CHAPTER SEVEN

ADVENTURES IN BODYBUILDING

When I wasn't out in the field collecting fossils, much of my graduate career was spent staring into a microscope, looking at how cells come together to make bones.

I would take the developing limb of a salamander or a frog, and stain the cells with dyes that turn developing cartilage blue and bones red. I could then make the rest of the tissues clear by treating the limb with glycerin. These were beautiful preparations: the embryo entirely clear and all the bones radiating the colors of the dyes. It was like looking at creatures made of glass.

During these long hours at the microscope, I was literally watching an animal being built. The earliest embryos would have tiny little limb buds and the cells inside would be evenly spaced. Then, at later stages, the cells would clump inside the limb bud. In successively older embryos, the cells would take different shapes and the bones would form. Each of those clumps I saw during the early stages became a bone.

It is hard not to feel awestruck watching an animal assemble itself. Just like a brick house, a limb is built by smaller pieces joining to make a larger structure. But there is a huge difference. Houses have a builder, somebody who actually knows where all the bricks need to go; limbs and bodies do not. The information that builds limbs is not in some architectural plan but is contained within each cell. Imagine a house coming together spontaneously from all the information contained in the bricks: that is how animal bodies are made.

Much of what makes a body is locked inside the cell; in fact, much of what makes us unique is there, too. Our body looks different from that of a jellyfish because of the ways our cells attach to one another, the ways they communicate, and the different materials they make.

Before we could even have a "body plan"—let alone a head, brain, or arm—there had to be a way to make a body in the first place. What does this mean? To make all of a body's tissues and structures, cells had to know how to cooperate—to come together to make an entirely new kind of individual.

To understand the meaning of this, let's first consider what a body is. Then, let's address the three great questions about bodies: When? How? And Why? When did bodies arise, how did they come about, and, most important, why are there bodies at all?

HABEAS CORPUS: SHOW ME THE BODY

Not every clump of cells can be awarded the honor of being called a body. A mat of bacteria or a group of skin cells is a very different thing from an array of cells that we would call an individual. This is an essential distinction; a thought experiment will help us see the difference.

What happens if you take away some bacteria from a mat of bacteria? You end up with a smaller mat of bacteria. What happens when you remove some cells of a human or fish, say from the heart or brain? You could end up with a dead human or fish, depending on which cells you remove.

So the thought experiment reveals one of the defining features of bodies: our component parts work together to make a greater whole. But not all parts of bodies are equal; some parts are absolutely required for life. Moreover, in bodies, there is a division of labor between parts; brains, hearts, and stomachs have distinct functions. This division of labor extends to the smallest levels of structure, including the cells, genes, and proteins that make bodies.

The body of a worm or a person has an identity that the constituent parts—organs, tissues, and cells—lack. Our skin cells, for example, are continually dividing, dying, and being sloughed off. Yet you are the same individual you were seven years ago, even though virtually every one of your skin cells is now different: the ones you had back then are dead and gone, replaced by new ones. The same is true of virtually every cell in our bodies. Like a river that remains the same despite changes in its course, water content, even size, we remain the same individuals despite the continual turnover of our parts.

And despite this continual change, each of our organs "knows" its size and place in the body. We grow in the correct proportions because the growth of the bones in our arms is coordinated with the growth of the bones in our fingers and our skulls. Our skin is smooth because cells can communicate to maintain its integrity and the regularity of its surface. Until something out of the ordinary happens, like, for instance, we get a wart. The cells inside the wart aren't following the rules: they do not know when to stop growing.

When the finely tuned balance among the different parts of bodies breaks down, the individual creature can die. A cancerous tumor, for example, is born when one batch of cells no longer cooperates with others. By dividing endlessly, or by failing to die properly, these cells can destroy the necessary balance that makes a living individual person. Cancers break the rules that allow cells to cooperate with one another. Like bullies who break down highly cooperative societies, cancers behave in their own best interest until they kill their larger community, the human body.

What made all this complexity possible? For our distant ancestors to go from single-celled creatures to bodied ones, as they did over a billion years ago, their cells had to utilize new mechanisms to work together. They needed to be able to communicate with one another. They needed to be able to stick together in new ways. And they needed to be able to make new things, such as the molecules that make our organs distinct. These features—the glue between cells, the ways cells can "talk" to each other, and the molecules that cells make—constitute the toolkit needed to build all the different bodies we see on earth.

The invention of these tools amounted to a revolution. The shift from single-celled animals to animals with bodies reveals a whole new world. New creatures with whole new capabilities came about: they got big, they moved around, and they developed new organs that helped them sense, eat, and digest their world.

