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VISUALIZING NATURE AND SOCIETY

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In addition to their standard uses—wayfinding and picturing geographic features and political boundaries—maps and related graphic methods have long played a significant role in scientific exploration, discovery, and explanation. In cartography, these latter uses are most well known under the rubric of "thematic cartography," but in fact, since the earliest such developments at the end of the seventeenth century, the histories of map-based and map-free information visualization have become increasingly intertwined. We thus construe our chapter title broadly to include various visual representations. We do not aim to give a comprehensive history of "first uses," but rather to explore the connections between image and scientific questioning through illustrative examples and their scientific context. In addition, we focus somewhat more on the side of cartography than of statistical graphics. More comprehensive historical treatments of data visualization may be found in Friendly (2006) and Friendly and Denis (2006), and of nineteenth-century thematic cartography in Palsky (1996, 2003).

The plan of this chapter is as follows: We first tell the story of two visual revelations that help us to understand how thematic maps and graphs can contribute to scientific explanation and discovery, and then try to identify some higher-level features shared by thematic maps and other data graphics in scientific inquiry and presentation. We then review the origin and development of thematic mapping, largely from a cartographic perspective. The fifth section illustrates some important developments in the history of statistical diagrams and graphs. Finally, we discuss the contributions of thematic maps and diagrams to the development of the social sciences.

VISUAL EXPLANATION AND DISCOVERY

Data and information visualization are fundamentally about showing quantitative and qualitative information so that a viewer can see patterns, trends, or anomalies, constancy or variation, in ways that other forms—text and tables—do not allow. Today, weather maps, maps of election results (for example, the "red" and "blue" states depicted in maps of U.S. presidential races; see figs. 115–16), and maps of disease incidence or outbreak (perhaps related visually to potential causes) are commonplace. But this was not always so; it took several small but significant conceptual leaps to move from showing purely geographic features (rivers, towns, terrain) that could be seen directly, to other things that might be measured locally, but could not be seen or understood globally without the aid of a map-based visual representation.

Thematic maps, overlaying a visual rendering of a spatial distribution of some data on the familiar forms of base maps, did not arrive until late in the seventeenth century, with meteorological charts and maps of magnetic declination at sea by Edmund Halley. Once invented, thematic maps provided a means for visual explanation and discovery that arguably could not have occurred otherwise.

In a parallel stream, the graphs and charts so widely used today had their origin in problems of physical, astronomical, and geodesic measurement also beginning in the seventeenth century. Throughout the eighteenth century, as new data-based problems were developing, graphic representation of scientific and economic data expanded to new domains and forms that were not primarily map based. To set the theme for this review, we briefly recount two stories of visual discovery.

The founding of geological cartography

If one can say loosely that geography is about seeing and understanding the distribution of things *above* the ground, one can also say that geology is about seeing and understanding what is *beneath* the ground. Geography is immedi-

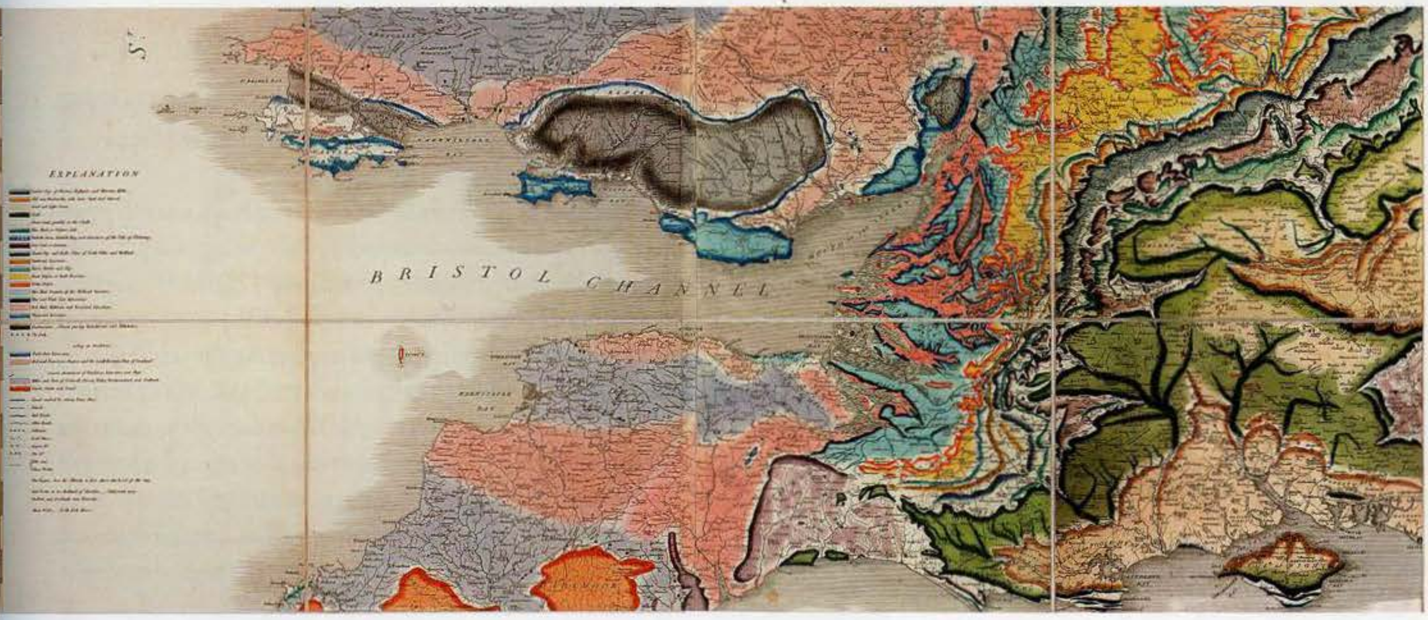


FIGURE 117.

William Smith, "A Delineation of the Strata of England and Wales with Part of Scotland," detail (1815).

ately visible, but geology is for the most part invisible, unless you happen on an exposed cliff or fault line. As we discuss below, mineralogical maps had been created as early as 1749. But the idea of mapping the invisible characteristics of the land beneath our feet and the first significant scientific breakthrough in what is now called "stratigraphic geology" came much later, in 1815–17, with William Smith's geological map of England and Wales (Smith 1815).

For more than thirty years, Smith traveled throughout the British countryside, surveying and recording the types of rocks and fossils that were found in places where various layers of soil and rock were exposed. Starting around 1799, he prepared a geologic table showing observed strata listed in order (from London clay and chalk at the top, to coal, slate, and granite at the bottom), together with the kinds of fossils found in each layer. He observed that the order of the strata *and* of the fossils were the same from place to place, a correspondence that compelled the view that geologic time and paleontologic time marched together in sequence through the layers of rock. Over time, he extended these observations and prepared maps showing the geographic variation of these geologic formations by colored shadings (fig. 117). The combination of paleontology, lithology, topography, and geographic location made visible by Smith's map and the final "Geological Table of British Organized Fossils" (Smith 1816) would lead to a deep understanding that geologic time and the history of the earth and its inhabitants could be studied by examining the layers in the ground beneath our feet.

The discovery of atomic number

The hallmark of good science is the discovery of laws which unify and simplify disparate findings and allow predictions of yet-unobserved events or phenomena. Mendeleev's periodic table, for example, allowed him to predict the physical and chemical characteristics of Gallium (Ga) and Germanium (Ge) before they were discovered decades later (Mendeleev 1889).

Mendeleev's table, however, arranged the elements only by a serial number, denoting an atom's position in a list arranged by increasing atomic mass. This changed in 1913–14, when Henry Moseley investigated the characteristic frequencies of X rays produced by bombarding samples of the elements from aluminum to gold with high-energy electrons, and measuring the wavelengths (and hence frequencies) of two specific peaks or spikes (called K and L) in their spectra (Moseley 1913). He discovered that, if the serial numbers of the elements were plotted against the *square root* of frequencies in the X-ray spectra emitted by these elements, all the points neatly fell on a series of straight lines (see fig. 118). This must mean that the atomic number is more than a serial number; that it has some physical basis. Moseley proposed that the atomic number is the number of electrons in the atom of the specific element.

Moseley's graph represents an outstanding piece of numerical and graphical detective work. Had he plotted *raw* wavelength or frequency itself, he would not have observed this remarkable linearity. In effect, Moseley had also predicted the existence of three new elements (without having observed them), corresponding to the gaps in the plot at atomic numbers 43 (Technetium), 61 (Promethium), and 75 (Rhenium). He also noted slight departures from linearity which he could not explain; nor could he explain the multiple lines at the top and bottom of the figure. The explanation came later with the discovery of the spin of the electron.

CONTENT, FORM, AND FUNCTION OF GRAPHIC DATA DISPLAY

Thematic cartography and data graphics share numerous visual features, general attitudes, and goals, but unfortunately do not share much in the way of a common language for analyzing the characteristics of each or explaining their historical development. However, both are ultimately concerned with the task of putting graphic marks on paper or some other medium to convey information to a viewer, and it may be of some use to consider them together from a wider perspective to discuss their development and contributions to visualizing nature and society.

In the abstract, maps and diagrams can be considered communication devices for conveying information from a source (author or creator) to a target (recipient or viewer) using visual signs and symbols. Various displays differ in terms of the information *content* (subject matter), the visual *forms* and attributes used to encode this information, and the *function* (task or communication goal) that the display is designed to serve. By analogy with language, visual form relates to the grammar and syntax of graphics (Wilkinson 2005),

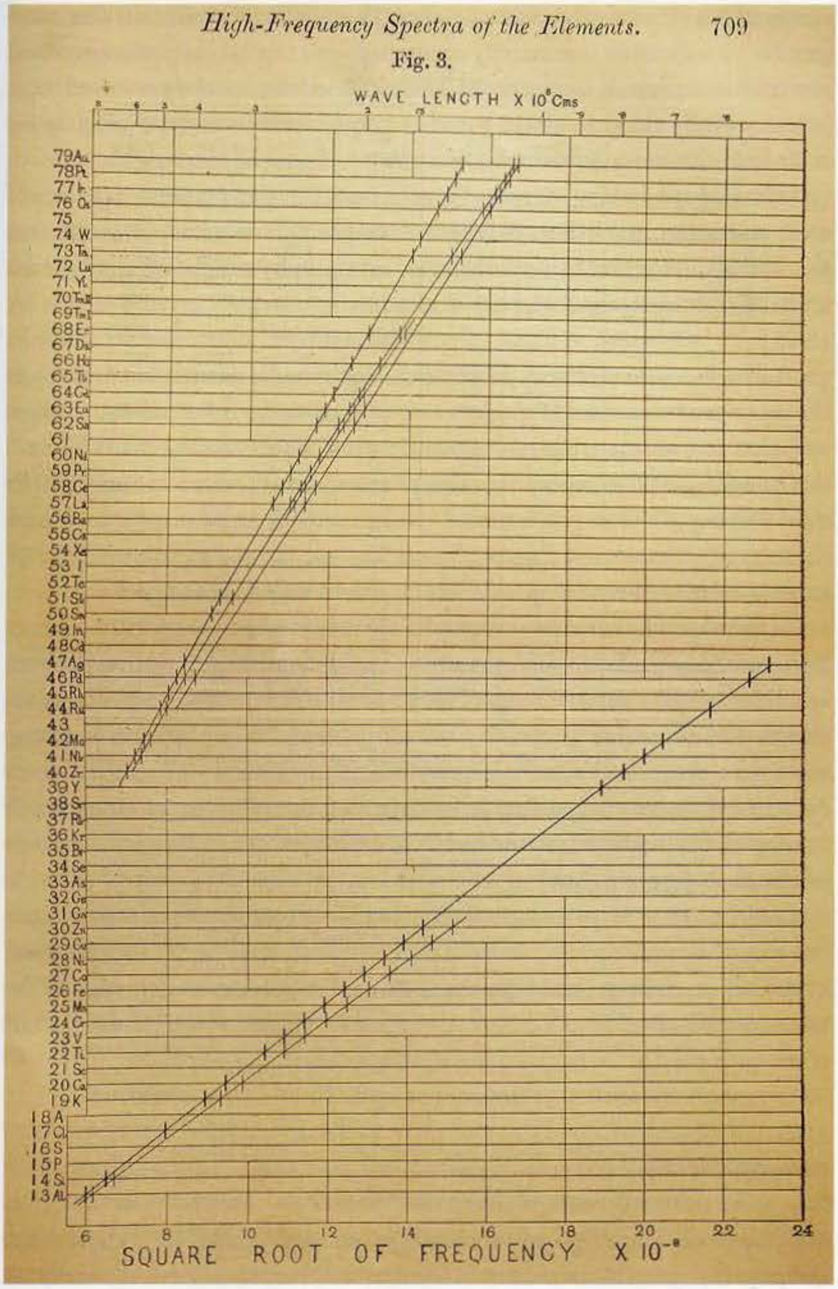


FIGURE 118.

Henry Moseley, graph of frequencies in X-ray spectra of chemical elements in relation to atomic number (1913).

content corresponds to meaning and semantics, while function relates to the pragmatic goals of communication.

At this level, both thematic cartography and data graphics are designed to convey quantitative or categorical information to a reader. They can use any of a wide range of visual attributes to map data items into graphic elements, and can be about similar subjects and topics. They differ, of course, in that cartographic visualization is primarily concerned with representation constrained to a spatial domain, but even spatially distributed data can be portrayed more or less usefully either in a map-based or graph-based form depending on the intended function or communication goal.

If we regard making maps and graphs from this perspective—as a form of communication, much like writing—we can distinguish at least three different functional roles served by both thematic cartography and data graphics, each with different design principles:

EXPLORATION. Exploratory data maps and graphs are designed to help reveal the pattern or structure of quantitative or qualitative information, to show variation across space, time, or circumstances. Most thematic maps fall into this category, as do data graphics used primarily to generate ideas and hypotheses. The use of dot or proportional symbol maps to show disease incidence (for example, Snow's dot map of cholera [fig. 140]) and of simple scatterplots to show relations between quantitative variables provide examples.

ANALYSIS. Analytic maps and graphs are driven more by goals of explanation, and are intended to aid in synthesizing, generalizing, or testing patterns and relations observed or suspected. To serve this end, the map or graphic design should provide for *direct* visual comparison. Examples include arranging several maps or diagrams side by side (figs. 126 and 133); overlaying additional information regarding potential risk factors for disease on a map; or overlaying the predicted relation under some model on a scatterplot, as shown in Moseley's graph (fig. 118).

PRESENTATION. Maps and graphs designed for presentation intend to stimulate thought or to convey conclusions. Their design principles include those of aesthetics, rhetoric, and exposition. Minard's well-known depiction of the fate of Napoleon's Grand Army is one example (Minard 1869); Playfair's chart of the national debt of England (fig. 130) is another.

THEMATIC MAPS

At first glance, the category of thematic maps, as distinct from general maps and even topographic maps, would seem both obvious and generally accepted. General maps attempt to show a variety of geographic features (waterways, roads, administrative boundaries, cities, and towns), while topographic maps add another layer of information to display something about an additional dimension, typically of elevation. These spatial features are all more or less concrete, fixed, and durable phenomena existing on the earth's surface. In contrast, the thematic map displays the occurrence, spatial pattern, or variation of one or a small number of phenomena in the physical, biological, social, or economic world, such as climate, natural resources, population characteristics, and commerce.

The term *thematic* was first used by the German geographer Nikolaus Creutzburg in 1952, entered common cartographic usage in the 1960s, and merited a book-length historical treatment by Arthur Robinson in 1982 (Robinson 1982). Among theoreticians of cartography, there has been lively debate over precise definitions and attributes that distinguish thematic maps from other maps. To begin with, in terms of graphic form and content, there are no simple criteria for distinguishing between a "topographic object" and a "thematic phenomenon." Besides, topography could be considered an entirely separate theme. On the other hand, some maps appear to belong neither wholly to the thematic nor to the topographic category; there is no clear boundary between the two kinds, and mixed or intermediary forms exist.

One rule of thumb that can serve to distinguish thematic maps from other kinds of maps is their selective aspect. Thematic maps are designed to highlight the spatial distribution of a subject, an aspect, or a specific distribution, as opposed to the topographic map, a general map which represents various phenomena together. However, this characteristic is not enough, for some maps illustrate a theme emerging from topography such as administrative limits, roads, or hydrography. Thus, the difference between a topographic and a nontopographic object has to be specified. Thematic maps are also more abstract; because they attempt to show phenomena that are more or less invisible, they are more an intellectual construction than a straightforward depiction of land surface. For Elizabeth Clutton, "the thematic map presents a mental ordering of space, generalizing and arranging beyond the limitations of the original data to offer a visual image of more abstract truths" (1983, 42). Barbara Petchenik describes this as the difference between maps whose meaning relates to "being in place," compared with those whose meaning relates to "knowing about space" (1979). A more detailed discussion of the difference between the two categories of maps can be found in Palsky (2003).

Nevertheless, before becoming a recognizable, "nameable" category, thematic maps evolved slowly, starting in the last half of the seventeenth century. Historically, forms of transition are observed that could be called "para-thematic" or "pre-thematic." In the seventeenth and eighteenth centuries, several cartographers proposed novel cartographic representations, either because they broke with the customary cartographic synthesis, or because they testify to new geographic curiosities and an enriched nomenclature of the world. We designate these two categories of maps as special-purpose and hybrid maps.

Special-purpose maps

Cartography in the early modern period progressed according to a principle of accumulation: it used symbols expressing an increasing number of places and seemed all the more useful when it expressed a large quantity of information. Even so, in the beginning of the seventeenth century some maps would emphasize *one* element of the topographic inventory.

Road maps were among the first examples. Ogilby's renderings, assembled in *Britannia—a Geographical and Historical description of the Principal Roads thereof* (1675), portrayed the principal roads in England by vertical bands juxtaposed on the same section, echoing the tradition of medieval itineraries (see the discussion in chapter 1 of the present text, pp. 39, 42–45 and fig. 15). Moreover, true maps of networks were conceived by the beginning of the seventeenth century. Nicolas Sanson (1632) traced royal roads and the location of stages on a general map of France. The map, designed for travelers and traders, replaced the manuscript lists in use until then. In England, Ogilby's work influenced John Adams and George Willdey's ([1712]) maps of the road network (fig. 119).

