

ROCKPORT

# Design for Information

An introduction to the histories,  
theories, and best practices behind  
effective information visualizations

Isabel Meirelles

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## CHAPTER 4

# SPATIAL MAPS STRUCTURES:

Fernanda Viégas and Martin Wattenberg, U.S.:  
"Wind Map," 2012.

The 2012 "Wind Map" is a personal art project by Fernanda Viégas and Martin Wattenberg devised to visualize the wind as a source of energy. The project shows wind forces over the United States using data from the National Digital Forecast Database and is revised hourly. The varying weights of lines represent the velocity of the wind flows. The screenshot depicts a "living portrait" at a given date. Patterns are easily distinguished given the orientation and thickness of lines, which ultimately reveal the hidden geography.

<http://hint.fm/wind>

We encounter the term **map**, as well as the act of **mapping** in diverse fields of knowledge, all, however, with the shared characteristic of being "a diagram or collection of data showing the **spatial distribution** of something or the **relative positions** of its components."<sup>1</sup> The oldest (c. 1527), and perhaps the most frequent, use of the term *map* refers to representations of geographical data, ranging from the Earth's surface to parts of it.<sup>2</sup> Maps are used in other disciplines, such as genetics, in diagrammatic representations of the order and distance of the genes (see page 53), and in mathematics, as correspondences between two or more sets of elements. These are just two fields in which maps are frequently used.

**BRIEF HISTORY**  
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This chapter focuses on **thematic maps**, which are representations of attribute data (quantitative and qualitative) on a base map. The latter is provided by the fixed positional data defined by geometry, such that spatial (geographic) relations are represented using locational reference systems (e.g., latitude/longitude, projections). In other words, and as the name suggests, thematic maps display a theme that can be a number of phenomena, such as social, political, economic, or cultural issues, with the purpose of revealing patterns and frequencies in the geography where they occur. As Robinson explains, "One of the major reasons for making a thematic map is to discover the geographical structure of the subject, impossible without mapping it, so as to relate the 'geography' of one distribution to that of others."<sup>3</sup>



"A New and Correct Chart Showing the Variations of the Compass in the Western & Southern Oceans as Observed in the Year 1701," was created by Englishman Edmond Halley and published in 1701. It is the first known use of isolines.

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### BRIEF HISTORY

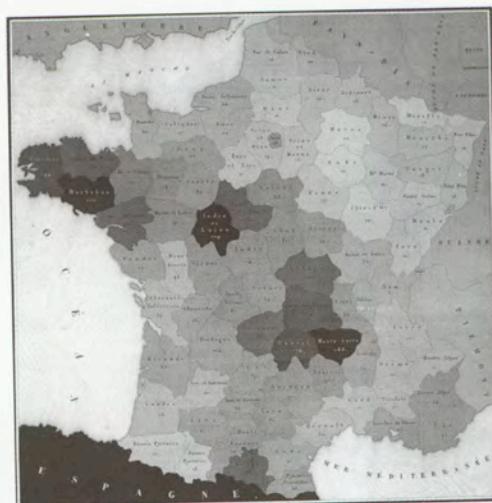
Thematic maps can be traced back to the second half of the seventeenth century, with large advances in the nineteenth century, when most graphical methods were devised between 1820 and 1860.<sup>4</sup> Initially, thematic maps represented data in the natural sciences. The 1701 isoline map of the magnetic fields by the Englishman Edmond Halley (1656–1742) is considered the first of these. The portrayal of social phenomena appeared a century later, and the first modern statistical map is credited to Frenchman Charles Dupin (1784–1873), and his 1826 choropleth map of France displaying levels of education by means of shaded gray administrative areas.<sup>5</sup> “As data built up from environmental observations and measurements during the Enlightenment,” Robinson expounds, “attention shifted from place to space. Focus shifted from analytical concern with the position of features to holistic concern with the spatial extent and variation of features. Thus, the idea of distribution was born. The conceptual leap from place to space led to distributional representations called thematic maps.”<sup>6</sup>

The enumeration of population was recorded during Egyptian, Greek, and Roman times, all of which used data primarily for administrative purposes, such as taxation. It is from the Romans, in fact, that the word *census* is derived from the Latin *censere*, “to estimate.” The systematic collection of social data started only in the late eighteenth century, with the first population census carried out by Sweden in 1749, followed by other countries, such as the United States in 1790, and France and England in 1801.

By 1870, most European countries, as well as the United States, were systematically collecting, analyzing, and disseminating official government statistics on population, trade, and social and political issues in publications such as statistical atlases, international expositions, and conferences.<sup>7</sup> The International Statistical Congress, which met eight times between 1835 and 1876, served as an important international forum for the discussion and promotion of the use of graphical methods, as well as attempts to set forth international standards.<sup>8</sup>

### ADVANCES IN THE MID-1800S

Overall, the use of graphs for illustration and analysis outside the domains of mathematics and the physical sciences was rare prior to the mid-nineteenth century, despite the graphical inventions of William Playfair in the late 1700s (see page 93). The unprecedented development in the mid-1800s of graphic methods to analyze data in many ways was fueled by most countries’ recognition of the importance of numerical information in planning for the general welfare of the population (social, economic, etc).



Baron Pierre Charles Dupin is credited with having created the first modern statistical map in 1826. The map, also the first known choropleth map, depicts with shades from black to white the distribution and intensity of illiteracy in France. It is an unclassed choropleth map, in which each unique value is represented by a unique gray value. Classes in choropleth maps started being used in the early 1930s.

*A thematic map is concerned with portraying the overall form of a given geographical distribution. It is the structural relationship of each part to the whole that is important. Such a map is a kind of graphic essay dealing with the spatial variations and interrelationships of some geographical distribution.*

Arthur H. Robinson

This period also marks the birth of new disciplines, such as statistics, geology, biology, and economics, to mention a few. New techniques developed by the emerging disciplines influenced each other as well as traditional fields like cartography, and led to advances in thematic maps that are examined in this chapter. For example, most innovations in graphical methods for statistical maps were devised by engineers and not by cartographers.<sup>9</sup> As Friendly stresses, “What started as the ‘Age of Enthusiasm’ in graphics and thematic cartography, may also be called the ‘Golden Age,’ with unparalleled beauty and many innovations.”<sup>10</sup>

As a side note, it is relevant to consider that we are currently experiencing a similar phenomenon powered by the collection of all sorts of digital data and the need to visually analyze them. Furthermore, we see the effect on several disciplines, from physics to biology, from political sciences to literature, all permeated by the growing field of data visualization.

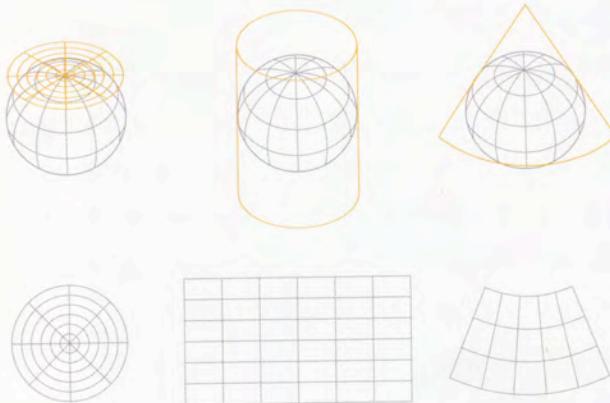
#### MAP DESIGN

Visualizing data with maps involves making decisions in three basic areas: projection, scale, and symbolization. This chapter focuses on the latter, and a brief explanation follows with regard to the first two items. There is vast literature on map making, and further readings are strongly recommended. A list of the books used here as resources, together with other suggestions, can be found at the end of this book.

**Map projections** are mathematical transformations of the curved three-dimensional surface of the globe onto a flat, two-dimensional plane. All map projections involve transformations that result in distortions of one or more of the geometric properties of angles, areas, shapes, distances, and directions. Throughout the years, different projections have been devised for transposing the globe into the plane.<sup>11</sup>

There are three basic *developable surfaces*—plane, cylinder, and cone—which result in three kinds of map grids—azimuthal, cylindrical, and conic. Distortion increases with the distances from the point or line of contact—tangent or secant—between the developable surface and the globe. For this reason, cartographers recommend cylindrical projections for continents around the equator (e.g., Africa, South America), conic projections for middle-latitude continents (e.g., Asia, North America), and azimuthal projections for polar regions.<sup>12</sup>

There are a variety of projections for each developable surface. Choosing a map projection involves understanding the geometric properties that one needs preserved with minimized distortion.



## PROJECTIONS

Robinson and colleagues warn, "There is no such thing as a bad projection—there are only good and poor choices."<sup>29</sup> All map projections result in distortions of one or more of the geometric properties of angles, areas, shapes, distances, and directions. As illustrated on the right, some projections preserve areas but not local angles; all projections distort large shapes, some more than others; all projections distort some distances; and so on. Distortions should be taken into consideration when selecting the projection that best fits the purpose of the map.

The maps on this page use Tissot's *indicatrix*, a graphic device that illustrates distortion when circles change into ellipses. Changes in geometry indicate the amount of angular and/or areal distortion at any particular location in the map. The device was devised by French mathematician Nicolas Auguste Tissot in 1859.

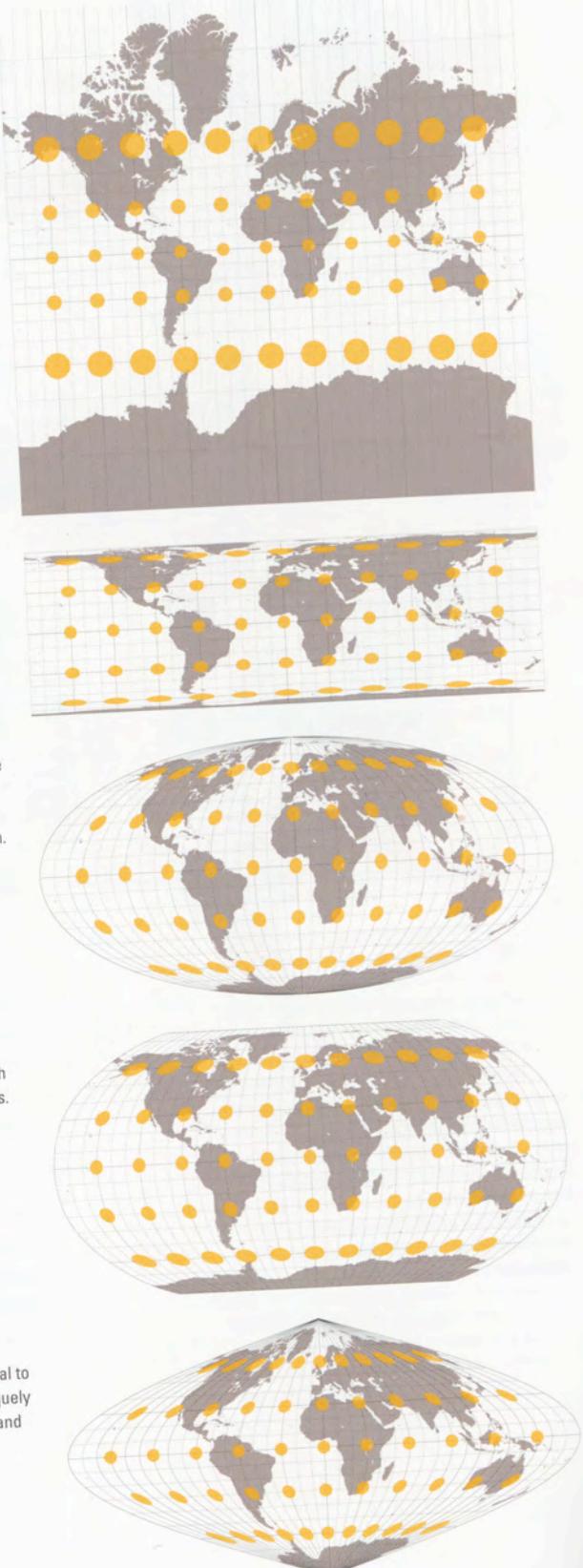
The **Mercator projection** is conformal. Areas and shapes vary with latitude, especially away from the Equator, reaching extreme distortions in the polar regions. All indicatrices are circles as there are no angular distortion.

The **equal-area cylindrical projection** preserves area. Shapes are distorted from north to south in middle latitudes and from east to west in extreme latitudes.

In the **Mollweide projection**, shapes decrease in the north-south scale in the high latitudes and increase in the low latitudes, with the opposite happening in the east-west direction.

In the **Robinson projection**, all points have some level of shape and area distortion. Both properties are nearly right in middle latitudes.

The **sinusoidal projection** preserves area, such that areas on the map are proportional to same areas on the Earth. Shapes are obliquely distorted away from the central meridian and near the poles.





In this Mercator projection map, Alaska and Brazil seem to be of similar size, when in reality Brazil is five times as large as Alaska. If used to compare land areas, a projection that preserves area should be selected, such as equivalent or equal-area projections. The illustration is based on the example in *Elements of Cartography*.<sup>20</sup>

For example, in 1569, the Flemish cartographer and mathematician Gerardus Mercator (1512–1594) introduced the Mercator projection, which helped solve a major problem of early navigators by providing a plane so that a straight line on the map would result in a line of constant bearing. On the other hand, if it is used to compare land areas, the Mercator projection is largely ineffective, because the regions, especially those at higher latitudes, are enlarged to a great extent.

