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To Engineer is Human
The Role of Failure in Successful Design
by
Henry Petroski

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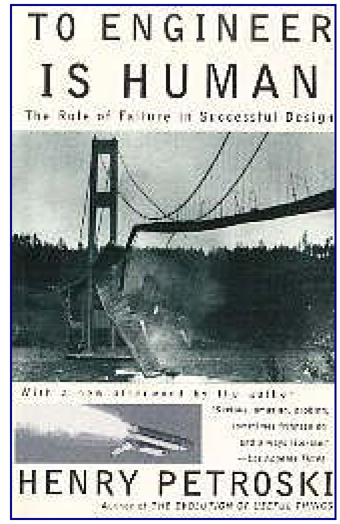

My first experience of Henry Petroski's work came through studying and reviewing his 2006 book, Success Through Failure, of which this current book is a predecessor and an early introduction to his theme. It came to my attention when I was searching for a book in my library and the name Petroski caught my eye on the binding edge. Here was my chance to read a precursor to a recent book and discover the underpinnings of Petroski's latest work. The cover of the book contains the famous photo of the Tacoma Narrows bridge collapse, a clear indication of his theme of investigating engineering failures to uncover their roots and to provide for safer designs for future projects. To engineer is human and to obviate the failure of designs is divine, one might say. Human designs fail because a successful design will challenge new engineers to tackle some improvement upon it and with that improvement comes a concomitant risk. "Make it lighter and less expensive while maintaining its function and safety", the customer might request. Or maybe "Place a walkway in mid-air over the hotel lobby in the Atrium," as Hyatt-Regency requested for a shortcut in its Kansas City location. The key to successful engineering is to "get the customer to relax their specifications", someone once told me. Certainly, telling the customer the walkway would be unsafe was an option, but the engineers chose to meet the customer's specs with a design which was safe, but one which neglected the difficulty of implementing it, and that led to a collapse of the walkway and 114 deaths.

To create a vehicle which never broke down was the subject of a poem by Oliver Wendell Holmes called The One Hoss Shay. By making every part as strong as the other, the designer assured its owner and users that there would be no weak link, that all parts would last equally long. But the logical conclusion to such a design is humorously played out when one day the entire shay falls completely apart. All the parts failed at the same time! In my work as a writer, my keyboards are subjected to constant wear, but this wear has a pattern which becomes obvious over time: the most frequently used letters in the English language tend to have their letters wear off the keys before the other ones. As a typist who learned to type without looking at the keys, this is a minor inconvenience to me at times. For example, when I have to enter some special codes which require me to look at the keys, I find that the I-O, K-L, M-N keys are blank and I have to consciously choose which of the adjacent keys are the I and O, etc. Samuel Morse designed his Morse code by counting the amount letters in each bin of a manual typesetter's work station, the E being the most frequent was chosen to be a DOT and the T the next most became the DASH. Today he could have looked at a heavily typed upon keyboard to make his code.

The Japanese recognized the dilemma posed by differential wear of components in a machine, and I remember hearing that the Japanese, when they performed a repair on a machine, replaced the broken part with a part that was stronger than the original part. I have used that same principle in repairing items around the house. My wife's hot roller hair curlers fit into a tray of metal cylinders which each heated up. One day she called me and said, "It's not working." I found that the on-off switch was defective, and I searched my box of repair parts and found a sturdy metal toggle switch which I installed in the place of the cheap, mass-produced plastic part which had lasted only a year under normal use. Now, 20 years later my wife was still using those hair curlers when the heating coil broke, and she had to buy another set. If after the switch broke she had bought another set, it might have lasted 2 years and she would have gone through about ten sets of hair curlers! The cheap switches on modern small appliances are often the first parts to break. My one-cup coffee pot that I used for almost twenty years lasted so long because I put it on a power strip to turn it off and on instead using the cheap plastic switch. If you want to extend the life of a device, replace the weakest link with a stronger part or find a way to avoid using it before it breaks.

Engineers are always trying new designs, and new designs are fraught with potential failures. No engineer can test a device for ten years to ensure it will last ten years. Ultimately the customer is the test bed for products engineered for consumers. We pay engineers to allow us to test their products. Recent experience of drivers of Toyotas (runaway accelerators) and GM's Volts (batteries catching fire) evince this *modus operandi*. I think of this process as the *pioneers get the arrows* and have learned to avoid the latest and greatest technology until other customers have tested it for me.

