THE HISTORY AND FUTURE OF GRAPHICS IN STATISTICS*

James R. Beniger and Dorothy L. Robyn
University of California, Berkeley

The scientific enterprise might be defined as the recasting of individual experience into collective, quantifiable imagery. Throughout the development of science, visual images and numbers have served, side by side, in such forms as coordinate systems and line graphs, histograms and scatterplots. If mathematics reigns as the Queen of Science, then quantitative graphics must rank among her most valuable handmaidens.

Systematic visualization did not begin with modern science, of course, but traces its origins to the dawn of socially-constructed reality. The earliest known map, extant on a clay tablet dated at 3800 B.C., depicts all of Northern Mesopotamia with conventions and symbols still familiar today. From about 3200 B.C., Egyptian surveyors abstracted their lands in terms of coordinates not unlike the Cartesian system still in use. By the 10th century, medieval astronomers depicted planetary movements as cyclic lines on spatial-temporal grids, diagrams strikingly similar to modern line graphs (see 45 for an example).

Despite the central role which collective, quantifiable imagery has played throughout the development of Western thought, there exists only a single monographic treatment of the subject in English (46). This borrows heavily from a French work (48) published nearly a century ago. Except for some renewal of interest in quantitative graphics among historians of statistics (49,50), visual forms remain virtually unnoticed by historians and sociologists of knowledge, in general, and of science, in particular. It is this oversight which the present paper, part of a larger effort in a number of areas (42,43,44), is intended to help correct.

Spatial Organization and Analysis

The problem of spatial organization, of using space to locate--and to assist analyses of-- multiple measurements and multivariate data points, dominated quantitative graphic development during the 17th and 18th centuries. The problem arose with the first stirrings of the Industrial Revolution, in a spate of new measuring devices: the air and water thermometer (c. 1590), micrometer (1636), barometer (1643), pendulum clock (1656), mercury thermometer (1714), etc. Contributions by Descartes, Fermat and other French mathematicians to analytic geometry, plus the reestablishment of Cartesian coordinates in mathematics, provided the basic analytic tools.

In 1686, 43 years after the barometer's invention, and 39 years after Descartes' famous Appendix on analytic geometry (2), Sir Edmund Halley published a Cartesian plot of barometric pressure vs. elevation above sea level(3), the first known analysis of empirical data using a scatterplot.

With such an impressive beginning, it might be reasonable to expect that Cartesian coordinates and analytic geometry became the dominant paradigms for spatial organization and analysis of data by the early 18th century. After an exhaustive search of 18th century journals and texts, however, Tilling concludes that "the use of experimental graphs, either with or without subsequent analysis, never became commonplace in that age" (50, p. 194).

One reason is that coordinate plotting and graphical analysis had major rivals in statistical tables and tabular inference. Tables began to appear in print in the early 1600's. Just as the Cartesian approach came to dominate mathematics, tabular inference captured the social and applied sciences. These alternative approaches to spatial organization and analysis were not reconciled until the 19th century.

Nothing illustrates the obsession of early experimental scientists for tabular data -- and their disregard for graphical plotting and analysis--better than the history of automatic recording devices. Between 1660 and 1800, scores of different mechanical recorders were invented that produced moving line graphs of various natural phenomena: temperature, barometric readings, wind speed and direction, tidal movements, etc. These automatic graphs were considered useless for analysis, and were routinely translated into tabular logs (the literature is reviewed in 47). By the 19th century, after graphical analysis came to be appreciated, scientific journals recorded painstaking graphing and linear extrapolation of data--much of which had originally come from machine-produced line graphs only decades earlier.

The dominance of tabular description was largely due to a vociferous movement of social scientists, which formed under the catchphrase <u>Die Tabellen-Statistik</u> in Germany in the early 17th century, and which came to be known as "Political Arithmetic" in Britain after 1687. The movement took impetus from the mounting collection and publication of state statistics or <u>Staatenkunde</u>--on population, land and agricultural production -- for the purpose of taxation in the new nation states of Europe.

