Representation and Misrepresentation: Tufte and the Morton Thiokol Engineers on the *Challenger**

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ABSTRACT: *This paper examines the role of the Morton Thiokol engineers in the decisions surrounding the launch of the* Challenger*, particularly with reference to an analysis of this event by Edward Tufte. The engineers at Morton Thiokol recommended against the launch of Challenger because the projected launch temperature between 26°F to 29°F was far outside their field database of successful launches. The engineers had asked for, but not received, data necessary to determine the cause of massive blow-by on the launch the previous January, and they had informed their managers and NASA that continuing flights could be catastrophic if the cause of the problems with the launches was not discovered. The authors conclude that the engineers thus did what they were ethically as well as professionally obligated to do.*

* This paper came about as a result of an experimental class called 'The Challenger' at the Rochester Institute of Technology (RIT) which drew faculty from four different disciplines, teaching about various aspects of the *Challenger* disaster. Wade Robison was one of those professors, and David Hoeker and Stefan Young were members of the class in their freshman year as engineering students. We all owe thanks to the other professors in the class—Dominique LePoutre (Language and Interpreting Education, National Technical Institute for the Deaf), Erhan Mergen (College of Business), and Rose Marie Toscano (Liberal Arts Support, National Technical Institute for the Deaf). We also need to thank Stan McKenzie, Provost at RIT, and Kit Mayberry, Associate Provost, for their conceiving of the program that supported the class and for their financial and moral support. The paper has been presented at three conferences and circulated widely. We want to thank those who forced us to rework the paper because of their cogent queries, especially Michael Pritchard, David Suits, Steve Warshaw, and an anonymous reviewer.

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It is prima facie unethical to hold people morally responsible for what they did not do or could not reasonably be expected to prevent. So, in judging ethically a person's particular past act or omission, this condition requires knowing (i) whether the person was competent and if so, if it is relevant, to what degree; (ii) whether the person acted voluntarily and if not, what precluded or diminished the capacity to act voluntarily; and (iii) what the person knew or believed, or should and could have known or believed, about the issue at hand. Each of these queries raises often subtle conceptual issues, the concepts involved being anything but clear, and even with conceptual clarity, each requires the gathering of evidence that is difficult to obtain and a parsing of it that can readily go wrong through biases or misconceptions.

Whatever the difficulties each presents, the set forms a triad for determining fault. Someone who knows everything about a problem at hand, acts voluntarily, and yet does wrong is judged incompetent. Someone who does wrong despite being competent and knowing everything about the problem at hand is presumed to have at least a diminished capacity to act voluntarily. Someone who does wrong despite being competent and acting voluntarily is presumed ignorant. Presuming that any two conditions are satisfied when a mistake has occurred forces an examination of the remaining condition as the source of the problem.

A judgment of fault depends upon an accurate assessment of the facts. It is wrong just to presume. Edward Tufte provides a telling example of this sort of ethical failure in his judgment in *Visual Explanations*[1] about the engineers at Morton Thiokol the night before the space shuttle *Challenger* disaster.

"The heart" of Tufte's book, as one reviewer, Ray Duncan, puts it, is "a chapter entitled 'Visual and Statistical Thinking,' based on analyses of the London cholera epidemic of 1854 and the *Challenger* disaster of 1986."[2 (p.2), a] Tufte gives the former as a good example of the representation of causal reasoning, the latter as a bad example. As H. Allison puts it, in a review:

> Tufte's close analysis demonstrates that the engineers had the information they needed—that O-ring failure rates rose as temperature declined—but didn't display it clearly. Seven astronauts' lives could have been saved with a simple graph of previous O-ring damage level against temperature.[3 (p.2)]

The necessity of perspicuous representation is seen most obviously in such cases as the *Challenger*, Tufte argues. The engineers' failure to display the data clearly led to the death of the astronauts, he claims, because with a clear representation the *Challenger* would not have been launched.

However, we will argue that Tufte's analysis goes wrong in three crucial ways. First, he fails to satisfy (iii) above, not determining what the engineers knew or

a. Tufte has printed Chapter 2 of *Visual Explanations* as a separate booklet, entitled *Visual and Statistical Thinking: Displays of Evidence for Making Decisions*, and it is this booklet which is often used and cited. The pagination differs from the book. We have used the pagination in the book, but the pagination of the pamphlet can be determined by subtracting 22 from the page number for the book. The reference on page 49 of the book can be found on page 27 of the pamphlet.

believed, or should and could have known or believed, about the issue at hand. He supposes that they knew the temperatures at launch of all the shuttles and, assuming they acted voluntarily, infers they were incompetent. In reality, they did not know the temperatures even though they did try to obtain that information. Tufte does not appear to have gotten the facts right even though the information was available to him had he looked for it. Second, he misidentifies the effect the engineers were concerned to prevent and so misunderstands and misrepresents the argument and evidence the engineers gave. Third, he provides a "simple graph", a scatterplot, that he thinks would have saved the astronauts' lives had the engineers presented it**.** However, by Tufte's own criteria, the scatterplot seems fatally flawed: the vertical axis tracks the wrong effect, and the horizontal axis cites temperature information not available to the engineers and, in addition, mixes O-ring temperature and ambient air temperature as though the two were the same.

Understanding Tufte's mistakes and the actual reasoning of the engineers depends upon understanding the full power and extent of Tufte's grave charge and his central thesis that perspicuous representation is essential to understanding data. We shall then be in a position to argue how Tufte misrepresents the engineers' position and thus the reasonableness—and the morality—of their recommendation.

1. A brief background

The booster rockets used to launch the shuttles were designed and manufactured at Morton Thiokol and consist of segments which stack on each other. To understand the problem this design created, imagine that we want a tall coffee cup and use cups with indented narrow bottoms so that they fit into each other in a tidy stack. If we cut the bottom out of three cups and stack them on a whole cup, we would have a smooth tall outer cylinder, but coffee poured into the "cup" would instantly come out the sides. We can try to prevent leakage by sealing the cups where they fit into each other with snugly fitting flexible rings, but each time we pour coffee or lift the cup, the joints would be under pressure and prone to leak.[b] In a similar way, each segment of the rocket was seated on the one beneath it and the joint sealed with two flexible and snugly fitting O-rings made from Viton, a rubber-like material. The O-ring closest to the rocket fuel is primary and the other is secondary, for back-up. Putty is laid inside at the joints to provide further protection.

The booster rockets create enormous pressure—1004 psi—and the O-rings must seal to prevent the fuel's hot gases from blowing by the O-rings and compromising the integrity of a booster segment, putting the flight at risk. In the launch of a previous shuttle on January 24, 1985, the primary O-ring on two of the joints had been

b. Wade Robison refers to this design as error-provocative. Since even the smallest of errors in stacking—a piece of lint, a hair—could cause the seal not to work, the design provokes problems even under the best of circumstances, with the greatest of care by the brightest and most highly trained technicians. For a brief explanation of the concept of an error-provocative design, to be supplemented by a book in progress entitled *Error-Provocative Designs: Ethics in Engineering*, see Wade Robison, *Decisions in Doubt: The Environment and Public Policy*.[4]

compromised by fuel blowing by and eroding them.[5 (p.155)] Only the secondary O-ring was left, holding off disaster, and though it was not eroded, blow-by had reached it. The flight was preceded by a "100-year cold", weather that could be expected in Florida only once every 100 years, and although the ambient air temperature at launch was 64°F, Roger Boisjoly, an engineer at Morton Thiokol, suspected that cold temperature might have affected the Viton, making the rings less flexible and thus less likely to seal or seal quickly enough to prevent blow-by. The Viton was calculated to have warmed up to only 53°F at launch.

