CHAPTER FOUR

TEETH EVERYWHERE

The tooth gets short shrift in anatomy class: we spend all of five minutes on it. In the pantheon of favorite organs—I'll leave it to each of you to make your list—teeth rarely reach the top five. Yet the little tooth contains so much of our connection to the rest of life that it is virtually impossible to understand our bodies without knowing teeth. Teeth also have special significance for me, because it was in searching for them that I first learned how to find fossils and how to run a fossil expedition.

The job of teeth is to make bigger creatures into smaller pieces. When attached to a moving jaw, teeth slice, dice, and macerate. Mouths are only so big, and teeth enable creatures to eat things that are bigger than their mouths. This is particularly true of creatures that do not have hands or claws that can shred or cut things before they get to the mouth. True, big fish tend to eat littler fish. But teeth can be the great equalizer: smaller fish can munch on bigger fish if they have good teeth. Smaller fish can use their teeth to scrape scales, feed on particles, or take out whole chunks of flesh from bigger fish.

We can learn a lot about an animal by looking at its teeth. The bumps, pits, and ridges on teeth often reflect the diet. Carnivores, such as cats, have blade-like molars to cut meat, while plant eaters have a mouth full of flatter teeth that can macerate leaves and nuts. The informational value of teeth was not lost on the anatomists of history. The French anatomist Georges Cuvier once famously boasted that he could reconstruct an animal's entire skeleton from a single tooth. This is a little over the top, but the general point is valid; teeth are a powerful window into an animal's lifestyle.

Human mouths reveal that we are all-purpose eaters, for we have several kinds of teeth. Our front teeth, the incisors, are flat blades specialized for cutting. The rearmost teeth, the molars, are flatter, with a distinctive pattern that can macerate plant or animal tissue. The premolars, in between, are intermediate in function between incisors and molars.

The most remarkable thing about our mouths is the precision with which we chew. Open and close your mouth: your teeth always come together in the same position, with upper and lower teeth fitting together precisely. Because the upper and lower cusps, basins, and ridges match closely, we are able to break up food with maximal efficiency. In fact, a mismatch between upper and lower teeth can shatter our teeth, and enrich our dentists.

Paleontologists find teeth wonderfully informative. Teeth are the hardest parts of our bodies, because the enamel includes a high proportion of the mineral hydroxyapatite—

higher even than is found in bones. Thanks to their hardness, teeth are often the best-preserved animal part we find in the fossil record for many time periods. This is lucky; since teeth are such a great clue to an animal's diet, the fossil record can give us a good window on how different ways of feeding came about. This is particularly true of mammal history: whereas many reptiles have similar teeth, those of mammals are distinctive. The mammal section of a typical paleontology course feels almost like Dentistry 101.

Living reptiles—crocodiles, lizards, snakes—lack much of what makes mammalian mouths unique. A crocodile's teeth, for example, all have a similar blade-like shape; the only difference between them is that some are big and others small. Reptiles also lack the precise occlusion—the fit between upper and lower teeth—that humans and other mammals have. Also, whereas we mammals replace our teeth only once, reptiles typically receive visits from the tooth fairy for their entire lives, replacing their teeth continually as they wear and break down.

A very basic piece of us—our mammalian way of precise chewing—emerges in the fossil record from around the world that ranges from 225 million to 195 million years ago. At the base, in the older rocks, we find a number of reptiles that look superficially dog-like. Walking on four legs, they have big skulls, and many of them have sharp teeth. There the resemblance stops. Unlike dogs, these reptiles have a jaw made up of many bones, and their teeth don't really fit well together. Also, their teeth are replaced in a decidedly reptilian way: new teeth pop in and out throughout the animals' lives.

Go higher in the rocks and we see something utterly different: the appearance of mammalness. The bones of the jaw get smaller and move to the ear. We can see the first evidence of upper and lower teeth coming together in precise ways. The jaw's shape changes, too: what was a simple rod in reptiles looks more like a boomerang in mammals. At this time, too, teeth are replaced only once per lifetime, as in us. We can trace all these changes in the fossil record, especially from certain sites in Europe, South Africa, and China.

The rocks of about 200 million years ago contain rodent-like creatures, such as *Morganucodon* and *Eozostrodon,* that have begun to look like mammals. These animals, no bigger than a mouse, hold important pieces of us inside. Pictures cannot convey just how wonderful these early mammals are. For me, it was a real thrill to see creatures like them for the first time.

When I entered graduate school, I wanted to study early mammals. I chose Harvard because Farish A. Jenkins, Jr., whom we met in the first chapter, was leading expeditions to the American West that systematically scoured the rocks for signs of how mammals developed their distinct abilities to chew. The work was real exploration; Farish and his team were looking for new localities and sites, not returning to places other people had discovered. Farish had assembled a talented group of fossil finders comprising staff from Harvard's Museum of Comparative Zoology and a few free-lance mercenaries. Chief among them were Bill Amaral, Chuck Schaff, and the late Will Downs. These people were my introduction to the world of paleontology.