DIGGING UP BODIES

Here's a humbling thought for all of us worms, fish, and humans: most of life's history is the story of single-celled creatures. Virtually everything we have talked about thus far—animals with hands, heads, sense organs, even body plans—has been around for only a small fraction of the earth's history. Those of us who teach paleontology often use the analogy of the "earth year" to illustrate how tiny that fraction is. Take the entire 4.5-billion-year history of the earth and scale it down to a single year, with January 1 being the origin of the earth and midnight on December 31 being the present. Until June, the only organisms were single-celled microbes, such as algae, bacteria, and amoebae. The first animal with a head did not appear until

October. The first human appears on December 31. We, like all the animals and plants that have ever lived, are recent crashers at the party of life on earth.

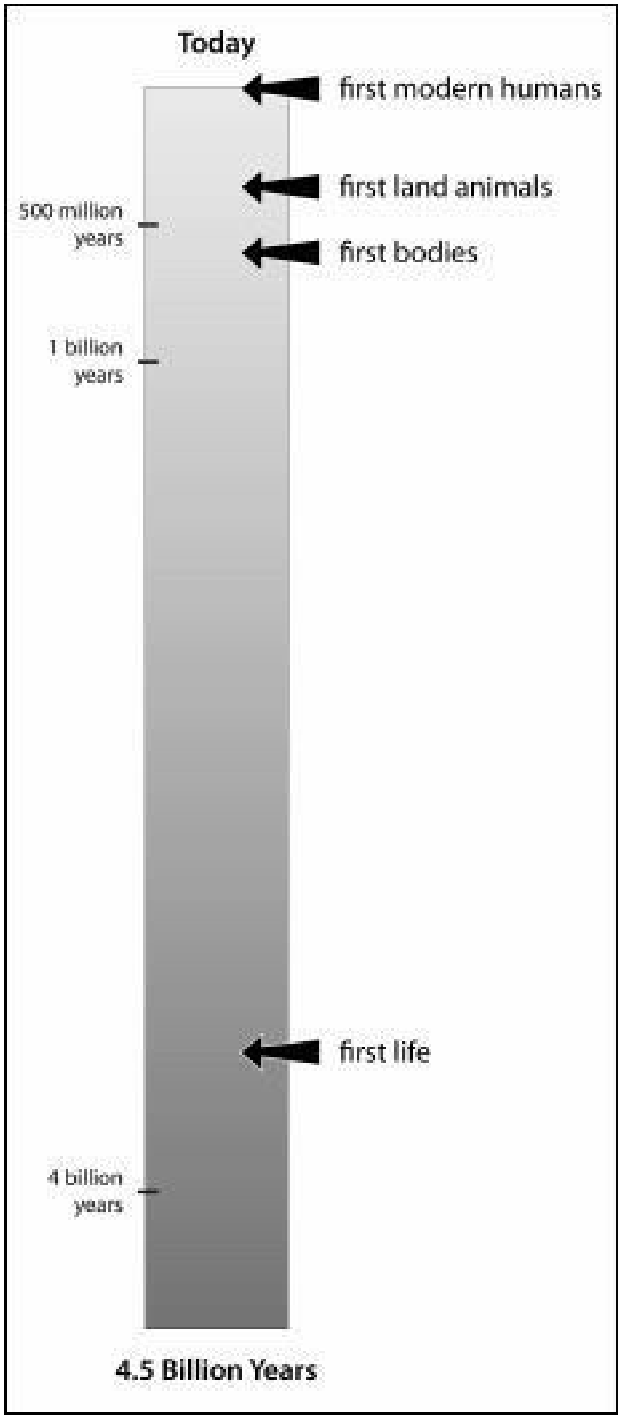
The vastness of this time scale becomes abundantly clear when we look at the rocks in the world. Rocks older than 600 million years are generally devoid of animals or plants. In them we find only single-celled creatures or colonies of algae. These colonies form mats or strands; some colonies are doorknob-shaped. In no way are these to be confused with bodies.

The first people to see the earliest bodies in the fossil record had no idea what they were looking at. Between 1920 and 1960 really odd fossils started popping up from all around the world. In the 1920s and 1930s, Martin Gurich, a German paleontologist working in what is today Namibia, discovered a variety of impressions of what looked like animal bodies. Shaped like disks and plates, these things seemed unremarkable: they could have been primitive algae or jellyfish living in ancient seas.

In 1947, an Australian mining geologist named Reginald Sprigg happened upon a locality where the undersides of the rocks contained impressions of disks, ribbons, and fronds. Working around an abandoned mine in the Ediacara Hills of South Australia, Sprigg uncovered a collection of these fossils and described them dutifully. Over time, similar impressions became known from every continent of the world except Antarctica. Sprigg's creatures seemed strange, but few people really cared about them.

The reason for the collective paleontological yawn was that these fossils were thought to come from the relatively young rocks of the Cambrian era, when many animal fossils with primitive bodies were already known. Sprigg's and Gurich's fossils sat relatively unnoticed, an assemblage of not terribly exciting, if weird, impressions from a period already well represented in the museum collections of the world.

