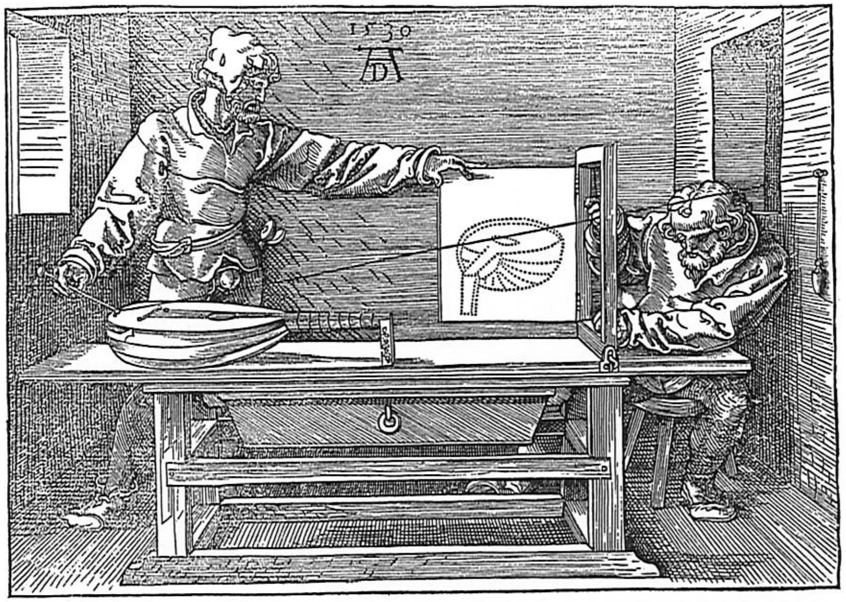


Albrecht Dürer, *Institutiones geometricae* (Paris, 1532), p. 185; the Latin edition of *Underweysung der Messung* [*A Course in the Art of Measurement*] (Nuremberg, 1525).

Edward R. Tufte

Visual Explanations

Images and Quantities, Evidence and Narrative

Graphics Press · Cheshire, Connecticut

2 *Visual and Statistical Thinking: Displays of Evidence for Making Decisions*

When we reason about quantitative evidence, certain methods for displaying and analyzing data are better than others. Superior methods are more likely to produce truthful, credible, and precise findings. The difference between an excellent analysis and a faulty one can sometimes have momentous consequences.

This chapter examines the statistical and graphical reasoning used in making two life-and-death decisions: how to stop a cholera epidemic in London during September 1854; and whether to launch the space shuttle Challenger on January 28, 1986. By creating statistical graphics that revealed the data, Dr. John Snow was able to discover the cause of the epidemic and bring it to an end. In contrast, by fooling around with displays that obscured the data, those who decided to launch the space shuttle got it wrong, terribly wrong. For both cases, the consequences resulted directly from the *quality* of methods used in displaying and assessing quantitative evidence.

The Cholera Epidemic in London, 1854

In a classic of medical detective work, *On the Mode of Communication of Cholera*,[1] John Snow described—with an eloquent and precise language of evidence, number, comparison—the severe epidemic:

> The most terrible outbreak of cholera which ever occurred in this kingdom, is probably that which took place in Broad Street, Golden Square, and adjoining streets, a few weeks ago. Within two hundred and fifty yards of the spot where Cambridge Street joins Broad Street, there were upwards of five hundred fatal attacks of cholera in ten days. The mortality in this limited area probably equals any that was ever caused in this country, even by the plague; and it was much more sudden, as the greater number of cases terminated in a few hours. The mortality would undoubtedly have been much greater had it not been for the flight of the population. Persons in furnished lodgings left first, then other lodgers went away, leaving their furniture to be sent for. . . . Many houses were closed altogether owing to the death of the proprietors; and, in a great number of instances, the tradesmen who remained had sent away their families; so that in less than six days from the commencement of the outbreak, the most afflicted streets were deserted by more than three-quarters of their inhabitants.[2]

[1] John Snow, *On the Mode of Communication of Cholera* (London, 1855). An acute disease of the small intestine, with severe watery diarrhea, vomiting, and rapid dehydration, cholera has a fatality rate of 50 percent or more when untreated. With the rehydration therapy developed in the 1960s, mortality can be reduced to less than one percent. Epidemics still occur in poor countries, as the bacterium *Vibrio cholerae* is distributed mainly by water and food contaminated with sewage. See Dhiman Barua and William B. Greenough III, eds., *Cholera* (New York, 1992); and S. N. De, *Cholera: Its Pathology and Pathogenesis* (Edinburgh, 1961).

[2] Snow, *Cholera*, p. 38. See also *Report on the Cholera Outbreak in the Parish of St. James's, Westminster, during the Autumn of 1854*, presented to the Vestry by The Cholera Inquiry Committee (London, 1855); and H. Harold Scott, *Some Notable Epidemics* (London, 1934).

Cholera broke out in the Broad Street area of central London on the evening of August 31, 1854. John Snow, who had investigated earlier epidemics, suspected that the water from a community pump-well at Broad and Cambridge Streets was contaminated. Testing the water from the well on the evening of September 3, Snow saw no suspicious impurities, and thus he hesitated to come to a conclusion. This absence of evidence, however, was not evidence of absence:

> Further inquiry . . . showed me that there was no other circumstance or agent common to the circumscribed locality in which this sudden increase of cholera occurred, and not extending beyond it, except the water of the above mentioned pump. I found, moreover, that the water varied, during the next two days, in the amount of organic impurity, visible to the naked eye, on close inspection, in the form of small white, flocculent [loosely clustered] particles. . . .[3]

[3] Snow, *Cholera*, p. 39. Writing a few weeks after the epidemic, Snow reported his results in a first-person narrative, more like a laboratory notebook or a personal journal than a modern research paper with its pristine, reconstructed science.

From the General Register Office, Snow obtained a list of 83 deaths from cholera. When plotted on a map, these data showed a close link between cholera and the Broad Street pump. Persistent house-by-house, case-by-case detective work had yielded quite detailed evidence about a possible cause-effect relationship, as Snow made a kind of streetcorner correlation:

> On proceeding to the spot, I found that nearly all of the deaths had taken place within a short distance of the pump. There were only ten deaths in houses situated decidedly nearer to another street pump. In five of these cases the families of the deceased persons informed me that they always sent to the pump in Broad Street, as they preferred the water to that of the pump which was nearer. In three other cases, the deceased were children who went to school near the pump in Broad Street. Two of them were known to drink the water; and the parents of the third think it probable that it did so. The other two deaths, beyond the district which this pump supplies, represent only the amount of mortality from cholera that was occurring before the irruption took place.
>
> With regard to the deaths occurring in the locality belonging to the pump, there were sixty-one instances in which I was informed that the deceased persons used to drink the pump-water from Broad Street, either constantly or occasionally. In six instances I could get no information, owing to the death or departure of every one connected with the deceased individuals; and in six cases I was informed that the deceased persons did not drink the pump-water before their illness.[4]

[4] Snow, *Cholera*, pp. 39–40.

Thus the theory implicating the particular pump was confirmed by the observed covariation: in this area of London, there were few occurrences of cholera exceeding the normal low level, except among those people who drank water from the Broad Street pump. It was now time to act; after all, the reason we seek causal explanations is in order to *intervene*, to govern the cause so as to govern the effect: "Policy-thinking is and must be causality-thinking."[5] Snow described his findings to the authorities responsible for the community water supply, the Board of Guardians of St. James's Parish, on the evening of September 7, 1854. The Board ordered that the pump-handle on the Broad Street well be removed immediately. The epidemic soon ended.

[5] Robert A. Dahl, "Cause and Effect in the Study of Politics," in Daniel Lerner, ed., *Cause and Effect* (New York, 1965), p. 88. Wold writes "A frequent situation is that description serves to maintain some *modus vivendi* (the control of an established production process, the tolerance of a limited number of epidemic cases), whereas explanation serves the purpose of *reform* (raising the agricultural yield, reducing the mortality rates, improving a production process). In other words, description is employed as an aid in the human *adjustment* to conditions, while explanation is a vehicle for ascendancy over the environment." Herman Wold, "Causal Inference from Observational Data," *Journal of the Royal Statistical Society*, A, 119 (1956), p. 29.

