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Shape-Shifters

Figure 4 A spectacular Ceratosomid nudibranch crawls along the dark bottom of Indonesia's Lembeh Strait. At Lembeh, as perhaps nowhere else on Earth, we can explore the full range of our far-flung distant relatives on the evolutionary tree.

As I hovered above a sandy bottom, twenty meters down in the Lembeh Strait, I surprised a Pharaoh cuttlefish that was gently snoozing above a small coral outcrop. Its outline was broken up by the many small lumps and protuberances all over its body, and its tentacles were crumpled into irregular shapes like complex pieces of origami. A blotched color pattern of green and yellow completed its disguise as an apparent lump of coral.

When I moved closer it woke, swiveled alertly to face me, and began to change its appearance. The many protuberances melted away in seconds, so that its body became smooth. Its arms and tentacles unfurled and straightened. Its color became lighter and more uniform. Within a minute it was transformed from an almost invisible coral-like object into a streamlined animal ready to flee. As I took my last picture of this whole-body makeover, the cuttlefish jetted away with a pulse of water from its siphon and disappeared into the darkness. The cuttlefish is one of the world's most accomplished shape-shifters, and it had just given me an effortless demonstration of its skill.

Surely no two organisms could be more dissimilar than the ingenious and graceful water-breathing cuttlefish and its clumsy air-gulping human observer. But in fact, even though present-day cuttlefish are expert shape-shifters and we are not, we had a common ancestor. And, at the time of that common ancestor, a far more astonishing shape-shift took place, one that had enormous evolutionary consequences.

How do we know that we are related to the cuttlefish? When and how did we first take such different evolutionary paths, and how have we and the cuttlefish converged in some of our abilities? What other animals have branched off from our different lineages during the long course of our evolutionary divergence? And is it possible to investigate, and perhaps even to recreate, the events that took place at the distant time when we and the cuttlefish began to diverge?

As a good Darwinian tourist, these evolutionary thoughts spun through my mind as I watched my remote relative propel itself into the dark.

Figure 5 A Pharaoh cuttlefish, *Sepia* sp., caught sleeping. Its body is covered with retractable protuberances and its tentacles are crumpled, so that it resembles a lump of coral.

Our immense family tree

When Darwin briefly visited the geologically young Galàpagos Islands in 1835, he was overwhelmed by evidence that recent evolutionary changes had shaped life on that remote archipelago. It gradually became clear to him that the closely related animals and plants on the different islands of the archipelago had radiated adaptively from a small number of ancestors that had made their way or been carried to the islands. His visit to the Galàpagos, along with many other observations that he made during his five-year voyage, helped to plant the germ of the idea of natural selection in his mind.

When I plunged into Indonesia's Lembeh Strait my experience was very different from Darwin's. I was overwhelmed by the almost insane diversity of life there. Traces of recent evolution are not common at Lembeh, though

Figure 6 The cuttlefish, newly streamlined, is now ready for its getaway.

there are some fish and other animals unique to this narrow passage between islands. But these examples of recent evolution are almost lost in the cacophony of more than half a billion years of evolutionary divergence.

The Lembeh Strait lies at the heart of one of the world's great biodiversity hot spots, where there is a greater variety of marine life than anywhere else in the world.[1] It is one of the waterways that surround the world's eleventh largest island, a jewel of rich tropical diversity called Sulawesi that lies just to the east of Borneo.

Sulawesi has been so thoroughly pushed and twisted by tectonic forces that the map of the island looks like a character from some forgotten alphabet. Indeed, the Portuguese explorers who first landed on different parts of Sulawesi's complex and deeply indented coastline were fooled into thinking that it was actually several islands. They named this hypothetical archipelago the Celebes, perhaps a mishearing of Sulawesi, which in turn may be derived from local words meaning "iron island."

Figure 7 An effigy of the deceased leads the coffin of its owner to its final resting place in Tana Toraja, Sulawesi.

The island is almost as large as Great Britain, but its biology is far richer. On land its ecosystems range from rainforest to grassland, encompassing a wide variety of animal and plant life. We will meet some of these remarkable terrestrial organisms later.

It was this exotic but still easily accessible world that I left behind when I took a diver's giant stride and splashed into the waters of the Lembeh Strait, which separates the tiny island of Lembeh from the main island's northeast coast. Above the surface the strait is a rather undistinguished narrow channel of water, flanked on each side by forested hills. The waters of the passage are deep and sheltered enough to make it safe for coastal shipping, though it can be dangerous for ocean-going vessels. The strait's shores are blemished by undistinguished lumbering and fishing towns, but beneath the surface its biological diversity has made it a mecca for scientists and scuba divers from around the world.

Coastal vessels have used the strait as a shortcut for centuries, and their sailors have tossed empty bottles and other trash over the side. The trash settles to the sandy bottom, where it is soon partially buried.

When I first entered the water at Lembeh, the thought of all that junk waiting for me on the bottom was less than thrilling. Lembeh's underwater world is far from glamorous. Fabulous coral gardens adorn other parts of Sulawesi's coast, but there are no extensive coral reefs here. Reefs cannot become established because the strait is repeatedly scoured by strong oceanic and tidal currents of nutrient-rich water. As a result corals grow only in small patches, wherever there is something solid that they can use as an anchor.

Instead of a maze of colorful corals I was greeted by a level plain of dark sand and mud that stretched off in all directions, broken only by islands of eel grass and a few coral-covered outcrops. By stretching out horizontally and using minimal fin movement to avoid stirring up the mud, I was able to swim smoothly from one clump of coral- and weed-covered detritus to the next.

Most marine animals live, not in the open water, but in what is called the benthic zone. The benthic zone is defined as the ocean bottom and the space immediately above it, along with a maze of burrows and secret places that lie just below the surface. Although the word benthic comes from the Greek *benthos,* meaning the deep sea, even shallow waters have benthic zones.

Organisms that inhabit benthic zones battle endlessly for space to live, with an intensity that would put Southern California real estate developers to shame. In Lembeh these battles ensure that each clump of overgrown debris on the bottom is covered with a riot of intensely competing creatures.

The fish of Lembeh provide a logical place to start to explore our immense family tree. Unlike most of the creatures that live on the bottom of the strait, fish are vertebrate animals that are quite close to us in evolutionary terms, such that we can all feel an immediate kinship with them. And yet even these close relatives of ours have evolved in unexpected directions.

Among the shyest of these diverse fish are the pygmy seahorses, a mere centimeter long or less, that make themselves seem even smaller by curling their tails around the branches of pink and orange sea fans. The sea fans dine on tiny free-swimming arthropod plankton that they snare using their stinging cells. Because the seahorses are unable to trap the plankton themselves, they browse delicately along the branches of the sea fans, nibbling on the tiny creatures trapped there.

These little equine fish show an uncanny resemblance to the branches of the fans on which they live. The colors of their bodies and the little warts on their skins help them mimic the details of the surfaces of the sea fan branches with precision.

I found one of these seahorses, whitish with pink bumps, clinging in a strong current to an actively feeding sea fan. Its pouch was swollen with hundreds of tiny young, so it was clearly a male. The pregnancies of male seahorses and pipefish provide one of the clearest cases in the natural world in which the roles of the sexes are reversed.[2] The seahorse female, after giving up her eggs to the male, has blithely left her progeny behind and moved on to sexual pastures new. During her reproductive life she will compete fiercely with other females and attempt to mate with as many other males as possible, each of whom will serve as incubators for her offspring.

Seahorses are only a small sample of the fish diversity of Lembeh. Consider the frogfish, which come in dramatic shades of red, white, pink, black, and green. They nestle on the bottom, in the branches of corals, and among the fronds of algae. Members of a single frogfish species can adopt different colors, depending on where they are trying to hide. They only reveal themselves when they open their mouths to suck in innocent fish. Frogfish have such capacious mouths that they have occasionally been seen to eat other frogfish almost as big as themselves.

