TO ENGINEER IS HUMAN

THE ROLE OF FAILURE IN SUCCESSFUL DESIGN

HENRY PETROSKI

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To Catherine

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BEING HUMAN

Shortly after the Kansas City Hyatt Regency Hotel skywalks collapsed in 1981, one of my neighbors asked me how such a thing could happen. He wondered, did engineers not even know enough to build so simple a structure as an elevated walkway? He also recited to me the Tacoma Narrows Bridge collapse, the American Airlines DC–10 crash in Chicago, and other famous failures, throwing in a few things he had heard about hypothetical nuclear power plant accidents that were sure to exceed Three Mile Island in radiation release, as if to present an open-and-shut case that engineers did not quite have the world of their making under control.

I told my neighbor that predicting the strength and behavior of engineering structures is not always so simple and well-defined an undertaking as it might at first seem, but I do not think that I changed his mind about anything with my abstract generalizations and vague apologies. As I left him tending his vegetable garden and continued my walk toward home, I admitted to myself that I had not answered his question because I had not conveyed to him what engineering is. Without doing that I could not hope to explain what could go wrong with the products of engineering. In the years since the Hyatt Regency disaster I have thought a great deal about how I might explain the next technological embarrassment to an inquiring layman, and I have looked for examples not in the esoteric but in the commonplace. But I have also learned that collections of examples, no matter how vivid, no more make an explanation than do piles of beams and girders make a bridge.

Engineering has as its principal object not the given world but the world that engineers themselves create. And that world does not have the constancy of a honeycomb's design, changeless through countless generations of honeybees, for human structures involve constant and rapid evolution. It is not simply that we like change for the sake of change, though some may say that is reason enough. It is that human tastes, resources, and ambitions do not stay constant. We humans like our structures to be as fashionable as our art; we like extravagance when we are well off, and we grudgingly economize when times are not so good. And we like bigger, taller, longer things in ways that honeybees do not or cannot. All of these extra-engineering considerations make the task of the engineer perhaps more exciting and certainly less routine than that of an insect. But this constant change also introduces many more aspects to the design and analysis of engineering structures than there are in the structures of unimproved nature, and constant change means that there are many more ways in which something can go wrong.

Engineering is a human endeavor and thus it is subject to error. Some engineering errors are merely annoying, as when a new concrete building develops cracks that blemish it as it settles; some errors seem humanly unforgivable, as when a bridge collapses and causes the death of those who had taken its soundness for granted. Each age has had its share of technological annoyances and structural disasters, and one would think engineers might have learned by now from their mistakes how to avoid them. But recent years have seen some of the most costly structural accidents in terms of human life, misery, and anxiety, so that the record presents a confusing image of technological advancement that may cause some to ask, "Where is our progress?"

Any popular list of technological horror stories usually comprises the latest examples of accidents, failures, and flawed products. This catalog changes constantly as new disasters displace the old, but almost any list is representative of how varied the list itself can be. In 1979, when accidents seemed to be occurring left and right, anyone could rattle off a number of technological embarrassments that were fresh in everyone's mind, and there was no need to refer to old examples like the Tacoma Narrows Bridge to make the point. It seemed technology was running amok, and editorial pages across the country were anticipating the damage that might occur as the orbiting eighty-five-ton Skylab made its unplanned reentry. Many of the same newspapers also carried the cartoonist Tony Auth's solution to the problem. His cartoon shows the falling Skylab striking a flying DC–10, itself loaded with Ford Pintos fitted with Firestone 500 tires, with the entire wreckage falling on Three Mile Island, where the fire would be extinguished with asbestos hair dryers.

While such a variety may be unique to our times, the failure of the products of engineering is not. Almost four thousand years ago a number of Babylonian legal decisions were collected in what has come to be known as the Code of Hammurabi, after the sixth ruler of the First Dynasty of Babylon. There among nearly three hundred ancient cuneiform inscriptions governing matters like the status of women and drinking-house regulations are several that relate directly to the construction of dwellings and the responsibility for their safety:

> *If a builder build a house for a man and do not make its construction firm, and the house which he has built collapse and cause the death of the owner of the house, that builder shall be put to death.*
>
> *If it cause the death of the son of the owner of the house, they shall put to death a son of that builder.*
>
> *If it cause the death of a slave of the owner of the house, he shall give to the owner of the house a slave of equal value.*

If it destroy property, he shall restore whatever it destroyed, and because he did not make the house which he built firm and it collapsed, he shall rebuild the house which collapsed from his own property.

If a builder build a house for a man and do not make its construction meet the requirements and a wall fall in, that builder shall strengthen the wall at his own expense.

This is a far cry from what happened in the wake of the collapse of the Hyatt Regency walkways, subsequently found to be far weaker than the Kansas City Building Code required. Amid a tangle of expert opinions, $3 billion in lawsuits were filed in the months after the collapse of the skywalks. Persons in the hotel the night of the accident were later offered $1,000 to sign on the dotted line, waiving all subsequent claims against the builder, the hotel, or anyone else they might have sued. And today opinions as to guilt or innocence in the Hyatt accident remain far from unanimous. After twenty months of investigation, the U. S. attorney and the Jackson County, Missouri, prosecutor jointly announced that they had found no evidence that a crime had been committed in connection with the accident. The attorney general of Missouri saw it differently, however, and he charged the engineers with "gross negligence." The engineers involved stand to lose their professional licenses but not their lives, but the verdict is still not in as I write three years after the accident.

The Kansas City tragedy was front-page news because it represented the largest loss of life from a building collapse in the history of the United States. The fact that it was news attests to the fact that countless buildings and structures, many with designs no less unique or daring than that of the hotel, are unremarkably safe. Estimates of the probability that a particular reinforced concrete or steel building in a technologically advanced country like the United States or England will fail in a given year range from one in a million to one in a hundred trillion, and the probability of death from a structural failure is approximately one in ten million per year. This is equivalent to a total of about twenty-five deaths per year in the United States, so that 114 persons killed in one accident in Kansas City was indeed news.

