Supplemental Chapter 1. Constructing King Kong

I would never have guessed, even this morning before I started to work, that I would be writing a chapter about King Kong. Even though I'm a great fan of Raymond Burr, who was the narrator on the American version of the original movie, I have never seen the movie in any of its incarnations. But in the world of science writing, you never know where you are going to end up.

Our brains have a linear bias in more ways than I described in Chapter 7. Our mental bias is to think of organisms scaling up, or down, in size in a linear fashion. But this is not how nature works.

For a more thorough overview of scaling than this book provides, I refer you to books by Schmidt-Nielsen[1] and McGowan.[2]

The Micro-World

Let's start with the opposite of King Kong: a single cell. What does this cell need in order to stay alive? It needs to absorb nutrients and to release wastes. Animal cells absorb water, oxygen, and food molecules. Plant cells absorb water, carbon dioxide, and mineral nutrients. Many plant cells also intercept light, using light energy in photosynthesis, to make their own food molecules out of carbon dioxide and minerals. Cells absorb nutrients and release wastes by the process of diffusion across the membrane surfaces that surround them. Organisms larger than a single cell are just a large number of cells doing this. There. That's what life is all about.

Diffusion results from the random movement of entities such as molecules. Molecules diffuse from places where they are highly concentrated to places where they are more sparsely concentrated for the simple reason that there are more ways for them to accidentally move away from each other than toward each other. As intuitive as this process sounds, it is mathematically complex. To fully understand it, I invite you to study the Second Law of Thermodynamics, even though I have never studied it myself.[3] Good luck.

And this is where, right away, we start running into yet more non-linear processes when our human bias would lead us to expect linear ones. Diffusion is a non-linear process. In order for molecules (such as water) to diffuse twice as far, it may take them four times as long, all other things (such as temperature) being equal. To diffuse a hundred times as far, it may take

them ten thousand times as long. Therefore, diffusion is very efficient at small distances, but to wait for diffusion to occur over great distances you could wait seemingly forever.

The Macro Solution: Cells

Imagine a small cell that is a cube one-tenth of a millimeter on each side. The furthest from the surface membrane that a molecule could possibly be inside such a cell is one-twentieth of a millimeter. Diffusion can bring molecules in and take molecules out of such a cell just fine. But if the cell were ten centimeters on a side, some molecules would be five centimeters away from the surface, which is ten thousand times as far as in the small cell. It may take ten thousand times ten thousand (which is ten billion; or for you Brits, ten thousand million) times as long for the molecule to diffuse out of the big cell (or for a molecule to diffuse into the middle of a big cell) as is the case with the small cell. The middle of the cell, thus effectively isolated forever from its environment, would die.

There is really only one conceivable solution to this problem: small cells. Large organisms (that is, larger than a millimeter or two) consist of cells. (There are a very few exceptions, such as an invertebrate that lives at the bottom of the sea, but has such a slow metabolism that it can in fact wait nearly forever for diffusion to occur. Besides, it has another adaptation that I will explain shortly.) Molecules can slip between cells, and from there they can diffuse rapidly into and out of cells. King Kong would have to consist of many cells. But this is not surprising; all animals large enough for you to see consist of many cells.

This principle holds true in every aspect of life, not just science. A small essay does not need any section divisions, but a book does. Imagine what a chore it would be to read this book if it consisted of just one long chapter! Typically, authors split chapters up into smaller pieces, sometimes with their own headings, sometimes just with little asterisks or something. These breaks allow the reader to stop, take a breath, and ask, “What did I just read?” The mark of a good writer, and of good chapter and subchapter divisions, is that the reader can answer this question without much hesitation. Composers divide symphonies into movements, and long performances have intermissions, for which we listeners and viewers are thankful.

Cellularity is only part of the answer. A larger animal (and that deep sea single cell that I mentioned earlier) also benefits from having wrinkles, creases, bubbles, and ridges to increase

the amount of surface area to which the cells are exposed. For example, your lungs have the same amount of internal surface area as a tennis court, through which oxygen molecules diffuse into the blood from the air you breathe in and carbon dioxide molecules diffuse out of the blood into the air you breathe out. This surface area is compressed into literally millions of little bubbles called alveoli. Insects don't have lungs but they do have little air tubes called tracheae. Similarly, your intestines have the same amount of surface area as a tennis court, through which food molecules diffuse into the blood. This surface area is compressed into folds and into literally millions of little projections called villi. Each villus is covered with cells, and each of these cells has microvilli. You, therefore, have enormous amounts of diffusive surface area, compressed inside your lungs and intestines. (Every textbook I have seen uses the tennis court analogy. I can only assume that God, in designing the human body, is a big fan of tennis.)