In the mid-1960s, Martin Glaessner, a charismatic Austrian ex-pat living in Australia, changed all that. After comparing these rocks to those in other parts of the world, Glaessner showed that without a doubt these fossils were 15 million to 20 million years older than originally thought. They were no dull collection of impressions—rather, Gurich, Sprigg, and others were seeing the earliest bodies.



A timescale for events in the history of life. Notice the extremely long period of time during which there were no bodies on earth, only single-celled organisms living alone or in colonies.

These fossils came from the period known as the

Precambrian, whose name literally means "Before Life." Our understanding of the antiquity of life had just exploded. Paleontological curiosities became scientific jewels.

The Precambrian disks, ribbons, and fronds are clearly the oldest creatures with bodies. As we'd expect from other early animal fossils, they include representatives of some of the most primitive animals on the planet today: sponges and jellyfish. Other Precambrian fossils look like nothing known. We can tell that they are impressions of something with a body, but their patterns of blobs, stripes, and shapes match no living creature.

One message from this is very clear: creatures with many cells began to populate the seas of the planet by 600 million years ago. These creatures had well-defined bodies and weren't just colonies of cells. They have patterns of symmetry that, in some cases, resemble those of living forms. As for those that cannot be compared directly with living forms, different parts of their bodies nevertheless have specialized structures. This implies that the Precambrian organisms had a level of biological organization that at the time was utterly new on the planet.

Evidence of these changes is seen not only in the fossil bodies but also in the rocks themselves. With the first bodies come the first trackways. Etched in the rocks are the first signs that creatures were actually crawling and squirming through the ooze. The earliest trackways, small ribbon-shaped scrapes in the ancient mud, show that some of these creatures with bodies were capable of relatively complicated motions. Not only did they have bodies with identifiable parts, but they were actually using them to move in new ways.

All of this makes total sense. We see the first bodies before we see the first body plans. We see the first primitive body plans before we see the first body plans with heads, and so on. Like the imaginary zoo we walked through in the first chapter, the rocks of the world are highly ordered.

As we said at the beginning of this section, we are after the when, how, and why of bodies. The Precambrian discoveries tell us the when. To see the how, and ultimately the why, we need to take a slightly different tack.

OUR OWN BODY OF EVIDENCE

A photo could never capture just how much of our bodies is to be found within those Precambrian disks, fronds, and ribbons. What could we humans, with all our complexity, ever share with impressions in rocks, particularly ones that look like crinkled jellyfish and squashed rolls of film?

The answer is profound and, when we see the evidence, inescapable: the “stuff” that holds us together—that makes our bodies possible—is no different from what formed the bodies of Gurich’s and Sprigg’s ancient impressions. In fact, the scaffolding of our entire body originated in a surprisingly ancient place: single-celled animals.

What holds a clump of cells together, whether they form a jellyfish or an eyeball? In creatures like us, that biological glue is astoundingly complicated; it not only holds our cells together, but also allows cells to communicate and forms much of our structure. The glue is not one thing; it is a variety of different molecules that connect and lie between our cells. At the microscopic level, it gives each of our tissues and organs its distinctive appearance and function. An eyeball looks different from a leg bone whether we look at it with the naked eye or under a microscope. In fact, much of the difference between a leg bone and an eye rests in the ways the cells and materials are arranged deep inside.

Every fall for the past several years, I have driven medical students crazy with just these concepts. Nervous first-year students must learn to identify organs by looking at random slides of tissue under a microscope. How do they do this?

The task is a little like figuring out what country you are in by looking at a street map of a small village. The task is doable, but we need the right clues. In organs, some of the best clues lie in the shape of cells and how they attach to one another; it is also important to be able to identify the stuff that lies between them. Tissues have all kinds of different cells, which attach to one another in different ways: some regions have strips or columns of cells; in others, cells are randomly scattered and loosely attached to one another. These areas, where cells are loosely packed, are often filled with materials that give each tissue its characteristic physical properties. For instance, the minerals that lie between bone cells determine the hardness of bone, whereas the looser proteins in the whites of our eyes make the wall of the eyeball more pliant.

Our students' ability to identify organs from microscope slides, then, comes from knowing how cells are arranged and what lies between the cells. For us, there is a deeper meaning. The molecules that make these cellular arrangements possible are the molecules that make bodies possible. If there were no way to attach cells to one another, or if there were no materials between cells, there would be no bodies on the earth—just batches of cells. This means that the starting point for understanding how and why bodies arose is to see these molecules: the molecules that help cells stick together, the molecules that allow them to communicate with one another, and the substances that lie between cells.

To understand the relevance of this molecular structure to our bodies, let's focus in detail on one part: our skeleton. Our skeleton is a powerful example of how tiny molecules can have a big impact on the structure of our body and exemplifies general principles that apply to all the body's parts. Without skeletons, we would be formless masses of goo. Living on land would not be easy or even possible. So much of our basic biology and behavior is made possible by our skeleton that we often take it for granted. Every time we walk, play piano, inhale, or chew food we have our skeleton to thank.

