Lecture on Animal Evolution, 4/28/2000
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The title of our three-day symposium is "At Home in the Universe." I want to talk to you about the emergence of the human race in terms of what it takes to make us feel at home in the universe.

The first thing I think we need to notice here is that what makes one person feel at home may give another person the creeps. Think, for example, about people who go to gatherings of strangers — say, to a party, or to an international congress of world religions. Some people at these gatherings are trying to fit in, while others are trying to stand out. The fitters-in want to be accepted as part of the community. The standers-out want to be noticed as different.

What applies to parties and parliaments applies equally to the universe. Some want to fit into it, while others want to stand out in it. People of the former sort feel comfy when they can see themselves and the rest of the human race as fitting into the big picture, as part and parcel of the network of natural laws and processes. Let's call these people integrators. They like to think of themselves as part of nature: objects among their fellow objects, animals among their fellow animals. They don't believe that there is a sharp boundary between people and other creatures, or that human life has a peculiar kind of sanctity, or that human souls have a unique supernatural existence or destiny. They tend to think that human mental and spiritual properties have at least some sort of rudimentary presence in other animals. They want to believe that the human species came into existence naturally, and that it it was exactly the sort of thing that you might have expected to happen.

Other people, by contrast, prefer to stand out from the universe. Let's call these people isolators. They like to see themselves and their fellow men and women as splendidly set apart from the stones and trees and beasts. They regard humans as radically different from the rest of the material world: unique in intellect, unique in moral perception, unique in conceptual thought — maybe even unique in being conscious of the world at all. They regard the creation of the human species as something of a miracle, or at least a billion-to-one coincidence. They tend to see the human mind and spirit as unique, and human interests and wishes as having a transcendental importance that utterly outweighs the interests and wishes of nonhuman creatures. They are seldom ethical vegetarians.

Of course, these are polar stereotypes, and most of us fall somewhere in the middle in our feelings about the place of humanity in the universe. Still, I think that most people tend to fall closer to one extreme or the other.

What I want to do for you here today is to sketch a very brief outline of the history of life that we see in the fossil record, or at least of those events that are especially important for explaining human origins. Then I'm going to lay out for you two alternative ways of looking at that history. The first is an isolator's view, which portrays the major events in the human evolutionary career as unpredictable accidents, and sees the emergence of human beings as a unique and highly unlikely happenstance. The second, which is the way I myself prefer to look at things, views those events as the sorts of things that might have been expected to happen sooner or later. I hope to persuade you that the emergence of intelligent life on this planet was chancy but not wildly improbable, and that it has in fact happened more than once. I hope also to persuade you that this way of looking at things helps us to feel more at home in the universe.

(SLIDES—PRECAMBRIAN LIFE) √

Multicellular life first shows up in the fossil record around 570 million years ago, in the so-called Precambrian period. All living things on earth at this time lived in the sea -- as we might expect, because life originated in the sea, and it took it a long time to work out ways of moving onto the land. Most organisms back then were microscopic, just as most organisms are today. But the multicellular life of the Precambrian doesn't look much like anything we find in our modern oceans. Most of the large Precambrian organisms are built on a body plan unlike anything known from the present. They were flattened mats of pasted-together tubes, spreading outward from a central core or axis.

(SLIDE— SEILACHER'S CROSS-SECTIONS) √

In cross-section, these things looked like an inflatable swim-mat or air-mattress. One popular theory among scientists who study these fossils is that these hollow tubes acted like greenhouses, in which photosynthetic bacteria grew in a protected environment and provided their tube-making host with food and oxygen.

(SLIDE—GRAPHOGLYPTID TRACE FOSSIL) √

What did the bacteria need to be protected from? We don't know for sure. Most of the fossils of these air-mattress creatures are found in coarse-grained sandstones deposited in shallow offshore waters, which is a kind of depositional environment that doesn't preserve most organisms very well. But other kinds of Precambrian deposits yield fossils like this one here, which can be described as worm tracks in mud — traces left by animals moving in or along the surface layer of the ocean floor. Presumably whatever left these Precambrian tracks was grazing on the the thin mat of tiny one-celled organisms that covered the bottoms of the shallow Precambrian seas. The hollow tubes of the larger Precambrian creatures may have sheltered their internal microorganisms from these grazers.