The eventual triumph of coordinate plotting and graphical analysis is well-documented in the commercial development of graph paper. Rectangular grid paper was first offered for sale by a Dr. Buxton in London in 1794. The first appearance of this paper in published research came in 1800, in an article on barometric variations in <u>Philosophical Magazine</u> (24), which included an advertisement for Buxton's product. Herschel made ingenious use of plotted data to calculate the elements of the elliptical orbits of double stars, and his 1832 paper on the subject included a ringing endorsement of graph paper (15, pp. 171-72). Lalanne introduced both a logarithmic grid (20) and polar coordinates (19) to the French Academy in 1843. Twenty years later, Jevons developed the use of semi-logarithmic paper in England (17), and in 1879 he included the first published instructions on the uses of graph paper in the third edition of his <u>Principles of Science</u> (18). In 1883, the British government issued the first patent on logarithmic paper.

Graphical methods also received a boost, as the dominant paradigm for spatial organization and analysis of empirical data, from the parallel development of statistical maps, an application for coordinate plotting that could not be duplicated by tabular presentation. In 1701, Halley again took the lead, publishing the first map with empirical

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data points, lines of magnetic declination gathered for all navigated waters of the world (5). In 1775, Charpentier published the first geological map, on which he plotted the distribution of various soils and minerals. Seven years later, using similar techniques, Crome published the first of his several geographical plots of demographic, political and economic statistics (1). Minard was the first to plot statistical symbols -- circles, squares and small bar graphs proportional to coal production -- on a map published in 1851 (22).

Discrete Comparison and Continuous Distribution

With the development of descriptive state statistics or Staatenkunde arose the problem of discrete quantitative comparison. Both tables of statistics in general, and comparative political data in particular, suggested the possibility of graphical comparison, especially for the growing volume of atlases and chartbooks intended for mass consumption. The first breakthrough in discrete comparison came in 1765, when Joseph Priestley published the first of his several time-line charts (8), which used individual bars to compare the life-spans of some 2,000 celebrated people.

Priestley's time-lines proved a commercial success and popular sensation, and directly inspired William Playfair's invention of the bar chart, which first appeared in his Commercial and Political Atlas (6), published in 1786. Ironically, Playfair was driven to his invention by lack of data; with the single exception, all of his other plates were line graphs or surface charts, the only published appearance of these forms in the 18th century (50, p. 199).

In the next 15 years, Playfair came to recognize the importance of his contribution. In 1801, he increased the inventory of discrete comparison with