Farish and the team had studied geological maps and aerial photos to choose promising areas where they might find early mammals. Then, each summer, they got in their trucks and headed off into the deserts of Wyoming, Arizona, and Utah. By the time I joined them, in 1983, they had already found a number of important new mammals and fossil sites. I was struck by the power of predictions: simply by reading scientific articles and books, Farish's team could identify likely and unlikely places to find early mammals.

My baptism in field paleontology came from walking out in the Arizona desert with Chuck and Bill. At first, the whole enterprise seemed utterly random. I expected something akin to a military campaign, an organized and coordinated reconnaissance of the area. What I saw looked like the extreme opposite. The team would plunk down on a particular patch of rock, and people would scatter in every conceivable direction to look for fragments of bone on the surface. For the first few weeks of the expedition, they left me alone. I'd set off looking for fossils, systematically inspecting every rock I saw for a scrap of bone at the surface. At the end of each day we would come home to show off the goodies we found. Chuck would have several bags of bones. Bill would have his complement, usually with some sort of little skull or other prize. And I had nothing, my empty bag a sad reminder of how much I had to learn.

After a few weeks of this, I decided it would be a good idea to walk with Chuck. He seemed to have the fullest bags each day, so why not take some cues from the expert? Chuck was happy to walk with me and expound on his long career in field paleontology. Chuck is all West Texas with a Brooklyn flourish: cowboy boots and western values with a New York accent. While he regaled me with tales of his past expeditions, I found the whole experience utterly humbling. First, Chuck did not look at every rock, and when he chose one to look at, for the life of me I couldn't figure out why. Then there was the really embarrassing aspect of all this: Chuck and I would look at the same patch of ground. I saw nothing but rock—barren desert floor. Chuck saw fossil teeth, jaws, and even chunks of skull.

An aerial view would have shown two people walking alone in the middle of a seemingly limitless plain, where the vista of dusty red and green sandstone mesas, buttes, and badlands extended for miles. But Chuck and I were staring only at the ground, at the rubble and talus of the desert floor. The fossils we sought were tiny, no more than a few inches long, and ours was a very small world. This intimate environment stood in extreme contrast to the vastness of the desert panorama that surrounded us. I felt as if my walking partner was the only person on the entire planet, and my whole existence was focused on pieces of rubble.

Chuck was extraordinarily patient with me as I pestered him with questions for the better part of each day's walk. I wanted him to describe *exactly* how to find bones. Over and over, he told me to look for "something different," something that had the texture of bone not rock, something that glistened like teeth, something that looked like an arm bone, not a piece of sandstone. It sounded easy, but I couldn't grasp what he was telling me. Try as I might, I still returned home each day empty-handed. Now it was even more embarrassing, as Chuck, who was looking at the same rocks, came home with bag after bag.

Finally, one day, I saw my first piece of tooth glistening in the desert sun. It was sitting in some sandstone rubble, but there it was, as plain as day. The enamel had a sheen that no other rock had; it was like nothing I had seen before. Well, not exactly—I was looking at things like it every day. The difference was this time I finally saw it, saw the distinction between rock and bone. The tooth glistened, and when I saw it glisten I spotted its cusps. The whole isolated tooth was about the size of a dime, not including the roots that projected from its base. To me, it was as glorious as the biggest dinosaur in the halls of any museum.

All of a sudden, the desert floor exploded with bone; where once I had seen only rock, now I was seeing little bits and pieces of fossil everywhere, as if I were wearing a special new pair of glasses and a spotlight was shining on all the different pieces of bone. Next to the tooth were small fragments of other bones, then more teeth. I was looking at a jaw that had weathered out on the surface and fragmented. I started to return home with my own little bags each night.

Now that I could finally see bones for myself, what once seemed a haphazard group effort started to look decidedly ordered. People weren't just scattering randomly across the desert; there were real though unspoken rules. Rule number one: go to the most productive-looking rocks, judging by whatever search image or visual cues you've gained from previous experience. Rule number two: don't follow in anybody's footsteps; cover new ground (Chuck had graciously let me break this one). Rule three: if your plum area already has somebody on it, find a new plum, or search a less promising site. First come, first served.

Over time, I began to learn the visual cues for other kinds of bones: long bones, jawbones, and skull parts. Once you see these things you never lose the ability to find them. Just as a great fisherman can read the water and see the fish within, so a fossil finder uses a catalogue of search images that make fossils seem to jump out from the rocks. I was beginning to gain my own visual impressions of what fossil bones look like in different rocks and in different lighting conditions. Finding fossils in the morning sun is very different from finding them in the afternoon, because of the way the light plays along the ground.

