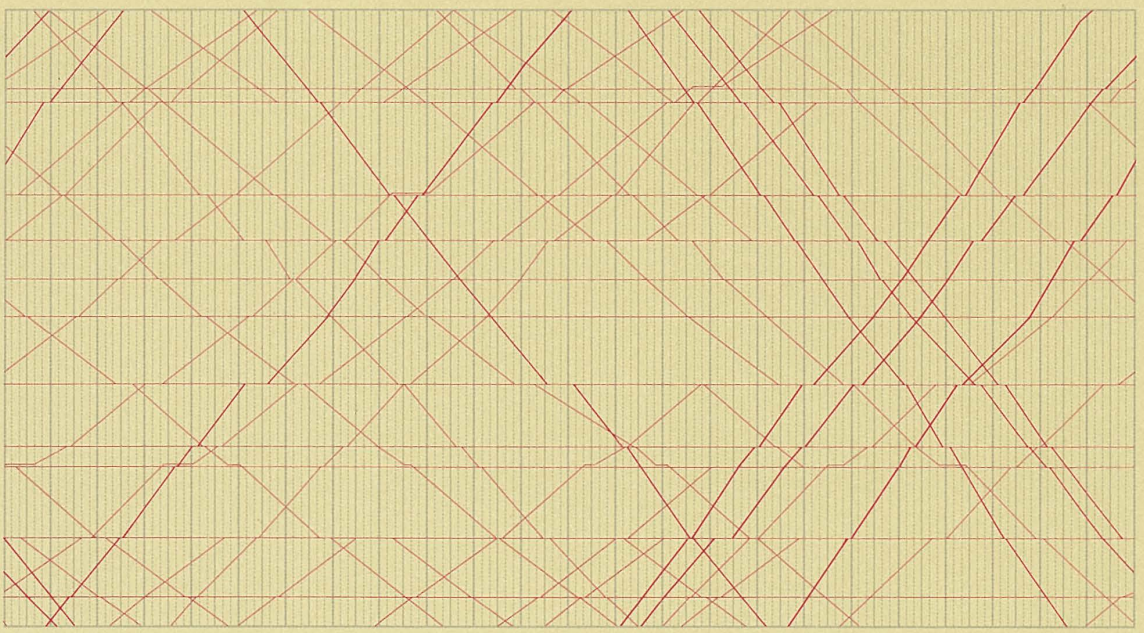
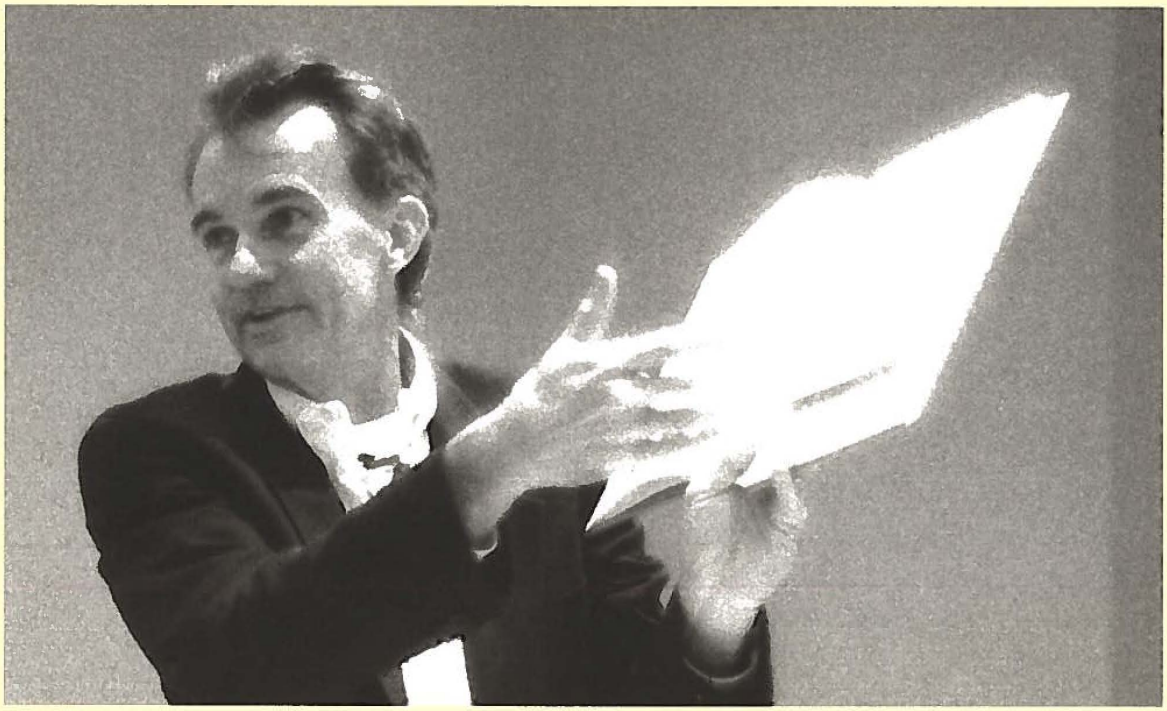


SECOND EDITION

The Visual Display of Quantitative Information

EDWARD R. TUFTE

InfoBionic, Inc.
Exhibit 1018
Page 001



GRAPHICS PRESS • CHESHIRE, CONNECTICUT

ISBN 978-0-9613921-4-7

InfoBionic, Inc.
Exhibit 1018
Page 002

Edward R. Tufte

The Visual Display of Quantitative Information

SECOND EDITION

Graphics Press · Cheshire, Connecticut

InfoBionic, Inc.
Exhibit 1018
Page 003

Copyright © 2001 by Edward Rolf Tufte
PUBLISHED BY GRAPHICS PRESS LLC
POST OFFICE BOX 430, CHESHIRE, CONNECTICUT 06410
WWW.TUFTE.COM

All rights to text and illustrations are reserved by Edward Rolf Tufte. This work may not be copied, reproduced, or translated in whole or in part without written permission of the publisher, except for brief excerpts in reviews or scholarly analysis. Use with *any* form of information storage and retrieval, electronic adaptation or whatever, computer software, or by similar or dissimilar methods now known or developed in the future is strictly forbidden without written permission of the publisher and copyright holder. A number of illustrations are reproduced by permission; those copyright holders are credited on page 197.