EARLY DEVELOPMENTS IN QUANTITATIVE GRAPHICS

c. 3200 B.C.	Coordinate systems to locate points in real space --Egyptian surveyors
10-11th cent. A.D.	Curves on time grid(planetary orbits) --unknown transcriber of commentary of Macrobius on Cicero's In Somnium Scipionis
12-13th cent.	Musical notation as true time series, with neumes (corresponding to notes) of fixed duration, introduction of bars to mark equal numbers of beats -- Franconian reform, following Franco of Cologne, Ars Cantus Mensurabilis
c. 1350	Proto-bar graph (of theoretical function)--Nicole Oresme (French mathematician)
early 17th cent.	Tables of empirical data -- Die Tabellen Statistik (Germany)
1620	Systematic graphic computation with scale of numbers (forerunner of slide rule, nomography)--Edmund Gunter (Eng. astronomer)
1637	Coordinate system reintroduced in mathematics, analytic geometry, to establish relationship between curve and equation --René Descartes (French)
c. 1660	Automatic recording device (weather-clock, producing moving graph of temperature)--Wren (Eng.)
1686	Bivariate plot of observations (barometric reading vs. height), graphical analysis of empirical data--Edmund Halley(Eng.)
1693	Mortality tables--Halley
1701	Isobar map (lines of magnetic declination, world) --Halley
1712	Literal line graph, inspired by nature of observation (section of hyperbola, formed by capillary action of colored water between two glass plates)--Francis Hauksbee (English)
1724	Abstract line graph (of barometric observations), not analyzed -- Nicolaus Cruquius
1752	Contour map -- Phillippe Buache (French)
1754	Hypothetical mortality curve -- Jean Phillippe Loys de Cheseaux (French)
1760	Curve-fitting and interpolation from empirical data points--J.H. Lambert (German)
1763	Graph of beta density-- Thomas Bayes (English)
1765	Theory of measurement error as deviations from regular graphed line --J. H. Lambert
	Historical time lines (life spans of 2,000 famous people, 1200 B.C. to 1750 A.D.); quantitative comparison by means of bars -- Joseph Priestley (English chemist)
1767-1796	Repeated systematic application of graphical analysis (line graphs applied to empirical measurements)--J.H. Lambert
1774	Graph of density functions -- Pierre Simon de Laplace (Norman)
1775	Geological map (showing distribution of soils, minerals) -- Charpentier (French)
1779	Graphical analysis of periodic variation (in soil temperature)--Lambert
1782	Statistical map --A.W.F. Crome (Professor of Political Economy and Statistics , University of Giessen, Germany)
1785	Superimposed squares to compare areas (of European states) --A.W.F. Crome
1786	Bar chart --William Playfair (English) , Commercial and Political Atlas
1792	Word "chart" for data arranged in graphic or tabular form
1794	Printed coordinate paper -- a Dr. Buxton (English)
1795	Multi - number graphical calculation (contours applied to multiplication table) -- Louis Ezéchiel Pouchet (French manufacturer)
1796	Automatic recording of bivariate data (pressure vs. volume in steam engine), " Watt Indicator " (pressure gauge produced horizontal motion in pen, piston in cylinder added vertical motion) --John Southern and James Watt (English), device kept secret until 1822

two new forms: the pie chart and circle graph (published in 25). Alexander von Humboldt, acknowledging Playfair's influence, combined the bar and pie chart ideas in the subdivided bar graph, first published in 1811 (16).

By the 1820's, a steadily increasing number of the scholarly publications of Europe contained graphs that described and compared (but did not analyze) empirical measurements of a wide range of natural and social phenomena. During the period 1830-35, graphical analysis of natural phenomena finally emerged as a regular feature of scientific publication, particularly in England.

The 1820's and 30's also brought new breakthroughs in the graphical problem of representing continuous distribution. This problem was central to two comparatively new fields: abstract probability theory and vital statistics. Although Halley published the first scientifically-constructed mortality tables in 1693 (4), he apparently never attempted a graphical analysis of his figures. The French mathematicians Loys de Cheseaux and d'Alembert graphed hypothetical curves of mortality, in the mid-18th century, but did not base their curves on actual data--though accurate mortality data had existed for some 60 years.

It appears that the graphics of spatial location lacked two ideas -- more obvious in comparative graphics--that were essential to the representation of continuous distributions. One was the notion of a cumulative distribution as the graph of change in discrete quantities in an ordered sequence, the other was the concept of a continuous curve as the limit of ordered categories represented in the area under the curve.

A breakthrough in the first area was made by J. B.J. Fourier in 1821 (11). Fourier began with a bar graph representing the population of Paris by age groupings, then placed the bars one atop the other to form the ordinate of a line graph of a cumulative frequency distribution (given the name "ogive" by Galton in 1875).

A breakthrough in the other conceptual area came with the development of the histogram. In 1818, the German astronomer Bessel published a graphic table which employed numerals as in a histogram (9). The French mathematician Guerry applied Playfair's bar chart idea directly to continuous variables like age and time, for which he had data in ordered categories, and published histograms suggestive of various theoretical curves (14).