In a clump of detritus lurked a spiny devilfish, which lived up to its name—with its glaring eyes and its tooth-filled, downturned mouth it is the stuff of nightmares. Its wing-like pectoral fins and the spines on its back are covered with weeds and other growths that effectively conceal its outline. It has evolved a surprisingly insect-like mode of locomotion, crawling forward on appendages formed from parts of its pectoral fins.

Figure 8 (*opposite*) A pregnant male pygmy seahorse, *Hippocampus bargobanti*, at Lembeh Strait. The males nurse the babies while the females are free to seek other mates. This seahorse was clinging to a fan coral in strong current, and in the background you can see the actively feeding polyps of the coral.

Figure 9 A painted frogfish, *Antennarius pictus*, lies in wait for its prey, which can include other frogfish.

The sandy flats between the different islands of detritus swarmed with life too. Gurnards and sea moths, shaped like stealth bombers, stirred up the bottom as they rowed across it using their fanlike pectoral fins. Goggle-eyed balloonfish cruised by, their spines ready to deploy whenever they swelled with water to scare off enemies. Black-and-white-striped convict snake eels writhed swiftly across the bottom in search of prey. In their shape and color, these eels mimic the air-breathing and highly poisonous sea snakes. One of the convict eels thrust its head swiftly into the sand right in front of me, moving so quickly that I could not see what tiny unfortunate animal it had caught.

Even objects that must surely be dead turned out to be alive. Many brown dead leaves from the nearby forests fall into the strait and litter the bottom. They drift along in the current at odd angles, as dead leaves would be expected to do. But on close examination some of these leaves turn out to be brown scorpionfish—leaf-shaped, leaf-colored, and covered with

Figure 10 This spiny devilfish, *Inimicus didactylus*, grows protuberances on its back that soon become covered with algae and other small creatures. It crawls along the bottom on leg-like modified fins.

vein-like patterns and irregular splotches that make them look even more like a real leaf.

The real leaves that drift along the bottom have been part of the scenery for millennia, and the scorpionfish have evolved not just to look like them but even to mimic how they drift. Like their brightly colored frogfish relatives, the scorpionfish wait until their incautious fish prey swim too close, under the blithe misapprehension that there is surely nothing to fear from a dead leaf.

More distant branches on the Lembeh family tree

We humans have a relatively close evolutionary kinship with all these fish, even with the rather creepy spiny devilfish. Despite our decidedly different shapes and habits we all share a backbone, and this shared trait places us all in the subphylum Vertebrata. But if we venture a little further among the

Figure 11 A hunting convict snake eel, *Elapsopis versicolor*, writhes swiftly across the bottom. These snake eels imitate the air-breathing and highly poisonous sea snakes.

spreading branches of our family tree we find other slightly more distant relatives. Some of these, unlikely as it may seem, are sea urchins.[3]

Jostling crowds of large sea urchins, known as fire urchins, are common at Lembeh. They form dense clusters, swarming with surprising speed across the sand and sucking up small creatures from the bottom as they go. Their spines, some long and striped and others purple-black, radiate out in all directions to protect their plump (and delicious) bodies.

As I peered down at this carpet of spines I immediately discovered why these roistering ragamuffins are called fire urchins. Their bodies, glimpsed among the spines, are colored the fiery red of hot coals. The red patches are outlined in electric blue spots that glow like sparks.

How do we know that these sea urchins share an evolutionary kinship with scuba divers and merchant bankers? At the end of the nineteenth century the English zoologist Walter Garstang compared the early embryonic stages of vertebrates with the early stages of sea urchins, starfish, and other echinoderms. He found that vertebrates and echinoderms have similar early development, and that this shared development differs markedly from the early embryonic stages of other large groups of animals such as insects and mollusks.[4] We may like to think that we have more in common with a hardworking and loyal honeybee than with a tousled and uncharismatic sea urchin, but the evidence of our shared youthful anatomies says otherwise.

It is not surprising that right down until the 1960s Garstang's conclusion was rejected by some other anatomists. This is in part because he went too far, and concluded that vertebrates had sprung from ancient echinoderm stock. We now know that our common ancestor probably didn't look much like either modern echinoderms or modern vertebrates. But it is now clear that he was right about his essential point, that we are indeed closely related to the echinoderms. A century after Garstang's pioneering studies, the subtle signs of kinship that he drew from the anatomy of early development were reinforced by molecular studies. Comparisons between echinoderm and vertebrate DNA sequences prove our close relationship beyond a doubt.

Figure 12 A leaf scorpionfish, *Taeniotus tricanthus*, drifts along the bottom, doing a most convincing imitation of a dead leaf while waiting for nearby fish to be fooled.

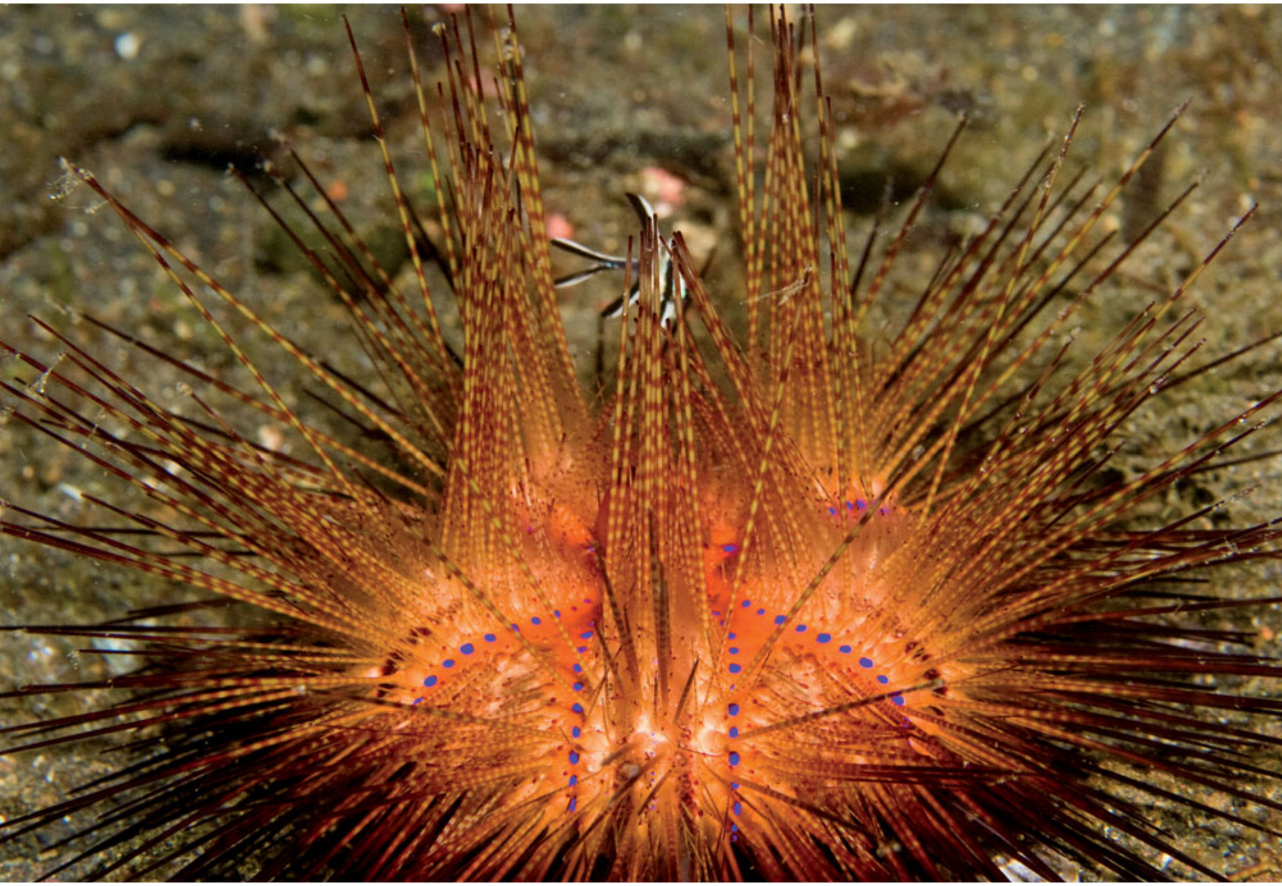


Figure 13 Fire urchin, *Astropyga radiata*. These urchins are close relatives of ours, even though they do not seem to resemble us in the least.

