Reference Guide on Engineering Practice and Methods

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I. Introduction

The products of engineering are everywhere, and it is unlikely that any person can spend a day without depending upon engineering of some kind for basic human needs, including health, food, and shelter. The very foundations of material civilization, in the form of its infrastructure and physical systems, are the results of deliberate engineering design. Even those things that have been in place for virtually the entire twentieth century and that now seem so mundane and are so often taken for granted, like the distribution networks that put clean water and ample electricity at our fingertips, require ongoing engineering monitoring and maintenance to ensure their reliability. Just as we have come to expect water and electricity to be givens of modern society, so we have come to expect automobiles to be in our garages and gasoline to be around the corner. These things would not be so without engineering.

Most people today tend to give scant notice to the marvels of engineering that once awed visitors to great exhibitions and world's fairs. It seems to be only when something goes wrong—a utility service is interrupted, the car does not start, or the computer crashes—that we take notice of engineering. And when something goes really wrong and results in injury or death, engineering tends to be not only noticed but also blamed and its practitioners held responsible. When blame results in litigation, the judge must make an assessment of the testimony offered by engineers in relation to the methods, customs, and practices of the profession.

II. Engineering and Science; Engineers and Scientists

A. Engineering and Science

The distinction between engineering and science, and between engineer and scientist, is not often made, yet it can be clearly stated: Science in its purest form theorizes about nature as it is found; engineering at its most basic re-forms the raw materials of nature into useful things. "The scientist seeks to understand what is; the engineer seeks to create what never was" is an oft-quoted way of putting it. Ironically, the quote is usually attributed to Theodore von Karman, who has been ambiguously identified at different times as a scientist and an engineer.

Many courts have struggled with this distinction. Until just recently the U.S. courts of appeals were split as to whether the *Daubert* standard for analyzing expert testimony of scientific evidence was applicable to engineering evidence.[1]

1. Daubert v. Merrell Dow Pharms., Inc., 509 U.S. 579 (1993).

Six courts held that the standard for scientific evidence should also be used for engineering evidence.[2] Four courts held that two different standards apply,[3] suggesting that scientific evidence and engineering evidence were quite different. The Eleventh Circuit concluded that "the Supreme Court in *Daubert* explicitly limited its holding to cover only the 'scientific context.'"[4] This issue was recently resolved by the Supreme Court in *Kumho Tire Co. v. Carmichael*.[5] The Court held that "[t]he *Daubert* factors *may* apply to the testimony of engineers and other experts who are not scientists."[6] The Court further noted that it would be difficult to distinguish "between 'scientific' knowledge and 'technical' or 'other specialized' knowledge, since there is no clear line dividing the one from the others . . . ."[7]

The fuzziness in the distinction between engineer and scientist can be attributed to the fact that what scientists sometimes do is engineering and the fact that engineers can make things that are not fully understood by scientists. A commonly given example of the former fact is that scientists were engaged in the Manhattan Project, whose purpose was the development of the first atomic bomb. A classic example of the latter fact is that the development of the steam engine by seventeenth- and eighteenth-century inventors (engineers) involved principles of nature that were not fully articulated by scientists until the advancement of thermodynamics in the nineteenth century. Indeed, it was the existence of working steam engines that prompted the development of the science of thermodynamics. For this reason, the science of thermodynamics is even more properly called an engineering science, that is, a science whose objects of study are not those that naturally occur in the universe, but those that are products of engineering, like the steam engine.

2. *See generally* Habecker v. Clark Equip. Co., 36 F.3d 278 (3d Cir. 1994); Freeman v. Case Corp., 118 F.3d 1011 (4th Cir. 1997), *cert. denied*, 522 U.S. 1069 (1998); Watkins v. Telsmith, Inc., 121 F.3d 984 (5th Cir. 1997); Smelser v. Norfolk S. Ry., 105 F.3d 299 (6th Cir.), *cert. denied*, 522 U.S. 817 (1997); DePaepe v. General Motors Corp., 141 F.3d 715 (7th Cir.), *cert. denied*, 525 U.S. 1054 (1998); Dancy v. Hyster Co., 127 F.3d 649 (8th Cir. 1997), *cert. denied*, 523 U.S. 1004 (1998).

3. *See generally* Bogosian v. Mercedes-Benz of N. Am., Inc., 104 F.3d 472 (1st Cir. 1997); McKendall v. Crown Control Corp., 122 F.3d 803 (9th Cir. 1997); Kieffer v. Weston Land, Inc., 90 F.3d 1496 (10th Cir. 1996); Carmichael v. Samyang Tire, Inc., 131 F.3d 1433 (11th Cir. 1997), *cert. granted sub nom.* Kumho Tire Co. v. Carmichael, 524 U.S. 836 (1998).

4. *Carmichael*, 131 F.3d at 1435 (quoting Daubert v. Merrell Dow Pharms., Inc., 509 U.S. 579, 580 n.8 (1993)).

5. 119 S. Ct. 1167 (1999).

6. *Id.* at 1169 (emphasis added).

7. *Id.*

B. Engineers and Scientists

Exactly who is a scientist and who is an engineer, and who is practicing science and who is practicing engineering are not always easy questions to answer. The educational background of individuals is no certain indicator, for it is not uncommon to encounter prominent "engineers" who do not have a single engineering degree, or individuals doing excellent "science" who have all of their degrees in engineering. Thus, on one hand, someone with three degrees in physics might be working on the foremost developments in computer storage devices, which are definitely products of engineering. On the other hand, an engineering faculty member educated as an engineer and specializing in electronic materials might also have a secondary academic appointment in a department of physics, definitely a science, and might be contributing original work to the literature of that field.

It is not uncommon to find, especially in a research-and-development context, an individual's position or title being given according to educational credentials rather than job description and vice versa. Membership in professional societies, however, very often does correlate with educational credentials, not only because individuals develop a loyalty to a profession and its organizations through student chapters but also because membership criteria are most easily satisfied by a degree in the relevant field. In contrast, professional certification, such as registration as a professional engineer, which in the United States is controlled by the individual states, can be obtained on the basis of experience and examination alone, regardless of educational credentials. Thus, for example, Jane Smith, P.E., who is responsible for the structural analysis of water-storage tanks, may have all of her degrees in mathematics. (In other countries, such as those of the British Commonwealth, professional registration is commonly under the auspices of professional societies or institutions.)

The most common route to registration or licensing as a professional engineer is for an individual to earn a bachelor's degree from an accredited engineering program (see section III.A.2). Such an individual can take the Fundamentals of Engineering examination during the senior year of college. Passing this eight-hour examination earns the individual the designation Engineer-in-Training (E.I.T.). The Fundamentals of Engineering is a standardized test, and hence the E.I.T. is recognized in all states of the United States. After gaining sufficient experience in responsible charge of engineering work, a person holding the E.I.T. designation may apply to a particular state board of registration to take a second examination in a specialty area, such as electrical engineering or mechanical engineering. Successful passing of this exam earns the individual the right to identify himself or herself as a Professional Engineer (P.E.) in the specialty area in which the P.E. examination was taken. There is reciprocity among states, but some are known to have more stringent requirements than others, for example, as to whether a new examination must be taken. It is not uncommon for a prominent consulting engineer with a nationwide practice to maintain registration in several dozen states.

An engineer registered as a P.E. is expected to adhere to a code of ethics. The elements of this code are often affixed to the application form that the engineer fills out to begin the registration process, and the engineer acknowledges awareness of the code at the time of application. (Many of the larger engineering societies have their own codes of ethics.) Increasingly, registered professional engineers are expected to participate in continuing professional development to maintain their registration. Whether such continuing professional development is mandatory currently varies from state to state.

Some states have special designations for certain engineering specialties. Thus, California and Illinois, which have special concerns about earthquake-resistant design and skyscraper design and construction, respectively, have separate registration procedures for structural engineers. Licensing and registration as a structural engineer in one of these states earns the individual the right to use the letters S.E. after his or her name.

Some engineering specialties have developed, independent of state registration laws, their own form of recognition and designation of professional practitioners. Thus, the American Academy of Environmental Engineers (AAEE) uses the term Diplomate Environmental Engineer (D.E.E.). The AAEE operates the specialty certification program, in which an engineer qualifies for the designation D.E.E. by holding a professional engineer's license, having at least eight years of progressively responsible civil engineering experience, and passing a peer review and examinations.[8] As another example, the American Institute of Hydrology (AIH), which includes the Society for Certification and Registration of Professional Hydrologists and Hydrogeologists, uses the terms Professional Hydrologist and Professional Hydrogeologist, among others, depending upon expertise, to designate engineers who it certifies and registers. Engineers practicing in such specialty areas may consider these designations to be more important than state registration as a P.E., and they may in fact consider them equivalent to the P.E. designation.[9]

Among the reliable indicators of who has done outstanding engineering are the prizes, awards, and distinguished membership ranks (such as Fellow) administered by professional societies and organizations. Although some of these recognitions are restricted to dues-paying members of the society and are thus of lesser reliability as indicators of true distinction, many of the most distinguished honors bestowed by the societies and institutions are independent of member-

8. *See* American Academy of Envtl. Eng'rs, *Board Certification Identifies Environmental Engineering Experts* (visited July 28, 1999) <http://www.enviro-engrs.org/experts.htm>.

9. *See* American Inst. of Hydrology home page (visited July 28, 1999) <http://www.aihydro.org>.

ship or educational background. Among the highest honors an American engineer can receive is membership in the National Academy of Engineering (NAE). That many of the members of the NAE were educated as scientists and have no degrees in engineering underscores the overlap between engineering and science. Indeed, many members of the NAE, including some who are engineers by education as well as by practice, are also members of the National Academy of Sciences, and a small number of these are also members of the Institute of Medicine.

In spite of this apparent open-mindedness and inclusiveness at the highest ranks of the profession, it is a common complaint among engineers who reflect on the nature of the profession and the public perception of it that science is often credited with technological achievements that are properly termed engineering. Although such observations, like most complaints of interest groups, are usually taken as sour grapes, there appears to be some validity to the engineers' claim, as newspaper stories about technological subjects frequently reveal. When, for example, the Mars Pathfinder mission approached its goal of landing on the red planet and deploying the rock-exploring rover in July 1997, a typical newspaper headline read, "A New Breed of Scientists Studying Mars Takes Control."[10] The scientists who were charged with studying the geology and chemistry of the planet's surface did indeed take over the news conferences and television interviews. The engineers who had conceived and designed the essential spacecraft and the rover it carried were, after some brief initial appearances, relegated to obscurity. A cultural critic writing for the *New York Times* even dismissed the engineers as prosaic and the Mars landing as not a television spectacular.[11] Whether or not it was spectacular, the physical mission was definitely an engineering achievement from which the scientific enterprise of planetary exploration benefited greatly.

Another common irritation among many engineers is when scientists are actually credited with an achievement that is clearly an engineering one. A new airplane, for example, might be heralded in the mass media as a "scientific breakthrough" when in fact it is an engineering one. More irritating to engineers, however, is the perception that when such an airplane crashes, as during a test flight, a headline is more likely than not to describe it as an "engineering failure."

The crediting of scientists over engineers with achievement was strikingly demonstrated when a U.S. postage stamp was issued in 1991 commemorating Theodore von Karman, one of the founders of the Jet Propulsion Laboratory,

10. John Noble Wilford, *A New Breed of Scientists Studying Mars Takes Control,* N.Y. Times, July 14, 1997, at A10.

11. Walter Goodman, *Critic's Notebook: Rocks, in Sharp Focus, but Still Rocks,* N.Y. Times, July 6, 1997, § 1, at 12.

which managed the Pathfinder mission. He was identified on the stamp as an "aerospace scientist," a fact that disappointed many engineers. It was only on the selvage of the stamp that von Karman was acknowledged to be a "gifted aerodynamicist and engineer." Yet von Karman's first degree was in engineering, and it was his desire to build and launch successful rockets—definitely an engineering objective—that drove him to study them as objects of science, just as an astronomer might study the stars as objects of nature, seeking to understand their origin and behavior. Unlike the engineer von Karman, who wanted to understand the behavior of rockets in order to make them do what he desired, however, the astronomer as scientist observes the stars with no further objective than to understand them and their place in the universe. A pure "rocket scientist," in other words, would be interested not in building rockets but in studying them.

