Shape of Life

Chordates

The Voyage to Us
Bones, Brawn and Brains

"Humanity is exalted, not because we are so far above every other living creature, but because knowing them well elevates the very concept of life"

E. O. Wilson, *Biophilia*

Elephant at the Smithsonian

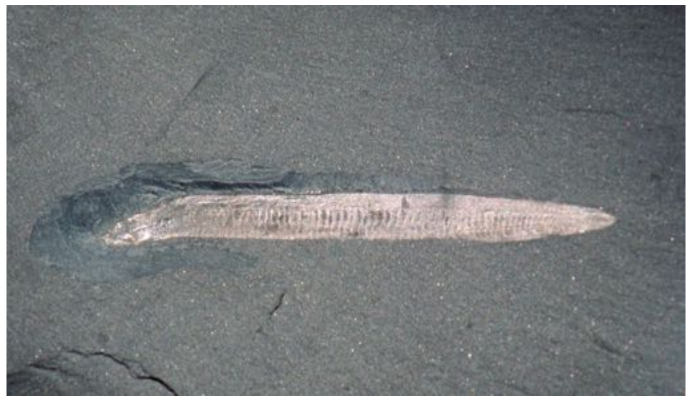
The main entrance to the Smithsonian Institution's Museum of Natural History is a grand rotunda with colonnades rising to a domed ceiling that magnifies the constant din of voices and the footsteps clattering on the marble floors below. It takes a few minutes to get used to the scale of the enormous hall and echoing chatter from rivers of meandering children tended by parents and teachers and the rest of humanity that gathers there every day to marvel at the story of life. Once you settle into the sound and the crowd, though, the sight of a giant elephant at the center of the rotunda banishes the sensory overload. The animal, long dead but perfectly life-like in a natural setting, is so much bigger than you could have imagined that it hardly seems of this world. This is a beast, a great beast, not some gray cartoon creature or decorated Indian ruler's mount or laborer on a circus lot. This is a rough, fierce, darkish brute that looks dangerous and quick, its bright white tusks hinting of the unthinkable damage they could inflict, its huge head easily twenty feet from the floor. It is an African bush elephant, you learn from reading the panel mounted on the rail around the display, the largest modern living land animal. It weighs 15,000 pounds and exhibits intelligence, nurturing instincts, and complex social behavior in the wild. As do we.

Radiating from the rotunda, the halls of the Smithsonian contain mounts or models of thousands of the creatures with whom we share Planet Earth. A great blue whale, the largest animal that ever lived, hangs overhead in one of the galleries. In another, a warren of display cases holds a collection of birds so vast you could spend most of a morning just there. In other halls of similar magnitude you'll find fishes, reptiles, amphibians, and more mammals. Because all of the animals alive today comprise only ten percent of all the animals that ever lived, the ancient fossilized bones of many members of these families of extinct creatures also tell their stories, including the legendary monsters in the Hall of Dinosaurs, the hit attraction of the Smithsonian for over a century. Since the rush to excavate their fossils began in the middle of the nineteenth century, so many people have seen dinosaurs in museums, movies, and books that they are as familiar to us as our pets. Many children can say *Tyrannosaurus rex* soon after they learn to talk.

Fewer than five percent of all the animals that ever lived on earth have backbones, but we humans remain quite chauvinistic about our own kind. Natural history museum collections tend to be heavy on chordates, particularly the branch to which humans and most familiar animals belong, the vertebrates. If you ask most people to name five animals, you'll almost certainly get a list of creatures with backbones and nothing else. Try it. Cat. Dog. Snake. Monkey. Horse. Some invertebrates, though, are represented in the exhibit cases and dioramas, including insects, spiders, and mollusc shells. And one entire wing of the Smithsonian is devoted to life in the ancient oceans, which were home to swarms of the spineless creatures that inhabit the first seven chapters of this book.

Examples of vertebrates: cobra, tigers, leaf monkeys, galapagose tortoises

Those ancient seas were also home to some of our earliest chordate relatives. They didn't look much like us, or the giant beast in the rotunda, and in fact didn't even have real backbones. To find one, you take a right from the elephant and pass under an archway into a dimly lit gallery where you can hear the sloshing sounds of the sea piped over unseen speakers. You walk past great slabs of crinoids, cases of trilobites, a collection of Walcott's beautiful Burgess Shale fossils, a wall of swimming ammonites and marine reptiles, and a stunning diorama of a Permian reef. And there, tucked into a corner to the right of the reef, in a shrine-like case that looks a little bit like a glass-covered draftsman's table, is a black slab of rock in which you can see the outlines of a worm-like creature named *Pikaia gracilens*.