Several other great branches of the tree of life, more remote from us than the echinoderms, are represented in abundance on the seafloor of the Lembeh Strait. One of them is the great phylum Arthropoda, made up of the animals with jointed legs.

Members of this phylum swarm everywhere on the bottom at Lembeh. Decorator crabs lurch out of their hiding places like camouflaged tanks whenever a diver poses a threat. Their swollen legs, covered with carefully groomed mini-gardens of sponges and small algae, look like the limbs of some body builder who has gone overboard on doses of growth hormone.

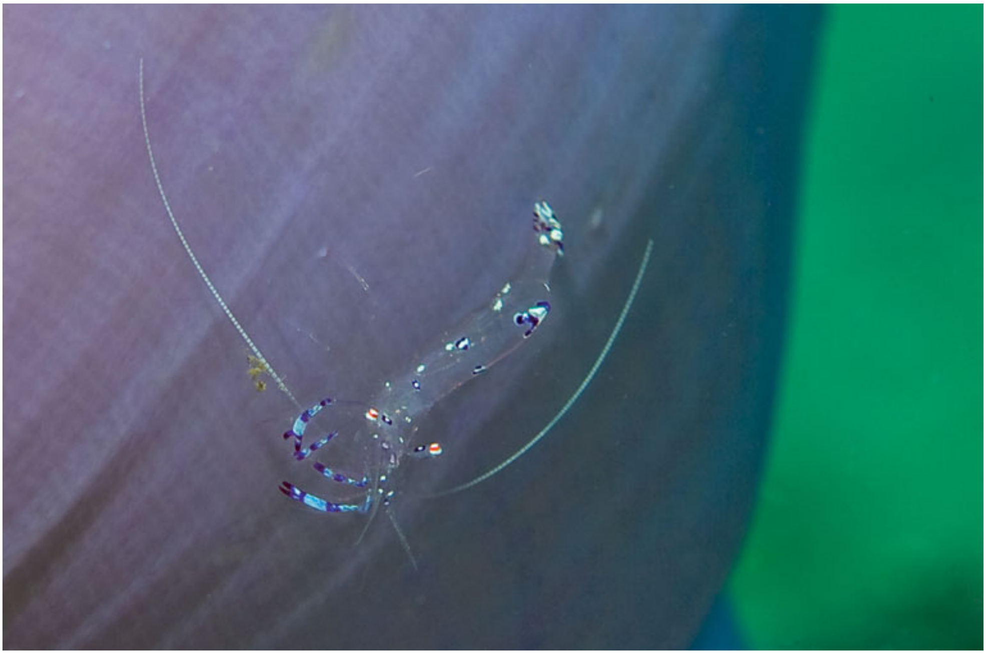


Figure 14 An almost invisible commensal anemone shrimp defends its sea anemone home.

Nearby are anemone shrimp, which defend their homes on pink and purple sea anemones. It is easy to see the surfaces of the anemones right through these shrimp, for they seem to be made of oddly shaped bits of glass. The only clues to the presence of these delicate transparent arthropods are bright medallions of color that accent their otherwise imperceptible bodies. If it weren't for their blobs of opaque color and their tiny striped eyes that float on the ends of transparent stalks, they would be invisible.

Other shrimp are colored and patterned all over. The marbled shrimp are the last word in understated elegance. One of them slowly inches forward out of its lair. Its designer-patterned carapace gives it a decidedly upscale air compared with the roistering crowd of less fashion-conscious creatures that surround it, though the effect is somewhat diluted by the shaggy moustache of cirri that it uses to ensnare its food.

The local king of the arthropods is undoubtedly a red, green, and blue shrimp, one of several species of brightly-colored mantis or boxer shrimps

Figure 15 An elegant marbled shrimp of the genus *Saron* uses brushlike cirri to snare its prey.

at Lembeh. It peered at me from its burrow in the sand through round robotic eyes on stalks. Its thick claws, ending in bulges shaped like a boxer's glove, were held at angles in front of its body like the claws of a praying mantis.

By any name these shrimp are formidable customers, even though they are only about twenty centimeters long. Their claws can snap forward at 80 kilometers an hour, moving so quickly that cavitation bubbles form in their wake.[5] As the bubbles collapse they actually generate flashes of light.

The claws are quite strong enough to crack a diver's face mask. Mantis shrimp have even been known to blast their way out of glass aquarium tanks. One assumes that the escapees enjoy a fleeting moment of triumphant freedom before they expire on the aquarium floor.

My shrimp scuttled swiftly out of its lair to defend itself. I chose discretion over valor and moved my vulnerable camera and facemask well back from its claws, leaving the field to this tiny action figure.

Figure 16 This mantis or boxer shrimp, *Odontodactylus scyllarus*, patrols the sea floor. The shrimp's claws can move so quickly through the water that cavitation bubbles form in their wake. As the bubbles collapse they generate flashes of light.

The incredible mollusks

The mollusks are the most diverse of this otherworldly zoo of creatures. We are of course familiar with the clams, oysters, mussels, and squid featured in all the world's great cuisines. These happen to be the mollusks that have committed the evolutionary mistake of being delicious. But the mollusks are far more diverse than restaurant menus would imply, and many mollusks are not tasty at all. More importantly from an evolutionary viewpoint, many of the mollusks have capabilities and lifestyles far beyond our reach—or at least beyond the reach of everybody but a shape-shifting comic book superhero.

The mollusks, like the arthropods, are distant from us on the animal evolutionary tree. But there is no doubt about our ultimate kinship with them, because we share divergent but still detectably similar DNA sequences.

Like the arthropods, the mollusks occupy their own phylum. The family tree of the mollusks can be followed back through the fossil record for more than half a billion years, chiefly because the limestone shells that many of them construct make excellent fossils.

The name mollusk simply means "soft of body," a catchall category if ever there was one. Pioneering Swedish taxonomist Carolus Linnaeus grouped them into the single phylum Mollusca, recognizing the anatomical similarities among their diversity.

Many mollusks are protected by hard shells, and live most of their lives in one place. Here at Lembeh, giant Tridacna clams are firmly buried in the mud amid clumps of coral. These clams have shells so large that they have often been used for baptismal fonts in churches. These huge animals must filter vast amounts of water for food. They get an additional shot of energy from tiny photosynthetic symbiotic algae that live in their soft mantles and give them their richly patterned blue, green, or brown colors. When the clams reproduce they spew forth great fountains of eggs or sperm into the surrounding water. The resulting larvae are carried away in the (mostly vain) hope that they will find somewhere to settle and eventually grow up into new giant clams like their parents.

Tridacna clams stare blurrily at the world through thousands of tiny window-like eyespots that can perceive only light or dark. Other shelled mollusks have more elaborate eyes that are highly sensitive to motion. Some of these eyes are faceted like the eyes of insects. Others are like miniature versions of the reflecting telescopes used by astronomers. All of these eyes, however, only form impressionistic images of the animals' surroundings.[6]

Other members of this great phylum have abandoned sight but embraced movement. The shell-less snails called nudibranchs ("naked gills") are the dazzling butterflies of the sea. They come in a rich variety of colors and patterns. On the seafloor at Lembeh I encountered an especially gorgeous nudibranch, the giant pink-colored *Ceratosoma trilobatum*, as it slid down a clump

Figure 17 This colorful nudibranch, *Ceratosoma trilobatum*, advertises to predators that it tastes terrible.

of coral and algae. A full ten centimeters long, it displayed exuberant clusters of spots that made it look like a glass of pink champagne.

