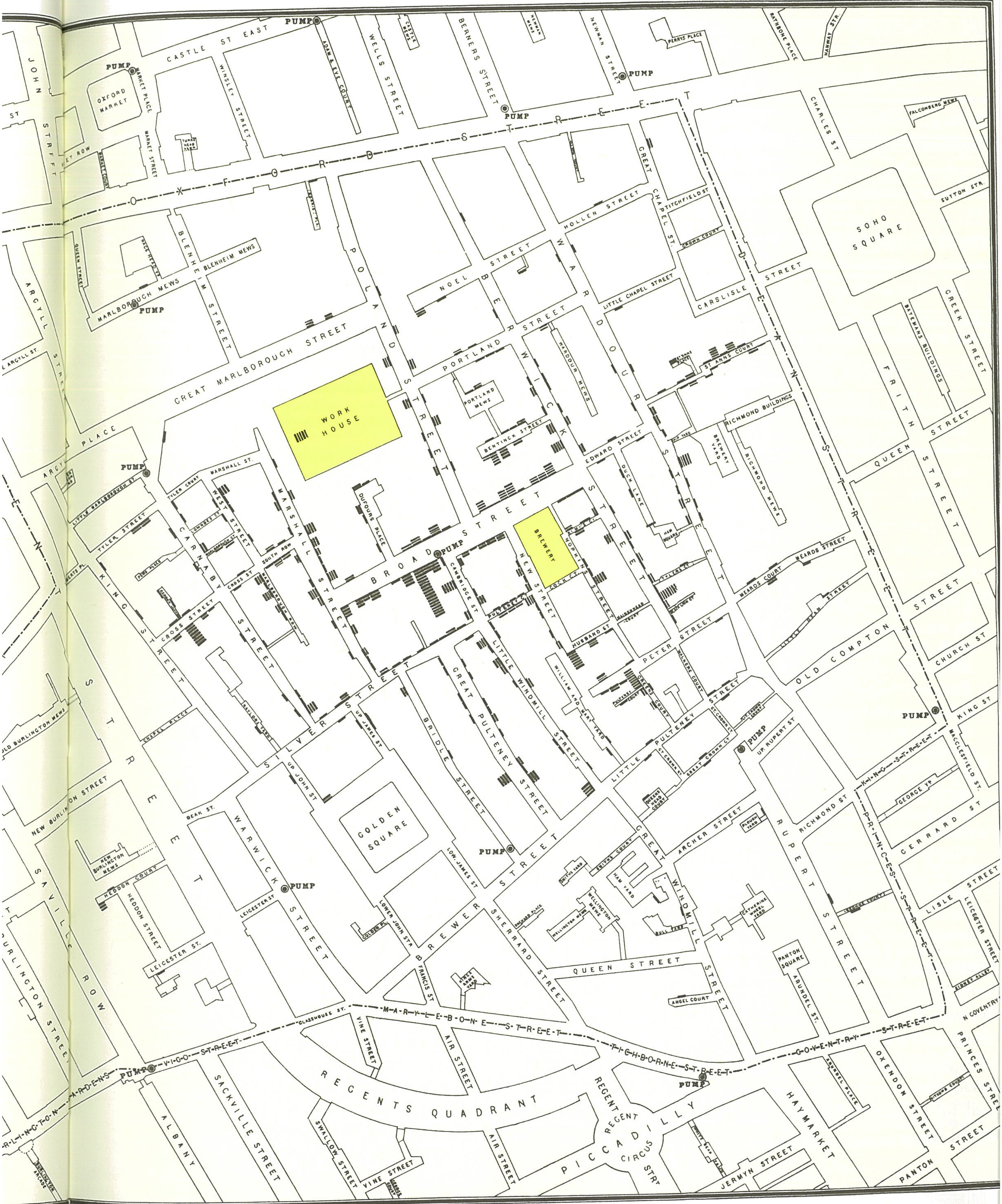
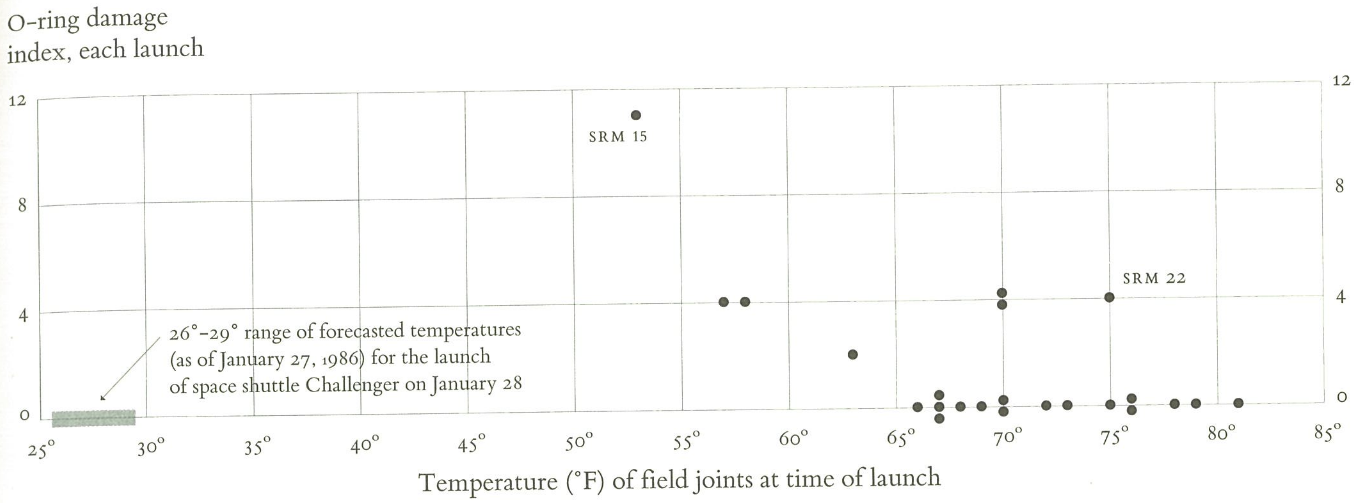


