Building to Code

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When my college roommate broke Harvard's record for the 600-yard race, I felt inspired to become a track star. My athletic career until then had been undistinguished, except for having once contributed to my high school's defeat by our football archrivals when I intercepted a pass and ran the wrong way for a touchdown. Now, at last, fame and atonement would be mine.

I went daily to the Harvard track and trained assiduously. With growing excitement I watched my best times shrink. Finally the day came when I considered myself ready to break the 60-second quarter mile. I was into the last leg, ahead of the necessary pace, when I suddenly stopped in pain, unable to push off from my right foot. A visit to my physician father sealed the ignominious end of my training: instead of breaking another personal record, I had broken a toe bone. I thought bitterly, What lousy design my bones have! The first time in my life that I try seriously to make them do what they were built to do, they break.

That happened when I was 20 years old. Now that I've reached the age of 55 without breaking any other bones, I have a much higher opinion of the design that I inherited. Other people can be equally pleased: at most, only a quarter of us will ever break even a single one of our 12 major limb bones. African mongooses, genets, and civets can also be pleased, to judge from a similarly low frequency of healed limbs. Gibbons, however, must be less satisfied--one study showed that some 40 percent of them had signs of healed fractures. That's not surprising, though, because gibbons live in trees, and broken bones from falling have to be viewed as an occupational hazard of gibbonhood. Still, gibbons might feel justified in asking--as I did--Why didn't natural selection just endow us with big, strong bones that would never break?

This question is part of a much broader discussion on the safety code designed into our bodies. While most of us are born with two kidneys, some of us seem to do perfectly well if we lose one. Why burden ourselves with two, when the kidney is a biologically expensive organ to operate? And if two kidneys are good, why don't we have four? How many kidneys do we really need? How many lungs? Or, for that matter, what quantities of our various enzymes?

These questions concern evolution in action--and right on the home front. They are not about an abstract debatable theory, nor about fruit flies and dinosaurs, but about the evolution of our own bodies. Moreover, we live with the consequences: they spell the difference not just between athletic success and failure but also between health, chronic illness, and premature death.

A biological safety code is not essentially different from the familiar safety codes that design engineers draw up for man-made structures and machines. Key to both is the concept of a safety factor, without which our lives would be, to say the least, considerably more tenuous than is already the case. For example, every engineered structure--an airplane, a building, an elevator--has an advertised peak load. For an elevator, that load is the posted maximum number of passengers--and pounds--that it's legally certified to lift. But of course you'd want any elevator you'd enter to really be able to support more than that advertised load. Who knows, after all, whether one morning everyone trying to cram into that elevator will take the time to read the sign? The ratio of the load that will cause failure (the human tonnage that will send your elevator plummeting to the bottom) to the actual peak load in operation (the posted maximum number of prudent, sign-reading passengers) is defined as the safety factor--so called because it tells you by what margin of safety your machine surpasses its required performance.

Minimum safety factors are specified by codes drawn up by governments or industries, and a knowledge of them may save you some anxiety. For example, suppose you're as terrified as I am by those glass- walled elevators on the outside of many modern high-rise hotels. As your elevator rises, crowded with ominously overweight people, and as the people on the street receding below look smaller and smaller, you suddenly ask yourself whether the elevator was really designed to bear this weight and whether that strange sound above you is the elevator cable ripping. At that frightening moment, comfort yourself with the knowledge that the specified safety factor for the cable of even a slow passenger elevator is 7.6. In other words, the cable is strong enough to support a weight at least 7.6 times the advertised peak load. That's why you almost never read about elevator cables ripping and elevators crashing. Other structures, too, have specified safety factors, which vary depending on the type of structure and the material used. For example, the factor is only about 2 for a steel bridge. Thus you should worry more about whether the bumper-to-bumper trucks stopped ahead of you on the Golden Gate Bridge are filled with lead bricks than you should about the weights of your fellow passengers in the elevator.

Part of the reason that safety factors are necessary is that the strengths of components vary somewhat unpredictably above and below their expected values. Even components off the same assembly line can differ in strength. That variation can be described by a number termed the coefficient of variation (CV), which tells you how widely the strengths measured for many supposedly identical components scatter around the average value of strength. For example, CVs of strengths are about 3 to 7 percent for concrete, 11 percent for steel, and 18 percent for green oak.