Why are the nudibranchs so colorful? Like the colors of the fire urchins their bright colors have obviously not evolved for sexual attraction, since the nudibranchs cannot see each other. They can only sense the presence of potential mates chemically, by using a pair of feathery olfactory organs called rhinophores. (You can see the rhinophores at the nudibranch's head near the bottom of Figure 17. At its rear, near the top of the picture, a cluster of naked gills adorns the nudibranch's body like a flower.)

It is clear from many experiments that the colors and patterns of the nudibranchs are actually sending warnings to other species that might otherwise be tempted to eat them. These sea snails store toxins collected from the small organisms that they eat, making them highly poisonous. Like the showy colors and patterns of some butterflies, the colors of the nudibranchs have evolved as a signal to predators that they are nasty-tasting and dangerous.[7]

Of course, this warning coloration will only succeed if the nudibranchs' predators exhibit some degree of sophistication. The animals that prey on the nudibranchs must see them clearly enough to detect their warning colors and patterns, and must also be smart enough to be able to recall previous unpleasant encounters with similar nudibranchs. It is likely that in much earlier times, when the world was patrolled by more stupid and forgetful predators with poorer vision, animals like the nudibranchs that depended on warning coloration would not have evolved. The evolution of nudibranchs in their full glory depended on the emergence of smarter predators from that early stupidworld.[8]

Other groups of mollusks have moved far beyond the clams and nudibranchs in sophistication. They have been able to harness both sight and movement to aid in their hunt for prey and for mates.

On a wide stretch of nearby sea bottom a tiny cuttlefish scoots along. It raises its stumpy arms cautiously as it pauses on the sandy plain.

Like octopuses, cuttlefish have eight grasping arms, but they also have two longer, extremely prehensile tentacles. Even schools of swift silvery fish are not safe from a cuttlefish as it hunts. Such fish tend to be invisible to most

Figure 18 A flamboyant cuttlefish, *Metasepia pfefferi*, with eyes that produce sharper images than human eyes.

predators because they take on the color of the surrounding water when seen from below. But cuttlefish can find them, because their eyes are sensitive to the polarized light that the fish reflect.

The animal in Figure 18 is known as the flamboyant cuttlefish, and its name is deserved—it blazes in ever-shifting patterns of purple, yellow, and red as it scans the surface of the bottom for small prey. Its eyes are shielded by curtain-like membranes that make them appear hooded and sleepy-looking, but in fact they are keener than our own.

Because of evolutionary convergence, the eyes of the flamboyant cuttlefish closely resembles ours. Their eyes, like ours, are camera-like marvels of evolutionary engineering, with pupils that let in light, irises that can dilate or contract to control the amount of light that enters, and crystal-clear lenses that refract the light and form an image on the retina. Like the lenses of our eyes, their lenses can change shape to focus the images of near and far objects. This is a big improvement over the awkward cameras that we humans carry around, with their clumsy focusing rings and motors that move the rigid glass lenses back and forth.

Our eyes and the eyes of the cuttlefish can both be traced back to a simple eyespot possessed by our common ancestor. This ancestral eye consisted of a few photosensitive cells, perhaps overlaid by a layer of transparent cells that protected them and concentrated the light. The evolutionary path that eventually led to the fancy capabilities of cuttlefish eyes diverged from the one that led to the equally fancy capabilities of our own eyes.

The cuttlefish eyes are better than ours in at least one important respect. They can form crisp images of their surroundings in full color across the entire span of their light-sensitive retinas. We have to be content with a fuzzy image that has a little clear spot in the center.

Why are the cuttlefish eyes better? The difference can be traced to how our eyes and those of cuttlefish develop. During embryogenesis our light-sensitive retina begins as a hollow ball of cells called an optic vesicle at the end of a stalk of brain tissue. The back region of this ball differentiates into pigmented light-sensitive cells and the front region becomes the nerve cells that will pick up the retinal signals. The two regions then collapse and fuse into a single cup-like structure. The result is a retina in which the nerve cells lie on top of the retinal cells. The nerve cells interfere with image formation, which is why most of our vision is blurred. The only clear part of our visual field is the fovea, a small region in which the nerve cells fan away from the underlying retinal cells so that they do not interfere with the image. You are looking at these words through your fovea.

The cuttlefish eye develops differently. An optic vesicle develops from its brain as well, but the ball does not dimple inwards and form two layers of cells. Instead it forms a single layer of nerve cells. Meanwhile, part of the outer layer of the embryo's developing head moves in to bond with this layer. It is this piece of ectoderm, rather than the optic vesicle tissue, that differentiates into the light-sensitive pigment cells. The result is a retina that gets it right. The nerves that transmit visual signals to the brain form a layer behind the retinal tissue rather than in front of it, so that they do not interfere with the image.

As I swam slowly closer to the flamboyant cuttlefish, our gazes met briefly across an immense evolutionary divide. I formed an image of the cuttlefish at the same time as it formed a much sharper image of me. We regarded each other through eye lenses that, like our retinas, were also constructed through different developmental pathways even though they have converged on similar structures. Starting with the simple eyes of our remote ancestor, the eyes of cuttlefish and humans have diverged and then converged again to provide this moment of mutual regard.

On another part of the flats I glimpsed for a moment the most talented of the local mollusks, the mimic octopus. This octopus, fast-moving and swift-burrowing, is a master of disguise, the Scarlet Pimpernel of the underwater world. As it flashed past me and disappeared, its arms were striped black and white, like a writhing collection of convict eels or sea snakes. Depending on the threat that it must defend against, this octopus can turn itself into a passable imitation of a lionfish, a sting ray, or a mantis shrimp. It can also imitate the movements of these dangerous predators. If all else fails, this molluskan changeling can transform itself into a clump of innocuous-looking brown seaweed.[9]

The mimic octopus accomplishes these feats by changing the color, pattern, and surface texture of its arms and body, just as the cuttlefish we met at the beginning of this chapter was able to transform itself into a good imitation of a clump of coral.

As I swam in a haze of delighted astonishment around the sandy bottom at Lembeh, I realized that it is an ideal place to explore the animal family tree. Most scuba divers in the tropics explore coral reefs, not gray muddy sea bottoms. These divers swim among a range of creatures as diverse as those at Lembeh, but many of them may remain invisible because there are so many places to hide in a coral reef. Here on the volcanic sand bottom of Lembeh, in the space of a dozen dives, I was able to contemplate a sampling of the full range of native exotic creatures, often observing and photographing their behaviors for minutes at a time.

Diving at Lembeh and at similar areas in Indonesia and Papua New Guinea is a relatively new activity, dating back only to the 1980s. Australian divers were the first to venture into these apparently unpromising shallow waters, at a site called Dinah's Beach in eastern Papua New Guinea. They were as dazzled by their experience as I was by Lembeh. They called their adventure "muck diving," after the mud and detritus that characterizes such sites. The name, if you will forgive me, has stuck.

Because so much of the evolution of life has taken place in the oceans, it is not surprising that life's diversity confronts us more vividly below the waves than above them. In a walk through the rainforest that shrouds the mountains near the Lembeh strait you will see a wide variety of flowering plants and many vertebrate animals. You will also encounter many insects and other arthropods such as giant centipedes. But if you swim around Lembeh's sandy bottom you will immediately find large and colorful animals from a far wider collection of phyla, ranging from the most primitive sponges to the most complex mollusks and vertebrates. The sea is an evolutionary time machine.

Muck-diving through evolutionary time

What would we have seen if we had been able to go muck-diving in earlier times? If we could travel back far enough, we would find a very different world.

The Solar System, including the Earth, formed four and a half billion years ago, but we can only trace the history of the Earth's crust back four billion years. Before that time our newly formed planet was being pounded mercilessly by massive objects from outer space, so that its crust was melting and solidifying repeatedly. After the crust finally cooled and was stable enough to accumulate oceans and support life, living organisms appeared surprisingly quickly, probably around three and a half billion years ago. Yet, for the first three billion of those years, any time-traveling muck-divers that ventured from the lifeless land into the oceans would have swum over a seemingly dull and uniform sea bottom. The divers would have seen featureless mud flats dotted with layered concretions of bacteria and algae called stromatolites.