*Equivalent* or *equal-area* projections preserve all relative areas, and are useful for visualizations in which the comparison of areas on the map is crucial, especially in the case of world maps. For example, dot-distribution maps rely on accurate area representation for the effective comparison of dot densities between regions on the map.<sup>13</sup> Maps used for instruction and small-scale general maps also require equivalent projections. Most common equal area projections are Alber's equal area, Lambert's equal area (especially recommended for middle-latitude areas, such as the United States), Mollweide (good for world distributions), and the Goode's homolosine.<sup>14</sup>

*Conformal* or *orthomorphic* projections conserve angular relationships, such that the angle between any two intersecting lines will be the same on the flat map as on the globe. Even though conformal projections also distort shapes, the result is less pronounced than in other projections, with preservation of the shape of small circles. They are often used for large-scale maps and include most modern topographic maps.<sup>15</sup> Conformal projections are also common in navigational charts. The conformal projections frequently used are Mercator, transverse Mercator, Lambert's conformal conic, and the conformal stereographical.<sup>16</sup>

Projections cannot preserve both angle and area—in other words, projections cannot be both conformal and equivalent. Monmonier explains, “Not only are these properties mutually exclusive, but in parts of the map well removed from the standard line(s), conformal maps severely exaggerate area and equal-area severely distort shape.”<sup>17</sup> There are, however, projections that offer acceptable compromises between conserving area and conserving angles. A good example is provided by the Robinson projection, devised by geographer Arthur Robinson for the National Geographic Society, and used for its general-purpose world reference map between the years 1988 and 1998. Monmonier recommends a low-distortion projection, such as the Robinson projection, for world maps in which the representation of both land and ocean areas are important, and the Goode's homolosine equal-area projection when only the land areas are relevant.<sup>18</sup>

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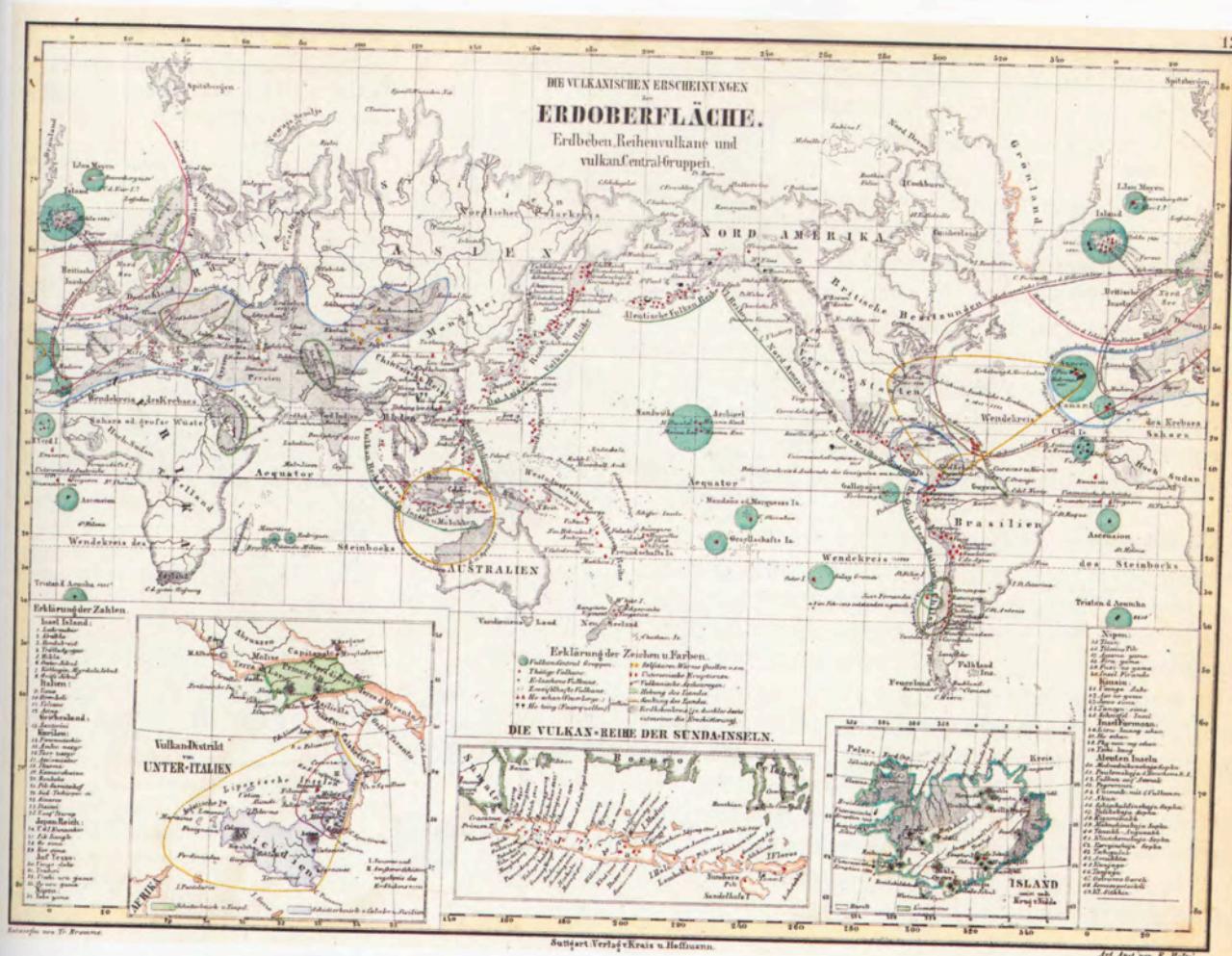
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Other projections were devised for special purposes; among the most common are the *azimuthal*, the *plane chart*, and the *Robinson* projection—the latter a compromise between the conformal and the equal-area projections, as explained previously.

The **map scale** refers to the degree of reduction of the map. It is the ratio between a distance on the map and the corresponding distance on the Earth. The ratio is often presented in the map by a verbal statement in addition to a graphic bar. The distance on the map is always expressed as one, such that in a map scale of 1:10,000, 1 unit on the map represents 10,000 units on the Earth. Because the units are the same in either side of the scale, units do not need to be stated. The ratio scale is a dimensionless number.

Two factors should be considered when selecting the map scale: the objective of the map and the intended output. The goal of the visualization will suggest the geographical scope of the map.

Considering that all projections will cause distortions, when using whole world maps, "recentering" the projection to favor parts of the globe is usual. Rather than using the usual European-centered projection, this 1851 map depicting volcanic activity around the world by Traugott Bromme is centered on Asia. Delaney expounds, "The large yellow circle around Indonesia and part of Australia shows the destructive reach of Mount Tambora's explosive eruption on April 11, 1815. Its magnitude has been given a 7 on today's Volcanic Explosivity Index, the highest rating of any volcanic eruption since the Lake Taupo (New Zealand) eruption circa AD 180." The map was part of a companion volume to Humboldt's *Kosmos*. Color encodes categorical data, with red dots standing for eruptions, green circles for volcanic regions, and colored lines for ranges.<sup>31</sup>

For example, if the goal is to portray political inclinations within a country, a world map is too small a scale, causing important details to be missed; if the goal is to study the distribution of languages around the globe, a world map is needed.

Similar to other types of visual displays, maps involve simplifications and generalizations. As Monmonier explains, "Generalization results because the map cannot portray reality at a reduced scale without a loss of detail."<sup>19</sup> As a result, it is often the case that symbols take more space than what they represent. For example, in order to make symbols legible and meaningful, lines demarcating the border of countries in a world map could be proportionately as wide as several miles, depending on the line thickness and the map scale. Symbol exaggeration is not uncommon in maps, but exaggeration should not hinder comprehension of that which the symbol represents.

Cartographers recommend that most thematic maps include features such as coastlines, major rivers and lakes, political boundaries, and latitude-longitude lines.<sup>20</sup> Deciding on which features to include will depend on the purpose of the map, with the caveat that the map scale imposes the level of details depicted in it. For example, a map portraying the transportation of goods in a country should include its major road system, which might not be needed for a map showing temperature, for example. The amount of features to include in a thematic map should suffice for the effective matching of the mental model of the spatial relations portrayed in the map in front of us. A locator inset map can always be added to maps to provide farther geographic context, effective in both static and dynamic maps.

The base map should provide enough contextual information about the general geographic space without eclipsing the visual representation of the thematic data. In other words, the base map elements should be depicted with similar degrees of generalization while being deemphasized and less detailed than the thematic distributions layered onto them. The same is true for how the geographic information is visualized, in that most world maps don't need to carry the level of detail for coastlines, for example, as a large-scale map of an island would. The smaller the map's scale, the less physical space available for visual marks and details. Robinson and colleagues alert, "This does not mean that symbols should merely shrink in size as map scale increases. Rather, the smaller the scale, the less feature detail there should be."<sup>21</sup>

## SPECTRUM OF CARTOGRAPHIC SCALES

Monmonier explains, "Maps are scale models of reality. That is, the map almost always is smaller than the space it represents."<sup>32</sup>

Sometimes, map scales are presented as fractions rather than ratios, but both carry the same information regarding the relationship between the map and Earth. Thinking about fractions can help viewers more easily grasp map scales, because the larger the fraction, the larger the map scale will be. For example,  $\frac{1}{2}$  is larger than  $\frac{1}{4}$ , the same way that 1:10,000 is larger than 1:50,000. The larger the scale, the greater the map's capacity for details.

The graph to the right is based on Monmonier's figure "Spectrum of cartographic scales, with selected examples and ranges for common applications."<sup>33</sup> Two series of maps illustrate the different scales depicted in the diagram. The maps were created by Stamen Design, which has experimented with different renditions for open source maps.

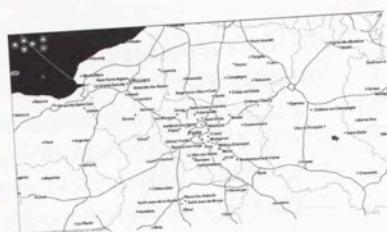
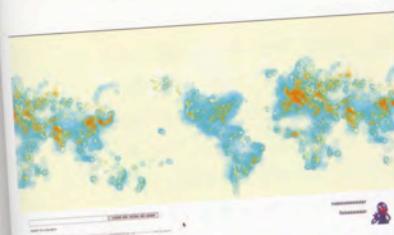
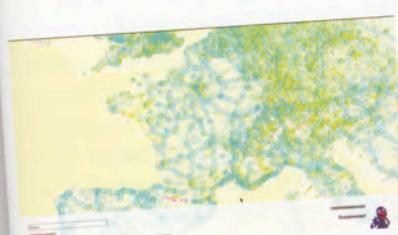
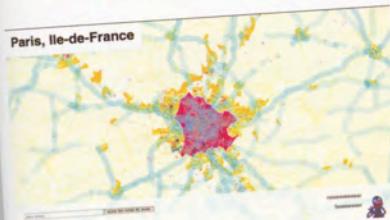
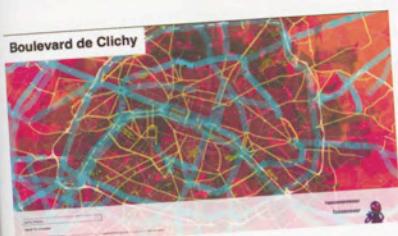
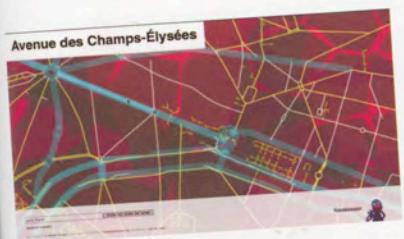
### Prettymaps

Initially designed in 2010, Prettymaps is an interactive map composed of multiple freely available, community-generated data sources: Flickr, Natural Earth, and the OpenStreetMap (OSM) project. Stamen explains that the map has "four different raster layers and six data layers (that means all the map data is sent in its raw form and rendered as visual elements by the browser) that may be visible depending on the bounding box and zoom level of the map."<sup>34</sup>