> **[page 62, 63] No one wants to learn by mistakes, but we cannot learn enough from successes to go beyond the state of the art. Contrary to their popular characterization as intellectual conservatives, engineers are really among the avant-garde. They are constantly seeking to employ new concepts to reduce the weight and thus the cost of their structures, and they are constantly striving to do more with less so the resulting structure represents an efficient use of materials. The engineer always believes he is trying something without error, but the truth of the matter is that each new structure can be a new trial. In the meantime the layman, whose spokesman is often the poet or the writer, can be threatened by both the failures and the successes. Such is the nature not only of science and engineering, but of all human endeavors.**

Engineers who strive to design based on success also face two big problems which are not obvious, problems often uncovered only after a failure. The first is that the apparently successful structure could be in the process of failing without anyone knowing. The second is that the re-design to make the new bridge lighter and cheaper may cause the modified structure to fail.

> **[page 73] Thus a bridge that has stood for decades but has developed innocuous cracks in certain spots may serve as the basis for an improved design of a bridge of approximately the same dimensions and traffic requirements. Or an existing design that has suffered no apparent distress after years or decades of service may lead the engineer to look for ways to make it lighter and thus less expensive to build, for the trouble-free prototype appears to be over-designed.**

Under the topic of design as revision, Petroski waxes eloquent when comparing engineering design to writing. Both fields are faced with the contradictory aims of leading people down a new road but following familiar landmarks all the way, the dilemma of producing the original using the familiar.

> **[page 75] There is a familiar image of the writer staring at a blank sheet of paper in his typewriter beside a wastebasket overflowing with crumpled false starts at his story. This image is true figuratively if not literally, and it represents the frustrations of the creative process in engineering as well as in art. The archetypal writer may be thought to be trying to put together a new arrangement of words to achieve a certain end . . . The writer wants the words to take the reader from here to there in a way that is both**

> **original and familiar so that the reader may be able to picture in his own mind the scenes and the action of the story or the examples and arguments of the essay. The crumpled pages in the wastebasket and on the floor represent attempts that either did not work or worked in a way unsatisfying to the writer's artistic or commercial sense. Sometimes the discarded attempts represent single sentences, sometimes whole chapters or even whole books.**
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> **Why the writer discards this and keeps that can often be attributed to his explicit or implicit judgment of what works and what does not. Judging what works is always trickier than what does not, and very often the writer fools himself into thinking this or that is brilliant because he does not subject it to objective criticism. Thus manuscripts full of flaws can be thought by their authors to be masterpieces.**

Engineering structures may be full of flaws, but it is the job of good engineering to flush out and remove the flaws during design and to provide for the structure to stand if any one piece were to fail. No one ever imagined that a 100-story skyscraper could collapse to the ground, much less two standing close by, before September 11, 2001. The intense heat of a jumbo airliner's full tank of jet fuel catching fire in an upper story was never calculated as a risk. The failure of one floor's support beams due to that heat caused the entire structure to collapse to the ground. Skyscrapers will be designed differently as a result of that dual catastrophe.

Paradoxically, designing from successes can also fail.

> **[page 98] While engineers can learn from structural mistakes what not to do, they do not necessarily learn from successes how to do anything but repeat the success without change. And even that can be fraught with danger, for the combination of good luck that might find one bridge built of flawless steel, well-maintained, and never overloaded could be absent in another bridge of identical design but made of inferior steel, poorly maintained or even neglected, and constantly overloaded. Thus each new engineering project, no matter how similar it might be to a past one, can be a potential failure.**

Relax, however, because there is a margin of error which is built in to take care of the unk-unk's, the buzzword for the unknown-unknowns. This called the *factor of safety*, focusing on the positive aspects of the problem, safety instead of error.

> **[page 98] No one can live under conditions of such capriciousness, and the anxiety level of engineers would be high indeed if there were not rational means of dealing with all the uncertainties of design and construction. One of the most comforting of means, employed in virtually all engineering designs, has been the factor of safety.**
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> **The factor of safety is a number that has often been referred to as a "factor of ignorance," for its function is to provide a margin of error that allows for a considerable number of corollaries to Murphy's Law to compound without threatening the success of an engineering endeavor. Factors of safety are intended to allow for the bridge built of the weakest imaginable batch of steel to stand up under the heaviest imaginable truck going over the largest imaginable pothole and bouncing across the roadway in a storm.**

But some well-meaning engineers can come, over time, to see that *factor of safety* as unnecessarily large and they decide to pare it down as a means of saving money and improving the design. Therein lies another danger which comes from a step into the unknown.