A great analogy for the workings of our skeleton is a bridge. The strength of a bridge depends on the sizes, shapes, and proportions of its girders and cables. But also, importantly, the strength of the bridge depends on the microscopic properties of the materials from which it is made. The molecular structure of steel determines how strong it is and how far it will bend before breaking. In the same way, our skeleton's strength is based on the sizes and shapes of our bones, but also on the molecular properties of our bones themselves.

Let's go for a run to see how. As we jog along a path, our muscles contract, our back, arms, and legs move, and our feet push against the ground to move us forward. Our bones and joints function like a giant complex of levers and pulleys that make all that movement possible. Our body's movements are governed by basic physics: our ability to run is in large part based on the size, shape, and proportions of our skeleton and the configuration of our joints. At this level, we look like a big machine. And like a machine, our design matches our functions. A world-class high jumper has different bone proportions from a champion sumo wrestler. The proportions of the legs of a rabbit or a frog, specialized to hop and jump, are different from those of a horse.

Now, let's take a more microscopic view. Pop a slice of a femur under the microscope, and you will immediately see what gives bone its distinctive mechanical properties. The cells are highly organized in places, particularly on the outer rim of the bone. Some cells stick together, whereas others are separated. Between the separated cells are the materials that define the strength of bone. One of them is the rock, or crystal, known as hydroxyapatite, which we discussed in Chapter 4. Hydroxyapatite is hard the way concrete is: strong when compressed, less strong if twisted or bent. So, like a building made of bricks or concrete, bones are shaped so as to maximize their compressive functions and minimize twisting and bending, something Galileo recognized in the seventeenth century.

The other molecule found between our bone cells is the most common protein in the entire human body. If we magnify it 10,000 times with an electron microscope, we see something that looks like a rope consisting of bundles of little molecular fibers. This molecule, collagen, also has the mechanical properties of a rope. Rope is relatively strong when pulled, but it collapses when compressed; think of the two teams in a tug-of-war running toward the middle. Collagen, like rope, is strong when pulled but weak when the ends are pushed together.

Bone is composed of cells that sit in a sea of hydroxyapatite, collagen, and some other, less common molecules. Some cells stick together; other cells float inside these materials. The strength of bone is based on collagen's strength when pulled, and on hydroxyapatite's strength when compressed.

Cartilage, the other tissue in our skeleton, behaves somewhat differently. During our jog, it was the cartilage in our joints that provided the smooth surfaces where our bones glided against one another. Cartilage is a much more pliant tissue than bone; it can bend and smush as forces are applied to it. The smooth operation of the knee joint, as well as most of the other joints we used during our jog, depends on having relatively soft cartilage. When healthy cartilage is compressed it always returns to its native shape, like a kitchen sponge. During each step of our run, our entire body mass slams against the ground at some speed. Without these protective caps at our joints our bones would grind against one another: a very unpleasant and debilitating outcome of arthritis.

The pliability of cartilage is a property of its microscopic structure. The cartilage at our joints has relatively few cells, and these cells are separated by a lot of filling between them. As with bone, it is the properties of this interstitial filling that largely determine the mechanical properties of the cartilage.

Collagen fills much of the space between cartilage cells (as well as the cells of our other tissues). What really gives cartilage its pliancy is another kind of molecule, one of the most extraordinary in the whole body. This kind of molecule, called a proteoglycan complex, gives cartilage strength when squeezed or compressed. Shaped like a giant three-dimensional brush, with a long stem and lots of little branches, the proteoglycan complex is actually visible under a microscope. It has an amazing property relevant to our abilities to walk and move, thanks to the fact that the tiniest branches love to attach to water. A proteoglycan, then, is a molecule that actually swells up with water, filling up until it's like a giant piece of Jell-O. Take this piece of gelatin, wrap collagen ropes in and around it, and you end up with a substance that is both pliant and somewhat resistant to tension. This, essentially, is cartilage. A perfect pad for our joints. The role of the cartilage cells is to secrete these molecules when the animal is growing and maintain them when the animal is not.

The ratios among the various materials define much of the mechanical differences among bone, cartilage, and teeth. Teeth are very hard and, predictably, there is lots of hydroxyapatite and relatively little collagen between the cells in the enamel. Bone has relatively more collagen, less hydroxyapatite, and no enamel. Consequently, it is not as hard as teeth. Cartilage has lots of collagen and no hydroxyapatite, and is loaded with proteoglycans. It is the softest of the tissues in our skeleton. One of the main reasons our skeletons look and work as they do is that these molecules are deployed in the right places in the right proportions.