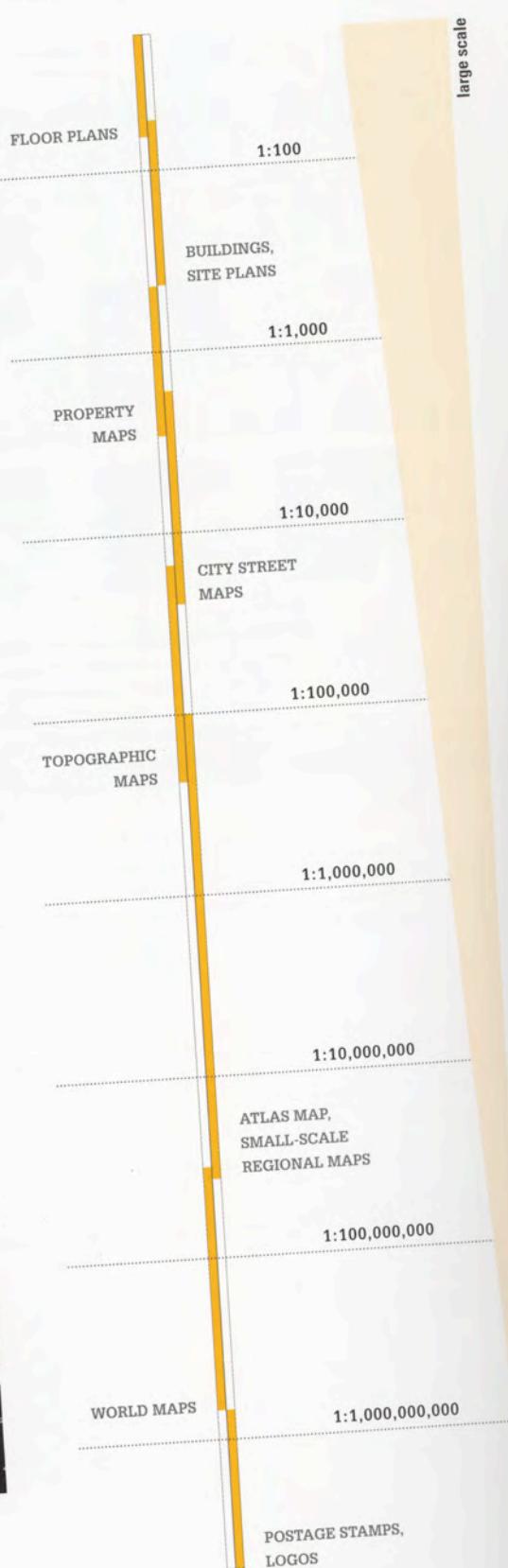
### Dotspotting

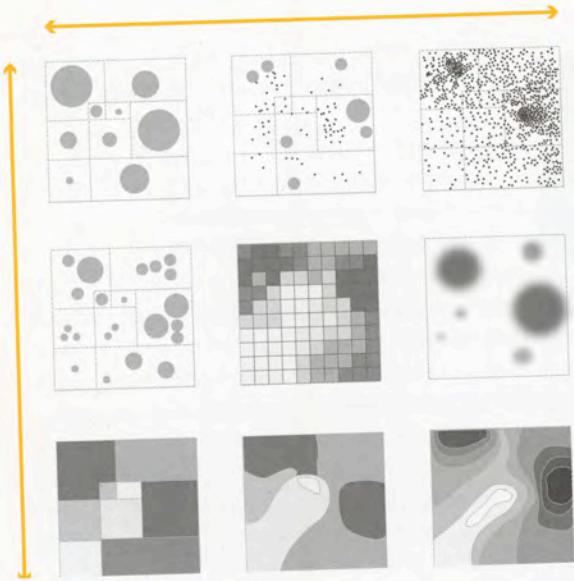
Dotspotting (2011) is the first project Stamen released as part of CityTracking, a project funded by the Knight News Challenge.

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DOTSPOTTING  
[www.dotspotting.org](http://www.dotspotting.org)





The diagram presents the syntaxes of map forms. It suggests the appropriate schema for interpretation of map forms based on the typology of data models. The diagram below provides examples of phenomena. The two diagrams were drawn after MacEachren.<sup>35</sup>



**Visual encoding** is the process of matching the phenomena to be visualized, which is provided by the dataset (data scale and attributes), to the most suitable type of representation (graphical elements and visual properties). Visual encoding in cartography is often called **symbolization**.

## DATA

In cartography and geo-informatics, **data** are divided into spatial phenomena (geography) and nonspatial phenomena, called thematic data. **Thematic** or **nonspatial phenomena** involve three levels of measurement (data scales) that increase in descriptive richness: nominal, ordinal, and quantitative.<sup>22</sup> Nominal scales, often called categorical or qualitative, allow differentiation between features (e.g., "A is different from B"), as well as sorting features into meaningful groups. Names of counties and political parties are examples of qualitative data. In addition to differentiation by class, ordinal data enable ranking, although without indication of magnitudes. For example, we can order the largest to the smallest counties in terms of population, without knowing the extent of differences among them. Quantitative data can be measured and are often numerically manipulated using statistical methods. For example, we can say, "County A has twice as many residents as county B." Or, given the area and population of counties, we can calculate the population densities (see appendix Data Types on page 204).

The **data attribute** of dimension is one of the most important characteristics when considering how to conceptualize visual marks in cartography, as well as in most other fields. For example, a point data such as a building (nominal) or an aggregated value of population (quantitative) in a city (nominal) can be symbolized by point marks. Area phenomena, such as the population density (quantitative) of a county (nominal), can be represented by area marks. In summary, data can have zero, one, two, or three **dimensions**, and be represented by the geometric elements of point, line, plane, and volume, respectively.

Another attribute relevant to thematic maps is whether data are **discrete** or **continuous**. Discrete data are composed of individual items, such as the cities on a map, which is different from continuous data, like temperature. Sometimes, discrete data, such as population, is transformed into continuous data by mathematical computations, as in the population density of an administrative unit. In some cases, this might not be ideal, if we consider that the population density will be visually represented as uniformly covering the entire area of the unit, and not depicting the "real" location of where people reside. On the other hand, this might not be easily avoided, in view that most social data are collected by administrative units.

Thematic maps can depict several sets of nonspatial data simultaneously. When a thematic map portrays exclusively one set of data, it is called **univariate**. If it shows two distinct sets of data, it is called **bivariate**, and for more than two sets, maps are called **multivariate**. For example, a map depicting population density would be a univariate map, and if in addition to the population density it portrays political affiliation, it would be considered a bivariate map. There is a limit on how many layers of visual information can be represented in a map without loss of legibility. Multiples are often used to represent such cases, as Bertin warns, "In any problem involving more than two components, a choice must be made between the construction of several maps, each one forming an image, and the superimposition of several components on the same map."<sup>23</sup>

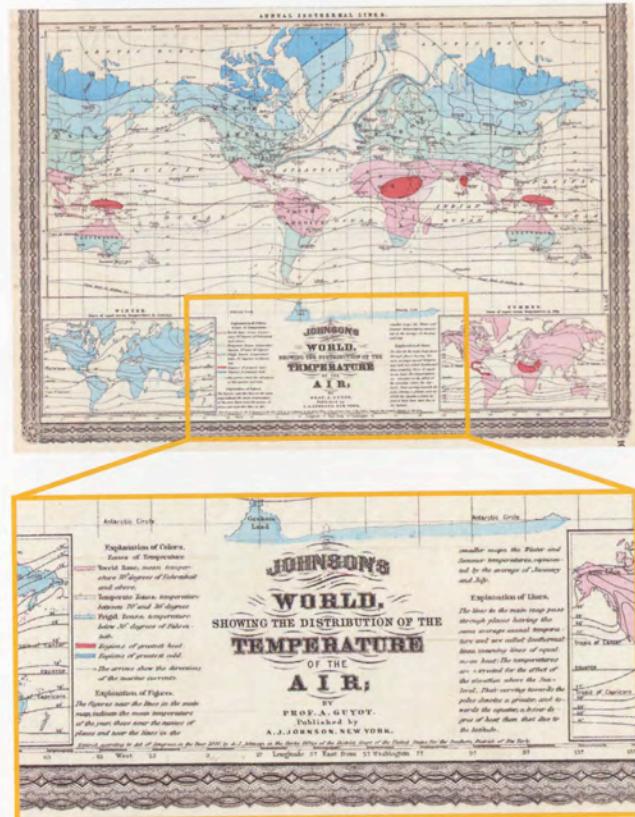
The data sources and any data manipulation should be indicated on the map, and they are most often reported in the legend. It is valuable information that enables verification of the sources, the accuracy of the representation, and the reliability of the map.

### TITLES AND LEGENDS

In general, titles provide the context for interpreting the visualization at hand. Titles should be as direct as possible and introduce the subject being represented on the map: the geographic, topical, and temporal context.

Legends or keys are essential to the effectiveness of any visualization and should be positioned in close proximity to the marks for which they stand for, to avoid forcing the viewer to search for meaning (grouping principle). Whenever possible it is recommended to include the verbal description, or label, for marks in the visualization itself, either in place of or in addition to the legend.

For ease of detection, marks should have the exact same appearance as on the map itself, including the size and orientation of symbols. Our perception of visual marks is sensitive to orientation, in that a symbol rotated 90 degrees or 180 degrees will be perceived differently, and might even be unrecognized with the additional burden of having to relearn it. For example, a square rotated 45 degrees becomes a diamond, which in this case also has a different verbal description.



This thematic map by Alvin Jewett Johnson depicts the average air temperatures for different parts of the world. It was published in the 1870 edition of his *New Illustrated Atlas*. Similar to other early thematic maps reproduced in the chapter, Johnson explains in length how to read the encoding.

## Segregation between Figure and Ground

The segregation between figure and ground principle describes the tendency to organize visual elements into units and to construct relationships. In this process some elements are selected as figure and the remaining as ground.

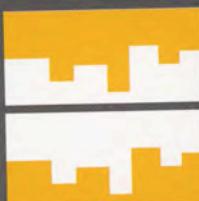
A central factor in perceiving objects is the detection of boundaries. Figure and ground should be easily distinguished. Otherwise, ambiguity is produced and they can be perceived as reversible.



Segregation between figure and ground is a dynamic process: perception shifts from one to the other possible image without stability. In the image above, we either perceive two white faces on a yellow background or a yellow vase on a white background—but not the two simultaneously.



Studies have shown that certain graphical variables enhance segregation of figure and ground. For example, the graphical variable of scale can influence how we perceive objects: a small shape in a larger shape will be viewed as the figure.



Another cue that has been reported is the tendency to perceive lower regions in the display as more figurelike than regions in the upper portion. The two images above are identically constructed. Despite the shift in color, people tend to perceive the bottom region as the figure.

## VISUAL VARIABLES

Bertin is considered to be the first to have proposed a theory of graphical representation of data for use in maps, diagrams, and networks, published in his seminal book *Semiology of Graphics* in 1967 in France, with the first English edition in 1983. His theory is based on semiology and associates the basic graphic elements with visual variables and types of phenomena. Although Bertin's system has been widely adopted by cartographers and designers when selecting the appropriate type of marks for encoding data, it also has been expanded to include other variables not considered initially. One finds in the literature various proposals for expansions that are geared toward different purposes and the needs of specific fields.<sup>24</sup> For example, most proposals have added the variable of color saturation to the other color variables of hue and value. Other proposals include tactile elements in maps for visually impaired users and dynamic variables for maps changing over time.

The system presented here builds on Bertin's initial framework with the addition of variables from other systems that are relevant to the visualizations analyzed throughout this book. The system is not prescriptive; rather, the goal is to provide guidelines for appropriately matching types of phenomena (described previously) with graphic elements and visual variables. For example, in cases involving ordered data, visual order should be perceived in the corresponding visual encoding. If that is not the case, then the visual encoding is unsuitable and could be misleading. As Ware explains, "Good design optimizes the visual thinking process. The choice of patterns and symbols is important so that visual queries can be efficiently processed by the intended viewer. This means choosing words and patterns each to their best advantage."<sup>25</sup>

The basic **graphic elements**, the primitives of visual representation, and their semantics are<sup>26</sup>

- **Point** has no dimension and provides a sense of place.
- **Line** has one dimension and provides a sense of length and direction.
- **Plane** has two dimensions and provides a sense of space and scale.

The **visual variables** correspond to visual channels and the way features are extracted in our brains. As Ware explains, "Visual information is first processed by large arrays of neurons in the eye and in the primary visual cortex at the back of the brain. Individual neurons are selectively tuned to certain kinds of information, such as the orientation of edges or the color of a patch of light."<sup>27</sup> Going back to chapter 1, in the section on the model of human visual information processing, you will notice that the variables listed below are among the preattentive features illustrated on page 23.