Twenty years later, I know that I must go through a similar experience every time I look for fossils someplace new, from the Triassic of Morocco to the Devonian of Ellesmere Island. I'll struggle for the first few days, almost as I did those days with Chuck in Arizona twenty years ago.

The difference is that now I have some confidence that a search image will kick in eventually.

The whole goal of the prospecting I did with Chuck was to find a site with enough bones to mark a fossil-rich layer that we could expose. By the time I joined the crew, Farish's team had already discovered such a zone, a patch of rock about a hundred feet long that contained skeleton after skeleton of small animals.

Farish's fossil quarry was in some very fine-grained mudstone. The trick to working on it was to realize that the fossils were coming from one thin layer, no more than a millimeter thick. Once you exposed that surface, you had a very good chance of seeing bones. They were tiny, no more than an inch or two long, and black, so they looked almost like black smudges against the brownish rock. The little animals we found included frogs (some of the earliest), legless amphibians, lizards and other reptiles, and, importantly, some of the earliest mammals.

The key point is that the early mammals were small. Very small. Their teeth were not much more than 2 millimeters long. To spot them, you had to be very careful and, more often, very lucky. If the tooth was covered by a crumb of rock or even by a few grains of sand, you might never see it.

It was the sight of these early mammals that really hooked me. I'd expose the fossil layer, then scan the entire surface through my 10-power hand lens. I'd scrutinize the whole thing on my hands and knees, with my eye and hand lens only about two inches from the surface of the ground.

Thus engrossed, I'd often forget where I was and accidentally trespass on my neighbor's spot only to have a bag of dirt dumped on my head as a sharp reminder to keep to my space. Occasionally, though, I'd hit the jackpot and see a deep connection for the first time. The teeth would look like little blades, with cusps and roots. The cusps on those little teeth revealed something very special. Each tooth had a characteristic pattern of wear at the face where upper and lower teeth fit together. I was seeing some of the first evidence of our pattern of precise chewing, only in a tiny mammal 190 million years old.

The power of those moments was something I'll never forget. Here, cracking rocks in the dirt, I was discovering objects that could change the way people think. That juxtaposition between the most child-like, even humbling, activities and one of the great human intellectual aspirations has never been lost on me. I try to remind myself of it each time I dig somewhere new.

Returning to school that fall, I developed the expedition bug big-time. I wanted to lead my own expedition but lacked the resources to do anything big, so I set off to explore rocks in Connecticut that were about 200 million years old. Well studied during the nineteenth century, they had been the setting for a number of important fossil discoveries. I figured that if I hit those same rocks with my hand lens and my wonderfully successful early mammal search image, I'd find lots of goodies. I rented a minivan, grabbed a case of collecting bags, and set off.

Yet another lesson learned: I found nothing. Back to the drawing board, or more precisely, the geology library at school.

I needed a place where 200-million-year-old rocks were well exposed: in Connecticut there were only roadcuts. The ideal place would be along the coast, where wave action would provide lots of freshly broken rock surface to look at. Looking at a map made my choice clear: up in Nova Scotia, Triassic and Jurassic rocks (roughly 200 million years old) lay along the surface. To top it off, the tourist literature about the area advertised the world's highest tides, occasionally over fifty feet. I couldn't believe my luck.

I called the expert on these rocks, Paul Olsen, who had just started teaching at Columbia University. If I was excited about fossil-finding prospects before I talked to Paul, I was frothing afterward. He described the perfect geology for finding small mammals or reptiles: ancient streams and dunes that had just the right properties to preserve tiny bones. Even better, he had already found some dinosaur bones and footprints along a stretch of beach near the town of Parrsboro, Nova Scotia. Paul and I hatched a plan to visit Parrsboro together and scan the beach for little fossils. This was wonderfully generous on Paul's part because he had dibs on the area and was under no responsibility to help me out, let alone collaborate.

I consulted with Farish on my emerging plans, and he not only offered money but suggested that I take the fossil-finding experts, Bill and Chuck. Money, Bill, Chuck, Paul

Olsen, excellent rocks, and decent exposures—what more could you want? The following summer, I led my very first fossil expedition.

Off I went in a rented station wagon to the beaches of Nova Scotia with my field crew, Bill and Chuck. The joke, of course, was on me. With Bill and Chuck along, who between them had more years of field experience than I had birthdays, I was the leader in name only. They called the fossil-finding shots, while I paid the dinner bills.

The rocks in Nova Scotia were exposed in absolutely gorgeous orange sandstone cliffs along the Bay of Fundy. The tides would go in and out about half a mile each day, exposing enormous flats of orange bedrock. It wasn't long before we started to find bones in many different areas. Small white flecks of bone were coming out along the cliffs. Paul was finding footprints everywhere, even in the flats opened by the moving tides each day.