C. Some Shared Qualities

Engineering clearly does share some qualities with science, and much of what engineering students study in school is actually mathematics, science, and engineering science. In fact, the graduate engineer's considerable coursework in these theoretical subjects distinguishes him or her more from the engineering technician than from the scientist. With this scientific background, an engineer is expected to be able to design and analyze and predict reliably the behavior of new objects of technology and not just copy and replicate the old. In addition to mathematics, science, and engineering science, however, the engineering student takes courses specifically addressing design, which is what distinguishes engineering from science.

1. Engineering is not merely applied science

That science forms a foundation for engineering is not to say that engineering is merely applied science and that engineers merely apply the laws of science in creating engineering designs. Although "applied science" is a commonly encountered pejorative definition of engineering, sometimes offered by scientists who consider engineering inferior to science and who do not fully appreciate the nature of engineering design, it is a patently false characterization. Engineering in its purest form involves creative leaps of the imagination not unlike those made by a scientist in framing a hypothesis or those made by an artist in conceiving a piece of sculpture.

Rather than following from scientific theory, an engineering design (hypothesis) provides the basis for analysis (testing the hypothesis) within that theory.[12] Engineering designs are not often likened to scientific hypotheses, but in fact

12. *See* Henry Petroski, To Engineer Is Human: The Role of Failure in Successful Design 40–44 (1985).

their origins can be quite similar and the testing of them remarkably analogous. Just as the conception of a scientific hypothesis is often the result of a creative, synthetic mental leap from a mass of data to a testable statement about it, from disorder to order, from wonder to understanding, so the origins of an engineering design can be spontaneous, imaginative, and inductive. Like the testing of the hypothesis, the analysis of the design proceeds in an orderly and deductive way. As in most analogies, however, the parallels are not perfect and the distinctions are not clear-cut. Design and analysis are in fact often intertwined in engineering practice. The design of a bridge may serve as a paradigm.

Imagine that a city wants a bridge to cross a river much wider and deeper than has ever been bridged before. Because the problem is without precedent, there is no existing bridge (no preexisting design) to copy. Engineers will, of course, be aware of plenty of shorter bridges in more shallow water, but can such models be scaled up? Even if it appears that they can technically, would it be practical or economical to do so? When presented with such a problem, the engineer must conceive a solution—a design—not on the basis of mathematics and science alone, but on the basis of extrapolating experience and, if necessary, inventing new types of bridges. The creative engineer will come up with a conceptual design, perhaps little more than a sketch on the back of an envelope, but clear enough in its intention to be debated among colleagues. This is the hypothesis—that the particular kind of bridge sketched can in fact be built and function as a bridge.

It is only when such a conceptual design is articulated that it can be analyzed to see if it will work. If, for example, the bridge proposed is a suspension bridge of a certain scale, it is possible to calculate whether its cables will be strong enough to support themselves, let alone a bridge deck hanging from them and carrying rush-hour traffic. Contrary to conventional lay wisdom, however, bridge designs do not follow from the equations of physics or any other science. Rather, the conceptual bridge design provides the geometrical framework for the engineer to use in applying the equations embodying the theory of structures to determine whether the various parts of the proposed bridge will be able to carry the loads they will have to after construction is complete. When a preliminary analysis determines that the conceptual design is in fact sound, the engineer can carry out more detailed design calculations, checking the minutest details to be sure that the structure will not fail under the expected loads.

The design of less critical and less costly products of engineering follows a similar process. Imagine that a company wants to develop a new product, perhaps because sales of its existing products are dropping off. The company's engineers are thus given the problem of coming up with something new, something better than all existing products, something unprecedented. The engineers, who often work in teams, will, perhaps by some ineffable process, conceive and articulate some new design, some new invention. Their hypothesis is, of course, that this design can be realized and the product sold at a competitive price. Testing the hypothesis may involve years of work, during which the engineers may find themselves faced with new problems of developing new materials and new manufacturing processes to fully and effectively realize the new design for a specified cost. The final product thus may be something that looks quite different from the first sketches of the original conceptual design. The engineers' experience will be not unlike that of scientists finding that they must modify their hypothesis as testing it reveals its weaknesses.

2. Engineering has an artistic component

The act of conceiving an engineering design is akin to the act of conceiving a painting or other work of art. Like the fine artist, the engineer does not proceed in a cultural vacuum, but draws upon experience in creating new work. Given the task of designing a bridge over obstacles between Point A and Point B, the engineer usually begins by sketching, literally or in the mind's eye, possible bridges. These preliminary concepts are likely to look not unlike those of bridges that cross over similar obstacles. Bridge designs that have worked in the past are likely to work in the future, if the new bridge is not too much longer or is not in too much deeper water than the earlier designs. However, each bridge project can also have its unique foundation, approach, or span problems, and the engineer must be prepared to modify the design accordingly, thus creating something that is different from everything that has come before.

Just as the artist chooses a particular block of stone out of which to chisel a figure or a specific size of canvas on which to paint, the engineer engaged in conceptual design also makes a priori choices about how tall a bridge's towers will be or how far its deck will span between piers. There are infinite geometrical combinations of these features of a bridge, as there are for the features of a figure in stone or the painting on canvas. It is the artistic decision of the engineer, no less than that of the artist, that fixes the idea of the form so that it can be analyzed, criticized, and realized by others. A recently published biography of a geotechnical engineer highlights the creative aspect of engineering practice through its subtitle, *The Engineer as Artist*.[13]

D. The Engineering Method

What is known as the engineering method is akin to the scientific method in that it is a rational approach to problem solving. Whereas the fundamental problem addressed via the scientific method is the testing of hypotheses, that ad-

13. Richard E. Goodman, Karl Terzaghi: The Engineer as Artist (1999). The book also provides insight into the many dimensions of personality and temperament—from the artistic to the scientific—that can coexist in an individual engineer.

dressed by the engineering method is the analysis of designs, which, as noted earlier, may be considered hypotheses of a sort. Once a conceptual design has been fixed upon, detailed design work can begin to flesh out the details. The engineering method is the collective means by which an engineer approaches such a problem, not only to achieve a final design but also to do so in such a way that the rationale will be understood by other engineers. Those other engineers might be called upon to check the work with the intention of catching any errors of commission or omission in the assumptions, calculations, and logic employed.

The starting point of much engineering work is in what has previously been done. That is not to say that engineers merely follow examples or use handbooks, for engineers are typically dealing with what has not been encountered before in exactly the same scale, context, or configuration. Yet, just as artists are ever conscious of the traditions of art history, so in the most creative stage of engineering, where conceptual designs are produced, engineers typically rely upon their knowledge of what has and has not worked in the past in coming up with their new designs. The development of these conceptual designs into working artifacts usually involves the greater expenditure of time and visible effort, and it is in this developmental stage that the engineering method most manifests itself.

Many engineering problems begin with shortcomings or downright failures with existing technology. For example, earthquakes in California have revealed weaknesses in prior designs of highway bridges: horizontal ground motion causing road decks to slide off their supports and vertical ground motion causing the support columns themselves to be crushed. To prevent such failures in the future, engineers have proposed a variety of ways to retrofit existing structures. Among the designs is one that wraps reinforced concrete columns in composite materials, with the intention of preventing the concrete from expanding to the point of failure. The idea is attractive because the flexible, textile-like materials could be applied relatively easily and economically to bridges already built. The basic engineering question would be whether it would be economical to wrap enough material around a column to achieve the desired effect.

The engineering method of answering such a question typically involves both theory and experiment. Since the material has a known strength and a known structure, calculations within the broad category of theory of strength of materials can produce answers as to whether the wrapping can contain the pressure of the expanding concrete during an earthquake. The problem and the calculations are complicated by the fact that a composite material is not a simple one, and its containing strength depends upon the structure of the wrapping material. Indeed, the engineering problem can very easily be diverted to one of establishing the best way to manufacture the composite material itself in order to achieve the desired result most efficiently. The calculations themselves will involve hypotheses about how the material is made and how it will perform when called upon to do so. In other words, all the calculations depend to a great extent upon theory and theoretical assumptions. Furthermore, there are fundamental questions about how the material will behave after prolonged exposure to the environment, including pollution and sunlight, which are known to have deleterious effects on certain composite materials. Also, there are questions about the long-term behavior of the composite wrapping when it would be in place on a column which itself was subjected to the repeated loads on the highway it supports. The repeated loading and unloading can cause what is known as fatigue, and what may be strong enough when newly installed may have its strength considerably reduced over the course of time. Experiments on the composite material, its components, and the wrapped column may be necessary to answer questions about the design and the theory upon which its analysis is based. What is central to the engineering method used to approach and attack such problems is its empirical and quantitative nature, and in this regard it is not unlike the scientific method.

While the design of bridges and analysis of proposed means to retrofit them against earthquake damage may appear to involve problems specific to civil engineering, the nature of the design process and the method used to analyze proposed designs is typical of engineering design and the engineering method generally. No engineer can design a crankshaft for an automobile engine or a circuit for an electronic calculator without first having a conceptual design that serves as a basis for the detailed design and development, including the confirming analysis that the thing is going to work when manufactured, installed, or assembled. The difference between a successful design and an unsuccessful one can often be traced to how carefully and thoroughly a design was in fact analyzed and tested—just as if it were a scientific hypothesis.

III. The Nature of Engineering

The practice of engineering is often separated into the two components of design and analysis, and different groups of engineers frequently carry out the distinct but hardly separable activities and pass their results back and forth over what has sometimes been described metaphorically as a wall. It is also a common complaint among engineers that when the designers and analysts have finished their work, they throw the "finished" design over another wall and let the manufacturing engineers worry about how to make the parts and assemble them. This model has historically been especially notorious in the aircraft manufacturing industry, with the notable exception of the Skunk Works operation of the

Lockheed Corporation, in which all engineers and assembly workers carried out their secret and highly successful projects in one big building.[14]

With the advent of computer-aided design and manufacturing, designers and manufacturers scattered around the world were able to combine design, analysis, and manufacturing in a highly integrated manner, as was done very successfully with the design and manufacture of the Boeing 777.[15] For all their importance in being but preludes to manufacturing, however, design and analysis are the aspects of engineering that are most commonly subject to dispute and thus to scrutiny. Indeed, even when there are problems with manufacturing, it is the tools and practices of design and analysis that are called upon to identify the causes of faults and to redesign the artifact or the process that manufactured it.

A. Design Versus Analysis

1. Design

Design, being dominated at its most fundamental level by the artistic component of engineering, and involving a lot of creativity, cannot be easily codified. A conceptual design can thus often be sketched more easily than it can be articulated in words, which is perhaps one of the reasons patents are not easy reading and almost always are accompanied by figures. It is debatable, therefore, whether design can be taught in any definitive way. That is not to say that design cannot be assessed in meaningful ways. Unlike an artistic design, which is often judged principally on the basis of aesthetics and taste, an engineering design is most properly judged by how well it functions. Indeed, engineers sometimes are rightly criticized for apparently seeing function as the only requirement of their designs.

The word *design*, used in an engineering context as a noun, verb, and adjective, has several different meanings, and is often used without distinguishing qualifiers. One engineer's conceptual design of a bridge or machine part is seldom, if ever, sufficiently fleshed out that the artifact can be built or manufactured without further details. This kind of design is high-level design, in the sense that it is typically conceived of or decided upon by someone in a leadership role on a project. With the conceptual design fixed, the engineering or detail design can proceed, usually by individual engineers or teams of engineers. This kind of design can be repetitive and tedious, full of calculations and small iterations, but the computer is increasingly being used to take over such tasks. A typical design task at this level would be to choose the sizes of the individual

14. *See* Ben R. Rich & Leo Janos, Skunk Works: A Personal Memoir of My Years at Lockheed (1994).