Moreover, the result of this intervention (a before/after experiment of sorts) was consistent with the idea that cholera was transmitted by impure water. Snow's explanation replaced previously held beliefs that cholera spread through the air or by some other means. In those times many years before the discovery of bacteria, one fantastic theory speculated that cholera vaporously rose out of the burying grounds of plague victims from two centuries earlier.[6] In 1886 the discovery of the bacterium *Vibrio cholerae* confirmed Snow's theory. He is still celebrated for establishing the mode of cholera transmission *and* consequently the method of prevention: keep drinking water, food, and hands clear of infected sewage. Today at the old site of the Broad Street pump there stands a public house (a bar) named after John Snow, where one can presumably drink more safely than 140 years ago.

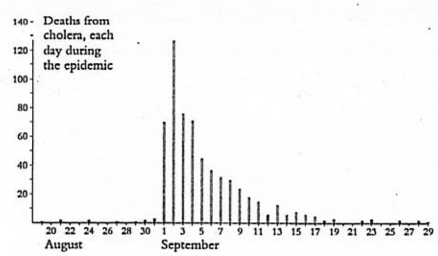
[6] H. Harold Scott, *Some Notable Epidemics* (London, 1934), pp. 3–4.

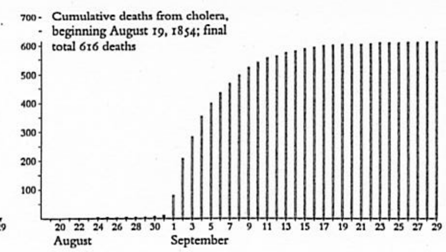
WHY was the centuries-old mystery of cholera finally solved? Most importantly, Snow had a *good idea*—a causal theory about how the disease spread—that guided the gathering and assessment of evidence. This theory developed from medical analysis and empirical observation; by mapping earlier epidemics, Snow detected a link between different water supplies and varying rates of cholera (to the consternation of private water companies who anonymously denounced Snow's work). By the 1854 epidemic, then, the intellectual framework was in place, and the problem of how cholera spread was ripe for solution.[7]

[7] Scientists are not "admired for failing in the attempt to solve problems that lie beyond [their] competence. . . . If politics is the art of the possible, research is surely the art of the soluble. Both are immensely practical-minded affairs. . . . The art of research [is] the art of making difficult problems soluble by devising means of getting at them. Certainly good scientists study the most important problems they think they can solve. It is, after all, their professional business to solve problems, not merely to grapple with them. The spectacle of a scientist locked in combat with the forces of ignorance is not an inspiring one if, in the outcome, the scientist is routed. That is why so many of the most important biological problems have not yet appeared on the agenda of practical research." Peter Medawar, *Pluto's Republic* (New York, 1984), pp. 253–254; 2–3.

Along with a good idea and a timely problem, there was a *good method*. Snow's scientific detective work exhibits a shrewd intelligence about evidence, a clear logic of data display and analysis:

1. *Placing the data in an appropriate context for assessing cause and effect.* The original data listed the victims' names and described their circumstances, all in order by date of death. Such a stack of death certificates naturally lends itself to time-series displays, chronologies of the epidemic as shown below. *But descriptive narration is not causal explanation;* the passage of time is a poor explanatory variable, practically useless in discovering a strategy of how to intervene and stop the epidemic.





Instead of plotting a time-series, which would simply report each day's bad news, Snow constructed a graphical display that provided direct and powerful testimony about a possible cause-effect relationship. Recasting the original data from their one-dimensional temporal ordering into a two-dimensional spatial comparison, Snow marked deaths from cholera (▮▮▮▮▮) on this map, along with locations of the area's 11 community water pump-wells (◉). The notorious well is located amid an intense cluster of deaths, near the D in BROAD STREET. This map reveals a strong association between cholera and proximity to the Broad Street pump, in a context of simultaneous comparison with other local water sources and the surrounding neighborhoods without cholera.

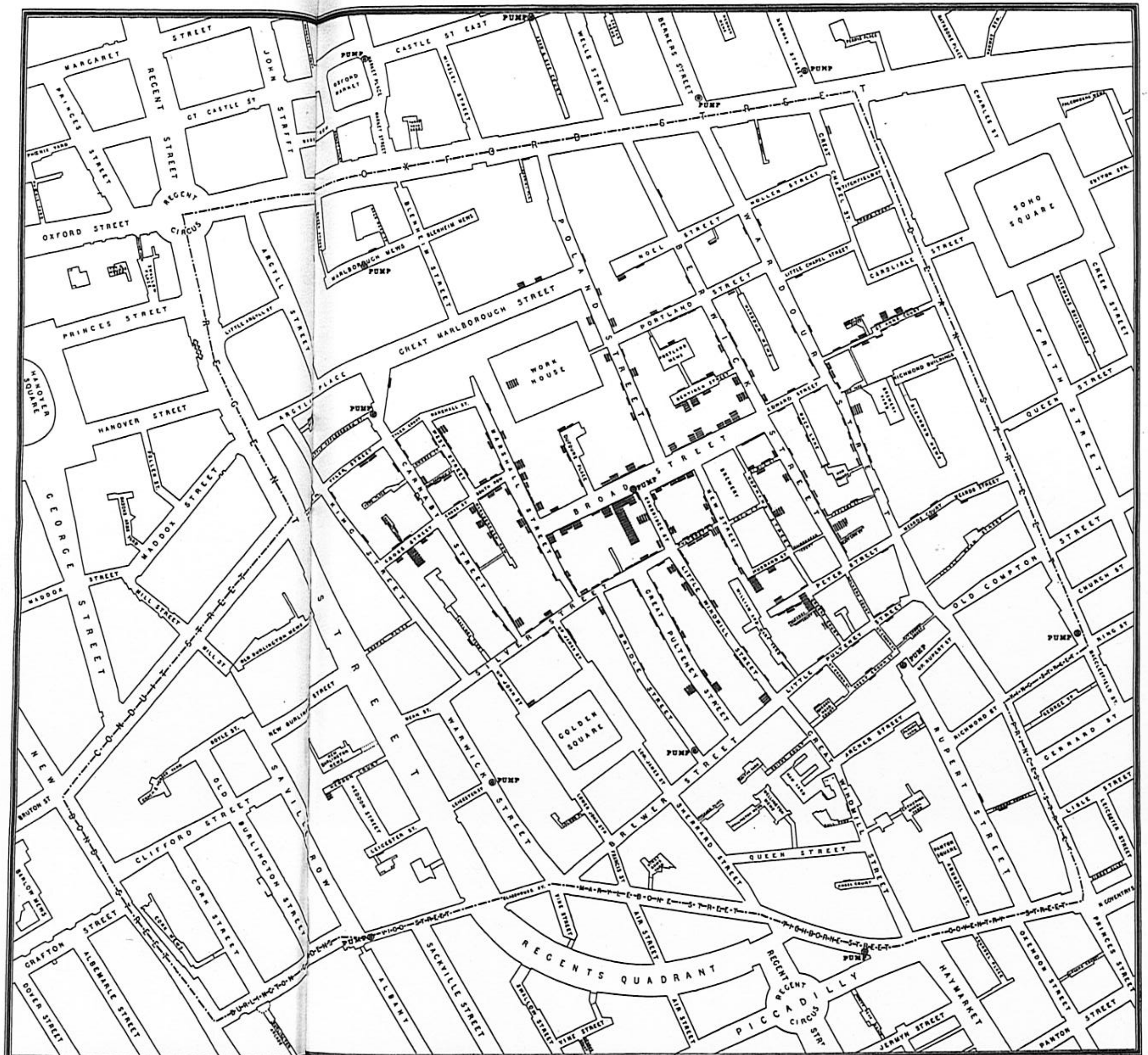
2. *Making quantitative comparisons.* The deep, fundamental question in statistical analysis is *Compared with what?* Therefore, investigating the experiences of the victims of cholera is only part of the search for credible evidence; to understand fully the cause of the epidemic also requires an analysis of those who *escaped* the disease. With great clarity, the map presented several intriguing clues for comparisons between the living and the dead, clues strikingly visible at a brewery and a workhouse (tinted yellow here). Snow wrote in his report:

> There is a brewery in Broad Street, near to the pump, and on perceiving that no brewer's men were registered as having died of cholera, I called on Mr. Huggins, the proprietor. He informed me that there were above seventy workmen employed in the brewery, and that none of them had suffered from cholera—at least in severe form—only two having been indisposed, and that not seriously, at the time the disease prevailed. The men are allowed a certain quantity of malt liquor, and Mr. Huggins believes they do not drink water at all; and he is quite certain that the workmen never obtained water from the pump in the street. There is a deep well in the brewery, in addition to the New River water. (p. 42)

Saved by the beer! And at a nearby workhouse, the circumstances of non-victims of the epidemic provided important and credible evidence about the cause of the disease, as well as a quantitative calculation of an expected rate of cholera compared with the actual observed rate:

> The Workhouse in Poland Street is more than three-fourths surrounded by houses in which deaths from cholera occurred, yet out of five-hundred-thirty-five inmates only five died of cholera, the other deaths which took place being those of persons admitted after they were attacked. The workhouse has a pump-well on the premises, in addition to the supply from the Grand Junction Water Works, and the inmates never sent to Broad Street for water. If the mortality in the workhouse had been equal to that in the streets immediately surrounding it on three sides, upwards of one hundred persons would have died. (p. 42)

Such clear, lucid reasoning may seem commonsensical, obvious, insufficiently technical. Yet we will soon see a tragic instance, the decision to launch the space shuttle, when this straightforward logic of statistical (and visual) comparison was abandoned by many engineers, managers, and government officials.



3. *Considering alternative explanations and contrary cases.* Sometimes it can be difficult for researchers—who both report *and* advocate their findings—to face up to threats to their conclusions, such as alternative explanations and contrary cases. Nonetheless, the credibility of a report is enhanced by a careful assessment of *all* relevant evidence, not just the evidence overtly consistent with explanations advanced by the report. The point is to get it right, not to win the case, not to sweep under the rug all the assorted puzzles and inconsistencies that frequently occur in collections of data.[8]

Both Snow's map and the time-sequence of deaths show several apparently contradictory instances, a number of deaths from cholera with no obvious link to the Broad Street pump. And yet . . .

> In some of the instances, where the deaths are scattered a little further from the rest on the map, the malady was probably contracted at a nearer point to the pump. A cabinet-maker who resided on Noel Street [some distance from Broad Street] worked in Broad Street. . . . A little girl, who died in Ham Yard, and another who died in Angel Court, Great Windmill Street, went to the school in Dufour's Place, Broad Street, and were in the habit of drinking the pump-water. . . .[9]

In a particularly unfortunate episode, one London resident made a special effort to obtain Broad Street well-water, a delicacy of taste with a side-effect that unwittingly cost two lives. Snow's report is one of careful description and precise logic:

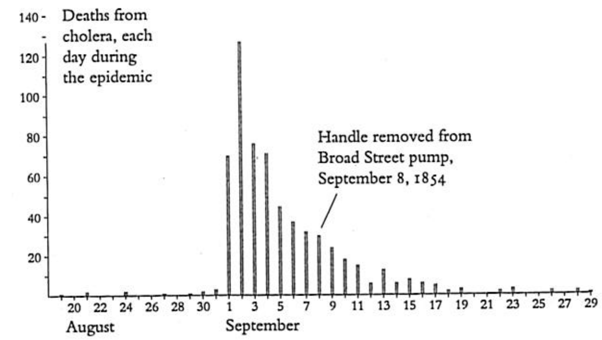
> Dr. Fraser also first called my attention to the following circumstances, which are perhaps the most conclusive of all in proving the connexion between the Broad Street pump and the outbreak of cholera. In the 'Weekly Return of Births and Deaths' of September 9th, the following death is recorded: 'At West End, on 2nd September, the widow of a percussion-cap maker, aged 59 years, diarrhea two hours, *cholera epidemica* sixteen hours.' I was informed by this lady's son that she had not been in the neighbourhood of Broad Street for many months. A cart went from Broad Street to West End every day, and it was the custom to take out a large bottle of the water from the pump in Broad Street, as she preferred it. The water was taken on Thursday, 31st August, and she drank of it in the evening, and also on Friday. She was seized with cholera on the evening of the latter day, and died on Saturday. . . . A niece, who was on a visit to this lady, also drank of the water; she returned to her residence, in a high and healthy part of Islington, was attacked with cholera, and died also. There was no cholera at the time, either at West End or in the neighbourhood where the niece died.[10]

Although at first glance these deaths appear unrelated to the Broad Street pump, they are, upon examination, strong evidence pointing to that well. There is here a clarity and undeniability to the link between cholera and the Broad Street pump; only such a link can account for what would otherwise be a mystery, this seemingly random and unusual occurrence of cholera. And the saintly Snow, unlike some researchers, gives full credit to the person, Dr. Fraser, who actually found this crucial case.

[8] The distinction between science and advocacy is poignantly posed when statisticians serve as consultants and witnesses for lawyers. See Paul Meier, "Damned Liars and Expert Witnesses," and Franklin M. Fisher, "Statisticians, Econometricians, and Adversary Proceedings," *Journal of the American Statistical Association*, 81 (1986), pp. 269–276 and 277–286.

[9] Snow, *Cholera*, p. 47.

[10] Snow, *Cholera*, pp. 44–45.



Data source: plotted from the table in Snow, *Cholera*, p. 49.

Ironically, the most famous aspect of Snow's work is also the most uncertain part of his evidence: it is not at all clear that the removal of the handle of the Broad Street pump had much to do with ending the epidemic. As shown by this time-series above, the epidemic was already in rapid decline by the time the handle was removed. Yet, in many retellings of the story of the epidemic, the pump-handle removal is *the* decisive event, the unmistakable symbol of Snow's contribution. Here is the dramatic account of Benjamin Ward Richardson:

> On the evening of Thursday, September 7th, the vestrymen of St. James's were sitting in solemn consultation on the causes of the [cholera epidemic]. They might well be solemn, for such a panic possibly never existed in London since the days of the great plague. People fled from their homes as from instant death, leaving behind them, in their haste, all the mere matter which before they valued most. While, then, the vestrymen were in solemn deliberation, they were called to consider a new suggestion. A stranger had asked, in modest speech, for a brief hearing. Dr. Snow, the stranger in question, was admitted and in few words explained his view of the 'head and front of the offending.' He had fixed his attention on the Broad Street pump as the source and centre of the calamity. He advised removal of the pump-handle as the grand prescription. The vestry was incredulous, but had the good sense to carry out the advice. The pump-handle was removed, and the plague was stayed.[11]

Note the final sentence, a declaration of cause and effect.[12] Modern epidemiologists, however, are distinctly skeptical about the evidence that links this intervention to the epidemic's end:

> John Snow, in the seminal act of modern public health epidemiology, performed an intervention that was non-randomized, that was appraised with historical controls, and that had major ambiguities in the equivocal time relationship between his removal of the handle of the Broad Street pump and the end of the associated epidemic of cholera—but he correctly demonstrated that the disease was transmitted through water, not air.[13]

[11] Benjamin W. Richardson, "The Life of John Snow, M.D.," foreword to John Snow, *On Chloroform and Other Anaesthetics: Their Action and Administration* (London, 1858), pp. xx–xxi.

[12] Another example of the causal claim: "On September 8, at Snow's urgent request, the handle of the Broad Street pump was removed and the incidence of new cases ceased almost at once," E. W. Gilbert, "Pioneer Maps of Health and Disease in England," *The Geographical Journal*, 124 (1958), p. 174. Gilbert's assertion was repeated in Edward R. Tufte, *The Visual Display of Quantitative Information* (Cheshire, Connecticut, 1983), p. 24.

[13] Alvan R. Feinstein, *Clinical Epidemiology: The Architecture of Clinical Research* (Philadelphia, 1985), pp. 409–410. And A. Bradford Hill ["Snow—An Appreciation," *Proceedings of the Royal Society of Medicine*, 48 (1955), p. 1010] writes: "Though conceivably there might have been a second peak in the curve, and though almost certainly some more deaths would have occurred if the pump handle had remained in situ, it is clear that the end of the epidemic was not dramatically determined by its removal."