Printed in the United States of America *Second edition, eighth printing, April 2013*

InfoBionic, Inc.
Exhibit 1018
Page 004

Contents

PART I GRAPHICAL PRACTICE

1 *Graphical Excellence* 13

2 *Graphical Integrity* 53

3 *Sources of Graphical Integrity and Sophistication* 79

PART II THEORY OF DATA GRAPHICS

4 *Data-Ink and Graphical Redesign* 91

5 *Chartjunk: Vibrations, Grids, and Ducks* 107

6 *Data-Ink Maximization and Graphical Design* 123

7 *Multifunctioning Graphical Elements* 139

8 *High-Resolution Data Graphics* 160

9 *Aesthetics and Technique in Data Graphical Design* 177

Epilogue: Designs for the Display of Information 191

InfoBionic, Inc.
Exhibit 1018
Page 005

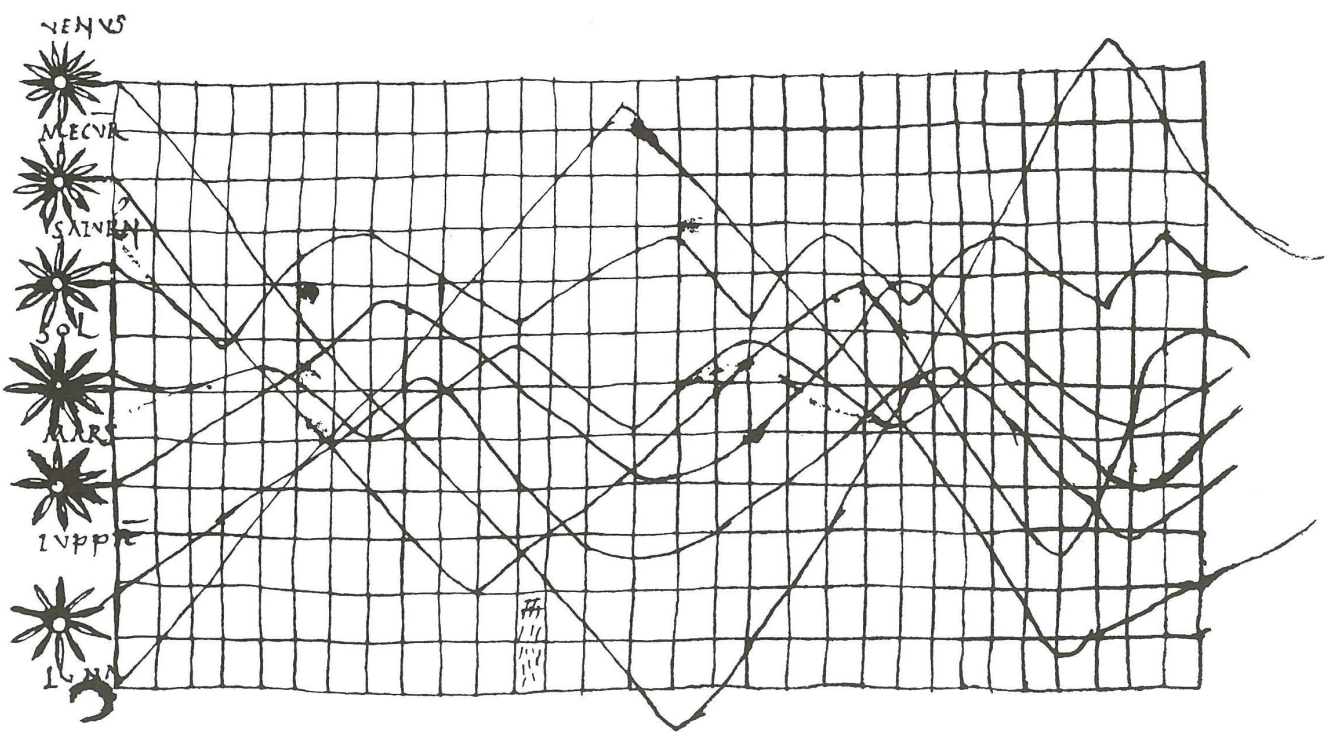
Time-Series

The time-series plot is the most frequently used form of graphic design.[8] With one dimension marching along to the regular rhythm of seconds, minutes, hours, days, weeks, months, years, centuries, or millennia, the natural ordering of the time scale gives this design a strength and efficiency of interpretation found in no other graphic arrangement.

This reputed tenth- (or possibly eleventh-) century illustration of the inclinations of the planetary orbits as a function of time, apparently part of a text for monastery schools, is the oldest known example of an attempt to show changing values graphically. It appears as a mysterious and isolated wonder in the history of data graphics, since the next extant graphic of a plotted time-series shows up some 800 years later. According to Funkhouser, the astronomical content is confused and there are difficulties in reconciling the graph and its accompanying text with the actual movements of the planets. Particularly disconcerting is the wavy path ascribed to the sun.[9] An erasure and correction of a curve occur near the middle of the graph.

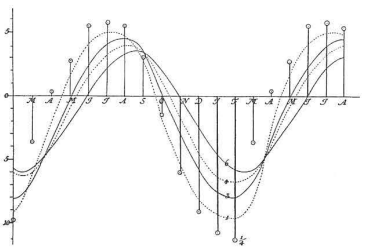
[8] A random sample of 4,000 graphics drawn from 15 of the world's newspapers and magazines published from 1974 to 1980 found that more than 75 percent of all the graphics published were time-series. Chapter 3 reports more on this.

[9] H. Gray Funkhouser, "A Note on a Tenth Century Graph," *Osiris*, 1 (January 1936), 260-262.

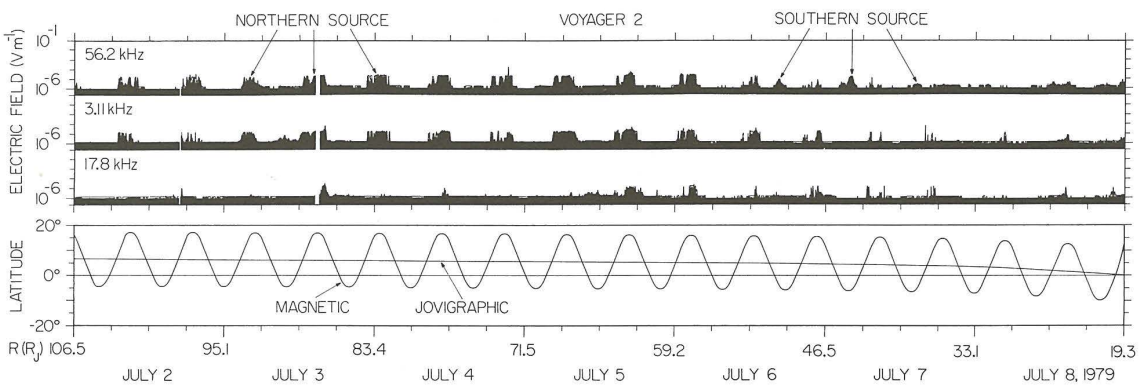


InfoBionic, Inc.
Exhibit 1018
Page 006

It was not until the late 1700s that time-series charts began to appear in scientific writings. This drawing of Johann Heinrich Lambert, one of a long series, shows the periodic variation in soil temperature in relation to the depth under the surface. The greater the depth, the greater the time-lag in temperature responsiveness. Modern graphic designs showing time-series periodicities differ little from those of Lambert, although the data bases are far larger.