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## VISUAL ELEMENTS

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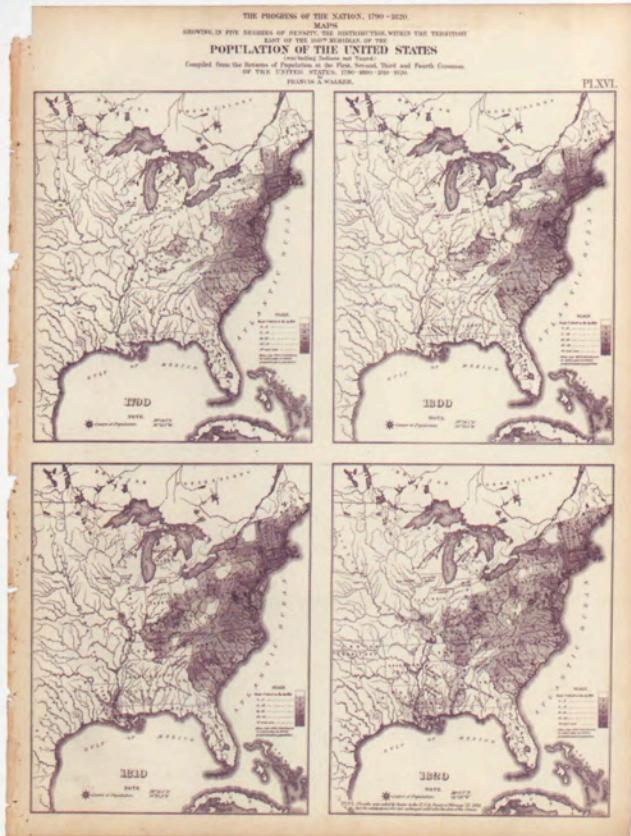
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### BERTIN'S SYSTEM OF PERCEPTUAL VARIABLES

Jacques Bertin introduced the term *visual variables* in his seminal book *Sémiolegraphie Graphique*. The diagram above presents his system of perceptual variables with the corresponding signifying properties. Dark gray stands for appropriateness.<sup>36</sup>

Bertin's system has been extended over time to include other variables, such as color saturation. Also included in the bottom table is a new visual variable introduced by MacEachren, *clarity*, that consists of the three subvariables listed in the table: crispness, resolution, and transparency. Other variables considered by map makers, but not included here, refer to motion, like velocity, direction, and frequency for example. The table was compiled after MacEachren, with middle gray standing for "marginally effective."<sup>37</sup>

Location	
Size	
Crispness	
Resolution	
Transparency	
Color value	
Color saturation	
Color Hue	
Texture	
Orientation	
Arrangement	
Shape	



The multiple maps by Francis A. Walker depict the population of the United States for the years 1790, 1800, 1810, and 1820 compiled with data from the first through fourth censuses accordingly. "The Progress of the Nation, 1720–1820 Maps" are classed into five groups of population density, from white (under 2 inhabitants to the sq. mile) to dark gray (90 and over). The maps were published in the *Statistical Atlas of the United States* in 1874, for occasion of the results of the ninth census.

These features can increase the performance of tasks requested by visualizations, such as target detection, boundary detection, region tracking, and counting and estimation.

The visual variables are organized into two functional groups: positional (in space, or where; and in time, or when) and visual properties of the entity (what). Positional variables are processed separately in the brain and have a dominant role in perceptual organization and memory; they are described by the two dimensions of the plane ( $x$  and  $y$ ), the time dimension (display time), and spatial arrangement.<sup>28</sup> Nine visual properties are considered: shape (and texture shape), size, color hue, color value, color saturation, orientation (and texture orientation), texture arrangement, texture density, and texture size.

Different from other visualizations, thematic maps are not concerned with conceptualizing the topological structure, which is provided by the geographic information in the form of the base map. All other visualizations in this book require the crucial step of deciding on the most appropriate topological structure, especially with regard to visual representation of abstract data.

#### GRAPHICAL METHODS

There are six graphical methods used primarily in thematic maps for representing all sorts of qualitative and quantitative data:

1. **Dot distribution maps**
2. **Graduated symbol maps**
3. **Isometric and isopleth maps**
4. **Flow and network maps**
5. **Choropleth maps**
6. **Area and distance cartograms**

What follows is a brief historical account of these techniques with a brief examination of recent best practices.

## WELL-KNOWN VISUAL ILLUSIONS TO WATCH FOR



The *Ebbinghaus illusion* or *Titchener circles* is an optical illusion of relative size perception. The two yellow circles are of identical size. The one surrounded by large circles (left) appears smaller in size than the one surrounded by small circles (right).



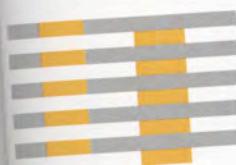
The *Delboeuf illusion*: Two identically sized circles that are near each other appear to have different sizes when one is surrounded by a ring. If the surrounding ring is closer to its inner circle, it will appear larger than the nonsurrounded circle, whereas it will look smaller if the surrounding ring is larger. The *Delboeuf illusion* is similar to the *Ebbinghaus illusion*.



The *Ponzo illusion*: two identically sized lines appear to have different sizes when placed over lines that seem to converge as they recede into the distance.



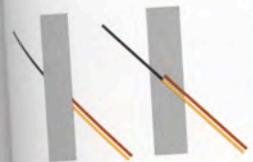
The *Muller-Lyer illusion* is an optical illusion of relative length perception: The three horizontal lines are identical, but they appear to have different lengths, depending on the direction of the arrow, if pointing inward or outward the line segment.



The *White's illusion*: the yellow rectangles on the left are perceived as lighter than the rectangles on the right, despite having the exact same color hue and color brightness.



The *Zöllner illusion* is an optical illusion of the misperception of orientation: The horizontal lines are parallel, but they do not appear parallel due to the different angles of the shorter lines.



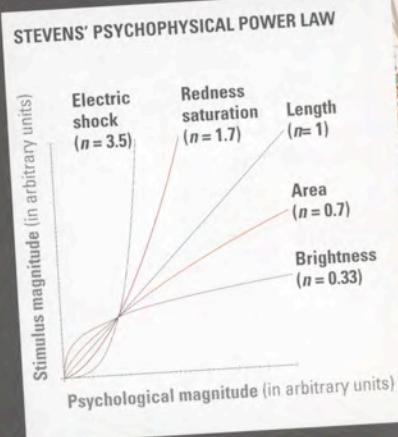
The *Poggendorff illusion* is an optical illusion of misperception of position. We perceive the red line to be a continuation of the black line when there is an obstacle between them. The apparent position shifting disappears when we remove the rectangle.

## Relative Judgments in Perception: Weber's Law + Stevens' Law

The nineteenth-century experimental psychologist Dr. Ernst H. Weber (1795–1878) noticed that the minimum amount by which stimulus intensity must be changed in order to produce a noticeable variation in sensory experience between two stimuli is proportional to the magnitude of the original stimulus. The minimum amount is also called the Difference Threshold or Just Noticeable Difference (JND). Imagine that we are holding one kilogram in each hand and that we add weight to one of the hands, up to when we start perceiving differences, for example, at around 1.1 kilograms. The difference threshold (or the JND) in this case would be 100 grams, and the Weber fraction would equal 0.1. The fraction can be used to predict JND for other magnitudes, such that we know we would need at least 500 grams to notice changes in sensory experience when we start with a 5-kilogram weight, because we wouldn't perceive differences by only adding 100 grams to this initial amount.

Gustav T. Fechner (1801–1887) built a theory around Weber's discovery, which he called Weber's law (also known as the Weber-Fechner law), stating that the subjective sensation is proportional to the logarithm of the stimulus intensity. In other words, the stimulus varies in geometric progression to a corresponding arithmetic progression of the sensation.

In 1975 Stanley Smith Stevens showed that the relationship between the magnitude of a physical stimulus and its perceived intensity follows a power law. His results show, for example, that the power for visual length is 1.0 (totally accurate), for visual area it is 0.7, and for redness (saturation) it is 1.7. In other words, when the dimension of the area attribute increases, so does our tendency to underestimate it. The opposite happens in relation to saturation: our tendency increases to



overestimating it. The graph above uses data from Stevens' seminal paper.<sup>38</sup>

Wilkinson cautions, "The presence of bias in human information processing does not imply that we should normalize the physical world to an inferred perceptual world."<sup>39</sup> On the other hand, if the goal is to represent differences in scale of the elements being represented, then we should pay closer attention to the bias, so as to afford discrimination between visual marks.

One implication to visual encoding is that the larger the number of visual attributes shared by marks, the harder it will be to note differences among them. Take, for example, the difficulties in reading text formatted using only uppercase letters, in contrast to uppercase and lowercase renditions.

Kosslyn advises, "Except for very large or very small starting levels, a constant proportion of the smaller value must be added in order for a larger value to be distinguishable...The law applies to size, lightness, thickness, density of dots, cross-hatching, and type of dashes."<sup>40</sup>

## CASE STUDY

# DOT DISTRIBUTION MAPS

Dot distribution maps aim at revealing the spatial distribution of phenomena using the basic element of a point as the visual mark. The maps can depict two sets of discrete data: discrete phenomenon with known geo-location information, such as medical mappings, or discrete phenomena with smooth variation, like most maps depicting census data, in which symbols are distributed within the corresponding geographic area in order to portray densities (not the specific locations of the phenomena). Whole numbers, rather than derived numbers, should be used in either case to equate to the value of symbols. In the first case, a dot equates to one phenomenon, and in the latter, it corresponds to an aggregated value (e.g., one dot representing 1,000 people).

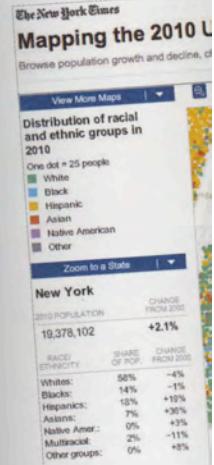
Given the current access to geo-tagged digital data, we now see a proliferation of maps with a one-to-one correspondence between datum and symbol. In these maps, dots are positioned according to a precise location ( $x$ -,  $y$ -coordinates) given by the phenomenon. The maps by Eric Fischer using Flickr data are good examples.



This 1830 map by Frère de Montizon depicts population in France by administrative departments. It is the earliest known use of irregularly spaced dots as an encoding. Each dot stands for 10,000 people. The innovation of dot distribution maps went unnoticed for a while, as Robinson explains, "except for a few rather crude, large-scale applications, without clear unit values... in medical mapping, we will see that this basically simple, logical idea had to wait some thirty years to be reinvented and much longer than that to become generally known."<sup>43</sup>

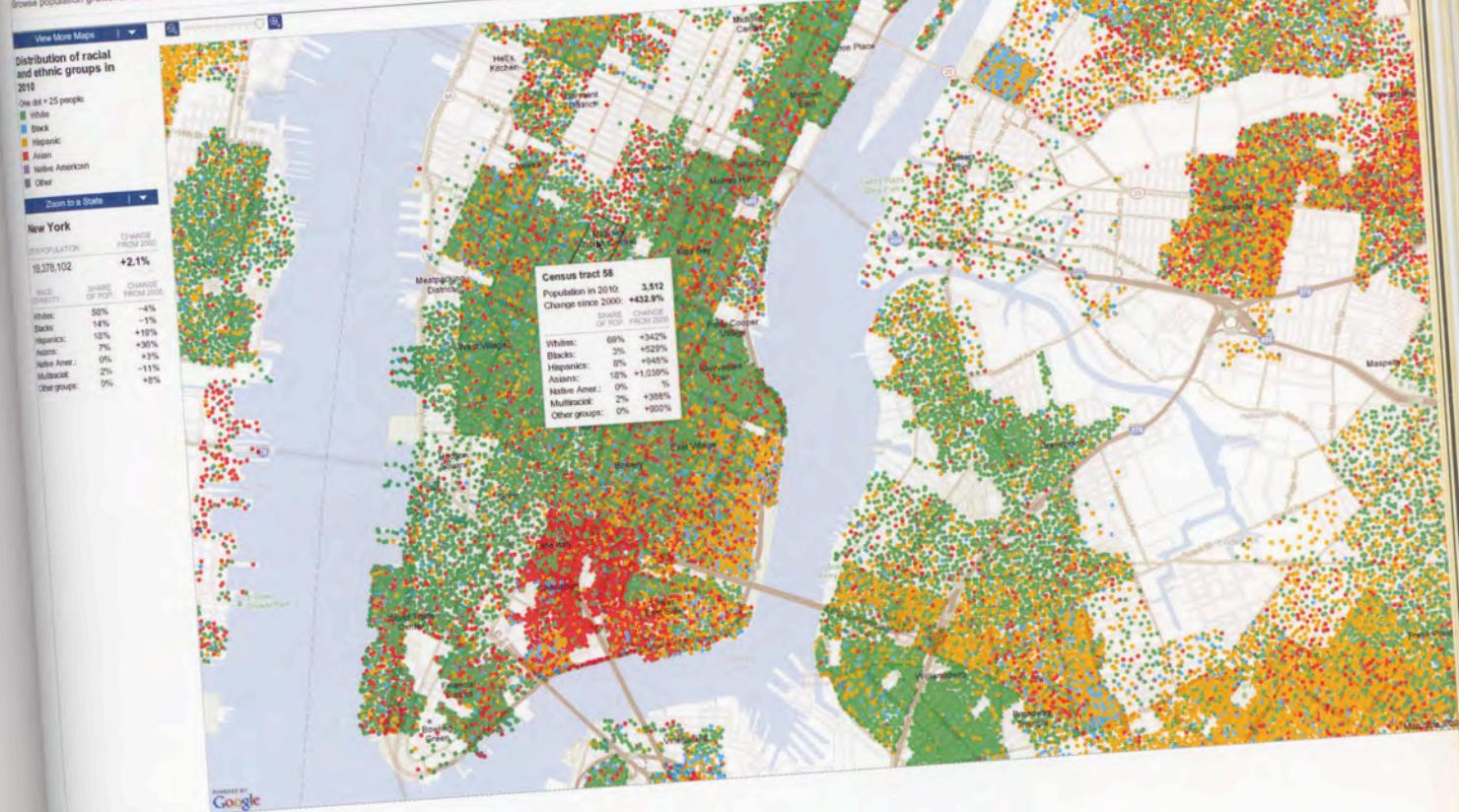
But, not all datasets contain geo-located information for individual occurrences. Rather, most data are provided by enumeration tracts, as exemplified in the demographic map published by the *New York Times*. In these cases, three parameters should be taken into account when creating the map: the unit value, the dot size, and the dot location.

