development is dynamic, especially in dynamic display, and so I expect that Andrew Donoho will almost surely have implemented even more tools by the time this commentary finds its way into print.

The DataDesk (Velleman and Velleman, 1986) is a statistical analysis program that also contains some rudimentary dynamic capability. It can produce spinning plots; indeed several windows with a three-dimensional plot in each of them (although only one spins at a time).

These two programs, used in concert, provide a powerful tool for the data analyst at a price that we all can manage. Moreover, being commercially available programs with wide usage means that they have been debugged in a way that more narrowly circulated experimental computer packages are not. The appearance of dynamic display capability in MacSpin and later in DataDesk portends well for the future. Who will buy a data analysis program without such accoutrement? Thus, other software developers will be forced to add these capacities to their programs and we will be the richer for it.

Let me conclude by expressing my gratitude to our Bell Labs colleagues in general, and to Becker, Cleveland and Wilks in particular, for their continuing research into data analytic tools that more fully utilize the computing power now available and the human information processing ability inbedded in our visual system. Their imagination and sweat has provided us with the knowledge of a battery of methods that every salt-worthy data analyst would want to have close at hand. Simultaneously, a second set of talented folks are working hard to make these tools available for the rest of us. To both groups I give my heartfelt thanks, and ask that they stop wasting their time reading this and get back to work—I have a data set that I've been looking at, and I think I'm missing something.

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Comment

Edward R. Tufte

Even though we navigate daily through a perceptual world of three spatial dimensions and reason occasionally about still higher dimensional arenas with mathematical and statistical ease, the world portrayed by our information displays is caught up in the two-dimensional poverty of endless flatlands of paper and video screen. Escaping this flatland is the major task of envisioning information—for all the interesting worlds (imaginary, human, physical, biological) we seek to understand are inevitably and happily multivariate worlds. Not flatlands.

Such escapes grow more difficult as ties of data to the familiar spatial world weaken and as the number of data dimensions increases. But the history of information displays and statistical graphics—indeed the history of communication devices in general—is nothing but a progress of methods for enhancing the density, richness, efficiency, complexity and dimensionality of communication. Methods for escaping flatland include layering and separation, micro/macro readings, contours, perspective, narratives, multiplying of images, use of color and dynamic graphics (Tufte, 1983, 1988).

The visual display tasks involved in dynamic graphics for data analysis are very nearly identical with the flatland portrayal of any dynamic physical system. It is, after all, data moving.

For example, when Galileo first looked through his telescope in 1610, he was confronted with displaying the dynamics of sunspots. In "The Starry Messenger" and "Three Letters on Sunspots," Galileo reported his observations in a large collection of small multiples sequenced on time, recording complex data of moving sunspots on a rotating sun observed from an orbiting and rotating earth (Figure 1).

Through some 370 years of astronomical research, sunspot records have evolved into data-rich time series. The Maunder butterfly diagram records the distribution of sunspots in latitude only moving over time, sacrificing area for time (Maunder, 1904) (Figure 2).

The modern version partially recovers area in reporting an enormous volume of information (Figure 3).

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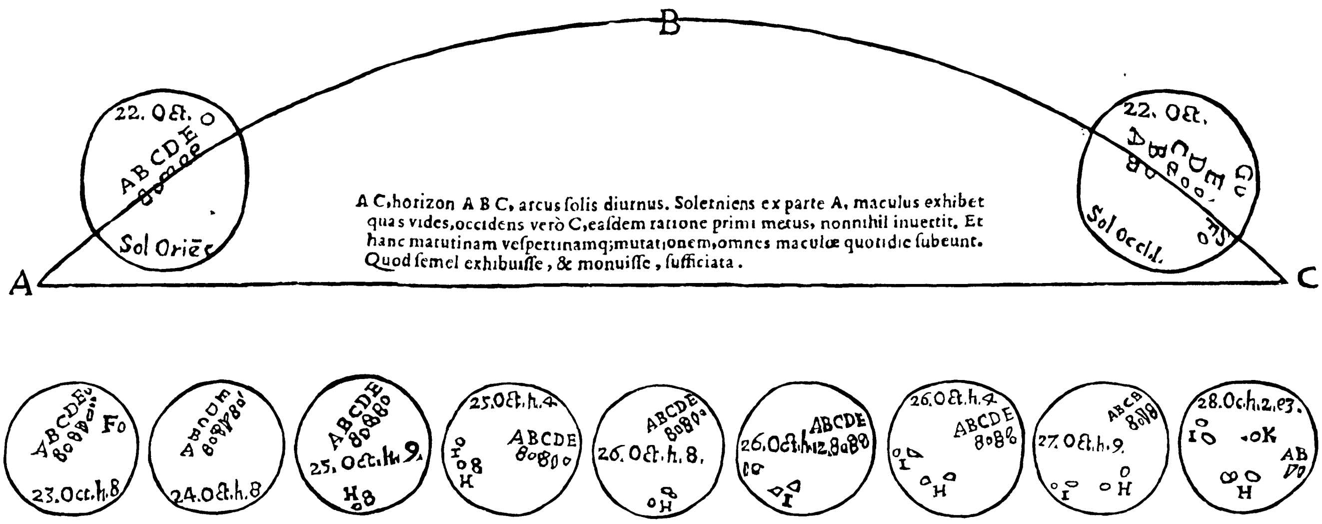