J. H. Lambert, *Pyrometrie* (Berlin, 1779).

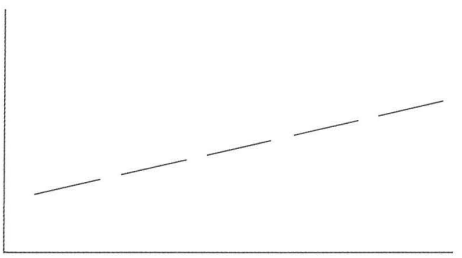


This plot of radio emissions from Jupiter is based on data collected by Voyager 2 in its pass close by the planet in July 1979. The radio intensity increases and decreases in a ten-hour cycle as Jupiter rotates. Maximum intensity occurs when the Jovian north magnetic pole is tipped toward the spacecraft, indicating a northern hemisphere source. A southern source was detected on July 7, as the spacecraft neared the equatorial plane. The horizontal scale shows the distance of the spacecraft from the planet measured in terms of Jupiter radii (R). Note the use of dual labels on the horizontal to indicate both the date and distance from Jupiter. The entire bottom panel also serves to label the horizontal scale, describing the changing orientation of the spacecraft relative to Jupiter as the planet is approached. The multiple time-series enforce not only comparisons within each series over time (as do all time-series plots) but also comparisons between the three different sampled radio bands shown. This richly multivariate display is based on 453,600 instrument samples of eight bits each. The resulting 3.6 million bits were reduced by peak and average processing to the 18,900 points actually plotted on the graphic.

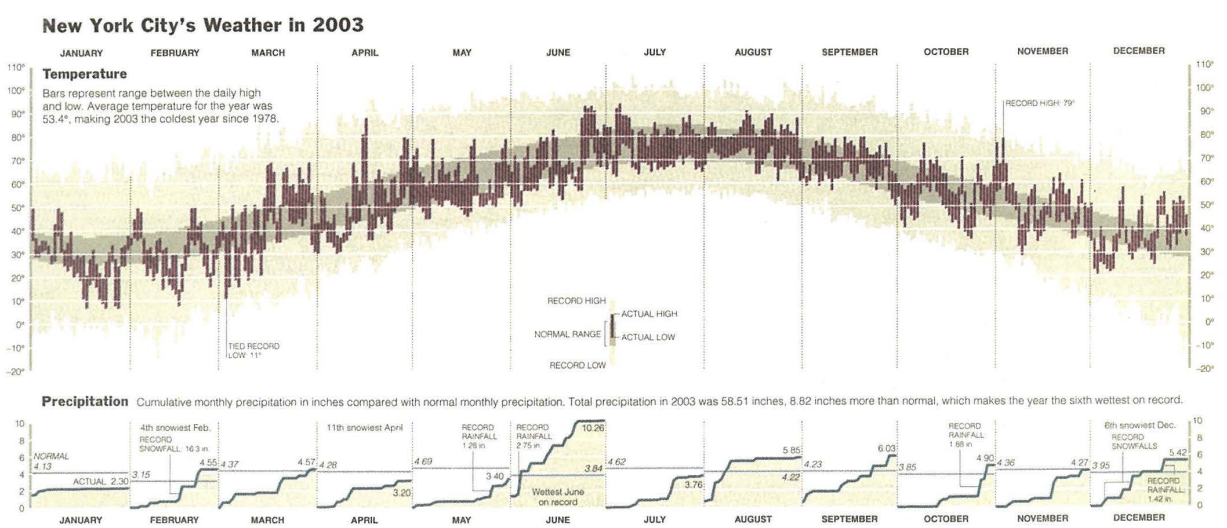
D. A. Gurnett, W. S. Kurth, and F. L. Scarf, "Plasma Wave Observations Near Jupiter: Initial Results from Voyager 2," *Science* 206 (November 23, 1979), 987-991; and letter from Donald A. Gurnett to Edward R. Tufte, June 27, 1980.

InfoBionic, Inc.
Exhibit 1018
Page 007

Time-series displays are at their best for big data sets with real variability. Why waste the power of data graphics on simple linear changes,