Automobile accidents claim on the order of fifty thousand American lives per year, but so many of these fatalities occur one or two at a time that they fail to create a sensational impact on the public. It seems to be only over holiday weekends, when the cumulative number of individual auto deaths reaches into the hundreds, that we acknowledge the severity of this chronic risk in our society. Otherwise, if an auto accident makes the front page or the evening news it is generally because an unusually large number of people or a person of note is involved. While there may be an exception if the dog is famous, the old saying that "dog bites man" is not news but that "man bites dog" is, applies.

We are both fascinated by and uncomfortable with the unfamiliar. When it was a relatively new technology, many people eschewed air travel for fear of a crash. Even now, when aviation relies on a well-established technology, many adults who do not think twice about the risks of driving an automobile are apprehensive about flying. They tell each other old jokes about white-knuckle air travelers, but younger generations who have come to use the airplane as naturally as their parents used the railroad and the automobile do not get the joke. Theirs is the rational attitude, for air travel *is* safe, the 1979 DC–10 crash in Chicago notwithstanding. Two years after that accident, the Federal Aviation Administration was able to announce that in the period covering 1980 and 1981, domestic airlines operated without a single fatal accident involving a large passenger jet. During the period of record, over half a billion passengers flew on ten million flights. Experience has proven that the risks of technology are very controllable.

However, as wars make clear, government administrations value their fiscal and political health as well as the lives of their citizens, and sometimes these objectives can be in conflict. The risks that engineered structures pose to human life and environments pose to society often conflict with the risks to the economy that striving for absolute and perfect safety would bring. We all know and daily make the trade-offs between our own lives and our pocketbooks, such as when we drive economy-sized automobiles that are incontrovertibly less safe than heavier-built ones. The introduction of seat belts, impact-absorbing bumpers, and emission-control devices have contributed to reducing risks, but gains like these have been achieved at a price to the consumer. Further improvements will take more time to perfect and will add still more to the price of a car, as the development of the air bag system has demonstrated. Thus there is a constant tension between manufacturers and consumer advocates to produce safe cars at reasonable prices.

So it is with engineering and public safety. All bridges and buildings could be built ten times as strong as they presently are, but at a tremendous increase in cost, whether financed by taxes or private investment. And, it would be argued, why ten times stronger? Since so few bridges and buildings collapse now, surely ten times stronger would be structural overkill. Such ultraconservatism would strain our economy and make our built environment so bulky and massive that architecture and style as we know them would have to undergo radical change. No, it would be argued, ten times is too much stronger. How about five? But five might also arguably be considered too strong, and a haggling over numbers representing no change from the present specifications and those representing five- or a thousand-percent improvement in strength might go on for as long as Zeno imagined it would take him to get from here to there. But less-developed countries may not have the luxury to argue about risk or debate paradoxes, and thus their buildings and boilers can be expected to collapse and explode with what appears to us to be uncommon frequency.

Callous though it may seem, the effects of structural reliability can be measured not only in terms of cost in human lives but also in material terms. This was done in a recent study conducted by the National Bureau of Standards with the assistance of Battelle Columbus Laboratories. The study found that fracture, which included such diverse phenomena as the breaking of eyeglasses, the cracking of highway pavement, the collapse of bridges, and the breakdown of machinery, costs well over $100 billion annually, not only for actual but also for anticipated replacement of broken parts and for structural insurance against parts breaking in the first place. Primarily associated with the transportation and construction industries, many of these expenses arise through the prevention of fracture by overdesign (making things heavier than otherwise necessary) and maintenance (watching for cracks to develop), and through the capital equipment investment costs involved in keeping spare parts on hand in anticipation of failures. The 1983 report further concludes that the costs associated with fracture could be reduced by one half by our better utilizing available technology and by improved techniques of fracture control expected from future research and development.

Recent studies of the condition of our infrastructure—the water supply and sewer systems, and the networks of highways and bridges that we by and large take for granted—conclude that it has been so sorely neglected in many areas of the country that it would take billions upon billions of dollars to put things back in shape. (Some estimates put the total bill as high as $3 trillion.) This condition resulted in part from maintenance being put off to save money during years when energy and personnel costs were taking ever-larger slices of municipal budget pies. Some water pipes in large cities like New York are one hundred or more years old, and they were neither designed nor expected to last forever. Ideally, such pipes should be replaced on an ongoing basis to keep the whole water supply system in a reasonably sound condition, so that sudden water main breaks occur very infrequently. Such breaks can have staggering consequences, as when a main installed in 1915 broke in 1983 in midtown Manhattan and flooded an underground power station, causing a fire. The failure of six transformers interrupted electrical service for several days. These happened to be the same days of the year that ten thousand buyers from across the country visited New York's garment district to purchase the next season's lines. The area covered by the blackout just happened to be the blocks containing the showrooms of the clothing industry, so that there was mayhem where there would ordinarily have been only madness. Financial losses due to disrupted business were put in the millions.

In order to understand how engineers endeavor to insure against such structural, mechanical, and systems failures, and thereby also to understand how mistakes can be made and accidents with far-reaching consequences can occur, it is necessary to understand, at least partly, the nature of engineering design. It is the process of design, in which diverse parts of the "given-world" of the scientist and the "made-world" of the engineer are reformed and assembled into something the likes of which Nature had not dreamed, that divorces engineering from science and marries it to art. While the practice of engineering may involve as much technical experience as the poet brings to the blank page, the painter to the empty canvas, or the composer to the silent keyboard, the understanding and appreciation of the process and products of engineering are no less accessible than a poem, a painting, or a piece of music. Indeed, just as we all have experienced the rudiments of artistic creativity in the childhood masterpieces our parents were so proud of, so we have all experienced the essence of structural engineering in our learning to balance first our bodies and later our blocks in ever more ambitious positions. We have learned to endure the most boring of cocktail parties without the social accident of either our bodies or our glasses succumbing to the force of gravity, having long ago learned to crawl, sit up, and toddle among our tottering towers of blocks. If we could remember those early efforts of ours to raise

ourselves up among the towers of legs of our parents and their friends, then we can begin to appreciate the task and the achievements of engineers, whether they be called builders in Babylon or scientists in Los Alamos. For all of their efforts are to one end: to make something stand that has not stood before, to reassemble Nature into something new, and above all to obviate failure in the effort.