> **[page 101] Confidence mounts among designers that there is no need for such a high factor of ignorance in structures they feel they know so well, and a consensus develops among designers and code writers that the factor of safety for similar designs should in the future be lowered. The dynamics of raising the factor of safety in the wake of accidents and lowering it in the absence of accidents clearly can lead to cyclic**

> **occurrences of structural failures. Indeed, such a cyclic behavior in the development of suspension bridges was noted following the failure of the Tacoma Narrows Bridge.**

In his chapter "Interlude: The Success Story of the Crystal Palace" Petroski goes into great detail about the building of the mid-19th Century exhibition hall in London's Hyde Park. Skeptics railed against the project, saying it would be unsafe, couldn't be built in time, would not survive a storm, etc. Joseph Paxton designed the Palace based on the greenhouse he had built earlier, but building the huge Exhibition required innovation techniques for assembling and constructing buildings. His completed project was so successful that its methods were adopted by large exhibition halls and led to the construction techniques used today in modern iron and glass skyscrapers. It was the "first building constructed using prefabricated, standardized units that were shipped to the construction site for rapid assembly." (Page 151)

> **[page 149] Yet, although the true skyscraper did not really come into its own until the twentieth century, the Crystal Palace prefigured it in many important ways. The light, modular construction ingeniously stiffened against the wind is the essence of modern tall buildings. And the innovative means by which the walls of the Crystal Palace hung like curtains from discrete fastenings, rather than functioning as integral load-bearing parts of the structure, is the principle behind the so-called curtain wall of many modern facades.**

Petroski takes up the problem with the de Havilland Comet 4 airplane which began to have unexplained crashes, seemingly falling apart in mid-air. Finally submerging a complete aircraft underwater and pumping air into it, the engineers began to simulate the compression and decompression of the aircraft over thousands of flights and the aircraft literally explode during one of the compressions. The trouble was then discovered to be associated with stresses on rivet holes near the window openings in the fuselage. The problem was fixed and the Comet 4 began to fly once more. This aircraft engineering incident was prefigured by a novel written by Nevil Shute (author of "On the Beach") in his novel, "No Highway". By coincidence my wife and I had watched a movie of this novel named "No Highway in the Sky" just before I read about the Comet. An engineer named Theodore Honey was doing some structural analysis and the theoretical calculations of his equations showed that the Reindeer aircraft of his own company would lose a tail section after 1431 hours of flying stress and vibration. He had acquired a full-sized Reindeer for his laboratory and had devised hydraulic arms to create those flying stresses. Before his simulation had run up to the full 1400 hrs, a Reindeer crashed off Nova Scotia and he was quickly dispatched to the site. Unbeknownst to him at takeoff he was flying in a Reindeer which would exceed the 1400 hrs before they reached Nova Scotia and would apparently take Honey (Jimmy Stewart) and a famous actress (Marlene Dietrich) and all the passengers and crew to their deaths in the icy waters of the North Atlantic. Here's the climax of the story.

> **[page 182] But the technocrats do not accept his theoretical calculations as relevant to the practical matter of real airplanes, even though fatigue problems accompanied the introduction of other new forms of transportation technology, such as the railroads. Thus Honey sets out to collect evidence from a Reindeer that had crashed in Canada after about the same number of flying hours as predicted by his calculations. That crash was attributed to simple pilot error, and hence an exhaustive investigation of the wreckage was not considered necessary to provide any essential evidence to the contrary. So Honey flies to Canada himself to collect the evidence of a fatigue failure that he is sure is lying there in the snow. While en route, Honey discovers that the plane he is traveling on is a Reindeer with about fourteen hundred hours of flying time, and thus he fears that its own tail plane will fall off at any moment due to metal fatigue. After his frustrated attempts to convince the crew to keep the plane on the ground at Gander, a refueling stop, until it can be properly inspected for dangerously large fatigue cracks, Honey keeps the Reindeer from taking off by sabotaging the landing gear. His uncommonly violent act convinces his superior to aid Honey in continuing his quest. When the wreckage in Canada is finally reached, the telltale signs of fatigue vindicate**

> **Theodore Honey, and a dangerous fatigue crack is also found in the grounded Reindeer at Gander.**

Here we have a case of fiction preceding fact, so closely did the case histories of the Comet and the Reindeer parallel each other. Six years after the novel and three years after the movie, the Comet model suffered two fatal crashes due to metal fatigue. Thankfully, Shute was more prescient in that novel than in his doomsday novel "On the Beach".