The selective approach is also found in maps showing different administrative and jurisdictional divisions, reflecting an extraordinary concern for marking off sovereignties. Maps of the hydrographic network provide another example of special-purpose cartography, though these were rarer. The first one designed on the scale of France was Sanson's work (1634), republished in 1641 (fig. 120). Sanson showed only the outline of rivers, their toponyms, and their channels. The big hydrographic basins were shown by watercolor.

How can this kind of cartography be interpreted? Its *analytic* principle presented several advantages. First of all, the choice of one element of the inventory allowed a new precision. Thus, Sanson aimed his map of rivers at the curious amateur, priding himself on providing more information. To this was added a visual advantage: the map was less dense, and therefore more easily readable. All the same, its superiority also lay in the level of understanding. In 1697, the Abbé de Dangeau underlined this in his treatise of geography:

> I realized by my own experience and those of others that all that prevents one from benefiting as much as one would like from maps and books, which until now were made to teach Geography, History and all that has a relation to it: mainly the multitude of objects that one sees simultaneously, in the poor order in which they are presented to the imagination. In order to improve this, I presented my work so as to show in sections on several different maps of the same country all that one sees in a single ordinary map. (Dangeau 1697, III)

The special-purpose map was in a way an echo of the Cartesian method of knowledge, which first invited a consideration of absolute things, that is to say singular, similar, equal, and independent, before going on to multiple and compound things. Moreover, Descartes proposed a comparison between his method of thought and the *view*, "for he who wishes to view several things simultaneously at a single glance sees none distinctly"; and similarly, "he who

FIGURE 119.

George Willdey, "The Roads of England according to Mr. Ogilby's Survey" (1712).

is used to thinking of many things at the same time in one single act, is confused" (1996, 67–68).

Hybrid maps

It was not until 150 years after Sanson's river map that another effort to map the hydrographic network of France appeared. It was drawn by the geographer-engineer Dupain-Triel (1781) and emerged in a very different context: the new interest after 1750 in the development of internal navigable waterways.

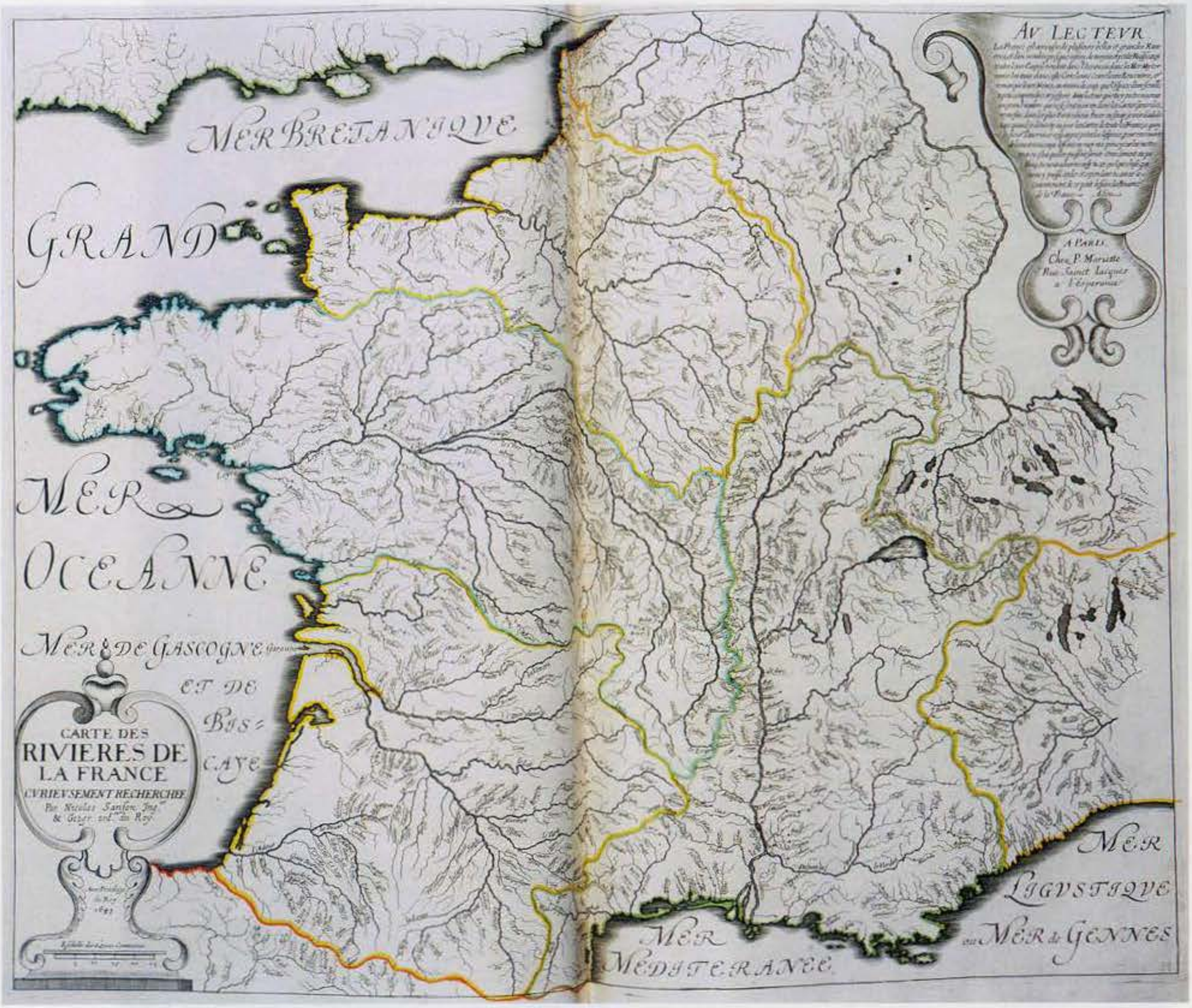


FIGURE 120.
Nicolas Sanson, "Carte des rivières de la France" [Map of the Rivers of France] (1634).

Selectivity remained rare in cartographic production in this period. Isolating an elementary geographic feature rather contradicted the natural tendency of cartographers, which was to add signs to complete the inventory.

At the beginning of the early modern period, many geographers drew attention to new objects, calling for their inclusion in maps. The Jesuit Antoine Lubin suggested, for instance, marking the outlines of big forests and distinguishing the types of trees, or indicating forges or mines, because of "the passion that men have always had for riches" (1678, 222). Initially, this advice had little effect. Knowledge and no doubt graphic language too was insufficient to supply these details.

The evolution was nonetheless irreversible: space was being differentiated, the inventory completed, stemming as much from a more utilitarian vision of nature as from the progress of natural sciences, especially during the eighteenth century. But if the map drew attention to new objects, it was often by adding, and accumulating. Most of the special maps before 1800 were mixed or "hybrid" maps, as Robinson noted: "Occasional thematic additions had been entered on otherwise general maps, but the idea of making a map solely for the purpose of showing the geographical structure of one phenomenon seems not to have occurred to anyone" (1982, 17).

Hybrid cartography was based principally on developments in the natural sciences; thematic additions related to various fields, such as meteorological phenomena, plant species, formations, land use, or natural catastrophes. Mineralogical maps were typical examples. Before 1700, some maps were already pioneers in localizing resources of precious metals, such as Olaus Magnus's "Carta marina" (Mariner's Map; 1539). During the eighteenth century, these maps multiplied. One of the most famous was Christopher Packe's "New Philosophico-Chorographical Chart of East Kent" (1743). Conceived to show the system of valleys in this part of England, it contains several mineralogical symbols besides the usual information in a county map. In France, the naturalist J. E. Guettard wrote several treatises on the nature of soils between 1746 and 1786. The geographer Philippe Buache illustrated a few, and in particular drew the first mineralogical map of North America in 1752 (fig. 121).

The maps described here differ sufficiently from modern thematic ones to be considered a special category. They reflect a progress in geographic knowledge, but this improvement was obtained without breaking totally with the cartographic spirit of the time: early "para-thematic" maps look very much like traditional topographic maps, because they either concentrate on one feature of the topographic inventory (roads, rivers) or they add a new feature or two (plants, minerals) to an already detailed inventory.

These para-thematic maps represent a transitional solution that can be understood from a dual scientific and graphic point of view. Scientifically, the thematic additions were adapted to the discontinuous nature of observations. In order to communicate scientific conceptions through thematic maps, Helen Wallis recalled the necessity of following several preparatory steps, including the collection of a sufficient corpus of data and its subsequent organization into a coherent system (1973). Thus, mineralogical maps, precursor elements of geologic cartography, followed this schema of construction of knowledge. Before 1780, it was exceptional to see the representation of a zonal composition of rocks. Guettard clearly indicated a three-band arrangement on his "Carte minéralogique où l'on voit la nature et la situation des terreins qui traversent la France et l'Angleterre" (Mineralogical Map Showing the Nature and Situation of the Terrain across France and England)—"sandy," "marly," and "slate or

FIGURE 121.

Philippe Buache, "Carte minéralogique où l'on voit la nature des terreins du Canada et de la Louisiane" [Mineralogical Map Showing the Nature of the Terrain of Canada and Louisiana] (1752).

metallic" (1746)—but his idea found little resonance, and pointwise additions remained the most frequent medium for translating new phenomena.

From the graphic point of view, para-thematic cartography followed old, familiar habits of presentation. As Umberto Eco put it, "The iconic representation produces real perception cramps and we are led to see things as they have long been presented to us by stereotyped iconic signs" (1972, 183). The situation is analogous to the usually slow pace of change in a society's art. Artists tend to paint the kinds of paintings their immediate predecessors painted, and people looking at paintings are troubled when they don't see the types of representations they are used to. The robust cartographic language that had developed since the Renaissance was ill suited to the depiction of new, invisible phenomena, and its very iconic familiarity delayed the introduction of a more flexible, autonomous language of thematic cartography.

THEMATIC MAPS OF THE PHYSICAL WORLD

Thematic sea maps

There is no doubt that a real thematic cartography was born a little before 1700 in the realm of the sea chart, which linked the selective approach and the expression of abstract phenomena. The development of navigation, due to commercial and colonial activities, permitted the multiplication of observations on winds, sea currents, and terrestrial magnetism. Knowledge that earlier was simply observational combined with scientific knowledge in this period. But mariners' knowledge related to a portion of the surface of the globe that constituted a blank page and was truly experimental, a place on which symbols could be created without conflicting with topographic elements. In a space devoid of visible objects, cartographers were forced to invent signs to show the invisible.

The idea of these maps once again preceded their material realization by several decades. In France, for instance, J. François invited cartographers as early as 1652 to think of "the horizon with winds . . . currents and other sea movements . . . , magnetic variations in several places in the sea and on earth" (1652, 359). The idea was taken up some years later by Lubin: "It would then be necessary to chart each of the winds on the sea map and register all the observations I have just evoked"—that is to say, their direction, their "length," their "breadth," their season. Nonetheless, these maps appeared very complicated to produce. Thus, for the winds, Lubin underlined that "the enterprise would be very new and difficult, but not impossible and (that) it would bring more glory to those who could do it" (1678, 281).

The Englishman Edmund Halley imagined the first thematic maps at the end of the seventeenth century. He drew a first map of oceanic winds (untitled; it is known as "Halley's chart of the monsoons and trade winds" [1686]); then, after a scientific journey on the *Paramour*, the first map indicating the magnetic variations in the Atlantic Ocean: "A New and Correct Chart Shewing the Variations of the Compass in the Western and Southern Ocean" (Halley 1701), followed by a world map on the same subject (fig. 53). Halley used a method borrowed from topography: isometric lines. He was convinced of the novelty and effectiveness of the application of "curve lines," as he called them, to terrestrial magnetism.

Halley's maps were distributed on the Continent and quickly imitated. A little after 1710, the map of magnetism was copied in France, probably by Guillaume Delisle, under the title "Carte des variations de l'aiguille dans l'océan occidental et méridional suivant les observations faites en 1700 par Edmund Hallei" (Map of the Variations of the Compass in the Western and Southern

Ocean according to Observations Made in 1700 by Edmund Halley). Winds, currents, and magnetism became the object of numerous representations during the eighteenth century. Among them can be cited the "Chart of the Gulf Stream" (fig. 122), drawn by Benjamin Franklin after Timothy Folger (Franklin 1768), which seems to have adopted François' suggestion—showing a marine current as a river in the ocean. These maps sometimes combined several themes: winds and currents, or winds and magnetism, as on J. N. Bellin's "Carte des variations de la boussole et des vents généraux" (Map of the Variations of the Compass and of the General Winds; Bellin 1765; fig. 123).

A representational novelty of limited distribution and constituting an end in itself, the thematic map thus evolved toward becoming a tool of comprehension and management of territory, an instrumental map, "capable of shedding light on complex features closely incorporated into natural and human space" (Konvitz 1980, 304). At the same time, graphic language underwent its own particular evolution. It was above all in the nineteenth century that it acquired its autonomy in relation to the figurative or analogical code of topography. With

FIGURE 122.
Benjamin Franklin and Timothy Folger, "A Chart of the Gulf Stream" (1768), detail.

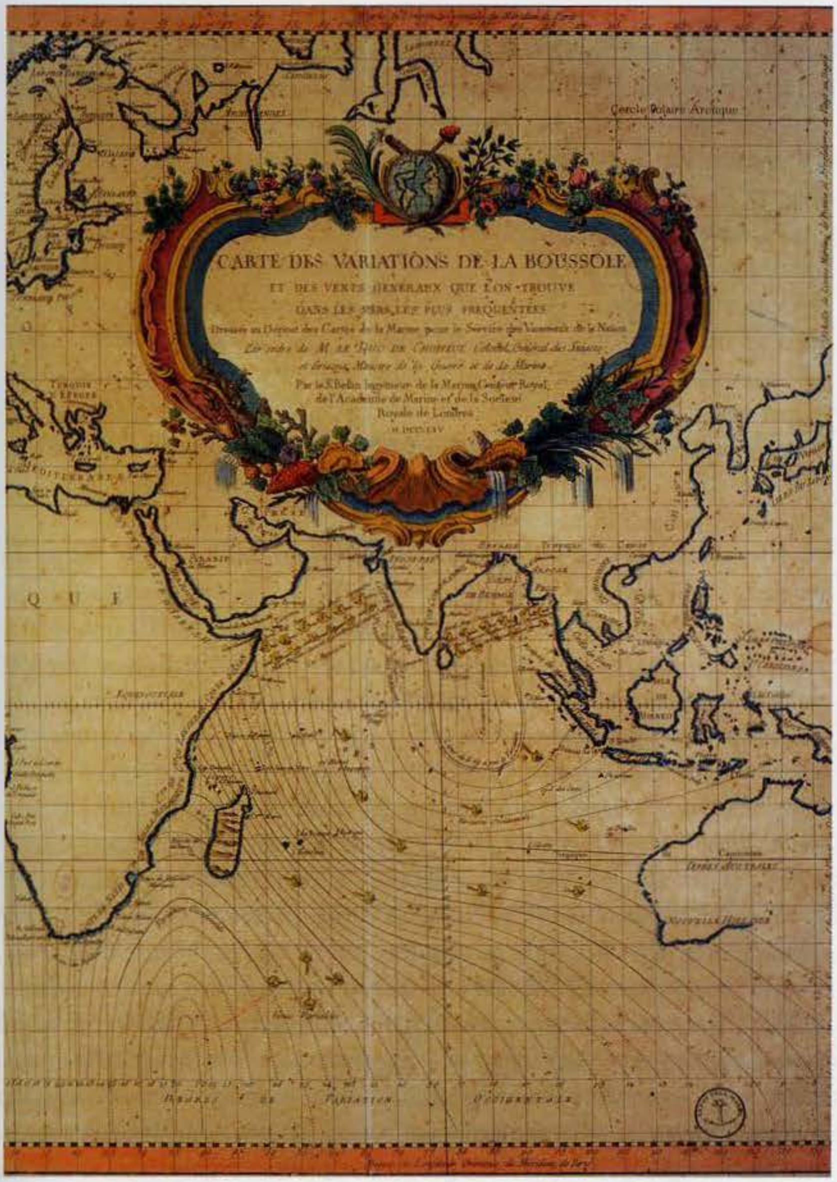


FIGURE 123.
Jacques-Nicolas Bellin, "Carte des variations de la boussole" (Map of Compass Variations), detail of the Indian Ocean (1765).

the development of an autonomous language of thematic mapping, the priority of representation was, in effect, reversed: topographic detail moved into the background and special themes into the foreground.

The influence of Carl Ritter and Alexander von Humboldt

The end of the eighteenth century saw an increasing number of maps featuring physical observations. Several colored maps recording the limits or extension of bedrock were produced in the framework of geognosy by Lommer (1768), Gläser

(1775), or Charpentier (1778). The first "zoographic" atlas, showing the distribution of animals on different continents with colored lines, appeared in 1800 (Jauffret 1800). These works, only a few examples of which are mentioned here, announced a flourishing cartography of physical phenomena in the nineteenth century. Carl Ritter and Alexander von Humboldt, the founders of scientific geography, played a fundamental role in the expansion of this cartographic field.

In 1806 Ritter published *Sechs Karten von Europa* (Six Maps of Europe), a small atlas that showed the distribution of cultivated plants, trees and shrubs, animals, and mountains, along with the limits of vegetation. The cartography remained very elementary: the essential information was expressed by text on the map and some colored highlights. However, the work enabled the correlation of natural data such as agricultural zones and climatic limits. It was the starting point of a rational and comprehensive physical cartography, itself an answer to Ritter's geographic project of a comparative knowledge of different parts of the globe (Ritter 1806).

Alexander von Humboldt's works appeared more original from the graphic point of view. As early as 1817, he drew the first "map" of isothermal curves, in reality a hybrid arrangement that was midway between a diagram and a map (fig. 124). This graphic was quite remarkable for several reasons. The top part shows smooth contours of constant temperature throughout the Northern Hemisphere; and although marked by scales of latitude and longitude, the map is nearly entirely implicit, save for a few place-names added for reference. Moreover, Humboldt recognized that temperature varies more with latitude and *altitude* than with longitude; to make visible this fourth dimension, he added the lower graph showing isothermal curves for altitude and latitude.