In addition, the actual loads on structures also vary somewhat. If you specify that an elevator is to hold no more than 10 people, you have to reckon with the risk that those people (weighing 150 pounds on average) could on some occasions happen to be 240-pound football players instead of 50-pound Cub Scouts, and that 14 people might ignore the sign and try to crowd into the elevator. Hence if you were foolish enough to build elevators exactly strong enough to lift a payload of 10 x 150 = 1,500 pounds, your products would be troubled by crashes. That variability in both strengths and loads explains why construction codes specify safety factors: to reduce the risk of failure to some acceptably low level.

Okay, that's why engineers don't cut corners. But they also don't build superstrong structures, with a safety factor of, say, 100, that would be sufficiently high to eliminate any risk of failure at all. That's because the bigger and stronger the structure, the more it costs to build and operate and the more space it occupies. A manufacturer could certainly build a passenger elevator able to lift 15,000 pounds without breaking, but the cost of that deluxe elevator would quickly drive customers to a less phobic competitor.

Thus the safety factors of engineered structures are basically determined by the economics of free-market competition. That's natural selection played out in shopping centers instead of in the jungle. Overly strong as well as overly weak products tend to get eliminated, and only the products whose strength is enough but not too much survive.

Differences among safety factors specified by codes for different products reflect the varying outcomes of this fundamental trade-off between safety and cost. The more unpleasant the consequences of a product's structural failure, the higher its safety factor must be set to ensure that failure occurs rarely. That's why the safety factor for a slow elevator is 7.6 if it's a passenger elevator, 6.65 if it's a freight elevator (whose crashes could still jeopardize a person or two riding with the freight), and only 4.8 for a powered dumbwaiter (because who cares if a ripped cable drops the room-service breakfasts for the hotel guests).

So much for the well-understood safety factors of engineered structures. Now let's tackle the corresponding questions, lying at the frontiers of current research, about biological safety factors.

The most straightforward biological example involves bone and other structural materials of our bodies. We can analyze the strengths of skeletons, and the loads on them, with the same equations used for the steel skeleton of a skyscraper. The strength of bones can be measured experimentally by determining the force necessary to damage or break them in a machine. (Naturally, scientists make those measurements on bones removed from human cadavers or dead animals, not from bones still in their live owners.) During bones' actual use, loads on them can similarly be calculated by implanting a strain gauge in a live animal and recording the strain as the animal carries out its normal activities.

It turns out that safety factors of bones typically range from 2 to 4. That is, when a kangaroo hops, a horse gallops, a dog jumps, or we run, the actual peak strain on these bones is only about one-quarter to one-half the strain required to damage them irreversibly. Human weight lifters raising heavy barbells operate with lower safety factors (under 2) and are at greater risk of crushing a vertebra, but then, the human body wasn't designed for competitive weight lifting.

Some structures other than bones have lower safety factors. The draglines of spiders--the very thin silk threads by which spiders lower themselves--have a safety factor of less than 1.5. That means they would break under a weight only 50 percent greater than that of the spider itself. Squid, nautiluses, and their relatives operate even closer to the edge of disaster, with the internal, gas-filled shell chambers by which they maintain their buoyancy: the pressure pushing inward on those hollow chambers increases with depth. It turns out that the pressures required to burst them are only 30 to 40 percent greater than the pressures at the maximum depths to which the squid dives. Hence the squid's safety factor is only 1.3 to 1.4, far less than even that of a dumbwaiter.

A more direct test of our bodies' safety factors is to remove varying fractions of an organ to see how much we really need in order to survive. (Again, this isn't something that mad scientists do to drugged victims; the information comes from observing patients who have undergone surgery for medical reasons.) As mentioned, people with one of their two kidneys removed can live normal lives. However, complications develop if that single remaining kidney gets whittled down, so we know that the safety factor for our kidneys is just slightly greater than 2. Similarly, we can live with about half the length of our small intestine removed, again implying a safety factor close to 2.

On the other hand, 90 percent of the pancreas can be destroyed by pancreatic cancer before our ability to digest food becomes impaired (from insufficient quantities of the digestive enzymes that the pancreas makes). That implies a safety factor of 10, which sounds wonderful--until you reflect that pancreatic cancer can reach a very advanced stage before you become aware of it. Other seemingly overdesigned organs are our gonads. A woman is born with hundreds of thousands of potential eggs, and one milliliter of a man's semen contains tens of millions of sperm--providing a very generous safety factor for making any number of babies.