Assigning the unit value and the unit size largely affect how the map is perceived. For example, if the dot size is too small, and each unit equates to large numbers, the map might be perceived as representing phenomena that are sparser than in actuality. Similarly, if a dot size is too large, and each unit equates to small numbers, the map might give a wrong impression of high density. Problems get even harder in datasets with large density variations, for which some cartographers have used a combination of graduated and distributed dot methods. Decisions on dot placement are also not trivial and will affect perception. For manually positioning dots, it is recommended to group features according to a center of gravity within the statistical unit, as well as cross relating with other meaningful geographic information, such as topography and the location of cities. For example, in maps portraying agricultural data, it would be meaningful not to cluster symbols in urban areas. The smaller the statistical area, the easier and more meaningful the distribution of symbols will be. There are, however, a number of available programs for producing dot distribution maps, because most maps are now produced digitally.<sup>41</sup> Also recommended is the *nomograph* developed by J. Ross Mackay as a tool to help determine the relationship between dot size and unit value.<sup>42</sup>



## The New York Times Mapping the 2010 U.S. Census

Browse population growth and decline, changes in racial and ethnic concentrations and patterns of housing development.

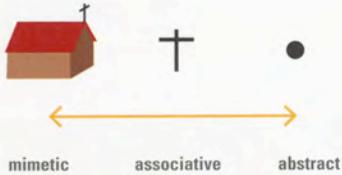


Matthew Bloch, Shan Carter, and Alan McLean  
(*New York Times*), U.S.: "Mapping the 2010 U.S. Census," 2010.

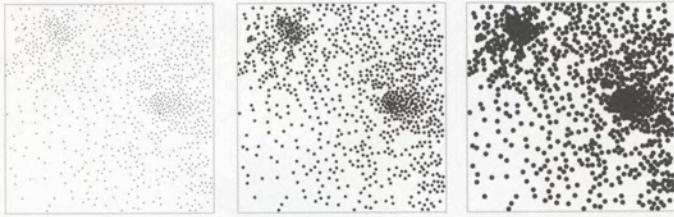
The *New York Times* published an online series of interactive maps showing data from the 2010 census (Census Bureau; [socialexplorer.com](http://socialexplorer.com)). The maps depict population growth and decline, changes in racial and ethnic concentrations, and patterns of housing development.

This map and the maps on the next page portray the distribution of racial and ethnic groups in the United States. The technique is dot distribution, where one dot in the map stands for twenty-five people. Dots are evenly distributed across each census tract or county. Because the map is interactive, one can look at different parts of the country and learn about their specific ethno-cultural configurations, including trends provided by changes from the previous census in 2000.

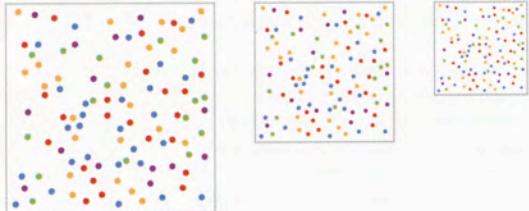
<http://projects.nytimes.com/census/2010/map>



The diagram exemplifies different types of point marks that can be used in maps as well as other visualizations: pictorial, associative, and geometric.



Changes in the size and value of the marks cause different impressions of the data in dot distribution maps. When the dots are too small, as in the first image, the patterns are hardly perceived. The converse situation happens in the far right image, where the dots are too large, giving an erroneous impression of densities.<sup>44</sup>



The smaller the marks, the harder it is to distinguish between the color hues of the marks.

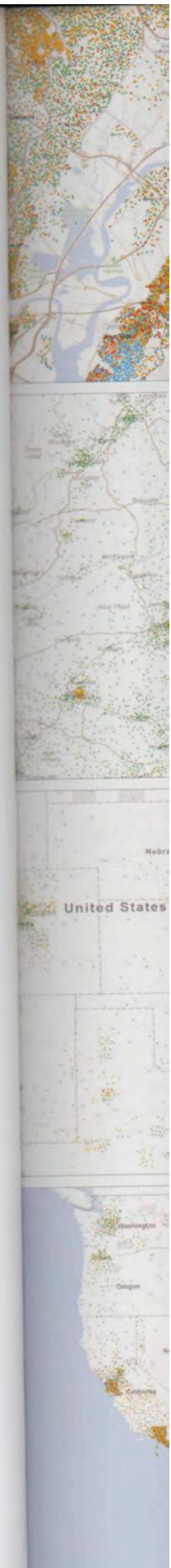


Legends are required in the case of maps where one dot equates to an aggregated value. This will help provide the viewer with some sense of estimation, especially because there is a tendency to perceive a dot with one instance. It is recommended to represent three examples of low, middle, and high densities in the map. Marks in the legend should have the same size as those in the map. Another important detail is to choose a round number for the unit value.

The circle is the most common shape, though some maps use the visual variable of shape to differentiate between categories (nominal scale). Color hue is also often used for this purpose, especially in the case of multivariate dot maps, though color hue should be used with care because it is difficult to perceive color differences in marks that are too small.

Dot maps provide an intuitive way for understanding data distribution, because variations in pattern are readily available, as clustering, for example. Dot maps are effective in portraying relative densities and, conversely, bad at displaying absolute quantities. There is, however, a tendency to underestimate the number of dots and the differences of densities between areas. As such, it is important that the unit value be a round number and clearly stated. It also helps to provide legend samples that illustrate different densities in the map, such as representations of low, middle, and high densities. As mentioned in the section on map projections, dot distribution maps require equal-area map projection, because the areas are not distorted, which is required for comparison of densities.

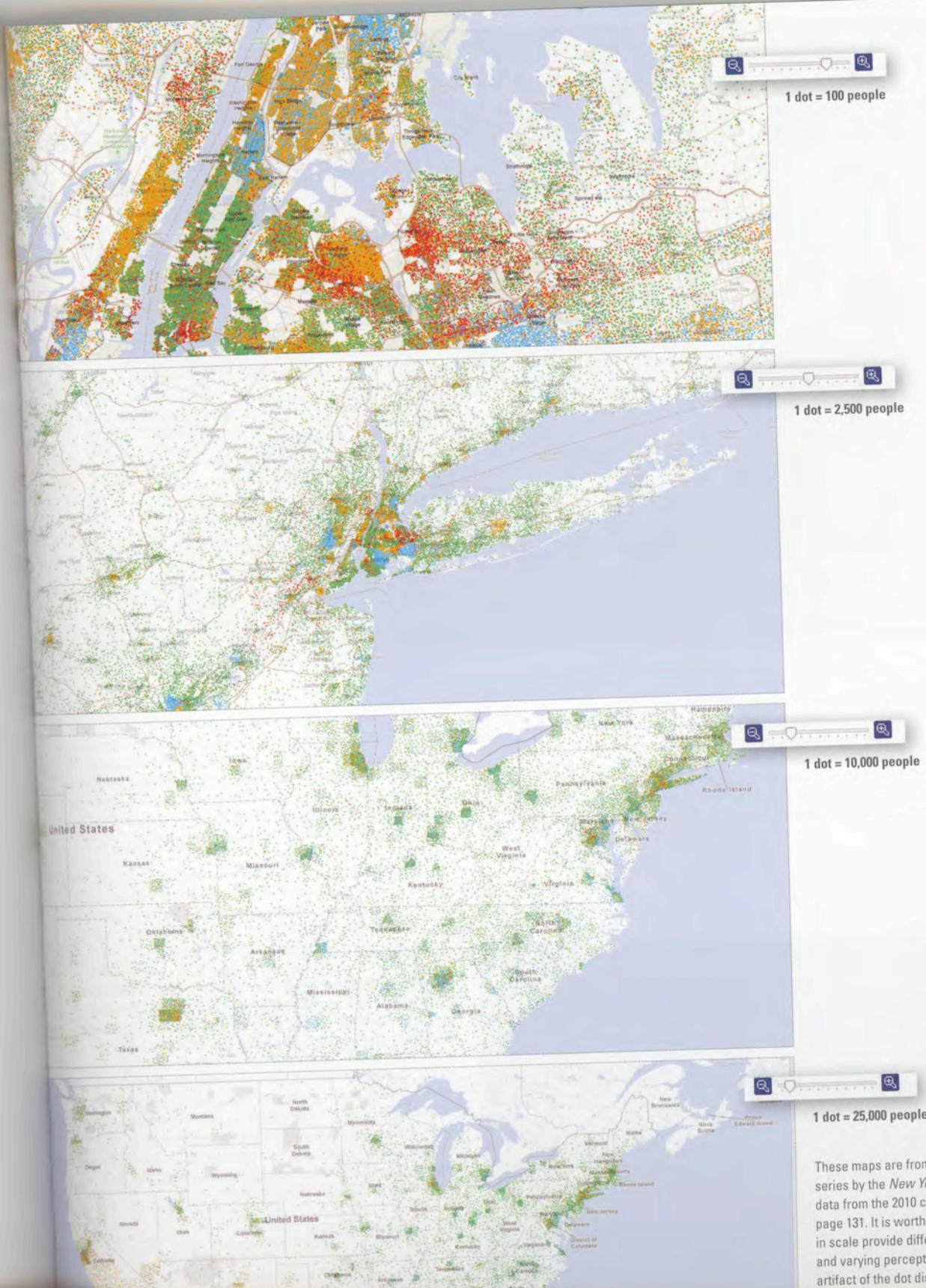
Because points are nondimensional elements, once the variable size is added to represent scale, the two dimensions of the plane are also added. What was a point is now a plane used to represent ordinal and quantitative data in a proportional symbol map, the focus of the next case study: graduated symbol maps.



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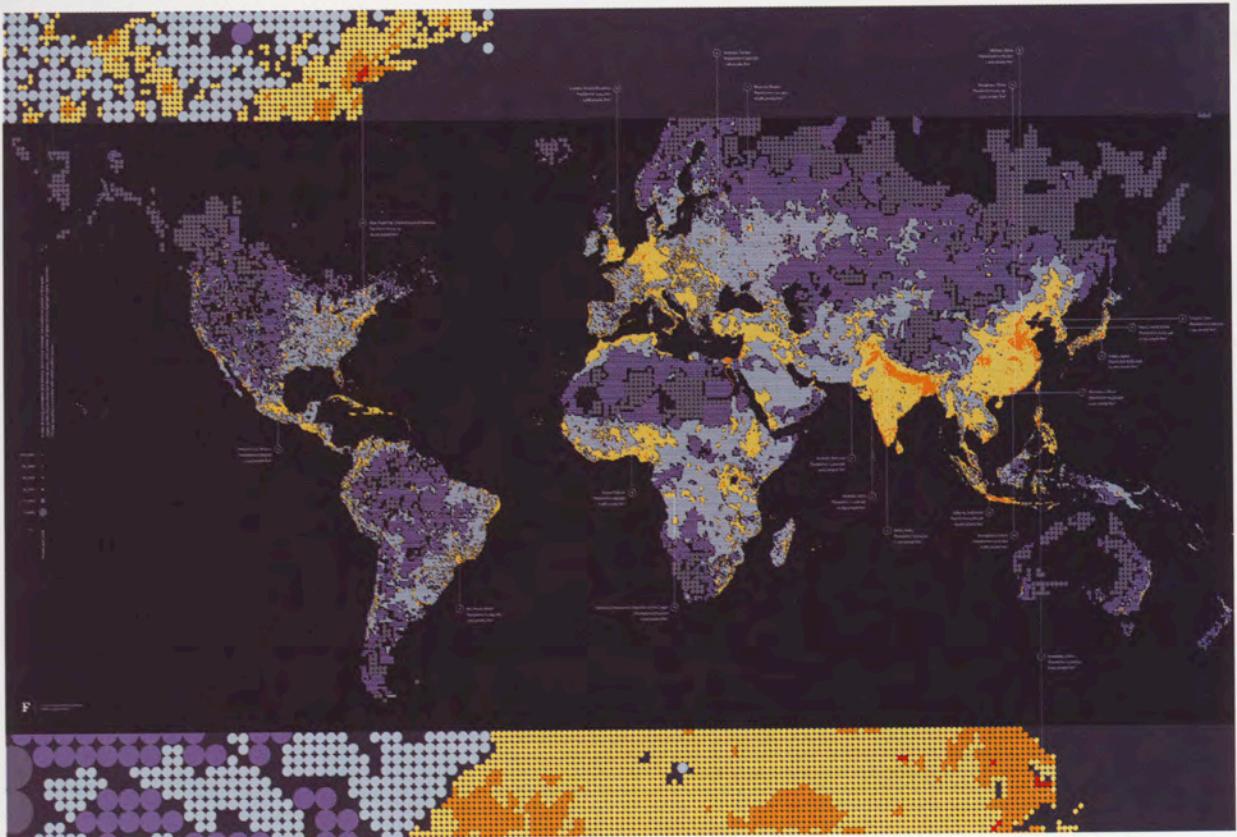
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1 dot = 25,000 people