This apparent dull uniformity masked a great deal of evolutionary activity that gave rise to some of life's most essential capabilities. Many different kinds of bacteria evolved soon after the first appearance of life. Some of them were able to photosynthesize, and some lineages of these bacteria eventually bequeathed these abilities to multicelled organisms that became the higher plants. As a result of these new ways of manipulating the environment to extract energy, the very chemical composition of the atmosphere and the oceans gradually changed, making the world's environment more like that of the present time.

Very little of this activity has been preserved in the fossil record. A few traces of possible bacteria may have been found in Australian rocks as old as three and a half billion years, although the exact nature of these early fossils is embroiled in controversy. Stromatolites were plentiful throughout the early history of life, but the oldest ones do not show clear signs of being built by layers of bacteria and may have simply been the result of geological processes.[10]

About 625 million years ago this superficially rather boring world of living organisms began to change. A scattering of modest-sized and extremely odd creatures with no obvious affinity to present-day organisms began to leave traces in the fossil record. These mysterious creatures make up the Ediacaran biota, named after regions in Australia where they were first found.

Even this collection of creatures, exciting though they were in comparison to the dull bacterial communities of earlier times, would have seemed pretty dull to our time-traveling scuba divers.[11] Although frond-like structures dotted the sea bottom like waving feathers, and strange flat creatures slithered among them, most of the Ediacaran organisms, like those that preceded them, were still too small to be seen with the naked eye. And yet, as we will see, this simple world might have provided an environment for evolutionary experimentation that would not have been possible during either earlier or later times.

Then, 542 million years ago, at the start of a geological period called the Cambrian, everything changed. Starting with a burst of small shelled mollusks, a multiplicity of animals soon appeared, presaging a world more like our own. The start of the Cambrian was like the beginning of a concert after an unconscionably long period during which the orchestra seems to have been merely tuning up. The sudden commencement of this full-throated evolutionary concert was so dramatic that geologists have named it the Cambrian explosion.

We have a good idea of what the bottom of early Cambrian seas might have looked like. Shale beds from the Chengjiang area that lies to the south of Kunming in southern China are filled with a wide variety of beautifully preserved fossils, prevented from decay by sudden underwater landslides. They have been dated to 525 million years ago, a mere 17 million years after the start of the Cambrian. Thriving communities of arthropods, mollusks, worms, chordates, and many other animals covered the bottom. Muck-divers in those shallow seas would have been entertained by this great diversity of creatures, though because of the lack of smart predators they would probably not have been as colorful as the creatures of Lembeh today.

The Cambrian explosion and the roots of animal divergence

The fossil record appears at first blush to show that the diversity of animal phyla arose rapidly at the start of the Cambrian. But the diversification of these animals began well before the Cambrian. At Chengjiang it is already clear that our chordate ancestors and the early mollusks were taking different paths.

A little chordate-like creature called *Cathaymyrus* from Chengjiang is the earliest animal with affinity to ourselves that has yet been found anywhere. But even this early hemichordate was already the proud possessor of gills, a heart, and a dorsal nerve chord.

The underwater landslides at Chengjiang preserved clusters of *Cathaymyrus*. These little animals apparently burrowed together in groups in the mud, like a present-day primitive hemichordate called *Amphioxus* that they resembled.

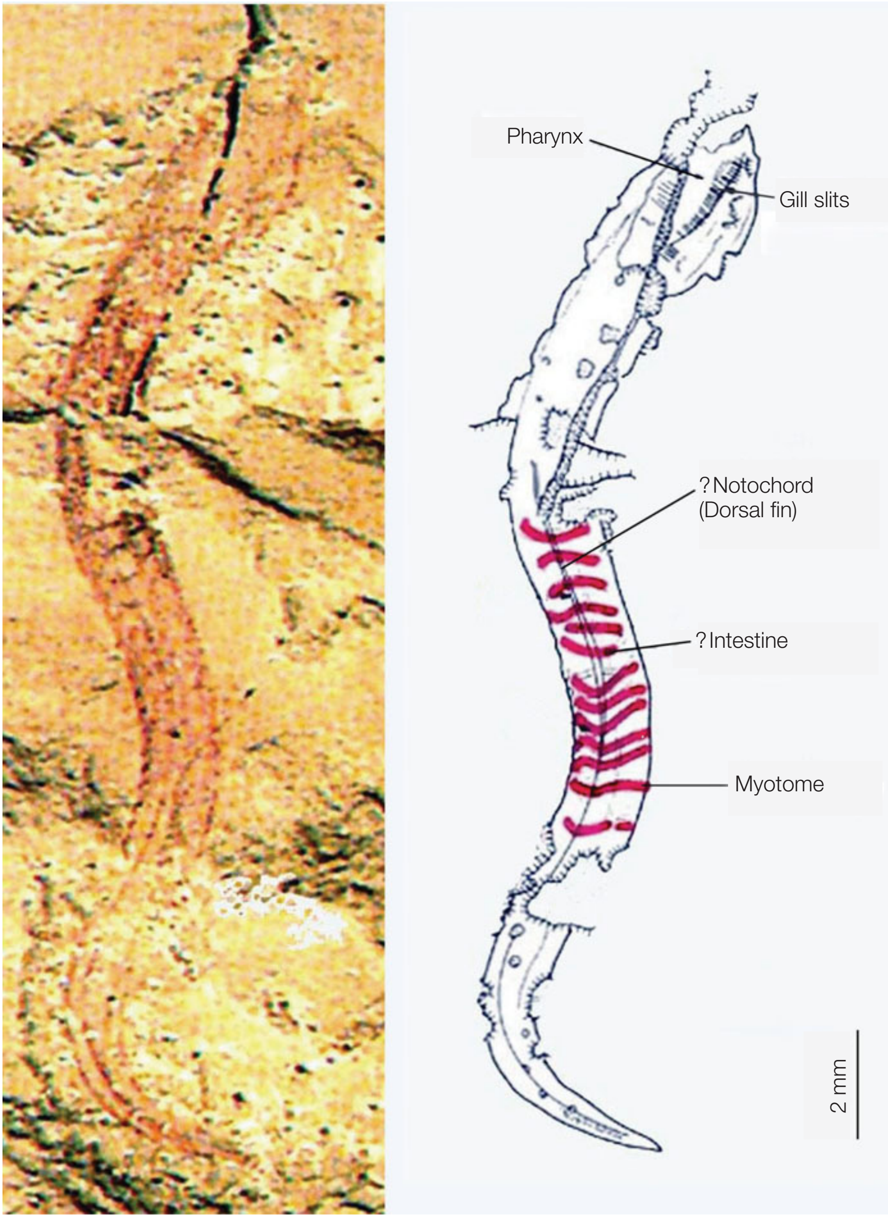


Figure 19 *Cathaymyrus*, our earliest known hemichordate ancestor, from early Cambrian rocks. These little animals, which lived in groups in soft mud, had exactly the same lifestyle as present-day lancelets, simple creatures with the scientific name of *Amphioxus*.
Courtesy of Professor Degan Shu.

Mollusks too were clearly differentiated into their own lineage by the start of the Cambrian. Millions of tiny mollusk shells, mixed with the hard parts of other organisms, are found in the very earliest Cambrian sedimentary rocks. The almost overnight suddenness of their appearance is astounding. Andrew Knoll and his colleagues have found beds of shale in southern China dated just nine million years before the Cambrian that are empty of such fossils, and contain only traces of a few simple algae. Then, nine million years later, these "small shelly fossils" suddenly appeared around the world.

We have few clues about the details of the bodies of the tiny creatures that inhabited these little shells. But the better-preserved fossils from Chengjiang show that 25 million years later mollusks were as advanced in their own way as *Haikouella*. Some of them resembled present-day clams. Others were more like present-day nudibranchs, using toothed mouth parts called radulas to scrub tiny organisms from rocks. The radulas are clearly preserved in many of these fossils.