Top: Animation still of Pikaia swimming in the Cambrian seas
Bottom: Pikaia with notochord barely visible above the segmented muscles

Charles Walcott himself brought the first specimen of *Pikaia* to the Smithsonian from his legendary quarry. It was one of thousands of messages from the Cambrian explosion embedded in the dark shale of the Canadian Rockies that would eventually change the way we know ourselves, and all other animals on earth. Walcott thought *Pikaia* was a worm, one of so many he found there on the high flank of Mt. Burgess, in British Columbia, Canada, along with the arthropods which seemed to dominate that epoch in the sea. His mistaken identification of this inch-long creature in the shale is quite understandable. It clearly has a head with a pair of horn-like appendages, a tail, and a flattened, elongated body in between. Even today, almost anybody would look at *Pikaia* and think, 'Worm.'

And so it remained for seventy years until modern paleontological tools and new understandings of the relationships among the animals combined to tell us its real story. And our own story. As so often happens in the world of paleontology, new fossils have since been found that are even older than our friend *Pikaia*. We now know that in these first chordate fossils lie the beginnings of the chordate body plan, expressed as a rod, or notochord, running the length of the backside of the body. When you look closely at *Pikaia* through the glass of the display case in the Smithsonian, you can actually see it, a wispy filament etched in the rock, not much thicker than one of the hairs on your head. You can also see a pattern left by the segmented muscles that are the harbinger of the creatures who would not only dominate Earth, but some day leave it to explore space.

And so the chordates arrived, soon to be followed by their powerful and enormously successful descendants, vertebrates with real backbones. Their basic animalness – multi-cellularity, a head, brain, nerves, and bilateral symmetry – is the legacy of the sponges, cnidarians, and ancient flatworm-like animals, each of which pioneered pieces of the architecture that led to complex animals like *Pikaia*, and us. From the Cambrian, by which time those basic traits had been established, all of the other body plans emerged that animals still use today. So in addition to the three pioneer groups continuing to evolve, all of the other groups of animals, including the annelids, arthropods, molluscs, and chordates, began their bilateral journeys through time into the present. (Echinoderms, of course, began at the same time but navigated into the future in their own way with their radially five-part interpretation of animalness.)

And though *Pikaia* could not walk, talk or write this book, its body plan contained all of the traits shared by every chordate and vertebrate that ever lived. Our chordate body plan is easily defined by three common features. Each of us has a single hollow nerve bundle running along our backs, and that stiff rod, called a notochord, containing jelly-like fluid sheathed in fibrous tissue that we saw etched in the fossil, *Pikaia*. In some living chordates, the notochord remains flexible, but in vertebrates, it is incorporated into the structures of the spine as discs between the vertebrae. The third trait shared by all chordates is the presence, at some stage of life, of gill slits in the throat. As embryos, our own gill slits close up and become parts of our ears and tonsils. At some point in our lives, all of us chordates have bilaterally symmetrical bodies with segmentation most clearly revealed in our muscles. Most of us have guts that run from a mouth to an anus, and a well-developed central body cavity in which our complex internal organs are suspended. Most of us reproduce sexually from the union of a large egg and a much smaller sperm, and the sexes are separate. We can see hints of ourselves in the fossil of the extinct *Pikaia gracilens* if we know what to look for, but how could evolution possibly have crafted our big complex bodies from those humble beginnings? Surprisingly, there is an animal alive today in which we also find clues to our ancestry.

