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Displaying Information:

From Woolly Mammoths to the Great Migration

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Graphs are the intermediary between
information and understanding.

with our apologies to Hans Hofmann

Successfully negotiating the modern world often requires full and facile comprehension of quantitative phenomena. Experience gathered over more than three centuries has taught us this is best done by transforming the evidence into various kinds of pictures, so that we can enlist the remarkable power of the human visual system to rapidly decode and store complex information. Tracing the evolution of data visualization reveals many mysteries whose solution requires that we begin at the beginning.

1. Evolution of Recording Numbers

The idea of a number is very old indeed, and ancient ways of writing down numbers can be traced back to Paleolithic tally sticks (dating from the Aurignacian, approximately 30,000 years ago), which had notches cut into a bone, ostensibly to represent counts of something of interest. For example, such counting sticks were subsequently used to keep track of domestic animals. A notch was made when an animal was released to pasture and then later, when they returned, the shepherd’s thumb would move down the stick, notch by notch. If no notches remained after the last animal returned, the shepherd would be assured that all was well. Such a system, though vastly better than relying on memory, had room for improvement. Adding an animal was easy, just another notch, but subtracting (perhaps because of a predator in the neighborhood or mutton for lunch) was more difficult and might require carving a new stick. Keeping separate track of several kinds of animals (e.g. goats and sheep or males and females) could be done with separate sticks for each type, but it would quickly become cumbersome to carry them around and to remember which was which.

Over time, the system of counting sticks evolved. The pre-Columbian Incans transformed their counting sticks into Quipus, ropes into which they tied knots that served the same role as notches. But knots could be untied, allowing subtraction. Also, two or more such ropes, each representing a different kind of animal, could be tied together and easily wrapped around the waist or thrown over the shoulder. Over time the Quipu evolved to include a summary: knots on the bottom portion of the rope each represented a single animal, but when ten knots accumulated, they were untied and a single knot representing ten was tied higher up on the rope. Some Quipus had three levels of knots, with a knot on the topmost level representing one hundred. These typically were above the joining of several strands (say goats, sheep and pigs), to indicate a grand total. In the evening, Quipus were sometimes hung on the wall of its owner’s dwelling as a display of the family's wealth. We assume that the use of a base-ten for the construction of Quipus was strongly related to having ten fingers, which almost surely was the basis for all subsequent counting devices. Had the Incans had six fingers on each hand, there is little doubt that their mathematics would have been base twelve.

The same forces that propelled the evolution of counting to yield the Quipu were at work in the Roman counting system, where a single knot became the written symbol “I” and a count of three was simply “III”. But instead of untying the knots and replacing them with another knot in a different place, Romans substituted a new symbol “V” to mean five and still another symbol (X) for ten, and so on. The position of the symbol had little meaning except when indicating subtraction (e.g., IV) to avoid possibly confusing repetition (IIII). The Roman system was an obvious formalism of the humble tally (/, //, ///) still in use today.

Roman numerals were systematic, but their use for anything beyond record keeping and decoration was cumbersome. Try to imagine how Roman engineers could have built anything whose construction required computation of a precise measurement (e.g. how would you multiply 6,342 by 18,327 with Roman numerals?). Despite this grave limitation, the evolution of written numbers, at least in Europe, was in stasis until the great Italian mathematician Leonardo Fibonacci (c.1175–c.1250) visited the Middle East during the time of the third Crusade.

In his travels in North Africa Fibonacci met with Middle-Eastern merchants and learned about the Hindu-Arabic numeral system, whose key component was zero. Upon his return Fibonacci told an engineer friend about this marvelous system, which used the digits 0–9 and place value to represent numbers but met with no enthusiasm. His friend rebuffed him, explaining that although this new method of recording numbers sounded interesting, he had a pressing problem in long division that had to be completed by next November and so he had no time to spare. This experience motivated Fibonacci to publish his justly famous 1202 treatise *Liber Abaci*. His book laid out in detail how the new system could be used in bookkeeping; interest calculations, money changing and other practical matters, and soon Roman numerals were relegated to being primarily decorative.

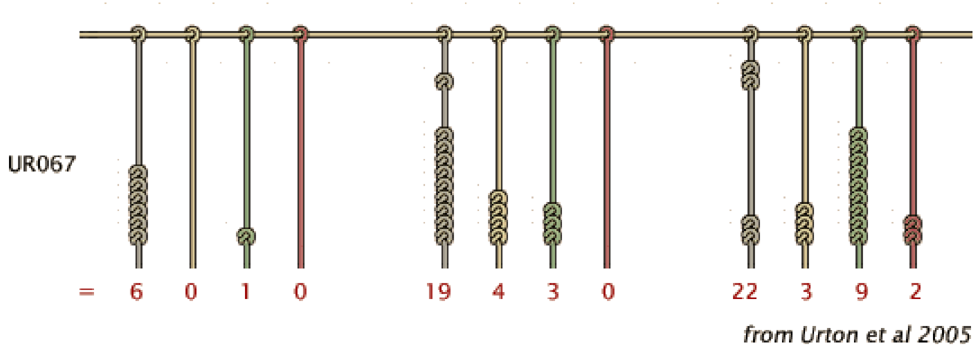

Figure 1. A Descriptive Quipu

2. Using Numbers

The search for truth has been a theme throughout human history. This search comprises two hierarchical categories – Do we use evidence? And, if so, what sorts of evidence have validity for the situation at hand?

The exploration of these great questions is called epistemology.

Epistemology is almost a foreign word and concept in common discourses. It typically makes its initial appearance, adjoined to metaphysics and phenomenology, as part of a trinity in the requisite undergraduate introductory philosophy course. But it rarely makes an impact on everyday life. Its definition usually contains a phrase like a "method for gaining knowledge," which might translate into "Scientific method" which might then be specialized to "procedures used by actual practicing scientists."

The iconic American physicist Richard Feynman provided, as only he could, a clear description of modern epistemology. In his famous Messenger Lectures, given at Cornell in 1964 (subsequently anthologized in his book *The Character of Physical Law)* he said,

> *In general, we look for a new law by the following process. First, we guess it. Then we compute the consequences of the guess to see what would be implied if this law that we guessed is right. Then we compare the result of the computation to nature, with experiment or experience, compare it directly with observation, to see if it works. If it disagrees with experiment it is wrong. In that simple statement is the key to science.*
>
> *It does not make any difference how beautiful your guess is. It does not make any difference how smart you are, who made the guess, or what his name is - <u>if it disagrees with experiment it is wrong.</u> That is all there is to it*.

Feynman answered the epistemological question of how and when evidence should be used by placing it in an exalted position. Evidence vetoed all else. Yet strangely, at least to us, this point of view has never been universal.

We hear the term 'evidence-based decision making' in many fields: medicine, education, economics and political policy, to pick four. The implication is commonly that this is a new and modern way to try to solve contemporary problems. If what we are doing now is evidence-based, what were we doing previously?[1]

How can we consider the use of evidence in science new? Hasn't evidence been at the very core of science for millennia? The short answer is no. Making decisions evidence-based has always been a tough row to hoe, for once you commit to it, no idea, no matter how beautiful, no matter how desirable, can withstand an established contrary fact, regardless of how ugly that fact might be. The conflict between evidence and faith in the modern world is all around us, even in scientific issues for which faith is not required. So it is not surprising that using evidence to make decisions is taking a long time to catch on. The formal idea of using evidence as a method for gaining knowledge is often dated, as are so many things, with Aristotle (384 BC–322 BC). Aristotle diverged from his teacher Plato's purely rational approach by advocating the

[1] Googling the term "Evidence-Based Medicine" reveals that the earliest reference is 1992. When I suggested that prior to that time medicine must've been faith-based my boss, a physician, said that he thought that it was intelligently designed.

crucial inclusion of experience.[2] Aristotle famously studied the prenatal development of chickens by collecting a number of freshly laid eggs and then sequentially opening them, one each day, and noting the changes in the development of the chick embryos that he observed within them.

But the path from Aristotle to Feynman was not smooth. Once one commits to using evidence to make decisions, facts take precedence over opinion. And not all supporters of an empirical approach had the muscular support of Alexander the Great. Hence it took almost 1500 years before it briefly reappeared with Roger Bacon [1214–1292], who observed that,

Reasoning draws a conclusion, but does not make the conclusion certain, unless the mind discovers it by the path of experience.

But once again it slipped away, only to gain a firmer foothold with the work of Francis Bacon [1561– 1626] who re-popularized the formal use of evidence, which was subsequently expanded and amplified by the British empiricists John Locke [1632–1704], George Berkeley [1685–1753], and especially the influential Scot David Hume [1711–1776], whose 1738 *Treatise on Human Nature,* as well as his 1741 *Essays, Moral and Political*, had a profound influence on Adam Smith, Jeremy Bentham and Immanuel Kant.

Although it took a very long time, by the late 18th century the stage was set. There was the beginning of a reasonably broad agreement on what constituted evidence, coupled with the by now well-established Hindu-Arabic number system, which itself provided a workable format for describing quantitative phenomena. And there were important and vexing problems requiring solutions, as well as a growing impetus to gather informative data. But what was lacking was a way to look at numbers and see meanings.

It is natural to ask how best to extract meaning from numbers. The answer is to transform numbers, which must be read, into pictures that could be seen. In doing so we enlist the extraordinarily powerful visual system, which allows us to see structure and, most importantly, to find what we were not expecting. This unanticipated benefit, obtained by visualizing quantitative evidence, profoundly changed the way science operated. It made the a theoretical plotting of points with the goal of finding suggestive patterns possible and, because of an evolving string of successes, acceptable. Those wildly successful applications helped the evolution of what has become one of the most powerful tools for scientific discovery and for the communication of phenomena to those who could not be present when they occurred.

The story of the origin and development of the various kinds of data visualization forms the basis of this chapter. Although the notion of looking at quantitative measures of observations (numbers) to uncover meaning is surprisingly modern, the idea of visualizations is ancient.

There are two types of graphics that in a sense are antithetical to one another, yet both are critically useful tools.

The marvelous discovery of graphical methods to visualize data is usually dated to 1786, specifically the publication of William Playfair's *Atlas*, though there were earlier stirrings of the

[2] Aristotle was certainly not the first to advocate the critical advantages provided by empirical evidence. Sun Tzu [544–496 BC] predated Aristotle by two centuries and was the author of the widely cited *The Art of War*. In it he was very clear about the value of direct experiential knowledge. He wrote that, "*Foreknowledge cannot be gotten from ghosts and spirits, cannot be had by analogy, cannot be found out by calculation. It must be obtained from people; people who know the conditions of the enemy.*"

idea. Playfair's work, however, represented a dramatic development: spatial representation of data—e.g., time, value of imports, and value of exports—that were not, in their essence, spatial. There was no *a priori* logical basis for believing that such a representation would bear fruit, but it did. In 1822, Playfair happily reported that in 1787 France's King Louis XVI, after reading his *Atlas*, said, “they (the graphs) spoke all languages and were very clear and easily understood.” Plotting of points in the search for unexpected patterns is now in full force. Mining big data intelligently would be insuperably more difficult without data graphics.

The sorts of graphics just described are defined by what is usually a synthetic spatial representation of data that are not, in their essence, spatial. They extend the visual idea of a two-dimensional map or town plan to data maps. There is a very long list of contemporary accounts explaining, exploring, and expanding the range of graphic possibilities. A modern list must include Jacques Bertin's 1973 keystone explication, Tukey's 1977 classic that called for a radically new graphical approach to statistics (the birth of “data science”), and Edward Tufte's 1983 masterful exposition showing that effective displays could provide "beautiful evidence.” There has been a torrent of valuable additions since.[3] Such applications, in which the word ‘graphic’ is a noun, we will refer to as Type I graphics.

But there is a second definition of the word graphic, when it is used as an adjective with the meaning of *literal lifelikeness*—as in “graphic violence” or “graphic novel.” This definition is quite the opposite of the synthetic displays that now dominate modern science. Ironically, this second definition is far older than the one that *Merriam-Webster* lists first, as are many of the data displays that represent it. These graphics not only satisfy the first goal of visualization, which is to answer basic questions, such as how do I get there, how do I do it, what happened, or even the causal, why did it happen? But they also serve the deeper purpose of acting as an intermediary between information and understanding.