Plants need to absorb and release molecules also. Of course, plants larger than about a millimeter in size also consist of cells. And they, too, have lots of organismal surface area. But their surfaces are on the outside, instead of the inside like the surface areas of animals. Plants intercept light, and absorb carbon dioxide, with their thin flat leaves, from which they release oxygen. They absorb water and minerals with their tiny but incredibly numerous roots. A botanist named Howard J. Dittmer, back in the 1930s, had his students estimate how much root length a single rye plant had. They had to carefully wash away the soil and measure each root and rootlet and root hair. (Actually, they just measured some of them, and then multiplied to get an estimate.) Their result: a single rye plant can have *a mile* of roots. Granted, this was a rye plant grown in a pot with all of the nutrients and water and light that its non-existent heart could desire. But still, a mile of roots is a lot.

Similarly, I had my college students estimate the number of twigs on some oak trees, using trigonometry and algebra. The estimates varied from 50,000 to 100,000 twigs. Each of these twigs has about ten small leaves (for one species of oak) or five large leaves (for another species). This adds up to a lot of leaves and a lot of leaf area. It is not unusual for a forest to have a leaf area index of two. That is, for each unit of ground area, there is twice as much leaf area. A square mile of forest may have two square miles of leaf area. Plants absorb carbon dioxide (on the average); animals release it. Plants release oxygen (on the average); animals absorb it. You can think of plants as metabolically backward animals. And they are also inside-out: animal surface areas are inside, while plant surface areas are outside.

So King Kong would need to have lungs and intestines. This is not surprising. All animals larger than the smallest flatworms have lungs (or gills or some other equivalent) and intestines. But King Kong would need extra-large lungs and extra-large intestines. And the reason for this gets us into one of the most fundamental concepts in all of science: *surface-to-volume ratio.* If you've never thought about surface-to-volume ratio, prepare to have your view of the world dimensionally enhanced as you read this.

Surface to Volume Ratio: The Most Important Thing You've Never Heard Of

We are all aware that physical processes and chemical reactions can occur more rapidly when the components involved have a greater surface area. For example, finely-ground sugar can dissolve in water more quickly than coarsely-ground sugar. (This does not apply to commercial powdered sugar, which actually has some flour mixed in to keep it from caking.) This is because each sugar molecule is closer to the water into which it dissolves if the sugar is finely ground. We all know that paper burns faster than an equivalent weight of wood from which it is made. Finely ground sugar and paper have a much higher surface-to-volume ratio than coarse sugar and wood.

Now here's the problem that you face, as a medium-sized animal, and that King Kong faces much more than you do. As any object such as an animal increases in size (in linear terms, such as height), its surface areas increase as the *square* of the linear factor, and its volume increases as the *cube* of the linear factor. A simple cube, if magnified by a linear factor of 10, will have 100 times as much surface area (two dimensions) but will have 1000 times as much volume (three dimensions). This magnification reduces its surface-to-volume ratio by a factor of ten. So if King Kong is a hundred times as tall as you are, then his lungs and intestines will have $100 \times 100 = 10{,}000$ times as much surface area but he would weigh $100 \times 100 \times 100 = 1{,}000{,}000$ (a million) times as much. His surface-to-volume ratio would be 100 times less than yours. That million-fold greater volume of living tissue has to be fed and aerated by lungs that can supply only ten thousand times as much food and oxygen. To compensate for that, King Kong would need *relatively* larger lungs and intestines; that is, lungs and intestines would take up a considerably greater *proportion* of his body than yours do.

Standing Up

King Kong would face other problems as well, such as being able to stand up. Aquatic mammals such as whales are essentially weightless in water. But the buoyancy of air is essentially nothing, and a large terrestrial mammal needs strong support structures, such as bones and legs and necks. The strength of a support structure depends upon its cross-sectional area. That is, if you have two columns, and one of them has a radius or diameter ten times as great as the other, the larger column can hold up a hundred times as much weight as the smaller one. Thus, if King Kong is a hundred times as tall as you but otherwise looks just like you (in terms of the proportions of body parts, not facial features and the like), his legs will be $100 \times 100 = 10{,}000$ times as strong, but he would (as noted previously) weigh a million times as much. If his legs were no thicker, relative to his height, than yours are relative to yours, his legs would snap and his torso would fall down on Raymond Burr and crush him.