Humboldt described the results of his voyages in the New World in several volumes, often enriched by numerous illustrations. From the sum total of his observations, he wished to deduce laws of distribution of forms and considered graphic representations an essential tool for treating data: "The use of graphic means will shed light on phenomena of the greatest interest for agriculture and for the social state of the inhabitants. If instead of geographical maps, we only possessed tables . . . , a large number of curious connections that continents manifest in their forms and their surface inequalities would have remained unknown" (Humboldt 1817, 105). For example, Humboldt drew maps that show hydrographic, geobotanical, and geologic information, as well as vegetation sections, histograms, and other types of diagrams.

The observations of naturalists in the first half of the nineteenth century provided raw material for a diversified cartography. However, it must be stressed that the data were necessary, but not sufficient in themselves, for thematic cartography to flourish. In the present case, the use of diagrams and above all of maps was part of the scientific project of geography: spatializing in order to compare, classify, and explain. Humboldt's great scientific authority influenced the diffusion of graphic methods among several authors. His work

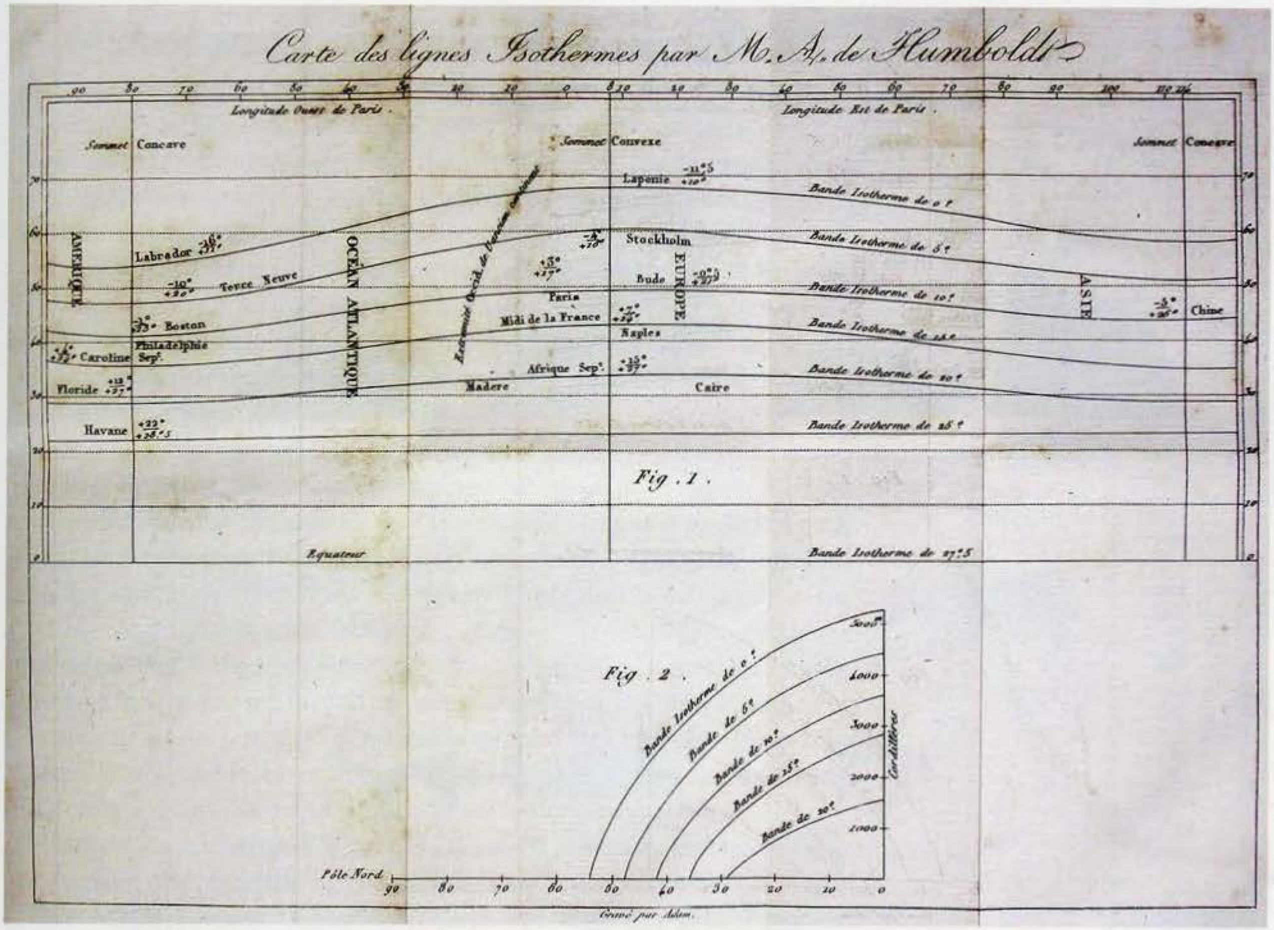


FIGURE 124.

Alexander von Humboldt, "Carte des Lignes Isothermes" [Map of Isothermal Lines] (1817).

on isothermal lines thus served as a reference for a veritable German school of cartographic treatment of meteorological data, marked by the works of Mahlmann and Kaemtz, the latter imagining "isobarometric" lines in 1832.

Nonetheless, the most important next step was Heinrich Berghaus's realization of the first big thematic atlas, the *Physikalischer Atlas* (Berghaus 1838–48; fig. 61). The work was undertaken on the suggestion of Humboldt, who saw it as the graphic counterpart of his project describing the "Kosmos." Borrowing from the best sources, it contained sixty maps, divided into six sections: Meteorology, Climatology, Hydrography, Geology, Magnetism, Phytogeography, and Zoogeography. The work was quickly copied and even plagiarized in Germany. It was also imitated abroad. In Scotland, A. K. Johnston (1848 and later editions) published the *Physical Atlas*, with plates (full-page illustrations) partly taken from Berghaus and partly original, among them the splendid, Humboldt-inspired planisphere of botanic geography decorated with vegetation profiles or sections (fig. 125). The German cartographer Augustus Petermann collabo-

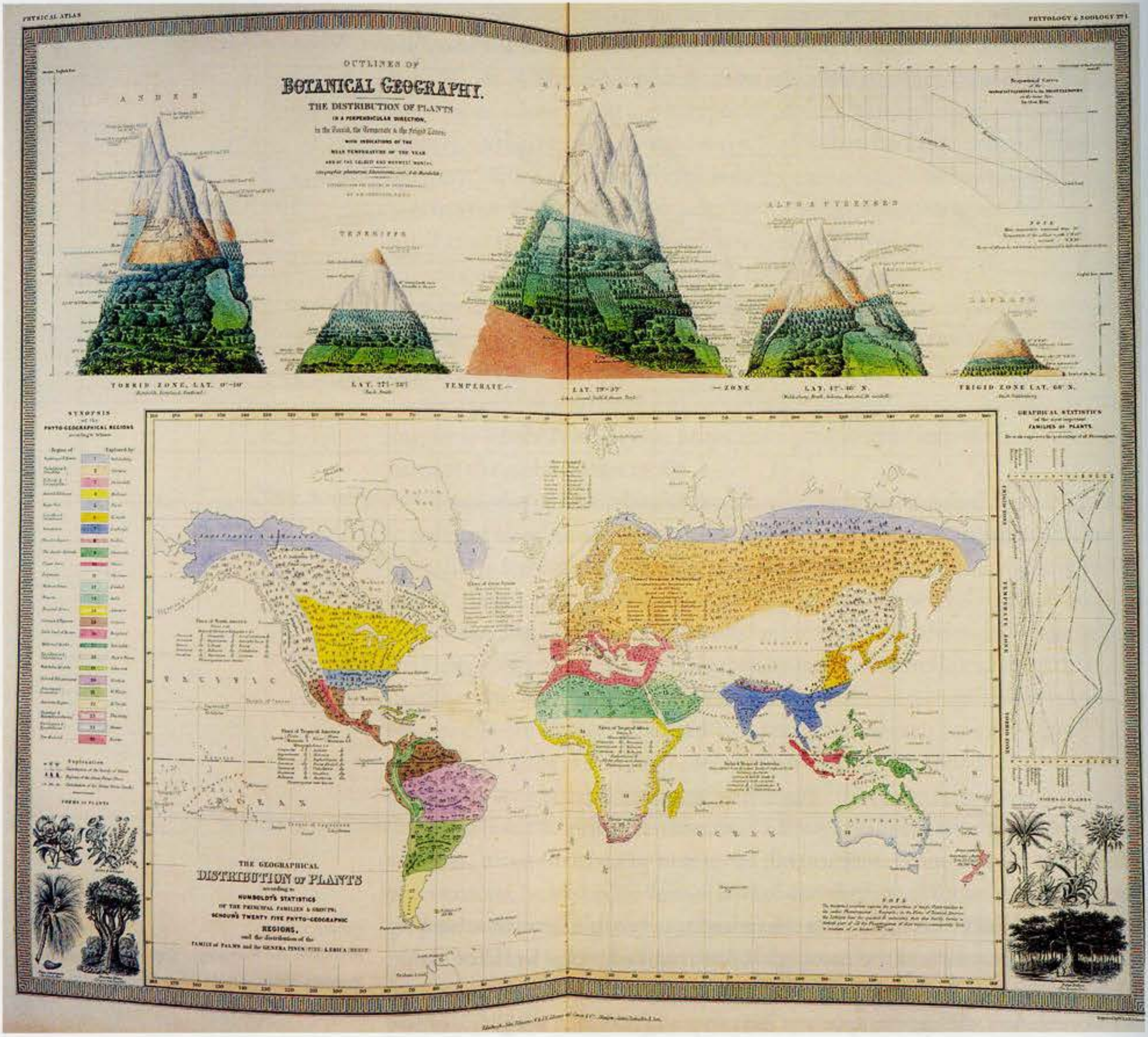


FIGURE 125.
Alexander Keith Johnston, "The Geographical Distribution of Plants" (1850).

rated in this production and then published his own *Atlas of Physical Geography* (1850). In France, physical maps were included in later atlases, such as Hercule Nicolet's *Atlas de physique et de météorologie agricoles* (Atlas of Agricultural Physics and Meteorology; 1855), or J. A. Barral's *Atlas du Cosmos* (1861).

Geologic maps

Alongside these major works were more isolated ones. This was the case of geologic maps produced at the beginning of the nineteenth century. Modern geologic science took shape between 1800 and 1830 around a certain number of concepts that were new or had matured for a long time, including distinguishing among sedimentary soils in *chronological* units, dated from the fossils found there, rather than lithological units, identified by soil and rock types. Stratigraphic paleontology replaced litho-stratigraphy. The first modern geologic maps were linked to these developments by color coding soils by age. A pioneering work was the "Carte géognostique des environs de Paris" (Geological Map of the Environs of Paris) by Cuvier and Brongniart (1808). Based on Lamarck's research on fossils, the authors identified nine sedimentary formations around Paris. The colors of their map, laid in flat tones, were reproduced in an inset, vertically arranged in the very order of the deposits. The legend and the sections joined to the map (including an "ideal cross section," or stratigraphic scale) thus provided structural information: they allowed the extrapolation of the rocky volume in three dimensions.

As we noted at the beginning of the chapter, the grand project of early geologic mapping was accomplished by William Smith. Begun at the end of the eighteenth century, it culminated with the publication of "A Delineation of the Strata of England and Wales with Part of Scotland" (Smith 1815) on a scale of 5 miles (8 km) to the inch (1:316,800) (fig. 117). The huge map, measuring nearly 6 feet by 9 feet (1.8 × 2.7 m), is a real masterpiece. Different strata are identified by twenty-three colors, all applied by hand in this period before color lithography. Simon Winchester (2001) makes a good case for the practical and theoretical importance of Smith's map, calling it "the map that changed the world."

After 1820, maps based on stratigraphy multiplied. A second general map of England was published by Greenough (1820), then completed and republished in 1839. Leopold von Buch (1826) drew a geologic map of Germany and neighboring countries, as did Heinrich von Dechen (1838). In France, the inspector general of mines, Brochant de Villiers, was concerned about the absence of a sufficiently precise geologic map enabling the development of the mining industry. He elaborated a project in 1822, whose realization was given to two polytechnicians and mine engineers, Dufrénoy and Elie de Beaumont (1840). They stayed in England to learn the methods of work, and then made their observations in France from 1825 to 1835. Their map was engraved in 6 sheets at a scale of 1/500,000 and presented to the Academy of Sciences in 1841.

Such small-scale maps served as a basis for the detailed renderings at larger scales that were undertaken in the following decades. Geologists' work also extended to colonies and young republics of the New World, which were ideal fields for the observations of naturalists. Thus, the geologically colored "Carte générale de la république de Bolivia" (General Map of the Republic of Bolivia) testified to the results obtained by the Frenchman Alcide d'Orbigny during his trip to South America from 1826 to 1834, at the request of the Museum of Natural History in Paris (Orbigny 1842).

The development of charts, diagrams, and graphs in many ways runs parallel to that of thematic maps, and arose from similar problems and similar desires to move from observations and evidence to understanding and explanation. Among the most important problems of the seventeenth century were those concerned with physical measurement—of time, distance, and space—for astronomy, surveying, mapmaking, navigation, and territorial expansion. This century also saw great new growth in theory and the dawn of practical application of data to scientific problems: the rise of analytic geometry and coordinate systems (Descartes and Fermat), early theories of errors of measurement and estimation (J. Mayer and Gauss), the birth of probability theory (Pascal and Fermat), and the beginnings of demographic statistics and "political arithmetic" (Graunt). We use two early examples to illustrate these beginnings.

Scheiner's sunspots

In late 1609, Galileo constructed one of the first astronomical telescopes and almost immediately made a series of important discoveries—craters on the moon, a huge number of new stars, observations on the moons of Jupiter, sunspots—which he published in *Sidereus nuncius* (The Starry Messenger) in March 1610. News of Galileo's discoveries traveled quickly, and Christophe Scheiner (1573–1650), a Jesuit in Augsburg with talents in mathematics and instrument making, constructed a device to record the position and movement of sunspots over time. The substantive and philosophical issue was the Jesuit-assumed perfection of the sun (could sunspots be explained as shadows cast by moons?), but the evidentiary issue was how to display *changes* in configurations of sunspots over time.

Scheiner (1612) adopted a display form that appears quite modern today. He simplified the recording from each day from October 23 to December 19 of 1611 into a spot map showing the location and extent of sunspots, and then arranged these into a semigraphic[1] table (fig. 126), using a principle of graphic design that allows the eye to track changes across these thirty-seven images (Tufte [1983] calls this "small multiples"). Two main legends are used to identify the seven sunspots tracked (by the letters A–G) and the changing orientation of the sun over time. Part map, part graph, but more, Scheiner's visual representations of sunspots could win awards for graphic design today.

Scheiner's greatest work on sunspots, *Rosa Ursina* (The Rose of Orsini, after Scheiner's patron; 1626), pioneered new ways of representing the motions of spots across the sun's face by combining the daily configurations with movement of the sun across the ecliptic. Shortly thereafter, sunspot activity decreased drastically (the so-called Maunder Minimum, ca. 1645–1710) and interest in sunspots waned. A cyclic pattern in sunspots of approximately eleven

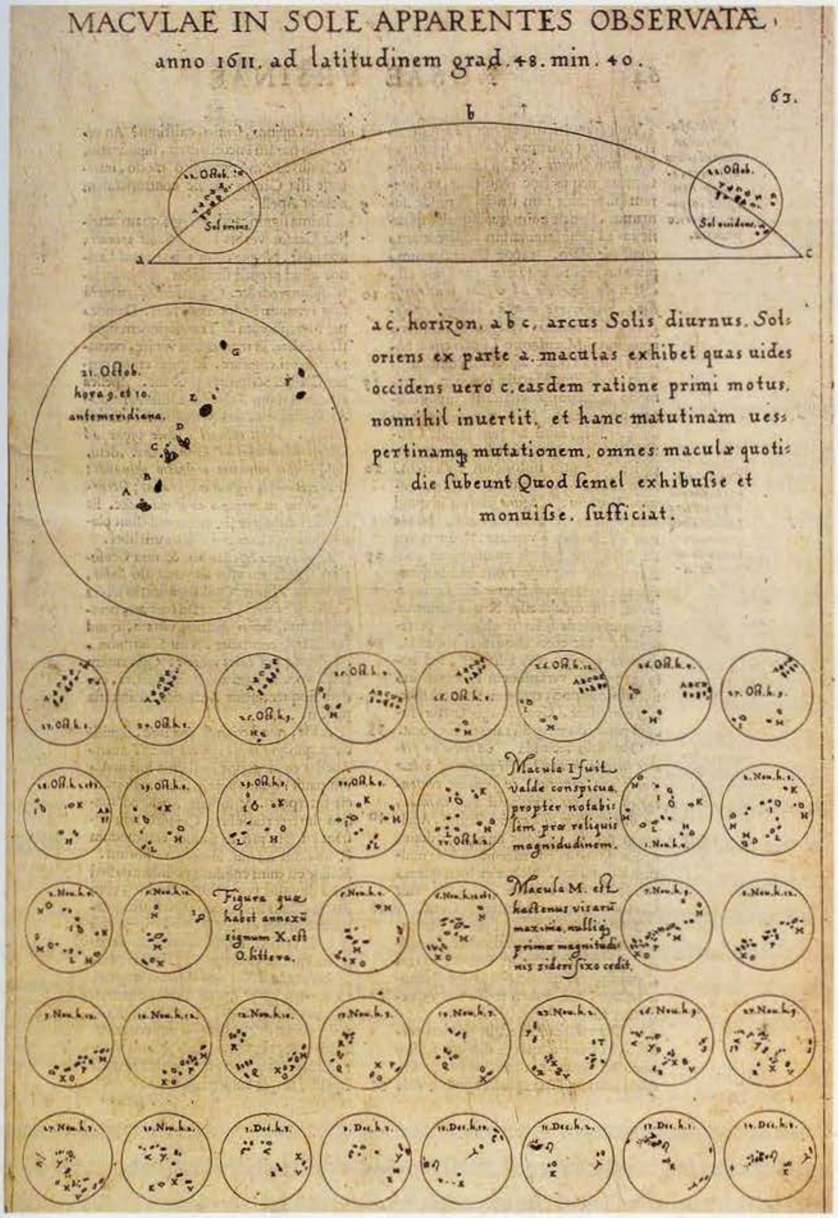


FIGURE 126.