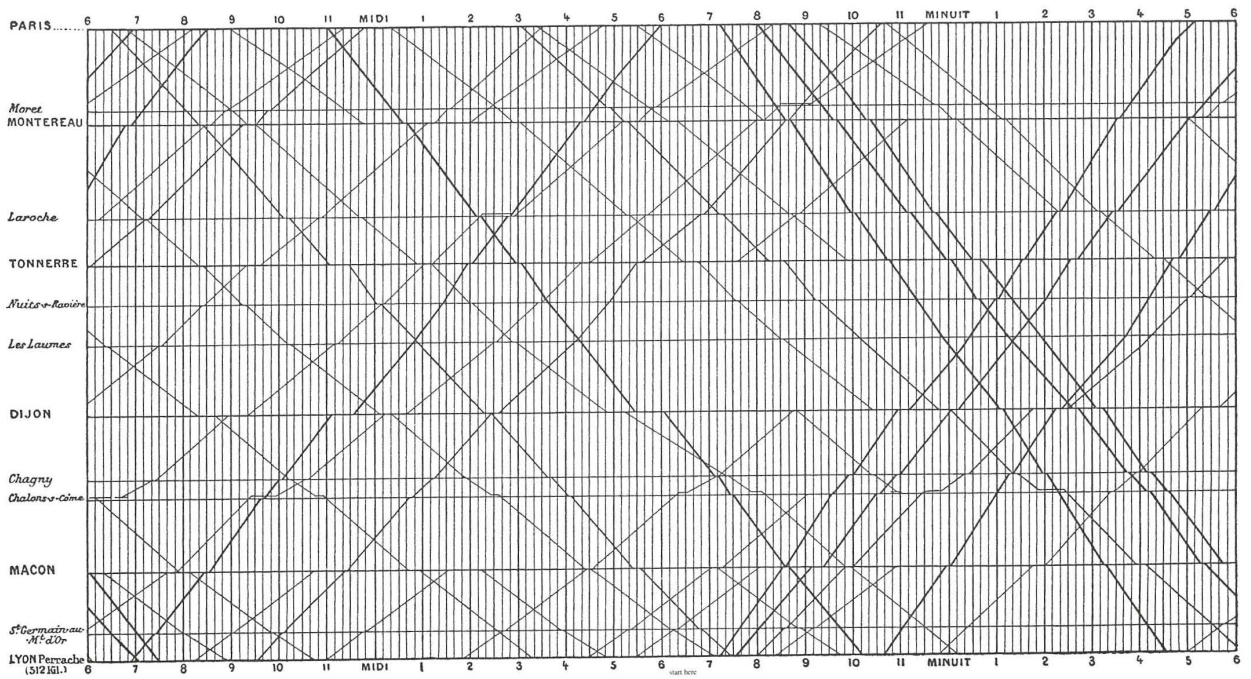


which can usually be better summarized in one or two numbers? Instead, graphics should be reserved for the richer, more complex, more difficult statistical material. This New York City weather summary for 2003 depicts 3,322 numbers. The daily high and low temperatures are shown in relation to the long-run average. The path of the normal temperatures also provides a forecast of expected change over the year; in the middle of February, for instance, New York City residents can look forward to warming at the rate of about 1.5 degrees per week all the way to July, the yearly peak. This distinguished graphic successfully organizes a large collection of numbers, makes comparisons between different parts of the data, and tells a story.



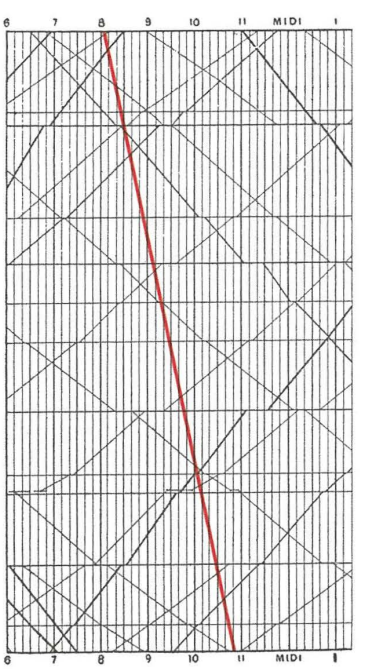
New York Times, January 4, 2004, A15.

InfoBionic, Inc.
Exhibit 1018
Page 008



E. J. Marey, *La méthode graphique* (Paris, 1885), 20. The method is attributed to the French engineer, Ibry.

A design with similar strengths is Marey's graphical train schedule for Paris to Lyon in the 1880s. Arrivals and departures from a station are located along the horizontal; length of stop at a station is indicated by the length of the horizontal line. The stations are separated in proportion to their actual distance apart. The slope of the line reflects the speed of the train: the more nearly vertical the line, the faster the train. The intersection of two lines locates the time and place that trains going in opposite directions pass each other.



In 1981 a new express train from Paris to Lyon cut the trip to under three hours, compared to more than nine hours when Marey published the graphical train schedule. The path of the modern TGV (*train à grande vitesse*) is shown, overlaid on the schedule of 100 years before:

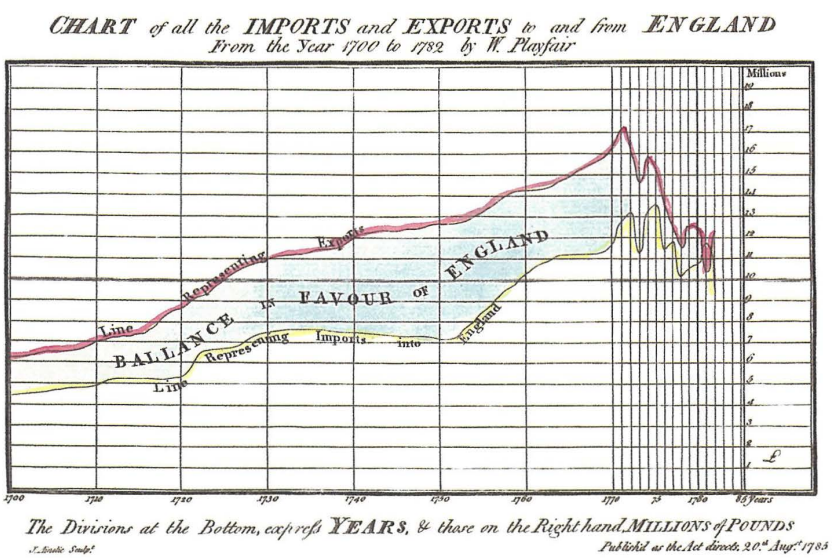
InfoBionic, Inc.
Exhibit 1018
Page 009

The two great inventors of modern graphical designs were J. H. Lambert (1728-1777), a Swiss-German scientist and mathematician, and William Playfair (1759-1823), a Scottish political economist.[10] The first known time-series using economic data was published in Playfair's remarkable book, *The Commercial and Political Atlas* (London, 1786). Note the graphical arithmetic, which shows the shifting balance of trade by the difference between the import and export time-series. Playfair contrasted his new graphical method with the tabular presentation of data:

> Information, that is imperfectly acquired, is generally as imperfectly retained; and a man who has carefully investigated a printed table, finds, when done, that he has only a very faint and partial idea of what he has read; and that like a figure imprinted on sand, is soon totally erased and defaced. The amount of mercantile transactions in money, and of profit or loss, are capable of being as easily represented in drawing, as any part of space, or as the face of a country; though, till now, it has not been attempted. Upon that principle these Charts were made; and, while they give a simple and distinct idea, they are as near perfect accuracy as is any way useful. On inspecting any one of these Charts attentively, a sufficiently distinct impression will be made, to remain unimpaired for a considerable time, and the idea which does remain will be simple and complete, at once including the duration and the amount. [pages 3-4]

For Playfair, graphics were preferable to tables because graphics showed the shape of the data in a comparative perspective. Time-

[10] Laura Tilling, "Early Experimental Graphs," *British Journal for the History of Science*, 8 (1975), 193-213.