Because man is fallible, so are his constructions, however. Thus the history of structural engineering, indeed the history of engineering in general, may be told in its failures as well as in its triumphs. Success may be grand, but disappointment can often teach us more. It is for this reason that hardly a history can be written that does not include the classic blunders, which more often than not signal new beginnings and new triumphs. The Code of Hammurabi may have encouraged sound construction of reproducible dwellings, but it could not have encouraged the evolution of the house, not to mention the skyscraper and the bridge, for what builder would have found incentive in the code to build what he believed to be a better but untried house? This is not to say that engineers should be given license to experiment with abandon, but rather to recognize that human nature appears to want to go beyond the past, in building as in art, and that engineering is a human endeavor.

When I was a student of engineering I came to fear the responsibility that I imagined might befall me after graduation. How, I wondered, could I ever be perfectly sure that something I might design would not break or collapse and kill a number of people? I knew my understanding of my textbooks was less than total, my homework was seldom without some sort of error, and my grades were not straight *A*s. This disturbed me for some time, and I wondered why my classmates, both the *A* and *C* students, were not immobilized by the same phobia. The topic never came to the surface of our conversations, however, and I avoided confronting the issue by going to graduate school instead of taking an engineering job right away. Since then I have come to realize that my concern was not unique among engineering students, and indeed many if not all students have experienced self-doubts about success and fears of failure. The medical student worries about losing a patient, the lawyer about losing a crucial case. But if we all were to retreat with our phobias from our respective jobs and professions, we could cause exactly what we wish to avoid. It is thus that we practice whatever we do with as much assiduousness as we can command, and we hope for the best. The rarity of structural failures attests to the fact that engineering at least, even at its most daring, is not inclined to take undue risks.

The question, then, should not only be why do structural accidents occur but also why not more of them? Statistics show the headline-grabbing failure to be as rare as its newsworthiness suggests it to be, but to understand why the risk of structural failure is not absolutely zero, we must understand the unique engineering problem of designing what has not existed before. By understanding this we will come to appreciate not only why the probability of failure is so low but also how difficult it might be to make it lower. While it is theoretically possible to make the number representing risk as close to zero as desired, human nature in its collective and individual manifestations seems to work against achieving such a risk-free society.

2

FALLING DOWN IS PART OF GROWING UP

We are all engineers of sorts, for we all have the principles of machines and structures in our bones. We have learned to hold our bodies against the forces of nature as surely as we have learned to walk. We calculate the paths of our arms and legs with the computer of our brain, and we catch baseballs and footballs with more dependability than the most advanced weapons systems intercept missiles. We may wonder if human evolution may not have been the greatest engineering feat of all time. And though many of us forget how much we once knew about the principles and practice of engineering, the nursery rhymes and fairy tales of our youth preserve the evidence that we did know quite a bit.

We are born into a world swathed in trust and risk. And we become accustomed from the instant of birth to living with the simultaneous possibilities that there *will* be and that there will *not* be catastrophic structural failure. The doctor who delivers us and the nurses who carry us about the delivery room are cavalier human cranes and forklifts who have moved myriad babies from delivery to holding upside down to showing to mother to cleansing to footprinting to wristbanding to holding right-side up to showing to father to taking to the nursery. I watched with my heart in my mouth as my own children were so moved and rearranged, and the experience exhausted me. Surely sometime, somewhere, a baby has been dropped, surely a doctor has had butterfingers or a nurse a lapse of attention. But we as infants and we as parents cannot and do not and should not dwell on those remotely possible, hideous scenarios, or we might immobilize the human race in the delivery room. Instead, our nursery rhymes help us think about the unthinkable in terms of serenity.

Rock-a-bye baby
In the tree top.
When the wind blows,
The cradle will rock.
When the bough breaks,
The cradle will fall.
And down will come baby,
Cradle and all.

Home from the hospital, we are in the hands of our parents and friends and relatives—and structurally weak siblings. We are held up helpless over deep pile carpets and hard terrazzo floors alike, and we ride before we walk, risking the sudden collapse of an uncle's trick knee. We are transported across impromptu bridges of arms thrown up without plans or blueprints between mother and aunt, between neighbor and father, between brother and sister—none of whom is a registered structural engineer. We come to Mama and to Papa eventually to forget our scare reflex and we learn to trust the beams and girders and columns of their arms and our cribs. We become one with the world and nap in the lap of gravity. Our minds dream weightlessly, but our ears come to hear the sounds of waking up. We listen to the warm whispers giving structure to the world of silence, and we learn from the bridges of lullabyes and play that not only we but also the infrastructure needs attention.

London Bridge is falling down,
Falling down, falling down.
London Bridge is falling down,
My fair lady.

Build it up with wood and stone,
Wood and stone, wood and stone.
Build it up with wood and stone,
My fair lady.

The parts of our bodies learn to function as levers, beams, columns, and even structures like derricks and bridges as we learn to turn over in our cribs, to sit up, to crawl, to walk, and generally to support the weight of our own bodies as well as what we lift and carry. At first we do these things clumsily, but we learn from our mistakes. Each time the bridge of our body falls down, we build it up again. We pile back on hands and knees to crawl over the river meandering beneath us. We come to master crawling, and we come to elaborate upon it, moving faster and freer and with less and less concern for collapsing all loose in the beams and columns of our back and limbs. We extend our infant theory of structures and hypothesize that we can walk erect, cantilevering our semicircular canals in the stratosphere. We think these words in the Esperanto of babble, and with the arrogance of youth we reach for the stars. With each tottering attempt to walk, our bodies learn from the falls what not to do next time. In time we walk without thinking and think without falling, but it is not so much that we have learned how to walk as we have learned not to fall. Sometimes we have accidents and we break our arms and legs. We have them fixed and we go on as before. Barring disease, we walk erect and correctly throughout our lives until our structure deteriorates with old age and we need to be propped up with canes or the like. For the majority of our lives walking generally becomes as dependable as one can imagine it to be, but if we choose to load the structure of our bodies beyond the familiar limits of walking, say by jogging or marathoning, then we run the risk of structural failure in the form of muscle pulls and bone fractures. But our sense of pain stops most of us from overexerting ourselves and from coming loose at our connections as we go round and round, hand in hand, day in and day out.