These maps are from the same online series by the *New York Times* depicting data from the 2010 census reproduced on page 131. It is worth noting how changes in scale provide different views of the data and varying perceptions of patterns, an artifact of the dot distribution technique as



**Ben Fry, U.S.: "Dencity," 2011.**

In 2011, Ben Fry designed "Dencity" to show the global population density as the world reached the 7 billion milestone. Circles with varying size and hue encode population density, with larger and darker circles covering areas with fewer people. The visual encoding is effective, because the map highlights the populous areas. Fry writes, "Representing denser areas with smaller circles results in additional geographic detail where there are more people, while sparsely populated areas are more vaguely defined."<sup>45</sup>

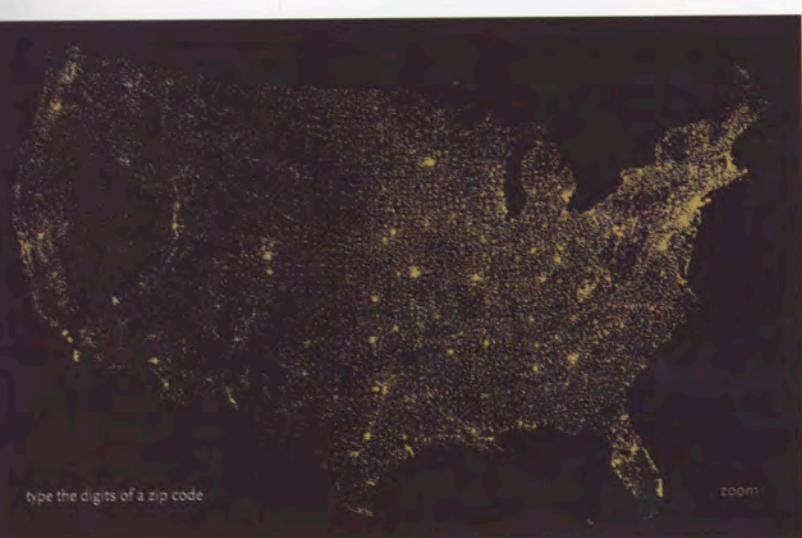
This map depicts the considered one of the within a perimeter of Dr. John Snow mapped that cholera was a w was believed at the ti weekly mortality rep individual deaths (rep represented as circ To the official data, h provided by Reverend

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Steve Johnson, in h "Snow's map deser importance rests o influence. The orig to map an epidemic etched across the was that wobbly ci version, the Vorone generated that dia in the first place. S was drawn from tr



**Ben Fry, U.S.: "Zip code map," 2004.**

In 2004, Ben Fry created this map out of curiosity about the system behind ZIP codes. The map is constructed out of all the ZIP codes in the United States. For each ZIP code number, the software positions a dot in space according to the latitude-longitude coordinates provided by the U.S. Census Bureau. The result is the rendition of the U.S. map with a clear understanding of population density in the country, because there are more ZIP code numbers in denser areas. Considering that it is an interactive online tool, it is possible to search for ZIP codes as well as highlight areas that share the same partial numbers, such as all codes starting with 0, or with 33, and so on. A detailed description of this project, together with the source code, can be found in his book *Visualizing Data*.<sup>46</sup>

<http://benfry.com/zipdecode>

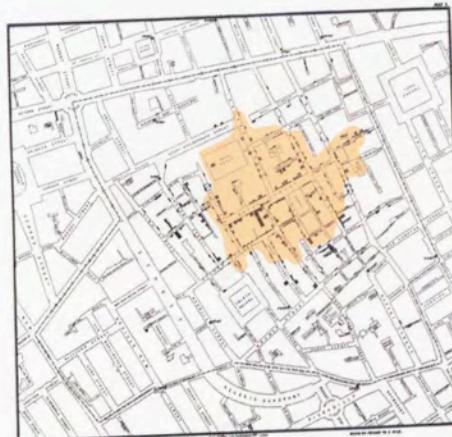
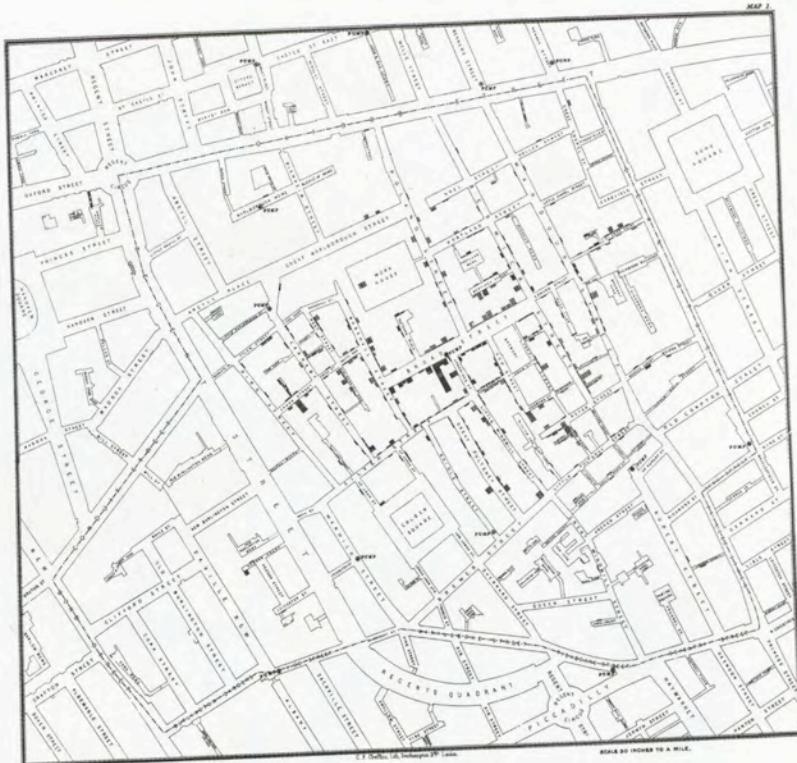
This map depicts the cholera epidemic of 1854 in the south of London, considered one of the worst ever, killing around 500 people in ten days within a perimeter of 250 yards (228 m).<sup>47</sup> The British anesthesiologist Dr. John Snow mapped the outbreak in an effort to argue for his theory that cholera was a waterborne illness, not an airborne disease, as was believed at the time. Dr. Snow used the General Register Office's weekly mortality report of London as the source for laying out the individual deaths (represented as bars) in relation to the water sources (represented as circles) in the urban area of St. James, Westminster. To the official data, he added local knowledge, such as information provided by Reverend Whitehead, who also had mapped the outbreak.<sup>48</sup>

The map did not pioneer the use of point marks to depict disease occurrences. As Robinson explains, "An Inquiry into the Cause of the Prevalence of the Yellow Fever in New York" from 1797 by Seaman is considered to be the first of its kind.<sup>49</sup> Several medical practitioners in the beginning of the nineteenth century in Europe used maps as a means to understand environmental aspects of disease outbreaks. In medicine as well as in other fields, maps served as visual arguments of spatially grounded theories.

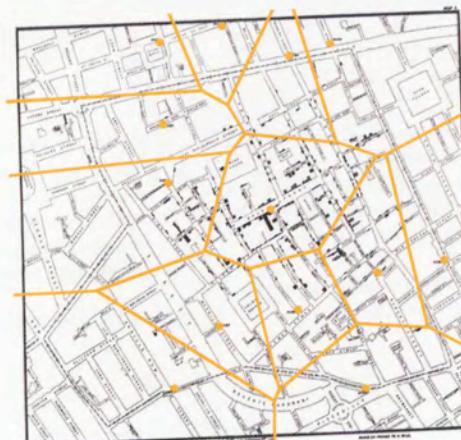
In the book *Disease Maps*, Tom Koch describes how "Snow developed a spatial theory that was tested in the map. This was not propaganda but an attempt at science. The map was the embodiment of Snow's proposition that if cholera was waterborne then its source had to be water, in this case, the Broad Street pump at the epicenter of the outbreak."<sup>50</sup> His spatial theory is more evident in the second version of the map, to which Dr. Snow added a dotted line to represent the walking distances of the neighbor population to the infected water pump. In other words, the line provided a temporal measure of how long it took to get to water sources.

Dr. Snow's map did not bring an end to the cholera epidemic, nor did it convince the health authorities of the waterborne theory. Discussions around the nature of cholera only settled in 1883, when bacteriologist Robert Koch identified Vibrio cholera as the waterborne agent.<sup>51</sup> The map, however, helped advance understanding of a public health issue (cholera epidemic) by revealing the disease pattern (inherently numerical) in the spatial context (walking distances to water pumps).

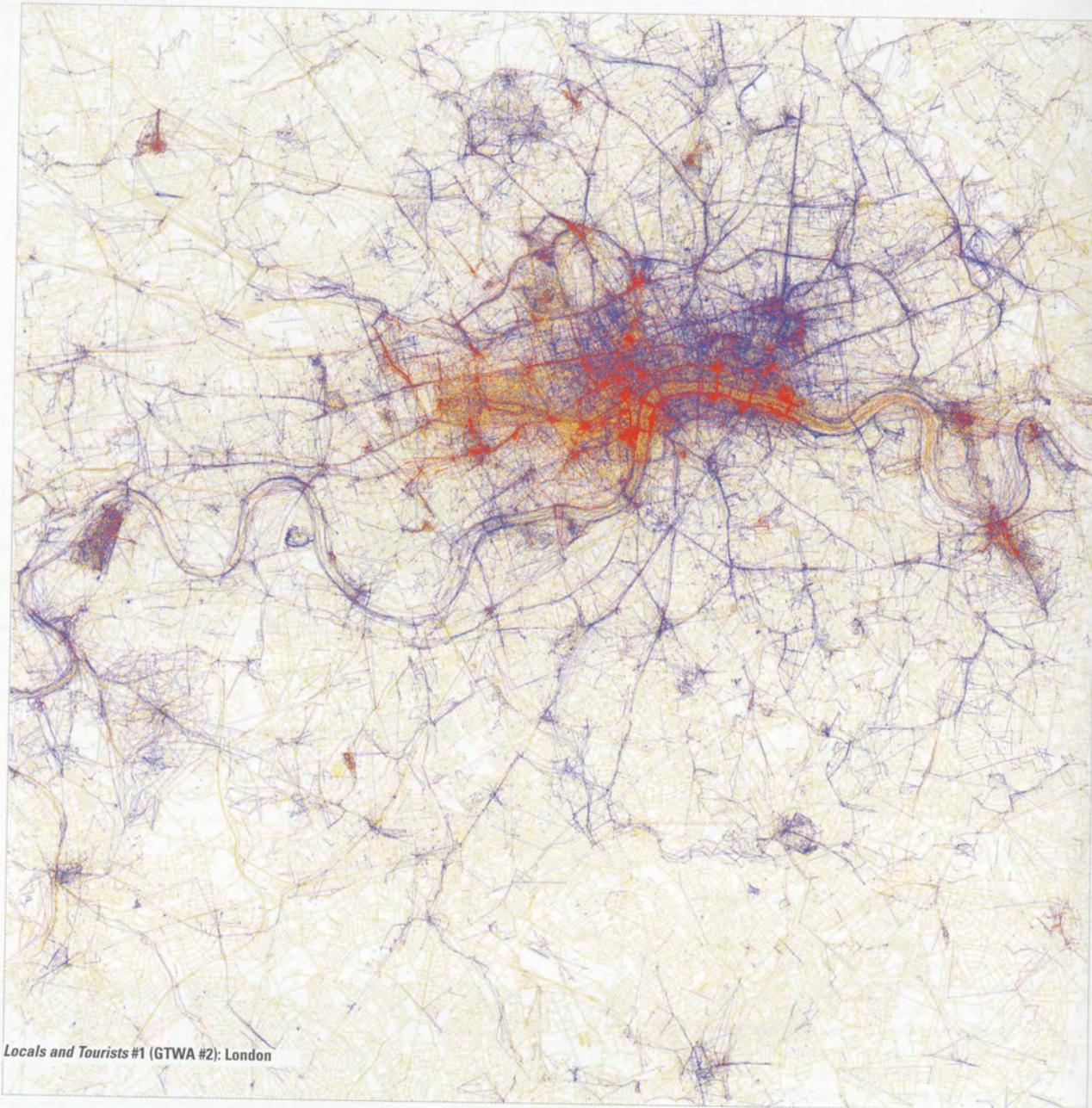
Steve Johnson, in his book *The Ghost Map*, writes about its legacy: "Snow's map deserves its iconic status. The case for the map's importance rests on two primary branches: its originality and its influence. The originality of the map did not revolve around the decision to map an epidemic, or even the decision to encode deaths in bars etched across the street diagram. If there was a formal innovation, it was that wobbly circumference that framed the outbreak in the second version, the Voronoi diagram. But the real innovation lay in the data that generated that diagram, and in the investigation that compiled the data in the first place. Snow's Broad Street map was a bird's eye view, but it was drawn from true street-level knowledge."<sup>52</sup>



The yellow area corresponds to the line Dr. Snow drew on the map to depict the equal walking distances between the Broad Street water pump and other pumps.



