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Henry Petroski: Success through Failure

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INTRODUCTION

Desire, not necessity, is the mother of invention. New things and the ideas for things come from our dissatisfaction with what there is and from the want of a satisfactory thing for doing what we want done. More precisely, the development of new artifacts and new technologies follows from the failure of existing ones to perform as promised or as well as can be hoped for or imagined. Frustration and disappointment associated with the use of a tool or the performance of a system puts a challenge on the table: Improve the thing. Sometimes, as when a part breaks in two, the focal point for the improvement is obvious. Other times, such as when a complex system runs disappointingly slowly, the way to speed it up may be far from clear. In all cases, however, the beginnings of a solution lay in isolating the cause of the failure and in focusing on how to avoid, obviate, remove, or circumvent it. Inventors, engineers, designers, and common users take up such problems all the time.

The earliest useful things were, of course, those found in nature. Not surprisingly, these same things became the earliest tools. Thus, rocks came to be used as hammers. Whether a particular rock makes a good hammer depends on its size and shape and on its hardness and toughness relative to the object being hammered. Rock types that failed to accomplish desired ends became known as poor hammers and so came to be

passed over. Better hammers resulted from eliminating the failures. However, even the best of rocks have limitations as hammers, and the recognition of their failure in this regard defined the design problem: Devise a better hammer. Among the problems with a hammer-rock can be that it is awkward or uncomfortable to wield. An improvement might be sought in the shape of the rock or in providing a handle for it—or from replacing the rock with something better. In time, a growing variety of metal hammer heads and wooden hammer handles, appropriate to a variety of tasks and grips, would reflect increasing specialization and diversification. Among such diversity, one might expect that there was a single best hammer for a particular task. All the others would fail to work as well at that task. Should all existing hammers fail to work properly for a newly developed task, then a still newer hammer might have to be developed. By the latter part of the nineteenth century, some five hundred different types of hammers were being produced in Birmingham, England, alone.

Technological systems also have their roots in the given world. The circadian and seasonal rhythms of nature drove the development of patterns of rest and migration. Even the simple act of sleeping when it is dark could be fraught with danger, however, as may have been discovered the hard way. If all the members of a group slept simultaneously, some might fail to survive the night. Recognizing this failure of the system would naturally lead to such concepts as the staggered watch and other means of protection. Thus, the group might begin sleeping in a cave whose single entrance could be guarded by a boulder rolled across it. The inconveniences of migration ultimately led to the development of systems of agriculture and

defense. No matter how well developed a thing or system becomes, however, it will never be without limitations. There are no mechanical utopias. Therefore, there will always be room for improvement. The most successful improvements ultimately are those that focus on the limitations—on the failures.

Success and failure in design are intertwined. Though a focus on failure can lead to success, too great a reliance on successful precedents can lead to failure. Success is not simply the absence of failure; it also masks potential modes of failure. Emulating success may be efficacious in the short term, but such behavior invariably and surprisingly leads to failure itself. Thus, a single type of rock that worked reasonably well as a hammer for every previously known task might be said to be *the* hammer-rock. Whenever anyone wanted an all-purpose hammer they would look for that type of rock, if they had not already become accustomed to carrying it around with them. In time, however, there would arise a task in which the hammer-rock would fail. This would occur, for example, when the implement was used to strike a newly discovered but harder and tougher rock, with the purpose of shattering it. But to everyone's surprise, it would be the hammer-rock itself that would shatter. Past successes, no matter how numerous and universal, are no guarantee of future performance in a new context.

This book explores the interplay between success and failure in design and, in particular, describes the important role played by reaction to and anticipation of failure in achieving success. Since the book grew out of a series of lectures, the nature of lectures generally—and specifically the technology of the illustrated lecture as an evolving system—suggested itself as a topic with which to begin. From its precursors to the magic lantern,

through the overhead and 35-mm-slide projector, to computer-based PowerPoint presentations projected through digital devices, successive improvements are shown to have been motivated by and arisen in response to the real and perceived failures of earlier means—and the systems within which they operated—to perform as well as could be imagined in the context of always-developing technologies and their attendant introduction of new expectations.

The vast majority of users of a technology adapt to its limitations. In fact, to use any single thing is implicitly to accept its limitations. But it is in human nature to want to use things beyond their intended range. Though a wooden pointer can be made only so long before it becomes too heavy and unwieldy to use on a stage, we invariably want to extend its reach. As a result, a lecturer might have to step into the field of a projected image to tap on a detail, thereby covering up some of the context. Of course, the limitations of the wooden pointer became moot with the development of the laser pointer, which has its own limitations. Its longer “reach” means that in an unsteady hand the movement of its “point” is amplified. Furthermore, the laser pointer’s light touch does not allow the projection screen to be tapped for emphasis. Also, sometimes it is difficult to pick out the pointer’s red dot from among a scattering of red data points. Technological advancement is not unqualified technological improvement.

Most things have more than a single purpose, which obviously complicates how they must be designed and how they therefore can fail. The more complicated the design problem, naturally the more difficult the solution and hence the more likely that some details and features may be overlooked, only to

have their absence come to the fore after the thing is manufactured or built and put to the test of use. And failure can manifest itself in extrafunctional ways, including the inability of a product to maintain market share, thus disappointing corporate managers, directors, and stockholders. Poor performance, whether in the lab or on the ledger, signals a failure to be addressed. Such matters are explored through the many examples contained in the second and subsequent chapters of this book.