15. *See* Henry Petroski, Invention by Design: How Engineers Get from Thought to Thing 129 (1996).

pieces of steel that will make up a bridge or to determine the detailed geometry of a machine part for an engine. The finished product of such tasks can itself be referred to as "the design." This is not to say that the result will be exactly the same no matter what engineer carries out the calculations, for the design process is replete with individual judgments and decisions that cumulatively affect the result.

2. Analysis

Analysis, in contrast, is highly codified and structured. Unlike design problems, which seldom if ever have unique solutions, problems in analysis have only one right or relevant answer. Thus, once produced on paper or computer screen, the design might be checked by analysts using well-established theories of engineering science and mechanics, such as strength of materials, elasticity, or dynamics. Given the now fixed geometry of a structural or machine component and the agreed-upon design loads it is expected to experience, the analyst is able to calculate deflections, natural frequencies, and other responses of the part to the loads. Assuming no errors are made, the value of these responses will not depend upon who does the calculations. The calculated responses serve to check that the design is correct within the specifications of the design problem, and this is one way engineering design proceeds within a system of checks and balances. If the magnitudes of the responses prove to be unacceptable, the design will be sent back to the designers for further iteration. Needless to say, sometimes the designer and the analyst are one and the same individual engineer, in which case the design should ultimately be checked by another engineer.

Because the end result of an analysis is often a single precise number, analysis lends itself more easily to explication in the classroom and to coursework in the curriculum, and, according to some critics, it is taught in engineering schools sometimes almost to the exclusion of design. Indeed, until recently, the Accreditation Board for Engineering and Technology (ABET), which accredits engineering programs in the United States, had specific and distinct minimum requirements for the number of both design and analysis courses in the curriculum. Although this bean-counting approach has been abandoned of late, ABET does expect each program it accredits typically to contain a capstone design course, in which engineering students, usually in their senior year, are involved in a major design project that forces them to draw upon and synthesize the use of the analytical and design skills learned throughout the curriculum.

The usual engineering curriculum in the United States now comprises four years of study leading to a bachelor's degree, typically a Bachelor of Science or a Bachelor of Science in Engineering. Thus, in engineering, unlike in law and medicine, it is common to encounter practitioners with only an undergraduate education, and often a highly specialized, technical one at that. This, along with the fact that engineering has no single membership organization analogous to the American Bar Association or the American Medical Association, has been identified as a reason that the engineering profession is not perceived to have the status of the legal and medical professions, at least in the eyes of many engineers. For decades, there have been ongoing debates within the profession as to whether the first degree in engineering should be a five-year degree,[16] but few serious movements have been made in that direction. Indeed, five-year engineering degrees were more common decades ago, and long-term trends have been to move away from an extended curriculum and even to reduce the requirements for the four-year degree. Increasingly, there has been discussion about expecting a master's degree to be the first professional degree, but this too is far from the universal point of view.

The Ph.D. in engineering is typically a research degree, and the doctoral-level engineer will most often be engaged in analysis rather than design. Indeed, a design-based dissertation is considered an oxymoron in most engineering graduate programs. That is not to say that the engineer with a doctorate will not or cannot do design; he or she will more typically serve in a consulting capacity, engaged in both design and analysis of a nonroutine kind. It is not at all uncommon to find doctoral-level engineers working in research-and-development environments who seldom if ever perform design tasks, however, and they may have had little if any design experience.

B. Design Considerations Are More Than Purely Technical

The considerations that go into judging the success or effectiveness of an engineering design are seldom only technical, and at a minimum they usually involve questions of cost and benefit, and of investment and profit. Other design considerations include aesthetics, environmental impact, ergonomics, ethics, and social impact. Although such implications may not be considered explicitly by every engineer working on every design project, an engineering team collectively is likely to be aware of them. Aesthetics, for example, have been discussed explicitly as a dominant design consideration for bridges of monumental proportions, such as long-span suspension bridges. The ratio of the sag to the span of the main cables, which can be set for aesthetic as well as technical objectives, subsequently can have a profound impact on the forces in the cables themselves and hence the economics of the project.[17]

16. *See, e.g.,* Samuel C. Florman, The Civilized Engineer 205–06 (1987).

17. *See* David P. Billington, The Innovators: The Engineering Pioneers Who Made America Modern 6–12 (1996).

1. Design constraints

Engineering has been defined as design under constraint. Design constraints are among the givens of a problem, the limitations within which the engineer must work. A bridge over a navigable waterway has to provide a clear shipping channel between its piers and sufficient clearance beneath its roadway, and these are thus nonnegotiable design constraints. The specification of such clearances forces the design to have piers at least a certain distance apart and a roadway that is a certain distance above the water. The design of a roof structure over an auditorium has to accommodate the architect's decision that the auditorium will have a given width and ceiling height and have no columns among its seats. Such constraints can have profound implications for the type of bridge chosen and the kind of roof structure devised by the structural designer.

2. Design assumptions

No engineering design can be advanced through analysis unless certain assumptions are made. These design assumptions can be implicit or explicit, and they often involve technical details that affect the difficulty and accuracy of any subsequent analysis. Common design assumptions for long-span suspension bridges in the 1930s were that wind blowing across a deck displaced it sideways only and that wind did not have any aerodynamic effect on the structure. The former was an explicit design assumption that was manifested in the calculation of how stiff the bridge deck had to be in a horizontal plane. The latter assumption was implicit in the sense that it was never considered, but it may be considered an assumption nevertheless, since no calculation or analysis was performed to verify that aerodynamic effects were of no consequence. It was only after the Tacoma Narrows Bridge was destroyed by wind in 1940[18] that the bridge-design community recognized that aerodynamic effects were indeed important and could not be ignored by engineers or anyone else.

3. Design loads

No structural engineering analysis can proceed without the loads on the structure being stated explicitly. This presents a dilemma for the designer who is charged with specifying how large the structural components must be. The components are chosen to support a given load, but the bulk of that load is often the weight of the structural components themselves. For example, the weight of the steel in a long-span bridge may be over 80% of the total load on the structure. The engineer proceeds with the analysis only by first making an educated guess about how much steel will be required for the bridge. Since most bridge design involves familiar spans and types of structures, the educated guess can be

18. *See* Northwestern Mut. Fire Ass'n v. Union Mut. Fire Ins. Co., 144 F.2d 274 (9th Cir. 1944).

guided by experience. After a "design by analysis" based on the assumed weight is carried out, the original assumption about the weight of steel can be checked. If there is not sufficiently close agreement, the guess (assumption) can be modified and an iteration carried out. In other engineering design problems, the design loads may be the electric currents expected in a circuit or the volume of water to be handled by a sewer system, but the nature of the design problem is analogous to that of designing a bridge.

A well-known failure resulting from an improper use of the iterative design process occurred early in the twentieth century in the design and construction of the Quebec Bridge across the Saint Lawrence River.[19] The chief engineer, Theodore Cooper, was approaching the end of a distinguished career when he was given the opportunity to design and build the longest cantilever bridge in the world. His concept was for a slender-looking steel span of 1,800 feet between piers. The detailed design, that is, the sizing of the steel members, was to be carried out by Peter Szlapka, an engineer who worked in the offices of the Phoenix Bridge Company but had no experience in the field. Since Cooper, who was not in good health, did not want to travel to the construction site from his office in New York, he could not heed in time warning signs that the steel was not bearing the load properly, and the bridge collapsed before it was completed. An investigation by a royal commission found that Szlapka had curtailed his iteration prematurely and had underestimated the actual weight of steel on the bridge. As a result, some of his calculations of strength were as much as 20% higher than existed in the actual structure. The Quebec Bridge was redesigned and completed in 1917, but to this day no cantilever bridge has been designed with a longer span.

The weight of a bridge structure itself is known as the dead load.[20] The weight of traffic and snow and the force of wind and earthquakes are known as live loads.[21] These live loads are often specified as design loads, and they involve assumptions about how much traffic the bridge will carry and how extreme nature can be at the location of the bridge. The specification of design loads[22] has a profound impact on the cost of a structure, and hence design loads are

19. *See* Henry Petroski, Engineers of Dreams: Great Bridge Builders and the Spanning of America 101–11 (1995).

20. *See* Space Structures Int'l Corp. v. George Hyman Constr. Co., No. 88-0423, 1989 U.S. Dist. LEXIS 5798, at *5 n.2 (D.D.C. May 24, 1989) (defining "dead load" as the weight of the frame and its components). *See also* Wright v. State Bd. of Eng'g Exam'rs, 250 N.W.2d 412, 414 (Iowa 1977) (defining "dead load" as the weight of the roof itself).

21. *See Space Structures*, 1989 U.S. Dist. LEXIS 5798, at *5 n.2 (defining "live load" as the weight of the snow, rain, and wind that a frame can support). *See also Wright,* 250 N.W.2d at 415 (defining "live load" as the weight of the snow).

22. *See Space Structures,* 1989 U.S. Dist. LEXIS 5798, at *5 n.2 (defining "load" as the weight-bearing capacity of the frame itself).

chosen carefully. A bridge might conceivably have to support bumper-to-bumper traffic consisting entirely of heavy trucks fully loaded, but designing for such a load would make for a heavy, and therefore expensive, bridge. For a wide bridge with many lanes, it is unlikely that trucks would ever occupy every lane equally (indeed, they might be prohibited from doing so at all), and so an engineering judgment is made as to what is a credible design load. Because engineers took into account such considerations, the George Washington Bridge, which was first opened to traffic in 1931, could be designed and built for an affordable price. Otherwise it might not have been built when it was.[23]

Another example involves the construction of library buildings. Whereas libraries built at the beginning of the twentieth century are likely to have the floors of their bookstacks supported by the shelving structure, libraries built after the middle of the twentieth century are more likely to have the bookcases supported by the floors of the building. The space devoted to bookcases in such structures is actually only about one-third of the floor space, since adequate aisle space must be allowed for access. The dead load of the modern library building is that of the structure itself. The bookcases, which can be relocated if necessary, the books they hold, and the library staff and patrons can be considered the live load. A typical design assumption might be that upper-stack floors would carry a live load of about 150 pounds per square foot. Because of the ever-present demands on libraries to find more space for shelving books without constructing a new building or expanding an existing one, compact shelving came to be increasingly considered. However, since such shelving might increase the design live load on a floor to 300 pounds per square foot or more, it could not be installed on upper floors without compromising the factor of safety of the structure (see section III.C.1). Basement floors, on the other hand, which might have been designed at the outset for heavier loads, such as those required for storing larger and heavier library materials like maps and newspapers, could be retrofitted with compact shelving.[24]

Increasingly, bridges, buildings, machine parts, and other engineering structures and components are being designed with computers by a process known as computer-aided design (CAD). Much of the iterative process and the loading considerations described earlier can be incorporated into the computer software and so is invisible to the engineer using the computer. The engineer still plays a central role in the design process, however, especially when specifying what goes into the computer model of the structure or machine part being designed. This input can typically include the overall size of the structure or part, the

23. Jameson W. Doig & David P. Billington, *Ammann's First Bridge: A Study in Engineering, Politics, and Entrepreneurial Behavior,* 35 Tech. & Culture 537 (1994).

24. *See* Henry Petroski, The Book on the Bookshelf 178–80, 206–08 (1999).

specification of loads, the strength of the materials chosen, and the details of connections between interacting parts of the design.