Some of these early snail-like animals, unlike the nudibranchs, were wildly armored. One of the strangest was the Cambrian creature called *Wiwaxia*. This animal was a total mystery to geologist Charles Walcott, who found the first complete specimens in 1911 in Canadian shale deposits that were laid down twenty million years later than Chengjiang. *Wiwaxia* was oval-shaped, covered with armored plates, and decorated with twin rows of flattened spines that jutted up vertically. It looks like a helmet suitable for a punk rock singer. Walcott thought at first that it must have been a strangely armored marine worm, and later investigators put it into a totally new phylum. But close examination by Simon Conway Morris and others eventually revealed that *Wiwaxia* had a radula-like pair of feeding structures. Argument continues, but it seems likely that the previously mystifying *Wiwaxia* is a kind of primitive and well-armored mollusk.[12]

If these little five-centimeter-long animals crawled along the bottom and scraped their food from rocks, like present-day nudibranchs, then why did they need such elaborate armor? For protection, it seems. There are signs that some *Wiwaxia* shells may have been crushed and damaged by predators before they were buried and fossilized. There were some formidable predators in those Cambrian seas, especially the "fierce crab" *Anomalocaris*.

Figure 20 The mysterious *Wiwaxia*, which turns out to be a bottom-crawling armored mollusk. © Royal Ontario Museum. Photo: J. B. Caron

Possibly *Wiwaxia* had to resort to armor because it did not have the chemical defenses available to present-day nudibranchs. If, as seems likely, the predators of the time were too stupid to remember which of their prey tasted bad, then chemical defenses would have been useless in any case.

Mollusks may be the exception to the rule that nothing resembling present-day animals left fossil traces before the Cambrian. A small flat animal called *Kimberella,* named after western Australia's ancient Kimberley Range, lived during the Ediacaran period twenty or thirty million years before the start of the Cambrian. There is growing evidence that this puzzling organism had a radula. And it appears to have left scratch marks behind it as it moved across the sea bottom to feed.[13]

The circumstantial evidence is now overwhelming that our ancestors and those of the mollusks had already parted company long before the beginning of the Cambrian. But we do not have the smoking gun—the fossil record of that early divergence has not yet been identified.

Our kinship with the many-talented mollusks

What talented and successful creatures the mollusks are! We are privileged to share the planet with them, and in some modest way to claim kinship with them.

The mollusks have survived by a wide variety of methods. The clams, the mussels, and their numerous relatives protect themselves from predation with strong shells. The cuttlefish and octopuses use jet propulsion to escape from predators. Many of the most highly mobile mollusks lay down decoys of ink clouds and escape in the resulting confusion. Various mollusks have evolved the widest variety of eyes found anywhere in the animal kingdom, eyes that can perceive dangers in their environment in many different ways. Because of their sophisticated eyes, cuttlefish and squid can use elaborate color and luminescence patterns to attract the opposite sex and warn against predators. And, as we have seen, the octopuses and cuttlefish are masters of disguise, using information gathered by their eyes to cleverly match their bodies to their environment.

We chordates, diverse as we are, are boringly predictable compared with the mollusks. Although it is true that vertebrate chameleon lizards can change color, we backboned animals are embarrassingly untalented in other ways. None of us can produce and retract colorful bumps all over our bodies within seconds, like a cuttlefish can (goosebumps don't count).

The most astonishing mollusks of all, the octopuses, have simultaneously evolved high intelligence, the most detailed and complex methods of disguise in the animal kingdom, and the ability to emulate Plastic Man and squeeze through impossible places. It is true that vertebrate snakes can fit through small holes, but they already have a small cross-section. A soft-bodied octopus can squeeze through any hole that is larger than the tiny soft cartilaginous "skull" that lies buried deep within its massive but highly deformable head. A two-foot octopus can squeeze through a one-inch hole!

The differences between ourselves and the mollusks, immense though they seem to be, are beginning to close. Because of convergent evolution our eyes are remarkably similar. And so, in some respects, are our behaviors. Octopuses are the only non-vertebrate animals known to be playful, having often been observed to play with floating objects in aquaria. And, like us, octopuses can quickly open a screw-top jar once they are shown the trick.

When, how, and why did the mollusk lineage part company with ours? We now have some answers to these profound questions.

Comparisons of DNA sequences show clearly that the mollusks and the chordates had a common ancestor. But when these sequences are compared base-by-base, it also becomes clear that many changes—single bases and entire chunks of sequence that have been substituted, inserted, and deleted—have taken place during our divergence from that common ancestor. The accumulation of these numerous differences shows that our common ancestor was remote from us in time. Indeed, that common ancestor lived so far back in time that it is also the ancestor of most of the organisms that I found at Lembeh.

This DNA sequence analysis shows that two major diverging branches of animals arose early from the common ancestor. A sub-branch of one of these two great branches gave rise to the mollusks, along with other important sub-branches that led to the arthropods and to various kinds of worms. The other major branch led to the vertebrates, including us. This second branch also gave rise to further sub-branches that led to—among others—the echinoderms. It is this second major grouping of lineages that sparked my evolutionary musings as I hovered over that spiny mob of fire urchins in the Lembeh Strait. The DNA evidence is unequivocal: the echinoderms are much more closely related to us than the mollusks or the arthropods.

We can put firm dates on some of the events in our ancestry. This is because, whenever we have both DNA evidence and fossil evidence about the ancestry of animals, they tend to agree beautifully. For example, there are a relatively small number of DNA differences between ourselves and chimpanzees—our DNA sequences are 96% identical, and we share almost all our genes. Such a high level of identity tells us that we do not have to travel very far back in time to find our common ancestor. The fossil record agrees with the molecular evidence. Both lines of evidence show that the common ancestor of humans and chimpanzees lived about six or seven million years ago.

The estimates agree so well because our own fossil record is so well studied and because the fossil record of the mammals provides multiple calibration points for the times at which various mammalian DNA divergences began.

But as we move back, to a time before the Cambrian when the fossil record becomes uncertain, it is as if we were walking off a cliff. Without fossils and relying only on molecular evidence, we can be certain that different groups of organisms had a common ancestor, but we are not sure when that ancestor lived. The further back we go, the greater the uncertainty over timing grows.

Part of this is the fault of the DNA sequences, which can diverge at different rates. For example, when Kevin Peterson of Dartmouth University and his colleagues built evolutionary family trees using vertebrate and mollusk DNA, they found that the vertebrate branches of the tree were only half as long as the mollusk branches. It seems that vertebrate DNA in general has evolved at only about half the rate of mollusk DNA. We do not know why these rates are different, and why these different rates have been maintained for well over half a billion years.

Despite these difficulties, many groups of scientists have used the growing library of DNA sequences to probe the distant past. They have been cautious, extrapolating back from well-supported dates, and using a variety of assumptions about the rates of DNA evolutionary change. Some of these studies estimate that the common ancestor of scuba divers and cuttlefish might have lived as much as a billion years in the past. Others, using different statistical methods, arrive at the more recent date of 650 million years ago, a mere hundred million years before the start of the Cambrian. Still other estimates fall between these extremes. But none of the dates are so recent that they fall within the Cambrian itself. The consensus is that these animal lineages did indeed begin to diverge at some point in time well before the start of the Cambrian.[14]

Thus, by the beginning of the Cambrian, the fossil and DNA evidence agree that much diversification had already taken place, though the exact nature of that diversification remains a mystery. At the time of the Cambrian explosion, environmental changes allowed each of these already-divergent lineages of small soft-bodied organisms to grow larger and evolve various hard parts such as skeletons or shells, so that they were more likely to be fossilized. Thus, the Cambrian explosion was not really sudden. In the memorable phrase of Simon Conway Morris of Cambridge University, it had a long fuse.

How we and the mollusks first parted company

The DNA evidence makes clear that my feeling of kinship with the mollusks of Lembeh is well founded. But how and why did we first part company, and why did we take such separate evolutionary paths? These questions are much harder to answer, because they require evidence from the fossil record that we do not yet have.