Christophe Scheiner, "Maculae in sole apparentes observatae" (Spots Observed Appearing on the Sun) (1626; first published 1612).

years' duration would later be discovered by E. W. Maunder (1904) using a "butterfly diagram" to depict changes in sunspot location and intensity over time.[2]

Problems of longitude

Another remarkable example of the early interplay between maps and graphs is the attempt by Michael Florent van Langren (1600–1675), a Flemish cosmog-

FIGURE 127.
Michael Florent van Langren, Variations in the estimates of the difference in longitude between Toledo and Rome (1644).

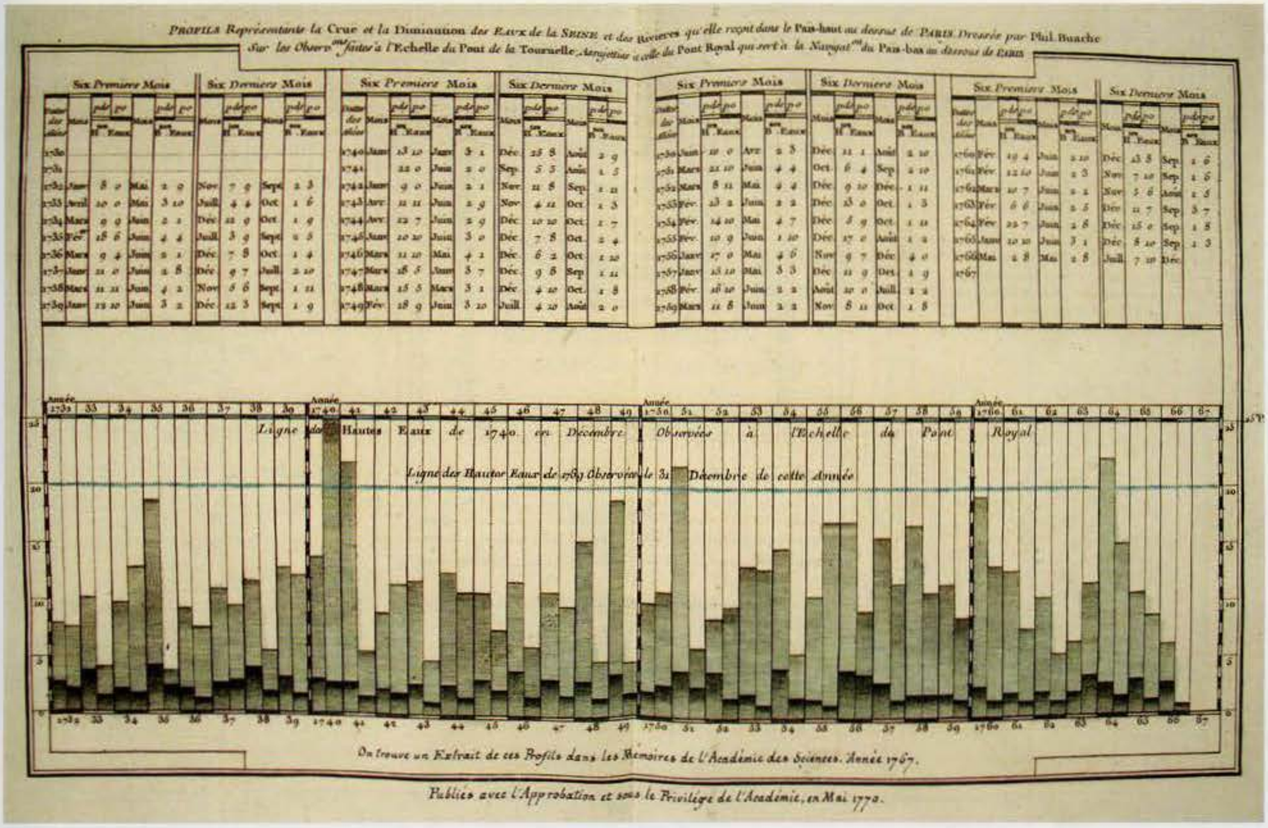
rapher to the court of Spain, to portray variations in the determination of longitude (fig. 127), believed to be the first visual representation of statistical data (Tufte 1997, 15). At that time, lack of a reliable means to determine longitude at sea hindered navigation and exploration (Sobel 1996).

This one-dimensional line graph (Langren 1644) shows all twelve known estimates of the difference in longitude between Toledo and Rome, and the name of the astronomer (Mercator, Tycho Brahe, Ptolemy, and so on) who provided each observation. What is notable is that van Langren could have presented this information more easily in various tables—ordered by author to show provenance, by date to show priority, or by longitude to show the range. However, only a graph shows simultaneously (1) the wide variation in the estimates (the range of values covers nearly half the length of the scale); (2) the central or estimated value (marked "ROMA"), along with (3) the names and values attached to the individual determinations.[3] Van Langren's graph is also notable as the earliest-known exemplar of the principle of "effect ordering for data display": "order information in graphs and tables according to what should be seen" (Friendly and Kwan 2003).

New graphic forms

With some rudiments of statistical theory, data of interest and importance, and the idea of graphic representation at least somewhat established, the eighteenth century witnessed the expansion of these aspects to new domains and new graphic forms. Abstract graphs and graphs of mathematical functions became widespread, and as economic and political data began to be collected, some novel visual forms were invented to portray them so the data could more easily "speak to the eyes."

Interest in a wider range of phenomena called for new abstractions and adaptations of visual forms. For example, in 1770, Philippe Buache published (with Guillaume Delisle) *Cartes et tables de la Géographie physique*, containing a chart and table of high and low water levels in the Seine over time, semiannually from 1732 to 1766 (fig. 128). Buache, a physical geographer, was quite used



to profile maps of terrain elevation over space. To show changes over time, he substituted time for space, and used two levels of shading to distinguish high and low water levels (Buache 1770). A modest change visually, the substitution of concrete space by a more abstract dimension of time anticipates time series graphs and bar charts that would develop shortly.

As another example, geometric figures (squares or rectangles) and cartograms to compare areas or demographic quantities were introduced by Charles de Fourcroy (1782) and August F. W. Crome (1785). Figure 129 shows the English version of a "map" of the "statistical relations of Europe," produced in 1819 by Crome and engraved by Aaron Arrowsmith, notable for the combination of superimposed squares (showing area) and divided circles showing data on population and finances. Time lines, or "cartes chronologiques," were developed to portray people and events in history by Jacques Barbeu-Dubourg (on a 54-foot [16.2-m] scroll) and by Joseph Priestley (1765, 1769). Priestley's invention would shortly serve as an inspiration for William Playfair, whose work can be considered the origin of modern statistical graphics.

Playfair (1759–1823) is widely considered the inventor of most of the graphic forms used today—first the line graph (to portray economic data over time)

FIGURE 128.

Phillipe Buache, "Profils représentants la crue̎ et la diminution des eaux de la Seine et des rivières qu'elle reçoit dans le païs-haut au dessus de Paris" (Profiles Showing the High and Low Waters of the Seine and Its Inflowing Rivers in the High Lands above Paris) (ca. 1770).

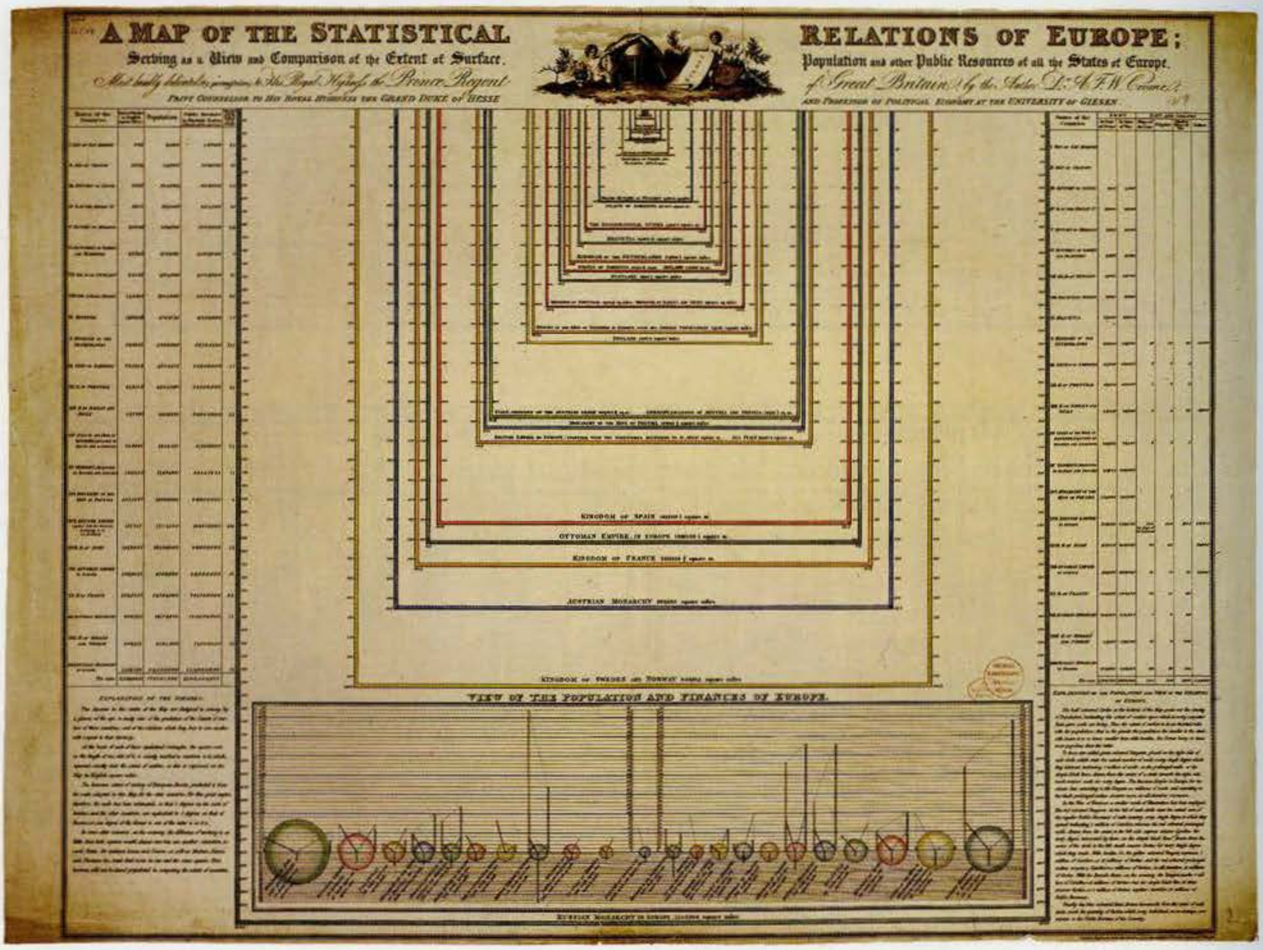


FIGURE 129.
August F. W. Crome, "A Map of the Statistical Relations of Europe" (1819).

and bar chart (1786), and later the pie chart and circle graph (1801). In the *Commercial and Political Atlas*, published in three editions in England (1786–1801) and one in France (1789) and the *Statistical Breviary* (1801; French translation 1802), Playfair adapted and invented an astonishing number of graphic constructions to convey economic data to the eye. "His genius was to realize that nonspatial quantities such as expenditures and historical time could be represented by physical space and that such representations offered advantages denied to tabular presentations" (Wainer and Spence 2005, 30). Such graphs were indeed novel; he referred to the idea to represent quantities by lengths of lines along a scale as "lineal arithmetic" and devoted several pages to description of how to read a graph.

Figure 130 shows his time series chart of the national debt of England. It is surprisingly modern in graphic design, with axis scales, major and minor grid lines, an aspect ratio (height to width) that enhances vertical differences, and text labels for significant historical events. Playfair's message is abundantly clear: the national debt has risen dramatically, and each sharp upward turn occurred in times of war.

Another chart (fig. 131) offers a creative combination of different visual forms: circles (used to show the area of nations), a pie chart (to show the divisions of the Turkish Empire), and lines (to show both population and taxes). In this figure the left axis and the left line on each circle shows population, while the right axis and line shows taxes in millions of pounds. Playfair intended that the slope of the line connecting the two would depict the *rate* of taxation, and argued that the British were overtaxed compared with the other nations. The graph is flawed, because the slope also depends on the diameter of the circle. It would also be considered sinful today, because separate *y* scales allow perceptions to be manipulated by rescaling one axis or the other. In Playfair's defense, the idea of calculating and graphing rates or other indirect measurements was still a half century away, and his main point is sustained because the line for Britain slopes in the opposite direction to most of the others.

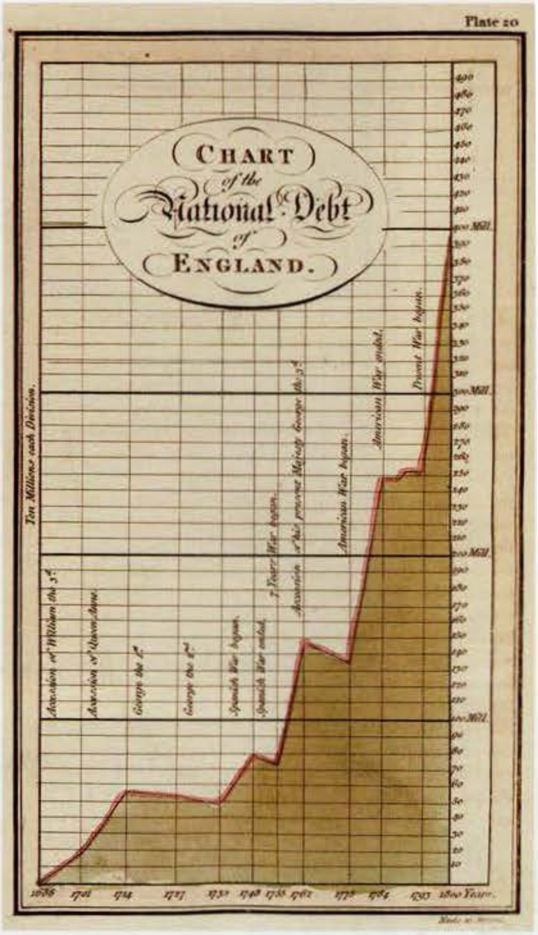


FIGURE 130.
William Playfair, "Chart of the National Debt of England" (1801).

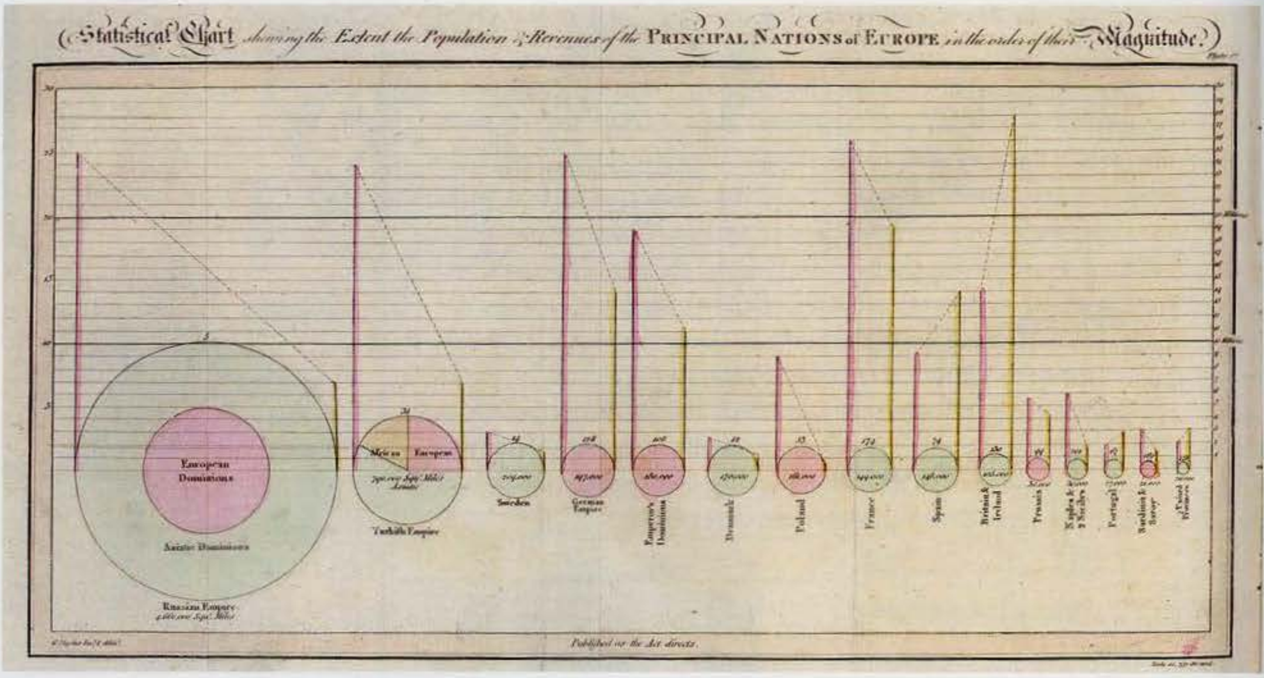
Beginnings of modern statistical graphics

In the first half of the nineteenth century, all the modern forms of data display were invented: bar and pie charts, histograms, line graphs and time series plots, contour plots, scatterplots, and so forth. But another development—the widespread collection of population, economic, social, and medical data—spurred explosive growth in applications of statistical representations by graphic displays at a rate that would not be equaled until modern times.

As the modern states of Europe developed, it was seen that statistics (originally meaning "numbers of the state") were crucial for national planning, social legislation, and economic progress. Where should railroads and canals be built? What was the distribution of imports and exports? What should be done to control crime? Statistical bureaus that were established in many countries created an "avalanche of numbers" (Hacking 1990), but graphic methods often proved essential in deciphering them.

The use of diagrams and maps in understanding social or "moral" statistics will be detailed in the final section. Here we illustrate this period with a novel 1844 *tableau figuratif* (fig. 132) by Charles Joseph Minard, engineer for the École Nationale des Ponts et Chaussées (national school of bridges and roads) in Paris. Minard is, of course, best known for his depiction of the fate of Napoleon's Grand Army in what has been called the "best statistical graphic ever drawn" (Tufte 1983).