And this simple set of calculations explains things that you already knew by intuition but may never have thought about. Spiders and daddy-longlegs (which are related to, but are not true, spiders) run around on spindly legs. But a Hollywood-sized spider could not even begin to lift itself up off the ground with those spindly legs. This is also why you could never have a King Kong sized wiener dog. Such a large body could not be supported by those spindly legs. The poor wiener dog's back would break if he even tried to lift himself. Actually, wiener dogs are about at the limit of what a dog's back can tolerate anyway, as any member of the American Veterinary Chiropractic Association could tell you. So if you had a dog the size of an elephant, it would look like an elephant.[4] That is, with thick legs, though not necessarily a trunk. Or might it not need a trunk also? It would not be able to stand up on its hind legs very well. Very large dinosaurs did not have trunks but they did have long necks, since standing on their hind legs was a risky business.

Apparently the upper limit for the size of a four-legged animal is about 140 metric tons.[5] At that weight, the four legs would have to be so large, relative to the size of the animal, that the legs could not move. They would snuggle right up next to one another. Some dinosaurs, weighing in at over 100 metric tons, got pretty close to that theoretical limit.

How do very large plants deal with the problem of support?

The largest plants are giant sequoia trees, *Sequoiadendron giganteum*, which live in the Sierra Nevada mountains of California. The giant sequoia forests of California are a remnant of the ancient forests from millions of years long past and are among the most beautiful places on Earth. Next time you visit California, if you don't already live there, skip Disneyland and Hollywood and go to Sequoia National Park. It is well worth the drive (through road construction) up the twisty little road to see these forests. If you have a tendency to be arrogant, one look at a giant sequoia tree will humble you. (But you have to really look. I've seen arrogant people stalking around the sequoias and remaining loudly arrogant, but I believe this is because they didn't really stop and look. They had their pictures taken by the trees and then left.) The tree trunks are as big around as a room, and fifty feet above the ground the trunks are still almost as large as at the base. The lowest boughs are about as big as the biggest tree east of the Mississippi. Many of them are almost three thousand years old. How can a tree grow so large?

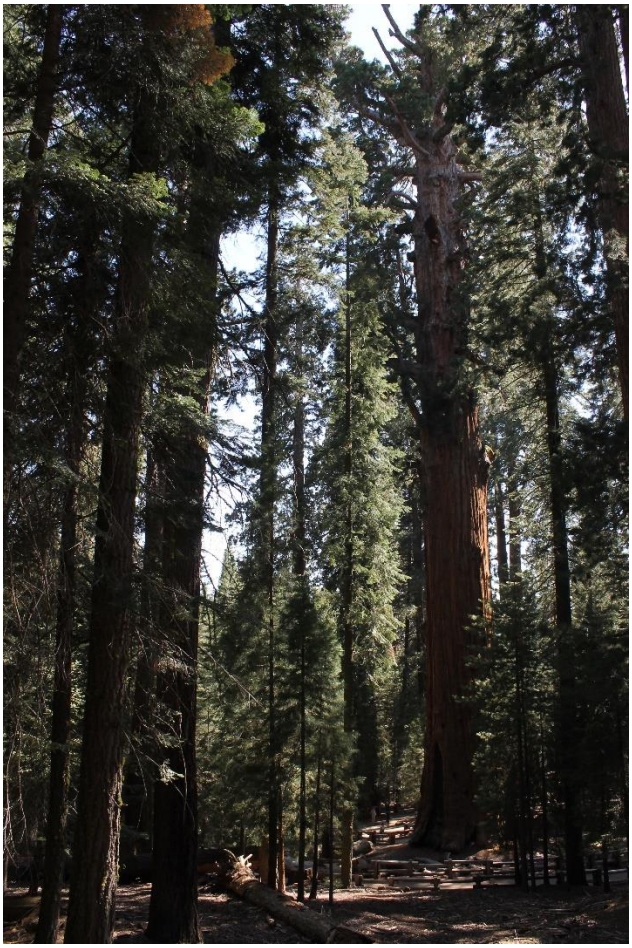

Figure S1-1. The General Sherman tree, a giant sequoia, is the largest organism on Earth. It is 275 feet (83 m) tall, and its base has a diameter of 36 feet (11 m). At sixty feet above the base, it is still 17.5 feet (5.3 m) tall. With a wooden fence to keep visitors from trampling on its relatively shallow roots, this tree is in the right half of the photo. (Author photo)

The way trees can grow so large is that they reach their full height within a relatively short period of time, maybe just five hundred years. As they do so, they have relatively small trunks, but also small branches. Their small trunks do not need to support much weight of branch and needle. Then they spend the next few millennia growing thicker and thicker trunks. Also, they shed their lower branches. Because of shedding old branches, if their growing trunks become, over time, a hundred times as strong, they may have only a hundred, not ten thousand, times as much branch and needle weight to support.