The important thing to notice here is that there is no evidence of predation — no multicellular organisms eating each other. Just microscopic plants and bacteria living directly or indirectly by photosynthesis, using sunlight, and a few larger organisms living off the bacteria, either by slurping them up from the sea floor or by culturing them internally and digesting their byproducts.

This collection of creatures is sometimes called the Ediacaran fauna, after the type locality in Australia. Mark McMenamin, who unfortunately had to cancel his appearance here today, has called this phase in the history of life the "Garden of Ediacara," with reference to the Garden of Eden in the Bible. And here at the dawn of terrestrial life, there does appear to have been something rather like a Peaceable Kingdom. There are no jaws or teeth in this world. As a corollary, there are no defensive structures — no shells or carapaces or spines or spikes — preserved in the fossil record. We can assume that the chase and the arms race between predator and prey had not yet begun. This was a world without weapons or armor; and therefore it was a world without speed, and a world without brains.

(SLIDE—CLOUDINA) √

Shells make their first appearance around 550 million years ago. This slide shows the shell of one of the first armored organisms, which lived during the last days of the Garden of Ediacara. Presumably the serpent had already put in an appearance in the Garden, because this organism needed to be protected from something.

At the end of the Precambrian, there is an abrupt change in the fossil record. Quite suddenly, in the space of a few million years of transition, hundreds of genera of armored animals appear in the rocks, covered with shells and carapaces and spikes and plates. This change marks the beginning of the Cambrian period.

(SLIDE—TRILOBITE) √

Among the most common and familiar of these Cambrian newcomers are the trilobites, which vaguely resemble armored seagoing centipedes. These creatures, once wildly successful but now extinct, represent a major group, or phylum, of animals called the arthropods. Other arthropods are still wildly successful today. They include all the hosts of insects on the land and crustaceans in the sea: segmented animals with external skeletons of chitin and many jointed legs.

(SLIDE—YOHOIA) √

There are a lot of arthropods in the Cambrian faunas, including some groups that are still with us and many others that are not. Most of the other major phyla of today's animals are represented in the Cambrian, including molluscs and brachiopods and echinoderms and various groups of worms, as well as a lot of strange-looking creatures of uncertain relationships—

(SLIDE—NECTOCARIS) √
(SLIDE—OPABINIA) √
(SLIDE—ODONTOGRIPHUS) √
(SLIDE—HALLUCIGENIA) √

—like this one. We now know that this reconstruction is upside down; these prongs aren't walking legs, but defensive spines on the back that would have made this bizarre creature — whose name, for obvious reasons, is Hallucigenia — less attractive to predators.

This defensive armor is one of three important Cambrian themes or motifs I want you to notice, that occur over and over again in many of these diverse groups. The second of these themes is bilateral symmetry. This thing has a head end and a tail end and left and right sides. That tells us that it's specialized for moving in one particular direction. In the case of Hallucigenia, we aren't sure which end is which, but in most other cases, it's pretty clear—

(SLIDE—ANOMALOCARIS) √

—because the head end has sense receptors and jaws and prey-catching organs. This is Anomalocaris, a relatively huge Cambrian animal that grew up to a meter in length and seems to have made its living by eating trilobites. It exemplifies the third Cambrian theme, which is predation. These Cambrian organisms are true animals; that is, they live by eating other organisms, biting chunks out of them and killing them and consuming their tissues — as we all do ourselves. The Garden of Ediacara is closed; and the air-mattress creatures of the Precambrian have abruptly vanished from history.

(SLIDE—PIKAIA) √

In several Cambrian localities around the world, fine-grained shales deposited in deep water have preserved soft-bodied animals in great detail. And in one of these, the

Middle Cambrian Burgess Shale in Canada, we find something close to the beginning of the human story. This wormlike creature is Pikaia. It is the first generally accepted representative of our own phylum, the chordates.

(15 min.)