The weather forecast for the night before the *Challenger* launch the following January indicated it was to be extremely cold, perhaps as low as 18°F—another "100-year cold"—with ambient air temperature at the time of projected ignition in the range of 26°F to 29°F. In a teleconference the evening before the launch, the Morton Thiokol engineers recommended that shuttles not be flown below 53°F, the calculated temperature of the O-rings during the launch of January 1985—the flight in which the O-rings came the closest to complete failure and disaster.

What happened subsequently that evening is the subject of much dispute, but any narrative will contain at least the following:

- The Morton Thiokol management accepted the recommendation of their engineers not to launch *Challenger* and sent that recommendation on to the National Aeronautic and Space Administration (NASA).
- NASA asked for a reconsideration of the recommendation.
- The burden of proof seemed to shift. Morton Thiokol had the burden to prove that the *Challenger* was not flight-ready apparently under the presumption that the flight would succeed otherwise.[c]
- The managers at Morton Thiokol caucused among themselves and approved the flight—despite their engineers' recommendation and sometimes vehement opposition.

2. Tufte's Representation

In the very making of the recommendation not to fly, the engineers tied together temperature and blow-by and also, as Tufte puts it, a "temperature trend":[1(p.49)] "O-ring failure rates rose as temperature declined."[3(p.2)] Tufte goes on to argue that the engineers failed to relate temperature with the compromising of the O-rings in any of

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c. Whether the burden of proof shifted is a matter of some contention among the participants to the teleconference. Thiokol's Brian Russell is quoted as saying, "In my own mind, it was very much like a Flight Readiness Review. In fact, that's what we were doing ... discussing the readiness of that vehicle to fly under the conditions that we anticipated."[5 (p.340)] What was at issue was the flight-readiness of the *Challenger*, and as George Hardy at Marshall Space Flight Center said, "I would hope that simple logic would suggest that no one in their right mind would knowingly accept increased flight risk for a few hours of schedule."[5 (p.343)] The engineers thought they were showing an increased flight risk, and from their perspective, the decision to launch reflected a judgment that there was no increased flight risk—given Hardy's "simple logic". One main difficulty of understanding whether the burden of proof shifted is that, at least in retrospect, it is hard to deny that there was an increased flight risk, if only because the booster rockets were being fired below the 40°F certification limit. Thus, it is hard to understand how those at NASA and Marshall could have thought the *Challenger* flight-ready unless they presumed that unless the engineers could show that the flight would fail, then it would succeed. Such a presumption is false, of course, and, in any event, an increased flight risk should be enough to cause pause. No one at NASA or Marshall seemed to pause.

the "13 charts prepared for making the decision to launch".[1 (p.45)] There is thus, Tufte argues,

> 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.[1 (p.45), **d**]

Whatever the difficulties in organizational structure that led to the *Challenger* disaster, "group think", or "technical decision-making in the face of political pressure,...there was a clear proximate cause: an inability to assess the link between cool temperature and O-ring damage on earlier flights."[1 (pp. 39, 40)]

This inability is represented nicely, Tufte is saying, in those 13 charts. Had the engineers been thinking clearly, and known how to represent that clear thinking graphically, they would have provided a single chart, a scatterplot that ordered the data, presenting all the flights, including those in which there was no damage, "*in order by temperature, the possible cause*".[1 (p.49)]

When arguing causally, "*variations in the cause* must be explicitly and measurably linked to *variations in the effect*."[1 (p.52)] When one map**s** variations in temperature and compromise to the O-rings, one obtain**s** a single scatterplot that presents clearly the relation between cause and effect (see Figure 1 below).

Figure 1: *Challenger* Scatterplot [1 (p.45)]

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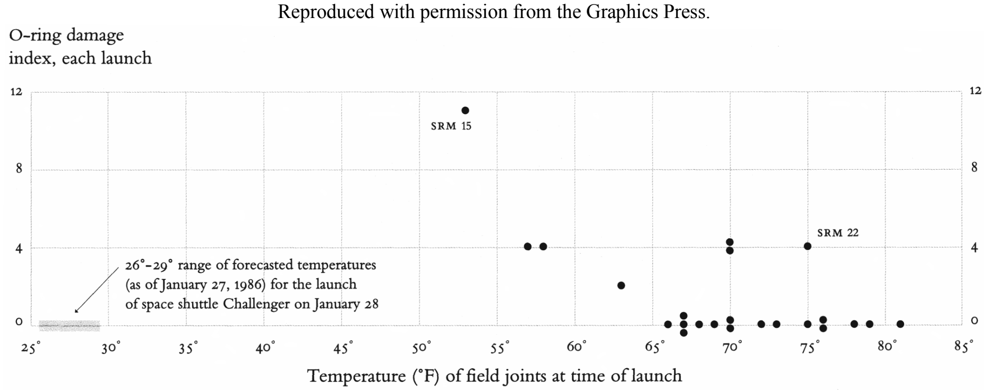

A purist might argue that any extrapolation from the available data is underdetermined, but with such an ascending curve of compromise to the O-rings as the temperature decreases from 65°F to 53°F, it would be difficult for an objective

d. Tufte footnotes Lighthall[6] who points out that of the 13 charts, "six contained no tabled data about either O-ring temperature, O-ring blow-by, or O-ring damage. 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*."[1 (p. 45, n37)] observer to deny that a flight in the 26°-29°F range would be decidedly risky. In other words, the *right* presentation of the relevant data, Tufte is arguing, would have revealed the risk in a way that was undeniable and so persuaded NASA not to launch.[e]

One finds astonishment in reviews of Tufte's work: how could the engineers have been so confused as to make a recommendation that related temperature to a compromise to the O-rings, but not present data to show the relation? This astonishment is natural given Tufte's analysis of what transpired the evening before the *Challenger* launch. By his analysis, the engineers' reasoning was intellectually flawed and their presentation was representationally "scandalous". Tufte's argument would seem to be that the engineers were guilty of an "overriding intellectual failure"[1 (p.52)] because although "[t]hey had the correct theory and they were thinking causally",[1 (p.44)] they failed to relate variations in cause with variations in effect despite claiming such a relationship. Moreover, the "discrepancy between the intellectual tasks at hand and the images created to serve those tasks" was "scandalous".[1(p.45)] Although thinking causally, they "were not *displaying* causally".[1(p.44)]

As a result, though "there were substantial pressures to get [the *Challenger*] off the ground as quickly as possible...these pressures would not have prevailed over credible evidence against the launch.... Had the correct scatterplot or data table been constructed, no one would have dared to risk the *Challenger* in such cold weather."[1(p.52)] A scatterplot would have been so convincing, Tufte is claiming, that even if the engineers had been inarticulate in the teleconference, the chart would have carried the day, *Challenger* would not have been launched, and the astronauts would not have died. Tufte's presentation of the situation implies that the engineers' behavior was unethical.