What does all this have to do with the origin of bodies? One property is common to animals, whether they have skeletons or not: all of them, including clumps of cells, have molecules that lie between their cells, specifically different kinds of collagens and proteoglycans. Collagen seems particularly important: the most common protein in animals, it makes up over 90 percent of the body's protein by weight. Bodybuilding in the distant past meant that molecules like these had to be invented.

Something else is essential for bodies: the cells in our bones have to be able to stick together and talk to one another. How do bone cells attach to one another, and how do different parts of bone know to behave differently? Here is where much of our bodybuilding kit lies.

Bone cells, like every cell in our bodies, stick to one another by means of tiny molecular rivets, of which there is a vast diversity. Some bind cells the way contact cement holds the soles of shoes together: one molecule is firmly attached to the outer membrane of one cell, another to the outer membrane of a neighboring cell. Thus attached to both cell membranes, the glue forms a stable bond between the cells.

Other molecular rivets are so precise that they bind selectively, only to the same kind of rivet. This is a hugely significant feature because it helps organize our bodies in a fundamental way. These selective rivets enable cells to organize themselves and ensure that bone cells stick to bone cells, skin to skin, and so on. They can organize our bodies in the absence of other information. If we put a number of cells, each with a different kind of this type of rivet, on a dish and let the cells grow, the cells will organize themselves. Some might form balls, others sheets, as the cells sort out by the numbers and kinds of rivets they have.

But arguably the most important connection between cells lies in the ways that they exchange information with one another. The precise pattern of our skeleton, in fact of our whole body, is possible only because cells know how to behave. Cells need to know when to divide, when to make molecules, and when to die. If, for example, bone or skin cells behaved randomly—if they divided too much or died too little—then we would be very ugly or, worse, very dead.

Cells communicate with one another using "words" written as molecules that move from cell to cell. One cell can "talk" to the next by sending molecules back and forth. For instance, in a relatively simple form of cell-to-cell communication, one cell will emit a signal, in this case a molecule. This molecule will attach to the outer covering, or membrane, of the cell receiving the signal. Once attached to the outer membrane, the molecule will set off a chain reaction of molecular events that travels from the outer membrane all the way, in many cases, to the nucleus of the cell. Remember that the genetic information sits inside the nucleus. Consequently, this molecular signal can cause genes to be turned on and off. The end result of all this is that the cell receiving the information now changes its behavior: it may die, divide, or make new molecules in response to the cue from the other cell.

At the most basic level, these are the things that make bodies possible. All animals with bodies have structural molecules like collagens and proteoglycans, all of them have the array of molecular rivets that hold cells together, and all of them have the molecular tools that allow cells to communicate with one another.

We now have a search image to understand the how of body origins. To see how bodies arose, we need to look for these molecules in the most primitive bodies on the planet, and then, ultimately, in creatures that have no body at all.

BODYBUILDING FOR BLOBS

What does the body of a professor share with a blob? Let's look at some of the most primitive bodies alive today to find the answer.

One of these creatures has the dubious distinction of almost never being seen in the wild. In the late 1880s, a strangely simple creature was discovered living on the glass walls of an aquarium. Unlike anything else alive, it looked like a mass of goo. The only thing we can compare it with is the alien creature in the Steve McQueen movie *The Blob.* Recall that the Blob was an amorphous glop that, after dropping in from outer space, engulfed its prey: dogs, people, and eventually small diners in little towns in Pennsylvania. The Blob's digestive end was on its underside: we never saw it; we only heard the shrieks of creatures caught there. Shrink the Blob down to between 200 and 1,000 cells, about two millimeters in diameter, and we have the enigmatic living creature known as a placozoan. Placozoans have only four types of cells, which make a very simple body shaped like a small plate. It is a real body, though. Some of the cells on the undersurface are specialized for digestion; others have flagella, which beat to move the creature around. We have little idea of what they eat in the wild, where they live, or what their natural habitat is. Yet these simple blobs reveal something terrifically important: with a small number of specialized cells, these primitive creatures already have a division of labor among their parts.

Much of what is interesting about bodies already exists in placozoans. They have true bodies, albeit primitively organized ones. In searching through their DNA and examining the molecules on the surface of their cells, we find that much of our bodybuilding apparatus is already there. Placozoans have versions of the molecular rivets and cell communication tools we see in our own bodies.

Our bodybuilding apparatus is found in blobs simpler than some of Reginald Sprigg's ancient impressions. Can we go further, to even more primitive kinds of bodies? Part of the answer lies in a piece of classic kitchenware: the sponge. At first glance, sponges are unremarkable. The body of a sponge consists of the sponge matrix itself; not a living material, it is a form of silica (glassy material) or calcium carbonate (a hard shell-like material) with some collagen interspersed. Right off the bat, that makes sponges interesting. Recall that collagen is a major part of our intercellular spaces, holding cells and many tissues together. Sponges may not look it, but they already have one of the earmarks of bodies.