Dr. Snow did not use a Voronoi diagram in his efforts to understand the cholera outbreak. However, when we draw a Voronoi diagram onto the original map, it shows that the cell containing the largest number of deaths coincides with the one where the Broad Street water pump is located.



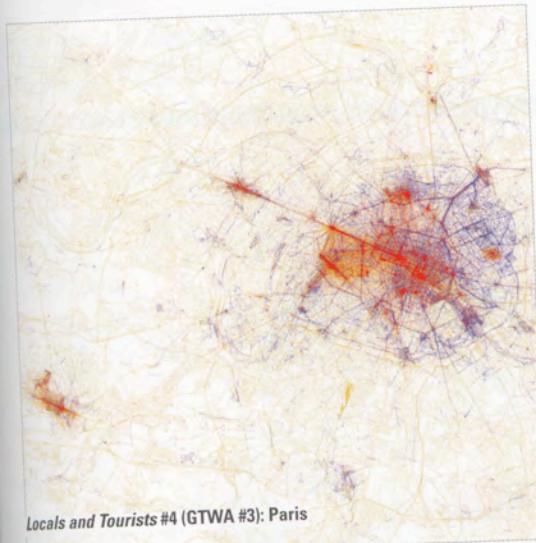
Eric Fischer, U.S.: "Locals and Tourists," 2010.

Eric Fischer created this set of thematic maps "Locals and Tourists" in 2010. The dots depict the location of photos that were geo-tagged and uploaded to the photo server Flickr. By analyzing the frequency of photos taken in the locations, Fischer was able to categorize photographers into three groups according to the criteria and color code as follows:

- Local photographers (blue dots): Locals are those who have taken pictures in this city over a range of a month or more.

- Tourists (red dots): Tourists are defined by two criteria: those who took pictures in this city for less than a month but also seem to be a local of a different city, provided by the number of photos there.
- Undefined (yellow dots): Undefined stands for images for which it was not possible to determine whether or not the photographer was a tourist, because pictures were not taken anywhere else for over a month.

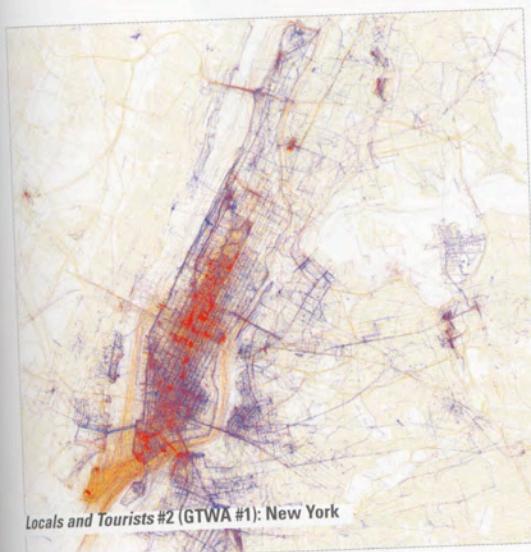
[www.flickr.com/photos/walkingsf/sets/72157624209158632](http://www.flickr.com/photos/walkingsf/sets/72157624209158632)



*Locals and Tourists #4 (GTWA #3): Paris*



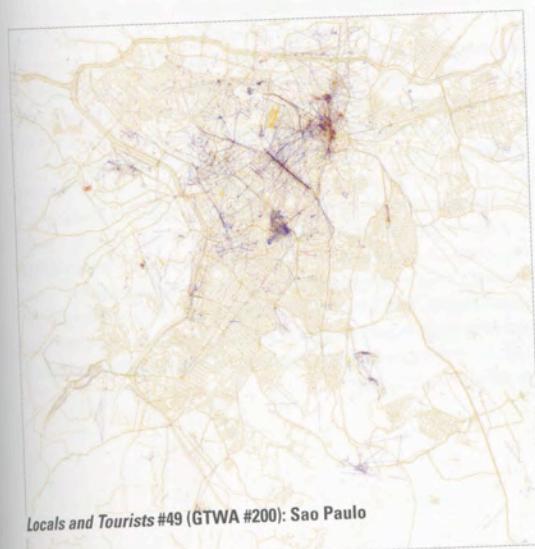
*Locals and Tourists #36 (GTWA #40): Moscow*



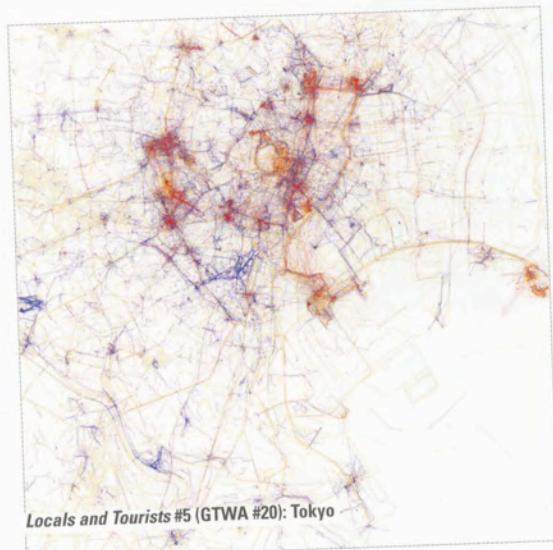
*Locals and Tourists #2 (GTWA #1): New York*



*Locals and Tourists #10 (GTWA #10): Toronto*

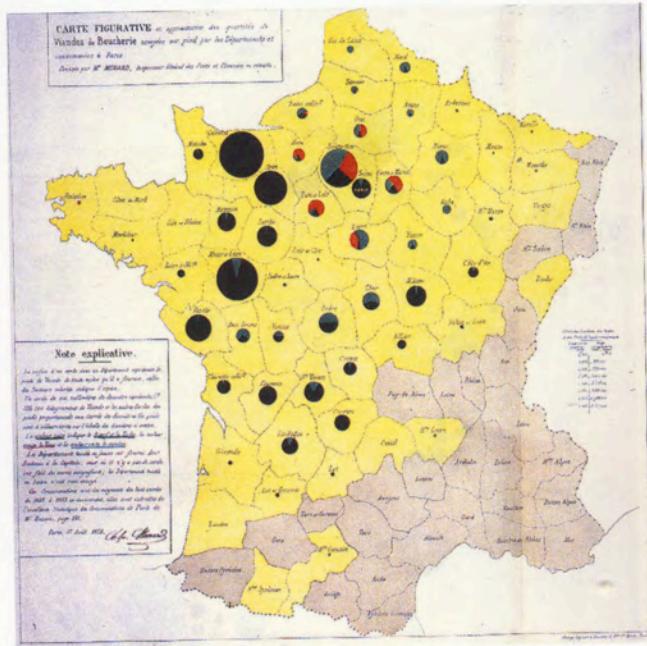


*Locals and Tourists #49 (GTWA #200): São Paulo*



*Locals and Tourists #5 (GTWA #20): Tokyo*

## GRADUATED SYMBOL MAPS



This 1858 map by Charles Minard is considered the first to have used graduated pie charts in maps.<sup>53</sup> It portrays the amount of butcher's meat supplied by each French department to the Paris market between the years 1845 and 1853 ("Carte figurative et approximative des quantités de viandes de boucherie envoyées sur pied par les départements et consommées à Paris"). Each circle is scaled to represent the proportional quantities of meat supplied by the administrative departments. The wedges of the pie charts refer to relative amounts of beef (in black), veal (in red), and mutton (in green). The color encoding the base map stand for departments supplying meat (in yellow) and not supplying meat (in bister). The departments lacking circles supplied meat, but in too small amounts to be noted.

Graduated symbol maps use the visual variable of size to proportionally represent magnitudes of thematic discrete data. The size is proportional to the quantities represented, but not dependent on the geographical area over which it stands. This characteristic helps avoid problems of confounding geographic area with data values, as in the case of choropleth maps (see page 142).

There are two main variables to consider when designing a graduated symbol map: the shape of the symbol and the scaling. The shape of the marks can vary, and the most common shape is the circle, although we see rectangular bars as well as triangles being used. There have been attempts at three-dimensional symbols, where the scaling is done to the cube rather than to the square root. But, if area perception is already hard in two dimensions, and often underestimated, then it gets even more problematic judging relative sizes of quantities provided by volumes. Glyphs have also been used for depicting more than one variable. The 1858 map by Minard is the first known example, where pie charts are used to portray different kinds of meat.

Selecting the scaling method is perhaps the biggest challenge in proportional symbol maps, as well as in choropleth maps. There are two ways to scale the size of symbols: classed, when size is range graduated, and unclassed, when sizes follow a proportional system.

In unclassed systems, the number of categories is equal to the number of data values. If there are five values, then there will be five encodings. For representing a large number of values, the most common strategy is the use of percentages. This strategy is more commonly employed in choropleth maps using color value graduation, rather than for scaling symbols, because differentiation would be almost impossible.

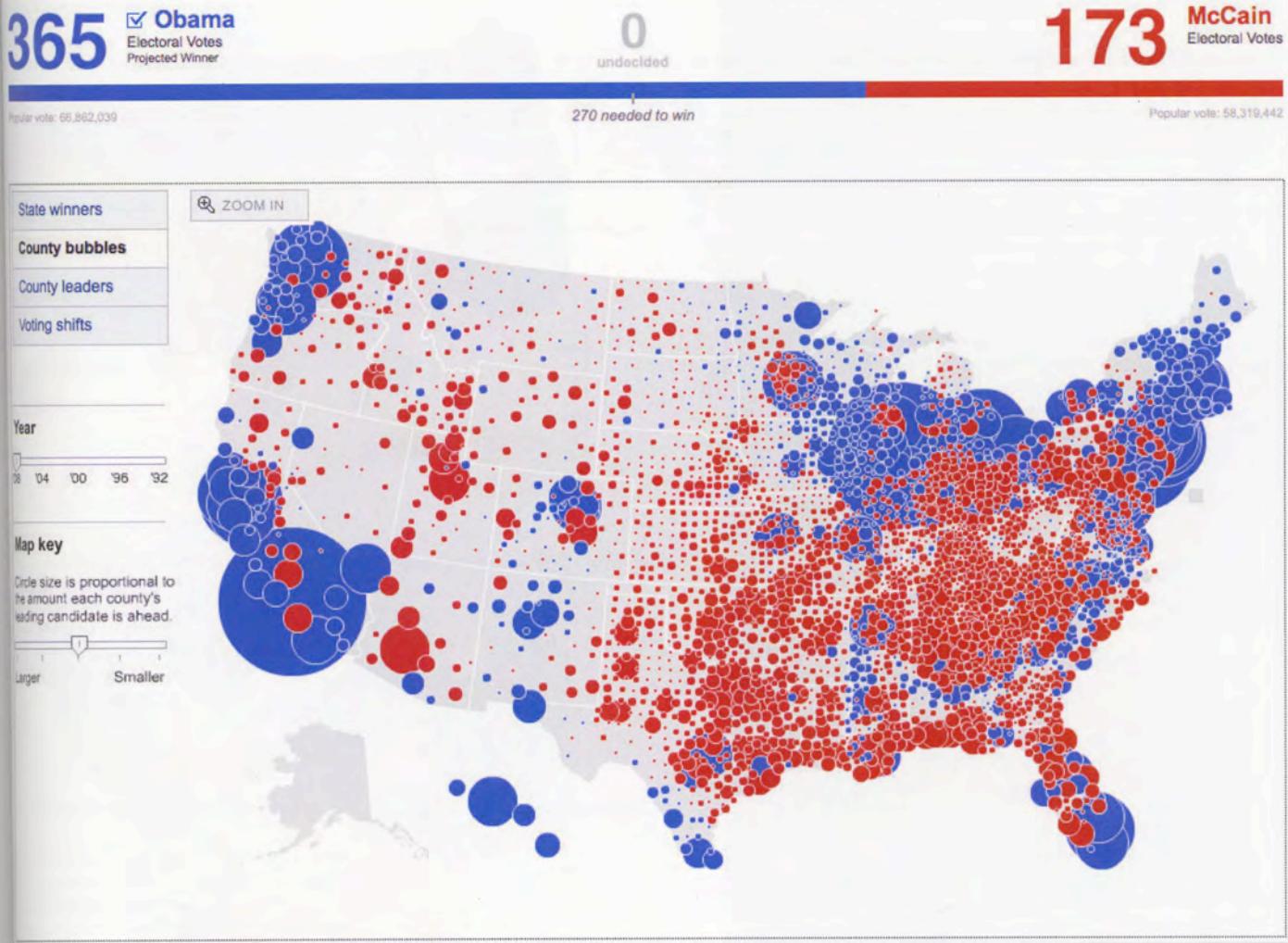
State winners  
County bubbles  
County leaders  
Voting shifts