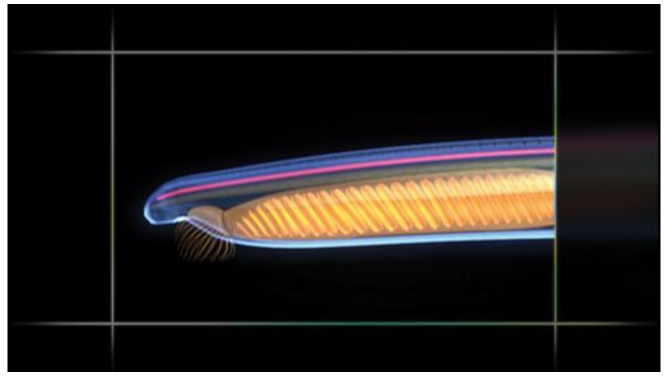
Primitive Chordates

It's a long way from Amphioxus, it's a long way to us,
It's a long way from Amphioxus, to the meanest human cuss,
Goodbye fins and gill slits, hello skin and hair,
It's a long, long way from Amphioxus, but we get here from there.

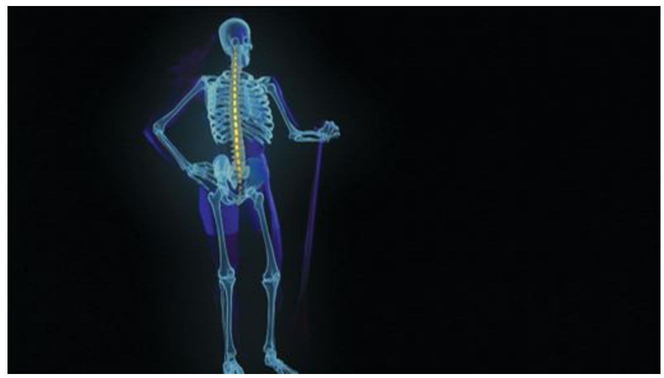
An Anonymous Paleontologist
To the tune of "It's a Long Way to Tipperary")

Ancient animals called *Amphioxus*, otherwise known as lancelets, emerged not too long after *Pikaia* and still exist as living fossils, giving us a wonderful window through which we can observe the behavior and genetic makeup of early chordates. They thrive in the sand of tidal flats with essentially the same anatomical equipment as *Pikaia*. The shallows of Tampa Bay, for instance, are alive with these tiny, translucent, fish-like little creatures that have no eyes, ears, or jaws but which carry one of the earliest chapters in the story of the evolution of animals like us.

By studying how an *Amphioxus* develops from an embryo to an adult, investigators like biologist Linda Holland trace the path taken through the millennia by our chordate ancestors. She has spent countless hours dredging *Amphioxus* embryos from the shallows and trying to piece together their story in her lab. *"Amphioxus* is giving us a lot of insight into how we evolved," Holland says. "We're interested in it because back in the fossil record there were little organisms that looked very much like this and we can begin to reconstruct a scenario for exactly how the vertebrates evolved from little invertebrate creatures like these." Like *Pikaia*, *Amphioxus* has a nerve chord, and underneath that a notochord that acts as a stiffening rod against which its segmented muscles work as it wiggles in the sand. It has gill slits for feeding on tiny particles of food from the surrounding water. This animal is definitely a chordate.



Animation still of Amphioxus showing orange gill slits and the notochord a faint yellow just below the red nerve cord.



The discs between the vertebrae in the human skeleton are all that remain of the notochord

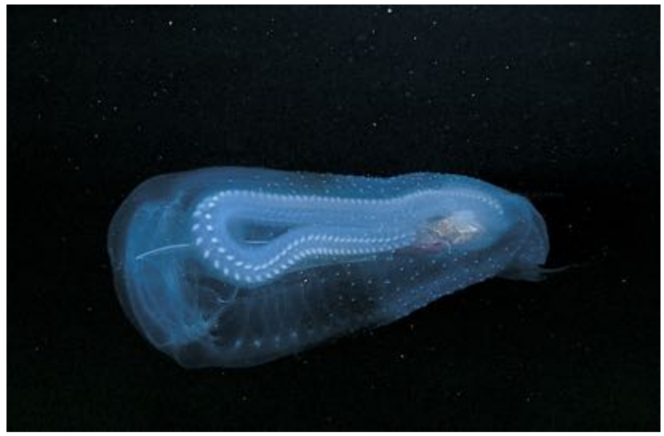
The big clue to the origins and relationships of these primitive chordates and us, though, is not in the gross anatomy but in the way its regulatory genes direct the formation of the adult body. During their first forty-eight hours of existence, *Amphioxus* embryos grow from pinpoint-sized eggs to actual swimming larvae that intermingle with the plankton in the water. Holland isolated and studied the genes of *Amphioxus* at this stage of development, compared them with those of vertebrates, and found remarkable similarities. "One of the most exciting moments was when I got the very first pattern of where a gene was turned on in the nerve cord of an *Amphioxus*," Holland says. "And it was the same as in the mouse nerve cord or in the human or the chick nerve cord." In a simple living descendant, we see how the genes that made the first chordate could have also created our bodies. This means that an animal very much like *Amphioxus* should be pasted on the first page of the vertebrate family album, because the genes that direct our own development are present in that little creature.