FIG. 1. *Galileo reports his dynamic observations, sunspots of October* 1611. *From his "Three Letters on Sunspots,"* 1613.

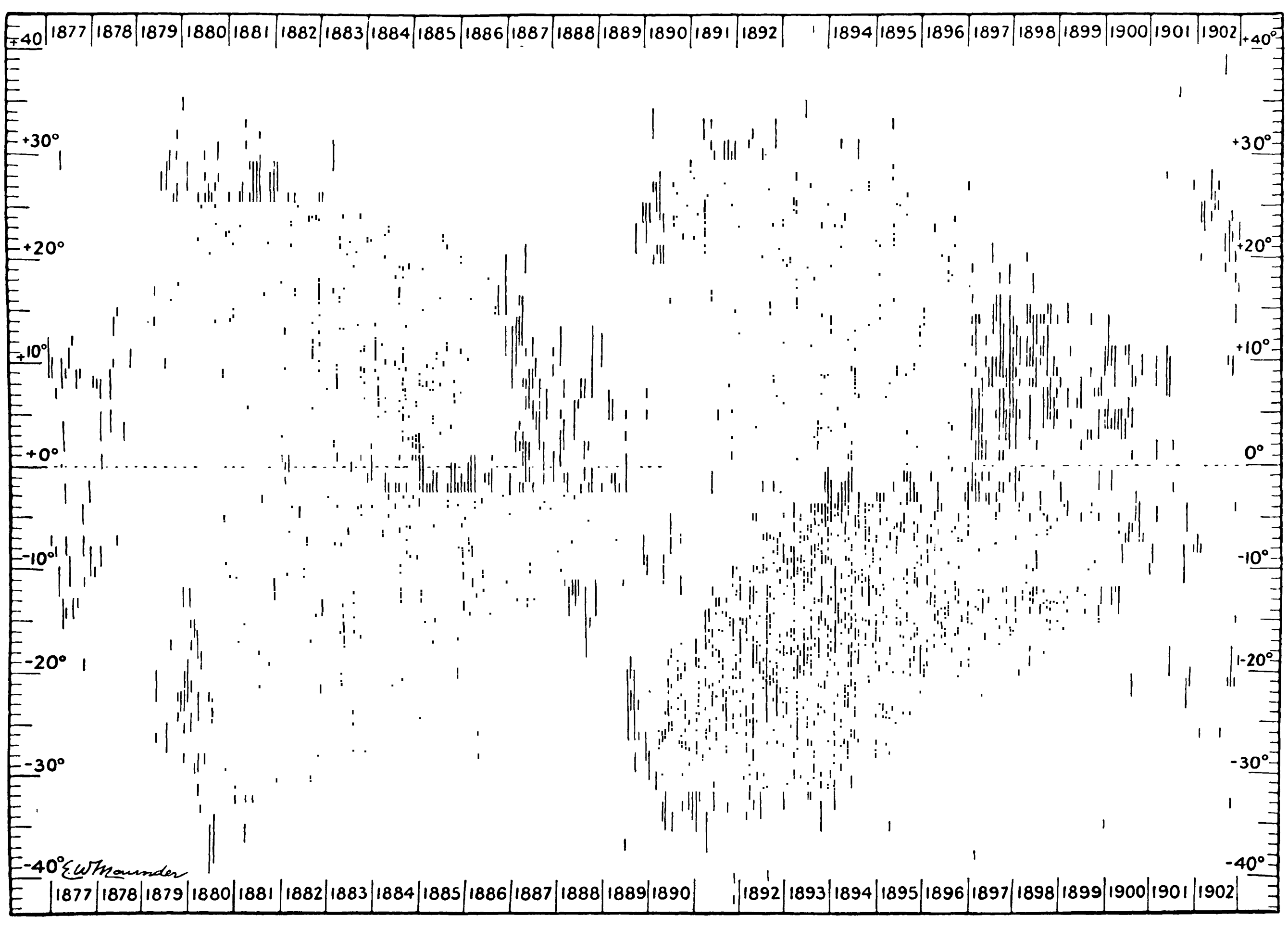

FIG. 2. *The Maunder butterfly diagram showing the distribution of sunspots in latitude*, 1877–1902.