(SLIDE—BRANCHIOSTOMA) √

We can get a more detailed idea of what the first chordates must have been like by looking at primitive chordates that survive today. This animal, known as a lancelet, lives in shallow sea bottoms off the coasts of Asia. It's a wormlike animal about 5 centimeters long, and it's not very impressive to look at. But it has four characteristics that we find in all chordates, including you and me. The first chordate peculiarity, which gives the group its name, is a stiffening rod called the notochord, a kind of primitive backbone that runs down the back of the animal. The second is another cord, made of nerve cells, the spinal cord, lying between the notochord and the skin. The third is these W-shaped blocks of muscle attached to either side of the notochord. These segmented muscles wiggle the animal's tail and send it scooting through the water. The fourth chordate trait is these holes, or gill slits, in the side walls of the throat. The animal breathes and feeds at once, by squirting sea water out through these slits and swallowing any solid leftovers. Human embryos still retain the notochord and gill slits; the muscle segments and spinal cord are evident in human adults.

The Cambrian fossil Pikaia had the muscle blocks, the swimming tail, and the notochord that we see in this modern lancelet. It had begun the development of a long series of key evolutionary inventions that were crucial for the eventual appearance of humankind. The first was a predatory habit of life — using other organisms for food. The second was the invention of bilateral symmetry, with a head and a tail end. I've already mentioned that both of these innovations are general themes of Cambrian life. A third novelty was the invention of a rudimentary internal skeleton — the notochord. We don't see this in most other Cambrian animals, who wear their hard parts on the outside for protection. A fourth was the invention of a centralized nervous system: a nerve cord running down the back, which could take in sensory stimuli, process them, and produce appropriate motor responses, like wiggling the tail to swim or burrowing into the mud to hide.

(SLIDE — BRANCHIOSTOMA HEAD) √

The lancelet is a chordate, but not a vertebrate. It has no jaws, no brain, no eyes or other special sense organs at the front end — just gill slits and tentacles. The spinal cord simply ends near the head end of the animal, and the notochord extends all the way to the end of the snout.

(SLIDE—LAMPREYS) √

Vertebrates added two more key inventions to the chordate list. The first was a true head with eyes and brain, more or less just pasted on up here in front of the notochord. We find the rudiments of this new add-on already in Pikaia. The second vertebrate innovation was an internal skeleton of bone or cartilage, with a brainbox surrounding the brain and a string of vertebral elements forming a primitive backbone around the notochord.

The early vertebrates appear to have been something like these living lampreys, which are found today in rivers and lakes and seas all around the world.

(SLIDE—LAMPREY HEAD) √

Lampreys have no jaws, and so they attack their prey with this rasping sucker surrounding the mouth opening. But they have eyes of the standard vertebrate sort, and a sort of tongue, and a skull and backbone of cartilage, and a small but clearly vertebrate brain elaborated out of the front end of the spinal cord.

(SLIDE—ORDOVICIAN OSTRACODERMS) √

The first true vertebrates appear in the period after the Cambrian, the Ordovician, about 430 million years ago. They had bony skeletons, and so they had a much better chance of fossilizing than soft-bodied animals like Pikaia or a lamprey. Most of their bones were worn right underneath the skin, forming a sort of dermal armor plating that presumably helped ward off attacks from predators. We still preserve some pieces of this dermal armor in our skulls and collarbones.

Most of these creatures had small, stiff, toothless mouths, and they were presumably bottom-feeders and worm-eaters like modern catfish. More aggressive predation on larger prey had to wait on the next major invention in the human lineage: namely, jaws that could cut and kill other big animals and tear them up into pieces small enough to swallow.

(SLIDE—COBELODUS HEAD) √

Vertebrate jaws evolved from the bones of the gill arches, the columns of tissue in between the gill slits. As you can see in this primitive shark, the upper and lower jaws appear to be just beefed-up versions of the gill-arch bones further back along the sides of the throat.

(SLIDE—COCCOSTEUS, ARTHRODIRE) √

The first vertebrates with jaws appeared about 400 million years ago. This one shows you the difference between the dermal armor of the head and the flexible internal bones of the spine.

(SLIDE—RHIPIDISTIANS) √

In most of these early jawed fish, the body was no longer covered with bony armor. It wore a flexible chain mail of small bony scales, coated with hard enamel. The scales inside the mouth were pointed and had sharp tips to help hold and tear prey. We still have a set of these enamel-coated scales in our own mouths: our teeth.