To illustrate the power of these “graphics of the second kind” and the questions they answer, we have chosen to look at two especially compelling examples drawn from the 18th and 19th century, specifically at examples of shipbuilding and the physical character of a wooly mammoth; of course, there are many more. The common characteristic of these graphics is that they provided a uniquely effective way to think about, reason about, and understand scientific phenomena; they illustrate how powerful and how broadly useful visualizations can be in the service of scientific and practical explanation.

2.1 How to build a ship from a forest

Looking at history from a modern perspective often reveals mysteries. One such mystery emerges when trying to imagine the combination of science and craft required for shipwrights to efficiently transform the contents of a local forest into a 19th century, 24-gun frigate for the

[3] To learn more, the interested reader could do no better than the rest of Edward Tufte's trio of graphical wonders (1990 and 1996) and, being unafflicted with modesty, we also recommend some of our earlier descriptions; more specifically Wainer (1984, 1993, 1997, 2005, 2009) and, most recent, Friendly & Wainer, 2020.

British Royal navy. This task must have involved a shipwright looking carefully at each tree to see what parts could be used for different purposes and somehow communicating those arboreal insights to a sawyer for execution.

Figure 2 from Charles-Joseph Panckoucke's 1783 marine encyclopedia, shows that that communication was graphical. Shipwrights drew a picture of a portion of the forest and on each tree were inscribed the parts of the ship they needed that were to be the contribution of that tree. Long straight tree trunks would become the ship's masts; shorter straight sections would be its spars or yardarms, and forked sections would naturally fill and buttress the bow or various overhangs. This graphic is an early example of visual thinking and visual explanation that compactly answers the questions: How do I do it? How do I transform the trees like those found in a local forest into the necessary parts to build a ship? Such instructions could be expressed verbally, similar to asking for turn-by-turn directions when you are lost. But, as with asking for directions and being drawn a map, this graphic gives immediate and memorable instructions that can be used and the lessons implicit in it are easily generalized for future use.[4]

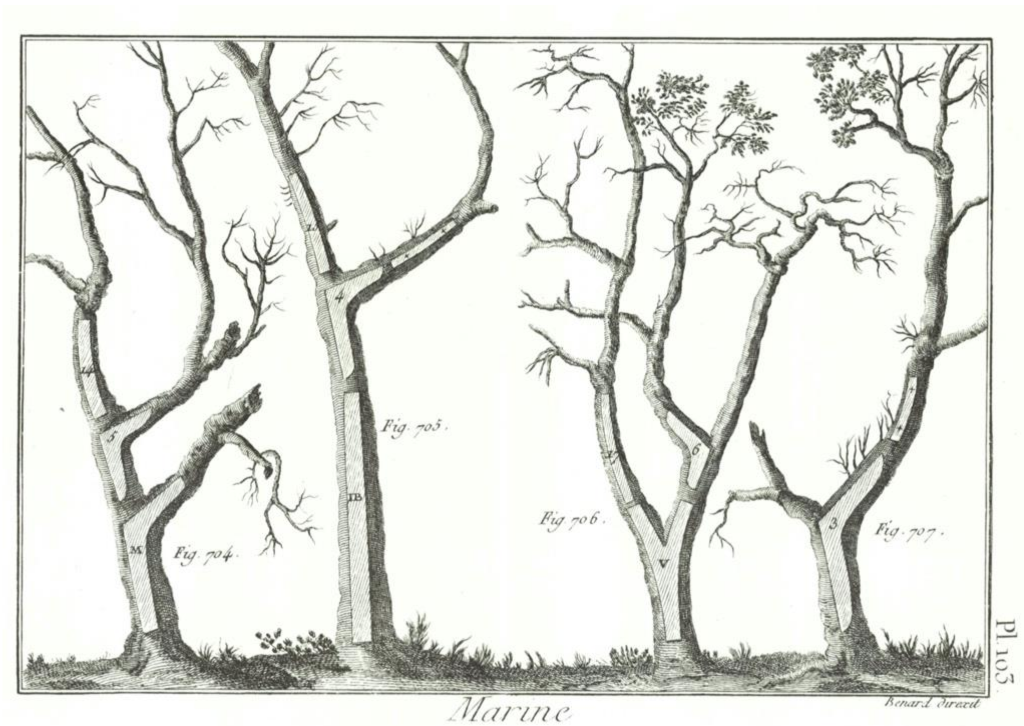

Figure 2. Plate 103 in Charles-Joseph Panckoucke's 1783 "*Encyclopédie Méthodique Marine*" showing how to harvest specific ship parts from trees. (Our thanks to Kaicong Wu, who brought

[4] Panckouke was, famously, the publisher of the *Encyclopédie méthodique*, the successor to the *Encyclopédie* of Diderot & d'Alembert whose 1751 publication marked the editors valiant attempt to represent the thought of the Enlightenment and to "*change the way that people think."*

this example to our attention).
http://www.epaves.corsaires.culture.fr/mediatheque/communs/images/grand_formats/1/449_4.jpg

2.2 What does a wooly mammoth look like?

In 1801, Charles Willson Peale, a curator of one of the first museums of natural history in the U.S., put a mammoth skeleton on display in Philadelphia's Philosophical Hall. The skeleton was a mixture of anatomy and guesswork, with missing bones replaced by wood or papier-mâché. The exhibit proved so successful that Peale took it on the road, displaying it in both London and Bristol. A contemporaneous drawing based on Peale's skeleton, (Figure 3), however, shows that, his display had numerous anatomical mistakes—he even had the tusks upside down.[5]

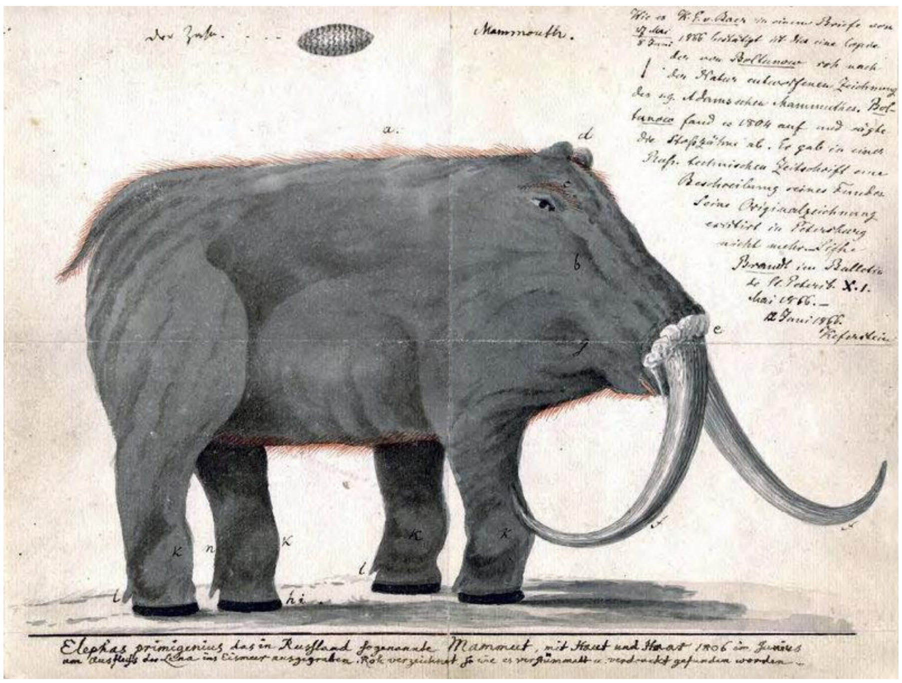

Figure 3: An 1802 drawing of the mammoth, based on Peale's skeletal reconstruction which they characterized as a "carnivorous animal of immense size" https://goo.gl/images/8xCpmD- Our thanks to Stephen Stigler for this figure.

But modern reconstructions have it right—upward curling tusks, humped shoulders, downward sloping spine. We should note that our modern conception was not solely obtained by studying bones but by looking closely at the art of those who observed the animals first-hand. More than

[5] Peale's construction was based on available fossilized bones, contemporary anatomical knowledge, analogical reasoning based on his knowledge of elephants. But there had to be other, even less accurate, sources based on his confusion about the mammoth's character -- for example he described it as carnivorous.

half of the hundreds of drawings left by Paleolithic artists on the walls of the Rouffignac Cave in the south of France were of wooly mammoths. The drawings answer the question: what did the animal look like? See Figure 4. What led Peale astray was that he didn't have the benefit of the visualizations of Paleolithic artists to guide him. Having an accurate answer to "what did they look like?" means that investigators can at least begin on the right path. The value of such visual communications has often proved to be profound. Through such depictions, the original artists, their very bones long dust, have reached out across the centuries and aided modern understanding.

Figure 4: One selected panel of a wooly mammoth, from the Rouffignac Cave, courtesy of the Bradshaw Foundation.

2.3 A Practical Type I Graphic - Marey's 1878 Train Schedule without showing locomotives

The popularity of visualizations owes much to the almost religious fervor of scientists and epistemologists of the 19th century who sought to banish subjectivity from science. They *"drew on a number of techniques including inferential statistics, double-blind clinical trials, and self-registering instruments to hold subjectivity at bay*"[i] But, the oldest and most important, of these was visualization.

By 1878 the French physiologist Etienne Marey, whose graphic schedule of all the trains between Paris and Lyons (reproduced in Figure 5) provides a powerful illustration of the breadth of value of this approach, expressed the feelings of most natural scientists of the value of graphical representation,

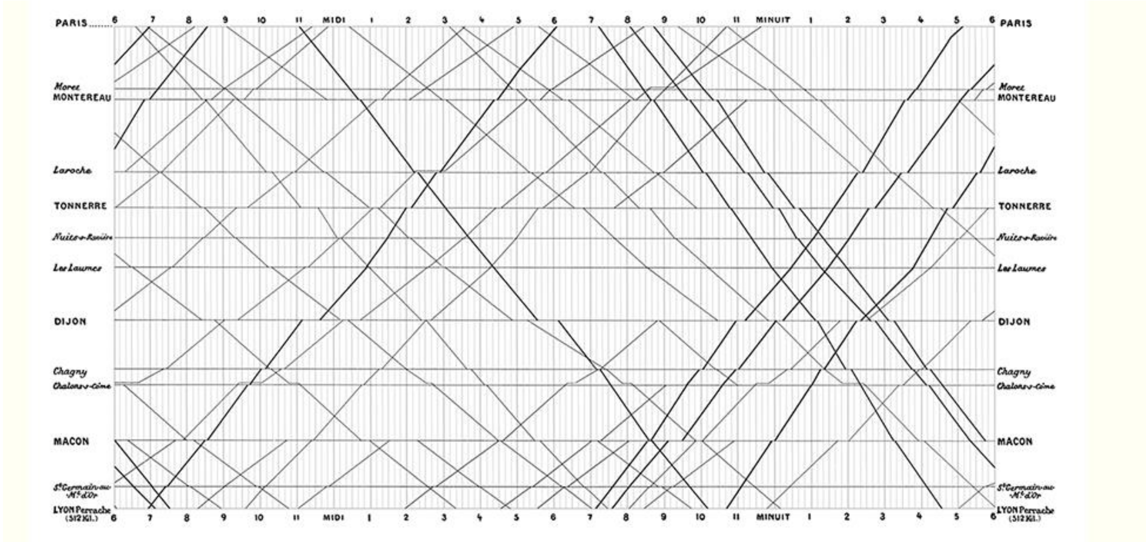

Figure 5. Marey's 1878 graphical train schedule, showing all trains between Paris and Lyons each day.

> *"There is no doubt that graphical expression will soon replace all others whenever one has at hand a movement or change of state – in a word, any phenomenon. Born before science, language is often inappropriate to express exact measures or definite relations."* [ii]
>
> *(Marey, 1878, p. iii)*

Marey was also giving voice to the movement away from the sorts of subjectivity that had characterized prior science in support of the more modern drive toward objectivity. Although some cried out for the "insights of dialectic," "the power of arguments," and the "flowers of language," their protestations were lost on Marey, who dreamed of a wordless science that spoke instead in high speed photographs and mechanically generated curves; in images that were, as he put it, in the "language of the phenomena themselves."