Our Chordate Relatives

The Phylum Chordata includes about 60,000 species, most of them vertebrates like us — fishes, amphibians, reptiles, birds, and mammals. About three percent of chordates are invertebrates, though, including *Amphioxus* and an extremely unlikely branch called tunicates. Some tunicates look for all-the-world like red, yellow, purple, orange, and green jelly smeared on rocks on the sea floor or in tide pools. Their name means 'enclosed in a cape.' We also call them sea squirts, but unless you know better, you would look at a tunicate and call it a sponge. Nobody could blame you. If you take a look at a tunicate larva through a microscope, though, its startling connection to us, and the rest of the chordate clan, is obvious. The first thing likely to pop into your mind when you look at a tunicate larva is 'tadpole.' That miniscule creature has the same features—a nerve cord, notochord, and gill slits — as the rest of us chordates until it attaches itself to the sea floor or some other object and metamorphoses into what looks like a schmear or a jellyfish cousin.

Tracing the roots and branches of one's family tree can be embarrassing enough, but anyone sufficiently curious to extend the search phylum-wide should be prepared to acknowledge some even more unlikely relatives.

Pearse and Buchsbaum
Living Invertebrates



Top: *Individual salp*
Bottom: *Salp chain*

Other invertebrate chordates, commonly called salps, skip the larval stage and instead of attaching themselves forever to one place, surround themselves with a mucous-like transparent sac. Some drift through the ocean like giant bubble chains. Swarms of individual salps can be gigantic, reaching densities of up to 25,000 individual animals per 35.3 feet cubic feet and covering vast expanses of the ocean. Fishermen who blunder into a large infestation are tormented by the chains and clumps of salps coming up in their nets and on their hooks, which are almost impossible to remove. Not many of those fishermen, of course, suspect that they are closely related to the goo that is driving them crazy.Nor do many trawlers and trollers tortured by the salps suspect how closely they are related to the fish they are *trying* to catch.

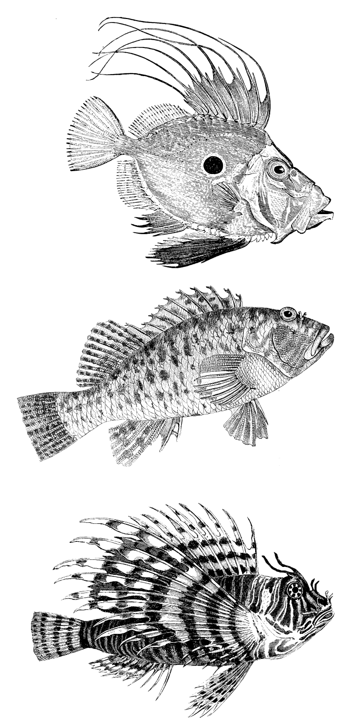
Our Fishy Relatives

> *Einstein was a fish. So were Mozart, Virginia Woolf, and Thomas Jefferson. Bruce Springsteen is a fish, and so are Ray Troll, Bill Clinton, and Camille Paglia.*
>
> Brad Matsen and Ray Troll
> *Planet Ocean: A Tale of Life, the Sea and Dancing to the Fossil Record*

The truth is, those fishermen themselves are more fish than not, because some ancient fish, about 530 million years ago, was the first true vertebrate. The very first vertebrates crossed the bridge from the spineless world by adapting the basic chordate body plan to become the most dominant predators in the history of the animal kingdom. *Pikaia* and *Amphioxus* are chordates, but they and other animals like them do not have backbones, skulls, or complex sense organs and nervous systems. So what had to happen to the body of an animal like *Amphioxus* to transform it into a fish?