Ring around the rosie,
A pocket full of posies,
Ashes, ashes,
We all fall down.

If ontogeny recapitulates phylogeny, if all that has come to be human races before the fetus floating in its own prehistory, then the child playing relives the evolution of structural engineering in its blocks. And the blocks will be as stone and will endure as monuments to childhood, as Erector Sets and Tinker Toys and Legos will not. Those modern optimizations will long have folded and snapped in the frames and bridges of experiment, though not before the child will have learned from them the limitations of metal and wood and plastic. These lessons will be carried in the tool box of the mind to serve the carpenter in all of us in time.

Step on a crack
And break your mother's back.

The child will play with mud and clay, making cakes and bricks in the wonderful oven of the sun. The child will learn that concrete cracks a mother's back but that children's backs are as resilient as springs and pliant as saplings. The child will watch the erection of flowers on columns of green but break them for the smiles of its parents. Summer will roof houses in the bushes, vault cathedrals in the trees. The child will learn the meaning of time, and watch the structures fall into winter and become skeletons of

shelters that will be built again out of the dark in the ground and the light in the sky. The child angry and victimized by other children angry will learn the meanings of vandalism and sabotage, of demolition and destruction, of collapse and decline, of the lifetime of structures—and the structure of life.

The Sphinx asked, "What walks on four legs in the morning, two legs in the afternoon, and three legs in the evening?"

The child learns that the arms and legs of dolls and soldiers break, the wheels of wagons and tricycles turn against their purpose, and the bats and balls of games do not last forever. No child articulates it, but everyone learns that toys are mean. They teach us not the vocabulary but the reality of structural failure and product liability. They teach us that as we grow, the toys that we could not carry soon cannot carry us. They are as bridges built for the traffic of a lighter age, and their makers are as blameless as the builders of a lighter bridge. We learn that not everything can be fixed.

Humpty Dumpty sat on a wall;
Humpty Dumpty had a great fall.
All the King's horses and all the King's men
Couldn't put Humpty together again.

The adolescent learns that bones can break. The arms counterbalancing the legs locomoting are as fragile as the steel and iron railroad bridges under the reciprocating blows of the behemoths rushing through the nineteenth century. The cast of thousands of childhoods reminds the arms and legs, while they have grown stronger but brittler, that they have also grown taller and wiser. They fall less and less. They grow into the arms and legs of young adults making babies fly between them, wheeeee, up in the air unafraid of the gravity parents can throw away. But the weight of responsibility and bills and growing babies brings the parents down to earth and they begin to think of things besides their bridges of muscles and columns of bones. They think of jobs and joys of a different kind, perhaps even if they are engineers.

Jack and Jill went up the hill
To fetch a pail of water,
Jack fell down and broke his crown
And Jill came tumbling after.

The natural fragileness of things comes to be forgotten, for we have learned to take it easy on the man-made world. We do not pile too high or reach too far. We make our pencil points sharper, but we do not press as hard. We learn to write without snap, and the story of our life goes smoothly, but quickly becomes dull. (Everyone wishes secretly to be the writer pushing the pencil to its breaking point.) We feel it in our bones as we grow old and then we remember how brittle but exhilarating life can be. And we extend ourselves beyond our years and break our bones again, thinking what the hell. We have wisdom and we understand the odds and probabilities. We know that nothing is forever.

Three wise men of Gotham
Went to sea in a bowl:
If the vessel had been stronger,
My song would be longer.

As if it were not enough that the behavior of our very bodies accustoms us to the limitations of engineering structures, our language itself is ambiguous about the daily trials to which life and limb are subjected. Both human beings and inhuman beams are said to be under stress and strain that may lead to fatigue if not downright collapse. Breakdowns of man and machine can occur if they are called upon to carry more than they can bear. The anthropomorphic language of engineering is perhaps no accident since man is not only the archetypal machine but also the Ur-structure.

Furniture is among the oldest of inanimate engineering structures designed to carry a rather well-defined load under rather well-defined circumstances. We are not surprised that furniture used beyond its intended purpose is broken, and we readily blame the child who abuses the furniture rather than the designer of the furniture or the furniture itself when it is abused. Thus a chair must support a person in a sitting position, but it might not be expected to survive a brawl in a saloon. A bed might be expected to support a recumbent child, a small rocking chair only a toddler. But the child's bed would not necessarily be considered badly designed if it collapsed under the child's wild use of it as a trampoline, and a child's chair cannot be faulted for breaking under the weight of a heavier child using it as a springboard. The arms and legs of chairs, the heads and feet of beds, just like those of the people whom they serve, cannot be expected to be strong without limit.

Mother Goose is as full of structural failures as human history. The nursery rhymes acknowledge the limitations of the strength of the objects man builds as readily as fairy tales recognize the frailties of human nature. The story of Goldilocks and the Three Bears teaches us how we can unwittingly proceed from engineering success to failure. Papa Bear's chair is so large and so hard and so unyielding under the weight of Goldilocks that apparently without thinking she gains a confidence in the strength of all rocking chairs. Goldilocks next tries Mama Bear's chair, which is not so large but is softer, perhaps because it is built with a lighter wood. Goldilocks finds this chair too soft, however, too yielding in the cushion. Yet it is strong enough to support her. Thus the criterion of strength becomes less a matter of concern than the criteria of "give" and comfort, and Goldilocks is distracted by her quest for a comfortable chair at the expense of one sufficiently strong. Finally Goldilocks approaches Baby Bear's chair, which is apparently stiffer but weaker than Mama Bear's, with little if any apprehension about its safety, for Goldilocks' experience is that all chairs are overdesigned. At first the smallest chair appears to be "just right," but, as with all marginal engineering designs, whether chairs or elevated walkways, the chair suddenly gives way under Goldilocks and sends her crashing to the floor.