At a minimum, removing the pump-handle prevented a recurrence of cholera. Snow recognized several difficulties in evaluating the effect of his intervention; since most people living in central London had fled, the disease ran out of possible victims—which happened simultaneously with shutting down the infected water supply.[14] The case against the Broad Street pump, however, was based on a diversity of additional evidence: the cholera map, studies of unusual instances, comparisons of the living and dead with their consumption of well-water, and an idea about a mechanism of contamination (a nearby underground sewer had probably leaked into the infected well). Also, the finding that cholera was carried by water—a life-saving scientific discovery that showed how to intervene and prevent the spread of cholera—derived not only from study of the Broad Street epidemic but also from Snow's mappings of several other cholera outbreaks in relation to the purity of community water supplies.

[14] "There is no doubt that the mortality was much diminished, as I said before, by the flight of the population, which commenced soon after the outbreak; but the attacks had so far diminished before the use of the water was stopped, that it is impossible to decide whether the well still contained the cholera poison in an active state, or whether, from some cause, the water had become free from it." Snow, *Cholera*, pp. 51–52.

4. *Assessment of possible errors in the numbers reported in graphics.* Snow's analysis attends to the sources and consequences of errors in gathering the data. In particular, the credibility of the cholera map grows out of supplemental details in the text—as image, word, and number combine to present the evidence and make the argument. Detailed comments on possible errors annotate both the map and the table, reassuring readers about the care and integrity of the statistical detective work that produced the data graphics:

> The deaths which occurred during this fatal outbreak of cholera are indicated in the accompanying map, as far as I could ascertain them. There are necessarily some deficiencies, for in a few of the instances of persons who died in the hospitals after their removal from the neighbourhood of Broad Street, the number of the house from which they had been removed was not registered. The address of those who died after their removal to St. James's Workhouse was not registered; and I was only able to obtain it, in a part of the cases, on application at the Master's Office, for many of the persons were too ill, when admitted, to give any account of themselves. In the case also of some of the workpeople and others who contracted the cholera in this neighbourhood, and died in different parts of London, the precise house from which they had removed is not stated in the return of deaths. I have heard of some persons who died in the country shortly after removing from the neighbourhood of Broad Street; and there must, no doubt, be several cases of this kind that I have not heard of. Indeed, the full extent of the calamity will probably never be known. The deficiencies I have mentioned, however, probably do not detract from the correctness of the map as a diagram of the topography of the outbreak; for, if the locality of the few additional cases could be ascertained, they would probably be distributed over the district of the outbreak in the same proportion as the large number which are known.[15]

> The deaths in the above table [the time-series of daily deaths] are compiled from the sources mentioned above in describing the map; but some deaths which were omitted from the map on account of the number of the house not being known, are included in the table. . . .[16]

[15] Snow, *Cholera*, pp. 45–46.

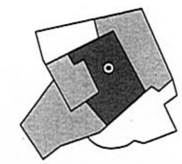
[16] Snow, *Cholera*, p. 50.

Snow drew a *dot map*, marking each individual death. This design has statistical costs and benefits: death *rates* are not shown, and such maps may become cluttered with excessive detail; on the other hand, the sometimes deceptive effects of aggregation are avoided. And of course dot maps aid in the identification and analysis of individual cases, evidence essential to Snow's argument.

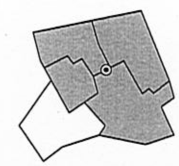
The big problem is that dot maps fail to take into account the number of people living in an area and at risk to get a disease: "an area of the map may be free of cases merely because it is not populated."[17] Snow's map does not fully answer the question *Compared with what?* For example, if the population as a whole in central London had been distributed just as the deaths were, then the cholera map would have merely repeated the unimportant fact that more people lived near the Broad Street pump than elsewhere. This was not the case; the entire area shown on the map—with and without cholera—was thickly populated. Still, Snow's dot map does not assess varying densities of population in the area around the pump. Ideally, the cholera data should be displayed on both a dot and a rate map, with population-based rates calculated for rather small and homogeneous geographic units. In the text of his report, however, Snow did present rates for a few different areas surrounding the pump.

[17] Brian MacMahon and Thomas F. Pugh, *Epidemiology: Principles and Methods* (Boston, 1970), p. 150.

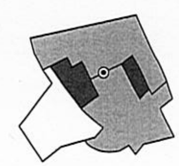
Aggregations by area can sometimes mask and even distort the true story of the data. For two of the three examples at right, constructed by Mark Monmonier from Snow's individual-level data, the intense cluster around the Broad Street pump entirely vanishes in the process of geographically aggregating the data (the greater the number of cholera deaths, the darker the area).[18]



In this aggregation of individual deaths into six areas, the greatest number is concentrated at the Broad Street pump.



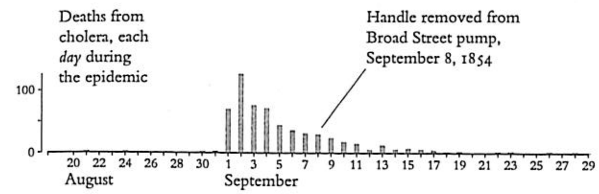
Using different geographic subdivisions, the cholera numbers are nearly the same in four of the five areas.

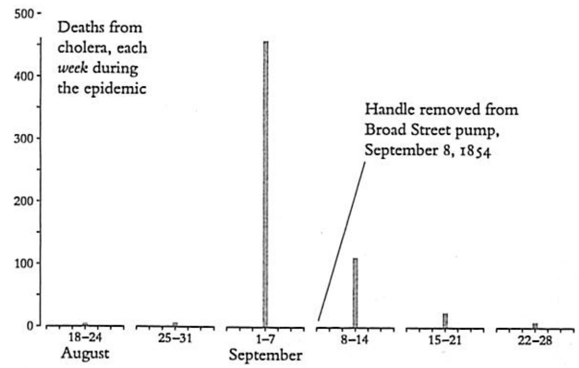


In this aggregation of the deaths, the two areas with the most deaths do not even include the infected pump!

In describing the discovery of how cholera is transmitted, various histories of medicine discuss the famous map and Snow's analysis. The cholera map, as Snow drew it, is difficult to reproduce on a single page; the full size of the original is awkward (a square, 40 cm or 16 inches on the side), and if reduced in size, the cholera symbols become murky and the type too small. Some facsimile editions of *On the Mode of Communication of Cholera* have given up, reprinting only Snow's text and not the crucial visual evidence of the map. Redrawings of the map for textbooks in medicine and in geography fail to reproduce key elements of Snow's original. The workhouse and brewery, those essential compared-with-what cases, are left unlabeled and unidentified, showing up only as mysterious cholera-free zones close to the infected well. Standards of quality may slip when it comes to visual displays; imprecise and undocumented work that would be unacceptable for words or tables of data too often shows up in graphics. Since it is *all* evidence—regardless of the method of presentation—the highest standards of statistical integrity and statistical thinking should apply to *every* data representation, including visual displays.

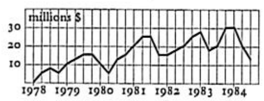
[18] Mark Monmonier, *How to Lie with Maps* (Chicago, 1991), pp. 142–143.



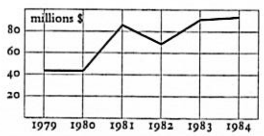


Aggregations over time may also mask relevant detail and generate misleading signals, similar to the problems of spatial aggregation in the three cholera maps. Shown at top is the familiar *daily* time-series of deaths from cholera, with its smooth decline in deaths unchanged by the removal of the pump-handle. When the daily data are added up into *weekly* intervals, however, a different picture emerges: the removal had the apparent consequence of reducing the weekly death toll from 458 to 112! But this result comes purely from the aggregation, for the daily data show no such effect.[19] Conveniently, the handle was removed in early morning of September 8; hence the plausible weekly intervals of September 1–7, 8–14, and so on. Imagine if we had read the story of John Snow as reported in the first few pages here, and if our account showed the weekly instead of daily deaths—then it would all appear perfectly convincing although quite misleading.

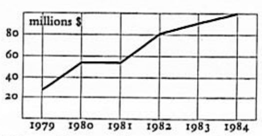
Some other weekly intervals would further aggravate the distortion. Since two or more days typically pass between consumption of the infected water and deaths from cholera, the removal date might properly be *lagged* in relation to the deaths (for example, by starting to count post-removal deaths on the 10th of September, 2 days *after* the pump



Above, this chart shows *quarterly* revenue data in a financial graphic for a legal case. Several dips in revenue are visible.