PUMP
CASTLE ST EAST
ADAM & EVE COURT
WELLS STREET
BERNERS STREET
NEWMAN STREET
PERRYS PLACE
RATHBONE PLACE
HANWAY STR
OXFORD MARKET
MARKET PLACE
WINSLEY STREET
MARKET STREET
O-X-F-O-R-D-S-T-R-E-E-T
CHARLES ST
FALCONBERG MEWS
JOHN STREET
GREAT CHAPEL ST
HOLLEN STREET
LITCHFIELD ST
SUTTON STR
SOHO SQUARE
BLENHEIM STREET
BLENHEIM MEWS
MARLBOROUGH MEWS
QUEEN STREET
POLAND STREET
NOEL STREET
BERWICK STREET
WARDOUR STREET
CROWN COURT
LITTLE CHAPEL STREET
CARSLISLE STREET
DEAN STREET
CREEK STREET
BATEMANS BUILDINGS
FRITH STREET
ARGYLL STREET
ARGYLL ST.
GREAT MARLBOROUGH STREET
PORTLAND STREET
PORTLAND MEWS
WARDOUR MEWS
ST ANNS COURT
RICHMOND BUILDINGS
WORK HOUSE
ARGYLL PLACE
BENTINCK STREET
EDWARD STREET
DUCK LANE
RICHMOND MEWS
QUEEN STREET
MARSHALL ST.
TYLER COURT
WEST STREET
MARSHALL STREET
DUFOURS PLACE
BREWERY
BROAD STREET
CAMBRIDGE ST
NEW STREET
HOPKINS STREET
MEARDS STREET
MEARDS COURT
LITTLE MARLBOROUGH ST
TYLER STREET
CARNABY STREET
CROSS ST
SOUTH ROW
KING STREET
CROSS STREET
PULTENEY CT
HUSBAND ST
PETER STREET
OLD COMPTON STREET
CHURCH ST
LITTLE WINDMILL STREET
WILLIAM AND MARY YARD
GREAT PULTENEY STREET
BRIDLE STREET
SILVER STREET
UP JAMES ST
UP JOHN ST
LITTLE PULTENEY STREET
GREAT CROWN CT
UP. RUPERT ST
KING STREET
MACCLESFIELD ST.
OLD BURLINGTON MEWS
CHAPEL PLACE
REGENT STREET
NEW BURLINGTON STREET
BEAK ST.
WARWICK STREET
GOLDEN SQUARE
LOW. JAMES ST
GREAT WINDMILL STREET
ARCHER STREET
RUPERT STREET
RICHMOND ST
GEORGE YD
GERRARD STREET
PRINCES STREET
NEW BURLINGTON MEWS
HEDDON COURT
HEDDON STREET
LEICESTER ST
LEICESTER ST.
BREWER STREET
LOWER JOHN STR
SHERRARD STREET
HAM YARD
WELLINGTON MEWS
CATHERINE WHEEL YARD
LISLE STREET
LEICESTER STREET
SAVILLE ROW
BURLINGTON STREET
FRANCIS ST
QUEEN STREET
ANGEL COURT
PANTON SQUARE
ARUNDEL ST.
N. COVENTRY
VIGO STREET
GLASSHOUSE ST.
VINE STREET
M-A-R-Y-L-E-B-O-N-E-S-T-R-E-E-T
TICHBORNE STREET
COVENTRY STREET
BURLINGTON GARDENS
AIR STREET
REGENTS QUADRANT
REGENT CIRCUS
PICCADILLY
HAYMARKET
OXENDON STREET
PRINCES STREET
SACKVILLE STREET
ALBANY
SWALLOW STREET
VINE STREET
AIR STREET
JERMYN STREET
PANTON STREET