Paul Olsen finding footprints in the tidal flats of Nova Scotia. At high tide, the water would come all the way to the cliffs at left. The arrowhead points to a spot where, if we timed our trip wrong, we would be stuck on the cliffs for hours at a time. Photograph by the author.

Chuck, Bill, Paul, and I spent two weeks digging in Nova Scotia, finding bits, flakes, and fragments of bones sticking out of the rocks. Bill, being the fossil preparator of the group, continually warned me not to expose much of the bones in the field but rather to wrap them up still covered in sandstone so that he could trace the bones in the laboratory under a microscope in more controlled conditions. We did this, but I'll admit to being disappointed with what we brought home: just a few shoeboxes of rocks, with small chips and flakes of bones showing. As we drove home, I recall thinking that even though we hadn't found much, it had been a great experience. Then I took a week's vacation; Chuck and Bill returned to the lab.

When I returned to Boston, Chuck and Bill were out to lunch. Some colleagues were visiting the museum and, having caught sight of me, came up to shake my hand, offer congratulations, and slap me on the back. I was being treated like a conquering hero, but I had no idea why; it seemed like a bizarre joke, as if they were setting me up for some big con. They told me to go to Bill's lab to see my trophy. Not knowing what to think, I ran.

Under Bill's microscope was a tiny jaw, not more than half an inch long. In it were a few minute teeth. The jaw's owner was clearly a reptile, because the teeth had only a single root at the base, whereas mammal teeth have many. But on the teeth were tiny bumps and ridges that I could see even with the naked eye. Looking at the teeth under the microscope gave me the biggest surprise: the cusps had little patches of wear. This was a reptile with tooth-to-tooth occlusion. My fossil was part mammal, part reptile.

Unbeknownst to me, Bill had unwrapped one of our blocks of rock, seen a fleck of bone, and prepared it with a needle under the microscope. None of us had known it in the field, but our expedition was a huge success. All because of Bill.

What did I learn that summer? First, I learned to listen to Chuck and Bill. Second, I learned that many of the biggest discoveries happen in the hands of fossil preparators, not in the field. As it turned out, my biggest lessons about fieldwork were yet to come.

The reptile Bill had found was a tritheledont, a creature known from South Africa as well as now from Nova Scotia. These were very rare, so we wanted to return to Nova Scotia the next summer to find more. I spent the whole winter tense with anticipation. If I could have chipped through the winter ice to find fossils, I would have done it.

In the summer of 1985, we returned to the site where we had found the tritheledont. The fossil bed was just at beach level, where a little piece of the cliff had fallen off several years before. We had to time our daily visit just so: the site was inaccessible at high tide because the water came up too high around a point we had to navigate. I'll never forget that first day of excitement when we rounded the point to find our little patch of bright orange rock. The experience was memorable for what was missing: most of the area we had worked the year before. It had weathered away the previous winter. Our lovely fossil site, containing beautiful tritheledonts, was gone with the tides.

The good news, if you could call it that, was that there was a little more orange sandstone to scan along the beach. Most of the beach, in particular the point we had to go around each morning, was made up of basalt from a 200-million-year-old lava flow. We were positive no fossils could be found there, for it is virtually axiomatic that these rocks, which were once super hot, would never preserve fossil bone. We spent five or more days timing our visits to the sites by the tides, pawing away at the orange sandstones beyond it, and finding absolutely nothing.

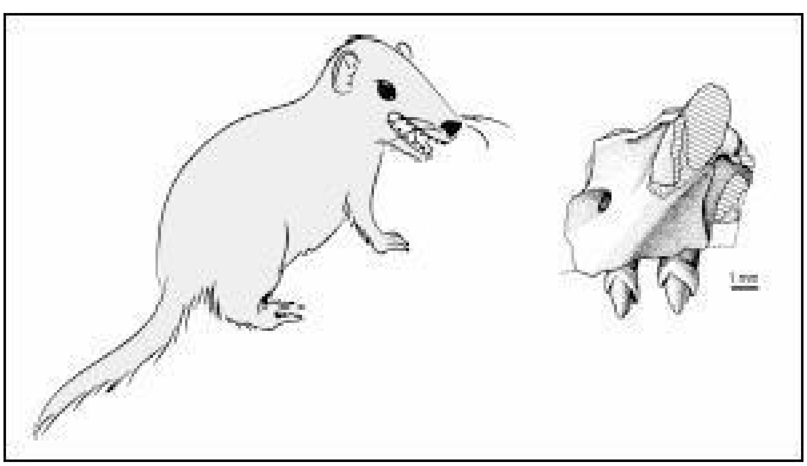
Our breakthrough came when the president of the local Lions Club came by our cabin one night looking for judges for the local beauty contest, to crown Parrsboro's Miss Old Home Week. The town always relied on visitors for this onerous task, because internecine passions typically run high during the event. The usual judges, an elderly couple from Quebec, were not visiting this year, and the crew and I were invited to substitute.