Those are examples of safety factors for our visible bones and organs. At the molecular level, safety factors also apply to the enzymes and transport proteins that constitute the operating machinery of our bodies. In my lab at the UCLA School of Medicine, my colleagues and I are studying the molecules that enable our intestines to digest and absorb food. Humans and animals possess a whole battery of such molecules to process each type of nutrient. For example, to digest carbohydrates our gut has an enzyme called amylase (it splits starch into short chains of sugars), and other enzymes (like maltase and sucrase) to split those short chains into simple sugars, as well as transport proteins (like the glucose transporter) to convey those simple sugars from the small intestine into our tissues.

We determine the capabilities of those enzymes and transport proteins by calculating the quantities of sugar that they could digest per day if they were functioning at a flat-out rate. (That's analogous to the weight that an elevator cable could support.) We also determine the load on the intestine, measured as the quantity of sugar that we actually consume each day. (That's analogous to the actual weight of the passengers in the elevator.) The resulting ratios of capacities to loads constitute the intestine's molecular safety factors, which typically are around 2, and occasionally somewhat higher.

To have capabilities barely equal to actual peak loads makes as little sense for our bodies as it does for engineered structures. Our biological parts need capacities that exceed the demands normally placed on them because, as is the case with engineered structures, both strengths and loads vary somewhat unpredictably. Suppose you happened to be the unfortunate individual whose bones were slightly weaker than average but were exposed to slightly greater than average strains. As you lay there broken in your hospital bed, you would not be consoled by the reflection that human bones are on average perfectly matched to their loads. Strengths of biological materials vary, just as do those of man-made materials. Bone, for example, is about as variable as steel. Both are more variable than concrete but much less variable than wood, a nautilus's shell, or a spider's silk.

You may be thinking that of course bones from different people will vary in strength, just like steel that's made according to different formulas in different factories. What really counts, you may argue, is the variation in the strength of bones specified by the same genes, which is analogous to unpredictable variations in the manufacturing process itself. What is that variation? Biomechanicist R. McNeill Alexander and his colleagues at the University of Leeds in England found an ingenious answer to that question by comparing the strengths of corresponding bones from the left and right legs (or wings) of the same bird. That coefficient of variation proved to be about 5 percent for seagulls and 15 percent for domesticated hens and pigeons. The higher CVs of hens and pigeons aren't surprising: those birds have been selected for other things, like egg- laying ability or appearance, whereas wild seagulls with imprecisely controlled bone growth are likely to end up in the mouth of a hungry coyote. At any rate, this study establishes that the variability in strength of bones grown according to the same genetic blueprint is comparable to the variability in strength of concrete batches manufactured to the same formula.

Not only bone strengths but also loads on bones vary somewhat unpredictably. My toe bones couldn't predict that I'd suddenly feel motivated, after a lifetime of inertia, to train for the quarter mile. Nor can my intestine's sugar transporters predict when I'll suddenly spot a two-pound chocolate raspberry cake and find it irresistible. The genes specifying body safety factors have to allow for these somewhat unpredictable events. The lowest safety factors that animals can get away with are for dealing with loads that the animal itself can control precisely, because it can sense when it's getting into trouble. That's why spiders can afford to spin draglines, and squid can tolerate buoyancy chambers, with such low safety factors. When the spider feels its silk thread starting to shake, it knows that it's time to spin a stronger thread.

Safety factors also have to be higher for biological structures whose failures would be fatal than for structures whose failures would merely be inconvenient. That's why cats have an especially high molecular safety factor of 7 for the transport protein of an amino acid called arginine. As carnivores, cats consume meat, which is high in protein but which also yields nitrogen-containing waste products. Those wastes can poison a cat if they're not quickly excreted. Cats depend on dietary arginine to run the metabolic cycle responsible for excreting those toxic wastes. (Humans, too, along with many other animals, also require arginine for the same purpose, but they make much of what they need themselves and aren't so dependent on a dietary source.) If a cat consumes a single meal without arginine, it may die of poisoning by those wastes. Hence it's worthwhile for a cat to maintain a big safety factor for arginine absorption, and to grab every bit of arginine that it can get from its food.