By mid-19th century, graphics had become an accepted part of the statistical discipline. The Third International Statistical Congress, meeting in Vienna in 1857, debated various graphic methods (10), and also organized the first exhibition display of graphs and cartograms. Statistical diagrams were introduced in school textbooks by the Frenchman Levasseur in 1868 (21). In 1872, the U.S. Congress appropriated the first money for a graphical treatment of statistical data, the cartograms of Ninth Census data which appeared in Statistics of Wealth and Public Indebtedness (26). Francis A. Walker, Superintendent of the Census, introduced two graphical forms--the age pyramid and the bilateral frequency polygon--in the Statistical Atlas published in 1874 (28).

Multivariate Distribution and Correlation

The rapid development of statistics in the latter half of the 19th century generated a new graphical problem: the representation of multivariate distributions and correlations. This problem was particularly crucial to vital statistics, which had need to treat interrelationships among at least three variables: population, age and time.

Léon Lalanne, French engineer and pioneer in mechanical computation, was first to reconstruct a three-way table as a two-dimensional contour map (19), published in 1845. Inspiration for Lalanne's idea came from nomographic tables, then essentially multiplication tables in contour form, which the French manufacturer Louis Pouchet published in 1795 (7), and which had been adopted by the French Artillery.

In 1869, Zeuner published a system that represented demographic trends as surfaces with three coordinates (29). Using axonometric projection, any "slice" of this surface, including 45-degree slices representing the history of various cohorts, could be shown in two dimensions. Ten years later, Luigi Perozzo, cartographic engineer for the Italian State Department of Statistics, produced a colored relief drawing (named a "stereogram") of Zeuner's theoretical surface, but based on actual data from the Swedish censuses of 1750-1875.

Lalanne had speculated that his contours of tables might be applied to geographical distributions, and 30 years later, in 1874, Vauthier published a map of Paris with contour lines showing densities of population (27). Galton cited the work of both Lalanne and Vauthier as inspirations for his normal correlation surface, published in 1886 (12). Two years later, Galton determined a coefficient of correlation by graphic means (13). The three-dimensional surfaces of Galton and Perozzo became favorites of instructors in probability theory and vital statistics, respectively, and--in various constructions of pasteboard and plaster of Paris--were standard equipment in statistical laboratories well into the 20th century.

Modern Developments

By the middle of the 20th century, interest in social and applied statistics in general, and graphical methods in particular, appeared to wane somewhat. Academicians increasingly turned their energies to theoretical concerns. This trend did not begin to reverse again until the mid-1960's, when developments in computer technology made possible the manipulation and analysis of large, multivariate data sets. Accompanying the renewed interest in data analysis was the development of computer graphics hardware and software, and advances in high-speed printing, xerography, microfilming, etc.

In the past 15 years, a spate of new quantitative graphical forms, which begin to exploit the modern technologies, have appeared in the technical literature of a variety of disciplines. As examples, one can cite Anderson's circular glyphs (30), the triangles of Pickett and White (36), Bachi's "graphical rational patterns" (32), the irregular polygons devised by Siegal and his collaborators (37), Andrews' Fourier form for generating multivariate plots (31), Chernoff's cartoons of human faces to represent multivariate data (34), and the color-coded bivariate matrix developed by the U.S. Bureau of the Census (33). John Tukey's various innovations for exploratory data analysis (39) seem particularly appropriate for the interactive capabilities of computer graphics, and have already been adapted for that purpose in various routines developed by the National Bureau of Economic Research.