These are grave allegations and need examination, beginning with the statement that the engineers were answerable for an "overriding intellectual failure". The scatterplot Tufte provides properly relates cause and effect, covering both those cases with damage and those with none. Since Tufte claims the engineers would have presented such a chart had they been thinking as clearly as he, why does he think they did not present such a scatterplot? What mistakes in reasoning does he think they made that led them to represent the data so poorly?

3. Tufte's understanding of the engineers' reasoning

Tufte's work on representation is marked by a deep insight. As he puts it, "*Clear and precise seeing becomes as one with clear and precise thinking*."[1 (p.53)] Putting the point negatively makes it easier to understand his criticism of the engineers: *poor representation mirrors poor reasoning and encourages and sustains it*. Once one goes astray in one's reasoning, one's visual representation not only confirms the bad

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e. As Tufte says, "The graphics of the cholera epidemic and shuttle, and many other examples, 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."[1 (p.45)] "Right" means intellectually cogent and ethical and not (just) "aesthetically pleasing".

reasoning it embodies, but can readily compound problems by leading to further errors.[f]

The charts the engineers used the night of the teleconference displayed poor reasoning, Tufte argues, and furthered it both by what they did and what they failed to do. First, most of the charts failed to relate cause and effect or even mention temperature and compromise to the O-rings. The first one goes directly to the "immediate threat to the shuttle" and displays information about the various kinds and degrees of compromise to the O-rings, but makes no reference to temperature.[1 (p.40)] The next chart shows how "erosion in the primary O-ring interacts with its back-up, the secondary O-ring", but, again, the effect is not linked to temperature.[1 (p.41)] Not only are these and the other charts irrelevant, but because none explicitly correlates cause and effect, the data just hangs there, leaving one to wonder about the cause of such damage.

Second, no charts explicitly relate compromise of the O-rings to temperature, and those that implicitly correlate the two variables are misleading. "Displays of evidence," as Tufte claims, "implicitly but powerfully define the scope of the relevant, as presented data are selected from a larger pool of material."[1 (p.43)] The charts the engineers provided define the scope of what is relevant by focussing on "blow-by (not erosion) and temperature for two launches, SRM 15 [on January 24, 1985, hereafter STS 15] and SRM 22 [on October 30, 1985, hereafter STS 22]."[1 (p.43)] [g] Focussing on

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f. Putting Tufte's point negatively brings out an important feature that is lost in the summation quoted. It is not just that representation mirrors reasoning, good or bad, but that poor representation can itself mislead us. Even if we reasoned well, we could represent our reasoning so poorly that the argument loses its power to persuade or, worse, misleads us into making errors in reasoning we would not otherwise have made.

g. A continuing cause of confusion in referring to the various flights is that no standard mode of reference exists. As Tufte points out, regarding one of the charts used by the engineers the night before the flight, "the same rocket has three different names: a NASA number (61A LH), Thiokol's number (SRM no. 22a), and launch date."[1 (pp.40-41)] We use STS (for Space Transport System) so as to have a different way of referring to the flights that will not cause confusion with NASA's numbers or Thiokol's use of SRM, and we have numbered each flight in order of launch, STS 1 being the first, STS 15 being the 15th, on January 24, 1985, and STS 25 being the 25th, *Challenger*. The correlations with NASA's designations and flight dates are as follows:

Flight Designation	NASA Designation	Flight Date
STS 1	NONE	4/12/81
STS 2	NONE	11/12/81
STS 3	NONE	3/22/82
STS 4	NONE	6/27/82
STS 5	NONE	11/11/82
STS 6	NONE	4/4/83
STS 7	NONE	6/18/83
STS 8	NONE	8/30/83
STS 9	NONE	11/28/83
STS 10	41-B	2/3/84
STS 11	41-C	4/6/84

Continued overleaf

blow-by "invited the rhetorically devastating...comparison of SRM 15 and SRM 22",[1(p.42)] but, Tufte argues, "the 53° launch [STS 15] barely survived with significant erosion of the primary and secondary O-rings on both rockets as well as blow-by; whereas the 75° launch [STS 22] had no erosion and only blow-by."[1 (p.42)]

Had the engineers focussed on "the more common erosion", Tufte is arguing, STS 22 at 75°F would not have been a counter-example to their argument,[1 (p.42)] but they set themselves up with a weak and misleading argument from analogy:

> STS 15 was launched when the O-rings were [calculated to be] 53°F.
> There was very significant blow-by in STS 15.
> Therefore, no flights below 53°F should be permitted.

An argument relating what happens in a single instance to other instances is inherently weak. It is even weaker when the instance itself is problematic. It is a measure of how weak such an argument is—by its very nature—that a single counter-example is as weighty as the original evidence. So any flight above 53°F with compromise to the O-rings serves to undermine the implicit assumption of the conclusion, namely, that the rate and extent of compromise to O-rings rose "as temperature declined".[3 (p.2)] It is for that reason that STS 22 becomes a devastating counter-example, given its launch with an O-ring temperature at 75°F and the blow-by that occurred. By Tufte's understanding of what the engineers were thinking, their "argument" should read like this if they put in all the data that focussing on blow-by made relevant:

> STS 15 was launched when the O-rings were 53°F.
> There was very significant blow-by in STS 15.
> STS 22 was launched when the O-rings were 75°F.
> There was significant blow-by in STS 22.
> Therefore, no flights below 53°F should be permitted.

Footnote f continued

Flight Designation	NASA Designation	Flight Date
STS 12	41-D	8/30/84
STS 13	41-G	10/5/84
STS 14	51-A	11/8/84
STS 15	51-C	1/24/85
STS 16	51-D	4/12/85
STS 17	51-B	4/29/85
STS 18	51-G	6/17/85
STS 19	51-F	7/29/85
STS 20	51-I	8/27/85
STS 21	51-J	10/3/85
STS 22	61-A	10/30/85
STS 23	61-B	11/26/85
STS 24	61-C	1/12/86
STS 25 (*Challenger*)	51-L	1/28/86

NASA's designations make no sense at all unless there were no flight delays at all.

Displayed in this way, the argument attributed to the engineers looks (and is) pitiful indeed, and as one reads through Tufte's account, one cannot help but wonder how the engineers could have convinced themselves, let alone anyone else.

Their first mistake, Tufte is claiming, was to misidentify the effect to which temperature ought to be related. The effect is not blow-by, but erosion, he claims. If they had gotten the effect right, he is arguing, at least their weak argument would not have been subject to such a devastating counter-example since STS 22 had blow-by, but no erosion.