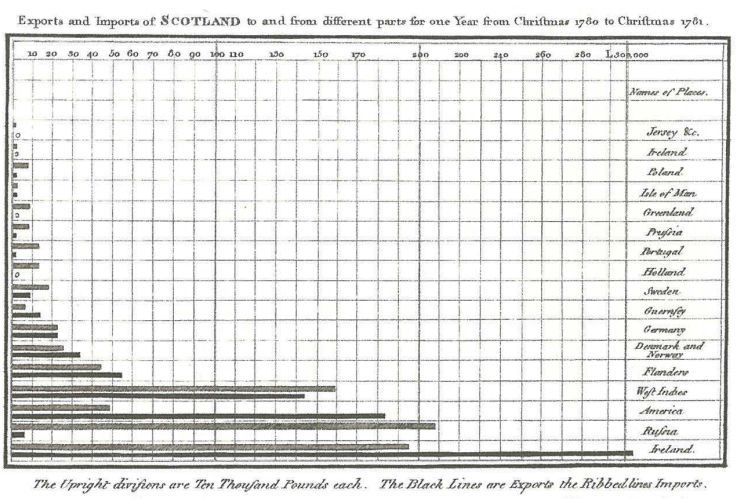


InfoBionic, Inc.
Exhibit 1018
Page 010

series plots did this, and all but one of the 44 charts in the first edition of *The Commercial and Political Atlas* were time-series. That one exception is the first known bar chart, which Playfair invented because year-to-year data were missing and he needed a design to portray the one-year data that were available. Nonetheless he was skeptical about his innovation:

> This Chart is different from the others in principle, as it does not comprehend any portion of time, and it is much inferior in utility to those that do; for though it gives the extent of the different branches of trade, it does not compare the same branch of commerce with itself at different periods; nor does it imprint upon the mind that distinct idea, in doing which, the chief advantage of Charts consists: for as it wants the dimension that is formed by duration, there is no shape given to the quantities. [page 101]

He was right: small, noncomparative, highly labeled data sets usually belong in tables.



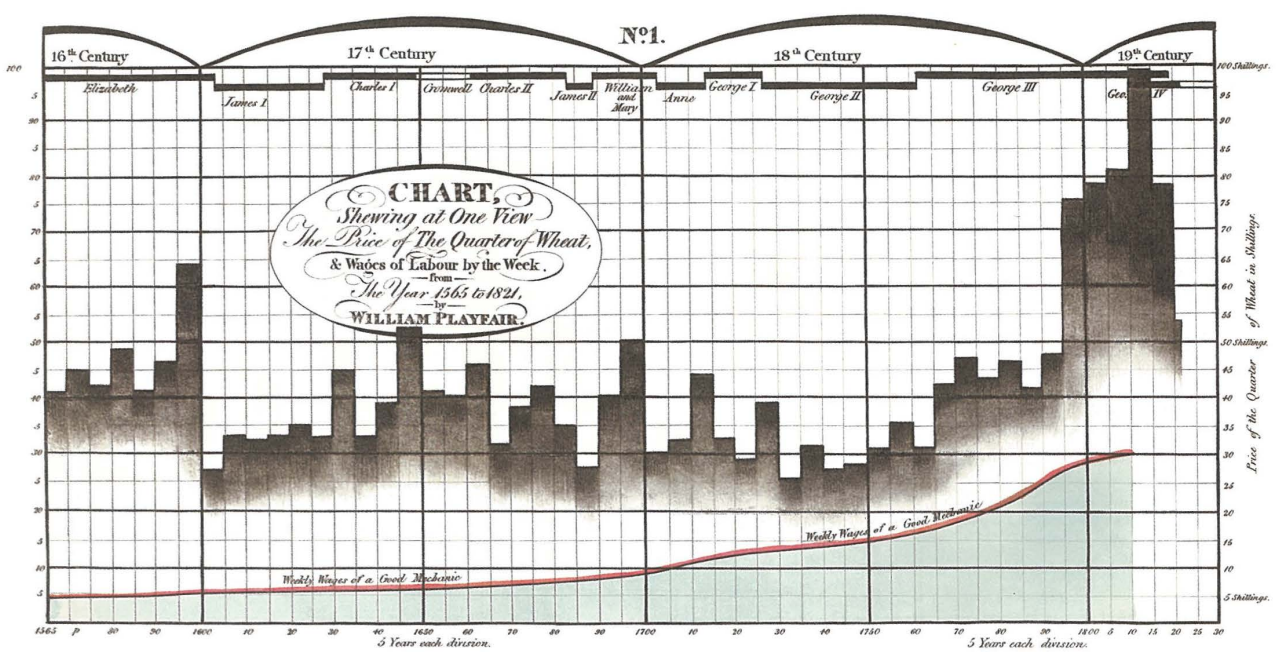
The chart does show, at any rate, the imports (cross-hatched lines) and exports (solid lines) to and from Scotland in 1781 for 17 countries, which are ordered by volume of trade. The horizontal scale is at the top, possibly to make it more convenient to see in plotting the points by hand. Zero values are nicely indicated both by the absence of a bar and by a "0." The horizontal scale mistakenly repeats "200." In nearly all his charts, Playfair placed the labels for the vertical scale on the right side of the page (suggesting that he plotted the data points using his left hand).

InfoBionic, Inc.
Exhibit 1018
Page 011

Playfair's last book addressed the question whether the price of wheat had increased relative to wages. In his *Letter on our agricultural distresses, their causes and remedies; accompanied with tables and copper-plate charts shewing and comparing the prices of wheat, bread and labour, from 1565 to 1821*, Playfair wrote:

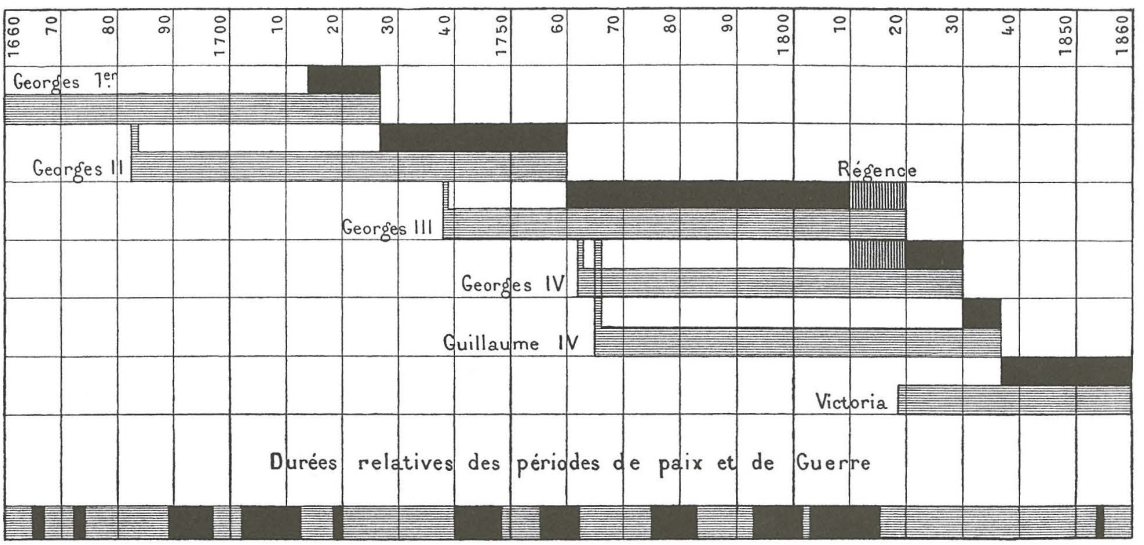
> You have before you, my Lords and Gentlemen, a chart of the prices of wheat for 250 years, made from official returns; on the same plate I have traced a line representing, as nearly as I can, the wages of good mechanics, such as smiths, masons, and carpenters, in order to compare the proportion between them and the price of wheat at every different period. . . . the main fact deserving of consideration is, that never at any former period was wheat so cheap, in proportion to mechanical labour, as it is at the present time. . . . [pages 29–31]