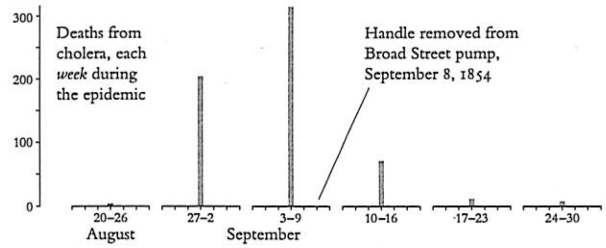


Aggregating the quarterly data into years, this chart above shows revenue by *fiscal year* (beginning July 1, ending June 30). Note the dip in 1982, the basis of a claim for damages.



Shown above are the same quarterly revenue data added up into *calendar years*. The 1982 dip has vanished.

[19] Reading from the top, these clever examples reveal the effects of temporal aggregation in economic data; from Gregory Joseph, *Modern Visual Evidence* (New York, 1992), pp. A42–A43.



handle was taken off). These lagged weekly clusters are shown above. The pseudo-effect of handle removal is now even stronger: after three weeks of increasing deaths, the weekly toll plummets when the handle is gone. A change of merely two days in weekly intervals has radically shifted the shape of the data representation. As a comparison between the two weekly charts shows, the results depend on the arbitrary choice of time periods—a sign that we are seeing method not reality.

These conjectural weekly aggregations are as condensed as news reports; missing are only the decorative clichés of "info-graphics" (the language is as ghastly as the charts). At right is how pop journalism might depict Snow's work, complete with celebrity factoids, over-compressed data, and the isotype styling of those little coffins.

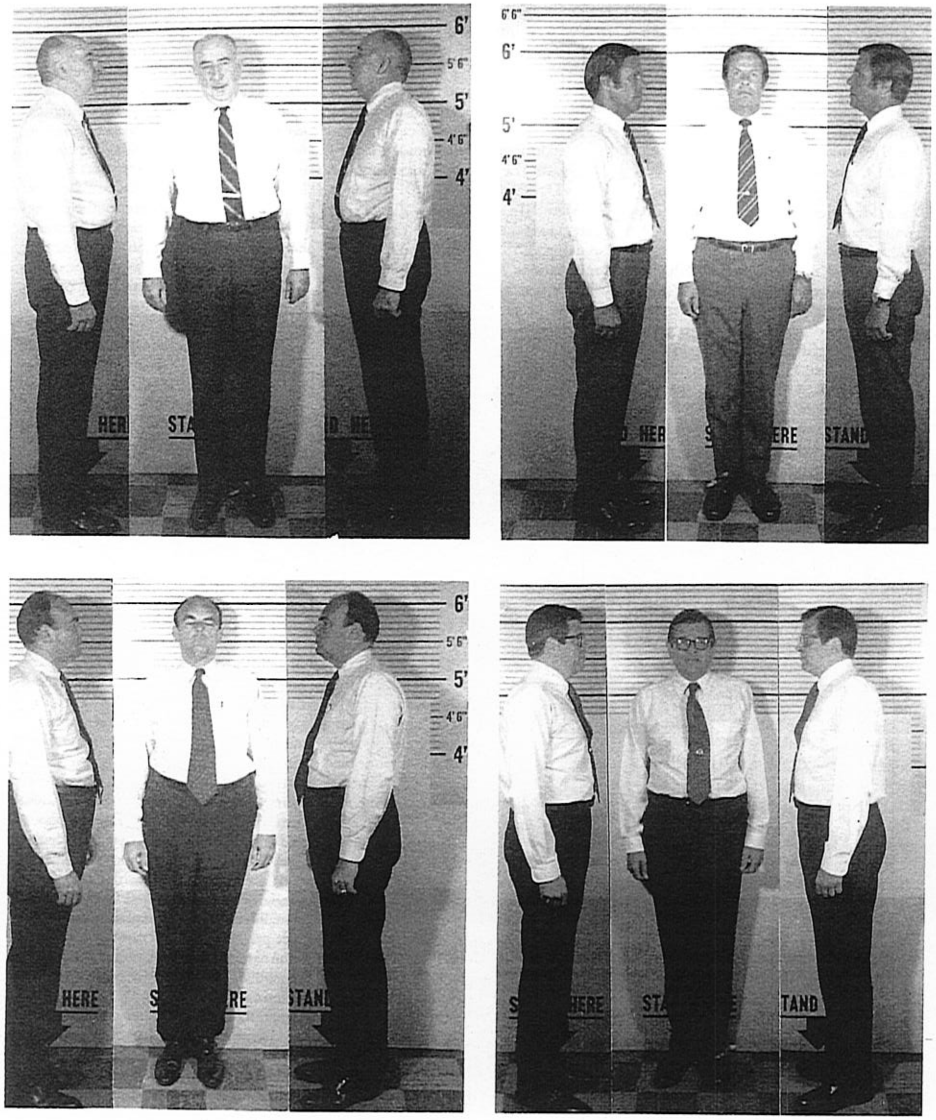
Time-series are exquisitely sensitive to choice of intervals and end points. Nonetheless, many aggregations are perfectly sensible, reducing the tedious redundancy and uninteresting complexity of large data files; for example, the *daily* data amalgamate times of death originally recorded to the hour and even minute. If in doubt, graph the detailed underlying data to assess the effects of aggregation.

A further difficulty arises, a result of fast computing. It is easy now to sort through thousands of plausible varieties of graphical and statistical aggregations—and then to select for publication only those findings strongly favorable to the point of view being advocated. Such searches are described as *data mining, multiplicity*, or *specification searching*.[20] Thus a prudent judge of evidence might well presume that those *graphs, tables, and calculations revealed in a presentation are the best of all possible results chosen expressly for advancing the advocate's case.*

EVEN in the face of issues raised by a modern statistical critique, it remains wonderfully true that John Snow did, after all, show exactly how cholera was transmitted and therefore prevented. In 1955, the *Proceedings of the Royal Society of Medicine* commemorated Snow's discovery. A renowned epidemiologist, Bradford Hill, wrote: "For close upon 100 years we have been free in this country from epidemic cholera, and it is a freedom which, basically, we owe to the logical thinking, acute observations and simple sums of Dr. John Snow."[21]

[20] John W. Tukey, "Some Thoughts on Clinical Trials, Especially Problems of Multiplicity," *Science*, 198 (1977), pp. 679–684; Edward E. Leamer, *Specification Searches: Ad Hoc Inference with Nonexperimental Data* (New York, 1978). On the other hand, "enough exploration must be done so that the results are shown to be relatively insensitive to plausible alternative specifications and data choices. Only in that way can the statistician protect himself or herself from the temptation to favor the client and from the ensuing cross-examination." Franklin M. Fisher, "Statisticians, Econometricians, and Adversary Proceedings," *Journal of the American Statistical Association*, 81 (1986), p. 279. Another reason to explore the data thoroughly is to find out what is going on! See John W. Tukey, *Exploratory Data Analysis* (Reading, Massachusetts, 1977).

[21] A. Bradford Hill, "Snow—An Appreciation," *Proceedings of the Royal Society of Medicine*, 48 (1955), p. 1012.



6 Multiples in Space and Time

MULTIPLE images reveal repetition and change, pattern and surprise—the defining elements in the idea of *information.*

Multiples directly depict comparisons, the essence of statistical thinking.

Multiples enhance the dimensionality of the flatlands of paper and computer screen, giving depth to vision by arraying panels and slices of information.