The failure of the chair does not keep Goldilocks from next trying beds without any apparent concern for their structural integrity. When Papa Bear's bed is too hard and Mama's is too soft, Goldilocks does not seem to draw a parallel with the chairs. She finds Baby Bear's bed "just right" and falls asleep in it without worrying about its collapsing under her. One thing the fairy tale implicitly teaches us as children is to live in a world of seemingly capricious structural failure and success without anxiety. While Goldilocks may worry about having broken Baby Bear's chair, she does not worry about all chairs and beds breaking. According to Bruno Bettelheim, the tale of Goldilocks and the Three Bears lacks some of the important features of a true fairy tale, for in it there is neither recovery nor consolation, there is no resolution of conflict, and Goldilocks' running away from the bears is not exactly a happy ending. Yet there is structural recovery and consolation in that the bed does not break, and there is thereby a structural happy ending.

If the story of Goldilocks demonstrates how the user of engineering products can be distracted into overestimating their strength, the story of the Three Little Pigs shows how the designer can underestimate the strength his structure may need in an emergency or, as modern euphemisms would put it, under extreme load or hypothetical accident conditions. We recall that each of the three pigs has the same objective: to build a house. It is implicit in the mother pig's admonishment as they set out that their houses not only will have to shelter the little pigs from ordinary weather, but must also stand up against any extremes to which the Big Bad Wolf may subject them.

The three little pigs are all aware of the structural requirements necessary to keep the wolf out, but they differ in their beliefs of how severe a wolf's onslaught can be, and some of the pigs would like to get by with the least work and the most play. Thus the individual pigs make different estimates of how strong their houses must be, and each reaches a different conclusion about how much strength he can sacrifice to availability of materials and time of construction. That each pig thinks he is building his house strong enough is demonstrated by the first two pigs dancing and singing, "Who's afraid of the Big Bad Wolf." They think their houses are safe enough and that their brother laboring over his brick house has overestimated the strength of the wolf and overdesigned his structure. Finally, when the third pig's house is completed, they all dance and sing their assurances. It is only the test of the wolf's full fury that ultimately proves the third pig correct. Had the wolf been a bugaboo, all three houses might have stood for many a year and the first two pigs never been proven wrong.

Thus the nursery rhymes, riddles, and fairy tales of childhood introduce us to engineering. From lullabyes that comfort us even as they sing of structural failure to fairy tales that teach us that we can build our structures so strong that they can withstand even the huffing and puffing of a Big Bad Wolf, we learn the rudiments and the humanness of engineering.

Our own bodies, the oral tradition of our language and our nursery rhymes, our experiences with blocks and sand, all serve to accustom us to the idea that structural failure is part of the human condition. Thus we seem to be preconditioned, or at least emotionally prepared, to expect bridges and dams, buildings and boats, to break now and then. But we seem not at all resigned to the idea of major engineering structures having the same mortality as we. Somehow, as adults who forget their childhood, we expect our constructions to have evolved into monuments, not into mistakes. It is as if engineers and non-engineers alike, being human, want their creations to be superhuman. And that may not seem to be an unrealistic aspiration, for the flesh and bone of steel and stone can seem immortal when compared with the likes of man.

3

LESSONS FROM PLAY; LESSONS FROM LIFE

When I want to introduce the engineering concept of fatigue to students, I bring a box of paper clips to class. In front of the class I open one of the paper clips flat and then bend it back and forth until it breaks in two. That, I tell the class, is failure by fatigue, and I point out that the number of back and forth cycles it takes to break the paper clip depends not only on how strong the clip is but also on how severely I bend it. When paper clips are used normally, to clip a few sheets of paper together, they can withstand perhaps thousands or millions of the slight openings and closings it takes to put them on and take them off the papers, and thus we seldom experience their breaking. But when paper clips are bent open so wide that they look as if we want them to hold all the pages of a book together, it might take only ten or twenty flexings to bring them to the point of separation.

Having said this, I pass out a half dozen or so clips to each of the students and ask them to bend their clips to breaking by flexing them as far open and as far closed as I did. As the students begin this low-budget experiment, I prepare at the blackboard to record how many back and forth bendings it takes to break each paper clip. As the students call out the numbers, I plot them on a bar graph called a histogram. Invariably the results fall clearly under a bell-shaped normal curve that indicates the statistical distribution of the results, and I elicit from the students the explanations as to why not all the paper clips broke with the same number of bendings. Everyone usually agrees on two main reasons: not all paper clips are equally strong, and not every student bends his clips in exactly the same way. Thus the students recognize at once the phenomenon of fatigue and the fact that failure by fatigue is not a precisely predictable event.

Many of the small annoyances of daily life are due to predictable—but not precisely so—fractures from repeated use. Shoelaces and light bulbs, as well as many other familiar objects, seem to fail us suddenly and when it is least convenient. They break and burn out under conditions that seem no more severe than those they had been subjected to hundreds or thousands of times before. A bulb that has burned continuously for decades may appear in a book of world records, but to an engineer versed in the phenomenon of fatigue, the performance is not remarkable. Only if the bulb had been turned on and off daily all those years would its endurance be extraordinary, for it is the cyclic and not the continuous heating of the filament that is its undoing. Thus, because of the fatiguing effect of being constantly changed, it is the rare scoreboard that does not have at least one bulb blown.

Children's toys are especially prone to fatigue failure, not only because children subject them to seemingly endless hours of use but also because the toys are generally not overdesigned. Building a toy too rugged could make it too heavy for the child to manipulate, not to mention more expensive than its imitators. Thus, the seams of rubber balls crack open after so many bounces, the joints of metal tricycles break after so many trips around the block, and the heads of plastic dolls separate after so many nods of agreement.