Here Playfair plotted three parallel time-series: prices, wages, and the reigns of British kings and queens.

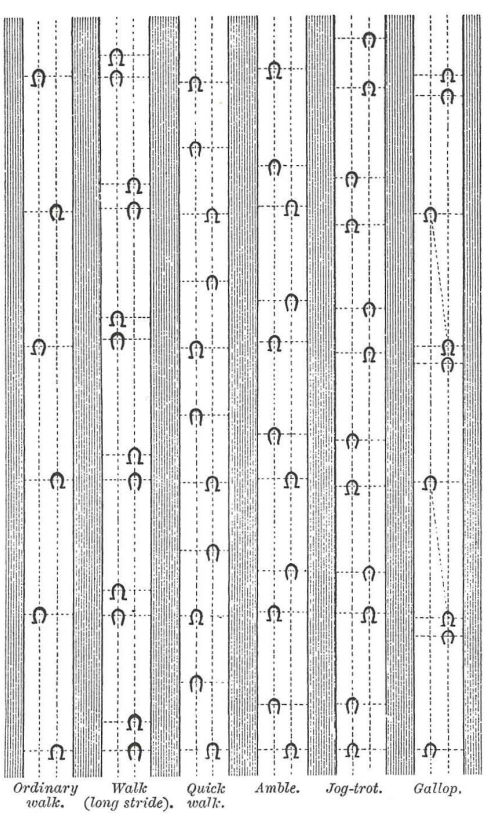


The history and genealogy of royalty was long a graphical favorite. This superb construction of E. J. Marey brings together several sets of facts about English rulers into a time-series that conveys a sense of the march of history. Marey (1830–1904) also pioneered the development of graphical methods in human and animal physiology, including studies of horses moving at different paces,

InfoBionic, Inc.
Exhibit 1018
Page 012



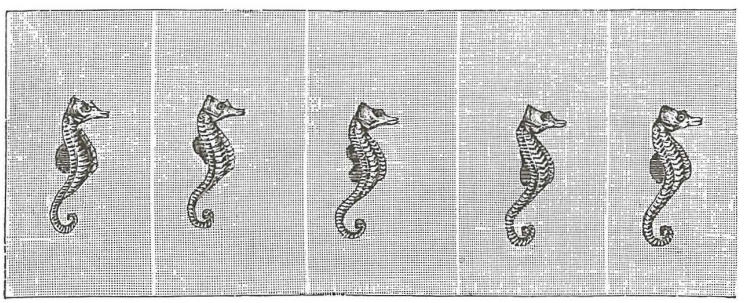
E. J. Marey, *La Méthode Graphique* (Paris, 1885), 6.

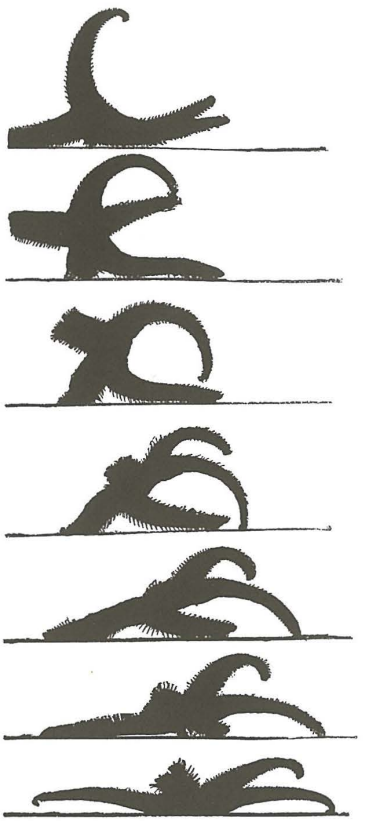


E. J. Marey, *Movement* (London, 1895). Beginning with the tracks of the horse, the time-series are from pages 191, 224, 222, 265, 60, and 61.

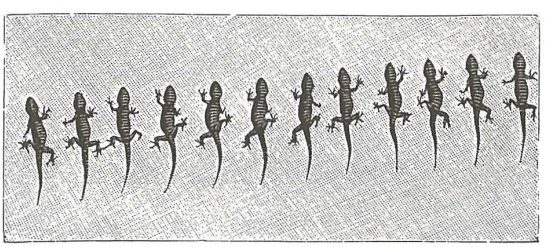
InfoBionic, Inc.
Exhibit 1018
Page 013

the movement of a starfish turning itself over (read images from the bottom upwards),