But in judging the beauty contest and arguing over its conclusion, we stayed up way too late, forgot about the next morning's tides, and ended up trapped around a bend in the basalt cliffs. For about two hours, we were stuck on a little promontory about fifty feet wide. The rock was volcanic and not the type one would ever choose to search for fossils. We skipped stones until we got bored, then we looked at the rocks: maybe we'd find interesting crystals or minerals. Bill disappeared around a corner, and I looked at some of the basalt behind us. After about fifteen minutes I heard my name. I'll never forget Bill's understated tone: "Uh, Neil, you might want to come over here." As I rounded the corner, I saw the excitement in Bill's eyes. Then I saw the rocks at his feet. Sticking out of the rocks were small white fragments. Fossil bones, thousands of them.

This was exactly what we were looking for, a site with small bones. It turned out that the volcanic rocks were not entirely volcanic: slivers of sandstone cut through the cliff. The rocks had been produced by an ancient mudflow associated with a volcanic eruption. The fossils were stuck in the ancient muds.

We brought tons of these rocks home. Inside were more tritheledonts, some primitive crocodiles, and other lizard-like reptiles. The tritheledonts were the gems, of course, because they showed that some kinds of reptiles already displayed our mammalian kind of chewing.

Early mammals, such as those Farish's team uncovered in Arizona, had very precise patterns of biting. Scrapes on the cusps of an upper tooth fit against mirror images of these scrapes on a lower tooth. These patterns of wear are so fine that different species of early mammals can be distinguished by their patterns of tooth wear and occlusion. Farish's Arizona mammals have a different pattern of cusps and chewing than those of the same age from South America, Europe, or China. If all we had to compare these fossils to were living reptiles, then the origin of mammalian feeding would appear to be a big mystery. As I've mentioned, crocodiles and lizards do not have any kind of matching pattern of occlusion. Here is where creatures like tritheledonts come in. When we go back in time, to rocks about 10 million years older, such as those in Nova Scotia, we find tritheledonts with an incipient version of this way of chewing. In tritheledonts, individual cusps do not interlock in a precise way, as they do in mammals; instead, the entire inner surface of the upper tooth shears against the outer surface of the lower tooth, almost like a scissors. Of course, these changes in occlusion did not happen in a vacuum. It should come as no surprise that the earliest creatures to show a mammalian kind of chewing also display mammalian features of the lower jaw, skull, and skeleton.



A tritheledont and a piece of its upper jaw discovered in Nova Scotia. Jaw fragment illustrated by Lazlo Meszoley.

Because teeth preserve so well in the fossil record, we have very detailed information about how major patterns of chewing—and the ability to use new diets—arose over time. Much of the story of mammals is the story of new ways of processing food. Soon after we encounter tritheledonts in the fossil record, we start seeing all sorts of new mammal species with new kinds of teeth, as well as new ways of occluding and using them. By about 150 million years ago, in rocks from around the world, we find small rodent-size mammals with a new kind of tooth row, one that paved the way for our own existence. What made these creatures special was the complexity of their mouths: the jaw had different kinds of teeth set in it. The mouth developed a kind of division of labor. Incisors in the front became specialized to cut food, canines further back to puncture it, and molars in the extreme back to shear or mash it. These little mammals, which resemble mice, have a fundamental piece of our history inside of them. If you doubt this, imagine eating an apple lacking your incisor teeth or, better yet, a large carrot with no molars. Our diverse diet, ranging from fruit to meat to Twinkie, is possible only because our distant mammalian ancestors developed a mouth with different kinds of teeth that can occlude precisely. And yes, initial stages of this are seen in tritheledonts and other ancient relatives: the teeth in the front have a different pattern of blades and cusps than those in the back.

TEETH AND BONES—THE HARD STUFF

It almost goes without saying that what makes teeth special among organs is their hardness. Teeth have to be harder than the bits of food they break down; imagine trying to cut a steak with a sponge. In many ways, teeth are as hard as rocks, and the reason is that they contain a crystal molecule on the inside. That molecule, known as hydroxyapatite, impregnates the molecular and cellular infrastructure of both teeth and bones, making them resistant to bending, compression, and other stresses. Teeth are extra hard because their outer layer, enamel, is far richer in hydroxyapatite than any other structure in the body, including bone. Enamel gives teeth their white sheen. Of course, enamel is only one of the layers that make up our teeth. The inner layers, such as the pulp and dentine, are also filled with hydroxyapatite.

There are lots of creatures with hard tissues—clams and lobsters, for example. But they do not use hydroxyapatite; lobsters and clams use other materials, such as calcium carbonate or chitin. Also, unlike us, these animals have an exoskeleton covering the body. Our hardness lies within.