In the early 1900s, H.V.P. Wilson showed just how amazing sponges really are. Wilson came to the University of North Carolina as its first professor of biology in 1894. There he went on to train a cadre of American biologists who were to define the field of genetics and cell biology in North America for the next century. As a young man, Wilson decided to focus his life's research on, of all things, sponges. One of his experiments revealed a truly remarkable capability of these apparently simple creatures. He ran them through a kind of sieve, which broke them down to a set of disaggregated cells. Wilson put the now completely disaggregated, amoeba-like cells in a dish and watched them. At first, they crawled around on the surface of the dish. Then, something surprising happened: the cells came together. First, they formed red cloudy balls of cells. Next, they gained more organization, with cells becoming packed in definite patterns. Finally, the clump of cells would form an entire new sponge body, with the various types of cells assuming the appropriate positions. Wilson was watching a body come together almost from scratch. If we were like sponges, then the Steve Buscemi character who gets minced in the woodchipper in the Coen brothers' movie *Fargo* would have been just fine. In fact, he might have been invigorated by the experience, as his cells might have aggregated to form many different versions of him.

It is the cells within sponges that make them useful in understanding the origin of bodies. The inside of the sponge is usually a hollow space that can be divided into compartments, depending on the species. Water flows through the space, directed by a very special kind of cell. These cells are shaped like goblets with the cup part facing the inside of the sponge. Tiny cilia extending from the rim of the goblet beat and capture food particles in the water. Also extending from the goblet part of each of these cells is a large flagellum. The concerted action of the flagella of these little beater cells moves water and food through the pores of the sponge. Other cells on the inside of the sponge process the particles of food. Still others line the outside and can contract when the sponge needs to change its shape as water currents change.

A sponge seems a far cry from a body, yet it has many of the most important properties of bodies: its cells have a division of labor; the cells can communicate with one another; and the array of cells functions as a single individual. A sponge is organized, with different kinds of cells in different places doing different things. It is a far cry from a human body with trillions of precisely packaged cells, but it shares some of the human body's features. Most significantly, the sponge has much of the cell adhesion, communication, and scaffolding apparatus that we have. Sponges are bodies, albeit very primitive and relatively disorganized ones.

Like placozoans and sponges, we have many cells. Like them, our bodies show a division of labor among parts. The whole molecular apparatus that holds bodies together is also present: the rivets that hold cells together; the various devices that help cells signal to one another; and many of the molecules that lie between cells. Like us and all other animals, placozoans and sponges even have collagen. Unlike us, they have very primitive versions of all these features: instead of twenty-one collagens, sponges have two; whereas we have hundreds of different types of molecular rivets, sponges have a small fraction of that number. Sponges are simpler than we and have fewer kinds of cells, but the basic bodybuilding apparatus is there.

Placozoans and sponges are about as simple as bodies get nowadays. To go any further, we have to search for the things that build our bodies in creatures that have no bodies at all: single-celled microbes.

How do you compare a microbe to an animal with a body? Are the tools that build bodies in animals present in single-celled creatures? If so, and if they are not building bodies, what are they doing?