When assessing evidence, it is helpful to see a full data matrix, all observations for all variables, those private numbers from which the public displays are constructed. No telling what will turn up.

Above, a scatterplot shows the experience of all 24 launches prior to the Challenger. Like the table, the graph reveals the serious risks of a launch at 29°. Over the years, the O-rings had persistent problems at cooler temperatures: indeed, *every* launch below 66° resulted in damaged O-rings; on warmer days, only a few flights had erosion. In this graph, the temperature scale extends down to 29°, visually expressing the stupendous extrapolation beyond all previous experience that must be made in order to launch at 29°. The coolest flight without any O-ring damage was at 66°, some 37° warmer than predicted for the Challenger; the forecast of 29° is 5.7 standard deviations distant from the average temperature for previous launches. This launch was completely outside the engineering database accumulated in 24 previous flights.

IN the 13 charts prepared for making the decision to launch, there is a scandalous discrepancy between the intellectual tasks at hand and the images created to serve those tasks. As analytical graphics, the displays failed to reveal a risk that was in fact present. As presentation graphics, the displays failed to persuade government officials that a cold-weather launch might be dangerous. In designing those displays, the chartmakers didn't quite know what they were doing, and they were doing a lot of it.[37] We can be thankful that most data graphics are *not* inherently misleading or uncommunicative or difficult to design correctly.

The graphics of the cholera epidemic and shuttle, and many other examples,[38] suggest this conclusion: *there are right ways and wrong ways to show data; there are displays that reveal the truth and displays that do not.* And, if the matter is an important one, then getting the displays of evidence right or wrong can possibly have momentous consequences.

[37] Lighthall concluded: "Of the 13 charts circulated by Thiokol managers and engineers to the scattered teleconferees, six contained no tabled data about either O-ring temperature, O-ring blow-by, or O-ring damage (these were primarily outlines of arguments being made by the Thiokol engineers). Of the seven remaining charts containing data either on launch temperatures or O-ring anomaly, *six of them included data on either launch temperatures or O-ring anomaly but not both in relation to each other.*" Lighthall, "Launching the Space Shuttle Challenger," 65. See also note 27 above for the conclusions of the shuttle commission and the House Committee on Science and Technology.