Our particular brand of hardness, with teeth inside our mouths and bones inside our bodies, is an essential part of who we are. We can eat, move about, breathe, even metabolize certain minerals because of our hydroxyapatite-containing tissues. For these capabilities, we can thank the common ancestor we share with all fish. Every fish, amphibian, reptile, bird, and mammal on the planet is like us. All of them have hydroxyapatite-containing structures. But where did this all come from?

There is an important intellectual issue at stake here. By knowing where, when, and how hard bones and teeth came about, we will be in a position to understand why. Why did our kind of hard tissues arise? Did they come about to protect animals from their environment? Did they come about to help them move? Answers to these questions lie in the fossil record, in rocks approximately 500 million years old.

Some of the most common fossils in ancient oceans, 500 million to 250 million years old, are conodonts. Conodonts were discovered in the 1830s by the Russian biologist Christian Pander, who will reappear in a few chapters. They are small shelly organisms with a series of spikes projecting out of them. Since Pander's time, conodonts have been discovered on every continent; there are places where you cannot crack a rock without finding vast numbers of them. Hundreds of kinds of conodonts are known.

For a long time, conodonts were enigmas: scientists disagreed over whether they were animal, vegetable, or mineral. Everybody seemed to have a pet theory. Conodonts were claimed to be pieces of clams, sponges, vertebrates, even worms. The speculation ended when whole animals started to show up in the fossil record.

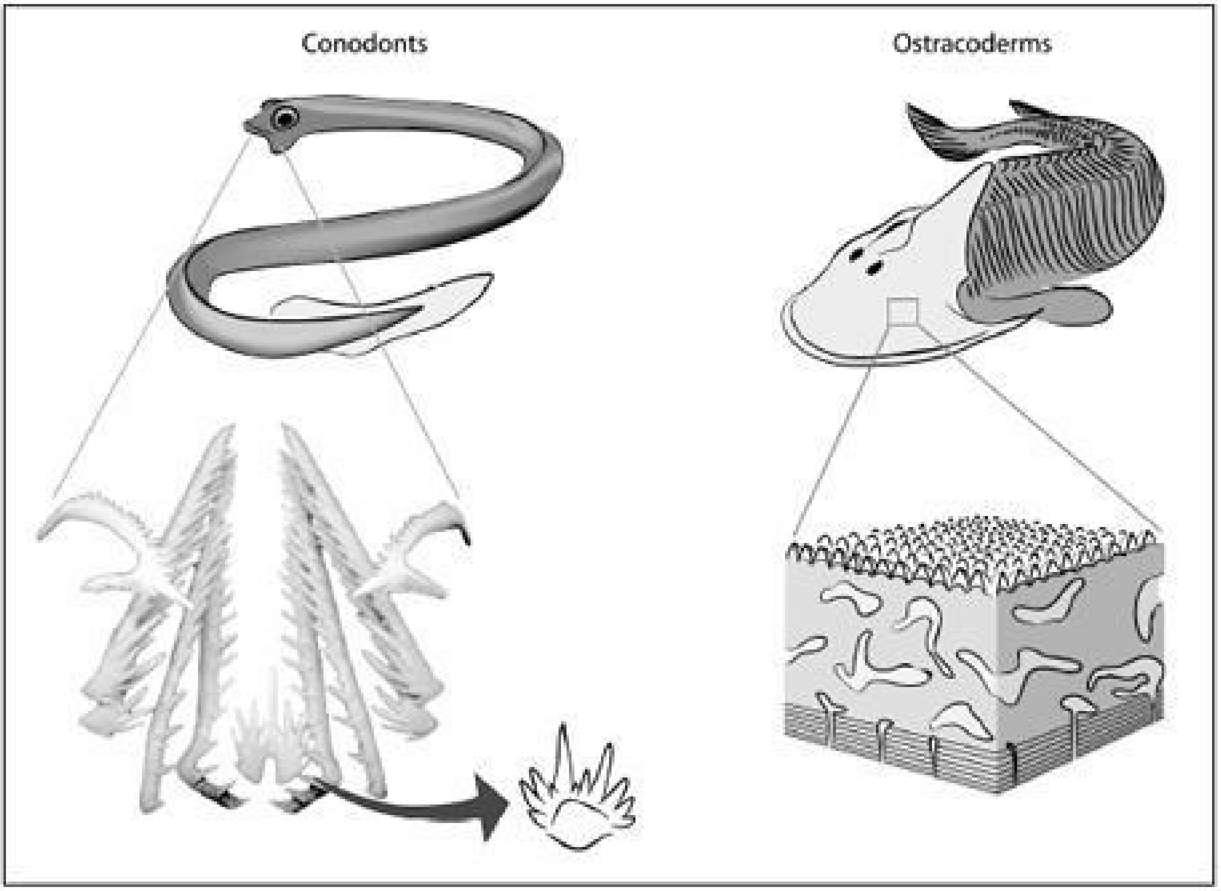
The first specimen that made sense of everything was found by a professor of paleontology rummaging through the basement at the University of Edinburgh: there was a slab of rock with what looked like a lamprey in it. You might recall lampreys from biology class—these are very primitive fish that have no jaws. They make their living by attaching to other fish and feeding on their bodily fluids. Embedded in the front of the lamprey impression were small fossils that looked strangely familiar. Conodonts. Other lamprey-like fossils started to come out of rocks in South Africa and later the western United States. These creatures all had an exceptional trait: they had whole assemblages of conodonts in their mouths. The conclusion became abundantly clear: conodonts were teeth. And not just any teeth. Conodonts were the teeth of an ancient jawless fish.