That mistake was compounded by another, at least equally fatal error, Tufte claims. What is conspicuously missing from the charts the engineers presented and thus missing from the argument the engineers mounted is any attempt to correlate what their recommendation implies are causally related variables, namely, damage and temperature. "Missing are 92% of the temperature data, for 5 of the launches with erosion and 17 launches without erosion."[1 (p.43)] Missing as well was any information about the launches without damage. One cannot begin to verify a claimed causal relationship without considering what is true of the supposed cause when the claimed effect is missing. As Tufte rightly puts it, "The flights without damage provide the statistical leverage necessary to understand the effects of temperature."[1 (p.44)] The engineers' last mistake, and the most important, was that only seven charts contained information about temperature and "O-ring anomaly" and no single chart contained data on "*both in relation to each other*".[1 (p.45)]

Had the engineers been thinking clearly, Tufte claims, they would have attempted to show the relationship between temperature and compromise on all flights, and that attempt would have clued them into the need for presenting all the temperatures and the different effects on the O-rings. They really needed only one chart, the scatterplot. Their failure to think through their argument led them into a failure of presentation that had "momentous consequences".[1 (p.45)]

In summary, Tufte's claim is that the engineers were guilty of flawed reasoning in two ways: (1) They misidentified the effect they were trying to prevent, and (2) having misidentified the effect, they proceeded to a generalization (do not fly below 53°F) from one example where both blow-by and erosion occurred. STS 22 thus became a devastating counter-example: how could they recommend not flying below 53°F on the basis of one instance when the same problem they claimed they were trying to prevent—blow-by—occurred at 75°F? Poor reasoning, indeed! Their poor reasoning led to their failure to provide a scatterplot, and, Tufte charges, that failure resulted in the *Challenger*'s launch. Tufte implies that the engineers' incompetence thus makes them ethically responsible for the *Challenger*'s failure and the death of the astronauts.

4. What the engineers were really trying to prove

Were the engineers so confused that they misidentified the effect? Tufte rightly says that representation defines "the database".[1 (p.43)] It determines what is relevant and irrelevant to making a decision. Tufte refers throughout to "O-ring distress" and "O-ring damage" as the effect and begins his analysis by stressing the failure to "assess the link between cool temperature and O-ring damage on earlier flights”.[1 p.40) h] His way of representing the object of concern is as much definitive of the database he thinks relevant as the engineers’.

On the scatterplot he thinks the engineers should have provided (Figure 1), the index is marked “O-ring damage”, a summarization, as he puts it, of the various ways in which the O-rings were themselves harmed.[1 (p.41)] STS 22 is given a 4 and STS 15 an 11, scores determined by “the severity-weighted total number of incidents of O-ring erosion, heating, and blow-by”.[1 (p.22, n.36)] The inclusion of blow-by and heating is confusing given Tufte’s stated reference to “O-ring damage” as the effect to be avoided, but far worse is the assumption that the two shuttle flights differed from others only in the total number of such “incidents”. What made STS 15 a red flag to the engineers was not that it presented a large number of incidents, but that it “was the first time we had actually penetrated a primary O-ring on a field joint with hot gas, and we had a witness to that event because the grease between the O-rings was blackened just like coal,” according to Boisjoly.[5 (p.155)] The primary O-ring was penetrated completely, and the secondary O-ring was impinged, though not eroded, with the hot gases leaving a residue of burnt grease. The indication of blackened grease on STS 15 from hot combustion gas blow-by was 80 degrees arc length on one case joint and 110 degrees arc length on another case joint.

Blow-by also occurred in STS 22, launched at a calculated O-ring temperature of 75°F, but the blow-by indication was a light gray color, not a homogeneous black, and with a much smaller arch length of 30 to 40 degrees.

The differences in the amount and color of the grease between STS 15 and STS 22 resulted from differences in the magnitude of the blow-by. The darker the color, the greater the amount of blow-by. STS 22 was launched at an ambient air temperature of 78°F and a calculated O-ring temperature of 75°F. It had experienced a small amount of blow-by. STS 15 was launched with a calculated O-ring temperature of 53°F and experienced a substantially greater amount of blow-by. One conclusion to draw was that the lower the temperature of the O-rings, the greater the blow-by and the closer the booster joint approaches complete failure. A second conclusion was that the primary O-rings could not be depended upon to seal at what anyone would consider a “normal” temperature—75°F.

Tufte’s chart thus fails to take into account what STS 15 and 22 told the engineers. If the primary O-ring does not seal, the secondary O-ring becomes primary. If it were not to seal or were eroded through, the results would be catastrophic. The red flag was that the status of the secondary O-ring changed.[i] The engineers were very concerned

h. Tufte thus says that the night before the launch the “rocket engineers needed a quick, smart analysis of evidence about the threat of cold to the O-rings,...”, emphasizing that it is damage to the O-rings that is the crucial variable along with cold.[1 (p.40)] He goes on in the same summary to refer to the history of eroded O-rings on launches prior to *Challenger*.[1 (p.40)]

i. Its status was changed in 1982 by Marshall. The Solid Rocket Booster Field Joints were reclassified from Criticality 1R (loss of mission/life with redundancy of the secondary O-ring) to Criticality 1 (loss of mission/life without redundancy of the secondary O-ring). That is, it was about the change: redundancy was lost, and the safety of the shuttle flights compromised.

Why did Tufte miss the point and concentrate on "O-ring distress" rather than blow-by? He apparently thinks blow-by is soot, or so his pairing of the two—"soot (blow-by)"—would lead even a careful reader to assume.[1 (p.42)] He has thus mistaken *an effect* of blow-by for blow-by. Blow-by occurs when hot gases *blow by* an O-ring which has failed to seal fully in time. When an O-ring does not seal fully, a gap exists through which the hot gases of the rocket can pass, burning off the grease on the O-ring and impinging on the secondary O-ring, depositing there what is left of the combustion and burned grease, namely, soot. The soot is a causal effect of the hot gases blowing by an O-ring and heating up the grease that coats them. Blow-by is not soot, and as the engineers knew, its effects are potentially catastrophic.

It seems that Tufte completely misunderstands the object of the engineers's concern, namely, that the O-rings might not seal at all, allowing hot gases to burn through the side of the rocket booster. Tufte is correct in thinking that erosion is not a minor problem. If an O-ring is eroded through, it does not matter whether it was sealed or not: the result is catastrophic. However, an O-ring that does not seal is subject to both "impingement erosion and bypass erosion, and the O-ring material gets removed ...much, much faster," according to Boisjoly.[5 (p.155)] The soot on the secondary O-ring in STS 15 occurred when the hot gases blew by the primary O-ring because it did not seal quickly enough. If, as Boisjoly suspected, the primary O-ring had not sealed because Viton loses resiliency when cold, the worry is not that an O-ring would seal and then be burned through, but that with colder temperatures the O-rings would not seal at all.

In summary, we argue that Tufte misidentifies the effect the engineers were concerned to prevent. The scatterplot he provides represents perfectly his mistaken reasoning: the vertical axis scores "O-ring damage". Yet since blow-by is at issue, the scatterplot directs attention away from what is relevant to making a decision. Since poor representation encourages poor reasoning, it is not surprising that Tufte makes another mistake as well: the horizontal axis is also wrong. To see how, it is necessary to consider what the engineers did after STS 15 jolted their belief that the O-rings sealed.

5. The engineers' test database

(1) The "fixed" tests—Tufte points out that the chart entitled "History of O-ring Temperatures" contains four "test motors that never left the ground" and so are "not to the point".[1 (p.43)] They were, he says,

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recognized that the secondary O-ring was "not redundant, as the design intended: if the primary O-ring failed, the crew and vehicle would be lost."[5 (p.56)] However, the engineers at Morton Thiokol were never notified of the official change, and the change had no practical effect because the Criticality 1 status was then waived.

> all fixed rockets ignited on horizontal test stands at Thiokol, never undergoing the stress of a real flight. Thus this evidence, although perhaps better than nothing (that's all it's better than), is not directly relevant to evaluating the dangers of a cold-weather launch.[1 (p.43)]

It is a mistake, however, to think that the tests of the fixed motors were not relevant to evaluating the effectiveness of the O-ring's sealing under the stresses of a real launch—whether in cold temperature or in warm. In fact, the tests subject the motors to more stresses than they would ever experience in flight.