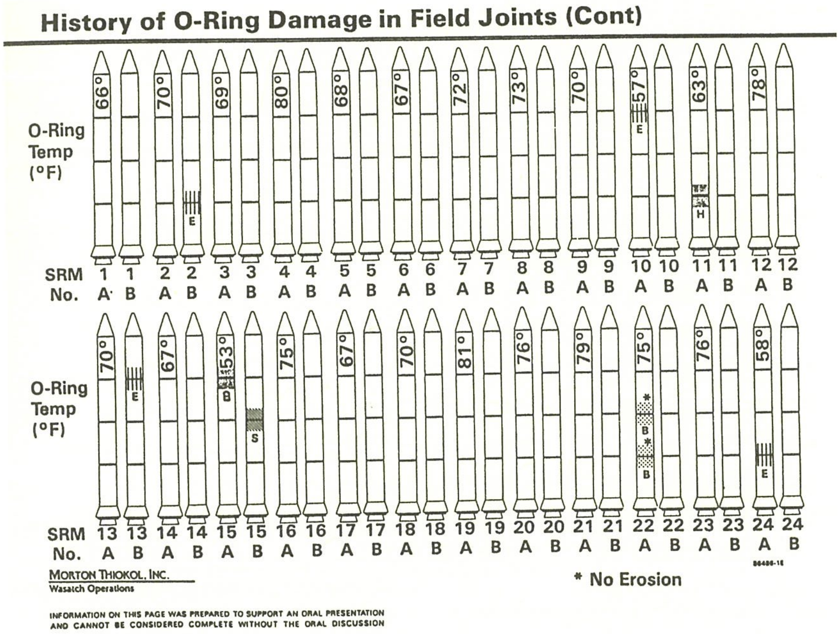
[38] Edward R. Tufte, *The Visual Display of Quantitative Information* (Cheshire, Connecticut, 1983), 13-77.

this particular display should not be taken quite at face value—you had to be there:

INFORMATION ON THIS PAGE WAS PREPARED TO SUPPORT AN ORAL PRESENTATION AND CANNOT BE CONSIDERED COMPLETE WITHOUT THE ORAL DISCUSSION

Such defensive formalisms should provoke rambunctious skepticism: they suggest a corporate distrust both of the chartmaker and of any viewers of the chart.[40] In this case, the graph is documented in reports, hearing transcripts, and archives of the shuttle commission.

The second chart in the sequence is most significant. Shown below are the O-ring experiences of all 24 previous shuttle launches, with 48 little rockets representing the 24 flight-pairs:



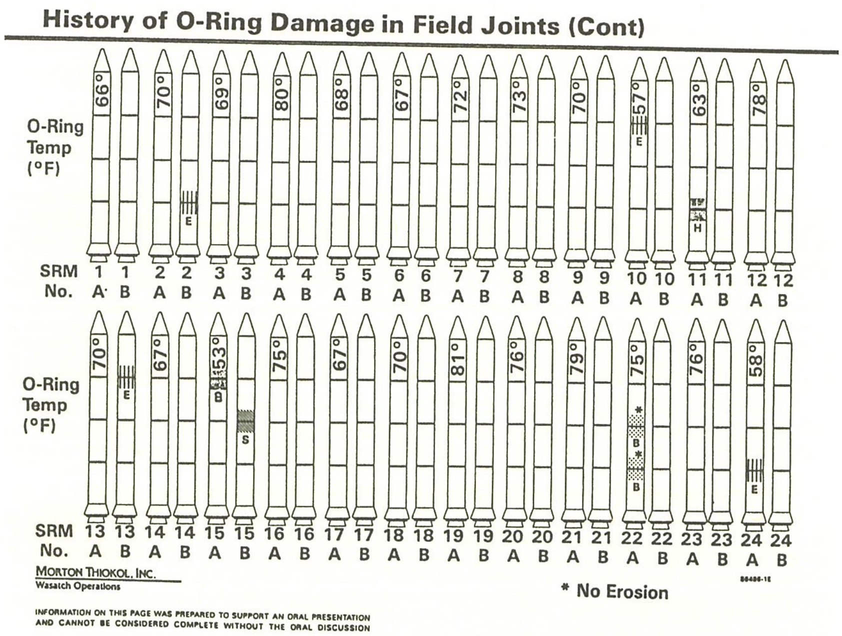
PCSSCA, volume v, 896.

Rockets marked with the damage code show the seven flights with O-ring problems. Launch temperature is given for each pair of rockets. Like the data matrix we saw earlier, this display contains *all* the information necessary to diagnose the relationship between temperature and damage, if we could only see it.[41] The poor design makes it impossible to learn what was going on. In particular:

The Disappearing Legend At the hearings, these charts were presented by means of the dreaded overhead projector, which shows one image after another like a slide projector, making it difficult to compare and link images. When the first chart (the nine little rockets) goes away, the visual code calibrating O-ring damage also vanishes. Thus viewers need to memorize the code in order to assess the severity and type of damage sustained by each rocket in the 48-rocket chart.