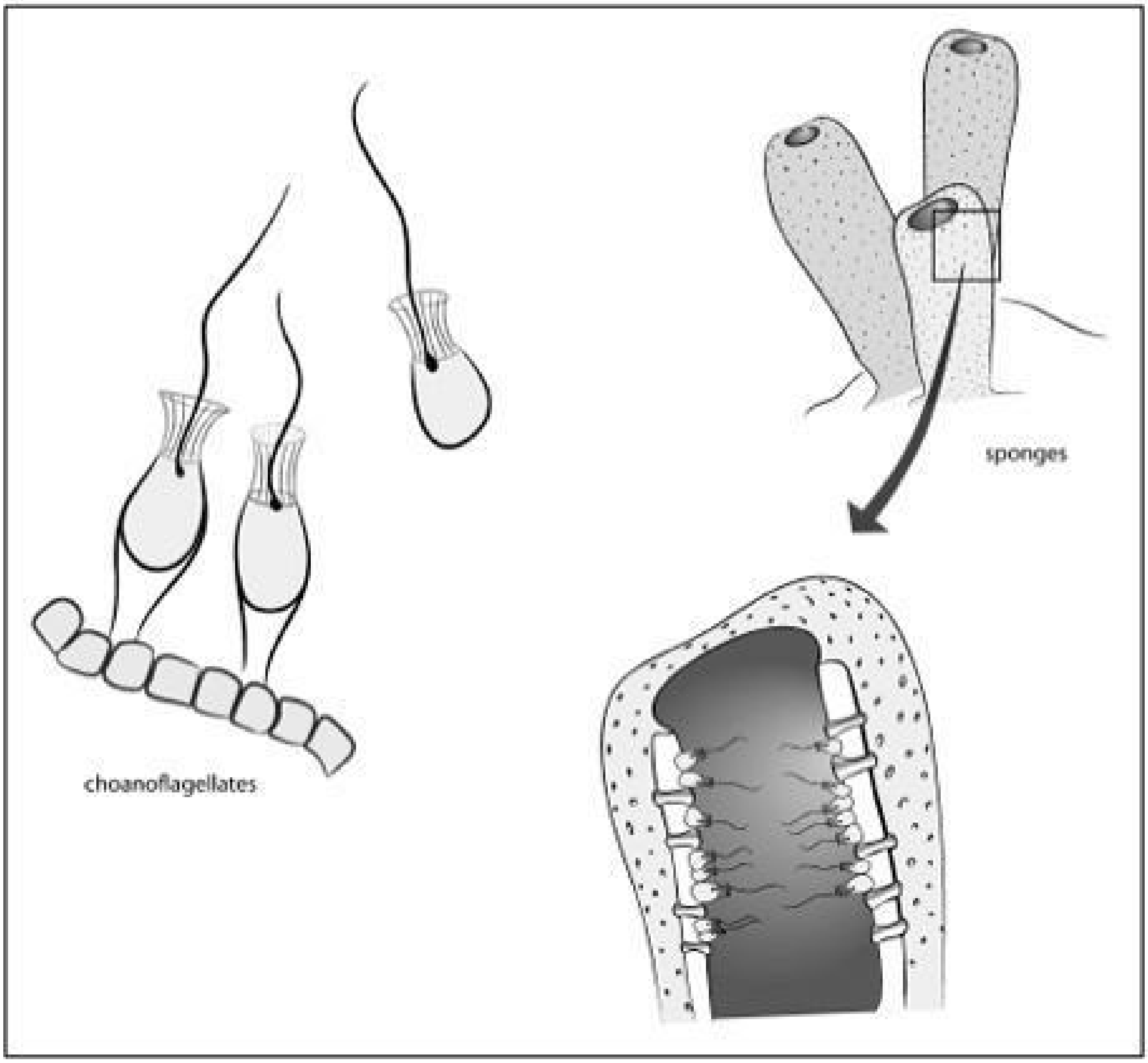
The most straightforward way to begin to answer these questions involves looking inside the genes of microbes to search for any similarities to animals. The earliest comparisons between animal and microbial genomes revealed a striking fact: in many single-celled animals, much of the molecular machinery for cell adhesion, interaction, and so on is just not there. Some analyses even suggested that more than eight hundred of these kinds of molecules are found only in animals with bodies while they are absent in single-celled creatures. This would seem to support the notion that the genes that help cells unite to make bodies arose together with the origin of bodies. And at first glance, it seems to make sense that the tools to build bodies should arise in lockstep with bodies themselves.

The story turned upside down when Nicole King, of the University of California at Berkeley, studied the organisms called choanoflagellates. King's choice of subject was no accident. From work on DNA, she knew that choanoflagellates are likely the closest microbe relatives of animals with bodies, placozoans, and sponges. She also suspected that hidden in the genes of choanoflagellates are versions of the DNA that make our bodies.

Nicole was aided in her search by the Human Genome Project, an enterprise that has succeeded in mapping all the genes in our bodies. With the success of the Human Genome Project came many other mapping studies: we've had the Rat Genome Project, the Fly Genome Project, the Bumblebee Genome Project—there are even ongoing projects to sequence the genomes of sponges, placozoans, and microbes. These maps are a gold mine of information because they enable us to compare the bodybuilding genes in many different species. They also gave Nicole the genetic tools to study her choanoflagellates.

Choanoflagellates look remarkably like the goblet-shaped cells inside a sponge. In fact, for a long time, many people thought that they were just degenerate sponges—sponges without all the other cells. If this were the case, then the DNA of choanoflagellates should resemble that of a bizarre sponge. It doesn't. When parts of the DNA of choanoflagellates were compared with microbe and sponge DNA, the similarity to microbe DNA turned out to be extraordinary. Choanoflagellates are single-celled microbes.

The genetic distinction between “single-celled microbe” and “animal with body” completely broke down thanks to Nicole’s work on choanoflagellates. Most of the genes that are active in choanoflagellates are also active in animals. In fact, many of those genes are part of the machinery that builds bodies. A few examples reveal the power of this comparison. Functions of cell adhesion and cell communication, even parts of the molecules that form the matrix between cells and the molecular cascades that ferry a signal from outside the cell to the inside—all are present in choanoflagellates. Collagens are present in choanoflagellates. The various kinds of molecular rivets that hold cells together are also present in choanoflagellates, although they are doing slightly different jobs.



Choanoflagellates (left) and sponges (right).