In general, this is the pattern of growth in plants, even in little weeds. I did part of my thesis work with a little weed called velvetleaf. As this weed grows taller, it accumulates stem weight. But it does not accumulate leaves. The older leaves die and fall off. Therefore, over time, the proportion of the plant's weight that consists of leaf material decreases. Interestingly, I demonstrated that, when different groups of these plants are compared on the basis of *weight* rather than *time*, they all (at least, all of the ones in my experiments) had exactly the same relationship between leaf weight and plant weight.[6] There is a whole field of study about how to compare organisms on the basis of weight rather than age; it is called *allometry*.[7]

Therefore, as a plant grows, its stem gets stronger, but not enough stronger to support all of the new branches and leaves that it produces. It responds to this situation by dropping old stems and leaves.

The exceptions prove the rule. What about palm trees? They look mighty spindly. The reason for this is that their trunks do not become wider as they grow taller. This seems rather odd. But you will notice that palm trees don't have branches, and also that they do not accumulate leaves. A very tall palm tree has a tuft of leaves at the top that is no larger than the tuft of leaves at the top of a short palm tree.

A Big Heart

Large animals need more than lungs and intestines. They need circulatory systems. Blood carries oxygen from the lungs to all the cells of the body, and carries carbon dioxide from all the cells, to the lungs. Because animal cells need so much oxygen, and oxygen does not dissolve in water (or blood plasma) very well, many animals have red blood cells with hemoglobin that carries more oxygen, and releases and absorbs it more readily, than water or plasma. (Insect blood is a yellowish green suspension called hemolymph, and does not have cells that carry oxygen. But insects are small enough that they can get all the oxygen they need from their tracheae.)

Even very small animals may have hearts. Even insects have little hearts, which help move their hemolymph. A very large animal needs a very large heart, of course. But here, for once, our linear bias proves correct. A large animal that is ten times as tall as a small animal needs a heart that is only ten times as large. From mouse to elephant, animals have hearts that weigh about 0.6 percent of body weight. A large heart might have structural difficulties, but an elephant's heart has essentially the same structure as a mouse's heart.

But some animals have, or have had, particular circulatory problems. I refer specifically to ancient dinosaurs that had long necks, and to modern giraffes. Their hearts were and are in their chests, but must pump blood up into their long necks. A giraffe's twenty-five-pound heart has huge muscle walls which can be three inches thick. And the giraffe's heart generates massive blood pressure; 300 over 180 is a typical measurement, compared to a typical human's 120 over 70. Perhaps not surprisingly, giraffes live only about twenty years and often die of heart attacks. Giraffes are pushing the limits of heart function. King Kong would not have this problem, because his heart would be not too far below his thick neck and would not have to push blood upward very far, compared to his body size, to keep his brain alive. It's that long neck that causes the problem in a giraffe.

And many dinosaurs had long tails as well as long necks. For example, a kind of large dinosaur that lived over a hundred million years ago in what is now Texas had a tail that weighs a ton. These dinosaurs left their footprints in mud that is now stone. But you almost never see any evidence that they dragged their tails. Not only did their circulatory systems keep these tails alive, but fed some really big muscles to keep the tails from dragging. It is likely that very large dinosaurs had some auxiliary pumping action in muscles surrounding some of the arteries that

were distant from their hearts—not really extra hearts, but some muscles that helped their circulation a little.

Big Blood Vessels

Perhaps the most surprising example of all, in the world of size and scale, is the ability of fluid to move through blood vessels and through the xylem tubes (wood vessels) of plants.

There are two major categories of fluid flow: laminar and turbulent. With laminar flow, the molecules or cells (water or blood) flow in nice smooth trajectories straight down the tube. With turbulent flow, however, the molecules or blood cells start to form eddies. Instead of moving along in night straight lines, they curl around in swirls, which considerably impede the blood flow. In a small enough tube, such as blood vessels and in the little conduits (known as *xylem*) through which water flows through plants, almost all of the fluid flow is laminar. In a large pipe or in a creek or river, however, a lot of the fluid has turbulent flow.