We had the earliest teeth in the fossil record for over 150 years before we realized what they were. The reason comes down to how fossils are preserved. The hard bits, for example teeth, tend to get preserved easily. Soft parts, such as muscle, skin, and guts, usually decay without fossilizing. We have museum cabinets full of fossil skeletons, shells, and teeth, but precious few guts and brains. On the rare occasions when we find evidence of soft tissues, they are typically preserved only as impressions or casts. Our fossil record is loaded with conodont teeth, but it took us 150 years to find the bodies. There is something else remarkable about the bodies to which conodonts belonged. They have no hard bones. These were soft-bodied animals with hard teeth.

For years, paleontologists have argued about why hard skeletons, those containing hydroxyapatite, arose in the first place. For those who believed that skeletons began with jaws, backbones, or body armor, conodonts provide an "inconvenient tooth," if you will. The first hard hydroxyapatite-containing body parts were teeth. Hard bones arose not to protect animals, but to eat them. With this, the fish-eat-fish world really began in earnest. First, big fish ate little fish; then, an arms race began. Little fish developed armor, big fish obtained bigger jaws to crack the armor, and so on. Teeth and bones really changed the competitive landscape.

Things get more interesting still as we look at some of the first animals with bony heads. As we move up in time from the earliest conodont animals, we see what the first bony-head skeletons looked like. They belonged to fish called ostracoderms, are about 500 million years old, and are found in rocks all over the world, from the Arctic to Bolivia. These fish look like hamburgers with fleshy tails.

The head region of an ostracoderm is a big disk covered by a shield of bone, looking almost like armor. If I were to open a museum drawer and show you one, you would immediately notice something odd: the head skeleton is really shiny, much like our teeth or the scales of a fish.



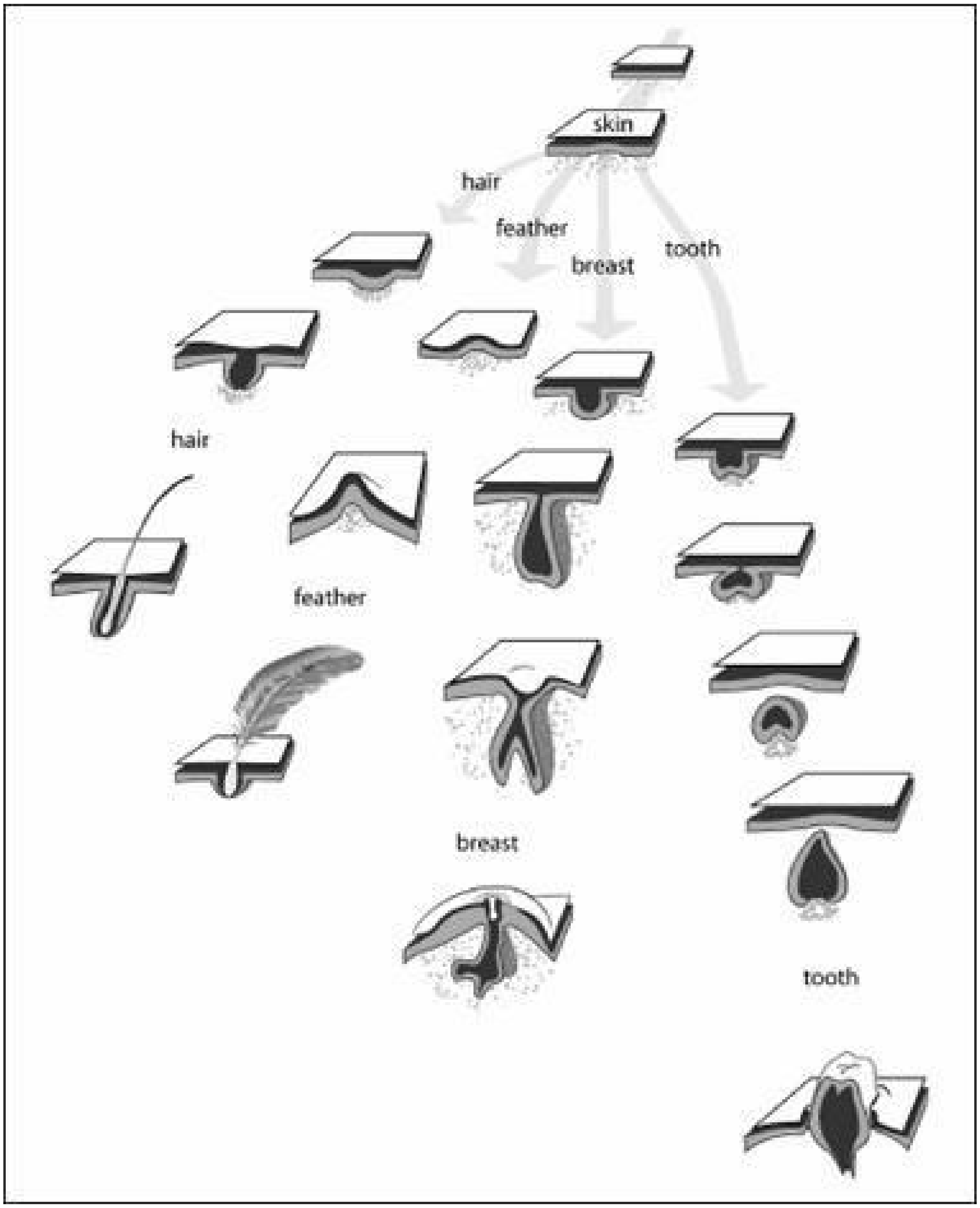
A conodont (left) and an ostracoderm (right). Conodonts were originally found isolated. Then, as whole animals became known, we learned that many of them functioned together as a tooth row in the mouths of these soft-bodied jawless fish. Ostracoderms have heads covered with a bony shield. The microscopic layers of that shield look like they are composed of little tooth-like structures. Conodont tooth row reconstruction courtesy of Dr. Mark Purnell, University of Leicester, and Dr. Philip Donoghue, University of Bristol.