"Vertebrates really became big, dominant animals by getting extra genes," says Linda Holland, whose *Amphioxus* larvae are the 'before' in a before-and-after picture. "An *Amphioxus*-like organism has relatively few genes, about the same number as your typical worm, your typical ant, your typical fly. But vertebrates have done something rather special. They've taken this basic number of genes, and instead of inventing a lot of extremely new genes, they've taken them and simply duplicated them." Flies have about 10,000 distinct genes; annelid worms about 13,000. Mice and humans, though, have about 60,000. "Vertebrates duplicated the genes of their simpler ancestors not once, but twice. Then they changed them just a little bit, and suddenly, you have four times as many genes to link together to make brand-new structures."

By quadrupling the amount of genetic information available for choreographing their development, fish could evolve big, complex bodies and forever change the world. Some of those duplicated genes directed the evolution of a true backbone, the key trait of the vertebrate group whose members would eventually dominate land, sea and air. Others eventually produced an innovation very nearly the evolutionary equal of the backbone, a group of specialized cells that began building body parts, like skulls and jaws. These fantastic cells develop near that nerve cord to form a very powerful component of vertebrates called the neural crest. In animals like *Amphioxus*, this neural crest hardly forms at all, and neither does a backbone. In true vertebrates, the neural crest has enough genetic horsepower from all those duplicated genes to send cells off on journeys through time and space to create such complex structures as skulls, and, eventually, jaws, teeth and parts of the nervous system.



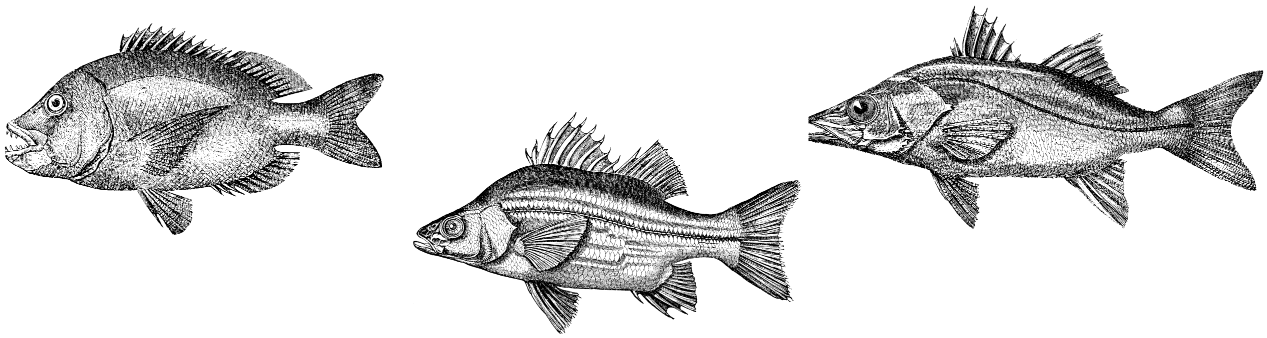
Examples of fish diversity

Working with this powerful genetic tool kit, fish became the first true vertebrates. They had inherited the basic architecture of all chordates, and then, about 450 million years ago, real bones arrived and started fish and vertebrates on the road to global dominance and space travel. Bone is an extraordinary building material, composed of living tissue that can grow and respond to increased weight and stress. The first fish were jaw-less vacuum cleaners, probably looking very much like enlarged, muscular *Amphioxus*. The first bone-like structures were external plates that covered the fish like armor, but eventually internal bone, skulls, and jaws evolved.

"Once jaws evolved," Linda Holland says, "chordates could switch . . . to becoming predators, eating other animals and increasing their body size and so we went from something as small as an *Amphioxus* to something as big as an elephant, a cow, a horse and a lion." Fish were also the

The development of jaws was important in the evolution of vertebrates. Many living fishes have large jaws

smartest animals around, with big brains that could process enormous amounts of sensory information from eyes, sense organs and lateral lines that detect motion, and translate all that information into complex behavior. They quickly became the top predators in the oceans. More than half of all vertebrates that ever lived have been fishes, including members of three extinct groups: the jaw-less fishes, the armored fishes, the spiny-ray sharks; and three living groups: the sharks, rays and chimeras; the lobefin fishes, and the ray-fin fishes, which are spectacularly diverse in today's oceans, lakes and rivers.