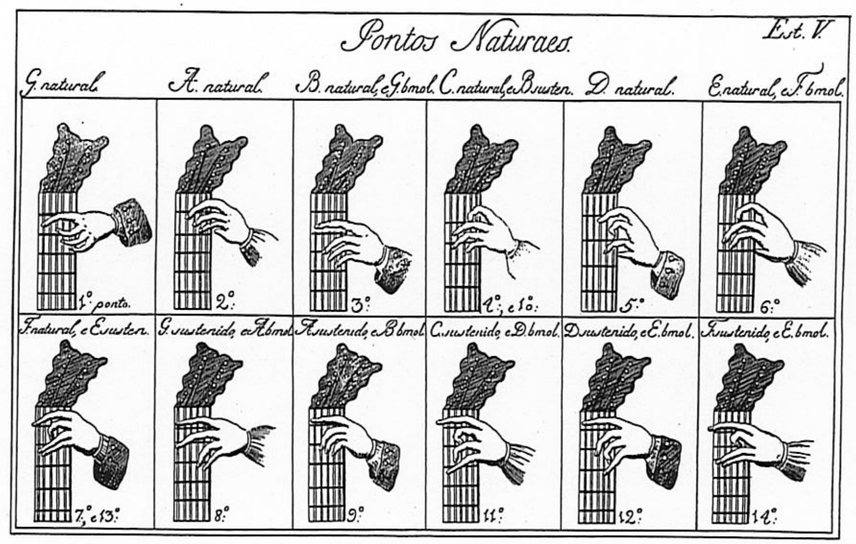
Multiples create visual lists of objects and activities, nouns and verbs, helping viewers to analyze, compare, differentiate, decide—as we see below with 12 hands in 12 positions for making 12 sounds.

Multiples represent and narrate sequences of motion.

Multiples amplify, intensify, and reinforce the meaning of images.

Clockwise, from top left: four of President Richard Nixon's closest associates: John Mitchell, H. R. Haldeman, Charles Colson, and John Ehrlichman, photographs taken when they were arraigned on March 9, 1974, after their indictments in the Watergate cover-up.

Manoel da Paixão Ribeiro, *Nova Arte de Viola* (Lisbon, 1789), appended figure v.



CHRISTIAAN HUYGENS reported his discoveries about Saturn in *Systema Saturnium*, published in 1659. Multiple images are used throughout to reveal new findings, narrate movements of the planet and its satellites, and catalog previous research. Below, a double-page spread shows a sharp, clear view of the rings of Saturn—the first such view, ending years of misconception that had started with Galileo's fragmentary glimpse and incorrect interpretation of the rings in 1610. Also below, a text-image sequence describes a series of nightly observations of the motion of Titan, Saturn's largest satellite. Galileo had used the same design, many years earlier, in his description (at right) of the four inner satellites of Jupiter.[1] A tight collation of explanatory text and small drawings, much like a scientific notebook, the Galileo-Huygens design narrates a sequence of observational slices in a time-series, as changes in the multiple images represent the verbs of motion.

In an another superb display of data, Huygens used multiple images to record and compare previous views of Saturn along with the names

Die vigeſimaquinta hora 1. min: 40. ita ſe habebat

Ori. * * ○ Occ.

conſtitutio, aderant enim duæ tantum Stellæ ex orientali plaga, eæque ſatis magnæ. Orientalior à media diſtabat min: 5. media verò à Ioue min: 6.

Die vigeſima ſexta hora 0. min: 40. Stellarum coordinatio eiuſmodi fuit. Spectabantur enim Stellæ

Ori. * * ○ * Occ.

tres, quarum duæ orientales, tertia occidentalis à Ioue: hæc ab eo min: 5. aberat, media verò orientalis ab eodem diſtabat min: 5. ſec: 20. Orientalior verò à media min: 6. in eadem recta conſtitutæ, & eiuſdem magnitudinis erant. Hora deinde quinta conſtitutio ferè eadem fuit, in hoc tantum diſcrepans, quod

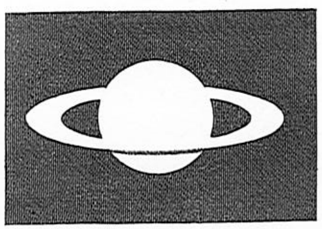
Ori. * * •○ * Occ.

[1] Galileo Galilei, *Sidereus Nuncius* (Venice, 1610), pp. 19–30; above, p. 24.

Christiaan Huygens, *Systema Saturnium* (The Hague, 1659), pp. 24–25.

24 CHRISTIANI HVGENII

Forma verò anſarum diſtinctè hac vice percipi potuit, quam figura hæc exhibet;



atque ea ad ultimam uſque harum obſervationum talis extitit.

24 Febr. hora dimidia poſt mediam noctem, comes erat in mediocri diſtantia, orientem verſus, rectâ anſarum paulo inferior.

25 Febr. horâ eadem orientalis denuo comes cernebatur, una Saturni diametro ab ipſo remotus.

14 Martij

SYSTEMA SATVRNIVM. 25

14 Martij, hora 12, comes recta fere infra Saturnum obſervatus, unius circiter diametri longitudine diſtans; paulum tamen verſus occidentem declinabat. *Comes infra Saturnii tranſire viſus.*

16 Martij, hora 11, ad latus occiduum poſitus erat, fere in maxima diſtantia, inferiorque paulo eâ quæ per anſas ducitur.

21 Martij, hora 11, rurſus ad eandem partem conſiſtebat comes, motu latitudinis integra Saturni diametro ſupra anſarum lineam elatus, longitudinis motu tantum dimidia diametro diſtans. *Idē ſupra Saturnii tranſiens.*

22 Martij, horæ quadrante ante undecimam; rurſus integra diametro ſuperior erat rectâ anſarum, ac fere ſupra orientalis anſæ extremam cuſpidem collocatus.

26 Martij, hora 10½ comes in maxima diſtantia videbatur; quam accuratè hac vice dimenſus, inveni inter comitem centrumque Saturni intervallum trium ſcrupulorum primorum, 16 ſecundorum.

Hucuſque obſervationes, & plures quidem quam neceſſe fuerat, recenſui; rem gratam tamen iis me facturum ratus, qui triennio iſto ſimul forſitan mecum novo

D Planetæ

of the astronomers who published these views. Depicted below are 13 interpretations of Saturn—all of them wrong—based on observations made before Huygens solved the puzzle of the rings. A foldout from *Systema Saturnium*, this multiple visually reviews the scientific literature from 1610 to 1645. All these squashed images appear to be stuck flat on the projection plane, as the rings were read two-dimensionally rather than as three-dimensional objects encircling the planet:

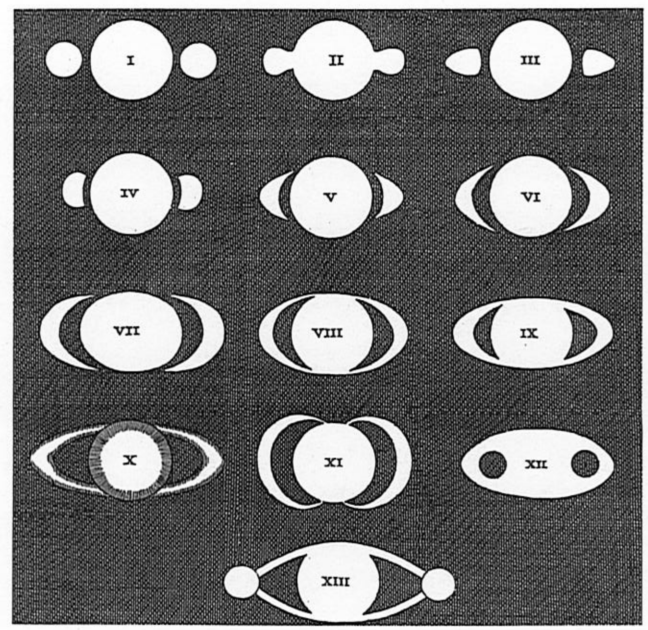
> Astronomers offered all manner of geometrical contrivances to explain the planet's behavior—two crescents attached to a tumbling planet; two large, dark satellites (the dark triangles) and two bright ones outside of those; or, perhaps an egg-shaped planet with four black spots. The most popular idea was some sort of vaporous exhalation of the planet condensed into an ever changing cloud or a thin elliptical corona that rotated with the planet.[2]

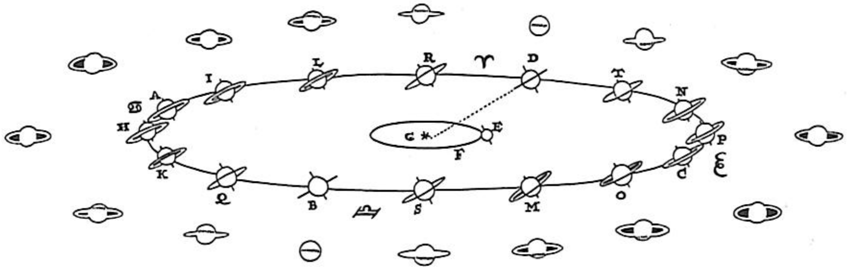
People can see more clearly if they have the right idea, as our cases of the cholera epidemic and Challenger accident suggest. Reasoning about planets in general and then developing a geometric model based on his discovery of Titan, Huygens became the first to see the rings as rings.