This inventive graph is related to the modern bar chart and mosaic plot (Friendly 1994, 2002), but Minard introduced two simultaneous innovations: the use of divided and proportional-width bars so that the *area* of each rectangle had a concrete visual interpretation. Through these variable-width, divided bars, the graph shows the transportation of commercial goods along one canal


Statistical Chart shewing the Extent the Population & Revenues of the PRINCIPAL NATIONS of EUROPE in the order of their Magnitude.
European Dominions
Asiatic Dominions
Russian Empire
4,000,000 Sqr. Miles
African
European
Asiatic
Turkish Empire
Sweden
German Empire
Emperor's Dominions
Denmark
Poland
France
Spain
Britain & Ireland
Prussia
Naples & 2 Sicilies
Portugal
Sardinia & Savoy
United Provinces
Published as the Act directs.

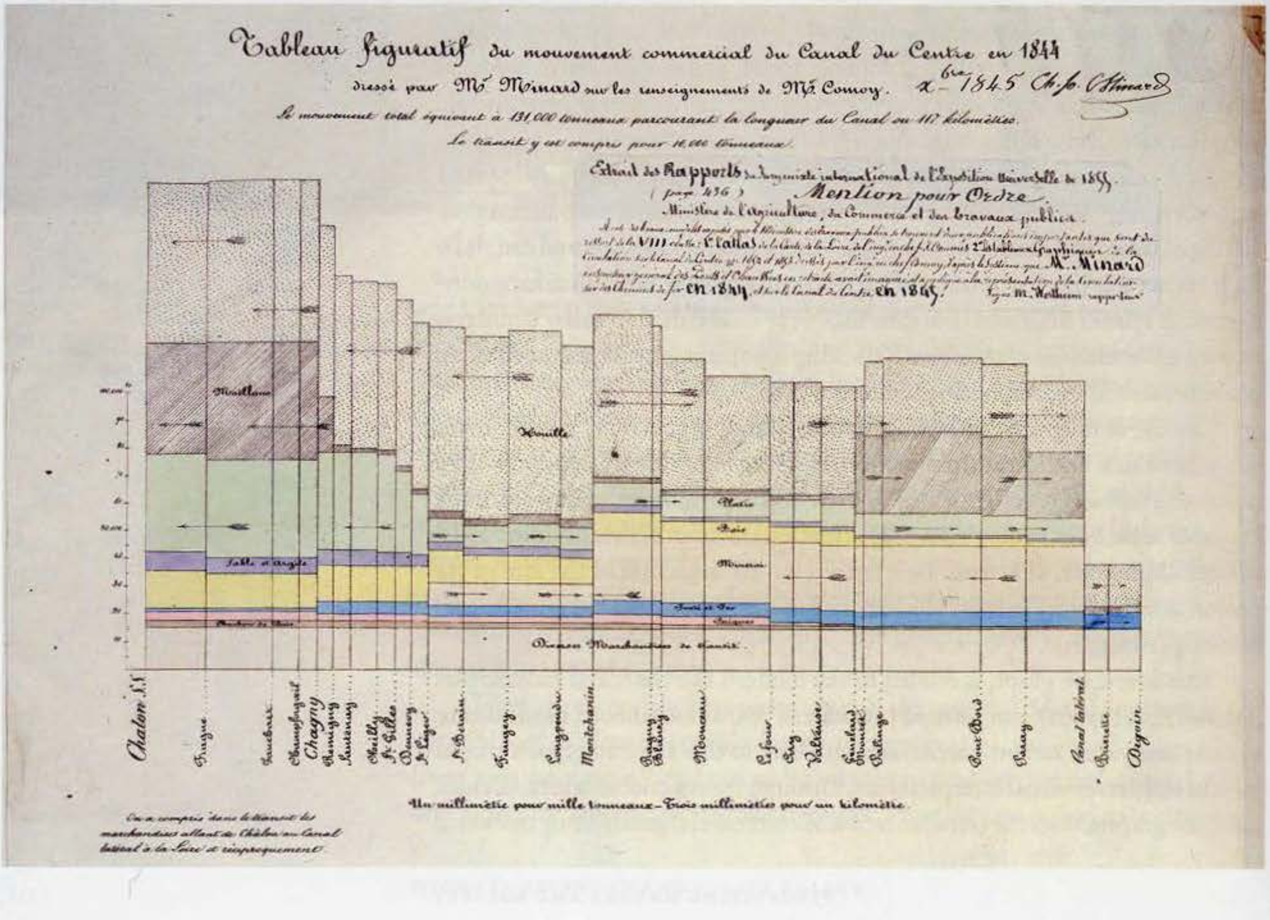


Tableau figuratif du mouvement commercial du Canal du Centre en 1844
dressé par Mr. Minard sur les renseignements de Mr. Comoy. 10bre 1845 Ch. J. Minard
Le mouvement total équivaut à 131,000 tonneaux parcourant la longueur du Canal ou 117 kilomètres.
Le transit y est compris pour 16,000 tonneaux.
Extrait des Rapports du Jury mixte international de l'Exposition Universelle de 1855.
(page 436)
Mention pour Ordre
Ministère de l'Agriculture, du Commerce et des travaux publics.
Moellons
Houille
Sable et Argile
Plâtre
Bois
Minerai
Fonte et Fer
Briques
Diverses Marchandises de transit.
Chalon S.S.
Fragne
Fontaines
Champforgeuil
Chagny
Remigny
Santenay
St. Gilles
St. Léger
St. Bérain
Longpendu
Montchanin
Blanzy
Monceau
Ecuisses
Pont-Bord
Canal latéral
Digoin
Un millimètre pour mille tonneaux – Trois millimètres pour un kilomètre.
On a compris dans le transit les marchandises allant de Châlon au Canal latéral à la Loire et réciproquement.

route in France (Minard 1845b). The questions at hand were how to plan and charge for transportation of various goods (coke, minerals, wood, and so forth) along various portions of the route (differential rates for partial versus complete runs; effect of direction of shipment). In this display the width of each vertical bar shows distance along this route; the divided bar segments have height proportional to amount of goods of various types (shown by shading), so the area of each rectangular segment is proportional to cost of transport. Direction of each type of shipment is indicated by arrows. Minard used this diagram to argue that differential rates should be set for various partial runs. Whereas Playfair had tried to make data "speak to the eyes," Minard wished to make them "calculer par l'œil" (calculate by eye) as well (Minard 1861, 4).

The golden age of statistical graphics

By the mid-1800s, the combination of abundant data of real importance, emerging statistical theory, and technological advances in reproduction provided the conditions for rapid growth—a "perfect storm" for advancements in data visualization. What started as the "Age of Enthusiasm" (Funkhouser 1937; Palsky 1996) for data graphics ended with what can be called a golden age, often with beauty difficult to find in modern graphics. So varied were these developments that it is even difficult to be representative; some highly selective examples must suffice to illustrate a few themes.

One important theme was the desire to display more complex phenomena and more than two variables simultaneously on a flat piece of paper. Earlier developments of isolines on thematic maps and contour diagrams of relatively simple and error-free physical data (variations of temperature or barometric pressure over time and space) were extended to three-dimensional surface plots of population by age and time (for example, by Gustav Zeuner in Germany and Luigi Perozzo in Italy) and, most important, to situations where the relations were statistical or only approximate, rather than functional ones or those measured with little error.

Among the scientific advances of this period that depended directly on insights gained from graphic analysis of statistical data in three or more dimensions, there are two that stand out, both due to Sir Francis Galton. The more well known is Galton's discovery of the bivariate normal correlation surface (Galton 1886), from data on the relation between heights of parents and their offspring. Galton constructed a table of grouped frequencies of heights of parents and children and drew smoothed isofrequency contours. He noticed that (1) the contours of equal frequency approximately formed a series of concentric ellipses and (2) the loci of the mean of y given x and of x given y were approximately the conjugate diameters of the ellipses. These relations would later form the basis for the theory of correlation and regression (Pearson 1901).

FIGURE 131.
[facing, top] William Playfair, "Statistical Chart Shewing the Extent, the Population and Revenues of the Principal Nations of Europe" (1801).

FIGURE 132.
[facing, bottom] Charles Joseph Minard, "Tableau figuratif du mouvement commercial du canal du Centre en 1844" (Figurative Chart of Trade on the Canal du Centre in 1844) (1845).

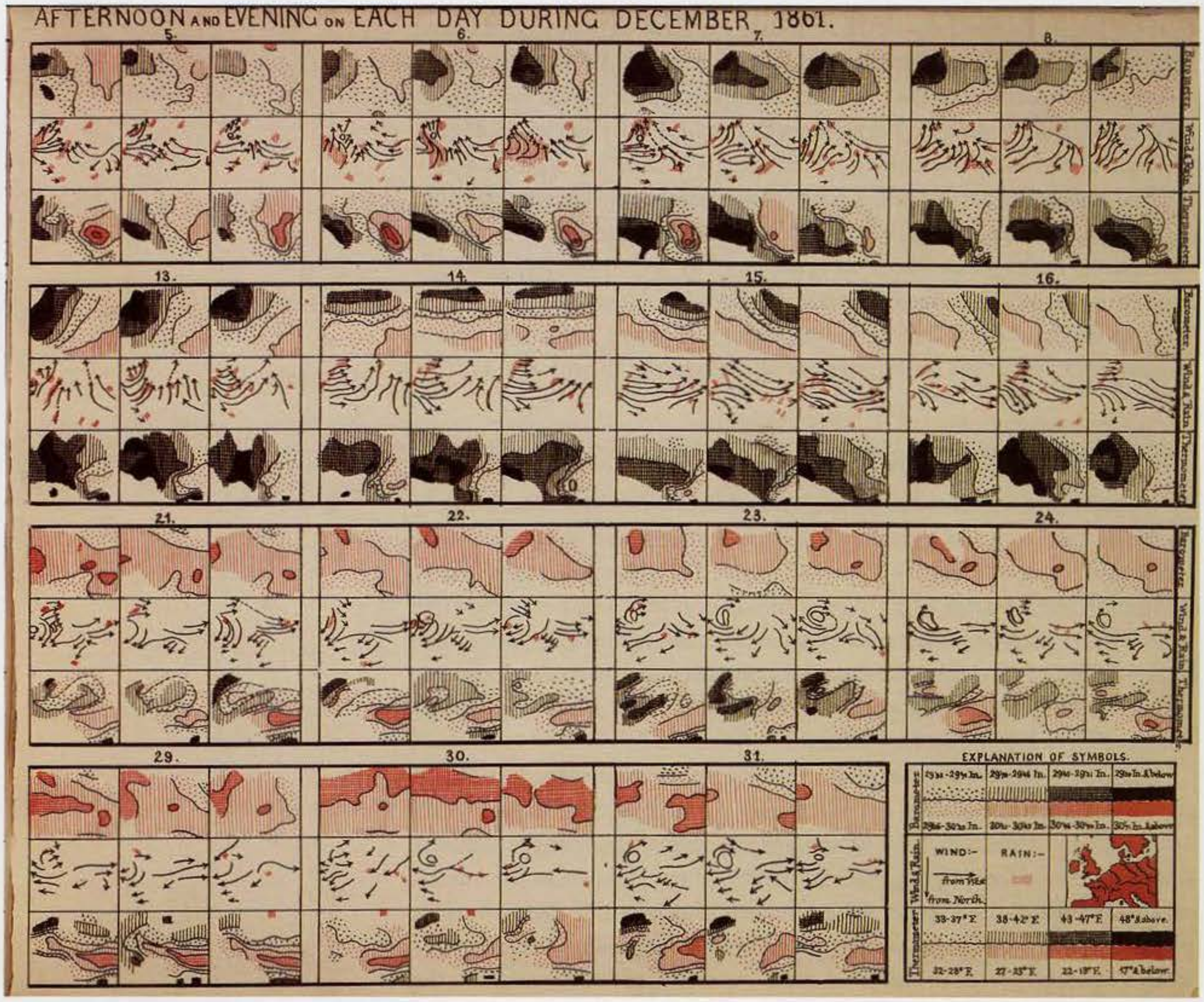


FIGURE 133.

Francis Galton, "Charts of the Thermometer, Wind, Rain, and Barometer on the Morning, Afternoon, and Evening on Each Day during December 1861," detail of right half (1863).

Less well known but perhaps the most notable nonstatistical graphic discovery of all time was that of the "anticyclonic" (counterclockwise) pattern of winds around low-pressure regions, combined with clockwise rotations around high-pressure zones. Galton's work on weather patterns began in 1861 and was summarized in *Meteorographica* (1863). It contained a variety of ingenious graphs and maps (over six hundred illustrations), one of which is shown in figure 133.

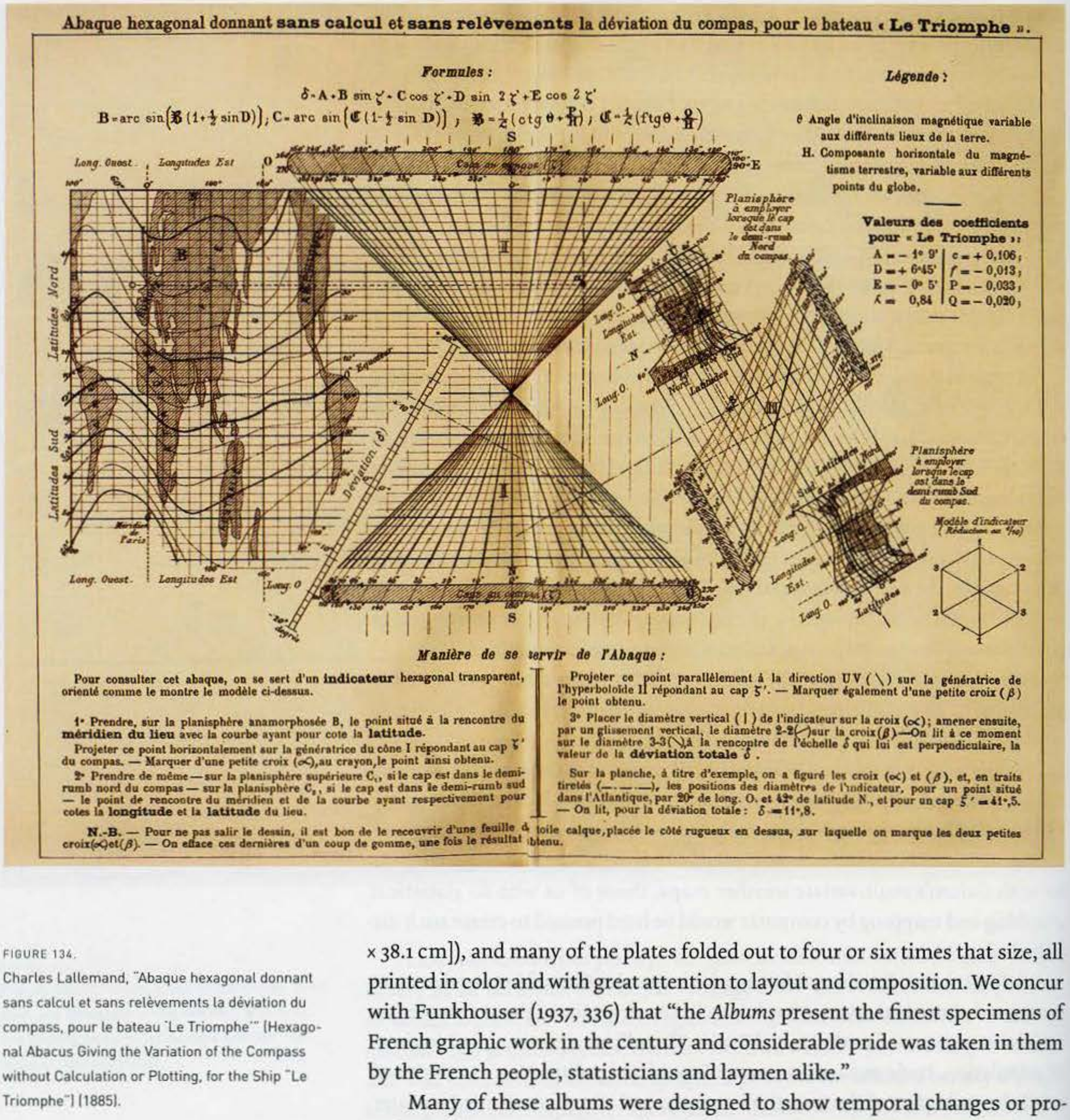
This remarkable chart, half of a two-page, multipanel display, shows observations on barometric pressure, wind direction, rain, and temperature from fifteen days in December 1861.[4] For each day, a panel of three rows and three columns shows nine schematic maps of Europe, mapping pressure (row 1), wind and rain (row 2), and temperature (row 3) in the morning, afternoon, and evening (columns). One can clearly see the series of black areas (low pressure) on the barometric charts for about the first half of the month, corresponding to the counterclockwise arrows in the wind charts, followed by a shift to red areas (high pressure) and more clockwise arrows. Howard Wainer remarks, "Galton did for the collectors of weather data what Kepler did for Tycho Brahe. This is no small accomplishment" (2005, 56).

This chart was not the source of Galton's inspiration. Rather, it is the summary graphic he devised from ninety-three separate schematic maps of his data, each one using special iconic symbols he devised to show the weather measurements. As with Scheiner's graph of sunspots, the composition of many small figures into a single, "small-multiple" display permits visual comparisons of changes and patterns that could not be seen otherwise.

A second theme concerns transformations of data and maps to make relations simpler and enable their use for direct, visual calculation. Some examples from this period are the semilogarithmic graphs introduced by the economist William S. Jevons (1863) to show *percentage* changes in commodity prices over time; log-log plots to show multiplicative relations (Lalanne 1846) as linear graphs; anamorphic maps by Émile Cheysson (reproduced in Palsky 1996 as figs. 63–64) using deformations of spatial size to show a quantitative variable (for example, the decrease in travel time from Paris to various places in France over two hundred years); and alignment diagrams or nomograms using sets of parallel axes (Ocagne 1885, 1899) for calculating complex functions.

We illustrate this slice of the golden age with figure 134, a tour-de-force graphic by Charles Lallemand (1885) for determination of magnetic deviation of the compass at sea in relation to latitude and longitude without calculation. Lallemand was an engineer, best known as director general of the geodetic measurement of altitudes throughout France. This graphic combines many variables into a multifunction nomogram using three-dimensional figures, juxtaposition of anamorphic maps, parallel coordinates, and hexagonal grids. As with Galton's multivariate weather maps, those of us who do statistical graphing and mapping by computer would be hard pressed to create such displays today.