Modern fish diversity

Clockwise from top left: lionfish, horn shark, blue-dot grouper, queen angelfish.

On to Land

> *The greatest step in vertebrate evolution is undoubtedly the transition from aqueous gill-respiring fishes to air-breathing, walking, land animals.*
>
> John A. Long, Vertebrate Paleontologist
> *The Rise of Fishes*

Life four-hundred-million years ago in the Devonian Period, also known as the Age of Fishes, was driven by the enormous evolutionary pressures of jaws, teeth, slashing tails and fins, and speed that produced an explosion of diversity. Among those ancient fishes, a group called lobefins emerged. They had paired fins with the same bone pattern that all terrestrial animals still retain in their arms and legs. They had strong hip and shoulder muscles to move those fins. They controlled their buoyancy with swim bladders that could later take over from their gills and evolve into lungs. While they still lived in the sea, such animals were well suited to eventually evolve into creatures that could make the leap to life on land and become four-legged terrestrial animals.

Jenny Clack

The Tetrapod Fossil, Boris

Powerful evidence that limbs evolved while tetrapods were still water-bound comes from a fossil discovered in the mountains of Greenland, in 1987, by Jenny Clack, a paleontologist at Cambridge University's Museum of Zoology. That evidence, a fossil dating back 360 million years ago, emerged from tons of rocks that Clack brought back to her lab and painstakingly investigated for clues to the origins of land vertebrates. Among the hundreds of specimens she uncovered was the most complete Devonian tetrapod ever found, a creature named Acanthostega that she affectionately calls 'Boris.'

"It's every paleontologist's dream to find a transitional form," says Jenny Clack, "something that falls between two groups that we are familiar with, that sort of links them both in terms of anatomy and lifestyle. When we fetched Boris from the field, most of the surface of the fossil was covered by rock that had to be dug out bit-by-bit. We suspected that we had gotten something exciting, because we could see lumps in the rock suggesting there was more to the specimen than met the eye. And we could see the cross cracks suggesting that there were things

Jenny Clack and Sarah Finney examine fossilized tetrapod tracks

inside waiting to come out." Sealed in its tomb of ancient stone, Boris is a fish-like animal with limbs.

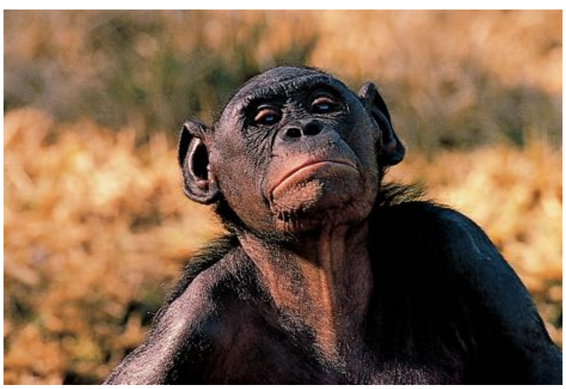
"This is a specimen of an animal that could be described as a missing link, except that we have one so it's not missing," Clack says, holding her fossil. "It's a transitional form between animals with fins that we'd call fish, and animals with legs, with fingers and toes on the end that we call tetrapods. We are tetrapods." Like us, Boris has a skull attached to a vertebral column. The vertebral column goes through an S-bend and goes off into a tail. There are forelimbs and some digits and there are gill bars. Significantly, the gill bars were grooved, and that means that there was an artery running up that groove, feeding the gills blood, so that the blood could get oxygen. And this suggests that the animal was still using gills to breathe, though it also had lungs. Boris was using both gills and the lungs, unlike later tetrapods, which did not have gills.

Clack has also found the tracks of an early tetrapod, *Acanthostega*, left in the fossilized mud of the shallows of an ancient shore, which further completes the puzzle of vertebrate landfall. These footprints are evidence of evolution in process, and though the species disappeared about 360 million years ago, its descendants have walked the earth since those first tentative footsteps left their marks on the surface of our planet. And so the genetic fire that began with those first chordates like *Pikaia* burned through fishes and amphibians and up onto the land where reptiles became the first fully terrestrial keepers of the chordate flame. Their limbs proved to be perfect for getting around on land, and though snakes abandoned them to better exploit their particular niche, arms and legs became the rule for survival ashore. The early reptiles also found a way to protect their young in the absence of the watery womb of the sea by evolving liquid-filled eggs with tough shells, which meant they didn't have to return to the ocean to reproduce.