Most modern fish have replaced these enameled scales with delicate little translucent chips of bone, but we're descended from a group that hung on to the big primitive scales for quite a while. This slide shows some of these fish. They manifest another invention that was crucial for the emergence of humankind: two pairs of limbs, a front pair just behind the head and a hind pair back near the anus. These fish are called by a Greek name that means "fleshy fins," because these fins were thick and muscular. It was lucky for us that they were, because this made it rather easy for these fins to evolve into arms and legs when some of these fish began coming out of the water.

(SLIDE—EUSTHENOPTERON LIMB BONES) √

The bones inside these muscular fins can be matched up with the larger bones in our own arms and legs. Here, for example, in the pelvic fin of one of these fish from the Upper Devonian, around 360 million years ago, we can make out the distant precursors of the hip bone, the thigh bone, the shin bone, ankle bones, and toe bones.

(SLIDE—ICHTHYOSTEGA) √

The first land vertebrates show up in the fossil record at about this time. Apart from their arms and legs, they still look quite a bit like big fleshy-finned fish. Some of the very early ones even have a fin on the tail. These weren't the first creatures to colonize the land. If they had been, there wouldn't have been anything for them to eat. Plants had preceded the vertebrates onto land by some forty million years, and various invertebrate groups — including the ancestors of insects — followed the plants onto the land not long afterward.

(SLIDE—PALEOZOIC AND MESOZOIC OXYGEN CURVES) √

The spread of land plants may have altered the earth's atmosphere. Changes in the chemistry of the sedimentary rocks suggest that oxygen levels began to rise back here in the Devonian, about 400 million years ago, at about the same time that plants were beginning to spread across the continents. During the next period, great forested swamps spread across the continental lowlands, and land plants underwent an evolutionary radiation. Much of our coal today is mined from deposits laid down in these swamps, which is why this period is called the Carboniferous. The air's oxygen content rose to a peak 280 million years ago in the early part of this next period, the Permian. It plunged back down again during the Permian to its earlier level, and then rose more slowly up to something like the levels we see today.

Some biologists think that these changes in the atmosphere were driving the evolution of animals as well. They contend that the rise in oxygen during the Carboniferous period would have made it easier to live by breathing air, and that this allowed the arthropods and the vertebrates to move out of the water onto the land. Some argue that these high oxygen levels and the high metabolic rates that must have gone with them allowed insects to take to the air as well. The high oxygen levels permitted the evolution of the famous giant insects of the Carboniferous, looking like dragonflies with a wingspread a meter across.

During the Permian and the period that followed it, the Triassic, the swamps of the Carboniferous tended to be replaced by deserts. One possible cause for this is the movement of the continents. The earth's continents float on the slowly moving liquid rock that underlies them, and are borne around by its currents like islands of scum on the surface of a simmering pot of soup.

The Permian continents slowly drifted together near the equator to form a single Triassic supercontinent, called "Pangaea," which is Greek for "all earth." The coalescence of Pangaea wiped out the shallow seas between the continents. The supercontinent's huge size and low latitude promoted the spread of deserts. And as the world's land masses grew drier and merged together, plant life suffered. The diversity of fossil land plants fell during the Permian — the only time this has ever happened in geological history. [Ross & Allman, p. 80] It is probably not a coincidence that oxygen in the earth's atmosphere dropped throughout the Permian [POINT TO GRAPH] and bottomed out with the Triassic consolidation of Pangaea.

[SLIDE—EARLY REPTILE WITH EGGS] √

This drying-out of the continents contributed to the success of the next great invention by our ancestors — the development of an egg that could be laid on land. The Carboniferous land vertebrates needed to lay their eggs in fresh water, just as frogs and salamanders do today. But the new eggs allowed vertebrates to move away from the water and adapt to a new sort of life in the dryer uplands.

[SLIDE—AMNIOTE EGG]

The new eggs were a marvel of economy. They had sealed-in supplies of food and water, complete with toilet facilities to store the wastes of the developing embryo. The shell was stiff enough to keep the egg from flattening out, and it was also tough enough and tight enough to keep bacteria out and water in. But it was also porous enough to let oxygen in and carbon dioxide out. This is a tricky set of conflicting demands for an eggshell to try to juggle. Some scientists claim that the uniquely high oxygen levels of the early Permian atmosphere were the only thing that made the evolution of this new egg possible.