2.4 The First 'Soaring National Debt Plot – William Playfair's Iconic 1801 graphic

Figure 6 is one of the most remarkable displays ever produced, containing a mixture of data and design innovations to provide a convincing visual argument that connected wars and debt. The design begins with the recognition that the grid of a plot serves the same purpose as the scaffolding that workers erect to construct a building; and just as the scaffolding is removed after the building is completed, so too should the graphical gridlines. Playfair recognized that no one is likely to be interested in what happened in 1700 or 1710 or 1720, but instead interest on specific dates would arise in two different kinds of situations:

a. When the outcome one sees in the data suggests a question, e.g. what happened in 1730 or in 1775 to make the debt suddenly rise? Or in 1748 or 1784 when the debt fell or stabilized?
b. When a plausibly impactful event occurs and we want to know what were its consequences on national debt, e.g. did the accession of Queen Anne in 1701 or that of George the 2nd in 1727 have any effect?

With this idea in mind Playfair built the graph shown in Figure 6. He then replaced the grid that he used to construct it with gridlines at interesting times. The vertical grid was no longer spaced equally across the century, and each vertical line is annotated with a plausible causal event.

We see that national debt increased in 1730 when the Spanish War began and dropped in 1748 when it ended; it jumped markedly in 1755 at the beginning of the Seven Years War and dropped in 1762 at its end (and the accession of George the 3rd), it jumped in 1775 when the American War began and abated in 1784 when the war ended. The message is clear; wars are bad for national debt.

Last, Playfair obviously understood that perception of the data is easily manipulated by the ratio of the width of the graph to its height – the aspect ratio. The determination of this ratio is entirely subjective. If the horizontal axis is much larger than the vertical scale a soaring mountain can be transformed to a gradual plain. To make his point about the soaring national debt more emphatically, Playfair chose to make this plot higher-than-wide.

Modern research on effective design[iii] reveals that the arbitrary choice of aspect ratio is most often best resolved by selecting a ratio that makes the plot as close to a diagonal line as possible. Playfair's prescient design adhered to this advice even though the experimental evidence that revealed this result lay almost 200 years in the future.

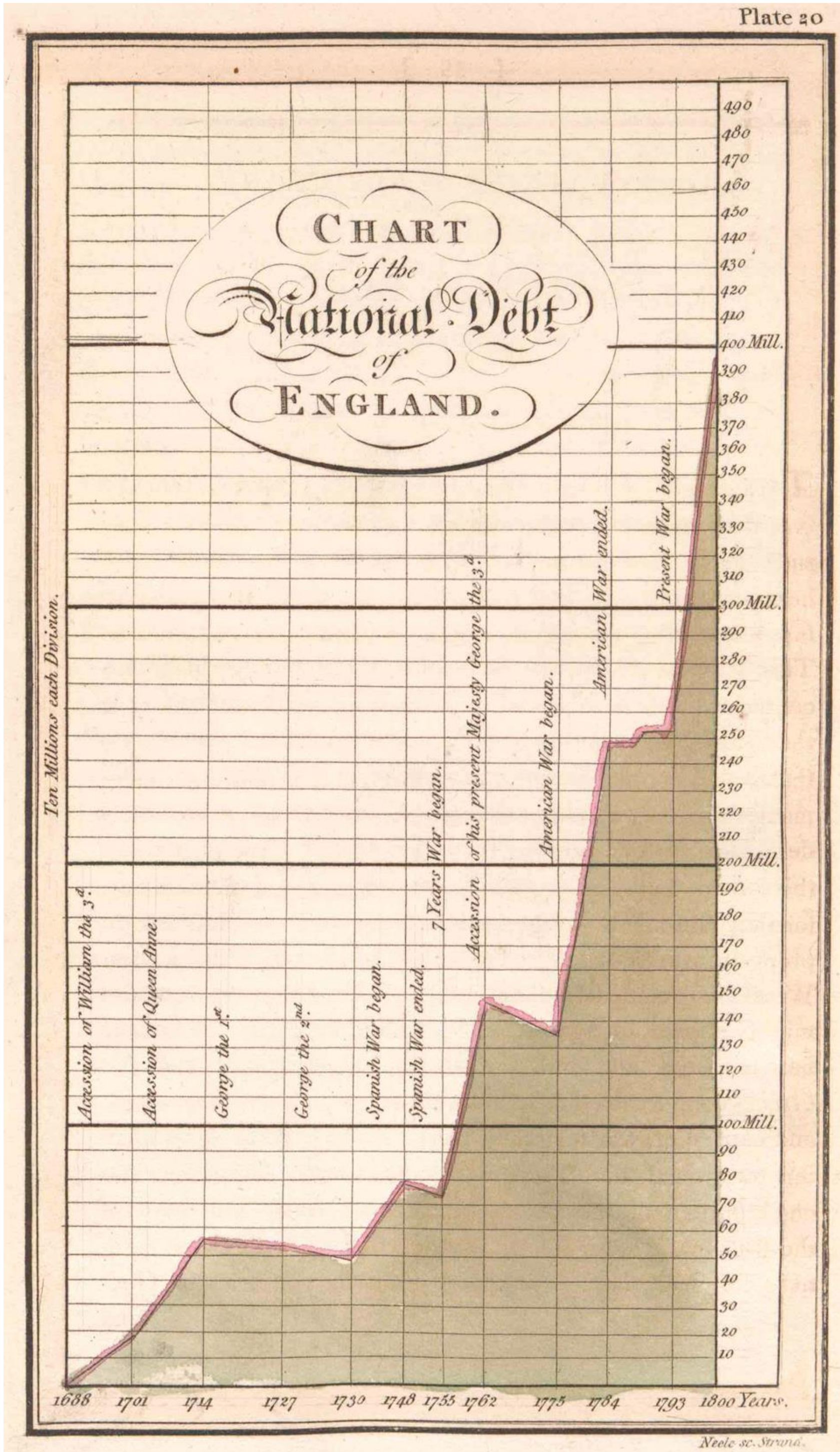

Figure 6. The first "Skyrocketing National Debt" plot containing a lot of explanatory collateral information brilliantly integrated (Playfair's Atlas, Plate 20)

3. Hybrid displays: Combining Type 1 and Type 2 displays

Maps, which date back at least 4,000 years, are among the oldest and most widely used of Type 2 displays. Their development isn't surprising, for it is a natural metaphor to represent space as space. But adding a third variable onto a geographic background is a more recent innovation. Of course, there were partially thematic maps (in China) as early as 164 BC, but the additional variables plotted were geographic variables such as altitude, which were ancillary to the main purpose of the map. A thematic map whose focus was primarily on the other variable did not appear until the 17th century.

The initial variables plotted on a geographic background were physical variables such as magnetic phenomena, currents, and geology. Such maps have obvious and immediate uses. Edmond Halley published what is believed to be the first meteorological chart in 1686. And, in 1815 William Smith (1769-1839) prepared a map depicting the geology of England that showed specific fossils were always found in corresponding layers of rock. This severely conflicted with the biblical interpretation, in which the rocks were laid down during the Great Flood. Smith's production has been called the "map that changed the world," instigating changes in thinking so that by the end of the 19th century, geology was—at least in terms of chronology and identification—advancing as a modern, evidence-based science.

The gathering of what might be called social statistics is often dated from John Graunt's 1662 analysis of the London Bills of Mortality. Graunt analyzed and published birth and death data collected by London parishes, but there were no graphs or maps included in his collection. John Arbuthnot (1710) famously used Graunt's data to illustrate his invention of null hypothesis testing, but he too did not include any graphs. In fact, the clerical errors in Arbuthnot's paper provide strong evidence that he never graphed the data. If he had prepared such a plot, the errors would have stuck out (literally) like sore thumbs and been corrected. That they weren't corrected provides support for the thesis that Arbuthnot never looked at Graunt's data in this way.

There were bits and pieces of graphic display of social data in the late 17th and early 18th centuries. Most notably, Christiaan Huygens drew a survival graph in a letter he sent to his brother in 1669. But graphs of social (economic) data only entered the scientific mainstream in 1786 with the publication of William Playfair's *Atlas*.

Playfair prepared wonderful, elegant graphs of economic data, but no maps. So far as is known, few maps of such social subjects as population, religion, or industrial production appeared before 1820. The preparers of the earliest such maps merely wrote the statistic of interest on the map.

An example of this practice is James Wyld's 1815 map, "Chart of the World Shewing the Religion, Population, and Civilization of Each Country." But such maps only barely "qualify as thematic since they do not graphically portray the character of the distribution effectively" (Robinson, 1982).

While it is surely true that putting numbers on a map to indicate the location where something is happening conveys more information than would merely listing them in a table, such a practice does not use the graphic medium at anywhere near its capability. This changed in 1830, when Frére de Montizon produced a map showing the population of France in which he represented the population by dots, each dot representing 10,000 people. Although no one remarked on it for the better part of a century, it remains perhaps the most important conceptual breakthrough in thematic mapping (Figure 7).

DES CHIFFRES ET DES CARTES

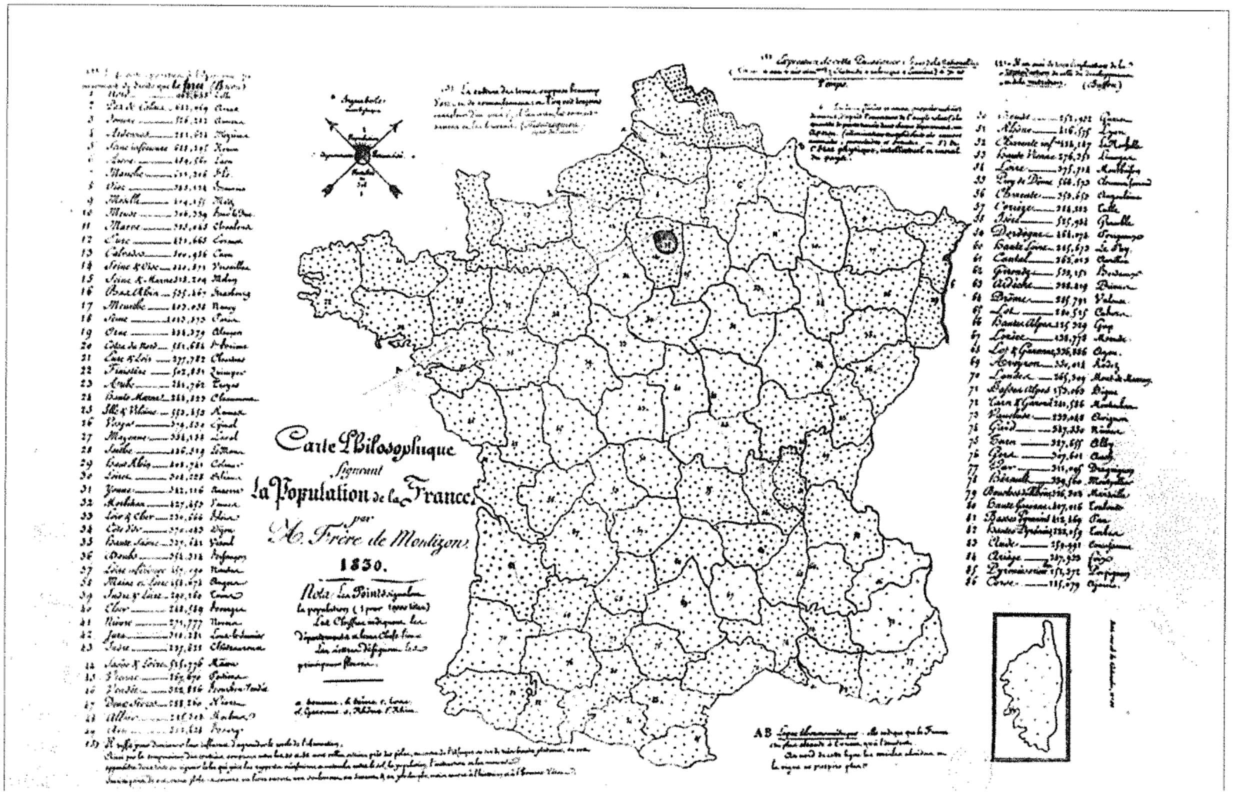

Figure 7. Frere de Montizon's 1830 map of the population of France using irregularly spaced dots to convey population density. Original at the Biblioteque Nationale. This one taken from Robinson (1982), Page 112.

After Montizon's map, there were a number of others that used shading to convey population between the years of 1830 and 1845. Often, they were roughly drawn and clearly meant to be of only secondary importance to the document in which they appeared. But a few were clever, remarkably polished displays. Exemplary among these were the population maps designed and prepared by Henry Drury Harness, a young lieutenant in the Royal Engineers that appeared in an 1837 *Atlas* that accompanied a report prepared by railway commissioners.