[2] James Elliot and Richard Kerr, *Rings: Discoveries from Galileo to Voyager* (Cambridge, 1984), p. 23. My other guides are A. F. O'D. Alexander, *The Planet Saturn* (London, 1962); and H. J. M. Bos, "Huygens, Christiaan," in Charles C. Gillispie, ed., *Dictionary of Scientific Biography* (New York, 1981), vol. 6, pp. 597–613.

Christiaan Huygens, *Systema Saturnium* (The Hague, 1659), foldout plate at pp. 34–35. The observations shown are:

I. Galileo, 1610
II. Scheiner, 1614
III. Riccioli, 1641 or 1643
IV–VII. Hevel, theoretical forms
VIII–IX. Riccioli, 1648–1650
X. Divini, 1646–1648
XI. Fontana, 1636
XII. Biancani, 1616; Gassendi, 1638, 1639
XIII. Fontana and others, 1644, 1645.





In this exquisite multiple from *Systema Saturnium*, the small inner ellipse traces Earth's annual journey around the Sun; the larger ellipse shows Saturn in orbit (some 29.5 Earth-years long) as viewed from the heavens. The outermost floating images depict Saturn as viewed through telescopes located on Earth—so that each matched pair of Saturns compares Earth-view with heaven-view. All told, we have 32 Saturns, at different locations in three-space and from the perspective of two different observers.[3] Huygens' substantive idea is to explain the periodic changes in Saturn's rings, when viewed from Earthbound telescopes. As the diagram indicates, twice each Saturn-year, the thin ring becomes oriented edgewise relative to Earth and thus disappears to our eyes—an explanation resolving a 50-year mystery, as astronomers (including Galileo) were baffled by long-run changes in the apparent shape of Saturn. Imaginative and original, this display is a classic, an exemplar of information design.

Huygens presents a series of still images in order to depict motion. To resolve such discontinuous spatial representations of continuous temporal activity, viewers must interpolate between images, closing up the gaps.[4] In the diagram above, about 1.8 Earth-years elapse between Saturns, an insignificant interruption because the depicted motion is smooth, deliberate, incremental. Representation of more abrupt and irregular motion, in contrast, demands a quicker tempo and greater density of time-sampling to build up a sequence of still images. For example, Muybridge shows 17 separate photographs to capture a few seconds of leapfrog. On the other hand, to demonstrate the theory of

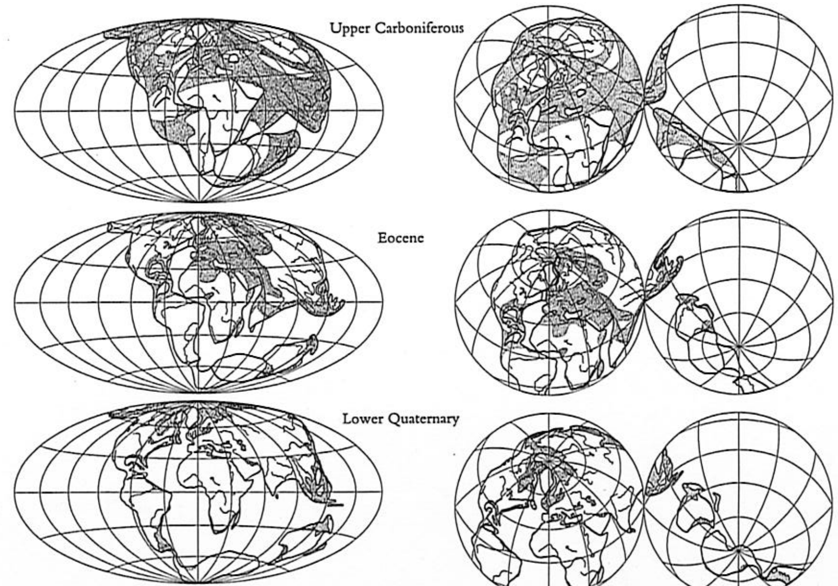
Christiaan Huygens, *Systema Saturnium* (The Hague, 1659), p. 55.

[3]On visual narratives, see Kurt Weitzmann, *Illustrations in Roll and Codex: A Study of the Origin and Method of Text Illustration* (Princeton, 1947); H. A. Groenewegen-Frankfort, *Arrest and Movement: An Essay on Space and Time in the Representational Art of the Ancient Near East* (Chicago, 1951); and Scott McCloud, *Understanding Comics* (Northampton, 1993), pp. 60–117.

[4]Below, viewers *extrapolate* to an implicit prior image, as the poor diver is poked by a rescue float. Different time-states are also suggested by the verbs (*grabbed, will flip, counterbalanced*) of the caption.

An inner tube grabbed suddenly will flip upright unless counterbalanced.

It would be better to express the moral of the diagram positively: *Grab an inner tube with both hands to keep it balanced.* From Albert Pierce, *Scuba Life Saving* (Champaign, Illinois, 1985), p. 149.

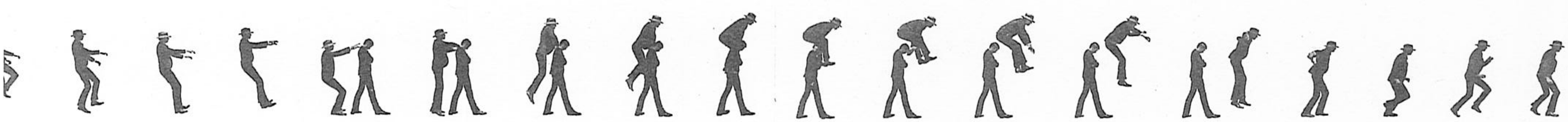


continental drift, Alfred Wegener placed projections of the Earth on a time-scale about 300 million years long, showing the original unified land mass ("Pangea") breaking up into today's continents.

For still-land images that depict movement, space replaces time as the sequencing dimension. The adjacency of images helps us to assess change and possibly rates of change within each image and between images in sequence—and we can do so at our own pace. Sequences of still images suffer the obvious (though no less important for being so) loss of the experience of the passage of time, the loss of the rates and rhythms of actual motion. In addition, that loss is sometimes magnified by a design error: many still-land multiples depicting motion omit any explicit time-scale. Dequantification all over again.

Alfred Wegener, *Die Entstehung der Kontinente und Ozeane* (Braunschweig, 1915; 4th edition, 1929), pp. 18–19. The stipled areas are shallow seas. Redrawn.

Eadweard Muybridge, *Animal Locomotion* (Philadelphia, 1887), plate 169, "Jumping over boy's back (Leapfrog)." Redrawn.



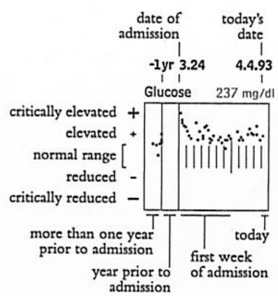
Multiples help to monitor and analyze multi-variable processes—ordinary occurrences in medicine, finance, quality control, and large-scale industrial and engineering operations. By providing a quick, simultaneous look at a continuing flow of different measurements, multiples help sort out the relevant substance from a flood of numbers.

Consider the conventional medical record, the patient's chart. For decades, medical treatment has been documented in folders stuffed with handwritten notes, laboratory reports, orders, print-outs, forms, referral letters, and an occasional identification tag from a transfused unit of blood or implanted prosthesis. For some hospitalized patients, a flow-sheet (similar to a spreadsheet) tabulates measurements; every time a reading is taken, however, another row is opened, a clumsy way to organize a data grid. Charts and flowsheets are bulky, difficult to file and retrieve, and sometimes even illegible. Medical records are gradually being computerized, making them more legible but hardly more comprehensible—since data are as easily lost in pages of print-out as in tangles of handwriting. These data dumps accumulate bits and pieces of information for administrative, regulatory, financial, legal, and clinical purposes. Largely a device for storage (a write-only memory!), the chart was not designed with the medical treatment of the patient in mind.