[BACK TO SEYMOURIA] √

The animals that were laying these eggs were the primitive reptiles, which appeared at the end of the Carboniferous. From the very beginning, there were two main groups. One group had one hole in the sides of the dermal armor of the skull; the other had two holes. The one-hole group contains our own ancestors. You can still trace this hole in the side of your own head; it's the soft area full of muscles between the dermal armor up here at the top and the dermal armor of the cheekbone.

The one-hole reptiles were the dominant land animals of the Permian, but their rule was short-lived. The end of the Permian saw one of the three greatest mass extinctions in the history of life on this planet. We aren't sure why this happened. The coming-together of Pangaea may have had something to do with it. Another theory holds that massive volcanic eruptions at this time altered the atmosphere, kicking already-stressed animal populations over the line into extinction. For whatever reason, most animal species disappeared. It has been estimated that 95% of all multicellular organisms may have become extinct at this time — including most of the one-holed reptiles.

[SLIDE—RETRO DINOSAUR PICTURE] √

The ecological roles that they vacated were quickly snapped up by the two-hole reptiles, which included the ancestors of the dinosaurs. The first dinosaurs made their appearance around 200 million years ago, in the late Triassic. The old-fashioned view of dinosaurs was that they were slow, cold-blooded, stupid, lumbering creatures who died out because they couldn't adapt to changing times. This is a Victorian steel engraving of that retro dinosaur image.

[SLIDE—NEO DINO, AVIMIMUS] √

But the current fashion is to see dinosaurs as active, nervous, birdlike creatures with warm blood and feathers. And if birds are surviving small dinosaurs, as the consensus has it nowadays, then at least some dinosaurs must have been warm-blooded and birdlike. Well, maybe not quite <u>this</u> birdlike.

By the end of the Triassic, the dinosaurs and their relatives had replaced the one-holed reptiles as the dominant land animals. But one small group of the losers had figured out a way to survive in the shadow of the dinosaurs.

[SLIDE—TRICONODONT] √

They became tiny, nocturnal, and warm-blooded, scurrying around in the darkness under the roots and leaves of the forest floor, protected against the chill of the night by a coat of insulating bristles. They were fierce predators — on beetles and worms and such — and they were also fiercely protective mothers, guarding and incubating their eggs, and feeding their hatchlings on fatty secretions from modified sweat glands on their bellies.

These were the early mammals, from which we are descended. The suite of innovations that made their way of life possible included a lot of the key inventions in the human lineage. I could list dozens of them, but they can all be summed up in two phrases: small size, and a constantly high metabolic rate. All the details of the teeth and jaws and fur and lungs and skin and reproductive system that are peculiar to mammals are corollaries of these two items.

The mammals stayed small and inconspicuous for the next 135 million years. Of course, they made some improvements during that period. Their teeth became more complicated and efficient at grinding and slicing food. Some of them evolved keener senses of smell or hearing. Others began eating plants. One group stopped putting shells around their eggs, and just let the embryos develop inside the warmth and safety of the mother's abdomen until they were ready to come out into the world and drink milk. But despite these innovations, mammals retained their nocturnal habits and their small size, from a few grams up to no more than four or five kilograms. They did not grow big or presume to compete with the dinosaurs. It took an astronomical collision to bring them out into the sunshine and raise them into prominence as the dominant land animals.

[SLIDE—DUCKBILLS AND K-T OBJECT] √

This fanciful drawing shows a herd of large plant-eating dinosaurs gazing with bovine serenity at a strange object moving across the sky. The object was a medium-sized asteroid, a rocky piece of space debris some 10 to 15 kilometers in diameter. It struck the earth 65 million years ago near what is now the northern coastline of Yucutan, in Mexico.

[SLIDE—CHICXULUB CRATER] √

We can still trace the outlines of this impact, which left a crater around 200 kilometers across. Sedimentary rocks all around the world from this time horizon carry debris thrown up by the impact — dust with enriched levels of the metal iridium, tiny spheres of molten glass, amino acids not found in terrestrial sources, and so on. In the rocks overlying this thin layer of debris, no one has ever found an undisputed fossil of a dinosaur. The conclusion seems inescapable. In one way or another, the asteroid impact was responsible for yet another great mass extinction, marking the boundary between the Mesozoic Age of Reptiles and the Cenozoic Age of Mammals.

(35 min.)