In 1847, a 34-year-old barrister named Joseph Fletcher published the first of several long papers. This paper was filled with tables and a single, rudimentary map. In fact, he rejected the use of maps explicitly, suggesting you could get all you needed by simply perusing the columns of numbers and thus avoid the bother and expense of drafting and printing maps. He reversed himself completely[6] two years later in two articles with the same title (but much greater length) as his 1847 paper. These included many shaded maps that were innovative in both content and format. Format first.

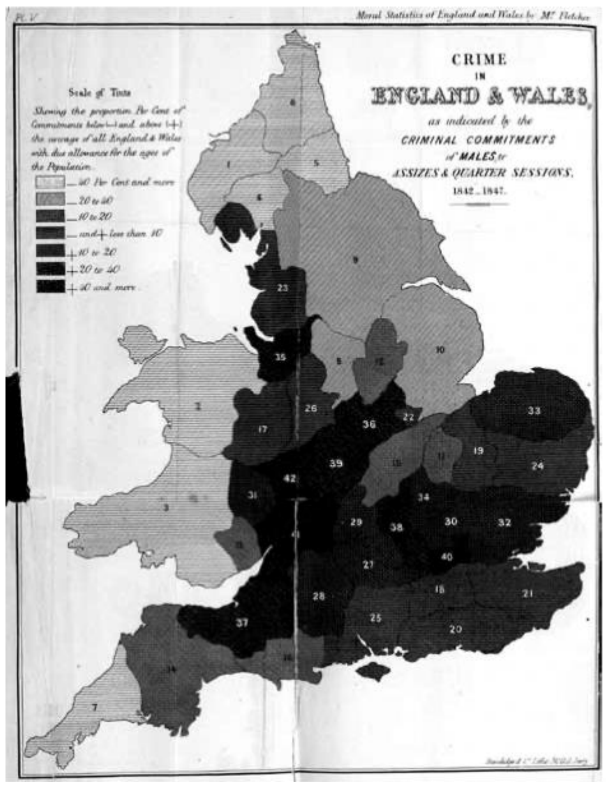

Figure 8. Ignorance in England and Wales taken from Fletcher (1849b).

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[6] Ordinarily, it would be hard to know exactly what it was that got Fletcher to change his approach so completely, but an evocative hint was provided in his 1849 paper when he states, "*A set of shaded maps accompanies these tables, to illustrate the most important branches of the investigation, and I have endeavoured to supply the deficiency which H. R. H. Prince Albert was pleased to point out, of the want of more illustrations of this kind.*"

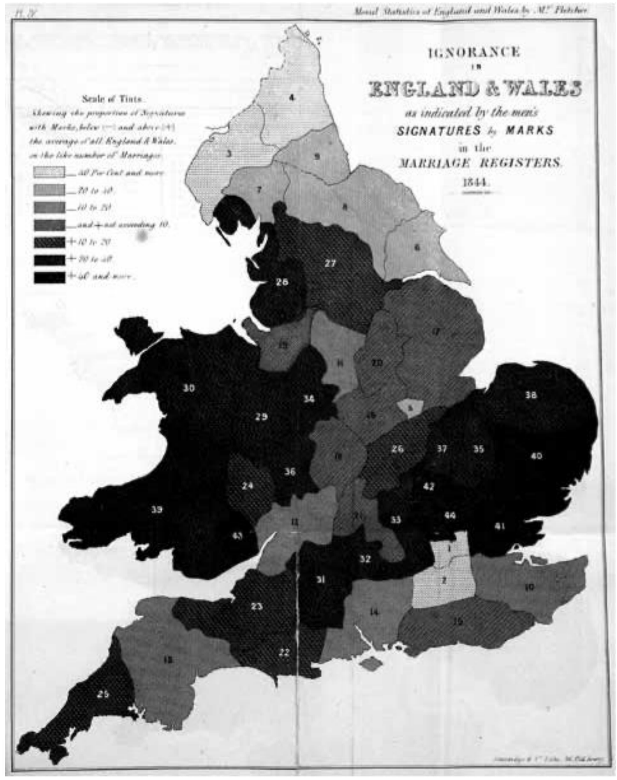

Figure 9. Crime in England and Wales taken from Fletcher (1849b)

Fletcher, having a background in statistics, or at least what was thought of as statistics in the mid-19th century, did not plot the raw numbers, but instead their deviations from the mean. And so, the scale of tints used varied from the middle. This approach is common now. For example, Andrew Gelman—in *Red State, Blue State, Rich State, Blue State*—uses increasing saturations of red to show the proportion of voters who voted Republican in states where they were the majority and increasing saturations of blue for those states that voted Democratic. The closer the vote came splitting 50:50, the closer the shading was to white, regardless of the final outcome.

But, in 1849, this format was new. The advantage of centering all variables at zero was that it allowed Fletcher to prepare a number of maps, on different topics and scales, and place them side-by-side for comparison without worrying about the location of the scale. He also oriented the shading, as much as possible, in the same way. In his words, “In all the maps, it will be observed that the darker tints and the lower numbers are appropriated to the unfavorable end of the scale.”

Of course, with variables such as population density, it is hard to know which end is favorable. He chose lesser population as more favorable because, we speculate, it seemed to accompany favorable outcomes on the other variables.

Although many of Fletcher’s innovations in format were noteworthy, it is the content he chose that makes him special. He did not make maps of obvious physical variables such as wind direction or altitude, or even the distribution of the population (although he did make one map of that for comparative purposes). No, he had more profound purposes in mind. Joseph Fletcher made maps of moral statistics and opposed these maps with others to suggest causal interpretations to his viewers.

For example, juxtaposed next to his plot of "Ignorance in England and Wales" (Figure 8), he also had maps of the incidence of crime (Figure 9). He opted for this juxtaposition on the basis of detailed analysis of subsets of the data. For example, he wrote, "*We thus find that the decline in total ignorance to be slowest in the most criminal and the most ignorant districts* ..."

And then, looking into the phenomenon at a more microscopic level, he observed:

"*The two least criminal regions are at the opposite extremes in this respect (the Celtic and the Scandinavian), with this important difference, that in the region where there is the greatest decline of absolute ignorance among the criminals (the Scandinavian), there is not one-half of the amount of it in the population at large which exists in the other ..."*

In addition to these maps, he also produced parallel plots of bastardy in England and Wales, improvident marriages, persons of independent means, pauperism, and many other variables that could plausibly be thought of as either causes or effects of other variables.

His goal in doing this was to generate and test hypotheses, which might then be used to guide subsequent social action and policy. His epistemological viewpoint was both wise and surprisingly modern. It is fitting that we close with three sentences of his on the use of the data and his maps (note the similarity to Richard Feynman's views quoted earlier):

"The man who studies society, however, labours under a great difficulty in being entirely denied the use of experiment, and limited most rigidly to observation; the observation of elements most subtilly combined, in a state of unceasing change, and wholly beyond his control. Analysis, there- fore, in the sense of the chemist, is absolutely impossible; but by exhaustive enumerations of facts, which are strongly indicative of the existence of many others, or are their invariable concomitants, we get a means of detecting the excess or deficiency of certain social elements in definite classes or localities; and by multiplying these lines of observation, and the combinations in which they are arranged for purposes of comparison, we gradually arrive at higher and safe inductions, which will sometimes corroborate principles which we have reached by deductive reasoning from the moral elements of individual character, and by observations on society in the limited field of our person experience, and at others will present irreconcileable results, which the bigot of theory will despise, but which the man of science knows how to prize as gems. He who seeks facts merely to illustrate a hypothesis in which he believes with a blind faith, will throw them away in disgust; but he who uses a hypothesis merely to discover truth, will, on the contrary, abandon its use in the moment that he arrives at acts which resist all efforts to reduce them into accordance with them."

4. More than just facts: Graphs as Poetry

So far, we have portrayed visual displays of empirical information as compact summaries that, at their best, can clarify a muddled situation. This is true, as far as it goes, but omits the magic. In this section we will show how the visualization of important data can be an alchemist that can make good scientists great and transform great scientists into giants.

In this coda we argue that sometimes, albeit too rarely, the combination of critical questions addressed by important data and illuminated by evocative displays can achieve a transcendent, and often wholly unexpected, result. At their best, visualizations can communicate emotions and feelings in addition to cold, hard facts.

The American poet Robert Frost [1874-1963] famously pointed out that:

Poetry is when an emotion has found its thought
and the thought has found its words.

We can reverse the idea, inferring that one goal of the poet is to present the words that will engender the emotion.

The communication of an emotion is a difficult task that is a goal of many other means of communication. Surely music is the most obvious; in his *Ode to Joy* Beethoven transformed his emotions through his ideas to music. The listener starts with the music and ends with exaltation. Visual artists have long followed this same path; Picasso transmitted his grief for the hundreds killed in the April 1937 bombing of the Basque town of Guernica during the Spanish Civil War in his mural *Guernica*, completed just two months after the bombing. For the receptive viewer "the emotion is so lacerating that the next step beyond would be either insanity or suicide."[iv]

Not all music is as transformational as *Ode to Joy*, nor are all paintings as evocative as *Guernica*; and most sequences of words are not poetic. But, happily, by Frost's definition, there have been poets in many media, and we can rejoice in their accomplishments. Goethe's observation that "Architecture is frozen music" suggests we might find the soul of a poet in many architects. One undeniable example is Maya Lin, whose design for the simple chronological carving of 57,661 fallen soldiers' names into polished blocks of black granite yielded the heart-rending Vietnam Memorial in Washington DC.

We can include some databased graphs in this elite company— graphs whose impressions on the viewer are so evocative to fully deserve the adjective 'poetic'. To reach this level requires a combination of data that have impact and a design of compact clarity. Reaching back to Frost's definition, it happens when an emotion has found its data and the data have found their design.

As should be obvious, a data display can only achieve this transcendent property when the data are worthy. Consider the formally competent plot shown in Figure 10, that shows the fluctuating preferences for three flavors of ice cream in NJ over the past 30 years. It is both informative and instantly forgettable.

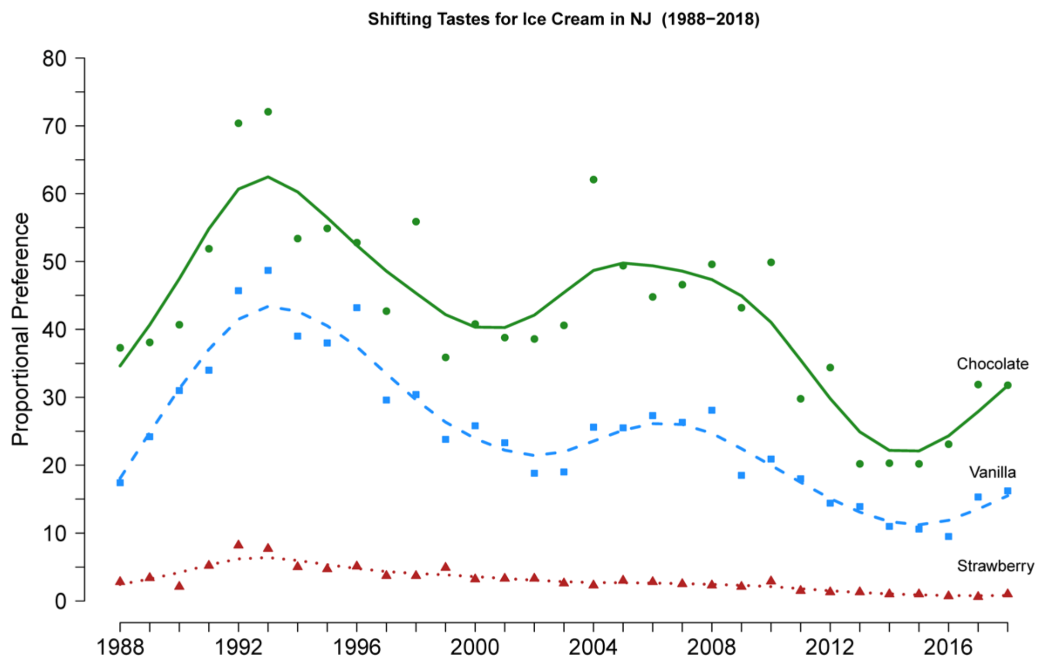

Figure 10. Preferences for three flavors of ice cream in NJ from 1988-2018.

Now, consider an identical plot in Figure 11 with the labels changed to reflect what the data actually were, augmented with one plausible causal covariate (the president during the time periods indicated).