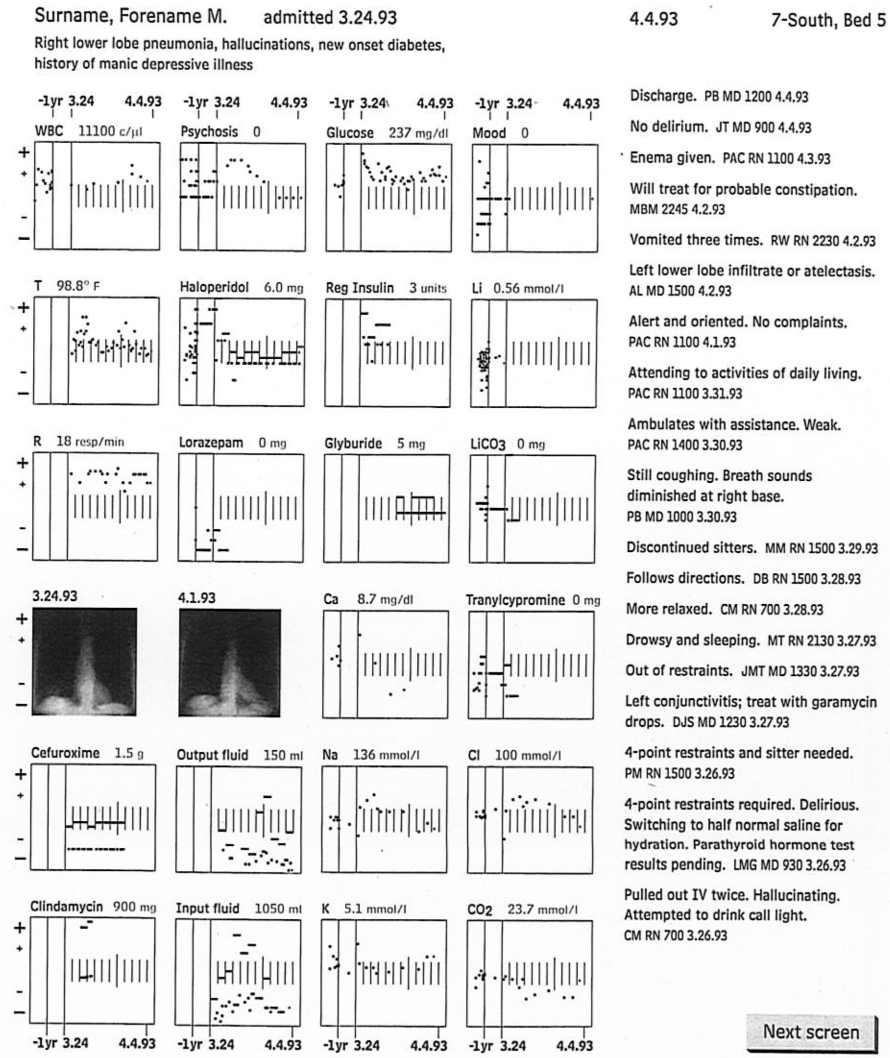
The page at right shows a *graphical* view of patient status, an overlay summary of the traditional medical record designed primarily to assist in the clinical care of the patient. Illustrated is a long and complex history, involving two medical and two psychiatric problems. Some 24 small images depict laboratory readings, medicines, and x-rays (showing an improvement in a cloudy lung). The legend at near right describes the basic graphical element in the multiple. A common horizontal time-scale, strongly emphasizing recent events, orders the flow of data. On the vertical scale, all measurements are referenced to normal limits (within the whiskered band); the most recent reading is shown both numerically and graphically (in red). Each column of multiples generally represents each medical or psychiatric problem; the lefthand column deals with pneumonia, for example. Thus data are seen in short-run and long-run contexts, and in relation to other measures (allowing, say, comparisons up and down a column between dosages and responses).

Combining overview with detail, this one-page, high-resolution set of multiples makes sense of thousands of items (the spreadsheet for this display contains 11,616 cells and 1,786 values) now scattered throughout standard medical records. Such graphical summaries will be especially helpful during case conferences or teaching exercises; all the participants, each with a copy, can quickly assess the history and treatment—with an improvement in the rate of information transfer of perhaps 10 to 20-fold compared with the standard talk talk talk presentation.[5]

This architecture—blending quantitative multiples, narrative text, and images—may prove useful for monitoring other data-rich processes.



[5] These two pages are based on Seth M. Powsner and Edward R. Tufte, "Graphical Summary of Patient Status," *The Lancet*, 344 (August 6, 1994), pp. 386–389.



Relying on the links of parallelism, well-crafted multiples provide high-resolution views of complex material. Illustrations of postage-stamp size are indexed by a category or a label, sequenced in time like the frames of a movie, or gathered along a fresh dimension not contained in each small element. For a broad range of problems in presenting numbers and images, small multiples will serve quite well. Since many slices of information are displayed within the eyespan, alert viewers may be able to detect contrasts and correspondences at a glance—uninterrupted visual reasoning. And some multiples, like good graphics of all kinds, are worth more than a glance; careful viewing may reveal subtle differences among the elements.

Fine distinctions in letterforms, for example, appear in the panel at near right: ten geometric constructions of the letter A, published from 1460 to 1529. These compass-and-rule constructions, developed in the Italian Renaissance, attempt to rationalize and make uniform the early inscriptional Roman letters (the Trajan Inscription was hand-painted and then cut into stone in 112 A.D.). The lines lay out a geometry for the systematic production of an entire alphabet. This methodical geometry is sometimes broken, however, in order to draw elegant brushlike curves of variable stroke-width; for these A's, perhaps a few of the serifs are fudged.

At far right, a redrawn panel of ten letters repairs several flaws in the original panel at near right. In the original, three A's are filled and seven are not, thereby creating two distinct—and meaningless—visual clusters (which vanish in the redrawing). Accidental communalities in design can easily induce false groupings in the eyes of viewers, who are often busy searching for visual hints that help to boil down, organize, group, and otherwise make sense of multiple images. False clusterings can result from inexpert use of color; for example, the icons of the upper computer screen here form two spatial clusters, the reds and the blues. Yet the only thing the members of each cluster have in common is the accident of their color, as viewers mistake the decorative tints for real information. Also, since multiples are distributed over time as well as space, false *temporal* clusters (the green sequence between screen 1 and screen 2) can arise as we move from image to image.[6]

The original panel of A's contains another flaw: the grids and the outlines of the letters are at the same visual level, with nearly equal line-weights throughout. In the revised panel, the construction lines are calmed down and differentiated (again, the smallest effective difference). We now see more clearly locations of the cross-bar, curls of the serifs, and thick-thin relationships among the strokes. Supplementing the redrawn letters are quantitative measures of stroke-thickness relative to the side of the square (ratios of 1:12 to 1:8 and corresponding proportions of .083 to .125), a matter of aesthetic controversy among 15th and 16th-century architects of letterforms.

Sources for original set of ten letterforms in the near-right panel: *The Alphabet of Francesco Torniello da Novara (1517)*, introduction by Giovanni Mardersteig (Verona: Officina Bodoni, 1971), shows the six Italian alphabets (three filled-in and three not, as in their first publication) with bibliography at pp. XXVII–XXVIII; Stanley Morison, *Fra Luca de Pacioli* (New York, 1933), p. 23, shows Schedel, Dürer (at 1 to 10) and Tory. Dürer (at 1 to 9) is reproduced from p. 134 of Albrecht Dürer, *Institutiones geometricae* (Paris, 1532), the first Latin edition of *Unterweysung der Messung* (Nuremberg, 1525). Mardersteig's and Morison's sources are (with variants in spelling of names): Damiano da Moyle, *Alphabetum* (Parma, 1480); Sigismondo Fanti, *Theorica et practica de modo scribendi* (Venice, 1514); Felice Feliciano, *Felice Feliciano Veronese: Alphabetum Romanum*, ed. Giovanni Mardersteig (Verona, 1960); Luca Paciolo, *Divina Proportione* . . . (Rome, 1540); Francesco Torniello, *Opera del Modo de Fare le Littere Maiuscole Antique* (Milan, 1517); Jeofroy Tory, *L'art et science de la proportion des letterres* (Paris, 1529); and Giovam Baptista Verini, *Luminario* (Tusculano, 1526).

[6] Aaron Marcus, *Graphic Design for Electronic Documents and User Interfaces* (New York, 1992), p. 86.