Choanoflagellates even give Nicole a road map for comparing our bodybuilding apparatus to that of other microbes. The fundamental molecular structure that makes collagens and proteoglycan aggregates is known from a number of different kind of microbes. *Streptococcus* bacteria—common in our mouths (and, one hopes, rare in other places)—have on their cell surface a molecule that is very similar to collagen. It has the same molecular signature, but does not aggregate to form ropes or sheets as collagens do in animals. Likewise, some of the sugars that make up proteoglycan complexes inside our cartilage are seen in the walls of different kinds of bacteria. Their functions in both viruses and bacteria are not particularly pleasant. They are associated with the ways that these agents invade and infect cells and, in many cases, become more virulent. Many of the molecules that microbes use to cause us misery are primitive versions of the molecules that make our own bodies possible.

This sets up a puzzle. In the fossil record, we see nothing but microbes for the first 3.5 billion years of earth history. Then, suddenly, over a span of perhaps 40 million years, all kinds of bodies appear: plant bodies, fungal bodies, animal bodies; bodies everywhere. Bodies were a real fad. But, if you take Nicole's work at face value, the potential to build bodies was in place well before bodies ever hit the scene. Why the rush for bodies after such a very long time with no bodies at all?

A PERFECT STORM IN THE ORIGIN OF BODIES

Timing is everything. The best ideas, inventions, and concepts don't always win. How many musicians, inventors, and artists were so far ahead of their time that they flopped and were forgotten, only to be rediscovered later? We need look no further than poor Heron of Alexandria, who, perhaps in the first century a.d., invented the steam turbine. Unfortunately, it was regarded as a toy. The world wasn't ready for it.

The history of life works the same way. There is a moment for everything, perhaps even for bodies. To see this, we need to understand why bodies might have come about in the first place.

One theory about this is extremely simple: Perhaps bodies arose when microbes developed new ways to eat each other or avoid being eaten? Having a body with many cells allows creatures to get big. Getting big is often a very good way to avoid being eaten. Bodies may have arisen as just that kind of defense.

When predators develop new ways of eating, prey develop new ways of avoiding that fate. This interplay may have led to the origin of many of our bodybuilding molecules. Many microbes feed by attaching and engulfing other microbes. The molecules that allow microbes to catch their prey and hold on to them are likely candidates for the molecules that form the rivet attachments between cells in our bodies. Some microbes can actually communicate with each other by making compounds that influence the behavior of other microbes. Predator-prey interactions between microbes often involve molecular cues, either to ward off potential predators or to serve as lures enticing prey to come close. Perhaps signals like these were precursors to the kinds of signals that our own cells use to exchange information to keep our bodies intact.

We could speculate on this ad infinitum, but more exciting would be some tangible experimental evidence that shows how predation could bring about bodies. That is essentially what Martin Boraas and his colleagues provided. They took an alga that is normally single-celled and let it live in the lab for over a thousand generations. Then they introduced a predator: a single-celled creature with a flagellum that engulfs other microbes to ingest them. In less than two hundred generations, the alga responded by becoming a clump of hundreds of cells; over time, the number of cells dropped until there were only eight in each clump. Eight turned out to be the optimum because it made clumps large enough to avoid being eaten but small enough so that each cell could pick up light to survive. The most surprising thing happened when the predator was removed: the algae continued to reproduce and form individuals with eight cells. In short, a simple version of a multicellular form had arisen from a no-body.

If an experiment can produce a simple body-like organization from a no-body in several years, imagine what could happen in billions of years. The question then becomes not how could bodies arise, but why didn't they arise sooner?

Answers to this puzzle might lie in the ancient environment in which bodies arose: the world may not have been ready for bodies.

A body is a very expensive thing to have. There are obvious advantages of becoming a creature with a large body: besides avoiding predators, animals with bodies can eat other, smaller creatures and actively move long distances. Both of these abilities allow the animals to have more control over their environment. But both consume a lot of energy. Bodies require even more energy as they get larger, particularly if they incorporate collagen. Collagen requires a relatively large amount of oxygen for its synthesis and would have greatly increased our ancestors' need for this important metabolic element.

But the problem was this: levels of oxygen on the ancient earth were very low. For billions of years oxygen levels in the atmosphere did not come close to what we have today. Then, roughly a billion years ago, the amount of oxygen increased dramatically and has stayed relatively high ever since. How do we know this? From the chemistry of rocks. Rocks from about a billion years ago show the telltale signature of having been formed with increasing amounts of oxygen. Could the rise in oxygen in the atmosphere be linked to the origin of bodies?

It may have taken the paleontological equivalent of a perfect storm to bring about bodies. For billions of years, microbes developed new ways of interacting with their environment and with one another. In doing so, they hit on a number of the molecular parts and tools to build bodies, though they used them for other purposes. A cause for the origin of bodies was also in place: by a billion years ago, microbes had learned to eat each other. There was a reason to build bodies, and the tools to do so were already there.

Something was missing. That something was enough oxygen on the earth to support bodies. When the earth's oxygen increased, bodies appeared everywhere. Life would never be the same.