Consider two blood vessels. The large one has ten times the radius or diameter of the smaller one. Our intuition would lead us to believe that the larger blood vessel, with a hundred times the cross-sectional area, would conduct a hundred times as much blood as the smaller. But this turns out to not be the case. The blood that drags along the sides of the vessel travels slowly (due to friction); the most rapidly moving blood is out in the middle of the vessel. In a large blood vessel, there is a whole lot more blood that is far enough away from the inner surface of the vessel that it experiences essentially no drag from that surface. Therefore, a blood vessel that is ten times as wide can conduct a lot more than a hundred times as much blood. For reasons I cannot fully explain to you, the amount of blood that can flow in a vessel is related to *the fourth power* of the vessel diameter. That is, the big blood vessel, with *ten* times as much diameter, can conduct *ten thousand times* as much blood.[8]

This has two consequences. First, this explains why a few large arteries can supply all the blood that miles and miles of little capillaries need. Second, this explains why even a slight loss of artery diameter—especially from cholesterol plaque buildup—can vastly reduce the amount of blood that the artery can conduct. According to the fourth-power law, if plaque buildup causes your arteries to lose one-half of their diameter, their blood flow will be reduced by fifteen-sixteenths! This fact alone should be enough to scare all of us into a healthy diet. This is not a

half-empty pessimist vs. half-full optimist scenario. You can't say "My arteries still have half of their diameter—pass the chips!" because, from the viewpoint of blood flow, your arteries are only one-sixteenth open.

But this might be good news for King Kong. If he needs (to use an arbitrary number) ten times as much blood flow, he does not need arteries that are ten times as wide. This is yet another reason that he would not need an exorbitantly large heart.

But then there's bad news for King Kong too. Once an artery gets large enough, there is the possibility that some of the fluid will experience turbulence. The fourth-power law applies only to laminar flow. If the vessels get large enough that the blood starts swirling around in them rather than moving right along in a laminar fashion, King Kong is in trouble.

Dinner Time!

Having read the foregoing, you would probably think that King Kong would need to eat a hugely disproportionate amount of food to stay alive, especially since he is warm-blooded. But it turns out that this is not true. The metabolic rate (and therefore the amount of food energy required) per unit body weight is smaller, not larger, for a big animal than for a small one. (To reduce the number of confusing factors, we will just talk about mammals, which are warm-blooded.) One important reason for this is that, in mammals, a lot of metabolic energy is used to maintain body temperature. And the very fact, as noted above, that large animals have a lower surface-to-volume ratio than small animals means that their bodies are much more efficient at holding in the heat. This brings up the question that has been discussed for decades: were dinosaurs warm-blooded? Well, it turns out that some of them were so large that they could not have avoided being warm on the inside. Were large dinosaurs warm on the inside just because they were large, or because their bodies produced additional body heat? A recent study indicates that they were somewhere between these two possibilities.[8]

The World of the Small and of the Large

If you could shrink to a very small size, like Osmosis Jones in the movie, you would find a very different world than the one to which you are accustomed. Underwater, it would be a

world in which gravity was nearly irrelevant; instead, the adhesive forces of water molecules would be the most important factor in your survival. There are some bacteria that use little magnets that orient them to the Earth's magnetic field so that they know which way is down, since they cannot feel gravity.[10] On land, you could be an animal that walks on very flimsy legs and carry what appear to be large burdens relative to your body size. Ants do not need to have prodigious muscles in order to carry objects as large as themselves, since such small objects do not weigh very much relative to their size. The ancient Greeks did not understand this, and thought that, if you could make ants as large as men they would be powerful warriors, like the Myrmidons who followed the warrior Achilles. Actually, big ants would not even be able to stand up. At the other extreme, if you were a very large animal, you might find it almost impossible to move. This is yet another way in which our linear bias leads us to misinterpret the world.

Endnotes

1. Schmidt-Nielsen, Knut. *Scaling: Why is Animal Size So Important?* Cambridge University Press, 1984.
2. McGowan, Christopher. *Diatoms to Dinosaurs: The Size and Scale of Living Things.* Penguin, 1999.
3. Atkins, Peter. *The Laws of Thermodynamics: A Very Short Introduction.* Oxford University Press, 2010.
4. Gould, Stephen Jay. "Size and Shape." Chapter 21 of *Ever Since Darwin*. Norton, 1977.
5. Benton, Michael. "Dinosaur Summer." Chapter 4 in Gould, Stephen Jay, ed. *The Book of Life.* Norton, 1993.
6. Rice, Stanley A., and Fakhri A. Bazzaz. "Quantification of plasticity of plant traits in response to light intensity: comparing phenotypes at a common weight." *Oecologia* 78: 502-507 (1989).
7. Niklas, Karl J. *Plant Allometry: The Scaling of Form and Process.* University of Chicago Press, 1994.
8. Rice, Stanley A., and John McArthur. "Water flow through xylem: An investigation of a fluid dynamics principle applied to plants." *American Biology Teacher* 66 (2004): 120-127.
9. Grady, John M., et al. "Evidence for mesothermy in dinosaurs." *Science* 344 (2014): 1,268-1,272.
10. Blakemore, Richard P. "Magnetotactic bacteria." *Annual Reviews of Microbiology* 36 (1982): 217-238.