A final theme for the golden age is the production of impressive state-sponsored statistical atlases that began in the 1870s throughout many countries in Europe as well as the United States. This effort to present graphic views of population, trade and commerce, and social and political issues continued until the early part of the twentieth century, and was accompanied by international statistical congresses (begun in 1853 in Belgium) that attempted to develop standards for graphic presentation and were closely tied to the state statistical bureaus. The pinnacle of this period was undoubtedly the *Albums de Statistique Graphique* published annually by the French Ministry of Public Works between 1879 and 1899 under the direction of Émile Cheysson (see Dainville 1972). They were published as large-format books (about 11 × 15 inches [27.9



Abaque hexagonal donnant **sans calcul** et **sans relèvements** la déviation du compas, pour le bateau « **Le Triomphe** ».

Formules :

$$\delta = A + B \sin\zeta' + C \cos\zeta' + D \sin 2\zeta' + E \cos 2\zeta'$$

$$B = \text{arc}\sin\left(\mathfrak{B}\left(1+\tfrac{1}{2}\sin D\right)\right);\ C = \text{arc}\sin\left(\mathfrak{C}\left(1-\tfrac{1}{2}\sin D\right)\right);\ \mathfrak{B} = \tfrac{1}{2}\left(\text{ctg}\,\theta + \tfrac{P}{H}\right);\ \mathfrak{C} = \tfrac{1}{2}\left(\text{ftg}\,\theta + \tfrac{Q}{H}\right)$$

Légende :

θ Angle d'inclinaison magnétique variable aux différents lieux de la terre.

H. Composante horizontale du magnétisme terrestre, variable aux différents points du globe.

Valeurs des coefficients pour « Le Triomphe » :

$A = -1^\circ 9'$	$c = +0{,}106$;
$D = +6^\circ 45'$	$f = -0{,}013$;
$E = -0^\circ 5'$	$P = -0{,}033$;
$\lambda = 0{,}84$	$Q = -0{,}020$;

Manière de se servir de l'Abaque :

Pour consulter cet abaque, on se sert d'un **indicateur** hexagonal transparent, orienté comme le montre le modèle ci-dessus.

1° Prendre, sur la planisphère anamorphosée B, le point situé à la rencontre du **méridien du lieu** avec la courbe ayant pour cote la **latitude**.

Projeter ce point horizontalement sur la génératrice du cône I répondant au cap ζ' du compas. — Marquer d'une petite croix (α), au crayon, le point ainsi obtenu.

2° Prendre de même — sur la planisphère supérieure C_1, si le cap est dans le demi-rumb nord du compas — sur la planisphère C_2, si le cap est dans le demi-rumb sud — le point de rencontre du méridien et de la courbe ayant respectivement pour cotes la **longitude** et la **latitude** du lieu.

Projeter ce point parallèlement à la direction UV (\ ) sur la génératrice de l'hyperboloïde II répondant au cap ζ'. — Marquer également d'une petite croix (β) le point obtenu.

3° Placer le diamètre vertical (|) de l'indicateur sur la croix (α); amener ensuite, par un glissement vertical, le diamètre 2-2 (/) sur la croix (β). — On lit à ce moment sur le diamètre 3-3 (\ ), à la rencontre de l'échelle δ qui lui est perpendiculaire, la valeur de la **déviation totale** δ.

Sur la planche, à titre d'exemple, on a figuré les croix (α) et (β), et, en traits tiretés (—.—.—), les positions des diamètres de l'indicateur, pour un point situé dans l'Atlantique, par 20° de long. O. et 42° de latitude N., et pour un cap $\zeta' = 41^\circ{,}5$. — On lit, pour la déviation totale : $\delta = 11^\circ{,}8$.

N.-B. — Pour ne pas salir le dessin, il est bon de le recouvrir d'une feuille de toile calque, placée le côté rugueux en dessus, sur laquelle on marque les deux petites croix (α) et (β). — On efface ces dernières d'un coup de gomme, une fois le résultat obtenu.

FIGURE 134.

Charles Lallemand, "Abaque hexagonal donnant sans calcul et sans relèvements la déviation du compass, pour le bateau 'Le Triomphe'" (Hexagonal Abacus Giving the Variation of the Compass without Calculation or Plotting, for the Ship "Le Triomphe") (1885).

× 38.1 cm]), and many of the plates folded out to four or six times that size, all printed in color and with great attention to layout and composition. We concur with Funkhouser (1937, 336) that "the *Albums* present the finest specimens of French graphic work in the century and considerable pride was taken in them by the French people, statisticians and laymen alike."

Many of these albums were designed to show temporal changes or provide graphic comparisons of related quantities for population, trade and commerce, and transportation in relation to the geography of France and the world. To do this, many forms of graphic symbols were appropriated and adapted to the problem at hand (flow lines, proportional and divided circles, divided rectangles, planetary diagrams, and so forth). The collection of these images can be regarded as an exquisite sampler of the graphic methods then known.

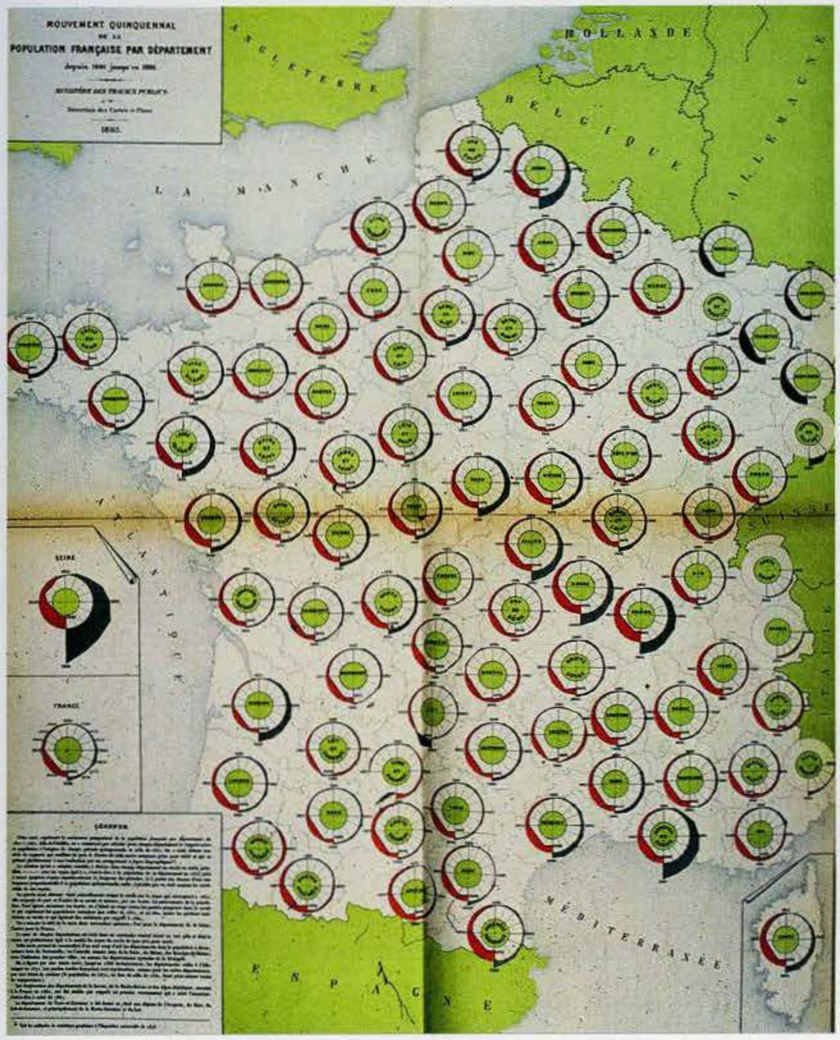


FIGURE 135.
"Mouvement quinquennal de la population par département depuis 1801 jusqu'en 1881" (Quinquennial Change of the Population by Department from 1801 to 1881) (1881).

Figure 135, for example, uses spiral symbols to show the population of each department (administrative district) over the five-year periods from 1801 to 1881. The radius of each circle corresponds to the population in 1841, and the area between this reference circle and the curve for actual population is shaded red or blue, respectively, according to whether the population was less than or greater than that in 1841.

At about the same time, other statistical albums and atlases were prepared in Europe and the United States, and among these, those from the U.S. Census Office deserve special mention. The *Statistical Atlas of the Ninth Census*, produced in 1874 under the direction of Francis Walker, contains sixty plates, including several novel graphic forms (United States Census Office 1874). It had the ambitious goal of presenting a graphic portrait of the nation, and covered a

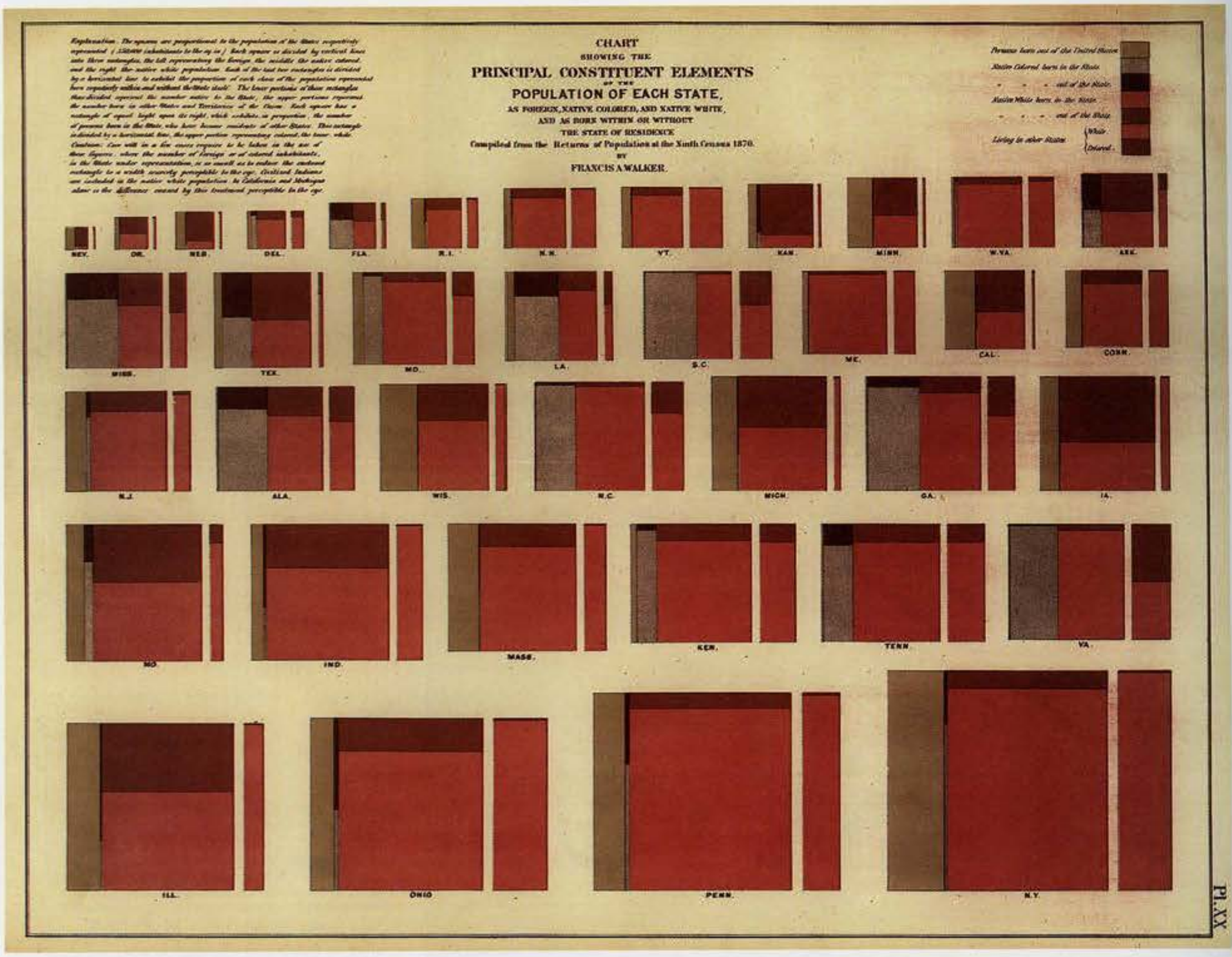


FIGURE 136.
Francis A. Walker, "Chart Showing the Principal Constituent Elements of the Population of Each State" (1874).

wide range of physical and human topics: geology, minerals, weather, population, wealth, literacy, rates of death and disease, and so forth. Figure 136, for example, uses mosaiclike divided rectangles to show state populations classed as foreign, native colored, and native white, and as born within or outside the state of residence. Walker is also credited with the invention of "age pyramids" (back-to-back bilateral frequency histograms and polygons), which he used to compare age distributions for two classes (male/female, married/single, and so forth). (For more on Walker and the *Statistical Atlas*, see chapter 4 of the present text, pp. 189–92 and figs. 103–106).

Following each subsequent decennial census for 1880 to 1900, reports and statistical atlases were produced with more numerous and varied graphic illustrations. The 1898 volume from the census of 1890, under the direction of Henry Gannett, contained over four hundred graphs, cartograms, and statistical diagrams (United States Census Office 1898). Figure 137 is an example

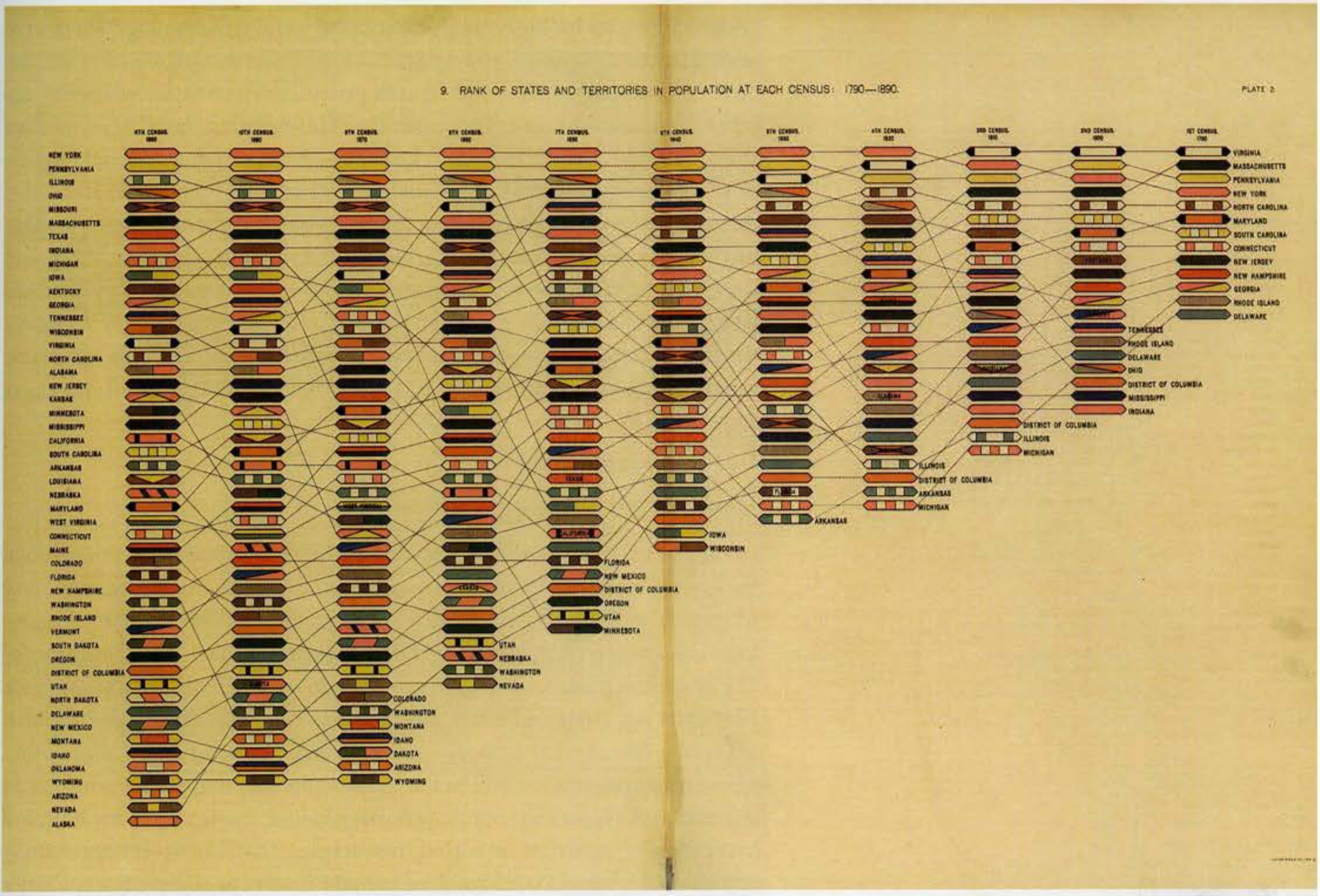


FIGURE 137.
Henry Gannett, "Rank of States and Territories in Population at Each Census, 1790–1890" (1898).

of a ranked-list, *semigraphic* display of a form similar to what is now called a parallel coordinate plot. The presentation goal was to show the ranking of populations of the states from all censuses from 1790 to 1890 and allow increase or decrease to be tracked by state. To achieve this, the symbol for each state was colored and shaded distinctively and connected across adjacent census periods by lines.

MAPS AND DIAGRAMS IN SOCIAL SCIENCE

If the early modern period (before about 1800) of thematic maps and graphs can be characterized as driven by concerns from the physical sciences, many innovations in the nineteenth century stemmed from a new concern with understanding human conditions and activities that would give rise to modern social science, including economics, sociology, and epidemiology. There were several forces at play here, among which an explosive growth in data collection on social and economic topics figured prominently, as we noted earlier. Another theme that arose was the possibility of formulating "laws" or relations of the social order, akin to those that had been developed to understand relationships of the physical order. The principal methods of present-day quantitative cartography were imagined in this context between 1826 and 1845; the graphic methods invented by Playfair for economic data were extended, modified, and appropriated to comprehend a wider range of social phenomena and their relations.[5] In this endeavor, the natural sciences offered a model to follow in the search for patterns of constancy and variation in social data, as can be inferred from early statisticians' frequent references to Humboldt, Berghaus, and others.