Even one of the most innovative electronic toys of recent years has been the victim of mechanical fatigue long before children (and their parents) tire of playing with it. Texas Instruments' Speak & Spell effectively employs one of the first microelectronic voice synthesizers. The bright red plastic toy asks the child in a now-familiar voice to spell a vocabulary of words from the toy's memory. The child pecks out letters on the keyboard, and they appear on a calculator-like display. When the child finishes spelling a word, the ENTER key is pressed and the computer toy says whether the spelling is correct and prompts the child to try again when a word is misspelled. Speak & Spell is so sophisticated that it will turn itself off if the child does not press a button for five minutes or so, thus conserving its four C-cells.

My son's early model Speak & Spell had given him what seemed to be hundreds of hours of enjoyment when one day the ENTER key broke off at its plastic hinge. But since Stephen could still fit his small finger into the buttonhole to activate the switch, he continued to enjoy the smart, if disfigured, toy. Soon thereafter, however, the E key snapped off, and soon the T and O keys followed suit. Although he continued to use the toy, its keyboard soon became a maze of missing letters and, for those that were saved from the vacuum cleaner, taped-on buttons.

What made these failures so interesting to me was the very strong correlation between the most frequently occurring letters in the English language and the fatigued keys on Stephen's Speak & Spell. It is not surprising that the ENTER key broke first, since it was employed for inputting each word and thus got more use than any one letter. Of the seven most common letters—in decreasing occurrence, E, T, A, O, I, N, S, R—five (E, T, O, S, and R) were among the first keys to break. All other letter keys, save for the two seemingly anomalous failures of P and Y, were intact when I first reported this serendipitous experiment on the fatigue phenomenon in the pages of *Technology Review*.

If one assumes that all Speak & Spell letter keys were made as equally well as manufacturing processes allowed, perhaps about as uniformly as or even more so than paper clips, then those plastic keys that failed must generally have been the ones pressed most frequently. The correlation between letter occurrence in common English words and the failure of the keys substantiates that this did indeed happen, for the anomalous failures seem also to be explainable in terms of abnormally high use. Because my son is right-handed, he might be expected to favor letters on the right-hand side of the keyboard when guessing spellings or just playing at pressing letters. Since none of the initial failed letters occurs in the four left-most columns of Speak & Spell, this proclivity could also explain why the common-letter keys A and N were still intact. The anomalous survival of the I key may be attributed to its statistically abnormal strength or to its underuse by a gregarious child. And the failure of the infrequently occurring P and Y might have been a manifestation of the statistical weakness of the keys or of their overuse by my son. His frequent spelling of his name and of the name of his cat, Pollux, endeared the letter *P* to him, and he had learned early that *Y* is sometimes a vowel. Furthermore, each time the Y key was pressed, Speak & Spell would ask the child's favorite question, "Why?"

Why the fatigue of its plastic buttons should have been the weak link that destroyed the integrity of my son's most modern electronic toy could represent the central question for understanding engineering design. Why did the designers of the toy apparently not anticipate this problem? Why did they not use buttons that would outlast the toy's electronics? Why did they not obviate the problem of fatigue, the problem that has defined the lifetimes of mechanical and structural designs for ages? Such questions are not unlike those that are asked after the collapse of a bridge or the crash of an airplane. But the collapse of a bridge or the crash of an airplane can endanger hundreds of lives, and thus the possibility of the fatigue of any part can be a lesson from which its victims learn nothing. Yet the failure of a child's toy, though it may cause tears, is but a lesson for a child's future of burnt-out light bulbs and broken shoelaces. And years later, when his shoelaces break as he is rushing to dress for an important appointment, he will be no less likely to ask, "Why?"

After I wrote about the found experiment, my son retrieved his Speak & Spell from my desk and resumed playing with the toy—and so continued the experiment. Soon another key failed, the vowel key U in the lower left position near where Stephen held his thumb. Next the A key broke, another vowel and the third most frequently occurring letter of the alphabet. The experiment ended with that failure, however, for Stephen acquired a new model of Speak & Spell with the new keyboard design that my daughter, Karen, had pointed out to me at an electronics store. Instead of having individually hinged plastic buttons, the new model has its keyboard printed on a single piece of rubbery plastic stretched over the switches. The new model Stephen has is called an E. T. Speak & Spell, after the little alien creature in the movie, and I am watching the plastic sheet in the vicinity of those two most frequently occurring letters to see if the fatigue gremlin will strike again.

Not long after I had first written about my son's Speak & Spell I found out from readers that their children too had had to live with disfigured keyboards. It is a tribute to the ingeniousness of the toy—and the attachment that children had developed for it—that they endured the broken keys and adapted in makeshift ways, as they would have to throughout a life of breakdowns and failures in our less than perfect world. Some parents reported that their children apparently discovered that the eraser end of a pencil fit nicely into the holes of the old Speak & Spell and thus could be used to enter the most frequently used letters without the children having to use their fingertips. I have wondered if indeed this trick was actually discovered by the parents who loved to play with the toy, for almost any child's finger should easily fit into the hole left by the broken button, but Mommy or Daddy's certainly would not.

Nevertheless, this resourcefulness suggests that the toy would have been a commercial success even with its faults, but the company still improved the keyboard design to solve the problem of key fatigue. The new buttonless keyboard is easily cleaned and pressed by even the clumsiest of adult fingers. The evolution of the Speak & Spell keyboard is not an atypical example of the way mass-produced items, though not necessarily planned that way, are debugged through use. Although there may have been some disappointment among parents who had paid a considerable amount of money for what was then among the most advanced applications of microelectronics wizardry, their children, who were closer to the world of learning to walk and talk and who were still humbled by their skinned knees and twisted tongues, took the failure of the keys in stride. Perhaps the manufacturer of the toy, in the excitement of putting the first talking computer on the market, overlooked some of the more mundane aspects of its design, but when the problem of the fractured keys came to its attention, it acted quickly to improve the toy's mechanical shortcomings.