The booster segments are not rigid, but highly flexible, settling out of round under their own weight, for instance, when transported on their sides. Vertical and stacked, in position for flight, the greatest stress comes from the hot gases against the inside of the booster rocket and occurs only in the first few seconds when the rocket is lifting off the launch pad. Strapped down on their sides and fired, the rocket bounces, subjecting the joints to additional stresses continuously as the rocket fires. Fixed and fired on its side, the rocket will tend to become out of round, and its elliptical shape affects the gap created between the joints, rendering blow-by and erosion more likely. In addition, during actual launch, stresses occur only for seconds while a fixed firing subjects the rockets to stresses for the entire two-minute burn. For these reasons, it was concluded that if a ground firing test was successful, the boosters were qualified for flight.

In addition, the four tests were conducted at O-ring temperatures calculated to be between 47°F and 50°F. If the fixed rockets were subjected in tests to far more stress than the rockets would experience at launch, at temperatures colder than any launch to date, and if the O-rings held (as they did), then the tests are far "better than nothing" for assessing whether the O-rings work effectively. Indeed, they provide evidence that even at temperatures lower than 53°F, the O-rings hold.

(2) The "plate" experiment—After STS 15, at the end of February and beginning of March 1985, Arnie Thompson performed a simple experiment to test O-ring resiliency in different temperatures. A groove the size of those in the booster rockets was made

> in a flat plate and [an O-ring] compressed...0.040 inches (1.02mm) with another flat plate. After temperature conditioning of the assembly, the plates were separated 0.030 inches (0.76mm) at a 2.0 inch per minute rate to simulate a flight rate of approximately 3.2 inches (8.13cm) per minute (slightly unconservative).[7 (p.1)]

The tests showed "no loss of contact at 100°F", but a "loss of seal contact for 2.4 seconds at 75°F" and "in excess of 10 minutes at 50°F".[7 (p.1)] These tests showed that the O-rings were not capable of filling the gap between the tang and the clevis created at launch in sufficient time even at 75°F. At that temperature, combustion gases would blow by the O-rings as they attempted to seal.

Thus, long before *Challenger*, the engineers knew both that the O-rings were not capable of sealing properly even at what no one would consider a cold temperature and that cold aggravated an already catastrophic problem.

(3) Conclusions—The military specification for Viton stated that it could be used at a temperature as low as -50°F, with the caution that verification is required in a specific application. Yet Thompson's experimental "verification" showed that Viton is not resilient enough even at 75°F to prevent disaster. The fixed tests at temperatures below 53°F were successful, however, with the seals subject to far more stress, and stresses of different sorts, for a much longer time, than they would be in a launch. Perhaps the pressure of the hot gases against the sides of the booster rocket worked to seal the O-rings. In any event, whatever the cause of the successes and failures, the test data regarding resiliency of the O-rings presented the engineers with a mixed bag, determining no definitive conclusion by itself about the use of Viton in O-rings during an actual burn.

Supplementing the test data with the engineers' field data provides a more accurate picture of the engineers' epistemological position.

6. The engineers' field database

The engineers had field data as well as test data. One set of field data came through the seven instances of blow-by and/or erosion on the shuttles before the *Challenger*. It is important to appreciate the difference between seeing all the data about the set of flights prior to the *Challenger* launch and seeing the data about each launch as they were produced. The engineers were in the midst of an unfolding process, and as they responded to problems with the shuttles, what stood out to them (and would stand out to anyone engaged as they were) may well differ from what would be apparent with all the data in hand.

(a) An historical narrative—The first problem involving the O-rings occurred in the second launch, STS 2. There was erosion "of 0.053" [inches] of the primary O-ring in the right SRB's [Solid Rocket Booster's] aft field joint.[5 (p.121)] Blow holes had formed in the putty when air trapped in the joint was compressed during joint assembly, and hot gases blew through the weak spots. However, that occurred in "only one of the 16 O-rings on the two boosters", and the conclusion was that the erosion was caused by "a deficiency in the putty in only that location", unrelated to the O-rings.[5 (p.121)]

Nine successful launches followed, and then, on August 30, 1984, blow-by occurred in the nozzle joint of STS 12, with erosion on two primary O-rings and soot behind a primary ring. The soot behind the primary O-ring was an indication that hot gases had penetrated behind that ring and put the secondary O-ring at risk. That there was only a small amount of soot "proved that the period during which hot gases passed the primary was short, verifying calculations that penetration by hot gases was a self-limiting phenomenon."[5 (p.143)]

The O-rings are tested before flight to determine whether they are properly sealed. The test requires putting air under pressure between the primary and secondary O-rings. That pressure ensures that the secondary O-ring is in place because it pushes that O-ring against the outer walls of its retaining groove, but if the pressure were high enough, it could push the primary O-ring away from its retaining groove sealing position. The tests up to and including STS 12 were made at 50psi, but Leon Ray of NASA asked himself whether the putty might hold at that pressure. If so, the pressure would not be testing whether the O-rings were incapable of sealing because they were contaminated in some way. The air might get past a primary O-ring, proving that it was not properly sealed, but be held back by the putty so that those doing the tests would not know that the O-ring was not sealed.

A series of pressure tests down to 40°F indicated a problem with using only 50psi, and so the leak check pressure was changed to 200psi to ensure that the putty did not mask that an O-ring was not sealed. Two successful launches followed before blow-by reached the secondary O-ring in STS 15 in the "100-year-cold" in January 1985.

The engineers anticipated that a 200psi check would push the primary O-ring out of its groove and so increase the likelihood of blow-by and erosion. Because they also thought that any blow-by of the primary O-ring was self-limiting, they judged this a tolerable risk and so took no corrective action after STS 15. However, a flight in April 1985 (STS 17) saw the "...most extensive blow-by on a primary O-ring to date."[5 (p.162)] Erosion was 0.068 inches and so was "outside the experience base" of STS 2. It was on a nozzle joint, and that design was different from the field joint design because it had a very safe secondary O-ring. (It was a "face" seal between two metal surfaces clamped together with 100 1⅛ inch diameter bolts.) Nevertheless, blow-by should not have occurred.

The testing pressure was decreased to 100psi. Tests had been done showing that the putty could withstand up to 150psi so that any test at that pressure or lower could mask the failure of an O-ring to seat. The engineers at NASA and at Morton Thiokol recommended 200psi. Yet NASA managers with the support of Morton Thiokol managers selected 100 psi as the leak test value.

Then came STS 22. At 75°F, the nozzle joint primary O-ring burned completely through with erosion of "0.171 [inches], exceeding both the experience base and the safety margin."[5 (p.163)] Because .09 inches is the maximum erosion that can occur if the primary O-ring seals, the judgment was that the "nozzle joint's primary O-*ring had never been in proper position to seal*."[5 (p.164)] Some "quality flaw" in the installation—"a hair or a piece of lint could do it"—had occurred, and "the 100 psi nozzle leak check had not detected that the ring was not in proper sealing position."[5 (p.165)] The pressure check was returned to 200-psi and remained there for all subsequent flights, including *Challenger*.