In these 20th century scientific performances, note the high resolution and high data densities (pushing the resolution of the printing process rather than merely that of the local computer output device) and the skill in the details of production (no jaggies, except those of the data, competent typography). Such resolution, data density and production quality are rarely attained in the statistical research literature on data

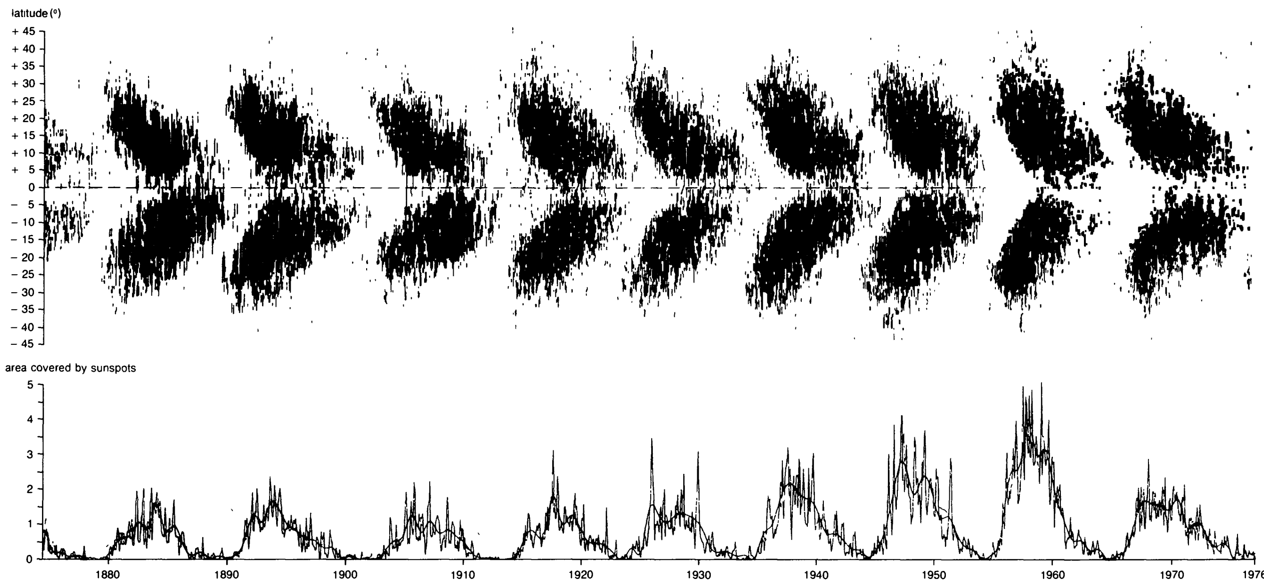

FIG. 3. *The Maunder butterfly diagram and time series of area of sun covered by sunspots*, 1877–1976. *From Science Research Council, Royal Greenwich Observatory* (*Andouze and Israël*, 1985).

横浜駅発東海道線

東海道線　横浜駅発時刻表

60 3 14改正

7・8番(品川・新橋・東京方面)	時	5・6番線(小田原・熱海・静岡方面)
59 09 4 54 25	5	25 47 4 52
56 51 47 38 34 20 (09) 04	6	14 31 54
52 49 45 42 38 35 31 27 21 16 12 04 00	7	07 16 32 36 (41) 51
47 43 39 35 31 27 24 20 17 13 10 06 03	8	03 13 25 27 34 41 48 58
52 57 40 36 28 14 05	9	05 12 25 27 35 46 59
58 56 47 37 32 24 19 10 06	10	10 19 25 34 49 55
56 43 (34) 30 21 16 08 05	11	04 19 25 29 39 49
59 41 36 23 09	12	04 19 25 34 49 55
56 45 35 28 10	13	07 19 34 45 55
49 36 31 26 09	14	04 19 34 (43) 50 55
51 40 31 20 09 04	15	03 19 32 36 49
56 51 40 32 30 19 05	16	01 23 35 49 59
56 44 35 33 19 12	17	03 14 17 23 29 34 42 48 55
56 51 36 25 06	18	01 07 13 20 26 29 36 39 47 57
59 53 49 41 30 13 (08)	19	04 12 15 22 24 29 39 49 59
53 37 24 09	20	09 18 29 39 42 50
48 34 18 05	21	03 13 24 27 34 45
43 22 06	22	04 19 34 49
51 13	23	06 (13) 18 44 54
07	0	23