Other considerations dictating high or low safety factors for our bodies' parts are their relative cheapness and ease of repair. Each sperm is very cheap to make. It would be false economy for a man to gamble on fertilizing his beloved by injecting just a single sperm. For almost no more time, effort, and biosynthetic energy he can inject millions of sperm and let them compete with one another to fertilize the egg. As for ease of repair, we need a much bigger safety factor for our pancreas, which can't regenerate after damage, than for our kidneys, intestine, or liver, which grow new tissue if a portion is damaged.

An interesting example of how safety factors can illuminate the most familiar features of animal behavior and anatomy involves bones again. No one needs to be told that elephant bones are bigger than mouse bones. However, you might be surprised to learn that the proportion between bone dimensions and body dimensions is roughly independent of body weight, from mice to elephants. That's astonishing if you think about it, because a bone's strength depends on its cross-sectional area, which increases as the square of bone diameter. But the strain on a bone depends on the animal's body weight, which increases more rapidly--as the cube--with body dimensions. That is, one would expect bones of big animals to be operating under higher strain, to have to make do with lower safety factors, and to be at greater risk of breaking than bones of small animals. Why don't elephants and humans collapse with multiple fractures as soon as they start to move, while mice watch and laugh?

Experiments by biologists Andrew Biewener, Lance Lanyon, Clinton Rubin, and others have suggested an answer. When they attached strain gauges to bones of live animals of different sizes, it turned out that the actual strains measured were virtually independent of the animals' size. Measurements were made of animals as diverse as kangaroo rats, geese, and horses as they hopped, flew, or galloped. Evidently, as they move, big animals hold their limbs in such a way as to apply less extra strain than do small animals. Big animals, like horses, stand erect and run with their legs almost fully extended, while small animals, like chipmunks, stand crouched and run with their legs bent. That's why chipmunks can often dodge coyotes, which could easily outrun them on a straightaway: the chipmunk's posture increases the strain, but it also lets the chipmunk accelerate, decelerate, and change direction far more quickly than the coyote. The coyote likewise can be more agile than a horse, and a horse more agile than an elephant.

That's also why human sprinters lunging unnaturally out of starting blocks occasionally rip their tendons; chipmunks never rip their tendons, despite more sudden starts; and elephants wouldn't dare think of lunging out of starting blocks. All those familiar differences in animal behavior reflect how animals of different sizes adjust their running styles, so that all operate their bones at very similar safety factors of 2 to 4.

Finally, let's ask why animal bodies aren't overdesigned, with safety factors large enough to ensure that bones would never get fractured. Why didn't nature fit us out with unbreakably thick arm and leg bones?

For the analogous question about engineered structures, we saw that the answer was natural selection by the economics of the marketplace. The answer for animals is similar, except that natural selection operates literally, in the sense meant by Darwin. Biological structures occupy space and are costly to build and operate. The costs are measured in biosynthetic energy, not in money, but the energy and space available to animals are as finite as the money and space available to consumers. Animals that squandered energy and space on one structure would have less to devote to other structures. They would tend to be outperformed, outbred, and driven into extinction by more economically designed animals.

For example, if you look inside an animal's (or person's) body, you'll see that there isn't space enough to double the size of the intestine without reducing the space devoted to something else. It wouldn't be practical to have a bigger intestine, providing a bigger safety factor for digestion, at the expense of having a smaller heart, liver, and kidneys. And would you really want to lug around unbreakable arms and legs twice as thick and heavy as they actually are?

The costliness of any biological structure explains why underused structures tend to get whittled down, and unused ones eliminated, by natural selection. Evolution operates on the principle of use it or lose it; if it doesn't pay its way, discard it. That's why we humans lost our tails and are in the process of losing our appendixes: we get much more value by devoting the saved tissue and weight to an enlarged cerebral cortex. It's also why cave-dwelling animals tend to lose their eyes, and why birds on remote, predator-free, oceanic islands tend to lose the big and expensive wing muscles necessary for flight.

It may be easy to laugh at, say, the dumbwaiter that drops a breakfast down the shaft (especially if it's someone else's breakfast). But when the failures are of our own bones and kidneys, the consequences are tragic. Yet the underlying principles are similar. Competition among elevator companies, and among animal bodies, leads to differential success in which only a few survive to make the next generation. While manufacturers of shoddy products fail, so--alas--do manufacturers of costly extravagances. It's a painful message for us to hear, but our bodies are on average just good enough, and no better than they need to be. As a result, we must reckon with the likelihood of occasional failure of one or another system. Natural selection decided that we weren't worth the cost of building better.