The rise of moral statistics

To express these new social phenomena, cartographers had to reform radically the graphic language for the portrayal of statistical data in order to create new relationships between graphic forms and numbers as well as establish a new logic and a new syntax, much as Playfair had done with his "lineal arithmetic." The first modern statistical map is credited to Baron Charles Dupin in France. His "Carte figurative de l'instruction populaire de la France" (Figurative Map of Popular Education in France) was the starting point of a graphic revolution, whose consequences can still be felt in contemporary mapping. Trained as an engineer at the École Polytechnique starting in 1801, Dupin turned his attention in the 1820s to "statistics, an entirely new science [that] had never been usefully applied. Mr. Charles Dupin resolved to make it serve to observe our country's progress in the path of moral and material interests" (Hoefer 1858–78, vol. 5, p. 320). Dupin presented some of his results in lectures at the Conservatoire National des Arts et Métiers. In 1826, he submitted his map (fig. 138) in a paper on the "effects of popular education on France's prosperity" (Dupin 1826). The map was printed one year later in his major work: *Forces productives et commerciales de la France* (Productive and Commercial Power of France; Dupin 1827). It illustrated primary education, considered a sign of general development. This topic allowed him to represent a basic opposition between northern and southern France through an original graphic method: "To render the most important of these differences visible," he wrote, "I hit upon the idea of giving those departments that sent fewer pupils to schools the darker shades" (Dupin 1827, 249).

The method, now called the choropleth map, had no known antecedent. However, a plausible hypothesis about its conception can be advanced. The map became famous as the "map of enlightened and obscure France"[6]; Dupin himself used the expression "enlightened France" when he presented it at the Conservatoire. It would be reasonable to conclude that a scale of moral values

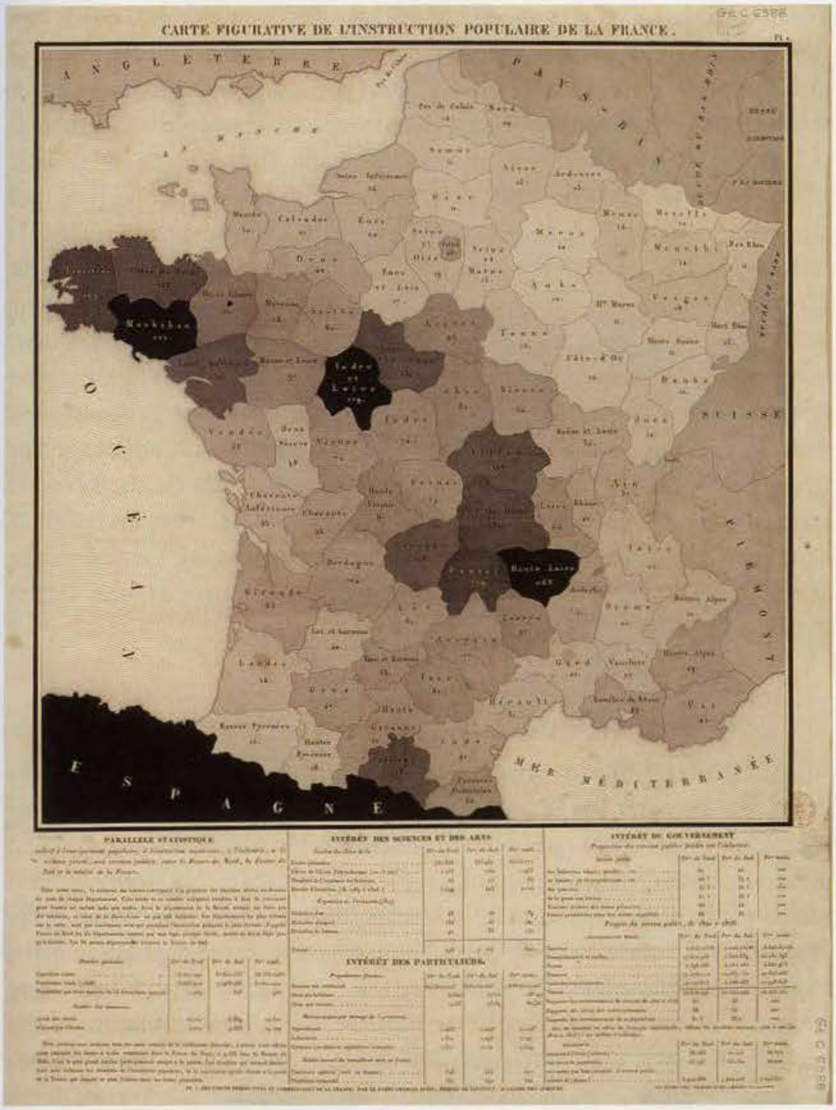


FIGURE 138.

Charles Dupin, "Carte figurative de l'instruction populaire de la France" (Figurative Map of Popular Education in France) (1826).

directly inspired the gradual shadings of the map. The shading gave the impression of a light cast on the map, comparable to the light of knowledge. Moreover, we will see that most of the maps that immediately succeeded Dupin's were based on the same principle: the scale of shadings always transcribed a scale of values, always with sense that darker meant worse.

Very quickly, Dupin's invention served a wider role in the origin of social science as "moral" and social statistics became more widely available. In 1825, the French Ministry of Justice instituted the first centralized, national system of crime reporting, recording the details of every charge laid before the courts. In 1829, André-Michel Guerry, a Parisian lawyer with a penchant for numbers, joined with the Venetian geographer Adriano Balbi to produce the first *comparative* maps of crime and education, to examine the *relation* between these moral variables (Balbi and Guerry 1829). By 1833, Guerry produced the first comprehensive study of such social data, also including data on suicides, donations to the poor, illegitimate births, and so forth. Using shaded maps and graphic tables, he showed that rates of crime, suicide, and other variables remained remarkably stable over time, yet varied systematically from place to place. He said, "We are forced to conclude that the facts of the moral order are subject, like those of the physical order, to invariable laws" (Guerry 1833, 14). This, along with the contemporaneous work of Adolphe Quetelet in Belgium (1831, 1835), may be regarded as the foundational study of criminology, sociology, and modern social science. Guerry's last work (1864) proposed a new form of *analytical statistics* presented visually with both maps and graphs, and comparing data from France and England over a thirty-year period. Figure 139 shows one of seventeen plates from that volume, here for crimes against persons in France. Recognizing that shading on the map is an overall summary, various graphs around the periphery were designed to dissect these by time or other factors or to highlight noteworthy patterns and trends.

Proportional symbols

Sometime after Dupin, A. Frère de Montizon, an officer who became a professor of sciences after the fall of the First Empire, conceived a second graphic method employing dot symbols. He published several educational works on morals or history at the beginning of the century. Later, his "Carte philosophique figurant la population de la France" (Philosophical Map Showing the Population of France; Frère de Montizon 1830) represented population distribution in absolute values. The population was indicated by departments, using a number of dots proportional to the number of inhabitants, 1 dot to 10,000 persons. The map was "philosophical" because Frère de Montizon wished to relate the population to "the physical, intellectual and moral state of the country." He thus traced a line *AB* on his map, going from Saint-Nazaire to Maubeuge—a "thermometric line" dividing the territory into two climatic zones of differing agricultural production. In his view, this fact explained the general distribution of population. The map was visually not very effective, for the procedure was difficult to master. The image presented was more of a uniform distribution, because the very small dots and the observation scale (by department) made the spatial contrasts less visible. Nonetheless, the "Carte philosophique" initiated an important method and revealed the new curiosity toward demography. This was shown yet again a few years later by George P. Scrope's publication of a map of the world's population according to three bands of density (Scrope 1833).

FIGURE 139.
André-Michel Guerry, "Crimes contres les personnes" (Crimes against Persons) (1864).

Innovations in the sphere of cartographic statistics in the 1830s were due above all to engineers. In the context of the industrial revolution, their major task was to establish the main railway lines. Laying out tracks called for the integration of varied data: physical and technical conditions, political or strategic contingencies, but also the distribution and mobility of population, resources, and wealth. Therefore, engineers were among the first to take an interest in demographic and economic data and sometimes turned to graphic language in order to better exploit them. The atlas presented by the railway engineer Henry Harness to accompany a report of the Irish Railway Commissioners provides a first example (Harness 1838). It included six very original maps on the distribution and circulation of goods and passengers: three of them applied the system of proportional circles to urban populations, and the other two were the first maps depicting the flow of passenger and freight road traffic. The cartography of population and transport then became a tool for objectively determining the main railway tracks.

Diffusion of procedures

The methods imagined by Dupin, Frère de Montizon, and Harness spread unevenly. Statistical maps with dots (or other discrete symbols) remained rare in the nineteenth century. The procedures reappeared in medicine, but quite independently of Frère de Montizon's map, which remained little known; cases or deaths linked to epidemics were localized on a large scale, often in an urban context (Palsky 1995). A well-known example was Dr. John Snow's 1855 map (fig. 140), which showed the effects of cholera in a London neighborhood and the link between the deaths and the probable source of infection from the public water pump on Broad Street (Snow 1855). Snow's map figures prominently in the history of epidemiology as a graphic argument linking cases of cholera to a probable cause: the Broad street pump around which the majority of deaths clustered (Koch 2005, 75–155).

This was not the first map of disease seeking to understand causation through its spatial distribution. In 1798, Valentine Seaman published two dot maps to illustrate the distribution of yellow fever in New York (Seaman 1798). After the first outbreak of Asiatic cholera in Great Britain, Dr. Robert Baker constructed a map showing the distribution of the 1,800 cholera cases in Leeds in the particularly severe outbreak in 1832 (Baker 1833). But Seaman's and Baker's graphic techniques, combined with their limited scientific understanding of the causes of disease, were insufficient to lead to Snow's eureka experience. For example, Baker simply used uniform hatching in red to denote "the districts in Leeds in which cholera had prevailed." He could only note "how exceeding the disease has prevailed in those parts of the town where there is a deficiency, often an entire want of sewage, drainage and paving" (Baker, 1833, 10).

Maps with proportional symbols soon found other applications. Several engineers drew flow maps after 1845 in France, Belgium, Austria-Hungary, and Russia. Thus, the French engineer Minard transposed to cartography the idea he had in 1844, when he drew diagrams of passenger and freight traffic (fig. 132 above). In March 1845, he presented his "Carte de la circulation des voyageurs par voitures publiques sur les routes de la contrée où sera placé le chemin de fer de Dijon à Mulhouse" (Map of the Circulation of Travelers by Public Conveyances over the Region through Which the Dijon to Mulhouse Railroad Will

FIGURE 140.
(facing) John Snow, "[Map] Showing the Deaths from Cholera in Broad Street, Golden Square, and the Neighbourhood" (1855), detail.

SOHO SQUARE
GREAT MARLBOROUGH STREET
BLENHEIM STREET
BLENHEIM MEWS
POLAND STREET
NOEL STREET
BERWICK STREET
WARDOUR STREET
DEAN STREET
FRITH STREET
PORTLAND STREET
PORTLAND MEWS
LITTLE CHAPEL STREET
CARLISLE STREET
RICHMOND BUILDINGS
RICHMOND MEWS
BENTINCK STREET
EDWARD STREET
WORK HOUSE
PUMP
BROAD STREET
MARSHALL STREET
CARNABY STREET
CROSS STREET
NEW STREET
BREWERY
HUSBAND ST
PETER STREET
QUEEN STREET
OLD COMPTON STREET
MEARDS STREET
LITTLE WINDMILL STREET
GREAT PULTENEY STREET
LITTLE PULTENEY STREET
SILVER STREET
BRIDLE STREET
GOLDEN SQUARE
WARWICK STREET
LEICESTER ST
BREWER STREET
SHERRARD STREET
GREAT WINDMILL STREET
ARCHER STREET
RUPERT STREET
UP. RUPERT ST
RICHMOND ST
ARUNDEL ST
PANTON SQUARE
ANGEL COURT
QUEEN STREET
MARYLEBONE STREET
VIGO STREET
TICHBORNE STREET
COVENTRY STREET
REGENTS QUADRANT
AIR STREET
VINE STREET
SACKVILLE STREET
PICCADILLY
HAYMARKET
OXENDON STREET
REGENT CIRCUS
GLASSHOUSE ST
FRANCIS ST
LOWER JAMES ST
LOWER JOHN ST
UP. JOHN ST
GOLDEN PL
WELLINGTON MEWS

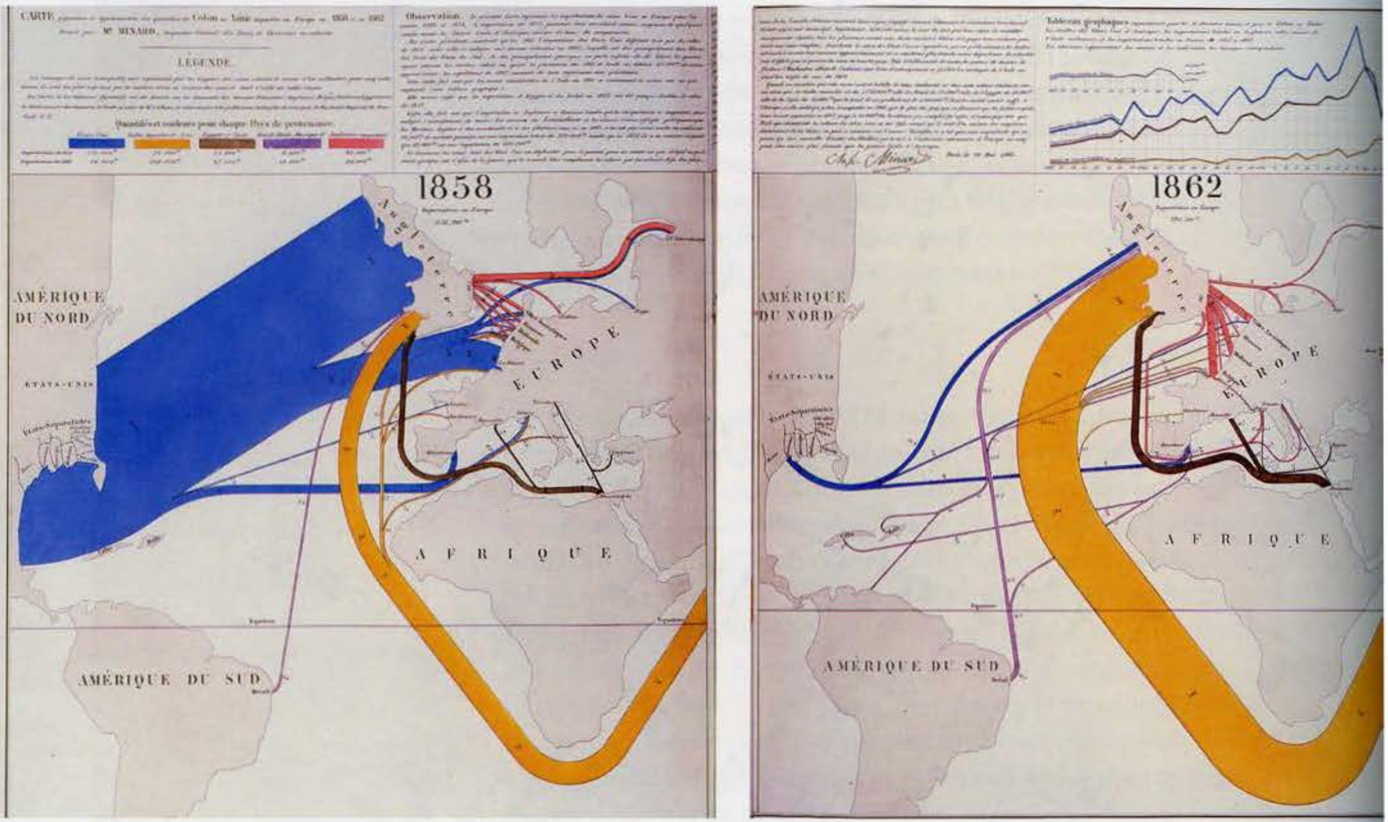


FIGURE 141.
Charles Joseph Minard, "Carte figurative et approximative des quantités de coton en laine importées en Europe en 1858 et 1862" (Figurative and Approximate Map of Quantities of Raw Cotton Imported to Europe in 1858 and 1862) (1863).

Run; Minard 1845a), in which he drew bands of thickness in proportion to the annual passenger traffic. This map was part of a running debate on two different routes for a railway line between Dijon and Mulhouse since 1841. It argued in favor of one of the routes (through Besancon and the Doubs valley), on the grounds of a clear distinction in the existing road traffic, which had more to do with visual evidence than with partisan interests.

Between 1845 and 1871, Minard drew several other "figurative maps," which often backed analysis of political economy and sometimes testified eloquently to the irregularity of the traffic. His maps of imports of raw cotton to Europe before and during the American Civil War (fig. 141) were among the most striking visual demonstrations (Minard 1863). In particular, the visual message of the comparison is clear: before the war, most imports came from the southern United States; by 1862, substantial amounts had been replaced by Indian and Egyptian cotton, but the clothing makers in Europe were probably still wanting.

Further, Minard, perhaps inspired by Playfair, was one of the first to draw proportional circles divided in sectors on maps, for example in order to translate harbor circulation, or show both the total and proportions of kinds of meat shipped to Paris. These proportional symbols were equally popularized by the famous German cartographer Augustus Petermann, who toward midcentury constructed several population maps according to this procedure (fig. 142), but also, more surprisingly, a map showing the quantity of rainfall (around 1852).