One of the joys of being a scientist is that the natural world has the power to amaze and surprise. Here, in ostracoderms, an obscure group of ancient jawless fish, lies a prime example. Ostracoderms are among the earliest creatures with bony heads. Cut the bone of the skull open, embed it in plastic, pop it under the microscope, and you do not find just any old tissue structure; rather, you find virtually the same structure as in our teeth. There is a layer of enamel and even a layer of pulp. The whole shield is made up of thousands of small teeth fused together. This bony skull—one of the earliest in the fossil record—is made entirely of little teeth. Teeth originally arose to bite creatures; later, a version of teeth was used in a new way to protect them.

TEETH, GLANDS, AND FEATHERS

Teeth not only herald a whole new way of living, they reveal the origin of a whole new way of making organs. Teeth develop by an interaction of two layers of tissue in our developing skin. Basically, two layers approach each other, cells divide, and the layers change shape and make proteins. The outer layer spits out the molecular precursors of enamel, the inner layer the dentine and pulp of the inside of the tooth. Over time, the structure of the tooth is laid down, then tweaked to make the patterns of cusps and troughs that distinguish each species.

The key to tooth development is that an interaction between these two layers of tissue, an outer sheet of cells and an inner loose layer of cells, causes the tissue to fold and makes both layers secrete the molecules that build the organ. It turns out that exactly the same process underlies the development of all the structures that develop within skin: scales, hair, feathers, sweat glands, even mammary glands. In each case, two layers come together, fold, and secrete proteins. Indeed, the batteries of the major genetic switches that are active in this process in each kind of tissue are largely similar.



Teeth, breasts, feathers, and hair all develop from the interactions between layers of skin.

This example is akin to making a new factory or assembly process. Once plastic injection was invented, it was used in making everything from car parts to yo-yos. Teeth are no different. Once the process that makes teeth came into being, it was modified to make the diverse kinds of organs that lie within skin. We saw this taken to a very great extreme in the ostracoderms. Birds, reptiles, and humans are just as extreme in many ways. We would never have scales, feathers, or breasts if we didn't have teeth in the first place. The developmental tools that make teeth have been repurposed to make other important skin structures. In a very real sense organs as different as teeth, feathers, and breasts are inextricably linked by history.

A theme of these first four chapters is how we can trace the same organ in different creatures. In Chapter 1 we saw that we can make predictions and find versions of our organs in ancient rocks. In Chapter 2 we saw how we can trace similar bones all the way from fish to humans. Chapter 3 shows how the real heritable part of our bodies—the DNA and genetic recipe that builds organs—can be followed in very different creatures. Here, in teeth, mammary glands, and feathers, we find a similar theme. The biological processes that make these different organs are versions of the same thing. When you see these deep similarities among different organs and bodies, you begin to recognize that the diverse inhabitants of our world are just variations on a theme.