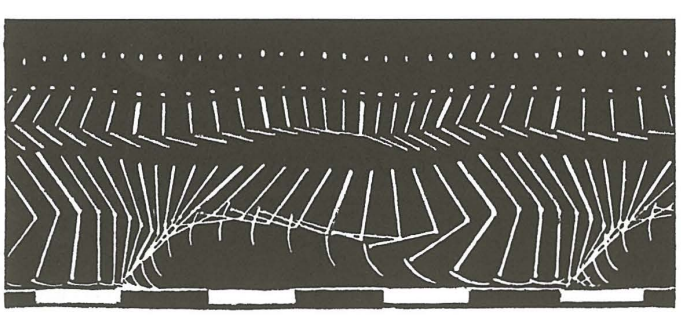


the undulations of the dorsal fin of a descending sea horse,



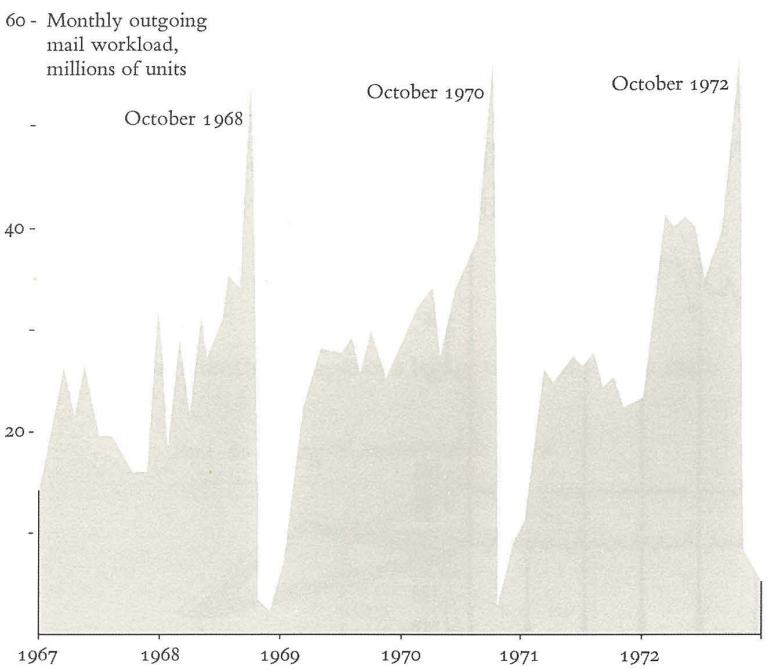
as well as the advance of the gecko.

Marey's man in black velvet, photographed in stick-figure images, became the time-series forerunner of Marcel Duchamp's *Nude Descending a Staircase*.



InfoBionic, Inc.
Exhibit 1018
Page 014

The problem with time-series is that the simple passage of time is not a good explanatory variable: descriptive chronology is not causal explanation. There are occasional exceptions, especially when there is a clear mechanism that drives the Y-variable. This time-series does testify about causality: the outgoing mail of the U.S. House of Representatives peaks every two years, just before the election day:



The graphic is worth at least 700 words, the number used in a news report describing how incumbent representatives exploit their free mailing privileges to advance their re-election campaigns:

FRANKED MAIL TIE TO VOTING SHOWN

Testimony Finds the Volume Rises Before Elections

WASHINGTON, June 1 (AP) —New court testimony and documents show that much of the mail Congress sends at taxpayer expense is tied directly to the re-election campaigns of Senate and House members. According to material filed in a lawsuit in Federal Court:

¶Senate Republicans put two direct-mail experts on the public payroll to advise them on how to use their free mailing privileges to get votes.

¶An election manual prepared for Senate Democrats refers to newsletters as a "free forum," and sets up a timetable for sending them as an integral part of a model re-election campaign.

¶Senator John G. Tower, Republican of Texas, mailed more than 800,000 special-interest letters at taxpayer expense as part of his 1972 re-election effort and received campaign volunteer offers and donations in response.

¶Senator Jacob K. Javits, Republican of New York, gave written approval in 1973 for a tax-paid mail program intended to better his image and pay off at the polls. He focused his mail on areas where he needed votes.

¶The volume of "official" Congressional mail rises in election years and peaks just before the general election.

None of this activity necessarily violates any law or regulation, since Congress has wide discretion in the use of tax-paid mail. Congress gave itself the right to send official mail at Government expense at the founding of the republic, and only Congress polices against abuses of the free mailings.

Complaints of political use of the free-mailing privilege, called the franking privilege, are heard every election year. Recently, however, the volume and cost of franked mail has multiplied. A new Federal law will limit what out-of-office challengers can spend to unseat incumbents.

In 1972, Congress passed a law prohibiting mass franked mailings within 28 days before an election. The sponsor of that legislation, Representative Morris K. Udall, Democrat of Arizona, said in an interview that further changes were needed to curtail political abuse of the frank.

Mr. Udall urged a 60-day pre-election cutoff for mass mailings and said he favored closing a loophole that recently allowed defeated Representative Frank M. Clark, Democrat of Pennsylvania, to send a franked newsletter to his old constituents after he had left office. Mr. Clark is seeking to regain his old post.

Practice Documented

Seldom has the political use of franked mail been so well documented as in recent testimony and documents filed in a Federal Court by Common Cause, the lobby group, which is suing for an end to tax-financed mass mailings by Congress.

For example, Joyce P. Baker, a political mail specialist, said in a 1973 job proposal that she wanted to set up direct-mail programs for Republican Senators using franked mail.

"The purpose of such a program is to help an incumbent Senator get re-elected," she said.

She was put on the Senate payroll at $18,810 a year in 1973 and 1974 and testified that during that time she aided Republican Senators Robert J. Dole of Kansas, Peter H. Dominick of Colorado, Charles McC. Mathias Jr. of Maryland

Another political mail specialist, Lee W. MacGregor, wrote a proposal for the use of franked mail by his chief, Senator Javits, in 1973.

"The over-all objective of the franked mail program can be to get the recipient of the mail to identify positively with a particular stand you have taken or a bill you have introduced; the kind of identification that can be translated into a vote at the polls on election day" Mr. MacGregor said.

Mr. Javits was out of the country and could not be reached. His administrative assistant, Donald Kellerman, defended the use of franked mail.

"It is a standard device to let voters, not voters but citizens, know what the Senator is doing here in Washington, he said.

Senator Tower's use of franked mail in his 1972 campaign was documented by memorandums.

Tom Loeffler, a high-ranking campaign aide, wrote in a memorandum dated Oct. 27, 1972, that during the campaign Senator Tower had sent "31 special interest letters totaling approximately 803,333 franked mailings."

Mr. Tower was not available for comment. His administrative assistant, Elwin Skiles, said the Senator's use of franked mail in 1972 was within the law, and he defended the free-mailing privileges.