When I entered college destined for a degree in physics I acquired my first slide rule. It was a small slide rule compared to the monstrosities which dangled from the side of engineers. I needed simple calculations in my endeavor to learn how the world worked and engineers needed complicated log-log and other scales to figure out how to make the technology and structures of the world work. I learned about significant digits, how slide rules can provide slightly over 3 digits of significant information, and how to remove excess and meaningless digits from my calculation results. When I worked on the early process computers in the 1960s, I found that significant digits were important again, this time due to the limitations of storing a floating point number in the computers' 24-bit word. The exponent was stored in 8 bits and the mantissa in 16 bits, giving 2 to 2 to the 8th power for the exponent, or 10 to the 8th power. More than enough exponent for chemical plant calculations. The mantissa, however, could only approximate 4.5 significant digits (2 to 16th power is 65,536, which provides 4 full digits, but not quite 5). That was better than the best slide rules could do at the time and engineers never complained about their calculations, taking the 4.5 digits as the best they could depend upon. Later I worked in a mini-computer factory in 1970 and the eight binary digits of the exponent were treated as exponents of hexadecimal or base-16 digits which gave an exponent of astronomically large size, 16 to the 256th power or about 10 to the 306th power, an enormously larger exponent, using the same eight bits! The mantissa was also treated as hexadecimal digits and we never bothered any more with significant digits, especially with the availability of double-sized floating numbers which were optional for applications requiring extraordinary accuracy. If you weren't sure of how much accuracy you needed, you used double-floating point calculations.

Today engineers have switched to hand-held calculators and PCs and most have never heard of significant digits. But for those of you who haven't, try this simple test which will only take seconds on your calculator: take a simple calculator and enter 2, hit the X (times) button, the = (Equals) button. That amounts to successive doubling or squaring of the result. Then hit the Square Root button the same number of times and you should get 2 again, right? Right, except if you exceed the significant digits of the machine! Then you will not get 2 exactly but only an approximation of 2, maybe 1.9999999995 if your machine has ten significant digits. My TI-1795 antique twentieth century calculator gives me an error if I try to square 65,536 because that exceeds the display width of eight digits which is likely coordinated with the number of significant digits the machine can contain. Machines with floating point capability will allow you go higher and when you take successive square roots will give you some approximation of 2, like 1.9999999995 due to exceeding the significant digits of the machine. In spreadsheets the number of significant digits is disguised because you decide on the size of digits to display, but a calculation like the above will reveal to you the actual significant digits.

Why bother with all this? Because if you pretend to have more significant digits than your computing device provides, your detailed engineering calculations may go askew without your knowing it, and the structure you designed may fall into ruin through the failure of some inadvertently under-designed part. With the loss of slide rules, we have lost the reason to train engineers about significant digits. *We have lost the significance of significant digits!*

> **[page 193] Engineering faculty members, like just about everyone else, got so distracted by the new electronic technology during the 1970s that more substantial issues than price, convenience, and speed of computation did not come to the fore. The vast majority of faculty members did not ask where all those digits the calculators could display were going to come from or go to; they did not ask if the students were going to continue to appreciate the approximate nature of engineering answers, and they did not ask whether**

> **students would lose their feel for the decimal point if the calculator handled it all the time. Now, a decade after the calculator displaced the slide rule, we are beginning to ask these questions, but we are asking them not about the calculator but about the personal computer. And the reason these questions are being asked is that the assimilation of the calculator and the computer is virtually complete with the newer generations of engineers now leaving school, and the bad effects are beginning to surface. Some structural failures have been attributed to the use and misuse of the computer, and not only by recent graduates, and there is a real concern that its growing power and use will lead to other failures.**

How quickly did slide rules disappear from shelves of bookstores after calculators became popular? The company Keuffel & Esser should know as they were the primary manufacturer of slide rules, especially the complicated engineering pendants in their tooled leather sheaths. But when the company paid for a study of the future: they completely missed the abrupt disappearance of their own product! Engineering teaching and practice were changing under their K&E's feet and they never looked down.

> **[191] But it was not then widely known, and as late 1967 as Keuffel & Esser commissioned a study of the future that resulted in predictions of domed cities and three-dimensional television in the year 2067 — but did not predict the demise of the slide rule within five years.**

During the time of slide rules, structures were often over-designed with large factors of safety. Engineers avoided complex structures because the calculations were so time-consuming and expensive. With complex computer modeling, these complicated structures can be built and their designs optimized, but that comes with a cost. The cost can be predicted if you know what I call, Matherne's Fundamental Theorem : *With every advantage, there is an associated, and not obvious, disadvantage.* The not-obvious disadvantage of the optimized design is clearly the reduction of the *factor of safety* — the margin of error becomes smaller and engineers may not be noticing the number of significant digits in their calculations and computer modeling programs. Disadvantage for the engineer translates into premature structural failure of a design which had passed all inspections, such as the Tacoma Narrows Bridge, the Hyatt Regency Skyway, and the DC-10's pylon flanges.