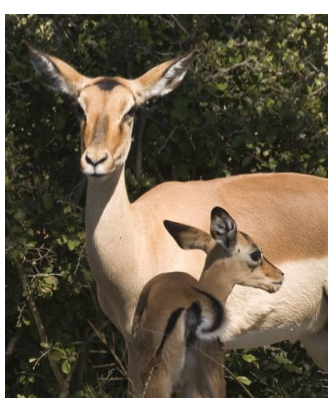
Animation still of the tetrapod walking in shallow water

For over fifty million years, reptiles were the sole vertebrate "terranauts," sharing islands and continents with insects, worms, snails, and the other animals that had preceded them onto land. Then, at some point just before the mass extinction that ended the Permian Period 235 million years ago, the reptiles were driven by evolutionary pressure to send off branches that became the earliest ancestors of dinosaurs and mammal. The radiation of vertebrates on the land took off in several directions at once. Reptiles also returned to the sea, where they grew into the giant mosasaurs, plesiosaurs, and ichthyosaurs that eventually became, for a time, the apex predators of all the world's oceans.

On land, the dinosaurs retained much of their reptilian ancestry, continuing to lay eggs, but the mammals evolved further terrestrial adaptations, grew hair, and began to bear live young. Mammals survived millions of years of ecological change in part by remaining small and resource-efficient, much like modern rodents. Somehow they managed to survive the asteroid strike and mass extinction that killed off the dinosaurs and marine reptiles. When the dust settled, mammals, and soon birds, exploded into the vacated environmental niches on land, in the sea, and in the air, and the chordate story continued, now with the familiar characters, that to most people, are *real* animals.








A few of the mammalian orders TOP: bonobo, toucan, and fruit bat
BOTTOM: lemur, antelope, zebra

There are about 4,500 species of mammals alive today. We are homeotherms. Warm blooded creatures. We have four-chambered hearts, with complete double circulation that keeps oxygen-rich blood separate from oxygen-depleted blood. We have hair on our skin at some stage of our lives, and we nourish our young with milk secreted by the mammary glands of females. Most of us reproduce sexually, and the fertilized egg develops inside the female, nourished in most mammals by a special organ, the placenta. Many of us have complex and differentiated teeth. We eat plants and other animals, including other mammals.

Some of the members of our class include rodents (squirrels, mice, and porcupines); insectivores (hedgehogs, shrews, and moles); chiropterans (bats); carnivores (dogs, cats, and bears); ungulates (deer, horses, cows, sheep, and goats); pinnipeds (seals and sea lions); cetaceans (whales and dolphins); and primates (lemurs, monkeys, apes, and human beings).

As primates, we share a common ancestry that we can clearly see in the great apes and bonobos whose features and behavior are indisputable evidence of the anatomy we share. Our connection to all other animals is less obvious, but we can see it if we fearlessly transport ourselves upstream in the genetic river through our vertebrate, chordate, and animal ancestors who don't look much like us at all. We are there in that sponge in a tide pool, in the anemone stuck to a dock piling, in the earthworm on Charles Darwin's lawn, and they are in us. And although we write books, leave Earth and land on the Moon, peer through telescopes looking for the origins of the universe, sing the great duet in the first act of *La Boheme*, and weigh the abstractions of good and evil in a world once governed only by the impulses of predator and prey, it is clear that we are neither more, nor less, than any other animals that ever lived.

> *And a little later on, your friend goes out to the moon. And now he looks back and he sees Earth, not as something big, where he can see the beautiful details, but now he sees Earth as a small thing out there. It is so small and so fragile and such a precious little spot that you can block it out with your thumb, and you realize that on that small spot, that little blue and white thing, is everything that means anything to you – all of history and music and poetry and art and death and birth and love, tears, joy, games, all of it on that little spot out there that you can cover with your thumb. And you realize that there's something new there, that the relationship is no longer what it was.*
>
> Russell Schweikart, Astronaut
> *Earth's Answer, An Exploration of Planetary Culture*