Year

Map key

Circle size is proportional to the amount each candidate received. Larger

Two issues : because they thus perceive for dividing influences t is recommended before making the method box Making recommendations characterist quantile me numbers—that identify different values color saturation however, p



of size to discrete represented, for which forms of as in the designing symbol and the most rectangular have been the scaling spot. But, if ons, and often automatic judging s. Glyphs have variable. The e, where pie mat. suggest as in the size rated, and stem. es is equal values, then a large number use of employed n, rather on would

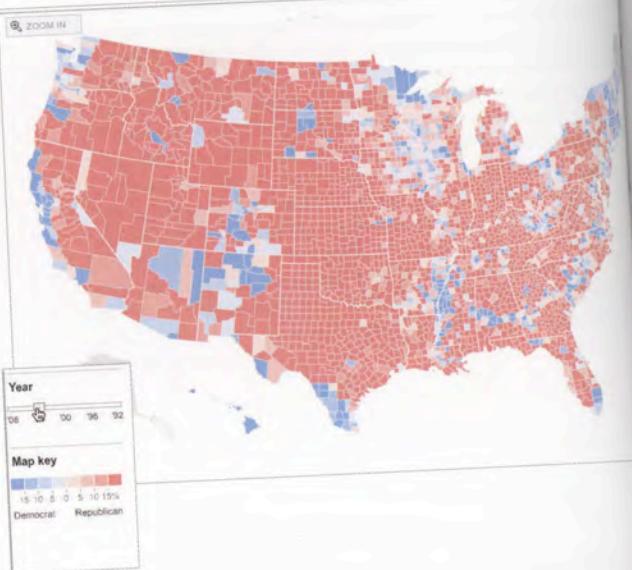
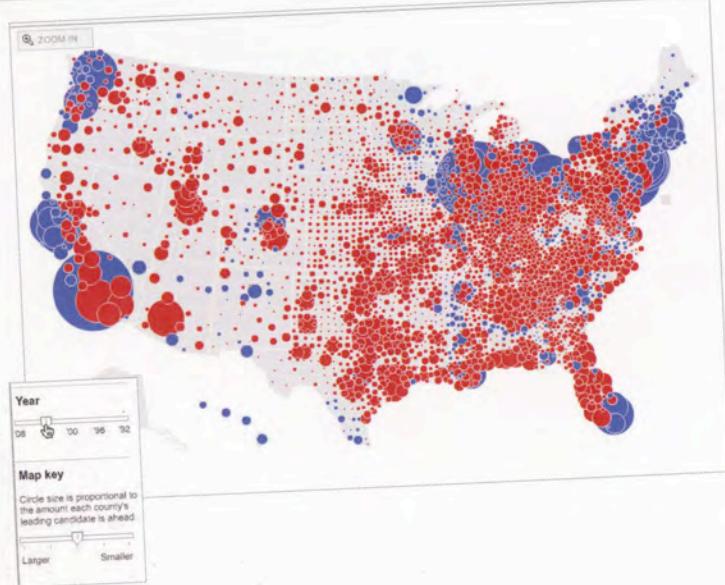
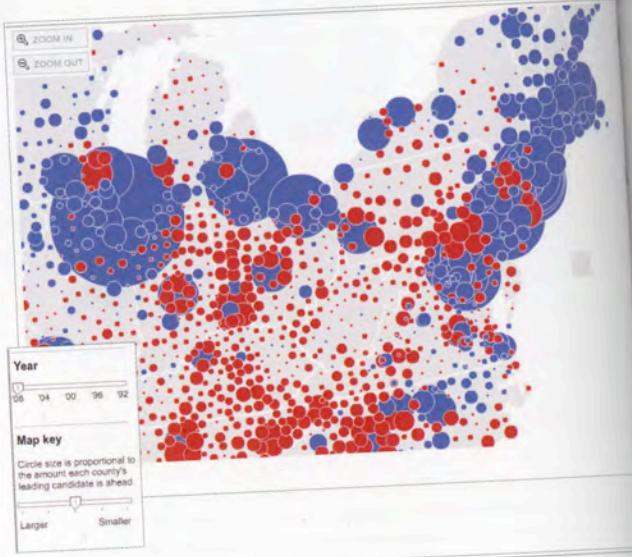
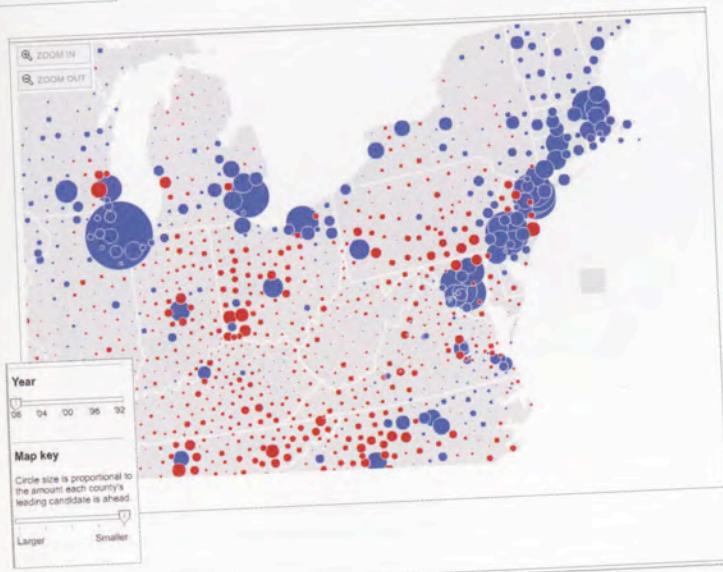
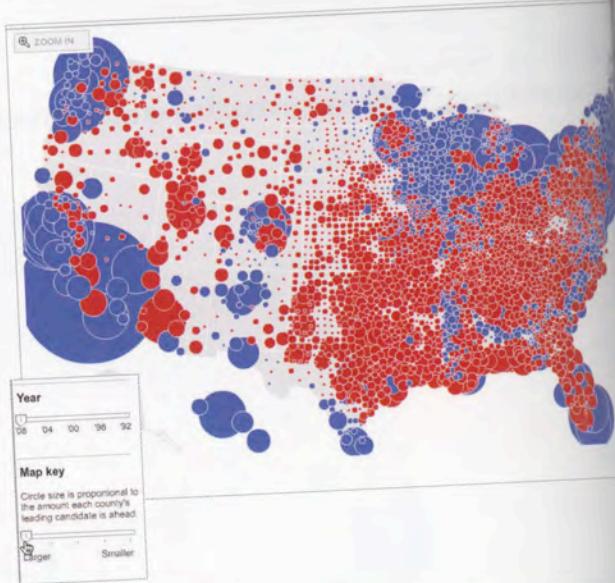
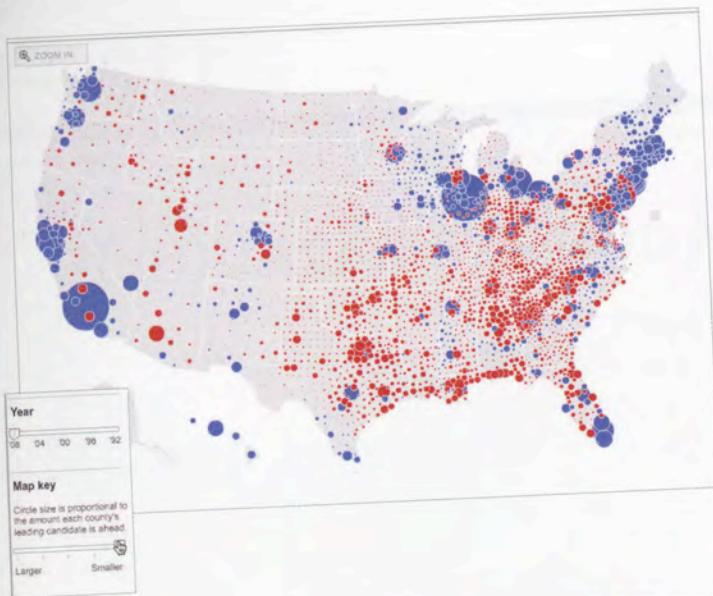
Two issues should be considered in classed systems because they influence how data are represented and thus perceived: the number of classes and the method for dividing the data. A differing number of classes influences the patterns revealed in the visualization, and it is recommended to experiment with the number of groups before making a final decision. The same holds true for the methods used for breaking down quantities (see the box Making Meaningful Groups on page 141). It is highly recommended to first analyze the data to understand certain characteristics, such as distribution. For example, using quantile methods—dividing quantities into groups of equal numbers—for representing skewed data is a poor choice, in that identical values will be divided into different groups, and different values will be grouped together. Color values and color saturation might be used to map other data attributes; however, perception is hindered in small marks.

#### New York Times, U.S.: "Election Results 2008," 2008.

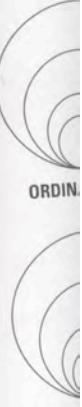
During the presidential election in 2008, the *New York Times* published a series of visualizations showing votes by counties and state. The maps include data on previous elections back to 1992. For each year, the application allows viewers to select the visual technique used to represent the data. This spread focuses on the graduated dot symbolization. A comparison with the choropleth technique is available on the next page.

<http://elections.nytimes.com/2008/results/president/map.html>

These maps are from the on the previous page. They by the New York Times during the 2008 election. Color coding the political affiliation of (blue) or Republican (red) represents quantitative to the amount of votes leading candidate. The to choose the graduate ways of scaling circles: perceiving the phenomenon of the circle scales. Finally, maps and how identical different methods: a g and a choropleth map.



Using the radius of the statistical area misrepresentation causes misperception of the increase in scale graduate



RATI

These maps are from the same online series shown on the previous page. The maps were published by the *New York Times* during the presidential election in 2008. Color depicts categorical data: the political affiliation of voters, whether Democrat (blue) or Republican (red). The area of circles represents quantitative data, which is proportional to the amount of votes in each county by the leading candidate. The application allows viewers to choose the graduated system providing five ways of scaling circles. Note the differences in perceiving the phenomena with the changes in the circle scales. Finally, compare the bottom row maps and how identical data is depicted using different methods: a graduated symbol map (left) and a choropleth map (right).

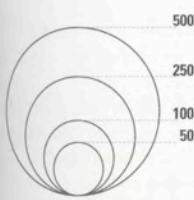


CORRECT METHOD: circles scaled proportional to area: calculated according to square roots

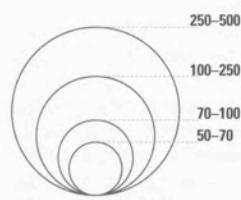


WRONG METHOD: circles scaled proportional to diameter: calculated according to radius

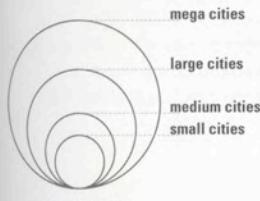
Using the radius of a circle symbol to stand for the statistical amount is erroneous and leads to misrepresentation of the data. Furthermore, it causes misperception of the phenomena, due to the increase in size of symbols as a consequence of the calculation. In sum, the radius of circles or the side lengths of squares should not be used to scale graduated symbols.



ORDINAL SCALE



RANGE-GRADED SCALE



RATIO SCALE

As the identical legends illustrate, we can use graduated symbols to stand for three types of scales: ordinal, range graded, and ratio. Illustration redrawn after Robinson and colleagues.<sup>54</sup>

## Making Meaningful Groups

The goal of breaking down quantities into groups (or classes) is to enhance patterns that might otherwise not be revealed in the more detailed representation (unclassed). Closely associated with how we reveal patterns is the other side of any visualization, which is how the viewer detects patterns given our own perceptual limitations. For example, we are unable to distinguish more than seven shades of gray (see the box *Magical Number Seven* on page 97). Finally, the purpose of the map also helps determine how the breaks and the number of classes are defined.

The methods used for breaking down quantities are especially important and will largely influence the graphical encoding as well as how the visualization will be perceived. Carefully chosen groups will enable identification of meaningful information.

There are three basic methods for defining boundaries between the groups (or classes):

1. **Equal steps.** Data are grouped into arbitrary equal divisions that can either be based on equal intervals, such as equal value steps (0–100, 100–200), or equal number of data values, such as on quantiles, where, after ordering values, data are divided by the number of classes into groups.
2. **Unequal steps.** Data are grouped using interval systems toward the upper or lower ends. Mathematical progressions help define the intervals using an arithmetic series (numeric difference) or a geometric series (numeric ratio). The method is used, for example, to depict increasing or decreasing values at either constant or varying rates. The resulting classes will contain members with similar data values.
3. **Irregular steps.** Data are grouped according to internal characteristics of the distribution. One reason for using such variable series is to highlight data values that would not be apparent when using a constant or regular series, while preserving an understanding of the whole distribution. To accomplish such complex tasks, especially when dealing with large datasets, we need to use statistical means involving both graphic and iterative techniques to help in selecting the breaks. Frequency and cumulative graphs are commonly used in those cases.

Isabel Meirelles

An introduction to the histories,  
theories, and best practices behind  
effective information visualizations

ROCKPORT

# Information Design for