C. "State of the Art"

The term "prior art"[25] is ubiquitous in the patent literature and designates existing technology that is being improved upon by something new, useful, and nonobvious. Virtually everything that is patented improves upon the prior art, and thus the prior art is in an ever-changing state. To work totally within the prior art at a given time is to design something that would be considered routine and thus hardly an invention. Engineers often work within the prior art, as when they design a common highway bridge that is very much like so many other highway bridges up and down the same road. Yet engineers are also often called upon to build bridges in new settings and under new circumstances, and in these cases they often must develop new types of bridges or devise new construction procedures. In such cases they may in fact have to go beyond the prior art and thus come up with something that is patentable.

When engineers are solving problems of an unusual kind or solving routine problems in a new way, they are in fact acting as inventors. Indeed, engineering can be thought of as institutionalized or formalized invention, though the terminologies of invention and engineering are commonly kept distinct. The term "prior art," for example, is seldom used in engineering; the term "state of the art" is used instead. Yet just as the prior art changes with each new patent, the "state of the art" in engineering also means different things at different times. At any given time, however, it designates what is considered the latest and generally agreed upon practice of engineers in a given area, whether that be bridge design, automobile design, or ladder design. To be considered innovative engineering, a new idea or design must not be obvious to someone versed in the state of the art.

To say that an engineer is practicing engineering within the state of the art is not a pejorative characterization, but rather an indication that the engineer is up-to-date in the field. The state of the art is advanced in engineering, as in science, by pioneers (inventors) who see limitations to the state of the art and who find fault with aspects of the state of the art that are not evident to those immersed in the paradigm.

25. *See* 35 U.S.C. § 103(a) (1999) (defining "prior art" as subject matter that as a whole would have been obvious to a person having ordinary skill in the subject area). *See also* Afros S.P.A. v. Krauss-Maffei Corp., 671 F. Supp. 1402, 1412 (D. Del. 1987) (discussing the scope of prior art as "that which is 'reasonably pertinent to the particular problem with which the inventor was involved'" (quoting Stratoflex, Inc. v. Aeroquip Corp., 713 F.2d 1530, 1535 (Fed. Cir. 1983))).

1. "Factor of safety"

Engineers recognize that they do not always fully understand the engineering–scientific theory or principles that underlie the functioning of their design. They also recognize that they necessarily have made assumptions in their analysis, and so the design as built will not behave exactly like the theoretical (mathematical) model that served as the basis for their analysis. They recognize further that a design as built does not necessarily have exactly the same details of workmanship or strength of materials as were assumed in the calculations. For these reasons and more, engineering designs are not made exactly to theoretical specifications but rather are made to practical ones.

If a machine part is calculated to carry a certain maximum load when in operation, the part as designed will in theory be able to carry a multiple of that load to allow for an abnormally weak part or batch of material being used, an exceptionally high load being applied, and other unusual but not fully unexpected conditions of use. The multiple is known as a "factor of safety,"[26] or sometimes jocularly (but not totally in jest), a "factor of ignorance" in recognition of the fact that not everything engineers do is fully understood by them and that there are likely to be unanticipated conditions that must somehow be taken into account in design. Although the concept of factor of safety is most readily articulated and understood in the context of loads on structures, the idea of a factor of safety can apply to engineering designs of all kinds.

2. Conservatism in design

An engineering design is said to be conservative when it carries an adequate factor of safety.[27] What is adequate may be a matter of judgment. There can actually be several different factors of safety identified with a given design. Thus, an airplane may be designed with one factor of safety against its wings fracturing and falling off and another against its fuselage being dented. A dented fuselage may have a small effect on how efficiently the plane flies, but a fractured wing would obviously jeopardize everyone on board. To apply a greater factor of safety to the wings makes sense even to a nonengineer.

What is an adequate factor of safety in a given application depends upon many things, including the state of the art of the theory underlying the design, the quality of materials that are used, and the quality and reliability of the workmanship that goes into realizing the design. In the middle of the nineteenth century, the theory of iron bridge design was in its infancy, and a responsible

26. *See generally* Baum v. United States, 765 F. Supp. 268, 273 (D. Md. 1991); *In re* Lloyd's Leasing Ltd., 764 F. Supp. 1114, 1127–28 (S.D. Tex. 1990); State *ex rel.* Fruehauf Corp. v. Industrial Comm'n, No. 90AP-393, 1991 Ohio App. LEXIS 2022, at *4 (Ohio Ct. App. 1991).

27. *See generally* Union of Concerned Scientists v. Atomic Energy Comm'n, 499 F.2d 1069, 1086–90 (D.C. Cir. 1974); United States v. Hooker Chem. & Plastics Corp., 607 F. Supp. 1052, 1065 (W.D.N.Y. 1985).

bridge engineer had to rely upon a large factor of safety—a good deal of conservatism—to ensure a safe bridge.

When a bridge over the River Dee collapsed in 1847 and the accident claimed some lives, a royal commission was appointed to look into the use of iron in railroad bridges. As part of the investigation, prominent engineers of the time were asked what factor of safety they applied to their bridges, and the responses ranged from 3 to 7.[28] Robert Stephenson, the engineer of the Dee Bridge, had been using factors between 1 and 2 for bridges like the Dee, and the Dee itself was found to have had a factor of safety of about 1.5.[29]

Dozens of bridges like the Dee, which was a brittle cast-iron beam trussed with malleable wrought iron, had been built in the preceding decade or so, and their successful performance justified to Stephenson, at least, the use of the lower factors of safety. The Dee was, however, the longest such bridge that had ever been attempted, and it collapsed after some heavy gravel was added to its roadway to reduce the possibility of its wooden deck being set afire by hot cinders spewed out of crossing steam engines. (The addition of the gravel also naturally lowered the factor of safety below 1.5.)

Although Stephenson was not as conservative as his contemporaries, he was not found negligent by the royal commission, and he went on to complete the landmark Britannia Bridge, whose design was being developed at the time of the Dee collapse and during its investigation. The Britannia, however, being of a more innovative design than the Dee, and with barely a precedent, was much more conservatively designed. Indeed, it was so conservative in its design that the chains that were to assist in holding up the box girder spans were deemed unnecessary, and so the towers to hold the chains remained a functionless frill on the completed bridge.

3. "Pushing the envelope"

As indicated in Figure 1 on the following page, Robert Stephenson was "pushing the envelope"[30] with his Dee Bridge and related bridges, in the sense that he was designing and building structures that were on the edge of the field of experience.[31] When the main-span length of such bridges was plotted against the year of construction, the data points representing Stephenson's bridges were in extreme positions on the graph.[32] Since the vague but generally smooth border formed by the extreme points in such a plot is known as an envelope of the

28. *See* Petroski, *supra* note 12, at 101.

29. *See* Henry Petroski, Design Paradigms: Case Histories of Error and Judgment in Engineering 85–86 & fig.6.2 (1994).

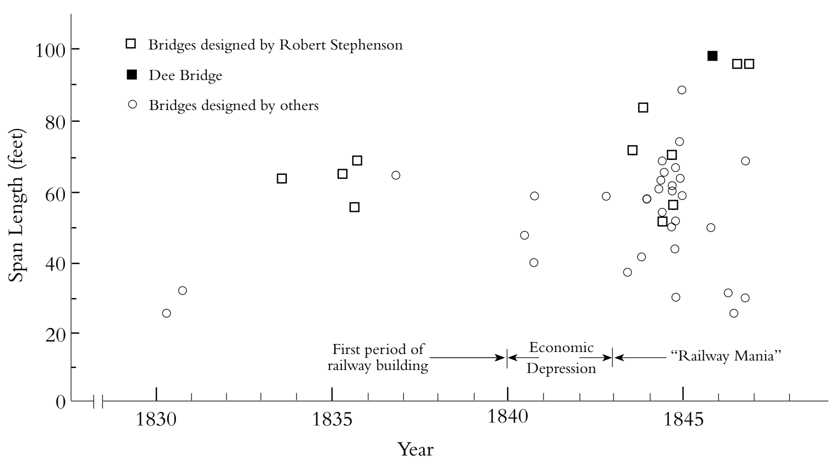
30. *See generally* Hataway v. Jeep Corp., 679 So. 2d 913, 920 (La. Ct. App. 1996) (defining "pushing the envelope" in the context of vehicle testing).

31. *See* Petroski, *supra* note 29, at 83–84 & fig.6.1.

32. P.G. Sibly, The Prediction of Structural Failures (1977) (unpublished Ph.D. dissertation, University of London).

points, Stephenson's designs represented by the extreme points were "pushing the envelope," that is, bulging it outward however slightly. It should be realized, however, that there are notable examples of successful bridges built well outside the envelope of experience. One was Stephenson's Britannia Bridge, and another famous one is the Forth Bridge, a cantilever bridge that was built at twice the span length of existing examples when there was very little experience with that genre.

Figure 1. The building and length of nineteenth-century trussed-girder bridges



From Petroski, *supra* note 29, at 84 & fig. 6.1 (after Sibly, 1977).

Although the term may be more familiar in aeronautical and aerospace applications, the phenomenon of "pushing the envelope" is a common and natural thing to do in all of engineering. When designs work, there is a natural tendency to pare down those designs to shed excess strength, which usually equates with weight and, therefore, cost. There are several good reasons for the lowering of the factor of safety. With experience comes confidence, not to mention familiarity, with a design, and the design does not command the same sense of conservatism that new and unfamiliar designs do. As familiar designs of a particular kind proliferate, there also tends to evolve a sense that they can be extended to new limits, because prior limitations, which were expressions of conservatism, are thought to be excessive. New materials, construction, and manufacturing techniques; greater theoretical understanding; and improved tools of analysis also argue for less conservatism, lower factors of safety, and the pushing of the envelope.

The development of cable-stayed bridges was following this pattern at the end of the twentieth century. Dating principally from the 1950s in post-war Germany, cable-stayed bridges are attractive design options because they are relatively light and can be constructed relatively quickly, as compared with, say, suspension bridges. Cable-stayed bridges soon proliferated, but their main spans were increased slowly and incrementally, a conservative way to push the envelope. It was generally held that cable-stayed bridges were the span of choice for many applications in the 1,000- to 1,500-foot range; conventional suspension bridges were specified for longer spans. In the 1990s, however, cable-stayed designs with longer spans—some on the order of 3,000 feet—began to be built, increasing the maximum span by about 50% in one fell swoop.[33]

Such severe pushing of the envelope—indeed, going beyond or outside the envelope—is not unheard of. As mentioned earlier, the 1,710-foot Forth Bridge of the cantilever type did so in 1890, and the 3,500-foot George Washington Bridge almost doubled the main span of the longest previous suspension bridge, the 1,800-foot Ambassador Bridge between Detroit and Windsor, Ontario. The Tacoma Narrows Bridge near Seattle was built to the same state of the art as the George Washington, and, with a 2,800-foot main span, was the third largest in the world when completed in 1940. The Tacoma Narrows differed from the George Washington in a significant way, however, in that it was extremely narrow in comparison with its length, something so far outside the envelope of experience that one consulting engineer reviewing the design recommended that the bridge be built only if it were widened.[34] It was not, and the bridge collapsed in a 42-mile-per-hour wind only three months after it was completed.[35] The state of the art had not included analyzing and designing suspension bridges for aerodynamic effects, which were considered irrelevant.

D. Design Experience and Wisdom

The engineer who had most to do with the design of the Tacoma Narrows Bridge, Leon Moisseiff, was among the most distinguished engineers working on suspension bridges at the time. He had had a hand, as consulting engineer, in the design of virtually every record-breaking suspension bridge conceived and built since the turn of the century, and he was responsible for the principal analytical tool that was used in making bridges lighter because the forces in them

33. *See* Petroski, *supra* note 29, at 175 fig.10.3.

34. *See* Petroski, *supra* note 19, at 297–300.