The future of statistical graphics might be expected to lie in solutions to those problems generated or made tractable by computer and associated technologies. These problems include:

NINETEENTH CENTURY DEVELOPMENTS IN STATISTICAL GRAPHICS

1800 Use of coordinate paper in published research (graph of barometric variations) —Philosophical Magazine, Vol. 7, p. 357

Idea for continuous log of automatically recorded time-series graphs (temperature and barometric pressure) --A. Keith (English)

1801 Pie chart, circle graph-- Wm. Playfair (English), Statistical Breviary

1811 Subdivided bar graph --F. H. Alexander von Humboldt (German)

1818 Graphic table, employing numerals as in a histogram -- Friedrich Wilhelm Bessel(German astronomer)

1819 Cartogram (map with shadings from black to white, showing distribution and intensity of illiteracy in France)--Charles Dupin (French geometer, statistician)

1820's An ever increasing number of scholarly publications begin to contain graphs which describe (but do not analyze) natural phenomena like magnetic variation, weather and tides

1821 Ogive or cumulative frequency curve (inhabitants of Paris by age groupings for 1817)--J.B.J. Fourier (French)

1828 Mortality curves from empirical data (for Belgium and France) --A. Quetelet (Belgian statistician)

1830-1835 Graphical analysis of natural phenomena begins to appear on a regular basis in scholarly publications, particularly in England

1831 Graph of frequency distribution--Quetelet

1832 Curve-fitting to scatterplot; advocacy of graph paper as standard tool of science --J.F.W. Herschel (English)

1833 Histogram (crimes by age groupings, and by months) --A.M. Guerry (French)

1833 Rank lists , with lines showing shifts in rank order between categories (shifts in rank of crimes from one age group to the next)--A.M. Guerry

1838 Published graph of normal curve--Augustus De Morgan (English probabilist)

1841 Graph in Journal of London Statistical Society (established 1837)

1843 Logarithmic grid -- Léon Lalanne (French engineer)

Polar coordinates (frequency of wind directions)--Lalanne

Contour map of table(temperature x hour x month) --Lalanne

1846 Results of urn schemata as symmetrical histogram, with limiting normal curve--Quetelet

1847 Statistical map (tone wash) in Journal of London Statistical Society

1851 Map incorporating statistical diagrams (circles proportional to coal production) --Charles Joseph Minard (French)

1852 Graphics used in lawsuit (Germany)

1857 Discussion of graphical methods before International Statistical Congress --Third, in Vienna

Exhibition display of graphs and cartograms -- Third International Statistical Congress, Vienna

Polar area charts, known as "coxcombs" --Florence Nightingale (English), in anonymous publication for campaign to improve sanitary conditions of army

1863 Semi - logarithmic grid (percentage changes in commodities) -- S. Jevons (English)

1868 Three-dimensional population surface or "stereogram," with axonometric projection to show curves of various "slices"--Gustave Zeuner (German)

1868 Statistical diagrams in a school textbook (geography) -- Émile Levasseur (French), La France, avec ses Colonies

1872 U.S. Congressional appropriation for graphical treatment of statistics

Use of statistical graphics by U.S. government in census reports (cartograms of Ninth Census data)--Statistics of Wealth and Public Indebtedness

Classification of statistical graphic treatments by form--H. Schwabe(Ger.)

1874 Age pyramid (bilateral histogram) , bilateral frequency polygon --Francis A. Walker (Superintendent of U.S. Census), Statistical Atlas of U.S. Based on Results of Ninth Census

Population contour map (orthographic projection, of Paris) --L.L. Vauthier (French), cited by Galton as inspiration for normal correlation surface

1879 Stereogram (three-dimensional population pyramid) modeled on actual data (Swedish census , 1750-1875)--Luigi Perozzo (Italian)

Published instructions on how to use graph paper -- S. Jevons (Eng.), Principles of Science, 3rd Ed.