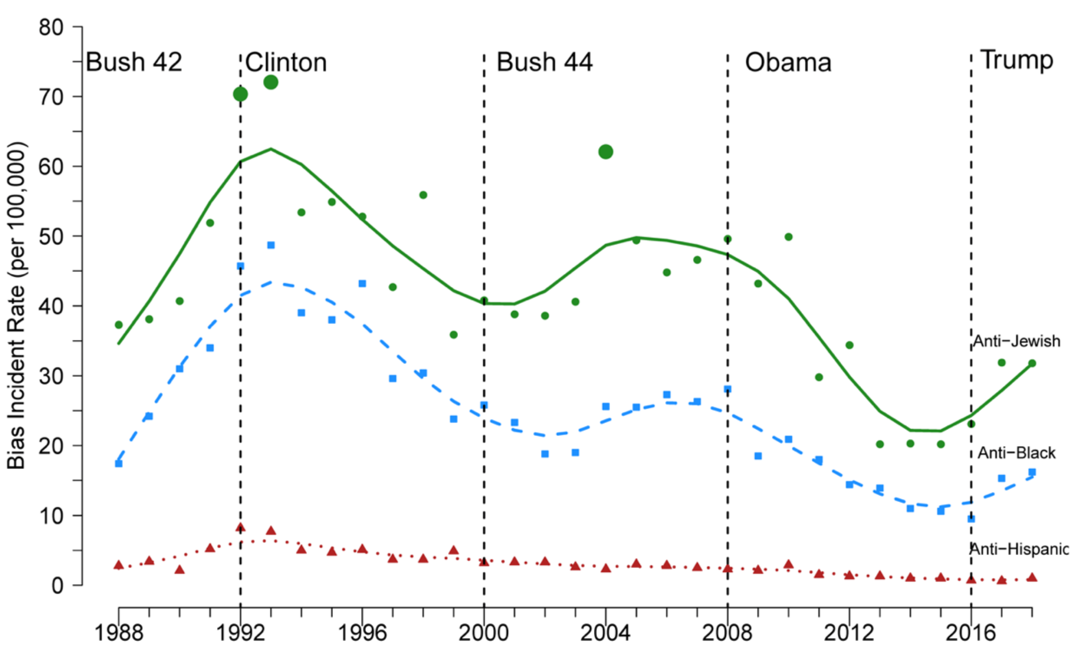

Figure 11. The rates per 100,000 of bias crimes in NJ from 1988-2018.

The responses to this plot that we have received so far, have led us to conclude that it is difficult, if not impossible, to avoid making some causal conjectures and to immediately begin looking for other sources of data to confirm or reject those conjectures. Those conjectures arose with considerable affect. Obviously, it wasn't the graph, it was the data; the graph was the *intermediary between information and understanding.*

Let us begin slowly, by first introducing one graphic poem that might otherwise be overlooked because of its plain appearance. Then we introduce two giants in their respective fields: Charles Joseph Minard, whose use of flow maps to communicate the horrors of war defied the limitations ordinarily associated with pen and ink, and W. E. B. Du Bois, who dedicated his long career to the difficult task of improving the lives and circumstances of African-Americans. He did this by broadly communicating more than a century of African-Americans' accomplishments despite their near-universal suffering under the yokes of slavery and racism. After this introduction to these men and their work we describe a plausible result of a *gedanken* collaboration between them.

4.1 One plain graphical poem

The conductor Ignat Solzhenitsyn, in a prelude to an all-Mozart concert, made the surprising observation, "*Mozart's music is often underestimated because it is so beautiful*." Similarly, the poetry in some graphic designs is often unappreciated because those designs are so mundane. Few graphic artists have Picasso's or Maya Lin's eye, but we ought not be blind to poetry from others with less refined skills.

The Kovno Ghetto

During the Nazi occupation of Lithuania the Nazis initiated a series of actions that resulted in the deaths of over 136,000 Jews. Initially, the Germans, in elaborately illustrated reports, meticulously documented these murders, but their production of records was reduced as the war continued. Indeed, in October of 1943, SS chief Heinrich Himmler, in a speech to his subordinates, rationalized the minimized record keeping, saying, "This is an unwritten and never-to-be-written page of glory in our history." Nonetheless, the Nazis did create some documents that tabulated what they considered their triumphs, and others also kept records of their atrocities.

In many ghettos, Jewish leaders organized committees to keep official chronicles of daily life. Indeed, from the outset of the establishment of the Kovno Ghetto, Elkhanan Elkes, chairman of the Jewish council (the Ältestenrat), asked Kovno's Jews to write their own history as a legacy for future generations. Artists drew pictures, writers wrote stories, musicians composed music, poets wrote verse. They all used the skills and talent that they had to record both facts and emotions for a posterity and an audience that they feared they would not be able to meet directly. Ghetto residents without such artistic talent used whatever skills they had. Those with scientific training recorded data and presented them in a variety of formats, tabular and graphical.

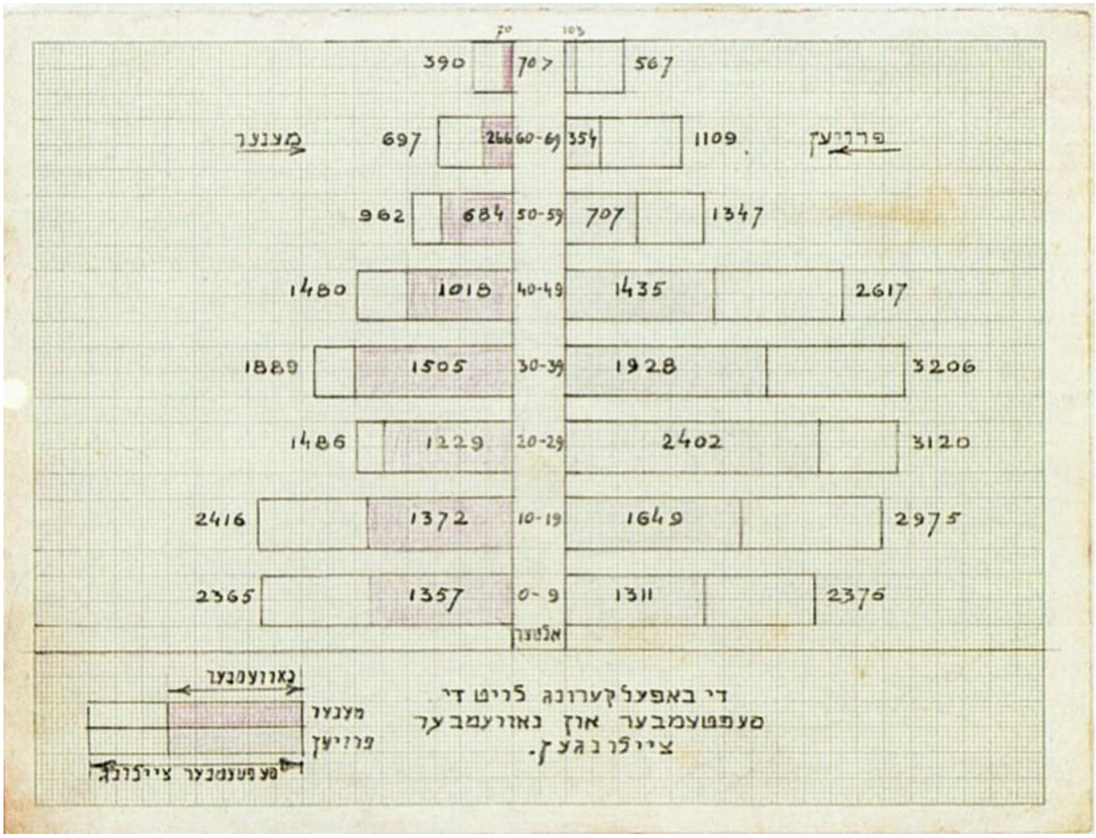

Figure 12: Kovno Ghetto: The population losses in the Kovno Ghetto due primarily to the "Great Action" of October 28, 1941. Males are represented on the left, females on the right. The shaded portion represents those still surviving in November. The central column indicates the age groups from 0-9 year olds at the bottom to 70 and older at the top. *Source:* Braun, H., & Wainer, H. (2004)

Figure 12 is one of those graphs, a traditional population pyramid, whose familiar simplicity and apparent banality belie its horrifying content. The bars represent the number of Jews in the ghetto by age, youngest at the bottom. The left side represents males, the right females. The total length of each bar is the number of inhabitants of the ghetto of that age and sex in the beginning of October 1941. The shaded portion represents those still alive in November, only a month later.

4.2 The Graphic Poetry of Charles Joseph Minard

Charles Joseph Minard [1781–1870] had a long and productive life. But official regulations forced him to retire from his long-held position at the National School of Bridges and Roads on March 27, 1851, his 70th birthday. Nevertheless, he continued working and teaching for the remainder of his life. The liberty he enjoyed in retirement allowed him to devote himself to projects he had begun earlier but that had been interrupted by the obligations of his job. Freed of other responsibilities, his development of new graphic forms and themes nearly doubled in rate for 20 years, and continued up to his death at age 89.[v]

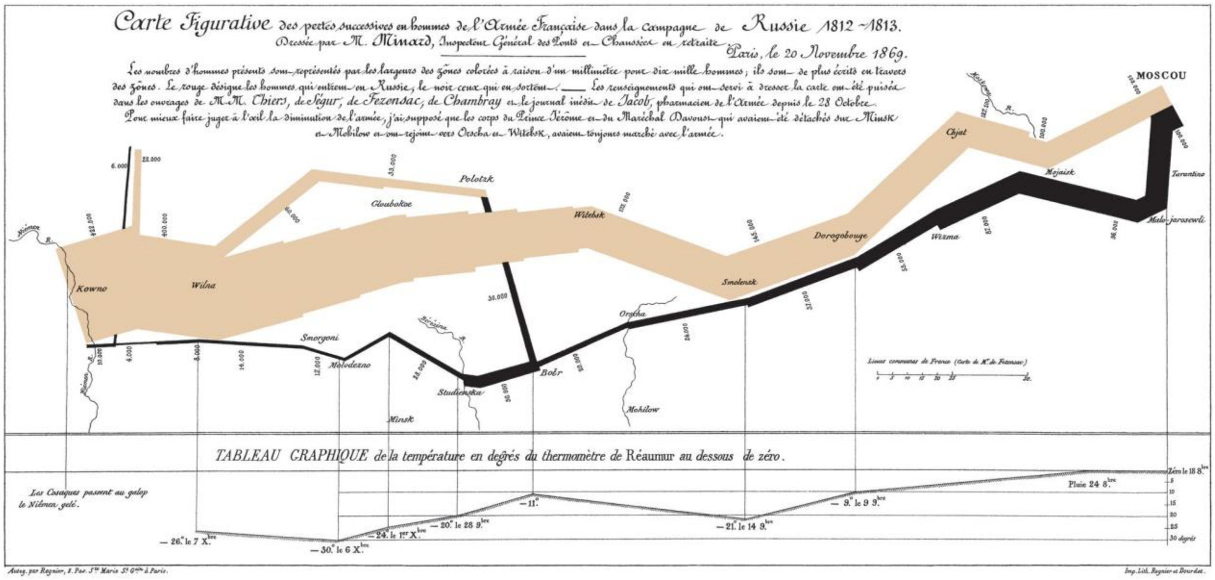

Figure 13: Napoleon march graphic: Charles Joseph Minard's narrative map of Napoleon's disastrous 1812 Russian campaign. The width of the orange 'river' is proportional to the size of Napoleon's invading army; its black continuation shows the size of the returning army. *Source:* Archives, École Nationale des Ponts et Chaussées, by permission.

Figure 13 is Minard's justly famous map of Napoleon's Russian campaign, in which the initially mighty metaphorical river of the 422 thousand men of the French Grand Army begins on the left by crossing the Nieman River into Russia, it gradually diminishes and is juxtaposed with the trickle of the surviving 10 thousand returning at the end. When the French army reached Moscow in October of 1812 with only 100,000 men, the moment captured at the far right of Minard's map, they found it sacked and largely deserted. They turned back and marched across the steppes into the teeth of the Russian winter— Minard coupled the returning march with the descending temperature, shown in an accompanying panel below the map. He used the falling temperature as one plausible causal variable to connect the decline of the army's size with something in addition to the sniping of Russian soldiers. When this graphic was first published, the French physiologist and chronophotographer E. J. Marey[7] [1830–1904] was in awe, saying that it "defied the pen of the historian by its brutal eloquence."