[40] This caveat, which also appeared on Thiokol's final approval of the Challenger launch (reproduced here with the epigraphs on page 26), was discussed in hearings on Challenger by the House Committee on Science and Technology: "U. Edwin Garrison, President of the Aerospace Group at Thiokol, testified that the caveat at the bottom of the paper in no way 'insinuates . . . that the document doesn't mean what it says.'" *Investigation of the Challenger Accident*, 228–229, note 80.

[41] This chart shows the rocket pair SRM 4A, SRM 4B at 80°F, as having *undamaged* O-rings. In fact, those rocket casings were lost at sea and their O-ring history is unknown.



PCSSCA, volume v, 896. This image is repeated from our page 47.

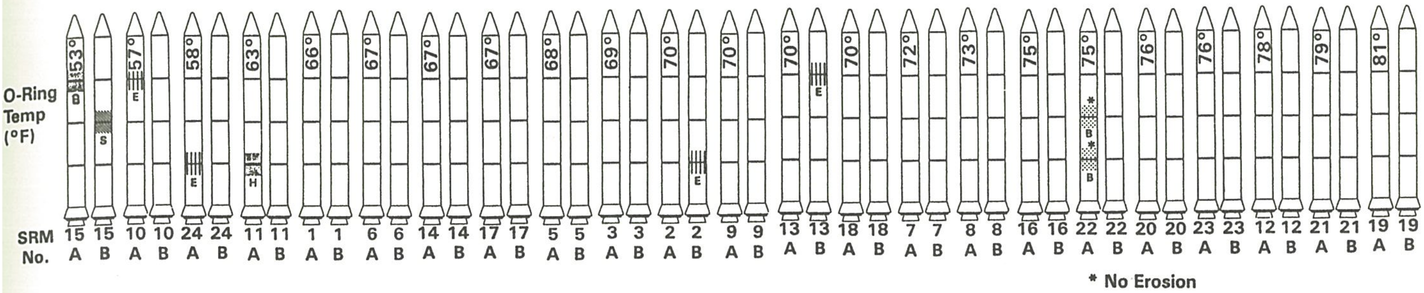
Chartjunk Good design brings *absolute attention* to data. Yet instead of focusing on a possible link between damage and temperature—the vital issue here—the strongest visual presence in this graph is the clutter generated by the outlines of the 48 little rockets. The visual elements bounce and glow, as heavy lines activate the white space, producing visual noise. Such misplaced priorities in the design of graphs and charts should make us suspicious about the competence and integrity of the analysis. Chartjunk indicates statistical stupidity, just as weak writing often reflects weak thought: "Neither can his mind be thought to be in tune, whose words do jarre," wrote Ben Jonson in the early 1600s, "nor his reason in frame, whose sentence is preposterous."[42]

Lack of Clarity in Depicting Cause and Effect Turning the temperature numbers sideways obscures the causal variable. Sloppy typography also impedes inspection of these data, as numbers brush up against line-art. Likewise garbled is the measure of effect: O-ring anomalies are depicted by little marks—scattered and opaquely encoded—rather than being totaled up into a summary score of damage for each flight. Once again Jonson's Principle: these problems are more than just poor design, for a lack of visual clarity in arranging evidence is a sign of a lack of intellectual clarity in reasoning about evidence.

Wrong Order The fatal flaw is the *ordering* of the data. Shown as a time-series, the rockets are sequenced by date of launching—from the first pair at upper left SRM No. 1 A 1 B to the last pair at lower right 24 A 24 B (the launch immediately prior to Challenger). The sequential order conceals the possible link between temperature and O-ring damage, thereby throwing statistical thinking into disarray. The time-series