35. *See* Northwestern Mut. Fire Ass'n v. Union Mut. Fire Ins. Co., 144 F.2d 274 (9th Cir. 1944).

could be calculated more accurately. When the critical but much less prominent engineer reviewing the Tacoma Narrows design recommended that it be widened to bring it more in line with demonstrated practice, Moisseiff dismissed the suggestion and essentially pointed to his considerable experience with suspension bridges and the theories of their behavior that he and a colleague had developed as his justification for leaving things as they were. Experience can be a dangerous thing in engineering if it blinds the engineer to the fact that envelopes can be pushed only so far.[36]

Another example of the arrogance of experience occurred in the design and construction of the Quebec Bridge across the Saint Lawrence River, discussed earlier. The chief engineer, Theodore Cooper, had an impeccable reputation, but his confidence seems to have been almost without bounds. The construction of the bridge was not properly monitored, and the incomplete structure collapsed in 1907. It was later found that the weight of the structure had been seriously underestimated in the design calculations and that the principal compression members in the structure were too slender.[37]

The examples of the Tacoma Narrows and Quebec Bridges are not typical of engineering practice, of course, but they are instructive in indicating that experience alone is no substitute for careful, correct, and complete analysis. These examples also illustrate that modes of failure that can be ignored in the design of structures of a certain proportion can be critical in the design of structures of the same genre but a different proportion. In the case of the Tacoma Narrows Bridge, aerodynamic effects that were of little consequence for wider, stiffer bridges like the George Washington proved disastrous for Moisseiff's narrow, flexible design. Similarly, the compression members of heavy, stubby cantilever bridges were not in danger of buckling, but they proved to be the weak links in a light, slender bridge like the Quebec.

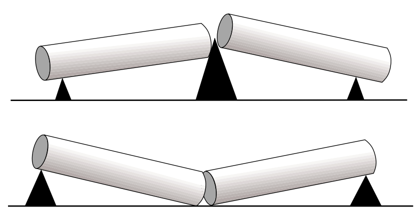
E. Conservative Designs

Although it would appear to be a truism that conservative designs well within the state of the art pose little danger of failing, what constitutes conservatism in engineering design can be elusive. Galileo, though commonly thought of as a scientist, was very interested in Renaissance engineering. In fact, the motivation for his mature work, *Dialogues Concerning Two New Sciences*, was in some of the limitations of engineering understanding that led at the time to the spontaneous failure of ships and obelisks, among other things. One story Galileo tells at the beginning of this seminal work on strength of materials is of a long piece of marble that was being kept in storage with a support under each of its ends. Because it was known at the time that long heavy objects like ships and obelisks

36. *See* Petroski, *supra* note 19, at 294–308.
37. *See id.* at 109–18.

could break under such conditions, one observer suggested that a third support be added under the middle of the piece of marble, as indicated in Figure 2. According to Galileo, everyone consulted thought it was a good idea, and it was done. After a while, however, the marble was found to have broken in two, anyway.[38] In their self-satisfaction in taking action to prevent one mode of failure from occurring, the Renaissance engineers did not think to worry about the new mode of failure they were making possible by adding an additional support and thus changing the whole system and enabling it to behave in an unanticipated way.

Figure 2. The two failure modes described by Galileo.



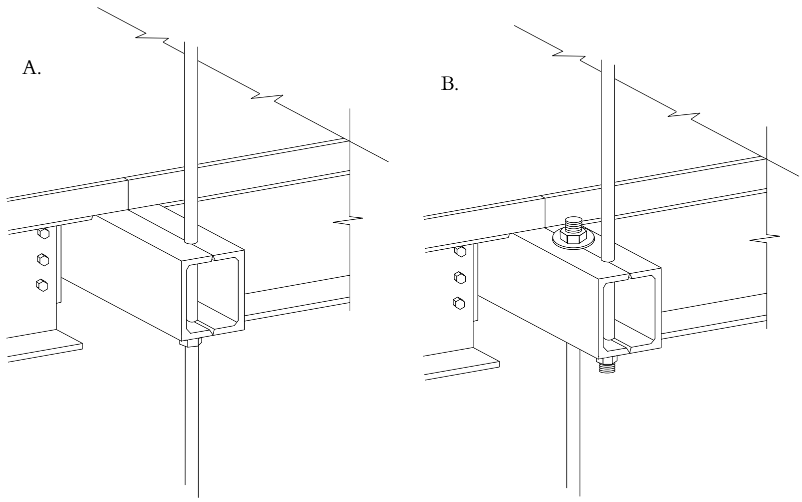
From Petroski, *supra* note 29, at 53 & fig. 4.3 (after Galileo, 1638).

An analogous event happened in 1981 in Kansas City, Missouri, when the elevated walkways of a hotel collapsed, killing 114 people.[39] The recently opened Hyatt-Regency Hotel had an expansive and towering lobby–atrium, and the elevated walkways, or skywalks, crossing it were designed to be supported from above so as to leave the floor of the lobby unobstructed by columns. The original design called for suspending one of the skywalks below another by means of long roof-anchored steel rods that would pass through the beams supporting the top walkway and support the lower one also, as indicated in Figure 3a. During construction, it was suggested that each single long rod be replaced by two shorter rods, one supporting the upper walkway from the roof and the other supporting the lower walkway from the upper. Such a design change could have been viewed as conservative because the unwieldy longer rods could have been bent and damaged during installation, whereas the shorter ones were more likely to survive installation without incident.

38. *See* Petroski, *supra* note 29, at 47–51.

39. *See* Deborah R. Hensler & Mark A. Peterson, *Understanding Mass Personal Injury Litigation: A Socio-Legal Analysis*, 59 Brook. L. Rev. 961, 972–74 (1993) (overviewing the events of the Hyatt-Regency skywalk collapse). *See also In re* Federal Skywalk Cases, 680 F.2d 1175 (8th Cir. 1982); *In re* Federal Skywalk Cases, 97 F.R.D. 380 (W.D. Mo. 1983).

Figure 3. Connection detail of upper suspended walkway in the Kansas City Hyatt Regency Hotel, as originally designed (A) and as built (B).



From Petroski, *supra* note 29, at 61 & fig. 4.7 (after Marshall et al., 1982).

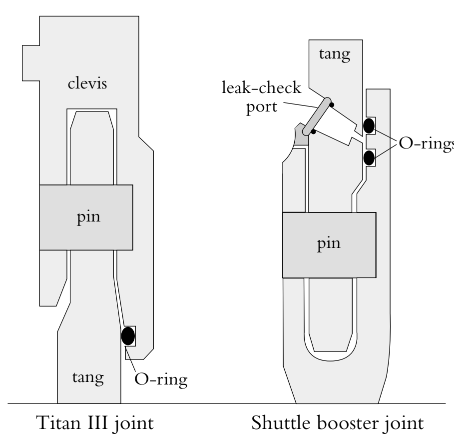
When the structural engineers were asked about the change from single rods to double ones, they apparently raised no objection, and the skywalks were built in the changed manner. When the skywalks collapsed, the design change was quickly identified as the structural culprit. Replacing the one-rod design with the two-rod design essentially doubled the bearing stress on the upper walkway beam, because the connection there had to support the weight of not only the upper walkway but also the lower walkway. In the original design, the lower walkway's weight was carried by the rod and not the upper walkway.[40] Thus, what might appear to be relatively simple design changes for the better can drastically alter a system's behavior by introducing failure modes not even possible in the original design. Seemingly simple and innocuous design changes can be among the most pernicious. Had the design change not been made, the skywalks would likely still be in place.

The explosion of the space shuttle *Challenger* might be attributed, at least in part, to an attempt to design a more conservative solid booster rocket than had ever flown. Prior booster rocket designs, such at that of the Titan III, had a single O-ring sealing the gap between mating sections of the rocket casing. The

40. *See* Petroski, *supra* note 12, at 86–88.

Titan design was a very successful and proven one, and this argued for its adoption for space shuttle use. However, to make the design even more reliable, or so it was thought, a second O-ring was added to the joint between the sections, as indicated in Figure 4. This design change must surely have been considered a more conservative approach. It was, however, the complication of having two O-rings, and the difficulty of checking the proper seating of the one hidden by the other from visual inspection, that was a factor in the development of the leak that caused the *Challenger* to explode. Indeed, the supposed conservatism of the double O-ring design might also have contributed to the ill-fated decision to launch the shuttle against the advice of engineers who knew the O-rings were susceptible to damage in cold weather, which prevailed on the morning of the launch.[41]

Figure 4. O-ring designs for Titan III and space shuttle booster rocket.



From Petroski, *supra* note 29, at 63 & fig. 4.9 (after Bell & Esch, 1987).

41. *See* Trudy E. Bell & Karl Esch, *The Fatal Flaw in Flight 51-L*, IEEE Spectrum, Feb. 1987, at 36. *See also* Hans Mark, The Space Station: A Personal Journey 218–21 (1987).

F. Daring Designs

If the belief that a design is conservative can be misplaced, so can a fear that any design innovation is doomed to fail. The *Apollo 11* mission to the moon demonstrated that an engineering system design of enormous complexity and novelty, that of the moon lander, could succeed the first time it was tried. Indeed, the history of engineering is full of examples of new designs succeeding the first time they have been attempted. Among the most famous and successful bridges in the world is the Forth Bridge in Scotland, described earlier. This innovative design comprising record-breaking cantilever spans was also the first major bridge to be made entirely of steel.

IV. Success and Failure in Engineering

A. The Role of Failure in Engineering Design

Failure is a central idea in engineering. In fact, one definition of engineering might be that it is the avoidance of failure. When a device, machine, or structure is designed by an engineer, every way in which it might credibly fail must be anticipated to ensure that it is designed to function properly. Thus, in designing a bridge, the engineer is responsible for choosing and specifying the type and size of the piers, beams, and girders so that the bridge does not get undermined by the current in the river the bridge spans, does not collapse under rush-hour traffic, and does not get blown off its supports. The engineer ensures that these and other failures do not occur by analyzing the design on paper, and the objective of the analysis is to calculate the intensity of forces in the structure and compare them with limiting values that define failure. If the calculated force intensities are sufficiently within the limits of the material to be used, the bridge is assumed to be safe, at least with respect to the modes of failure considered. (Each separate mode of failure must be identified and checked individually.)

In a suspension bridge, for example, the total force in the main cable depends upon the geometry of the bridge and the traffic it must carry. The force the cable must resist determines how large the cable must be if a certain type of steel wire is used. Since the steel wire, like every engineering material, has a breaking (failure) point, the engineer calculates how far from the breaking point the cable will be when the bridge is in service. If this difference provides the desired factor of safety, the engineer concludes that the bridge will not fail, at least in the mode of the cable breaking, even if the wire installed is somewhat weaker than average and the traffic load is heavier than normal. Other possible ways in which failure may occur must also be considered, of course. These may include such phenomena as corrosion, ship collision, and earthquakes. The collection of such calculations and considerations constitutes a complete analysis of the design.

B. The Value of Successes and Failures

It is an apparent paradox of science and engineering that more is learned from failures than from successes. Indeed, Karl Popper's philosophy of science holds that a scientific hypothesis must be falsifiable. What this means is that a given hypothesis can be found false by a single counterexample. Thus, if a scientist puts forth a hypothesis that states that no living thing can exist for more than 100 years, the documented existence of a living tree more than 300 years old disproves the hypothesis. If, however, no one can produce a living thing that is more than 100 years old, this does not prove the hypothesis. It merely confirms it as a (true) hypothesis, still subject to being proven false by a single counterexample.

Engineering has hypotheses also, and they are equally refutable by a single counterexample. In the first half of the nineteenth century, it was a commonly held belief (or hypothesis) that a suspension bridge could not safely carry railroad trains. John Roebling explained his reason for studying the failures of suspension bridges that had occurred during that time by stating that he could not know how to design a successful bridge unless he knew what he had to design it against. In the 1850s he designed and built a suspension bridge over the Niagara Gorge that did carry railroad as well as carriage traffic. In other words, Roebling's bridge provided the counterexample to the hypothesis that suspension bridges could not carry railroad trains. At the same time, his successful bridge did not prove that all suspension bridges would be safe.