What was the inspiration for Minard's graphical poetry? Minard's personal history makes the source clear. As a young engineer in Anvers in 1813, he had witnessed the horrors of war in a siege by the Prussian army. In his 89th year, 1869, he was deeply troubled by what he foresaw as an inevitable new war with Prussia and the havoc that it would wreak on the Second French Empire. His "figurative map" of Napoleon was published on 20 November 1869.

Minard's fears proved correct. The Franco-Prussian War began on July 19, 1870. France was ultimately defeated, and, following a long siege, Paris fell on January 28, 1871. Minard foresaw this too and, though now infirm and requiring crutches, he left Paris for Bordeaux on September 11, 1870, leaving behind nearly all his books and papers. He carried with him only a few works-

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[7] This is the same Étienne-Jules Marey we met previously when we discussed his well-known and easy-to-use graphical schedule for all trains between Paris and Lyon shown in Figure 5.

in-progress, but these apparently have been lost. Sadly, six weeks later he contracted a fever, and on October 24, 1870, he died.

Very little of Minard's personal life is known; the main historical source is the obituary written by his son-in-law, Victor Chevallier in 1871.[vi] He said, "Finally, ...as if he could sense the terrible disaster that was about to disrupt the country, he illustrated the loss of lives that had been caused by ... Napoleon. ... The graphical representation is gripping; ...it inspires bitter reflections on the human cost of the thirst for military glory." This may well be the reason that this graphic story has become the iconic example of Minard's graphic poetry.

4.3 Using graphs in a narrative argument

Using a series of graphical displays to construct an empirical narrative was not common in Minard's time. More often, a single display was used to convey a single idea. Napoleon's March (Figure 13), as breathtakingly marvelous as it is, is still a short story, with the limitations commonly associated with that form. Embedding a sequence of displays in an empirical narrative has been too rarely used. But when used effectively, this approach forms a memorable image that has remarkable impact.

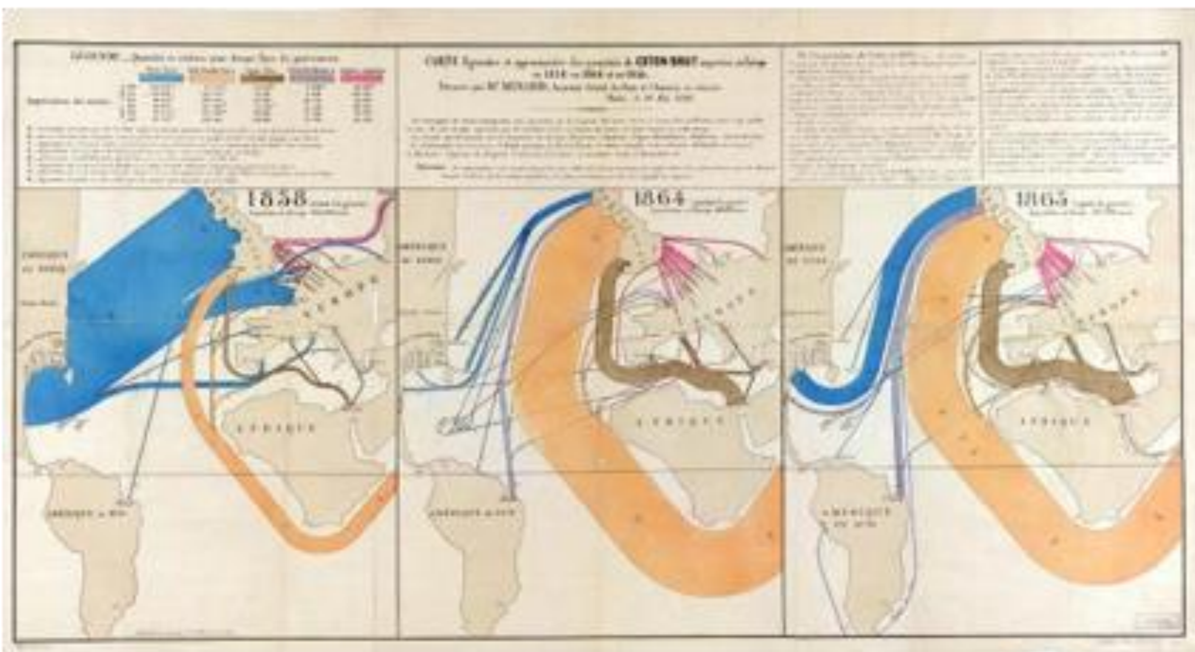

Figure 14: Minard: imports of cotton: A sequence of three graphs showing the sources of cotton imports to Europe for 1858, 1864, and 1865. The metaphorical blue river represents imports from the U.S., the orange from India. *Source:* National Archives https://www.loc.gov/item/99463789/.

Minard himself sometimes used comparative graphs to tell a story. As one example, he prepared a sequence of plots to show how the Union blockade of Confederate ports during the American Civil War affected the supply of cotton to English mills. In Figure 14 we reproduce his three-part plot (for 1858, 1864, and 1865) which made it clear that before the U.S. Civil War the southern U.S. states were the principal supplier for British mills. But when that supply was effectively cut off by the blockade, the mill owners replaced it with cotton from India and Egypt, which continued, at a slightly diminished level, even after the war had ended.

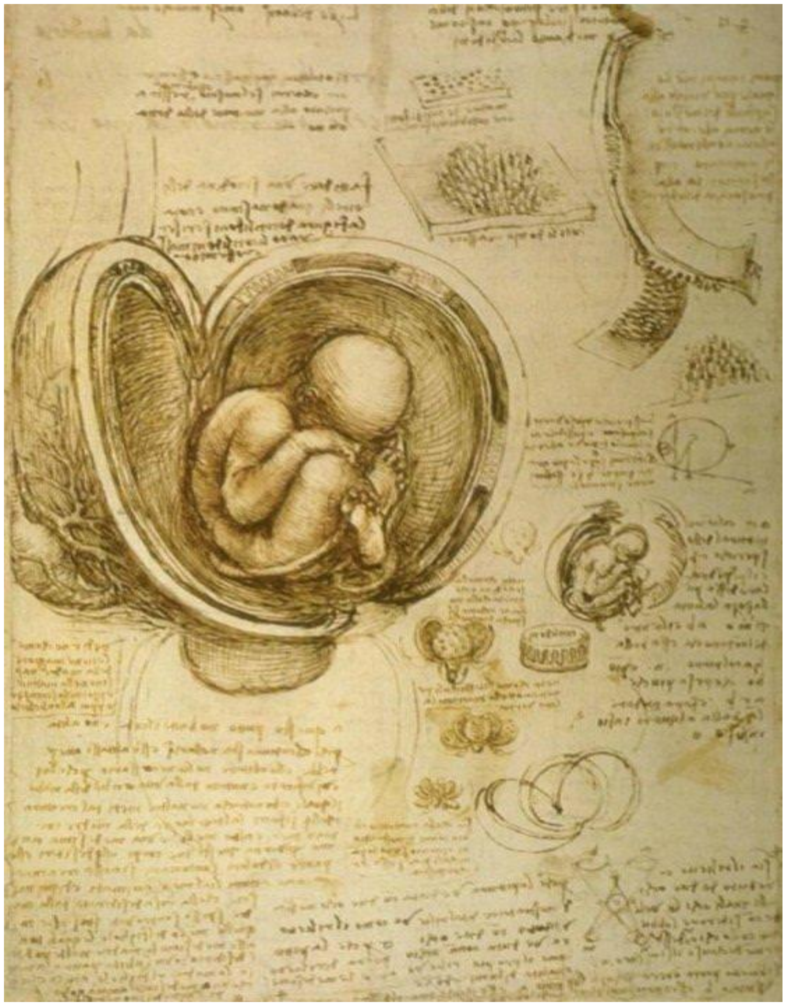

Figure 15: Da Vinci's notebook: Leonardo's graphic story of a fetus told with words and incomparable pictures that disproved Galen of Pergamum's claim about women's bicameral uterus that had persisted unchallenged for 1400 years. *Source:* Wikipedia, public domain.

Arguably, the most famous (and perhaps the first) use of a coordinated sequence of displays to complement an integrated verbal explanation was Leonardo's magnificent tale (Figure 15) of how a human fetus is carried in a womb. It challenged Galen's 1400-year-old description of the human womb as bicameral (having two sinuses) to carry multiple births.

4.4 W. E. B. Du Bois

William Edward Burghardt (W. E. B.) Du Bois was born in Great Barrington, Massachusetts on February 23, 1868, shortly after the end of slavery in the United States. He died in Accra, Ghana on August 27, 1963. During the course of his 95 years he accumulated an extraordinary list of accomplishments. He earned a PhD from Harvard— the first African-American to do so. He was by turns a sociologist, historian, civil rights activist, and author. His many books included: *The Souls of Black Folk*, *The Suppression of the African Slave Trade*, *Dusk of Dawn, Darkwater*, and *The Talented Tenth*. He was also a skilled data scientist devoted to the power of unadorned facts.

It is natural to ask how DuBois, more than a century ago, was able to look at numbers and extract meaning. Certainly the consensus then, and now, is that the extraction of meaning from the huge tables of numbers that might carry that meaning is wearisome to the eye and difficult for the brain; as the American economists Farquahr & Farquahr so memorably put it in 1898, it is a task akin to extracting sunbeams from cucumbers. We can plausibly conclude that DuBois was best able to read meaning from numbers after they had been transformed to visual displays. His remarkable success at this means that as a data scientist, he contributed to the development of the modern approach to constructing a narrative argument based on evidence through his use of a series of graphic displays. In this way he is a direct, lineal, descendant of Leonardo and Minard.

In 1900 Du Bois collaborated with Booker T. Washington on "The Exhibit of American Negroes" at the Paris World Fair (the *Exposition Universelle Internationale)*. It included 400 patents by African-Americans as well as 200 books with African-American authors. In addition, a large number of facts about African-Americans were woven into a memorable narrative by transforming them into data graphics.[vii]

The nearly 60 graphs and thematic maps spanned a wide range of characteristics of African-Americans and their lives. This section of the exhibit was titled "A series of statistical charts illustrating the condition of the descendants of former African slaves now in residence in the United States of America."

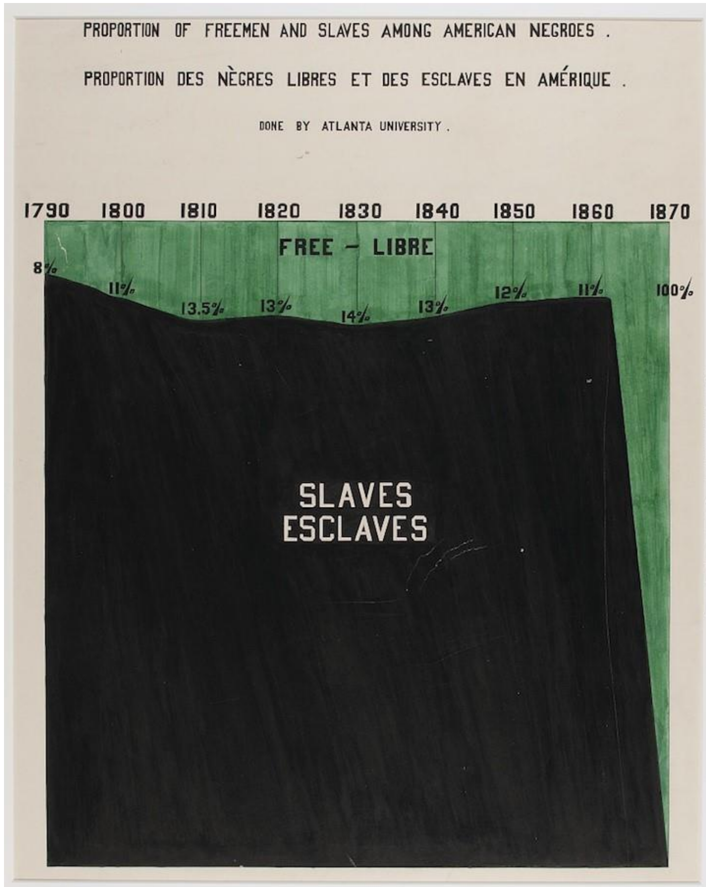

Figure 16: Effect of the Emancipation Proclamation: Proportion of Slaves and Free Negroes from 1790 until 1870. *Source:* Library of Congress, http://hdl.loc.gov/loc.pnp/ppmsca. 33913.

