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

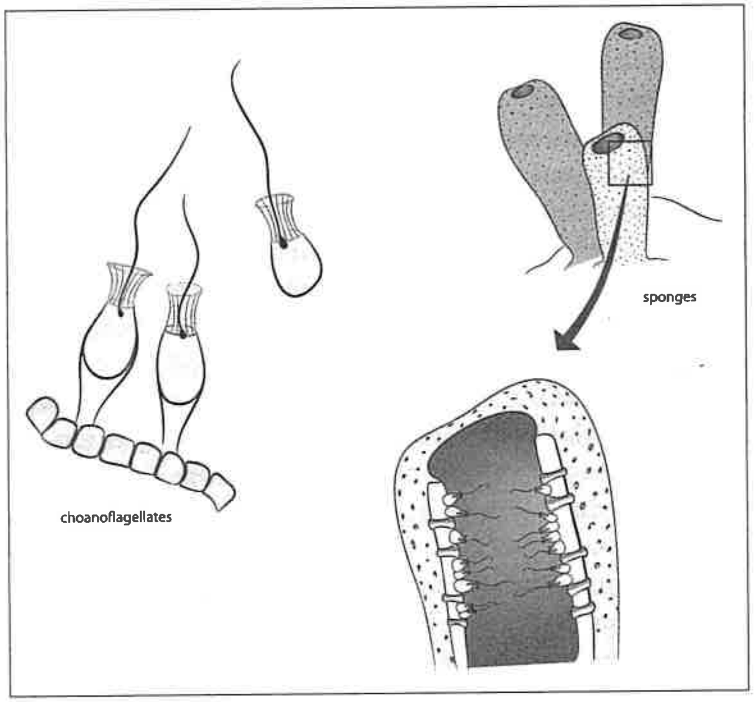
together with the origin of bodies. And at first glance, it seems to make sense that the tools to build bodies should arise in lockstep with bodies themselves.

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 exam-



Choanoflagellates (left) and sponges (right).

ples 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 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.

CHAPTER EIGHT

MAKING SCENTS

In the early 1980s, there was tension between molecular biologists and people who worked on whole organisms—ecologists, anatomists, and paleontologists. Anatomists, for example, were seen as quaintly out-of-date, hopelessly entranced by an antiquated kind of science. Molecular biology was revolutionizing our approach to anatomy and developmental biology, so much so that the classical disciplines, such as paleontology, seemed to be dead ends in the history of biology. I was made to feel that, because of my love of fossils, I was going to be replaced by one of those new automated DNA sequencers.

Twenty years later, I'm still digging in the dirt and cracking rocks. I'm also collecting DNA and looking at its role in development. Debates usually begin as either-or scenarios. Over time, all-or-nothing positions give way to a more realistic approach. Fossils and the geological record remain a very powerful source of evidence about the past; nothing else reveals the actual environments and transitional structures that existed during the history of life. As we've seen, DNA is an extraordinarily powerful window into life's history and the formation of bodies and organs. Its role is particularly important where the fossil record is silent. Large parts of bodies—soft tissues, for example—simply do not fossilize readily. In these cases, the DNA record is virtually all we have.

Extracting DNA from bodies is incredibly easy, so easy you can do it in your kitchen. Take a handful of tissue from some plant