When a bridge carries traffic successfully or a skyscraper stands steady in the wind, the structure does not reveal much beyond the fact that it is fulfilling its function. Although design claims that the structure would not fail will have been verified by the successful structure, and measurements of how much the structure moves under load will confirm quantitatively what the design calculations predicted, that does not prove that the design analysis was total or complete. If the design calculations did not include aerodynamic effects, for example, like the flutter of a bridge's roadway in the wind, that does not mean the wind cannot bring the structure down, as it did the Tacoma Narrows Bridge. Nature does not ignore what an engineer may have overlooked.

If an unexpected failure occurs, however, such as the collapse of the Tacoma Narrows Bridge, then it provides incontrovertible evidence that the design was improperly (or incompletely) analyzed or something was overlooked. Whereas aerodynamic effects might have been insignificant in bridges that were wide and heavy, like the George Washington Bridge, they could not be ignored in light and narrow structures like the Tacoma Narrows Bridge. Unfortunately, it often takes a catastrophic failure to provide the clear and unambiguous evidence that the design assumptions were faulty.

There were precursors to the collapse of the Tacoma Narrows Bridge, in that several other bridges built in the late 1930s displayed unexpected behavior in the wind. Indeed, engineers were studying the phenomenon, trying to understand and explain it, and debating how properly to retrofit the bridges affected when the landmark failure occurred. It provided the counterexample to the implicit engineering hypothesis under which all such bridges were designed, namely, that the wind did not produce aerodynamic effects in heavy bridge decks sufficient to bring them down. Thus, the failure of the Tacoma Narrows Bridge proved more instructive than the success of all the bridges that had performed satisfactorily—or nearly so—over the preceding decades.

1. Lessons from successful designs

Strictly speaking, a successful design teaches engineers only that that design is successful. It does not prove that another design like it in every way but one will also be successful. For example, there is a size effect in engineering, as in nature, and it appears to have been known, though not necessarily fully understood, for millennia. Vitruvius, who wrote in the first century B.C. what is generally considered to be the oldest work on engineering extant, related the story of the ancient engineer Callias, who convinced the citizens of Rhodes with the aid of a model that he could build a machine to defend their city against any siege the enemy could launch. When the enemy did attack with an unprecedentedly large heliopolis, Callias confessed that he could not defend the city as promised because although his defense machine worked as a model, it would not work at the scale needed to conquer the gigantic heliopolis.

Galileo, writing fifteen centuries later, described how limitations to size were appreciated in the Renaissance, even though still not fully understood. He told of the spontaneous failure of wooden ships upon being launched and of stone obelisks upon being moved. It was Galileo's work that finally explained what was happening. Since the volume of a body, natural or artificial, increases faster than the area of its parts as they are scaled up in a geometrically similar way, there will come a time when the weight is simply too much for material of the body to bear. This, as Galileo explained, is why smaller animals have different proportions than larger ones, and it is also why things in nature grow only so large. So it is with engineered structures.

The phenomenon of the size effect is not the only one that has taken engineers by surprise. The aerodynamic instability manifested in suspension bridges in the late 1930s was absent or insignificant and thus unimportant in early designs of those structures. However, it became dominant and thus significant in evolved designs, which were so much larger, lighter, narrower, or more slender.

Another example relates to metal fatigue, a mechanical phenomenon in which the repeated loading and unloading of a structural component leads to crack growth, which in turn can lead to catastrophic failure of the weakened part.

Metal fatigue had long plagued the railroad industry. In time it came to be understood that if the intensity of loading was kept below a certain threshold, cracks would not develop and thus the structure would not be weakened. When commercial jet aircraft were first developed after the Second World War, metal fatigue was not believed to be relevant, but the mysterious failures of several de Havilland Comets in the 1950s led one engineer to suspect that fatigue was indeed the cause of the mid-air disasters. It was in fact true that the cyclic pressurization and depressurization of the cabin with every takeoff and landing was producing fatigue cracks that grew until the fuselage could no longer hold together. The engineer was able to confirm his hypothesis about fatigue by testing to failure an actual Comet fuselage under controlled conditions.[42]

The phenomenon of fatigue does not affect only large structures made of metal. A fatigue failure of a more modest kind but nevertheless of significant consequence to those who used the device was the breakage of keys on the child's toy Speak & Spell. Introduced by Texas Instruments in the late 1970s, not long after electronic calculators had become embraced by engineers, this remarkable device employed one of the first microelectronic voice synthesizers. Speak & Spell would ask a child to spell a word, and the child responded by pecking out the word letter by letter on the keyboard, each letter appearing as it was typed on the calculator-like display. Upon hitting the enter key, the child was told that the spelling was correct or was asked to try again. Children enjoyed the toy so much that they used it for hours on end, thus flexing the plastic hinges of the letter keys over and over again. This repeated loading and unloading of the plastic hinges led some of them to exhibit fatigue and break off. Children could still fit their little fingers into the keyholes, however, and so they could continue to use the toy, disfigured as it was. What makes the experience with Speak & Spell so instructive as an example of a fatigue failure is that the first key to break was invariably the one used most—the E key. For those Speak & Spells that continued to be used, subsequent keys tended to break in the same sequence as the frequency of letters used in the English language—E, T, A, O, I, N, and so forth—thus demonstrating the fundamental characteristic of fatigue failure, namely, that all other things being equal, the part subjected to the most loadings and unloadings will break first.[43]

The Speak & Spell example also shows how engineering designs are changed in response to repeated failures. In time, a new model of the toy was introduced, one with a redesigned keyboard. In place of the plastic keys that fit individually into recesses there was a flat keyboard printed on a rubbery plastic sheet that overlay all the switches for the letters. Not only did the new design reduce the incidence of key failure, but it also made for a flat surface that was much easier

42. *See* Petroski, *supra* note 12, at 176–84.

43. *Id.* at 22–27.

to clean than the original model, which collected the snack residue that children are likely to leave on their toys. The redesign of the Speak & Spell is a representative example of how engineers are attentive and responsive to failures.

2. Lessons from failures

Unanticipated failures may be thought of as unplanned experiments. While failures are also unwanted, of course, the surprise result of any failure is clearly interesting, and it reveals a point of ignorance that engineers must then seek to correct. Thus, when the Tacoma Narrows Bridge collapsed, bridge engineers could no longer argue that they did not have to analyze large suspension bridge designs for their susceptibility to aerodynamic effects. Indeed, it was the unanticipated motion of bridge decks (the failure of them to hang steady in the wind) that prompted wind-tunnel tests of the deck designs for future suspension bridges. Although such model tests were still open to some criticism as to their relevance for the full-scale bridge, comparative wind-tunnel tests could be conducted on alternative deck designs, and such tests led to new designs in the wake of the Tacoma Narrows collapse. The wing-like decks of the Severn and Humber Bridges in Britain are examples of such new designs.

Failures in machine parts are equally revealing of design weaknesses. A bracket that keeps breaking in an automobile engine, for example, indicates a poorly designed detail, and it is likely that this bracket will in time be redesigned to give it greater strength in the vulnerable location. As a result, replacement parts will come to be manufactured in a slightly different form than the original, and later models of the same automobile are likely to come with the redesigned bracket factory-installed.

C. Successful Designs Can Lead to Failure

A major advance in the design and construction of long-span suspension bridges was made in the mid-nineteenth century by John A. Roebling. His career culminated in his design of the Brooklyn Bridge, the completion of which was overseen by his son, Washington A. Roebling, and his wife, Emily Warren Roebling. For half a century from 1883, when the Brooklyn Bridge was opened to traffic, suspension bridges evolved in several directions. The most obvious change was that the length of the main span increased from the 1,595 feet of the Brooklyn Bridge to the 4,200 feet of the Golden Gate Bridge, which was completed in 1937. Another important development was the increasing slenderness of suspension bridges, perhaps best exemplified by the shallow roadway of the George Washington Bridge as completed in 1931 with only a single deck. (The lower deck was not added until the early 1960s.) The evolution to slenderness of suspension bridges culminated in several long-span suspension bridges of the late 1930s, including the Bronx-Whitestone and Deer Isle Bridges, which used shallow plate girders instead of deep deck trusses to support the roadway.

Another important change in the design of suspension bridges after the Brooklyn Bridge was the elimination of the cable stays that radiate from that bridge's Gothic towers to its roadway. In the Brooklyn Bridge this feature results in the web-like pattern of its cables that is characteristic of Roebling designs. John Roebling had incorporated this feature, as well as guy wires steadying the bridge from beneath, in his Niagara Gorge Bridge of 1854, which was the first suspension bridge to carry the heavy and violent loads of railroad trains. As suspension bridges came in time to be built larger, the feature of guy wires was dispensed with, as the effect of the wind on vertical motions of the deck was believed to be insignificant. In this way, the successful designs of more than a half century earlier evolved into the light, narrow, slender, and unadorned Tacoma Narrows Bridge that could not withstand a 42-mile-per-hour wind.

The evolution of bridges is a paradigm for the development of all designed structures and for the evolution of artifacts generally. The more successful a design, the more likely it is to be a model for future designs. But because engineering and construction are influenced by aesthetics, economics, and, yes, ethics or their absence, designs tend to get pared down in time.[44] This paring down can take the form of enlargement in size without a proportional increase in strength, in defiance of the size effect; streamlining in the sense of doing away with what is believed to be superfluous; lightening by the use of stronger materials or materials stressed higher than before; and cheating, which can take the form of leaving out some indicated reinforcement in concrete or deliberately substituting inferior materials for specified ones. The cumulative effect of such paring down of strength is a product that can more readily fail. If the trend continues indefinitely, failure is sure to occur.

When failures do occur, engineers necessarily want to learn the causes. Understanding of the reason for repeated failures—structural or otherwise—that jeopardize the satisfactory use and therefore the reputation of a product typically leads to a redesigned product. Thus, the vulnerability of automobile doors to being dented in parking lots led to the introduction of protective strips along the length of car bodies. The propensity of pencil points to break under relatively light writing pressure led pencil manufacturers in the 1930s to look into the reasons for the failures. When it was found that the pencil lead was not being

44. *See* Baum v. United States, 765 F. Supp. 268, 274 (D. Md. 1991) (noting the often conflicting factors, the court commented that "National Park Service officials have more than safety in mind in determining the design and use of man-made objects such as guardrails and signs along the parkway. These decisions require balancing many factors: safety, aesthetics, environmental impact and available financial resources.").

properly glued to the wood case, research-and-development efforts were initiated to design a more supportive joining process. This led to proprietary pencil manufacturing processes with names such as "Bonded," "Chemi-Sealed," "Pressure Proofed," and "Woodclinched," some of which can be found still stamped on pencils sold today.[45]

Failures that cause more significant property damage or that claim lives are usually the subject of failure analyses conducted by consulting engineers or forensic engineers. Such investigations may be likened to puzzle solving or to design problems worked in reverse, in that the engineer must develop hypotheses and then test them with analysis. However, with direct design there is no unique solution; in a forensic engineering problem, there presumably is a unique cause of a particular failure, but it might not easily be found.

The failure analyst or forensic engineer must essentially come up with a hypothesis of how the particular failure under investigation was initiated and progressed. The hypothesis obviously must be consistent with the evidence, which should be preserved as much as possible in the state in which it existed when the failure occurred. This means, for example, that the configuration of an accident scene should be recorded before anything is moved, that the fracture surfaces of broken parts should not be touched or damaged further, that bent and twisted parts should be left in their as-found condition, and generally that each and every piece of potential evidence should be carefully labeled and handled with care. In other words, the scene of an engineering failure should as much as possible be treated as if it were the scene of a crime. The urgent need to move material objects to reach persons involved in an accident takes precedence, of course, and how this may have affected forensic evidence must itself be taken into account in the analysis of evidence from the accident scene.