Du Bois began his story with a graph dramatically showing the profound effect of Lincoln's Emancipation Proclamation (Figure 16). It shows the balance of enslaved versus free African-Americans from 1790 until 1870. From this we learn that the proportion of free African-Americans during slavery hovered around 12% of the total African-American population until January of 1863, when Lincoln's Emancipation Proclamation[8] was the key to the dramatic change shown.

[8] Although all slaves in the Confederate States were freed by Lincoln's proclamation in 1863, it was not until the ratification of the 13th amendment on December 6, 1865 that all slavery was truly abolished in the United States.

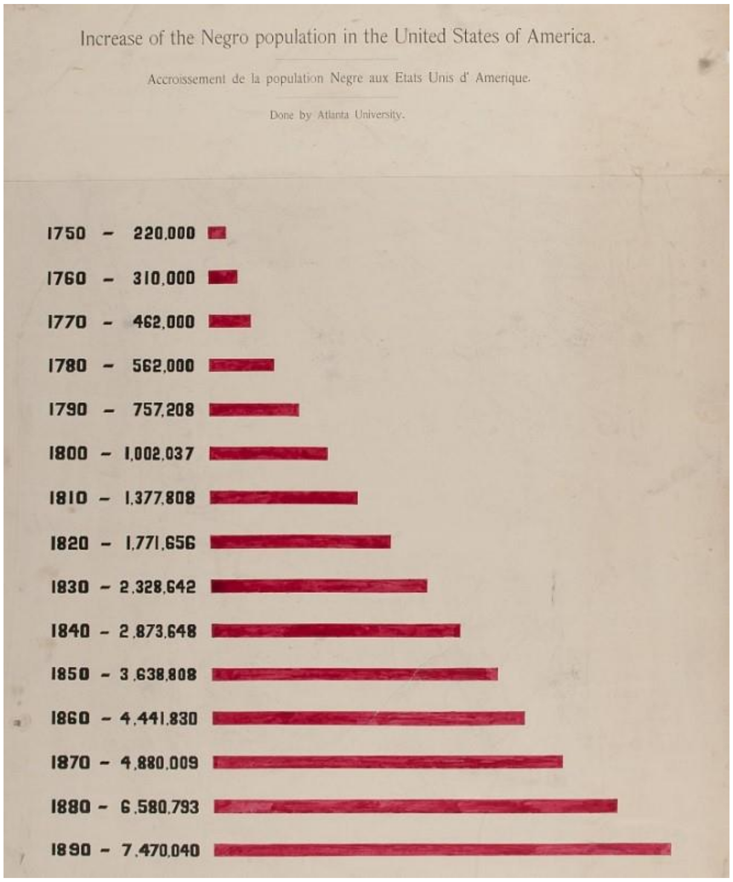

Figure 17: Du Bois's bar chart: Increase of the Negro population of the United States from 1750 until 1890. *Source:* Library of Congress, http://hdl.loc.gov/loc.pnp/ppmsca.33901.

Having established the status of African-Americans in the United States, he then used a simple bar chart (Figure 17) to show that there were seven-and-a-half million African-Americans in 1890 and also the exponential growth of that population over the prior 150 years. Although a simple time series line graph in the style of Playfair might have been used, Du Bois chose the format of a horizontal bar chart in the style of Minard to also show the exact numbers.

Du Bois used these displays to answer fundamental questions of existence: How many of us are there? Are we increasing or decreasing in number? How fast? The next obvious questions are "Where do we live?" and "Where did we come from?" He addressed the first of these in Figure 18, which showed dramatically the heavy concentration of African-Americans in what had been the states of the Confederacy, but there were signs of a movement out of the Deep South into the Northeast. He addressed the second question (Figure 19) with the very first display of his exhibit, showing the sources and destinations of the slave trade

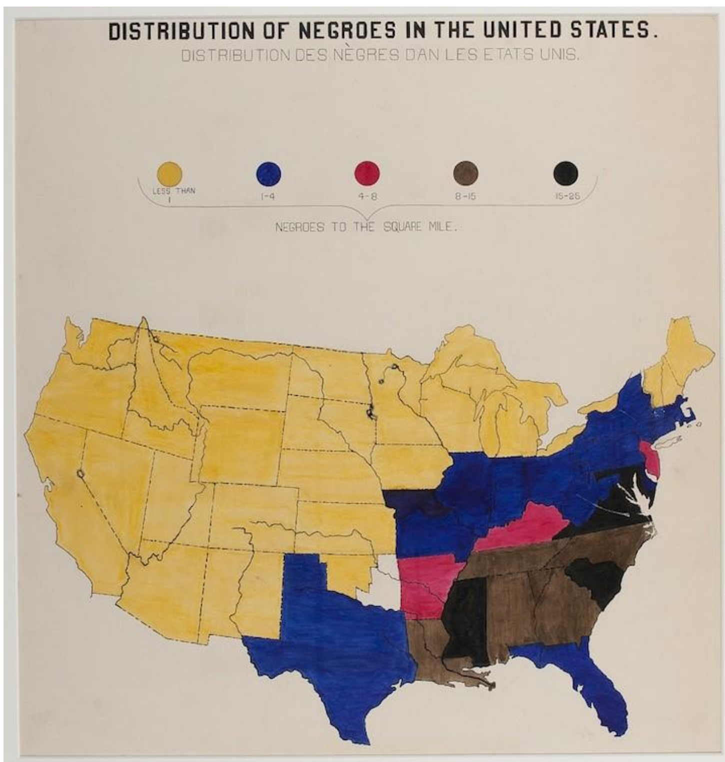

Figure 18: Population density map: The distribution of the population of Negroes in the United States. Shading color shows "Negroes per square mile."
Source: Library of Congress, http://hdl. loc.gov/loc.pnp/ppmsca.33900.

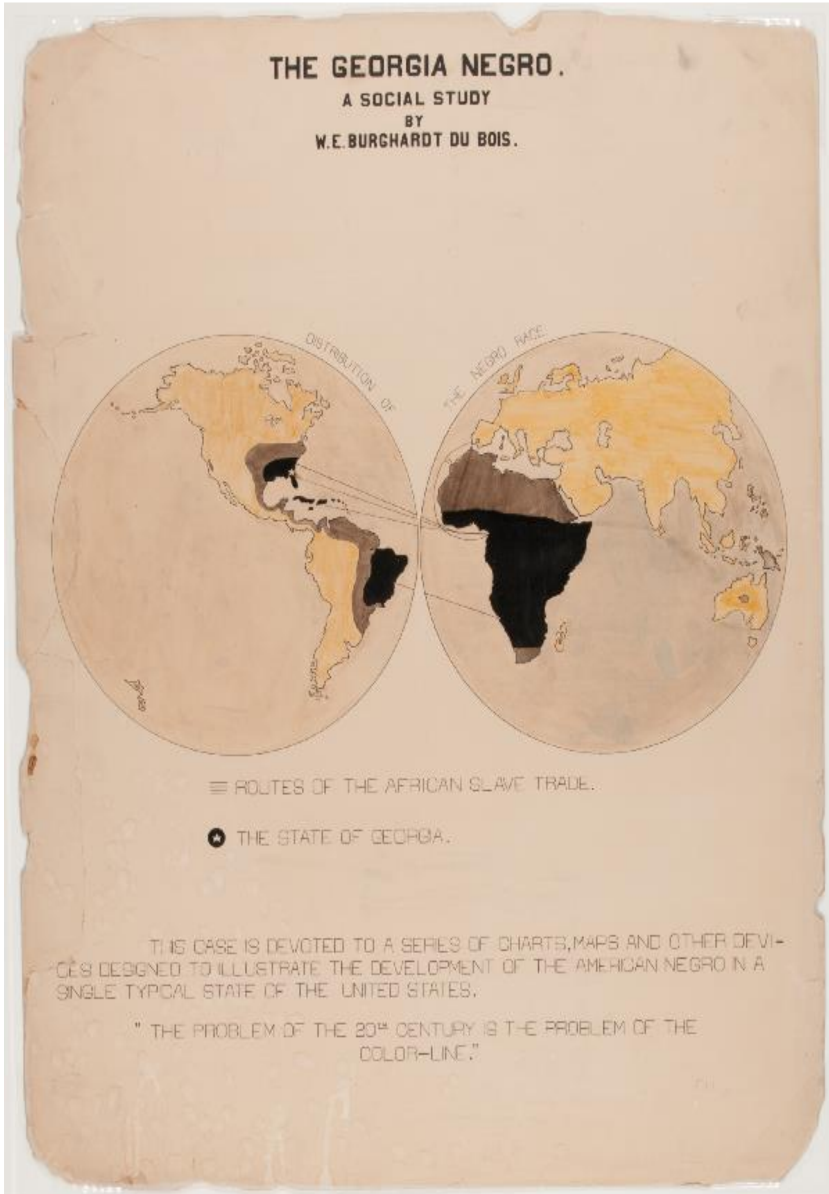

Figure 19: The Routes of the African Slave trade.
Source: Library of Congress, http://hdl. loc.gov/loc.pnp/ppmsca.33866.

He continued with 53 other plots, expanding and enriching the narrative. This fact-based description was made possible by the 1870 expansion of the U.S. census, which, for the first time, included the African-American citizens in the national accounting.

Absent, however was any sort of coherent representation of the gigantic migration of African-Americans out of the South that took place after Reconstruction and continued for the first half of the 20th century. This phenomenon could have been beautifully communicated with a collaborative effort between Du Bois and Minard.

4.5 The Great Migration

As we have seen in Figures 17 and 18, there were 7.5 million African-Americans in 1890, the great majority of whom lived in the rural south of the United States. Between 1916 and 1970 more than 6 million had migrated to the industrial North and West. Historians have dubbed this the Great Migration, commemorating it as the largest peacetime movement of people within a country in history.[viii]

Such a movement cries out for description and explanation. The biggest initial question is, of course, “Why?” But before one can tackle such an interpretative question, one faces the descriptive questions: “From where to where?” “When?” and “How Many?” These questions are fully answered with data, indeed, the sorts of data that are routinely and rigorously gathered by the U.S. decennial census. But extracting geographic structure from the entangled tables of numbers describing it brings to mind the cucumbers of the brothers Farquahr. And communicating the messages contained in these census tables beyond the eyes of experts is far better done graphically. But how are we to transform the tables to graphs?

To answer this question we adjoin the life work of the two giants whose work forms the center of this chapter: Du Bois’s passion for improving the lives of African-Americans and widely communicating their accomplishments, and Minard’s genius for transforming complex data into compelling pictures that impacts both the intellect and the emotions.

Although their long lives overlapped by but two years (and even during that brief period they were separated by language, culture, and an ocean) the work and goals of Minard and Du Bois were complementary. In the balance of this chapter we demonstrate of how a blending of their work yields an evocative narrative of such awakening power that it can rightfully be described as poetic.

The census has always been tasked with counting all residents of the United States; in 1863 its’ scope was expanded to include those African-Americans who had been emancipated from slavery. Thus, the 1870 census, just after the Civil War, included counts of African-Americans for the first time.[9] The census data provided counts, by race, place of birth and place of residence, making it straightforward to study migration patterns of people.

The newly freed African-Americans faced impossibly difficult times. They were desperately poor, largely illiterate, and living in a region whose plantation economy offered little chance for improvement. Most worked as sharecroppers, tenant farmers, or farm laborers. In addition to economic woes, the post Reconstruction South was racist and violent: Jim Crow laws instituted *de jure* racial segregation, and racist organizations like the Ku Klux Klan, the White League, and the Red Shirts made terror a part of daily life for African-Americans living in the post-Civil War

[9] Previously the census included slaves as merely counts within various categories (e.g., age and sex) as part of the household goods of their owners.

Confederate South. Thus, it isn't surprising that large numbers of African-Americans opted to migrate to the North for greater opportunities. World War I created a huge demand for workers in northern factories; northern railroads needed workers so badly they provided free train passes for thousands of southern blacks.