特 L ○ △ ● ▲ ※ 無印 品
寝台特急 特急 急行 土休日運転 休日運休 土休日運休 運転日に注意 東京行 品川行

特 L ○ △
寝台特急 特急 急行 土休日運転
● ▲ ※ 沼 小 静 平 伊
国 熱
国府津行 熱海行
下 修 兵 御
伊豆急下田行 修善寺行 兵松行 御殿場行

FIG. 4. 1985 *timetable, Tōkaido Line at Yokohama Station, Sagami Tẹtsudo Company, page* 72. *Similar designs are used in Tokyo subway station signage to show subway schedules.*

graphics; indeed, it is a literature routinely filled with low resolution, low density displays and, ironically, with visually clunky graphics. The production values in the literature are amateurish, compared to ordinary workaday professional graphic design.

This same research is generating quite an elaborate jargon, partly no doubt to facilitate technical communication and all that, but it does appear now and again to be an attempt to own a concept by naming it. Giving old ideas new names does not yield new ideas. Of course new words and new usages of old words are needed, preferably reserved for new ideas of some consequence. Jargonizing the familiar may even impede communication. For example, without ever knowing it (fortunately), Tokyo train passengers have been looking for decades at schedules in the form of what statisticians now call "the back to back stem and leaf display" (Figure 4).

Finally, those interested in dynamic graphics should also take a look not only at the skilled paper of Becker, Cleveland and Wilks in hand but also at MacSpin (Donoho, Donoho and Gasko, 1985). MacSpin is a genuine masterpiece, a marvelous interactive program accompanied by a marvelous manual that gracefully explains the straight-forward computer mechanics involved and, more importantly, shows dynamic data analysis in action and chronicles the development of such displays. Alas, even in the MacSpin book, the graphics have the jaggies and murkies, too.

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Rejoinder

Richard A. Becker, William S. Cleveland and Allan R. Wilks

We would like to thank the discussants for their interesting comments. Our responses cover six areas: implementation of the methods of the paper, presentation of the graphs, the underlying software, the computing environment, brushing and rotation.

Since writing the paper we have studied dynamic methods in a color graphics environment—a Silicon Graphics IRIS 2400T workstation. Most of the original paper is based on an implementation of methods in a distributed processing system with an AT&T Teletype 5620 graphics terminal, which is monochrome. Our responses here will reflect more of the experience with the IRIS implementation.

1. IMPLEMENTATION

Experimental vs. Tested: Field Testing

Comments by Huber and Eddy made us realize that one deficiency in the paper is an explicit statement about whether the methods in Sections 2.1 to 2.6 are experimental or well tested. We have examined a large number of dynamic methods by field testing, which will be described shortly. With one exception, the methods of Sections 2.1 to 2.6 are those that we tested and judged to be useful tools for data analysis. (The one exception is advanced strategies for rotation control, which we only reported but did not test.) We strongly urge software developers to implement these methods in their software systems. Wainer is quite right—we tried many other ideas that did not work out.

Field testing a method means using it on a variety of data sets including those where data analysis is in progress. At the moment, because the amount of theory about data display is small, extensive field testing is the only way to effectively judge a graphical method. Armchair thinking is not enough. In 1982, Tukey (1987b) wrote the following about the development of a graphical method:

- now we try it [the graphical method] on diversified data—trying to understand when its performance is less than adequate,
- and then we try to understand something of what modifications would help,
- and then we try the modifications,
- and then we repeat the last 3 steps as needed!

There is no substitute for adequate iteration. *Such iteration is the original developer's obligation.*

It is particularly important to try out methods in settings where people are attempting to learn about the world from the data, and where the methodology is a means to an end. One cannot fully assess a method by using just old data sets no longer of interest to anybody and dredged up just to test the method. In the paper, though, we used familiar or easy-to-convey data sets because of space limitations.

NIH Means Not Implemented Here

In his first sentence, Eddy refers to "bias in favor of methods they and their colleagues have developed." "Developed" should be changed to "implemented." Many of the methods of the paper were invented by us. Many were invented elsewhere; we hope the extensive citations and bibliography make this clear. But except for the advanced strategies of Section 2.6, we discussed only methods that we implemented. This is as it must be. We could not write with much insight about methods that we did not field test, and we could not field test a method that we did not implement.

2. PRESENTATION

Excitement

We quite agree with Tukey that "paper versions of screens with highlighted points are rather weak and