There have been attempts to formalize the procedures involved in the investigation of failures, especially those of a recurring nature, such as the collapse of structures.[46] However, with the exception of aircraft accident sites, which are under the control of the National Transportation Safety Board (NTSB), there is no uniform way in which structural failure sites are controlled. In the case of the Kansas City Hyatt-Regency walkways collapse, for example, the owner of the building had the one surviving walkway removed within a day or so of the accident, thus depriving engineers of the opportunity to study an undamaged structure of similar design to see if it provided any clues to the cause of the collapse of the other two walkways.

Regardless of how the failure or accident site is treated, investigating engineers must seek clues to the cause in whatever way they can. The most helpful information naturally comes from the most well-preserved pieces of the puzzle.

45. *See* Henry Petroski, The Pencil: A History of Design and Circumstance 244–45 (1990).

46. *See, e.g.,* Jack R. Janney, Guide to Investigation of Structural Failures (1979).

Thus, broken parts should be handled with care so as not to destroy evidence of how a crack might have begun and propagated or how two broken pieces may or may not fit together. Cracks in metal and plastic generally leave telltale clues as they grow, and the failure-analysis expert can read these clues under a microscope with some degree of certainty. Broken pieces that fit together to produce a part that could be mistaken for new were it not for the fracture indicate that the material was extremely brittle when the part broke, something that may or may not have been appropriate for the design. In contrast, pieces that when fitted together show the part to have been stretched and bent before breaking indicate a ductile material and give some indication of the nature of the loads before the fracture. Such conclusions can be drawn with a high degree of certainty, and the kind of information they yield can often lead to the construction of a very likely scenario for what happened.

Investigators for the NTSB look for such clues, and more of course, when they collect the parts of a crashed plane and assemble them on the floor of a hangar. No matter how sure the board's final conclusion might be, however, it is always presented as a "most likely cause" rather than a proven fact, in recognition that fundamentally the proffered cause is but a hypothesis. Just as scientific hypotheses can be confirmed and verified but never proven with mathematical certainty, so the cause of an engineering failure can only be confirmed and verified by the surviving evidence. The evidence can often be so overwhelmingly convincing, however, that engineers use it to guide their redesigns and future designs.

The more catastrophic and dramatic failures, especially those that claim lives, are often the subject of public and formal investigations. The explosion of the space shuttle *Challenger*, in which all seven astronauts on board died, was investigated by a presidential commission, whose hearings were televised. The collapse of the Quebec Bridge, which claimed the lives of about seventy-five construction workers, was looked into by a royal commission. And the failure of the elevated walkways in the Kansas City Hyatt-Regency Hotel in 1981 was investigated in some detail by what was then the National Bureau of Standards. (The role of the engineers in the collapse of the walkways was the subject of a case presented by the professional engineering licensing board of Missouri before a commissioner.[47]) In all such cases, there have been extensive formal reports, which are often very informative not only about the particular case under consideration but also about the nature of the engineering design process generally. Collectively, such reports can point to patterns regarding failures and thus to generalizations about what engineers might be watchful for in the future.

For example, the history of bridges over the last century and a half reveals a

47. Missouri Bd. of Architects, Prof'l Eng'rs & Land Surveyors v. Duncan, No. AR-84-0239, 1985 Mo. Tax LEXIS 50 (Mo. Admin. Hearing Comm'n Nov. 15, 1985).

disturbing pattern of success leading to failure. Beginning with the Dee Bridge failure in 1847, roughly every 30 years there has been a major bridge failure—each of a different type of bridge—and each failure can be traced to the gradual transformation of a successful bridge design.[48] Among the explanations for this haunting pattern is that novel types of bridges are designed by engineers who take care with the designs, since they have few precedents, and the designs that are successful are copied and in time come to be attempted in longer lengths, in more slender profiles, and with increasing casualness by a younger generation of engineers that is unaware of or does not remember the assumptions that went into the early designs or the limitations of those designs. Such a pattern was being repeated in the late twentieth century for cable-stayed and post-tensioned bridges, and such bridges may well be expected to suffer a catastrophic failure early in the new millennium.

D. Failures Can Lead to Successful Designs

Just as successful designs can lead to failures, so can failures lead to revolutionary successes. The same history of bridge failures described earlier (in section IV.C) also reveals that with a catastrophic failure, a type of bridge or a construction practice falls out of favor. This occurs often more for extratechnical reasons, such as an attempt to regain the public's confidence so that the new bridge will attract the public to a railroad or a toll highway.

If a type of bridge ceases to be used, then a new type must be developed for the building of new bridges. In the wake of a major failure, new engineers are likely to be retained, engineers with solid reputations and impeccable credentials. Furthermore, because a novel type of bridge is being proposed, its design must proceed with deliberate attention to detail and explicit consideration of all relevant modes of failure. In the wake of the failure, the bridge tends to be overdesigned to further ensure its reliability.[49]

E. Engineering History and Engineering Practice

The historical pattern described in the preceding two sections points to the value of history for present and future engineering. As suspension bridges were being designed with ever longer lengths and with ever more slender profiles, engineers of the 1920s and 1930s looked to the history of bridges for aesthetic models. Among the bridges often referred to was the Menai Strait Suspension Bridge in Wales, which was designed and built by Thomas Telford in the 1820s. The stone towers, iron chains, and wooden deck of this classic bridge influenced greatly the bridges of a century later, but the Menai served only as an aesthetic

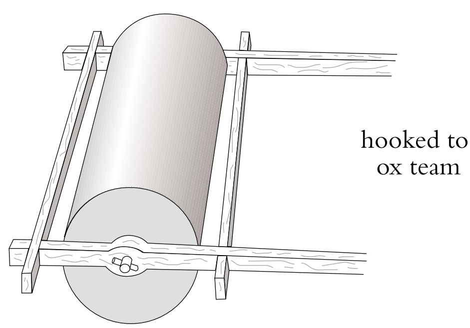
48. *See* Petroski, *supra* note 29, at 168–69.
49. *Id.* at 176–77.

model and thus only to a limited extent. The repeated destruction in the first half of the nineteenth century of the Menai Strait Bridge's deck in the wind was dismissed as irrelevant to the state of the art of modern bridge building. This was so because it was believed that the force of the wind could not produce the same effects on a heavy steel deck that it did on the Menai Strait's light wooden fabric. This, of course, proved to be a totally unfounded assumption.

The history of engineering, even of ancient engineering as recorded 2,000 years ago by Vitruvius, has a relevance to modern engineering because the fundamental characteristics of the central activity of engineering—design—are essentially the same now as they were then, have been through the intervening millennia, and will be in the new millennium and beyond. Those characteristics are the origins of design in the creative imagination, in the mind's eye, and the fleshing out of designs with the help of experience and analysis, however crude. Furthermore, the evolution of designs appears to have occurred throughout recorded history in the same way, by incremental corrections in response to real and perceived failures in or inadequacies of the existing technology, the prior art. There also is strong evidence in the historical record that engineers and their antecedents in the crafts and trades have always pushed the envelope until failures have occurred, giving the advance of technology somewhat of an epicyclic character. Thus, according to this view, the fundamental characteristics of the creative human activity we call design are independent of technological advances in analytical tools, materials, and the like.

The way artifacts were designed and developed in ancient times remains a model for how they are designed and evolve today. This is illustrated in a story Vitruvius relates of how the contractors and engineers Chersiphron, Metagenes, and his son Paconius used different methods to move heavy pieces of stone from quarry to building site. The method of Chersiphron—which was essentially to use column shafts as wheels, into whose ends hollows were cut to receive the pivots by which a pulling frame was attached, as indicated in Figure 5—worked fine for the cylindrical shapes that were used for columns, but the method failed to be useful to move the prismatic shapes of stones that were used for architraves. Metagenes very cleverly adapted Chersiphron's method by making some evolutionary modifications in how the stone was prepared for hauling. He essentially used an architrave as an axle, around whose ends he constructed wheels out of timber, as indicated in Figure 6. When Paconius was faced with a new problem, however, involving a stone that could not be defaced in the way the earlier methods had to be to receive pivots, he devised a scheme to prepare the stone without damaging it. As indicated in Figure 7, he enclosed the stone in a great timber spool around which a hauling rope could be wound. The method would also appear to be but an incremental evolutionary development from that of his predecessors, but it proved to be a colossal failure because the spool and its cargo could not be kept on a straight path, and all the time and effort spent in getting the spool back to the center of the road led to the bankruptcy of the contracting business. Understanding the way in which Chersiphron's successful method evolved through Metagenes's method to Paconius's dismal failure is a paradigm for the design process. It behooves engineers and those who wish to appreciate the enterprise of engineering to understand through such a paradigm the process independent of the particular application and the state of the art in which it is embedded at any given point in history.[50]

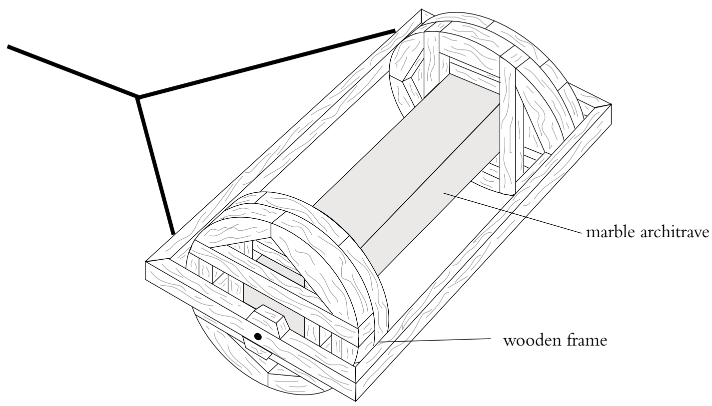
Figure 5. Chersiphron's scheme for transporting circular columns.



From Petroski, *supra* note 29, at 19 & fig. 2.1 (after Larsen, 1969).

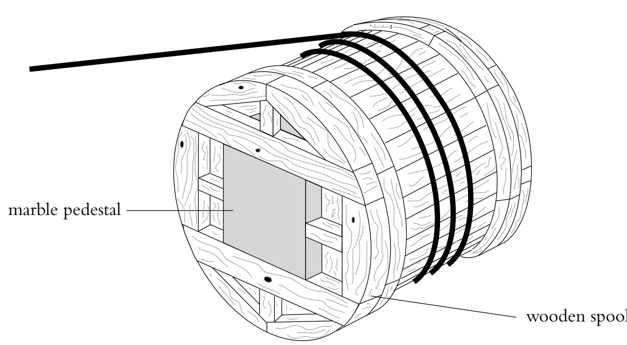
50. *Id*. at 17–26.

Figure 6. Metagenes's scheme for transporting architraves.



From Petroski, *supra* note 29, at 20 & fig. 2.2 (after Coulten, 1977).

Figure 7. Paconius's scheme for transporting the pedestal for the Statue of Apollo.



From Petroski, *supra* note 29, at 22 & fig. 2.3 (after Coulten, 1977).

Although the examples in this reference guide are drawn mainly from the fields of civil and mechanical engineering and are largely historical, the principles of design, analysis, and practice that they illustrate are common to all fields of engineering and are relevant to twenty-first century engineering. The nature of engineering design is such that emerging fields like bioengineering and software engineering can be expected to follow similar paths of development as have the older and more traditional fields, in that design errors will be made, failures will occur, and designs will evolve in response to real and perceived failures. Biomedical engineering, which grew mainly out of electrical engineering, is already a well-established discipline with its own academic departments, professional journals, and societies. One such journal is the *IEEE Transactions on Biomedical Engineering*, published by the Engineering in Medicine and Biology Society of the Institution of Electrical and Electronics Engineers.