I remember being rather angry when my son's Speak & Spell lost its first key. For all my understanding of the limitations of engineering and for all my attempted explanations to my neighbors of how failures like the Hyatt Regency walkways and the DC–10 could happen without clear culpability, I did not extend my charity to the designers of the toy. But there is a difference in the design and development of things that are produced by the millions and those that are unique, and it is generally the case that the mass-produced mechanical or electronic object undergoes some of its debugging and evolution after it is offered to the consumer. Such actions as producing a new version of a toy or carrying out an automobile recall campaign are not possible for the large civil engineering structure, however, which must be got right from the first stages of construction. So my charity should have extended to the designers of the Speak & Spell, for honest mistakes can be made by mechanical and electrical as well as by civil engineers. Perhaps someone had underestimated the number of *E*s it would take a child to become bored with the new toy. After all, most toys are put away long before they break. If this toy, which is more sophisticated than any I ever had in my own childhood, could tell me when I misspelled words I never could keep straight, then I would demand from it other superhuman qualities such as indestructibility. Yet we do not expect that of everything.

Although we might all be annoyed when a light bulb or a shoelace breaks, especially if it does so at a very inconvenient time, few if any of us would dream of taking it back to the store claiming it had malfunctioned. We all know the story of Thomas Edison searching for a suitable filament for the light bulb, and we are aware of and grateful for the technological achievement. We know, almost intuitively it seems, that to make a shoelace that would not break would involve compromises that we are not prepared to accept. Such a lace might be undesirably heavy or expensive for the style of shoe we wear, and we are much more willing to have the option of living with the risk of having the lace break at an inopportune time or of having the small mental burden of anticipating when the lace will break so that we might replace it in time. Unless we are uncommonly fastidious, we live dangerously and pay little attention to preventive maintenance of our fraying shoelaces or our aging light bulbs. Though we may still ask "Why?" when they break, we already know and accept the answer.

As the consequences of failure become more severe, however, the forethought we must give to them becomes more a matter of life and death. Automobiles are manufactured by the millions, but it would not do to have them failing with a snap on the highways the way light bulbs and shoelaces do at home. The way an automobile could fail must be anticipated so that, as much as possible, a malfunction does not lead to an otherwise avoidable deadly accident. Since tires are prone to flats, we want our vehicles to be able to be steered safely to the side of the road when one occurs. Such a failure is accepted in the way light bulb and shoelace failures are, and we carry a spare tire to deal with it. Other kinds of malfunctions are less acceptable. We do not want the brakes on all four wheels and the emergency braking system to fail us suddenly and simultaneously. We do not want the steering wheel to come off in our hands as we are negotiating a snaking mountain road. Certain parts of the automobile are given special attention, and in the rare instances when they do fail, leading to disaster, massive lawsuits can result. When they become aware of a potential hazard, automobile manufacturers are compelled to eliminate what might be the causes of even the most remote possibilities of design-related accidents by the massive recall campaigns familiar to us all.

As much as it is human to make mistakes, it is also human to want to avoid them. Murphy's Law, holding that anything that can go wrong will, is not a law of nature but a joke. All the light bulbs that last until we tire of the lamp, all the shoelaces that outlast their shoes, all the automobiles that give trouble-free service until they are traded in have the last laugh on Murphy. Just as he will not outlive his law, so nothing manufactured can be or is expected to last forever. Once we recognize this elementary fact, the possibility of a machine or a building being as near to perfect for its designed lifetime as its creators may strive to be for theirs is not only a realistic goal for engineers but also a reasonable expectation for consumers. It is only when we set ourselves such an unrealistic goal as buying a shoelace that will never break, inventing a perpetual motion machine, or building a vehicle that will never break down that we appear to be fools and not rational beings.

Oliver Wendell Holmes is remembered more widely for his humor and verse than for the study entitled "The Contagiousness of Puerperal Fever" that he carried out as Parkman Professor of Anatomy and Physiology at Harvard Medical School. Yet it may have been his understanding of the seemingly independent working of the various parts of the human body that helped him to translate his physiological experiences into a lesson for structural and mechanical engineers. Although some of us go first in the knees and others in the back, none of us falls apart all at once in all our joints. So Holmes imagined the foolishness of expecting to design a horse-drawn carriage that did not have a weak link.

Although intended as an attack on Calvinism, in which Holmes uses the metaphor of the "one-hoss shay" to show that a system of logic, no matter how perfect it seems, must collapse if its premises are false, the poem also holds up as a good lesson for engineers. Indeed, Micro-Measurements, a Raleigh, North Carolina-based supplier of devices to measure the stresses and strains in engineering machines and structures, thinks "The Deacon's Masterpiece" so apt to its business that it offers copies of the poem suitable for framing. The firm's advertising copy recognizes that although ". . . Holmes knew nothing of . . . modern-day technology when he wrote about a vehicle with no 'weak link' among its components," he did realize the absurdity of attempting to achieve "the perfect engineering feat."

In Holmes' poem, which starts on p. 35, the Deacon decides that he will build an indestructible shay, with every part as strong as the rest, so that it will not break down. However, what the Deacon fails to take into account is that everything has a lifetime, and if indeed a shay could be built with "every part as strong as the rest," then every part would "wear out" at the same time and whoever inherited the shay from the Deacon, who himself would pass away before his creation, would be taken by surprise one day. While "The Deacon's Masterpiece" is interesting in recognizing that breaking down is the wearing out of one part, the weakest link, it is not technologically realistic in suggesting that all parts could have exactly the same lifetime. That premise is contrary to the reality that we can only know that this or that part will last for *approximately* this or that many years, just as we can only state the probability that any one paper clip will break after so many bendings. The exact lifetime of a part, a machine, or a structure is known only after it has broken.

Just as we are expected to know our own limitations, so should we know those of the inanimate world. Even the pyramids in the land of the Sphinx, whose riddle reminds us that we all must crawl before we walk and that we will not walk forever, have been eroded by the sand and the wind. Nothing on this earth is inviolate on the scale of geological time; and nothing we create will last at full strength forever. Steel corrodes and diamonds can be split. Even nuclear waste has a half-life.