Arnie Thompson suggested "thicker shims and larger-diameter O-rings", but only the shims were added. There followed four successful launches before troubles again surfaced.

The launch on October 30, 1985 found soot behind two primary O-rings. Then, after one more success, the launch of Colombia on January 12, 1986 produced erosion at three joints. But that erosion was "within the experience base" and not unexpected given the increase in the pressure check to 200psi.[5 (p.285)]

(b) A summary of the history—Seven troublesome shuttle launches occurred before *Challenger*—STS 2 (11.12.81), 12 (08.30.84), 15 (01.24.85), 16 (04.12.85), 17 (04.29.85), 22 (10.30.85) and 24 (01.12.86). STS 2 and STS 17 had causes seemingly unrelated to the composition of the O-rings. In the five other cases, each time a joint exhibited a problem found at disassembly after a flight, the problem was studied and assessed in preparation for the next flight. The engineers identified and corrected the underlying cause, and the problem either disappeared (as it did after STS 2) or a new problem appeared which was not unexpected given the corrective action taken.

At only one point in the series of space shuttle launches was temperature ever considered a possible issue. Until STS 15, none of the damage exceeded the 0.053 inches found after STS 2, and so flights were occurring within the field database created by STS 2. That more hot gases blew by the primary O-ring in STS 15 was a surprise, and Boisjoly suspected that the subsequent erosion was outside the parameter set by STS 2 because the cold weather affected the resiliency of the O-ring.

(c) Lessons from the history—The troublesome effects the engineers saw in the history of shuttle flights seemed random in two different ways. First, different joints were involved. Sometimes the problem occurred in a forward joint, sometimes in a center joint, sometimes in an aft joint, and sometimes in the nozzle joint. Second, different positions on each joint were involved. No one location of the joint cross section was singled out by the troublesome flights.

The most likely cause of the problems, if there were a common cause, would seemingly have to be something that could vary as the problems varied. A suspect whose potential for failures could match the randomness of the effects was the putty, with its variable behavior. If the putty failed at any one point, all the internal pressure would be concentrated at that one point rather than being evenly distributed around the inside perimeter of the rocket. Indeed, at one time it was suggested that the putty be removed to ensure the equalization of the pressure from the burn.

Putty formulations had changed during the flights due to the Environmental Protection Agency's banning asbestos from the original putty. Replacements were found, but it was clear that all of them bordered on being unusable in a normal ground environment. For instance, putty in the high humidity at Cape Kennedy needed to be placed in freezers and removed only just prior to use because otherwise it would become too soft and sticky to put in place. When used in Utah, however, with its low humidity, no such precautions were necessary. In any event, it was unclear, for instance, whether the putty varied from batch to batch, whether the way in which the putty was applied varied from flight to flight, or whether the temperature or humidity affected the putty on a flight.[j]

j. The putty was changed because the asbestos in the original Fuller O'Brien putty was banned by the EPA. The subsequent putty used did not contain asbestos. There were several vendors used, one of whom, Randolf, immediately followed the use of the Fuller O'Brien putty. The change in putty has been blamed by some for the increase in joint O-Ring erosion problems, but all that is just speculation without tests to confirm or disprove the theories.

The engineers requested that the putty be tested, but no test was ever approved. As a result, it is not possible to determine whether the blow-by and erosion were the result of (1) the increase to 200psi, (2) variability in the putty, (3) some combination of the two, or (4) some other factor.

7. What the Engineers Did

So far this paper has examined what the engineers knew or believed, or should and could have known or believed, about the shuttle problems as they occurred. Added to the mix is the crescendo of problems that suddenly surfaced over a relatively short time. From the first flight in 1981 until the end of 1984, two flights had difficulties. The subsequent history of successful flights indicated the problems on those two flights were explained and resolved. Then came "the 100-year cold" of January 1985 followed quickly by four more troublesome flights. By the summer of 1985, the engineers knew that there were potentially catastrophic problems with the shuttle, but they did not know the cause of the problems.

Given this, the engineers did two things they were professionally and ethically obligated to do.

(1) They informed those in authority—After the problems with STS 15 in January 1985 and the two flights in April, the engineers were rightly concerned, and on July 31, 1985, Roger Boisjoly sent a memo to the Vice President of Engineering at Morton Thiokol pointing out that if the blow-by problem of STS 17 were repeated in a field joint, "[t]he result would be a catastrophe of the highest order—loss of human life."[7(p.4)] "[D]uring the July/August time period," NASA headquarters asked Morton Thiokol "to prepare and present a summary of problems with all the booster seals on August 19, 1985. This was done... ."[7(p.4)] NASA's judgment was that despite the problems, flights would continue while a redesign was in progress. The problems were judged not so severe as to require the two-year delay in flights that would occur were they to wait for a new design to be ready.[k]

NASA was thus aware of the difficulties with the shuttle design by the end of August 1985, and the engineers knew that NASA and all the other interested parties, including the managers at Morton Thiokol, knew there were problems. So when the engineers gathered together their charts to make their recommendation the night before the *Challenger* launch, they went into the room to *remind* everyone in the chain of command what everyone already knew. The charts were not new to anyone, and the information in them and the implications of that information were not news.

It is also important to note that NASA's decision in August to continue the flights, despite knowing there were potentially catastrophic problems with no known cause, made futile any later recommendation that no further shuttle launches should occur at

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k. Morton Thiokol had on hand a number of unused boosters, representing a considerable investment, and NASA's judgment may have been partially influenced by the waste of money were those boosters not used.

any temperature. NASA's decision in August to continue flights forced the engineers to choose, regarding *Challenger*, some temperature below which flights could not occur, and, as we shall see, 53°F was the obvious choice.

(2) They tried to determine the cause—Ignorant of the cause, and trying not to overlook any possibility, Roger Boisjoly compiled a list in September 1985 of information the engineers thought they might need to determine what variables were relevant to the effects they had observed. Among the items listed was the ambient air temperatures at launch since the engineers knew only that the O-rings on STS 15 and 22 were calculated to be 53°F and 75°F respectively at launch.[1 (p.44)]

Tufte never says that the engineers had the temperature data at hand, but he implies they did by suggesting they should have presented the scatterplot he developed. In describing his work, one writer says that Tufte goes through the charts "[w]ith heartbreaking thoroughness" and "demonstrates how one simple graph of the data *they had at hand*—information about the failure of the booster rocket's O-rings at various temperatures—would have alerted them to the dangers they faced" (our italics).[8 (p. 276)] In fact, to repeat, they did not have that data—though not for want of trying.

In addition, finding out the ambient air temperature at time of launch is not the same as determining the temperature of the O-rings at that time. In Arnie Thompson's plate experiment where an O-ring was placed in a groove on one steel plate and compressed by another, there had to be "temperature conditioning of the assembly",[7(p.1)] that is, the engineers had to be sure that all the components were at the chosen temperature for the test. For example, an O-ring taken from storage for test at 100°F would not be at 100°F until it warmed up. Similarly, even if one knows the ambient air temperature at the time of launch, one still needs to calculate the temperature of the O-ring. STS 15 had been sitting out in temperatures below 50°F for some days, and the calculation was that the O-ring was 53°F when the ambient air temperature at launch was 64°F. The O-ring temperature of STS 22 was calculated to be 75°F when the ambient air temperature was 78°F.[7 (p.6, fig.8)] So even if the engineers had had the data about ambient air temperatures, they would have needed more information to calculate with an acceptable degree of probability the temperature of the O-rings: how long was the shuttle on its pad? what were the variations in temperature during that time? how great was the variation? how long was the shuttle at each temperature? And so on. Calculating the O-ring temperature for each flight would have been demanding of time and energy—and not a worthwhile expenditure of a valuable resource, time, when the variable was not thought relevant.