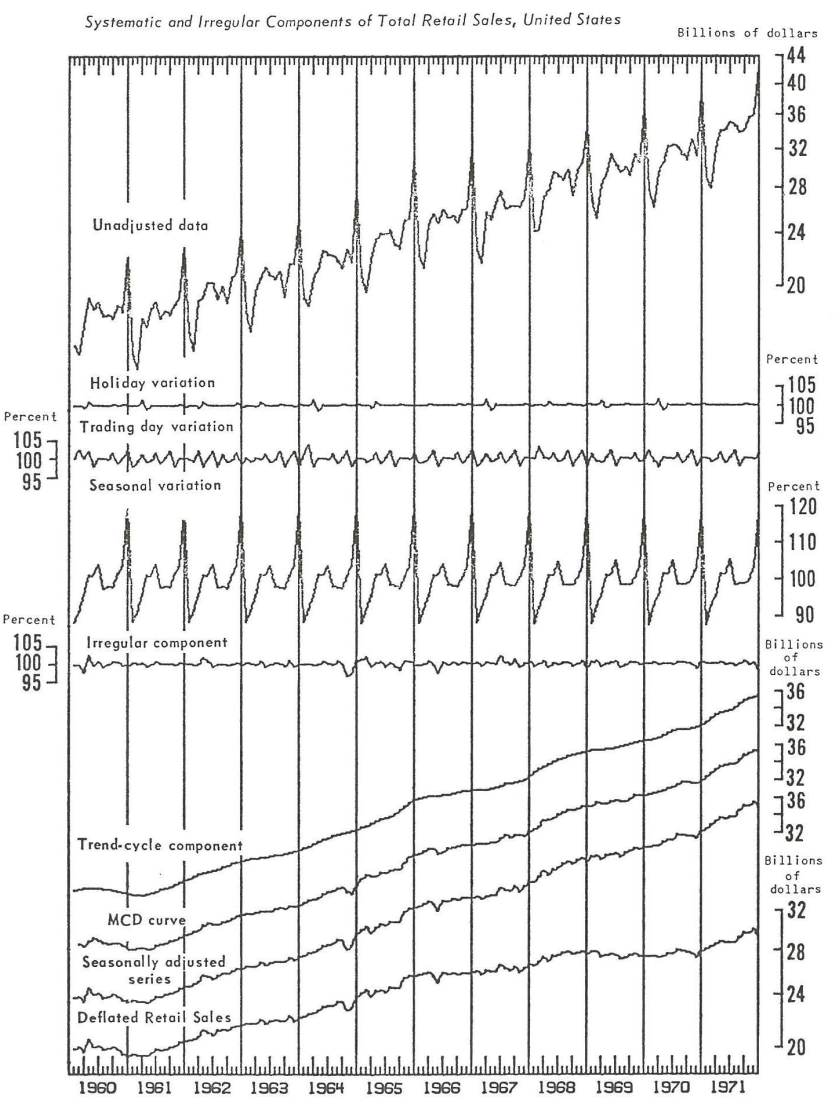
Postal Service figures show that in the 12 months before November, 1973, Congress sent 222.9 million franked pieces of mail. But in the next 12 months, covering the election season of 1974, Congress sent 350.6 million, a jump of 57 per cent about what's happening," Mr. Skiles said.

InfoBionic, Inc.
Exhibit 1018
Page 015

Time-series plots can be moved toward causal explanation by smuggling additional variables into the graphic design. For example, this decomposition of economic data, arraying 1,296 numbers, breaks out the top series into seasonal and trading-day fluctuations (which dominate short-term changes) to reveal the long-run trend adjusted for inflation. (Note a significant defect in the design, however: the vertical grid conceals the height of the December peaks.) The next step would be to bring in additional variables to explain the transformed and improved series at the bottom.[11]

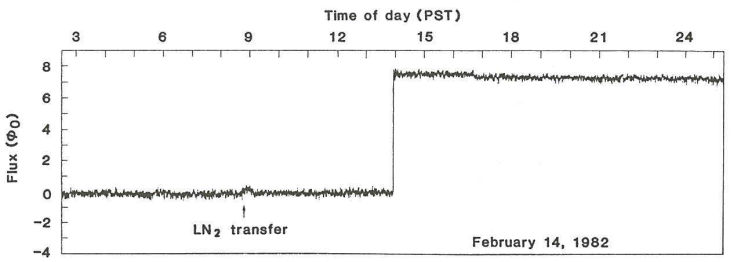
[11] See William S. Cleveland and Irma J. Terpenning, "Graphical Methods for Seasonal Adjustment," *Journal of the American Statistical Association* 77 (March 1982), 52-62.

Julius Shiskin, "Measuring Current Economic Fluctuations," *Statistical Reporter* (July 1973), 3.



InfoBionic, Inc.
Exhibit 1018
Page 016

Finally, a vivid design (with appropriate data) is the before-after time-series:

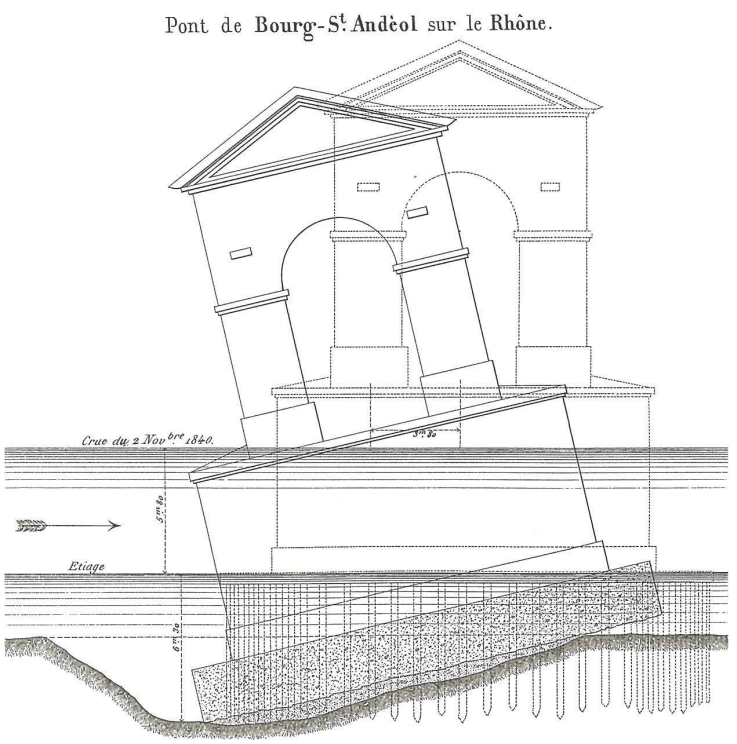


A monopole?

Cabrera's candidate monopole signal looms over a disturbance caused by a liquid nitrogen transfer earlier in the day. The jump in magnetic flux through the superconducting detector loop (or equivalently, the jump in the loop's supercurrent) is just the right magnitude to be a monopole. Moreover, the current remained stable for many hours afterward.

M. Mitchell Waldrop, "In Search of the Magnetic Monopole," *Science* (June 4, 1982), 1087.

And before and after the collapse of a bridge on the Rhône in 1840:



Charles Joseph Minard, "De la Chute des Ponts dans les grandes Crues," (October 24, 1856), Figure 3, in Minard, *Collection de ses brochures* (Paris, 1821–1869), held by the Bibliothèque de l'École Nationale des Ponts et Chaussées, Paris.

InfoBionic, Inc.
Exhibit 1018
Page 017