In this next passage, Petroski shows off his sense of humor several times as he makes important observations for the engineers faced with newer and more powerful computers every day.

> **[page 195] The electronic brain is sometimes promoted from computer or clerk at least to assistant engineer in the design office. Computer-aided design (known by its curiously uncomplimentary acronym CAD) is touted by many a computer manufacturer and many a computer scientist-engineer as the way of the future. But thus far the computer has been as much an agent of unsafe design as it has been a super brain that can tackle problems heretofore too complicated for the pencil-and-paper calculations of a human engineer. The illusion of its power over complexity has led to more and more of a dependence on the computer to solve problems eschewed by engineers with a more realistic sense of their own limitations than the computer can have of its own.**

Should we design more and more complex structures, given the plethora of new design aids engineers have at their disposal. Yes, but there is a serious caveat, as serious as the one Daedalus gave his son Icarus, "Don't fly too close to the Sun." Engineers should keep this epigram posted on their desktops. Engineers in early days had a feel for the structures they designed, they could walk around it during its construction and that gave them a close personal experience which one cannot receive from a computer printout or analysis of a proposed structure.

> **[page 200, 201] And as more complex structures are designed *because* it is believed that the computer can do what man cannot, then there is indeed an increased likelihood that**

> **structures will fail, for the further we stray from experience the less likely we are to think of all the right questions.**

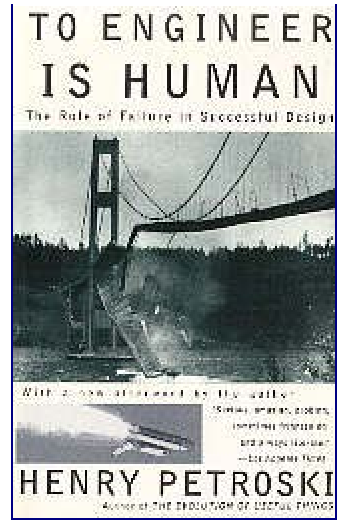
Petroski says that, "More than ever before, the challenge to the profession and to educators is to develop designers who will be able to stand up to and reject or modify the results of a computer aided analysis and design." Educators must ensure that their charges learn this process well enough to build structures which will endure for the lifetimes of use they predict. And they must teach new engineers to understand the implications of the paradox of design he outlines below.

> **[page 163] The paradox of engineering design is that successful structural concepts devolve into failures, while the colossal failures contribute to the evolution of innovative and inspiring structures.**

When I chanced upon the idea of how dolphins and other cetaceans communicate with each other, I began a search through the literature. My first stop was with John Lilly, and I wrote about my idea in the review I did of his book, Lilly on Dolphins. Through my research, I envisioned a method of two-way communication with dolphins based on the way I understand them speaking and hearing through the receiving and transmitting of moving pictures. What Lilly and his crew attempted was to my mind as silly as trying to interpret television images dolphins were emitting using a radio receiver to change them into words! To communicate my vision for the first inter-species communication, I decided against a scientific treatise, and chose instead creative writing, a novel. The Spizznet File contains my expounding of the engineering design required for communicating with dolphins, and, in Petroski's book, I found an author recommending such an approach to bring an innovative idea to the technical community.

> **[page 21] No individual's list of the causes of failures or choices of case studies or of categories in which to put them or of lessons to be drawn from them is likely to satisfy everyone, and hence all such attempts are likely to be doomed to failure themselves. However, there is another, technologically unorthodox method of expounding on engineering design and structural failure that has the advantage of being at the same time less precise and more thought provoking. That is the method of creative writing, in which the plot of a novel or a narrative poem is constructed around a technical idea. Superficially the story can be entertaining while its message or moral can have profound implications. Furthermore, since fiction and poetry are open to interpretation, each reader can bring his own experiences and take away his own wisdom. And if the technological ideas are correct and consistent, the technical community will sit up and read.**

As long-standing designs are taken as a sign of success, engineers modify them, and the previous path that led to "success ultimately leads to failure: aesthetic failure, functional failure, and structural failure. The first can take away the zest for life, the second the quality of life, and the third life itself." (Page 222) I can think of no better way of ending this review than the way Petroski did his book, with a quotation by George Santayana, "We must welcome the future, remembering that soon it will be the past; and we must respect the past, knowing that once it was all that was humanly possible."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