The data necessary for a calculation of O-ring temperatures was thus not collected all along during the shuttle history. When Boisjoly asked for that data in September, along with much other data, any one of which might have been the crucial missing piece to explain the anomalous cause, it was not supplied. In fact, the engineers received none of the data they requested.

To summarize, the engineers did what they were professionally and ethically obligated to do: (1) they informed those in authority, and (2) they tried to determine the cause. Arnie Thompson's plate experiment was part of the effort to determine the cause, and his suggestions to add shims and increase the diameter of the O-rings were part of what they did to make the best of a bad situation. They did what they could to mitigate the problem given NASA's decision to continue the flights despite knowing of the risk of catastrophic failure.

8. The engineers' reasoning

It is with trepidation that one tries to reconstruct how a decision was made, particularly when it is a joint decision of different individuals who may have had different understandings and intentions, when it was conveyed under hectic conditions, and when those making the decision were not called upon to justify it until long after it was made. Nonetheless, what the engineers knew and did not know at the teleconference gives a clue to their reasoning.

First, the blow-by on STS 22 was a crucial field confirmation of Arnie Thompson's plate experiment as were the differences in the amount and color of the soot in STS 22 and STS 15. It does not take a rocket scientist to fear a line of increasing blow-by from 75°F to 53°F to 29°F and thus an increasing risk of catastrophic failure. The argument here is not an argument from analogy, using a single problematic case as its basis. It is an inductive inference based on a correlation between increasing blow-by at lower temperatures and a theory about what was wrong, i.e. O-rings become less resilient the colder the temperature.

This is not in and of itself a very strong argument. Two instances of a correlation do not generally provide powerful grounds for an inference. On formal grounds, that is, no one ought to accept the conclusion that blow-by will increase at 29°F. However, in conditions of uncertainty and risk, engineers operate with a decision-procedure that the rational choice is to avoid unusual risk. Using that decision-procedure, the argument is far more powerful. Both experience and experiments suggest that if one is to be risk-averse, one ought not to recommend launching a shuttle at a colder temperature, particularly at a temperature so much colder than 53°F as the ambient air temperature of 29°F projected for *Challenger* at launch.

Second, the engineers knew that they did not *know* that decreased temperature was correlated with greater blow-by. They could at most infer the likelihood of an increased risk. However they were arguing with full knowledge that the design was flawed and without knowledge of the complete causes of the blow-by. Both NASA and the Morton Thiokol managers were also aware of this lack of information.

Third, ignorance of the cause of the problem plays an additional role in the engineers' reasoning. While it is always risky to attribute a single view to a group of individuals, and even more risky when the view is never fully articulated and put to paper, hovering in the background during the teleconference was the engineers' belief that no shuttles should be launched until the problem was found and fixed. If blow-by occurred at 75°F, it could occur at any temperature, and the secondary O-ring becomes primary. That was unacceptable. The engineers had made this argument to NASA in August and lost and so felt precluded from making it again. Instead, they recommended that there be no launch outside their *field database*. As Tufte puts it, in a line which sums up the general premise from which the engineers were arguing, though Tufte does not recognize that, "This launch was completely outside the engineering database accumulated in 24 previous flights."[1 (p.45)]

Engineers distinguish carefully between test data and field data—experimental evidence and experiential evidence. They are cognizant, as Tufte rightly implies they should be, that what is shown in tests may not hold under real conditions. One premise of their decision-procedure is thus that *experience trumps experiments*. Though they knew that the tests in Utah showed that the O-rings had held without blow-by or erosion under cold down to 48°F,[1] these were experiments. Experience showed that at 53°F they had significant blow-by. They had done no experiments to determine what would happen when the temperature was in the high twenties or low thirties. A launch at the expected temperature of 29°F was far outside the field database.

The engineers did not correlate temperature and blow-by even though their recommendation tied together risk and temperature because they had only four pieces of data—the differing amounts of blow-by at the calculated O-ring temperatures of 75°F and 53°F. One does not need a scatterplot to make the point that it is risky to fly at an ambient air temperature of 29°F given what had happened when O-rings were at 75°F and 53°F. In any event, given that they were not sure that they knew the cause of the blow-by problem, the engineers' basic premise was that *Challenger* would be flying "beyond their database".

9. Tufte's misrepresentation

Tufte's concern is with the visual representation of data, but one can also represent information in a narrative form. Just as there are criteria for graphic representations, as Tufte nicely lays out in his works, there are criteria for narrative representations, criteria that can vary depending upon what is being represented.

In representing historical events in which the actions (and omissions) of historical personages are the focal point, for instance, one tries to take on their point of view—their place in time and in space—as much as possible. It would be an odd kind of "history" indeed which faulted Caesar for not foreseeing his death at the hands of Brutus, or queried why, given what was going to happen, Robert E. Lee ordered Pickett's charge at Gettysburg. Such criticisms would come from taking a point of view that assumes these historical personages were somehow privy to current understanding of the results of their acts. The minimal condition required in writing of historical personages is that one restrict the database to what was, or ought to have been, available to those who were deciding what to do. It is still possible to find fault

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1. The ambient air temperature was 40°F while the temperature of the O-rings for that flight was calculated to be 48°F. See "History of O-ring Temperature" in Table 2.

with what they did—Lee's order at Gettysburg seems misconceived even given what he knew—but it would be unfair to fault anyone for not knowing what would happen.[m]

Tufte has said that he is not interested in history: "I'm not particularly interested in who did what first, or development. Because it is one damned thing after another. It's unconceptual."[9] Yet Tufte's judgment of what the engineers should have done the night before the launch requires an historical appreciation of where they found themselves. It was "one damned thing after another", and the frustrating part for the engineers was that they lacked the data—despite having asked and even pleaded for it—to back up their collective sense that the flight should not be launched at such a temperature. Tufte presumed wrongly that the engineers had full information. Given the conditions for judging ethically whether a person is morally responsible, he inferred from that presumption and the presumption that the engineers acted voluntarily that they were incompetent. Tufte has taken, as it were, a God's eye view of the data, faulting the engineers for providing only a few temperature data points and not properly connecting those with the known effect. People are historical beings and can, at best, make decisions that reflect the data they have. They can do a good job of that or a bad job, and may fail to have data they should have and could have, but it is ethically wrong to upbraid them for not making a decision not even God could have made if God were restricted to the only evidence available.

Those few data points were all the engineers had. They did not connect them with temperature because they suspected, but did not know, that cold and O-ring compromise were causally related; indeed, they were not arguing that they were. Tufte's analysis does not accurately represent the engineers' position. With the data available to them, and with NASA knowing as well as they that the design was flawed and that temperature might be a causal factor, the engineers argued that the *Challenger* ought not to fly so far out of the field database, the firmest evidence available.