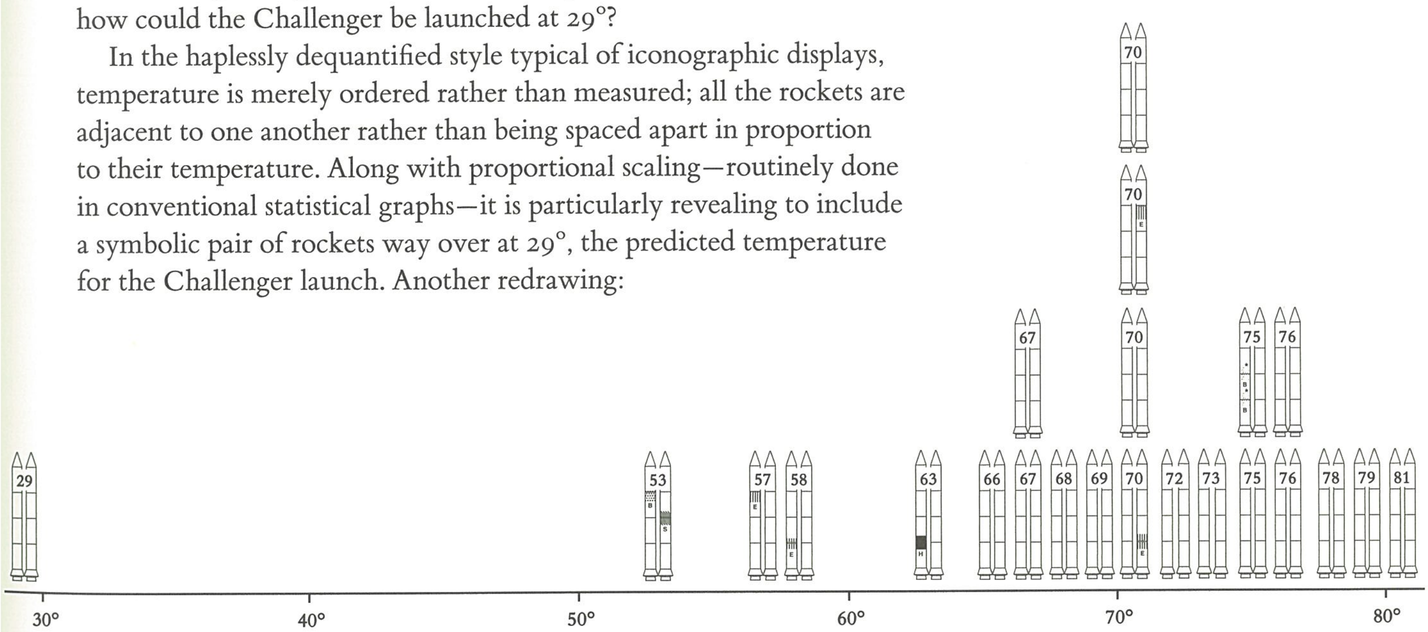
[42] Ben Jonson, *Timber: or, Discoveries* (London, 1641), first printed in the Folio of 1640, *The Workes . . .*, p. 122 of the section beginning with *Horace his Art of Poetry*. On chartjunk, see Edward R. Tufte, *The Visual Display of Quantitative Information* (Cheshire, Connecticut, 1983), 106–121.

chart at left bears on the issue: Is there a time trend in O-ring damage? This is a perfectly reasonable question, but not the one on which the survival of Challenger depended. That issue was: Is there a temperature trend in O-ring damage?



Information displays should serve the analytic purpose at hand; if the substantive matter is a possible cause-effect relationship, then graphs should organize data so as to illuminate such a link. Not a complicated idea, but a profound one. Thus the little rockets must be *placed in order by temperature, the possible cause.* Above, the rockets are so ordered by temperature. This clearly shows the serious risks of a cold launch, for most O-ring damage occurs at cooler temperatures. Given this evidence, how could the Challenger be launched at 29°?

In the haplessly dequantified style typical of iconographic displays, temperature is merely ordered rather than measured; all the rockets are adjacent to one another rather than being spaced apart in proportion to their temperature. Along with proportional scaling—routinely done in conventional statistical graphs—it is particularly revealing to include a symbolic pair of rockets way over at 29°, the predicted temperature for the Challenger launch. Another redrawing:



Even after repairs, the pictorial approach with cute little rockets remains ludicrous and corrupt. The excessively original artwork just plays around with the information. It is best to forget about designs involving such icons and symbols—in this case and, for that matter, in nearly all other cases. These data require only a simple scatterplot or an ordered table to reveal the deadly relationship.