1883 Patent issued on logarithmic paper --England

1884 Pictogram--Michael George Mulhall (English) , Dictionary of Statistics

1885 Normal correlation surface--Galton, "Regression towards Mediocrity in Hereditary Structure"

1888 Correlation "coefficient" by graphic means--Galton

1895 Word "histogram" -- Karl Pearson (English) , lectures on graphical representation in statistics

1899 Idea for "log-square" paper ruled so normal probability curve appears as a straight line--Galton

(1) representation of large, multivariate data sets in two dimensions (as in Chernoff's "faces"), which has an informal history in medical diagnosis (37);

(2) representation of sampling and measurement error in traditional forms like bar charts, line graphs and statistical maps (for a discussion, see 35);

(3) representation of variables simultaneously with geographical and population distributions (what Tukey has called the "patch map" problem), as in Bachi's applications (32);

(4) representation of two or more intervally-measured variables in a single map, as in the color-coded cross-classification maps of the U.S. Census Bureau's Urban Atlas series (40); and

(5) more general development of graphics for use in computer-assisted analysis of large, multivariate data sets, as in Tukey's "exploratory data analysis."

In each of these areas, computer graphics applications have just begun to break away from imitations of forms--bar charts and line graphs, histograms and scatterplots -- which were commonplace a hundred years ago, and which do not seem inherently suited to dynamic or interactive applications. The potential uses of dynamic, three-dimensional and color graphics in quantitative applications remain largely unexplored. If the centuries-old struggle to use graphical representation in science and technology has any bearing on recent and future developments, then we can expect work in at least some of the problem areas to give way to more abstract and radically different forms--and perhaps even to new paradigmatic solutions.

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TWENTIETH CENTURY DEVELOPMENTS IN STATISTICAL GRAPHICS

1905	Lorenz curve (cumulative distribution by rank order, to facilitate study of concentrations) --M.O. Lorenz (U.S.)
c. 1910	Statistical diagrams in U.S. textbooks (graphs of temperature, population, in texts of arithmetic, algebra)
1913	Arithmetic probability paper, ruled so ogive appears as straight line (applied to problems of surface drainage) --Allen Hazen (U.S. engineer)
1913-1914	College course in statistical graphic methods--M. F.P. Costelloe (Dept. of Agricultural Engineering, Iowa State College)
1914	Published standards of graphic presentation for U.S.--American Society of Mechanical Engineers
	Pictograms, uniform size (to replace bar graphs, pictograms of varying size)--W.C. Brinton(U.S.)
1916	Correspondence course in graphic methods (20 lessons, 50 dollars) --Frank J. Warne (U.S.)
1917	Published exposition of use of semi-logarithmic paper--James Field (U.S.)
1918-1933	Annual college course in statistical graphic methods--E.P. Cubberly (Stanford University)
1924	Social statistics graphics museum -- Social and Economic Museum, Vienna (Otto Neurath, Director)
1931	"Log square" paper --F.C. Martin and D.H. Leavens
1933	Standard statistical symbols established by government decree -- Soviet Union (for schools, public posters)
mid-1950's	Application of cathode ray tube graphic terminals -- SAGE Air Defense System (U.S.)
1960	Circular glyphs, with rays to represent multivariate data -- Edgar Anderson (U.S.)
1962	Use of cathode ray tube graphic terminals in nonmilitary environments -- Ivan E. Sutherland (U.S.) "Sketchpad," Lincoln Lab
1965	Improvements on histogram in analysis of counts, tail values--John Tukey
1966	Triangles to represent simultaneously four variables, using sides and orientation -- R. Pickett and B.W. White (U.S.)
1968	Systematic, tested patterns for graphic presentation--R. Bachi (Israel)
1969	Graphic innovations for exploratory data analysis (stem-and-leaf, box-and-whisker plots, hanging and suspended rootograms) --John Tukey
1971	Irregular polygon to represent multivariate data --J.H. Siegel, R.M. Goldwyn and H.P. Friedman
1972	Form of Fourier series to generate plots of multivariate data--D.F.Andrews
1973	Cartoons of human face to represent multivariate data--Herman Chernoff
	U.S. Government chartbook devoted exclusively to social indicator statistics -- Social Indicators 1973, OMB
1974	Color-coded bivariate matrix to represent two intervally - measured variables in single map--U.S. Bureau of Census, Urban Atlas series
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