Some intriguing hints of such evidence come from Precambrian shales and carbonate rocks in the Doushantuo formation of Guizhou Province in southern China. These beds, which date from 40 million years before the Cambrian, have yielded some tiny but well-preserved fossils that look like dividing cells. They might, as their discoverers suggest, be the remains of simple one-celled animals with cells like ours.

Tiny vase-shaped fossils from the same beds look as if they might have been the embryonic stages of small animals. But these embryos, if that is what they are, are not accompanied by any signs of the animals that they might have grown into. Nowhere in the Precambrian rocks have scientists yet discovered anything that looks like the later Cambrian organisms, aside from fragmented glassy skeletons of early sponges and that enigmatic proto-mollusk *Kimberella*.

Why were the ancestors of the Cambrian organisms so small and soft-bodied that they left such sparse and enigmatic fossils? Andrew Knoll suggests that two things may have happened. First, oxygen levels gradually rose to the point at which larger organisms could have been supported. But at the outset this rise may have had little effect, because the ecological niches of the Precambrian world were already full and there were simply no opportunities for such large-bodied creatures. At the beginning of the Cambrian, however, there is evidence for an extinction event. The resulting wave of extinctions emptied ecological niches everywhere on the planet. These new opportunities for life, coupled with the more plentiful oxygen, may have been the trigger for the Cambrian explosion.

If this hypothesis is correct, then the tiny ancestors of mollusks, worms, arthropods, and chordates that lived at the beginning of the Cambrian and survived the extinction event were finally able to take advantage of high oxygen levels and evolve into big active animals in an empty world where new ecological opportunities abounded. The oxygen-extinction hypothesis has the virtue that it explains the suddenness of the Cambrian explosion, while a scenario that relies solely on a gradual increase in oxygen levels does not. In Chapter 5, we will see evidence for a similar explosive takeover of ecological niches as mammals took over from the dinosaurs, aided in their efforts by newly emerging properties of flowering plants.

How to start on new evolutionary paths

The remaining questions that confronted me in Lembeh were perhaps the most profound. What actual physical changes took place in the bodies of our ancestors when they parted company with the ancestors of the mollusks? And might it be possible to recreate, in present-day laboratories, some approximation of those ancient changes?

Let us begin by looking at the genes that control how animals look and behave, because it is such genes that must have been involved in those dramatic Precambrian events. These genes, known as regulatory genes, govern our development from embryo to adult. They control the time and place at which other genes are switched on and off. And it is the regulatory proteins coded by these genes that must hold the answer to the shape-shifting that took place during the early divergence of multicellular life.

When regulatory genes are damaged by mutations, the results can be profound. Such developmental changes can affect the entire organism as it grows and matures. The consequences are sometimes dramatic and grotesque. In fruit flies, some of these mutations produce flies with four wings rather than the usual two, or legs that grow out of their heads instead of antennae.

My colleague Marty Yanofsky has produced equally extreme regulatory mutants in plants. He has made mutant forms of the little wild mustard plant *Arabidopsis*. These mutants have flowers in which all the different parts have been converted to sepals, the outer leaves of the flower bud. If such mutant plants had appeared in nature rather than in Marty's laboratory they would have died without reproducing.

Susan Lindquist and her colleagues at the Whitehead Institute in Cambridge, Massachusetts, have gained further insights into mutations that have such large effects by working with the fruit fly, *Drosophila melanogaster*. Under the microscope this tiny fly is revealed to be a complex and jewel-like creature, with bright red faceted eyes, subtly patterned wings, and antennae that allow it to home in on the tiniest chemical signals from that slice of cantaloupe you are eating.

Lindquist and Suzanne Rutherford examined fruit flies that make a defective form of a protein called a chaperonin.[15] Chaperonins are proteins that, as their name suggests, act as guardians of other proteins.

Many of the proteins in our cells are extremely fragile. When they are being synthesized by the cellular machinery they tend to flop around like newborn babies. Chaperonins bind firmly to these delicate proteins during the critical birth process, coercing them to take the right shape so that they can play the correct role in the cell's development. Like Mary Poppins, the chaperonins permit no nonsense from their unruly young charges. They make sure that their protein pupils, many of which play important regulatory roles, get to their proper place in the cell and bind to the right parts of other proteins or to the right regions of DNA, without the molecular equivalent of making funny faces in the process.

The chaperonin that Rutherford and Lindquist investigated is a "heat-shock protein" called Hsp90. High temperatures are dangerous to proteins, and many organisms, ourselves included, synthesize plentiful amounts of these heat-shock chaperonins to protect our other proteins under these extreme conditions.

Fruit flies cannot survive if they make no Hsp90, so Rutherford and Lindquist used flies that carried one damaged and one normal form of the Hsp90 gene. These mutant flies made half as much of this chaperonin as normal flies. This small genetic change was enough to cause a few of the flies to develop abnormally. Among the many different kinds of abnormalities, some of these flies had misplaced and misshapen eyes, while others had wrinkled wings.

When Rutherford and Lindquist picked some of these abnormal flies and bred them, they found that within a few generations all the progeny were abnormal. Even the progeny flies that had two functioning Hsp90 genes continued to show abnormalities.

What had happened? When Rutherford and Lindquist saw funny-looking flies among the progeny of their crosses, they were finding the flies that had the least robust developmental pathways and that were therefore most likely to be sensitive to low chaperonin levels. After they had selected and bred these flies for several generations, they ended up with lines of flies with developmental pathways that always tended to be easily disturbed. The flies' development was abnormal even when chaperonin molecules were present in their usual numbers and were doing their best to maintain discipline.

Rutherford and Lindquist's developmentally disturbed fruit flies had so many things wrong with them that they could never have survived outside of the laboratory. Such organisms would probably not have survived the kinds of large developmental disturbances that might have sent Precambrian creatures off on new evolutionary paths. But perhaps the criteria for survival are less strict for animals smaller and simpler than fruit flies. Small life forms that consist of only a few cells, such as the early animals that lived in the Precambrian, might have a better chance of surviving drastic body-plan modification than large complicated organisms such as present-day fruit flies.

What if we could perform experiments like those of Rutherford and Lindquist on organisms simpler than fruit flies? How drastically could we modify such simple organisms and still leave them able to survive and even thrive?

There are signs in present-day animals that drastic modifications of their remote ancestors' body plans did indeed take place. Early in the nineteenth century the French anatomist Geoffroy Saint-Hilaire came to a remarkable conclusion about a major pair of branches in the tree of life. Vertebrates, he declared, are simply upside-down arthropods (or vice versa). At some point early in our history we (or they) flipped over, so that our spinal cords form along our backs and those of the arthropods form along their bellies.

However, our faces and the faces of arthropods do not show this rotation. Both groups of animals have their eyes above and their mouths below. So it may be that the first Precambrian ancestor to undergo the flip did so by a feat of contortion worthy of the Boneless Wonder in a circus sideshow. Its body rotated 180° behind its head, leaving its head in the original orientation.

Saint-Hilaire's explanation of the body plan difference between arthropods and chordates, widely ridiculed at the time, has turned out to be correct.[16] It is of course difficult to imagine such a drastic rearrangement happening in stages. And the rearranged organism was more likely to have survived if it was a small simple Precambrian creature than if it was a larger and more complicated creature living at some later point in time.

Recreating the Precambrian

We cannot yet recreate the drastic developmental mutations of the Precambrian in the laboratory, because we have no Precambrian organisms to experiment on. But it is not beyond the realm of possibility to make and study similar changes in simple laboratory organisms available today.

A good candidate for such experiments is the tiny roundworm *Caenorhabditis*, which is a mere one millimeter long. This worm normally lives in soil, but it can easily be raised in the laboratory. And its development is delightfully simple and predictable. An adult worm's body is made up of exactly 959 cells, no more and no less.

Caenorhabditis has genes for Hsp90 and other chaperonins. It is now possible using molecular techniques to "knock out" this and any other of the genes of these little worms. It has been found that damage to the Hsp90 gene causes problems with the worms' metabolism and shortens their lives.