However, data is not all that counts. As Tufte argues well, one can have the most powerful position possible for something and completely fail to convince anyone if the presentation is poor. Both the presentation of data and the arguments that inform it are crucial.

Tufte's scatterplot well represents the point he wants to make, but he has the wrong data. The scatterplot is preceded in his text by Table 1:[n]

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m. It is not unfair, however, to fault those who do not know what they could have known and should have known. It is a moral complaint against President Reagan that he could and should have known about the Iran-Contra scandal—assuming, of course, that he did not know. The difficulties do not lie in that general principle, but in its application to particular cases. Drawing the line between what it is reasonable to expect people to know and what would not be reasonable can be a difficult matter.

n. Tufte has printed his books in order to ensure that the tables and illustrations are done properly. We cannot replicate the following table as we should because in the original, nine numbers are shown in red. These are the data "exhibited at some point in the 13 pre-launch charts" with the data in black not included.[1 (p.44)] The data in red are: two temperatures—53° for STS 15 (51-C in the chart) and 75° for STS 22 (61-A in the chart); five erosion incidents—all except the one for STS 24 (41-B); and both blow-by incidents.

Table 1: Data Matrix Table [1 (p.44)]

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Flight	Date	Temperature °F	Erosion incidents	Blow-by incidents	Damage index	Comments
51-C	01.24.85	53°	3	2	11	Most erosion any flight; blow-by; back-up rings heated.
41-B	02.03.84	57°	1		4	Deep, extensive erosion.
61-C	01.12.86	58°	1		4	O-ring erosion on launch two weeks before Challenger.
41-C	04.06.84	63°	1		2	O-rings showed signs of heating, but no damage.
1	04.12.81	66°			0	Coolest (66°) launch without O-ring problems.
6	04.04.83	67°			0	
51-A	11.08.84	67°			0	
51-D	04.12.85	67°			0	
5	11.11.82	68°			0	
3	03.22.82	69°			0	
2	11.12.81	70°	1		4	Extent of erosion not fully known.
9	11.28.83	70°			0	
41-D	08.30.84	70°	1		4	
51-G	06.17.85	70°			0	
7	06.18.83	72°			0	
8	08.30.83	73°			0	
51-B	04.29.85	75°			0	
61-A	10.30.85	75°		2	4	No erosion. Soot found behind two primary O-rings.
51-I	08.27.85	76°			0	
61-B	11.26.85	76°			0	
41-G	10.05.84	78°			0	
51-J	10.03.85	79°			0	
4	06.27.82	80°			?	O-ring condition unknown; rocket casing lost at sea.
51-F	07.29.85	81°			0	

Table 1, taken from Tufte, does not indicate whether these are ambient air temperatures or temperatures of the O-rings, but this Table is preceded in Tufte's text by the engineers' "History of O-ring Temperatures".

Table 2: History of O-Ring Temperature [1 (p.42)]

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HISTORY OF O-RING TEMPERATURES
(DEGREES - F)

MOTOR	MBT	AMB	O-RING	WIND
DM-4	68	36	47	10 MPH
DM-2	76	45	52	10 MPH
QM-3	72.5	40	48	10 MPH
QM-4	76	48	51	10 MPH
SRM-15	52	64	53	10 MPH
SRM-22	77	78	75	10 MPH
SRM-25	55	26	29 27	10 MPH 25 MPH

Tufte says of Table 2, "While it was true that the blow-by on SRM 15 was on a cool day, the blow-by on SRM 22 was on *a warm* day at a temperature of 75° (temperature chart [referring to Table 2], second column from the right)."[1 (p.42)] Tufte's assumption seems to be that the ambient air temperature and O-ring are the same—despite the engineers' chart indicating differences between the two. If Tufte is not making that mistake, it would be hard to explain either the scatterplot (Figure 1) or his remarks on the engineers' table (Table 2) since both list temperature as one variable. The scatterplot refers to it as "Temperature (°F) of field joints at time of launch", but Table 2, provided by the engineers, distinguishes between the ambient air temperature (the third column) and the temperature of the O-rings (the fourth column), giving known and calculated figures for STS 15 and 22 and predicted and projected figures for *Challenger* (STS 25) on the morning of the launch. The blow-by on STS 22 did occur "on a *warm* day", as Tufte says, but the ambient air temperature was 78°F, not 75°F. The latter temperature, along with the 53°F indicated for STS 15, is the calculated temperature of the O-rings at the time of launch. The other temperatures Tufte lists on Table 1 are of the ambient air at time of launch. Tufte has mixed apples and oranges. Tufte thus has both coordinates on the scatterplot wrong. The vertical axis should be "blow-by", not "O-ring damage", and the horizontal axis should be "O-ring temperature", not a mixture of O-ring temperature and ambient air temperature.

10. Moral Responsibility

Were the engineers morally responsible for the *Challenger* disaster? There are at least four reasons for judging they were not.

First, if they had had all the data readily at hand, they could be faulted, but they did not.

Second, someone who makes a judgment based on lack of information is prima facie not morally responsible if there was a good-faith effort to obtain that information.

Third, someone who tries to rectify the situation that may be causing the problem is less responsible than someone who ignores the problem, and the engineers did what they could given the cards they were dealt. They tried to gather more information to get a definite fix on the problem, made such adjustments as adding shims as Arnie Thompson suggested, and brought the problem to NASA's attention. They lacked the power to halt the flights, and they exercised the only powers they had and did so in a timely manner.

Fourth, they succeeded in convincing their managers originally—if only because they had a collective sense that a launch should not occur and were, after all, the best positioned to make such a judgment. The managers overturned that recommendation when NASA refused to accept it and changed the burden of proof by asking for evidence that *Challenger* was not flight-ready. By shifting the burden of proof, NASA shifted from a risk-averse decision procedure to a decision procedure congenial to high fliers, willing to risk catastrophe unless it could be shown it would in fact occur.

This is not to say that the engineers' presentation was not flawed or that even if conceptually correct, could not have been better done. It is to say that they should not bear the moral fault for a flight they had recommended against, especially since, under normal circumstances, they would have seen their recommendation upheld. Indeed it was not their recommendation that *Challenger* be launched. It was the recommendation of their managers at Morton Thiokol who took decision-making out of their hands**.**

Tufte asserts that the engineers were guilty of "an overriding intellectual failure"[1(p.52)] and of a "scandalous discrepancy between the intellectual tasks at hand and the images created to serve those tasks."[1 (p.45)] Tufte's analysis thus implies that they failed to save the lives of the astronauts by producing a scatterplot so clear that "no one would have dared to risk the *Challenger* in such cold weather".[1 (p.52)] This is a grave, and we believe, improperly substantiated accusation.

It would, of course, be wrong to criticize Tufte**'**s analysis had he tried to obtain the information about what the engineers knew, but could not for reasons beyond his control. However, as we have noted, all the information cited herein was available to Tufte had he sought it.

Clear and informative representation is an ideal to strive for. We conclude that Tufte**'**s analysis has dramatically failed to achieve this ideal in its critique of the engineers at Morton Thiokol. The narrative and scatterplot do Tufte's thesis a disservice because his criticism misrepresents the position of those being critiqued and fails to capture the problem they were facing. The damage caused by this analysis is magnified to the extent that the *Challenger* case is identified as a paradigmatic example of what can go wrong when not achieving what Tufte argues is the ideal.

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