citations, then "rich areas" become even richer over time—which might not be intended.

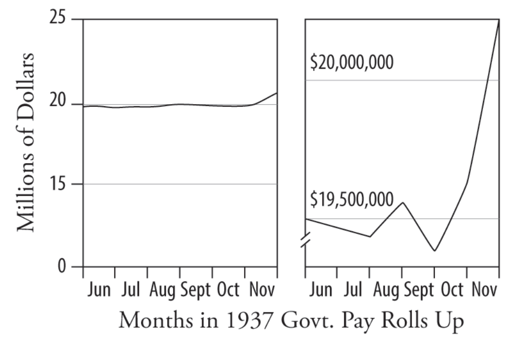
Scales

The same data plotted on a linear scale will appear quite different when plotted on a logarithmic scale. Data that grows exponentially (e.g., the increase in world population from 1 billion in 1800 to 7 billion in 2011; see graph on **pages 2–3** in *Atlas of Science*) will look like a straight line in a logarithmic plot (see the United Nations population estimates below for different continents between 1950 and 2050).



Distortions

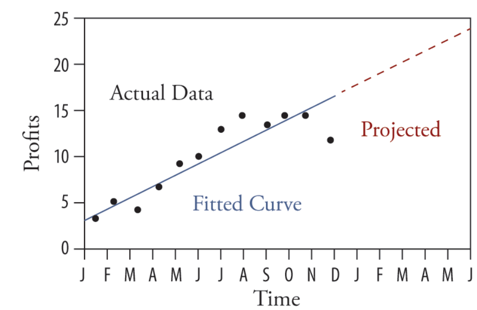
Visualizations can be distorted in many different ways, making them difficult or impossible to interpret correctly. Two renderings of the same data—government payrolls in 1937—are shown here; the left image with the broken y-axis scale is meant to suggest an increase in payrolls, whereas the right image confirms payroll stability.

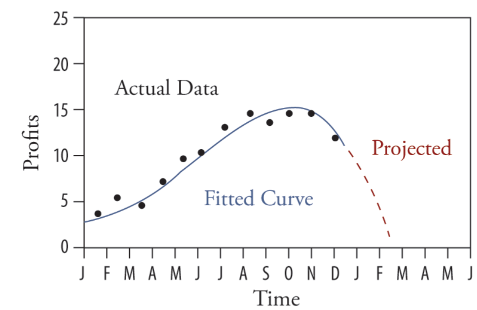


Not only elements of the reference system (e.g., axes) but also data overlay (e.g., graphic symbol types such as bars; see **page 46, Comparisons**) may be broken.

Regressions

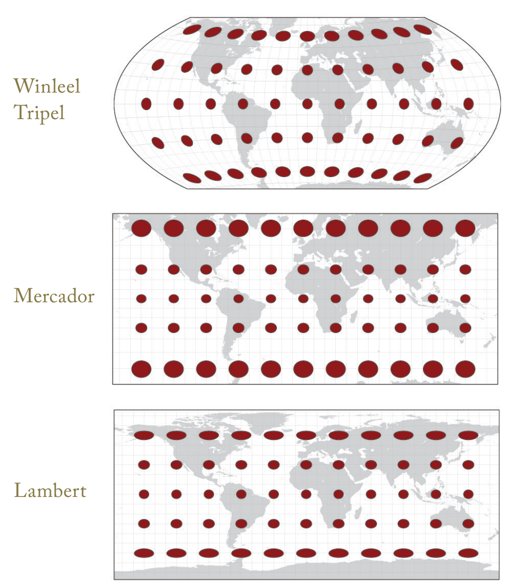
As discussed in **Statistical Studies** (**page 44**), the selection of different curve fittings strongly influences the prediction of future values. Shown here are a linear (top) and polynomial (bottom) fitting of the same data; notice the vastly different projections that appear for the month of March.





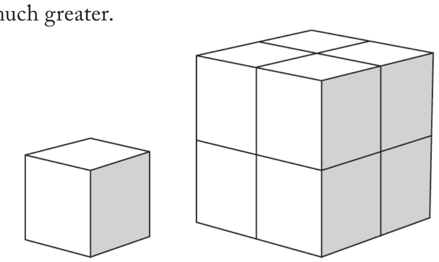
Projections

Changes made in geospatial projections have a major impact on area sizes and the distances between data points. Shown below are three common projections, with Tissot's indicatrices placed at the same geospatial position to illustrate the different distortion at these points for each of the various projections.



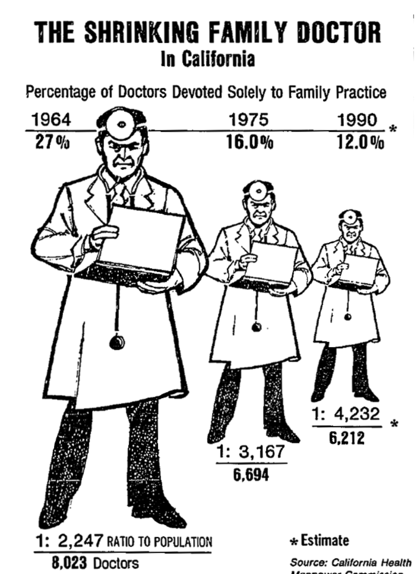
Dimensions

Representing data using three-dimensional objects tends to lead to confusion in interpretation. For example, changing the height of a 3D object (e.g., doubling the height of a 1" x 1" x 1" cube) changes its width and depth proportionally, effectively increasing its volume eight times (so that it becomes a 2" x 2" x 2" cube), see below. Another example can be found in Darrell Huff's *How to Lie with Statistics* that uses three-dimensional drawings of two moneybags to show how the weekly salary for a carpenter from the fictional country of Rotundia differs from that of a U.S. carpenter. According to the fictional data, U.S. carpenters earn twice as much, and the U.S. moneybag is about twice the height—however the impression of the difference is much greater.



Perspective

Linear perspective has parallel lines converging to a single point; that is, objects of the same size that are placed further away appear smaller than nearby objects. This can cause confusion in data visualizations. For example, the doctors in this example appear to be proportionally the same size, contrary to the data values they represent.



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This section lists more than 1,500 citation references, as well as image credits requested by copyright holders, data credits, and software credits. More than 160 scholars provided input on the material presented in the *Atlas*, and their contributions are acknowledged here. As some spreads have up to 50 references, and adding 50 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 and in alphabetical order. The website at **http://scimaps.org/atlas2** supports a search for specific names and works. It also provides easy access to high-resolution versions and credits for the more than 350 images featured in the *Atlas*.

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André Skupin provided expert comments.

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Andrea Scharnhorst uses a stripe graph to visualize author publications on different topics.

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Michael P. Ginda compiled the data and rendered the visualization.

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André Skupin provided expert comments.

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Indiana University's Virtual Reality Theater

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David E. Polley digitized Science and Society in Equilibrium data.

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