Suppose that we damaged these and other chaperonin genes in the worms and placed the resulting mutants in a variety of new environments? Would it be possible to select for worms with a different body plan? Could some of these changed worms survive, and even thrive, under the altered conditions that we impose on them? Perhaps we could produce changes in these worms that are as far-reaching as the dramatic reorganizations that happened to our tiny ancestors during the Precambrian, more than half a billion years ago.

Something similar has been done using computerized life forms. In 2000, Hod Lipson and Jordan Pollack of Brandeis University carried out an important study of such cyber-creatures.[17]

Lipson and Pollack created a diverse population of replicating life forms in a computer, and competed them to see which could move most quickly across a virtual flat surface. These virtual life forms were simple. They were controlled by a collection of virtual electronic circuits representing a minimalist "brain." The brain circuits were connected to a variety of virtual body parts such as rods and ball joints. The brains of these computer creatures could move the rods and cause them to change their length, and could rotate the ball joints that linked these rods together.

These "organisms" were allowed to replicate themselves in the computer. The computer program that directed their replication was instructed to introduce occasional random changes, so that mutant organisms arose each generation. At random, the brain circuits could be switched to new patterns, the linkages between the various rods and joints could change, and body parts could change their character from one type to another. Because the mutations happened at random, just as in the real world, most of the mutant organisms were grotesque constructs that received random signals from their "brains" and flailed about uselessly. A minority of them, however, could do something useful.

The computer program then dumped each generation of organisms onto a virtual flat surface, and monitored how quickly they could crawl, hump, writhe, or wriggle their way across it. The slowest creatures were condemned to cyber-oblivion, and the fastest creatures were allowed to replicate and to undergo further random mutations.

In experiment after experiment, selection for the fastest organisms resulted in the emergence of certain types of body plans. One especially effective type was a little rigid pyramidal shape enclosing an angled rod that could change its length. The little creature's brain was wired to drive the rod repeatedly down and backwards, sending it across the level surface like a pole-driven punt on the River Cam. Another extremely efficient creature was shaped like an arrow. It "rowed" itself forward by two extensible arms set at angles to its "head," just like a little rowboat. A third creature, a twisted parallelopiped,

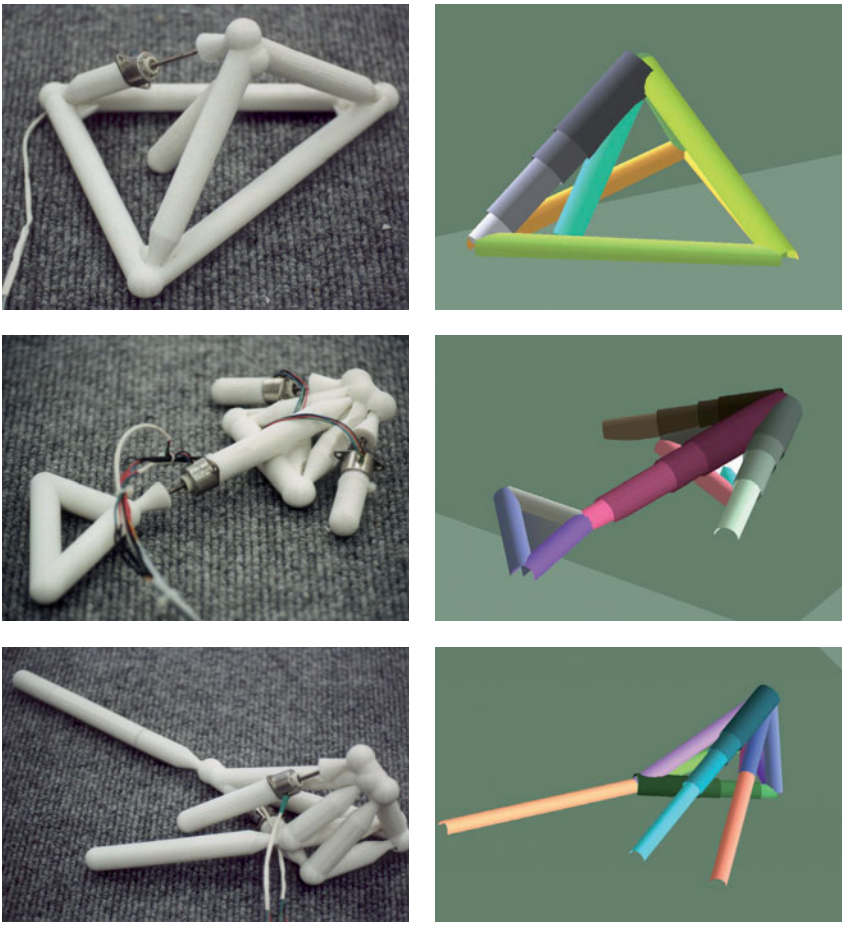
a
b
c


Figure 21 Some of the more successful robots that were produced by artificial selection in the computer world of Lipson and Pollack. The creatures generated by the computer program are on the right, and on the left are real models of them that turned out to be equally successful in moving across a flat surface. Note that creature (b) is clearly bilaterally symmetrical, a body plan that took minutes to emerge in the computer but may have taken millions of years to emerge in the Precambrian seas! (From Figure 5 of Lipson and Pollack, *Nature* 406 (2000): 974-8.) © Hod Lipson and Jordan B. Pollack, Brandeis University

hobbled along by extending and contracting itself like a distorted inchworm. When the experimenters constructed real models of these virtual organisms, the models were able to move swiftly across a real surface.

One striking feature of this strange menagerie was how often these virtual creatures "evolved" a head and a tail end and bilateral symmetry. Like our own bilateral body plan, their left and right sides were sometimes mirror images of each other. Convergence on this body plan happened repeatedly, even though the cyber-creatures' ancestors had started out as different random and ineffectual collections of parts.

It is perhaps not coincidental that one of the earliest events in the evolution of animals, an event that happened long before the Cambrian, was the emergence of bilateral symmetry from ancestors that had previously been round or irregular in shape and that lacked a head or a tail. Bilateral symmetry gives organisms the ability to move directionally through the environment. It seems to be a highly favored evolutionary path, both in Precambrian organisms crawling across a mud sea bottom and in virtual organisms that must make their way across a computer-generated surface.

Lipson and Pollack's experiment provides us with some guidance on how to design our *Caenorhabditis* experiments. Because this worm is already bilaterally symmetrical, we will have to select for other types of body-plan changes. Perhaps collections of mutated *Caenorhabditis* could be selected for the ability to wriggle quickly across a smooth surface, while at the same time they are being buffeted by a current of water flowing in the opposite direction. Would we select for worms that can adhere to the surface, so that they can wriggle forward despite the current? Or would we select for worms with sail-like structures that would allow them to tack against the current? The possibilities are endless. Perhaps we could create a world like the Precambrian one, in which it is possible to select for many different body plans simultaneously.

Closing the gap between scuba divers and cuttlefish

As I roamed the floor of the Lembeh Strait I met many radially and bilaterally symmetrical creatures that are the remote descendants of Precambrian developmental mutants. When I locked gazes with my inconceivably distant relative, the flamboyant cuttlefish, I felt a kinship that reached across the 600 million years of accumulated genetic differences that separate us.

Cuttlefish and octopuses are the world's most expert shape-shifters. We have lost that ability, but our remote ancestors and theirs were shape-shifters too. They underwent changes in shape as they evolved in the Precambrian seas, and it was those alterations that set us on our different paths. And now we are on the verge of recreating and understanding such changes.

As I hovered in the magic world of Lembeh another question occurred to me.

If we and other vertebrates were to go extinct, leaving the field open for octopuses, could these organisms too develop culture and science? Could an intelligent and daring octopus eventually propose a theory of natural selection? And perhaps other octopuses, offended by the presumptuous scientist's attack on the octopus god that created them, would exclaim: "Nonsense! We could not possibly be descended from that ugly *Wiwaxia* creature!"