In the realm of statistical graphics, Florence Nightingale (1857) introduced a polar-area chart, or "coxcomb diagram," showing mortality in the British army in the Crimean War over time by angular sectors whose area was pro-

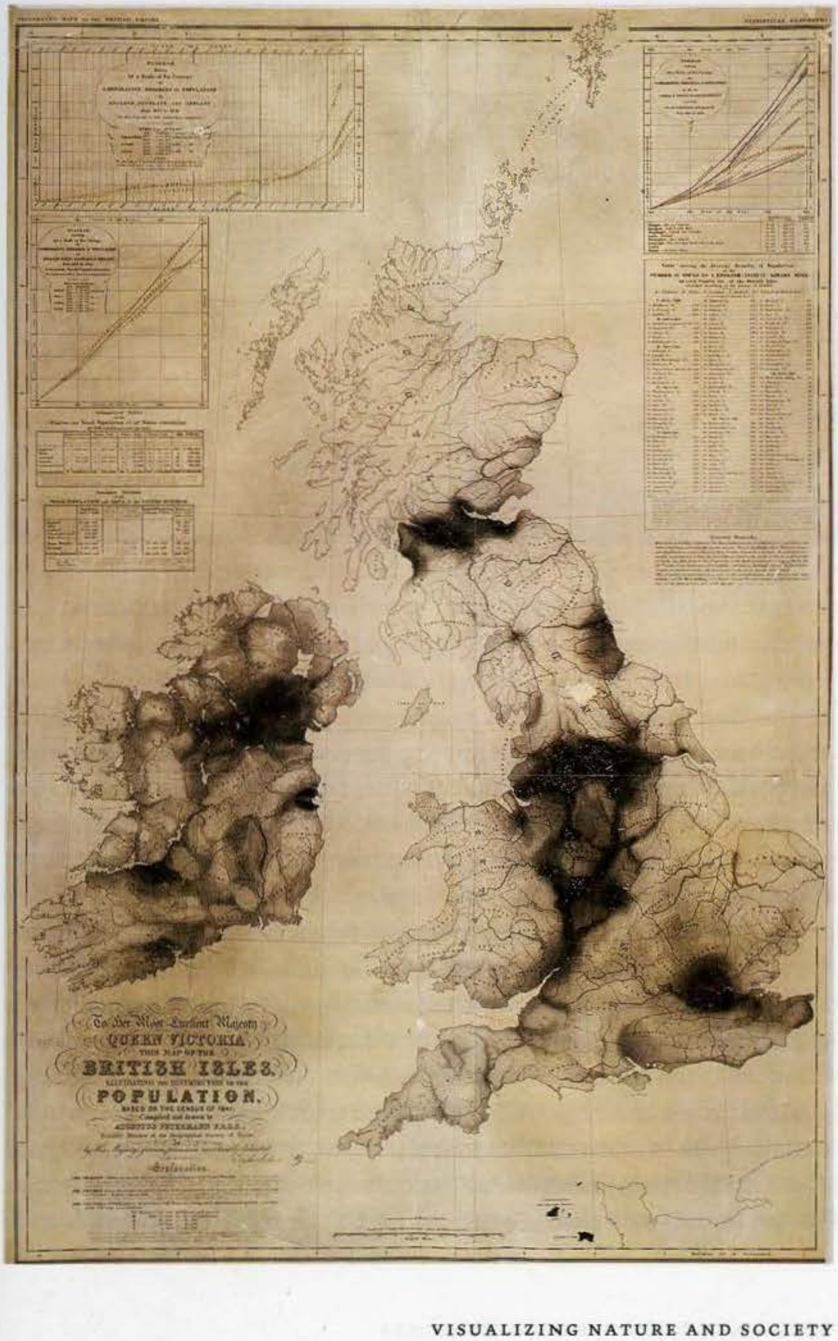


FIGURE 142.
Augustus Petermann, "Map of the British Isles, Elucidating the Distribution of the Population" (1850).

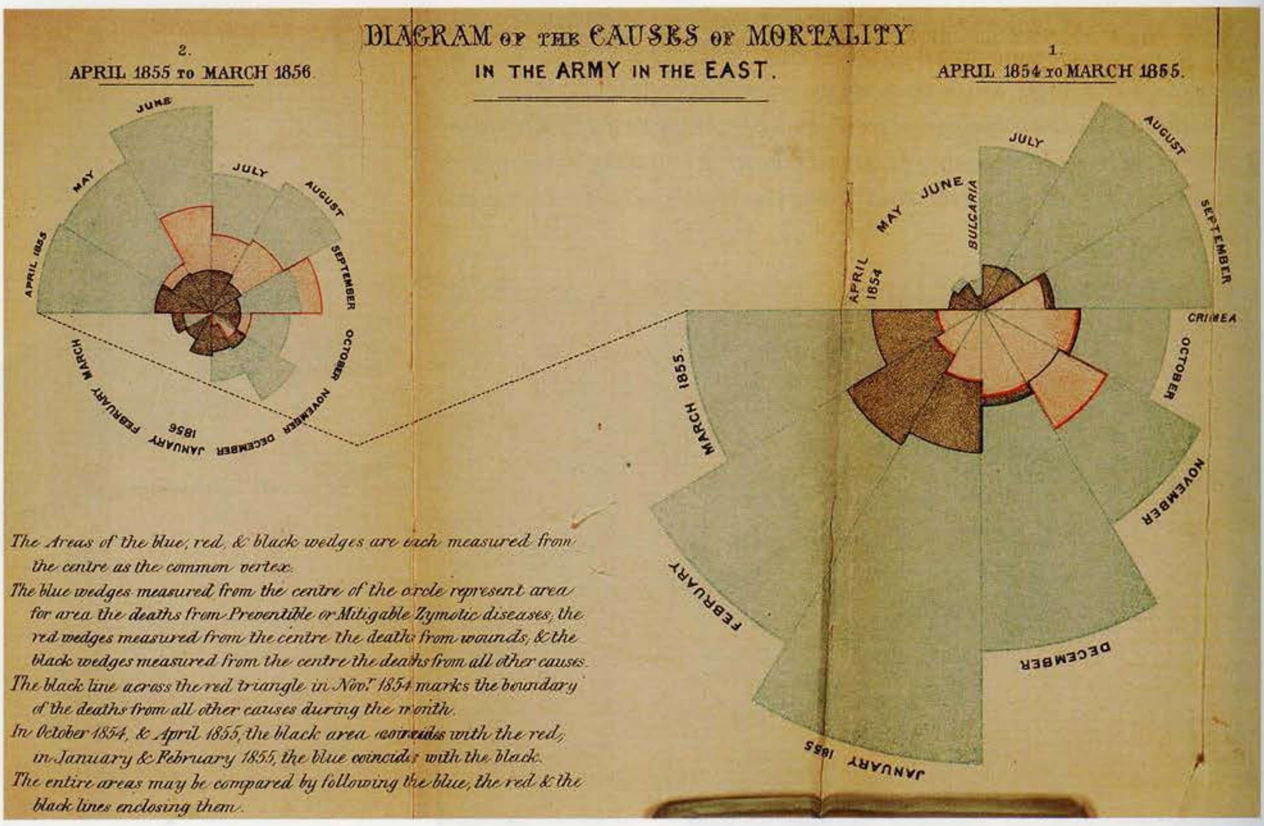


DIAGRAM OF THE CAUSES OF MORTALITY IN THE ARMY IN THE EAST.

2. APRIL 1855 TO MARCH 1856.

1. APRIL 1854 TO MARCH 1855.

The Areas of the blue, red, & black wedges are each measured from the centre as the common vertex.
The blue wedges measured from the centre of the circle represent area for area the deaths from Preventible or Mitigable Zymotic diseases, the red wedges measured from the centre the deaths from wounds, & the black wedges measured from the centre the deaths from all other causes.
The black line across the red triangle in Novr. 1854 marks the boundary of the deaths from all other causes during the month.
In October 1854, & April 1855, the black area coincides with the red; in January & February 1855, the blue coincides with the black.
The entire areas may be compared by following the blue, the red & the black lines enclosing them.

FIGURE 143.
Florence Nightingale, "Diagram of the Causes of Mortality in the Army in the East" (1857).

portional to the number of deaths (fig. 143). The dark inner portions for each month show direct deaths on the fields of battle; the larger, outer portions show deaths due to "other causes," meaning largely preventable death due to wounds and disease. She used such diagrams to argue persuasively to the British public and parliament for the institution of better battlefield nursing (the modern mobile army surgical hospital, or MASH unit). She became known as the Lady with the Lamp, the mother of modern nursing. If Playfair was the father of statistical graphics, we might well consider Florence Nightingale its mother.

But one graphic method of cartography appears to have spread most widely outside the restricted circle of cartographic specialists: the map with graduated shadings introduced by Dupin and elevated to a tool for the scientific study of moral and social statistics by Guerry. Other applications of this method in the social realm appeared in France (Angeville 1836; Parent-Duchâtelet 1836), Holland (Somerhausen 1827), England (J. Fletcher 1847–49; Mayhew 1851–62), and elsewhere in Europe as the general study of "moral statistics" took shape. These shaded maps dealt with education, criminality, begging, prostitution, poverty (called "pauperism," a peculiar English term likening destitution to a disease), and other social topics. Like Nightingale's coxcomb diagrams but on a much wider scale, maps, with their striking and persuasive aspect, figured prominently as arguments in scientific or political debates. For example, Guerry (1833) argued from his maps that levels of crime are not related to the level of instruction, as many in his time believed, and that crimes against persons and against property show different relations to other variables.

Progressively, the connection between shadings and moral values seemed to fade as the method was applied to other topics, now with dark representing "more" and light representing "less."[7] However, the association between colors and moral values remained, perhaps unconsciously, for a long time, as shown by the maps on poverty that Charles Booth attached to his monumental social inquiry of London (1889–91). Booth applied a color to each street that corresponded to a social category. He used dark and cold colors for the poor (black for "the lowest, most vicious, semi-delinquent class"; dark blue for the "very poor, occasional workers. Chronic misery," etc.) and hot colors like pink, red, and orange for middle and higher categories (fig. 144). By combining the codifications of moral cartography from the beginning of the nineteenth century, Booth stigmatized the most ignorant, the most criminal, or the most miserable parts of the urban territory by dark shades.

Near the turn of the twentieth century, several social surveys were modeled after Booth's study. Residents of Hull-House, a social settlement on Chicago's West Side, published the results of their investigation of the neighborhood, a poor immigrant district (Addams 1895). They created a series of detailed maps, directly inspired by those of Booth, and retaining in particular his use of thematic coloring. As with previous "moral" maps, the Hull-House renderings were intended as graphic evidence of social problems, in order to promote reform.

CONCLUDING REMARKS

Over the last decades of the nineteenth century, state-sponsored statistical bureaus flourished throughout Europe and the United States, and the discipline of social statistics became solidified in national and international organizations, which began to consider the adoption of international standards for graphic methods in both maps and diagrams.[8] Between 1869 and 1901, the congresses held by the International Institute of Statistics in The Hague, Vienna, St. Petersburg, and Budapest debated the variety of visual encodings used in maps and diagrams in an attempt to define a universal grammar, with much of the discussion concerning scales of values and coloring schemes for choropleth maps. By 1914, a set of more general recommendations for statistical diagrams was published by the American Statistical Association (Joint Committee on Standards for Graphic Presentation 1914), and by this time graphic methods

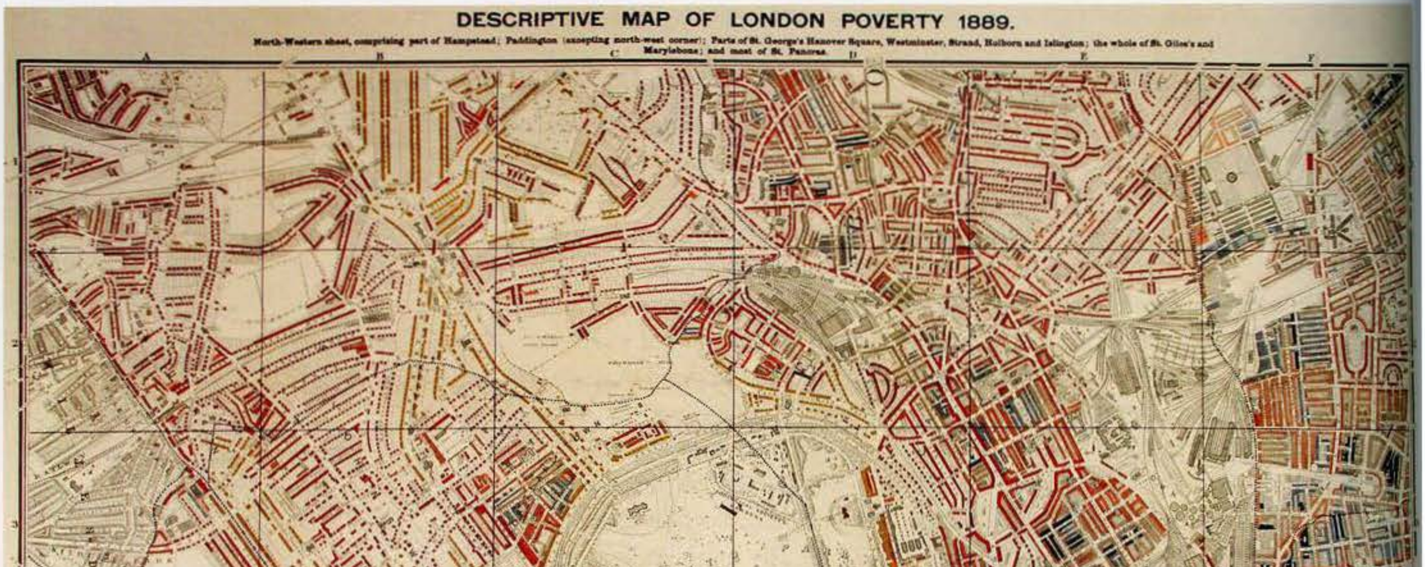


FIGURE 144.

Charles Booth, "Descriptive Map of London Poverty," northwestern sheet (1889).

became mainstream, entering textbooks, the curriculum, and standard use in government, commerce, and social and natural science.

Paradoxically, the golden age of innovation, enthusiasm, and graphic excellence in statistical graphics and thematic cartography had drawn to a close in the early 1900s, being supplanted by the "modern dark ages" of visualization, the rise of quantification and formal models in the social sciences (Friendly and Denis 2000). Statistical models and parameter estimates were precise; graphs and maps, on the other hand, were just pictures: pretty or evocative, perhaps, but incapable of stating a "fact" to three or more decimal places. So it seemed to many statisticians.

The Zeitgeist for statistical mapping and graphics changed again beginning in the 1950s, with several significant developments. At this time, postwar rebuilding and economic planning spurred huge developments in the application of thematic cartography, and the framework for a modern theoretical appraisal of visual symbolism was laid by Arthur Robinson (1952). In France, Jacques Bertin published the monumental *Sémiologie Graphique* (1967) that appeared to some to do for graphics what Mendeleev had done for the organization of the chemical elements. In the United States, John Tukey (1962) issued a call for the recognition of informal, robust, and graphically based data analysis distinct from mathematical statistics. Finally, initial steps in the computer processing of statistical data and computer-generated visual displays offered the possibility to construct new graphic forms (or at least construct them more quickly) and interactive graphic applications.

The present landscape for visualizing nature and society includes many new specialties, including geographic information systems (GIS), an emerging science of geovisualization (for example, Dykes, MacEachren, and Kraak 2005), volumetric brain and medical imaging, and visualization of high-dimensional and massive data sets. But it also faces new and globally important challenges: biotechnology, threat detection, global warming and environmental change, and patterns of propagation of AIDS and influenza are just a few current topics of application. Coupled with these forces, new technology now provides the means for dynamic interaction with statistical data and graphs. As new graphic methods are developed to help comprehend such phenomena, it is useful to understand also the deep roots that these methods have in the history of thematic cartography and statistical graphics. And although we think of these maps and graphics as the products of science, their makers' desire to communicate information effectively produced work that is often elegant and even beautiful.

Notes

This work was supported by Grant 8150 from the Natural Sciences and Engineering Research Council of Canada to M. Friendly. We are grateful to the members of Les Chevaliers

des Albums de Statistique Graphique for historical information, images, and helpful suggestions.

1. The term *semigraphic* was invented by John Tukey (1972) to refer to visual displays that were a mix of graph, table, and numbers. In French, Charles Joseph Minard and others referred to *tableaux figuratifs* and *cartes figuratives* to denote combined forms of tables, maps, and graphs.
2. Maunder plotted latitude of sunspot activity on the sun versus time and observed a cyclic pattern that resembled the wings of a butterfly (see http://www.windows.ucar.edu/tour/link=/sun/activity/butterfly.html). The explanation for this recurrent migration is still unknown.
3. The estimates were all biased upward from the true distance (16" 30'), likely due to underestimation of the earth's circumference (Tufte 1997).
4. In July 1861, Galton distributed a circular to meteorologists throughout Europe, asking them to record these data synchronously, three times a day for the entire month of December, 1861. About fifty weather stations supplied the data; see Pearson (1914, 37–39).
5. Not everyone concerned with statistical data and social problems was enthusiastic about graphic methods. In France, the influential early statistician Jacques Peuchet (1805) considered Playfair's figures childish games, irrelevant to science. In England, early statisticians ("statists," as they called themselves) who formed the basis for the Royal Statistical Society were more concerned with the presentation of statistical "facts" in tables, leaving the generalization to laws and theories to others.
6. It showed a relatively clear-cut separation between the north and south of France along a line from Geneva to Saint-Malo in Brittany. This sharp cleavage between "la France éclairée" (enlightened France) and "la France obscure" would become reified as the "Saint-Malo–Geneva line" and generate much debate about causes and circumstances through the end of the nineteenth century.
7. The direction of the visual encoding of "more" and "less" is also crucial in understanding the relations between different data shown on maps. Thus, Guerry (1833) was careful to arrange the scales of data on crime, instruction, suicide, and so forth, so that darker always meant "worse" (more crime, less education—or more illiteracy).
8. Initially, at the 1832 founding of the Statistical Section of the British Association for the Advancement of Science (later to become the Royal Statistical Society), the view was expressed that its concerns were restricted "to facts relating to communities of men which are capable of being expressed by numbers, and which promise when sufficiently multiplied to indicate general laws." That might sound good, until it is realized that the "facts" were to be expressed simply as numbers in tables, and the "general laws" were to be inferred by others: "the sciences of morals and politics are far above the spec-

ulations of our philosophy" (Mouat 185, 15). By 1885, at the Silver Jubilee of the Royal Statistical Society, graphic methods and reasoning to conclusions had become mainstream, as Alfred Marshall addressed the attendees on the benefits of the graphic method, and Émile Levasseur presented a survey of the wide variety of graphs and statistical maps then in use (see Marshall 1885; Levasseur 1885).