It is not only concrete things like projectors and pointers that pose problems in design and its limitations. Among the intangible things considered in the third chapter are intellectual and symbolic ones like national constitutions and flags, where the failure to anticipate how such politically charged things might not please their varied intended constituencies can be disastrous. Strategies for playing games like basketball, while perhaps of lesser consequence than political contests, are also matters of design, and the failure of a coach to defend against a boring offense or to match a hot shooter with a tenacious defender can result in a disappointing game for players and spectators alike. Successful design, whether of solid or intangible things, rests on anticipating how failure can or might occur.

Failure is thus a unifying principle in the design of things large and small, hard and soft, real and imagined. The fourth chapter emphasizes the sameness of the design problem for all sorts of things. Whatever is being designed, success is achieved by properly anticipating and obviating failure. Since earlier chapters focus primarily on smaller, well-defined things and contexts, this chapter also employs examples of larger things and systems, such as the steam engine and the railroad. With

the underlying sameness of the design process established, the discussion turns to differences in the behavior of small and large things. In particular, the testing process, by which an unanticipated mode of failure is often first uncovered, must necessarily vary. Small things, which typically are mass produced in staggeringly large numbers, can be tested by sampling. However, very large things, which are essentially custom or uniquely built, do not present that same opportunity. And, because of their scale, the failure of large structures or machines can be devastating in all sorts of ways, not the least of which is economic.

The remaining chapters focus exclusively on large things. The fifth chapter considers buildings, especially tall and supertall buildings. Though the desire to build tall did not originate with the skyscraper, it is in that genre of architecture and structural engineering that failure can have the most far-reaching consequences. The decision to build tall is often one of ego and hubris, qualities that not infrequently originate in and degenerate into human failings of character that can lead to structural ones. In the twenty-first century, limitations on the height of buildings are not so much structural as mechanical, economic, and psychological. Structural engineers know how to build buildings much taller than those now in existence, but they also understand that height comes only at a premium in space and money. The taller buildings go, the more people must be transported vertically in elevators. The more elevators that are needed, the more elevator shafts must be provided, thus taking up more and more volume. This reduces the available office space per floor, which in turn threatens the economic viability of the enterprise. Nevertheless, for reasons of

pride and striving, taller buildings will continue to be built. Still, no matter how many supertall buildings stand around the world, their success does not guarantee that of their imitators. The collapse of the twin towers of the New York World Trade Center demonstrated that unanticipated outside agents (and unperceived internal weaknesses) can create scenarios that can trigger novel failure modes.

In the sixth chapter, the book's focus turns to bridges, which provide a paradigmatic study of the paradoxical nature of success and failure in design. Overconfidently building increasingly longer bridges modeled on successful prior designs is a prescription for failure, as has been demonstrated and documented repeatedly over the past century and a half. The designers of the first Quebec Bridge, for example, were emboldened by the success of the Forth Bridge and set out to better it with a lighter and longer structure of its type. Unfortunately, the Quebec collapsed while under construction, an event that gave the cantilever form upon which it was based a reputation from which it has yet to recover in the world of long-span bridge building. Though the Quebec Bridge was successfully redesigned and rebuilt and stands today as a symbol of Canada's resolve, no cantilever bridge of greater span has been attempted since. The Tacoma Narrows Bridge, the third longest suspension bridge when completed in 1940, proved to have too narrow and shallow a deck, which accounted for its collapse just months after it was opened to traffic. A relatively unknown engineer without his ego invested in the design had actually warned against the excessive narrowness of the deck, but his objections were overcome by the hubris and influence of the design consultant, whose confidence in his theory was backed

by numerous prior successes. Such examples provide caveats against success-based extrapolation in design. Past success is no guarantee against future failure.

The final chapter looks at the historical record of colossal failures, especially in the context of the space shuttle program and of long-span bridges. In the case of bridges, there is a striking temporal pattern of a major failure occurring approximately every thirty years since the middle of the nineteenth century and continuing through the millennium. All of the half-dozen remarkable failures that occurred within this time span resulted from designs based on successful precedents rather than on a more fundamentally circumspect anticipation and obviation of failure. Such compelling evidence argues for a greater awareness among designers of the history of the technology within which they work, but such looking back is not generally in the nature of forward-looking engineers working on the cutting edge. Still, the historic pattern has been persistent, and it should be convincing. It even suggests that a major bridge collapse can be expected to occur around the year 2030. Such a prediction gains credibility from the fact that bridge building in the twenty-first century continues to go forward in a way not unlike that which preceded the failures of the Quebec, Tacoma Narrows, and other overly daring bridges. But failures are not inevitable, of course, for if they were there might be no technological advancement. Indeed, future failures can be anticipated and thereby avoided through an appreciation for the past, which reveals in case after case an incontrovertible if paradoxical relationship between success and failure in the design process generally.

Failure and responses to it may not explain every aspect of

every design, but from the engineering perspective of this book it is presented as a unifying theme for describing the functional evolution of things. In particular, the interplay between failure and success in the development of technological artifacts and systems is presented here as an important driving force in the inventive process. Most of the examples are drawn from the fields of mechanical and civil engineering, in which the author has the most direct experience. There are, of course, countless examples besides mechanical devices and civil structures that the reader may call to mind to test further the paradoxically opposed hypotheses that failure drives successful design and that success can ultimately threaten it. But the genesis of this book dictated that it not take up more than a narrow space on the library shelf, and so it could not be overly wide ranging. Hence its focus on the functional. There are numerous other factors that affect design—including the aesthetic, cultural, economic, egotistical, ethical, historical, political, and psychological—but no single book can hope to say everything about everything.