Although there has been some opposition among professional engineers to the term "software engineering" and to the use of the title "software engineer" by those without engineering degrees, there are clear indications that this opposition is lessening. The State of Texas, for example, now licenses software engineers under that title. The software engineering community itself has for some time felt a kinship to engineering more than to computer science, and the name of their principal professional society, the Association for Computing Machinery (ACM), is certainly more suggestive of an engineering organization than a science one. Software engineering publications have run at least one extensive interview with a prominent bridge designer, and at least one expert on bridge failures has been invited to give keynote addresses at meetings of software engineers. Thus, those engaged in software design and development are recognizing the validity of the analogy between what they and civil engineers do and the lessons to be learned by analogy from structural engineering history and failures. There is also on the Internet a very well-established and closely read Forum on Risks to the Public in Computers and Related Systems (comp.risks), which is operated by the ACM Committee on Computers and Public Policy, and moderated by Peter G. Neumann.[51] That the newest engineering fields share a methodology and an interest in failures with the oldest engineering fields should be no more surprising than the fact that the newest scientific fields share the scientific method with older sciences like chemistry and physics.

51. This publication is available on request from risks-request@csl.sri.com with the single-line message "Subscribe."

V. Summary

In summary, engineering and science share many characteristics and methodologies, but they also have their distinct features and realms of interest. Among the points that have been made in this reference guide that might be considered in evaluating an engineering expert's testimony are the following:

- Engineering and scientific practice share qualities, such as rigor and method, but they remain distinct endeavors.
- Engineering in its purest form seeks to synthesize new things; science seeks to understand what already exists.
- Engineering is more than applied science; engineering has an artistic and creative component that manifests itself in the design process.
- Engineering designs are analogous to scientific hypotheses in that they can be proven wrong by a single counterexample (such as a failure) but cannot ever be proven absolutely correct or safe.
- Engineering always involves an element of risk; it is the engineer's responsibility to minimize that risk to within socially acceptable limits.
- Engineering designs are tested by analysis; it is when engineers are doing analysis that they behave most like scientists.
- Engineering in a climate of repeatedly successful experience can lead to overconfidence and complacency, and this is when errors, accidents, and failures can happen.
- Engineering failures provide reality checks on engineering practice, and the information generated by a failure investigation is very valuable not only to explain the failure itself but also to point to shortcomings in the state of the art.
- Engineering is always striking out in new directions, but that is not to say that new fields of engineering are different in principle from traditional ones.
- Engineering has a rich history, which is dominated by successes but punctuated by some colossal failures, and that history provides great insight into the nature of engineering and its practice today.

Glossary of Terms

ABET. Accreditation Board for Engineering and Technology, a consortium of engineering professional societies that accredits academic engineering and engineering technology programs.

analysis. The study of an engineering system that leads to a usually quantitative understanding of how its constituent parts interact. See also design.

applied science. Science or a scientific endeavor pursued not merely for an understanding of the universe and its materials and structures but with a practical objective in mind. Seeking the fundamental nature of subatomic particles is considered pure science if it has no other objective than an understanding of the nature of matter. Using scientific principles relating to the interaction of atoms to define specifications for a nuclear reactor is applied science. Engineering, which involves a synthesis of science, experience, and judgment, is frequently but mistakenly termed applied science.

computer-aided design (CAD). The use of digital computers to model, analyze, compare, and evaluate how changes in an engineering system affect its behavior, with the objective of establishing an acceptable design. The most sophisticated applications of CAD eliminate much of the paper calculations and drawings long associated with engineering design and allow the data associated with a design to be transferred electronically from the design to the manufacturing stage.

conservatism (in engineering). When choices are encountered in engineering modeling, design, or analysis, choosing the option that makes the design safer or causes the analysis to predict a lower load capacity rather than a higher one.

constraints. Anything outside the designer's control that restricts choices in design is known as a constraint. Thus, if a certain clearance above mean high water or a certain width of channel is required of a bridge, these are design constraints for the bridge. Other constraints may be more abstract, but nonetheless physically meaningful, for example, in the mathematical analysis of two machine parts interacting with one another in a computer model, the constraint that one solid part is not allowed to share the same position in space at the same time as another.

dead load. The load on a structure that is due to the weight of the structure itself.

design. The aspect of engineering that creates new machines, systems, structures, and the like. Design involves an artistic component, in that the design engineer must create something, usually expressed in a sketch or physical model, that can be communicated to other engineers, who can then analyze and criticize it, and flesh it out.

design assumptions. No engineering design can proceed through analysis without some assumptions being made about what its salient features are or what physical phenomena are important to its operation. Thus, it is a common assumption that the series of bolts connecting a steel beam to a column is so tightened that no movement is allowed between the parts. This design assumption defines conditions under which the analysis must proceed.

design constraints. See constraints.

design load. The load that a component of a structure is designed to support.

E.I.T. See Engineer in Training.

Engineer in Training (E.I.T.). An engineer who has passed the Fundamentals of Engineering Examination, the first step in becoming licensed as a professional engineer.

engineering method. Akin to the scientific method, the engineering method uses quantitative tools and experimental procedures to test and refine designs.

engineering science. Disciplines that follow the rigors of the scientific method but have as their objects of study the artifacts of engineering rather than the given objects and phenomena of the universe.

equilibrium state. The condition of an engineering system whereby it is in equilibrium with its surroundings, that is, no change in the system will occur without some change in the forces applied or the configuration obtaining.

"factor of safety." The ratio of a load that causes failure to the design load of a structure.

failure. The condition of not working as designed. A bridge that collapses under a railroad train is obviously a failure of a catastrophic kind. A less dramatic but nonetheless bothersome design failure might be a skyscraper that sways in the wind not so much as to endanger the structure but enough to cause the occupants of upper stories to become sick to their stomachs. A project that goes over budget or is not aesthetically satisfying might also be considered a failure by some engineers.

failure analysis. The determination of the sequence of events and cause of a failure. Failure analysis can involve not only a detailed physical examination of the broken parts of a failed structure or system but also the development of conceptual and computer models to demonstrate how the failure progressed.

failure load. The load at which a structure fails to support the loads imposed on it.

fatigue. The phenomenon whereby a part of a machine or structure develops cracks (fatigue cracks) that grow under continued, repeated loading. When the cracks grow to critical lengths, the machine part or structure can fracture.

forensic engineering. That branch of engineering that deals with the investigation, nature, and causes of failures.

Fundamentals of Engineering Examination. The test that is used to qualify engineers to use the Engineer-in-Training (E.I.T.) designation.

hypothesis. In engineering, a design on paper or in a computer. The design is a hypothesis in the sense that it is an unproven assertion, albeit one that may have a high level of professional experience and judgment backing up its veracity. Also like a scientific hypothesis, an engineering design cannot be proven absolutely to be correct, but can only be falsified. The falsification of an engineering design (hypothesis) is known as a failure.

instability. The phenomenon whereby a small disturbance of an engineering system results in a large change from its equilibrium state or condition of stability. An aluminum beverage can that crumples under a slightly too strong grip could be said to exhibit a buckling instability.

iteration. The engineering design process whereby successive calculations yield successively more accurate predictions of an engineering system's behavior. Iterations often proceed in reaction to the degree to which the latest calculation differs from the previous one, with an increment based on the difference. The process is necessary in steel design, for example, because the principal load on a structure is its dead weight, which naturally depends on the size of the steel members used. The choice of the size of the members, in contrast, depends on the weight of the structure. To begin to iterate toward a fixed design in this vicious circle requires an educated guess at the outset of how heavy the structure must be. The more experienced an engineer, the more accurate the guess is likely to be.

licensing. The process by which engineers progress from E.I.T. to P.E. status.

live load. The load on a structure that is due to things other than the weight of the structure itself. Live loads can include people, furniture, and materials stored in an office building or warehouse, or the traffic on a bridge.

load. In structural engineering, the weight of a structure and the weight of any objects resting upon it or moving across it. See also dead load, design load, live load.

metal fatigue. See fatigue.

mode of failure. The manner in which an engineering system can fail. Most systems have multiple modes of failure, and for design purposes the one that is likely to occur under the smallest load on the system is termed the governing mode of failure.

model. A physical, mathematical, or computer-based representation of an engineering system. Although a model is clearly not identical to the real system, this fact is often forgotten in the interpretation of results from testing a model or running a computer program.

P.E. See Professional Engineer.

prior art. In the field of patents, the technology that is in place at the time a patent is applied for. To be patentable, an invention must not be obvious to one versed in the prior art. See also state of the art.

professional engineer (P.E.). An engineer who has completed a number of years in responsible charge of engineering work and who has passed both the Fundamentals of Engineering and the Professional Engineering Examinations. Under certain circumstances in some states, exemptions to examination may be granted. Abbreviated P.E. in the United States.

"pushing the envelope." Designing beyond engineering experience. Much of engineering is making ever larger, lighter, faster, or smaller things. Such evolutionary developments can, of course, be guided by experience with what has already been made and is operating successfully. All examples of a thing that have been successfully designed are said to be contained within an envelope, which metaphorically encloses them. When data points representing individual engineering systems of a certain kind are plotted on a graph, a smooth curve going through the data points on the fringes of the collection of points is said to be an envelope. To push the envelope is to extend the range of experience, or to add a data point that moves the envelope curve beyond the realm of experience, something that is a natural activity of engineers. When it is done a little at a time, there is little chance that engineers will be surprised by some totally new behavior or not have time to react to it if it does appear to be developing. When the envelope is pushed too violently, however, the design can surprise engineers with totally unexpected and uncontrollable behavior.

scientific method. See engineering method.

S.E. A registered Structural Engineer.

size effect. Something that works fine on a small scale will not necessarily work as well when it is scaled up. In structural engineering this phenomenon has been known since ancient times but was not explained until Galileo did so in the Renaissance. In structural engineering, the phenomenon has to do with the fact that the weight of an object is proportional to its volume, which is related to its size (height, length, or width) to the third power. The strength of an object, however, is only proportional to the area that resists it being pulled apart, and the area is related to size to the second power. There will invariably be a point in the scaling up of a structure geometrically at which the weight exceeds the strength and the structure cannot hold together. Size or scale effects can be exhibited in all kinds of engineering systems, as in a manufacturing process that works fine in the laboratory but is a complete failure when scaled up to factory proportions. It is for this reason that novel power plant designs go through several stages of being scaled up.

stability. An engineering system is said to be stable if it exhibits a small response to a small disturbance. Stable behavior is exhibited when the top of a tall building moves just slightly to the side when the wind increases and returns to its equilibrium position when the wind stops blowing. In contrast, if the top of the building begins moving in an erratic way when the wind increases from 40 to 42 miles per hour, the structure is said to be unstable at that wind speed.

"state of the art." The sum total of knowledge, experience, and techniques that are known and used by those practicing a particular branch of engineering at a given time. See also prior art.

strength of materials. The engineering science that relates how the change of shape of a body is related to the forces that are applied to it, and, by extension, how much resistance it offers to breaking.

structural engineer (S.E). A civil engineer who specializes in the design and analysis of structures, especially large structures like bridges and skyscrapers. A licensed structural engineer is entitled to use the letters S.E. after his or her name.

structure. An assemblage of parts made of a material or materials (steel, concrete, timber, etc.) and designed to carry loads.

truss. An arrangement of structural elements, usually in a series of triangular configurations, used to build up a larger structural component that can span long distances with minimal weight. Trusses are usually made of metal or timber, the former being common in bridges and industrial applications and the latter in domestic roof structures.

wind tunnel. An experimental facility in which models can be placed in a controlled air stream to test their behavior in the wind or the air currents flowing around them. Wind tunnels are commonly used in the development of airplanes and large structures like suspension bridges and skyscrapers, which are likely to be subjected to large wind forces. Prior to the collapse of the Tacoma Narrows Bridge in the wind, bridge decks were not subjected to wind-tunnel testing. Subsequent to the 1940 accident, it became standard practice to test for stability in a wind tunnel the model of any proposed bridge deck design.

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