Engineering deals with lifetimes, both human and otherwise. If not fatigue or fracture, then corrosion or erosion; if not war or vandalism, then taste or fashion claim not only the body but the very souls of once-new machines. Some lifetimes are set by the intended use of an engineering structure. As such an offshore oil platform may be designed to last for only the twenty or thirty years that it will take to extract the oil from the rock beneath the sea. It is less easy to say when the job of a bridge will be completed, yet engineers will have to have some clear idea of a bridge's lifetime if only to specify when some major parts will have to be inspected, serviced, or replaced. Buildings have uses that are subject to the whims of business fashion, and thus today's modern skyscraper may be unrentable in fifty years. Monumental architecture such as museums and government buildings, on the other hand, should suggest a permanence that makes engineers think in terms of centuries. A cathedral, a millennium.

The lifetime of a structure is no mere anthropomorphic metaphor, for how long a piece of engineering must last can be one of the most important considerations in its design. We have seen how the constant on and off action of a child's toy or a light bulb can cause irreparable damage, and so it is with large engineering structures. The ceaseless action of the sea on an offshore oil platform subjects its welded joints to the very same back and forth forces that cause a paper clip or a piece of plastic to crack after so many flexures. The bounce of a bridge under traffic and the sway of a skyscraper in the wind can also cause the growth of cracks in or the exhaustion of strength of steel cables and concrete beams, and one of the most important calculations of the modern engineer is the one that predicts how long it will take before cracks or the simple degradation of its materials threaten the structure's life. Sometimes we learn more from experience than calculations, however.

Years after my son had outgrown Speak & Spell, and within months of his disaffection with the video games he once wanted so much, he began to ask for toys that required no batteries. First he wanted a BB gun, which his mother and I were reluctant to give him, and then he wanted a slingshot. This almost biblical weapon seemed somehow a less violent toy and evoked visions of a Norman Rockwell painting, in which a boy-being-a-boy conceals his homemade slingshot from the neighbor looking out a broken window. It is almost as innocent a piece of Americana as the baseball hit too far, and no one would want to ban slingshots or boys.

I was a bit surprised, however, to learn that my son wanted to *buy* a slingshot ready-made, and I was even more surprised to learn that his source would not be the Sears Catalog, which might have fit in with the Norman Rockwell image, but one of the catalogs of several discount stores that seem to have captured the imagination of boys in this age of high-tech toys. What my son had in mind for a slingshot was a mass-produced, metal-framed object that was as far from my idea of a slingshot as an artificial Christmas tree is from a fir.

Stephen was incredulous as I took him into the woods behind our house looking for the proper fork with which to make what I promised him would be a *real* slingshot. We collected a few pieces of trees that had fallen in a recent wind storm, and we took them up to our deck to assemble what I had promised. Unfortunately, I had forgotten how easily pine and dry cottonwood break, and my first attempts to wrap a rubber band around the sloping arms of the benign weapon I was making met with structural failure. We finally were able to find pieces strong enough to withstand the manipulation required for their transformation into slingshots, but their range was severely limited by the fact that they would break if pulled back too far.

My son was clearly disappointed in my inability to make him a slingshot, and I feared that he had run away disillusioned with me when he disappeared for an hour or so after dinner that evening. But he returned with the wyes of tree branches stronger and more supple than any I found behind our house. We were able to wrap our fattest rubber bands around these pieces of wood without breaking them, and they withstood as much pull as we were able or willing to supply. Unfortunately, they still did not do as slingshots, for the rubber bands kept slipping down the inclines of the Y and the bands were difficult to hold without the stones we were using for ammunition slipping through them or going awry.

After almost a week of frustration trying to find the right branch-and-rubber band combination that would produce a satisfactory slingshot that would not break down, I all but promised I would buy one if we could not make a top-notch shooter out of the scraps of wood scattered about our basement. Stephen was patient if incredulous as I sorted through odd pieces of plywood and selected one for him to stand upon while I sawed out of it the shape of the body of a slingshot. He was less patient when I drilled holes to receive a rubber band, and I acceded to his impatience in not sanding the plywood or rounding the edges before giving the device the test of shooting. I surprised him by producing some large red rubber bands my wife uses for her manuscripts, and he began to think he might have a real slingshot when I threaded the ends of a rubber band through the holes in the plywood Y. With the assembly completed I demonstrated how far a little pebble could be shot, but I had to admit, at least to myself, that it was very difficult to keep the pebble balanced on the slender rubber band. My son was politely appreciative of what I had made for him, but he was properly not ecstatic. The pebbles he tried to shoot dropped in weak arcs before his target, and he knew that his slingshot would be no match for the one his friend had bought through the catalog.

In my mind I admitted that the homemade slingshot was not well designed, and in a desperate attempt to save face with my son I decided to add a second rubber band and a large pocket to improve not only the range but also the accuracy of the toy. These proved to be tremendous improvements, and with them the slingshot seemed almost unlimited in range and very comfortable to use. Now we had a slingshot of enormous potential, and my son was ready to give it the acid test. We spent an entire weekend practicing our aim at a beer bottle a good thirty yards away. The first hit was an historic event that pinged off the glass and the second a show of power that drilled a hole clear through the green glass and left the bottle standing on only a prayer. As we got better at controlling the pebbles issuing from our homemade slingshot we changed from bottles to cans for our targets and hit them more and more.

With all our shooting, the rubber bands began to break from fatigue. This did not bother my son, and he seemed to accept it as something to be expected in a slingshot, for it was just another toy and not a deacon's masterpiece. As rubber bands broke, we replaced them. What proved to be more annoying was the slipping of the rubber band over the top of the slingshot's arm, for we had provided no means of securing the band from doing so. In time, however, we came to wrap the broken rubber bands around the top of the arms to keep the functioning ones in place. This worked wonderfully, and the satisfaction of using broken parts to produce an improved slingshot was especially appealing to my son. He came to believe that his slingshot could outperform any offered in the catalogs, and the joy of producing it ourselves from scrap wood and rubber bands gave him a special pleasure. And all the breaking pieces of wood, slipping rubber bands, and less-than-perfect functioning gave him a lesson in structural engineering more lasting than any textbook's—or any fanciful poem's. He learned to make things that work by steadily improving upon things that did not work. He learned to learn from mistakes. My son, at eleven, had absorbed one of the principal lessons of engineering, and he had learned also the frustrations and the joys of being an engineer.