A *gedanken* collaboration

Let us now imagine a collaboration between Du Bois, who chose the topic on which we focus our attention, the Census, which supplied the data, and Minard, who invented and perfected the graphical method that would allow us to see the character of the Great Migration, which, over the 55 year span from 1915 until 1970 saw more than six million African-Americans leave the South.[ix]

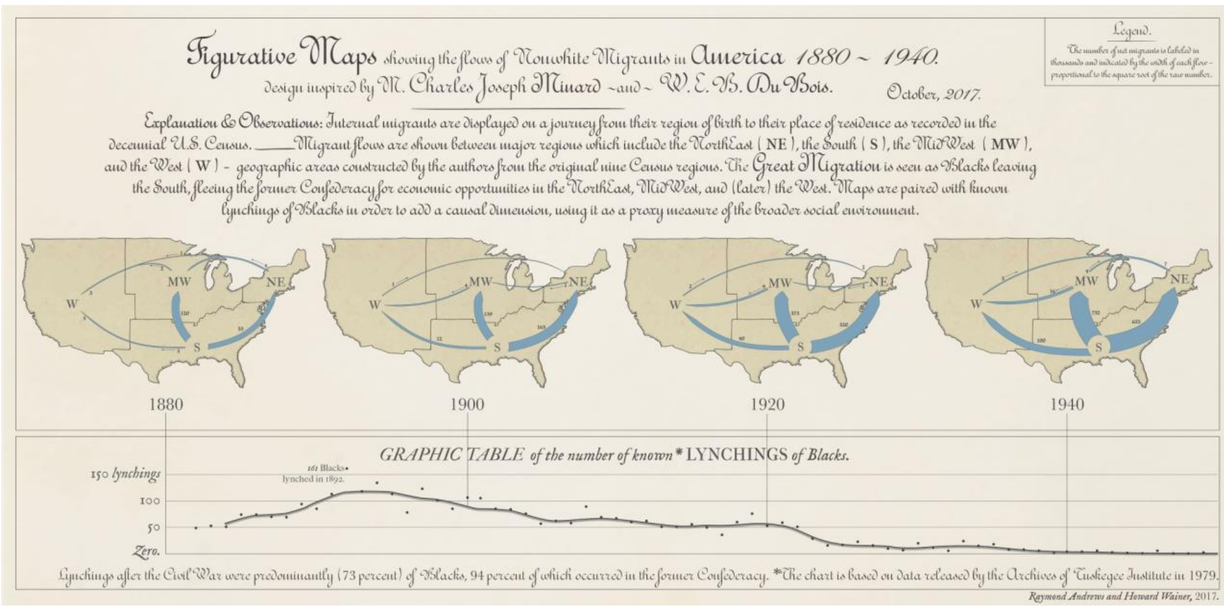

Figure 20: Flow maps of migration: Figurative maps showing the flows of non-white migrants in America, 1880–1940, using a design inspired by Minard and Du Bois. *Source:* Graphic designed and executed by Raymond J. Andrews & Howard Wainer reprinted with their permission.

Shown in Figure 20 is a compound plot of four flow maps drawn in the style of C. J. Minard. The four panels are spaced 20 years apart, showing the movement of non-whites (the census designation, which consisted primarily of African-Americans). The arrows show the net migration (outflow MINUS inflow), and the widths of the arrows are proportional to the number of migrants. The panel at the bottom depicts the annual number of lynchings of African-Americans; 94% of these were in the former Confederacy. We are using this variable in the same way that Minard used temperature in his map of Napoleon's march— as one possible causal variable.

The left-most panel of Figure 20 (for 1880) shows the beginning of the post-reconstruction exodus. Most of the migrants left the South for the industrial cities of the North and Northeast (Chicago, Detroit, Pittsburgh, D.C.). The number of lynchings increased, peaking in 1890, and in 1900 the migration more than doubled. The need for labor expanded during World War I and is manifested by the further increases shown in the 1920 panel, when 454,000 left the South in the decade 1910-1920, and the 1940 panel, when another 1,500,000 left during the Depression and the build-up to World War II. Another principal cause of this part of the migration was the great

Mississippi Flood of 1927, in which more than 200,000 African-Americans were displaced from their homes on the lower Mississippi River.

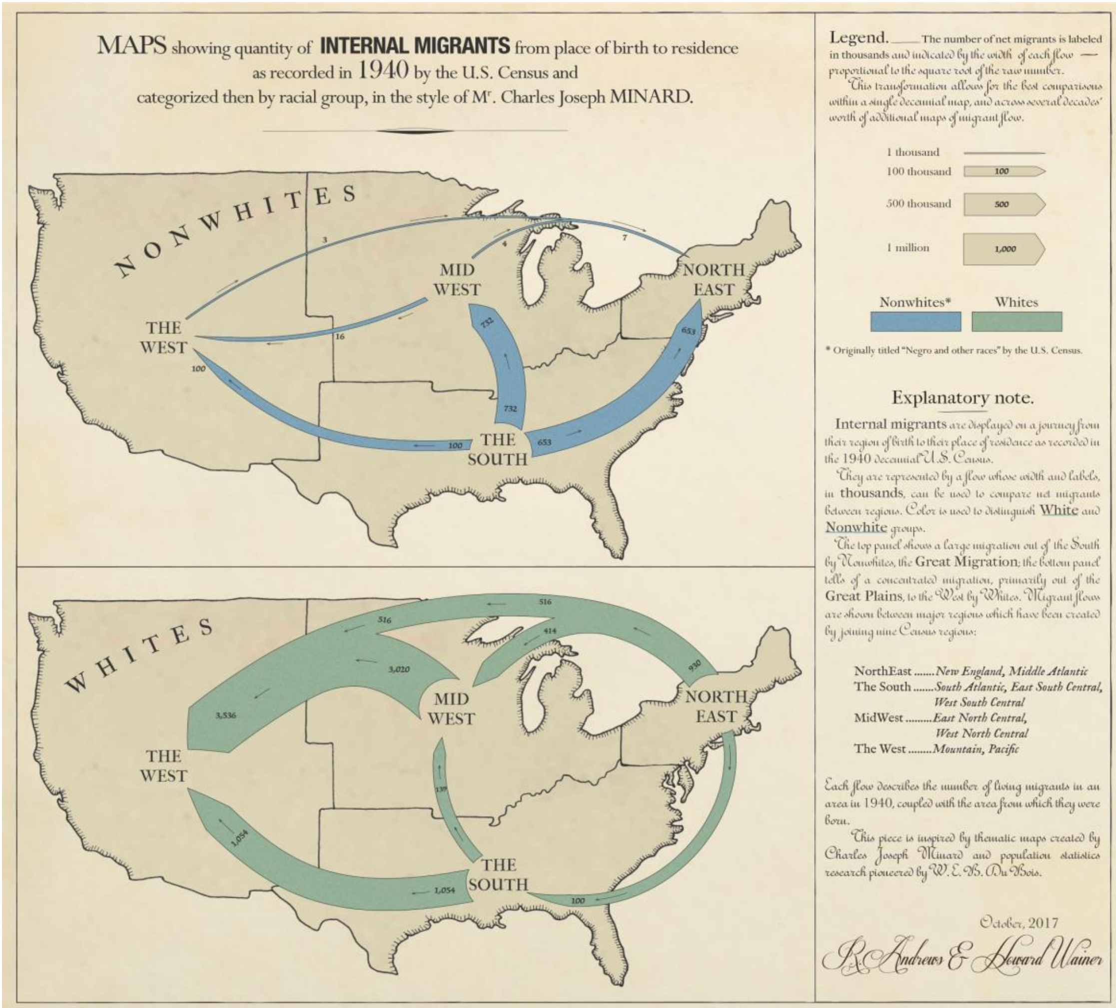

Figure 21: Flow maps for 1940: Maps showing the numbers of internal migrants by birthplace and place of residence, as recorded in the 1940 US Census, categorized by racial group, using a design inspired by Minard. *Source:* Graphic designed and executed by Raymond J. Andrews & Howard Wainer and reprinted with their permission.

The Great Depression affected huge numbers of people, both White and Black, many of whom lost their homes (particularly in the Dust Bowl states) and left for a better life elsewhere. This is shown for African-Americans in the top panel of Figure 10.14 (an enlargement of the 1940 panel of Figure 10.13). The bottom panel (1940 data for Whites) provides a dramatic contrast. Although African-Americans fled the South in the decades of the Great Depression in much the same patterns as they did in the decades before and after, the Whites were often farmers whose economic lives were ruined by the Dust Bowl catastrophe (think of the Joads in Steinbeck's *Grapes of Wrath*, who piled all their belongings onto the family truck and headed West to California).

4.6 Conclusion

"So we beat on, boats against the current, borne back ceaselessly into the past."

Nick Carraway's haunting last line
from F. Scott Fitzgerald's
The Great Gatsby

This chapter, in a very real sense, provides a history and framework for modern science. We have found that, whenever we face a new problem it is always wise to look backward first; this provides the benefit of helping us to understand the thinking of those who have preceded us. The hubris that drives some to believe that we are wiser than our forebears rarely yields a happy result. This chapter is driven by the belief that we are best prepared to move into the unknown future by better understanding the past. In addition to illuminating the past, we wished to draw attention to the extraordinary power of visual depiction of quantitative phenomena to communicate efficiently both facts and emotion— how a graph can be a poem.

To illustrate these points, we have provided a portrait of the Great Migration of African-Americans from the South of the United States in the century following their emancipation from slavery. Sensible space limitations forced us to make some simplifications. In doing so we found that Mies van der Rohe's dictum "less is more" was spectacularly true and faced some of the same choices for level of detail vs. fidelity that Du Bois and Minard encountered in their work.

Looking at decade-by-decade plots added little that was not more clearly shown by collapsing to 20-year periods; showing migration destinations to the nine census regions, rather than the four super-regions we constructed added more noise than structure; including a 1960 plot that contains the final stage of the exodus, when almost 3.5 million left the South for the North and the West adds quantity to what we have already shown, but does not change the overall message. Thus, we believe that this summary is both accurate and complete, and provides a suitable continuation of the task that W.E.B. Du Bois began more than a century ago.

Du Bois's graphical narrative showed facts about African-Americans; how they started out and what they became. We added some details of how they got there and where they came from. The tool we chose to do this we snatched from the past, mining the ideas of the great C. J. Minard. We shamelessly borrowed his metaphor of the flow of goods or people across a geographic background. Minard's adjoining the delicate curve of declining temperature with the rapid shrinkage of Napoleon's army in their death march across the Russian steppes in the winter of 1812 forces the viewer to share the great sadness that enveloped all of France. Our use of the ancillary variable of lynchings was meant to generate a similar emotion, as one empathizes with the terror that African-American southerners must have felt as they made the decision to leave their homes and seek to rebuild their lives elsewhere.

It doesn't take an excessive amount of imagination to connect this same methodology to the Jewish diaspora from Nazi Germany, or the Hebrews from Pharaoh's Egypt, or peasants during the eastern European pogroms, or the Cherokees' Trail of Tears, or the Bataan Death March. We will leave it to others to prepare graphic accounts so that we can better understand and remember the facts and the emotions of these tragic events. For poetic data visualizations, combining both the communication of facts that can be learned, with emotions that can live in your heart forever can help provide a bulwark against future horrors, for "*there is a magic in graphs. The profile of a curve reveals in a flash a whole situation—the life history of an* *epidemic, a panic, or an era of prosperity. The curve informs the mind, awakens the imagination, convinces."*[x]

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End Notes

[i] From page 17 in Lorraine J. Daston & Peter Galison, marvelous 2007 book, *Objectivity*
[ii] Marey, 1878, p. vi

[iii] Cleveland, 1994
[iv] Mumford, 2000, p. 12
[v] See Friendly (2002) for a timeline of Minard's works.

[vi] V. Chevallier, Notice nécrologique sur M. Minard, inspecteur général des ponts et chaussées, en retraite, *Annales des ponts et chaussées*, 2 (1871), 1-22. An English translation was prepared by Dawn Finley, https://www.edwardtufte.com/ tufte/minard-obit. For further detail on Minard's life, see Friendly (2002b) and a biography, http://datavis. ca/gallery/minard/biography.pdf

[vii] Du Bois's account of this exhibit appears in Du Bois (1900). Nearly the entire collection, comprising over 200 photographs and numerous charts and maps, has been digitized by the Library of Congress. See: https://blogs.loc.gov/picturethis/2014/02/du-boiss-american-negro-exhibit-for-the-1900-paris-exposition/.

[viii] Lemann (1991)

[ix] This section borrows from Andrews and Wainer (2017).

[ix] Nick Carraway's haunting last line from F. Scott Fitzgerald's *The Great Gatsby*
[ix] Henry D. Hubbard in the preface to Brinton (1939)