[SLIDE—MICROCEBUS} √

Within ten million years, most of the niches that had been occupied by dinosaurs had been filled by furry upstarts. And this mammalian radiation also encompassed some new ways of life that hadn't been explored by members of the dinosaur group. One group of mammals stayed small and nocturnal, but took to climbing around in trees to feed on fruit and insects. They developed soft, moist, prehensile hands and feet for grasping the thin twigs they crept around on, and they enlarged their eyes and moved them around to the front of the head so that they became more useful for detecting prey. These were the earliest representatives of our own mammalian order, the Primates. In addition to their fossils, we have some surviving primitive primates, like this mouse lemur from Madagascar, to give us an idea of what early primates were like.

[SLIDE—MIOCENE APES] √

Several lineages of primates quickly began experimenting with larger body size and plant-eating habits, feeding on the leaves and fruits of the trees they lived in. These include the ancestors of modern monkeys and apes — and humans. These so-called higher primates have tended to evolve daylight activity patterns, dextrous hands, and big brains. This slide shows a reconstruction of some of the monkey-like fossil apes of the Miocene, around 10 million years ago. The apes were a successful group back then, but they have since been largely replaced in the tropical forests of the Old World by langurs, macaques, and other monkeys that have more efficient teeth and guts than the apes have.

[SLIDE—ORANGS] √

The surviving apes share a suite of peculiar features of their arms and shoulders that allow them to feed while hanging underneath branches, instead of running along the tops of branches on all fours. Our own ancestors came from this group, and we retain their arm-swinging specializations. We can still do this if we have to, though we're not nearly as good at it as these orangutans.

[SLIDE—LUCY PELVIS] √

Here in Africa around five million years ago, some of these arm-swinging apes started coming to the ground and walking on their hind legs. These are the earliest representatives of our own peculiar lineage, with no living descendants except ourselves. These so-called man-apes, the australopithecines, looked something like chimpanzees with human legs and feet. You'll be hearing about them in more detail from Ron Clarke, who is one of the world's leading experts on these creatures. I'll just say that we know that they were bipeds—partly because of the evidence of their limb bones, like this pelvis of the famous "Lucy" skeleton from Ethiopia—

[SLIDE—LAETOLI FOOTPRINT] √

—but also because we are lucky enough to have some actual fossil footprints, laid down around 3.6 million years ago in a fresh fall of volcanic ash in Tanzania.

It isn't clear why these man-apes took to walking around on their hind legs, and scientists debate how much their locomotion resembled ours.

[SLIDE—LOVEJOY LOCOMOTOR MODEL] √

Some think that these early hominids had an essentially human form of terrestrial bipedalism. Others, as you will probably hear from Dr. Clarke, think that they were still spending a lot of time up in the trees, and that their locomotor habits were significantly different from ours.

[SLIDE—NARIOKOTOME] √

But there is general agreement that bipedalism had been perfected by around two million years ago, when the first fossils of our own genus, Homo, show up in the rocks of Africa and Java. These early species of Homo were still subhuman; but their bodies were essentially like ours from the neck down, their brains were far larger than any modern ape's, and they made and used simple stone tools. The rest of the story of human evolution is mainly a matter of the enlargement of the brain, culminating some 50,000 years ago in the appearance of people indistinguishable from ourselves—

[SLIDE—LASCAUX] √

—with fully human language and culture, capable of making the celebrated cave art of France and Spain or the rock art of Africa and Australia.

[40 min.]

I've used 30 minutes of our time to sum up the story of human evolution. That works out to around a million years every four seconds. As you might imagine, I've skimped on the details. But I think we have enough facts at hand to go back to the question I started with — namely, was the emergence of humankind something that could have been expected, or was it a miraculous billion-to-one shot?

Many of the scientists who study this 500-million-year-long story would take the latter position. And we can see why if we look at a list of what I've been calling the key inventions.

[SLIDE—"KEY INNOVATIONS"] √

In order for an intelligent, upright, and bipedal vertebrate to emerge from the long, complicated history of this planet, all of these things had to happen in just the right order — and at the just the right time to take advantage of environmental opportunities, like surges in atmospheric oxygen or asteroid impacts. Let's assume, for the sake of argument, that the chances of each of these 13 events happening were fairly high. Say the odds against each event were no more than ten to one. That means that the probability of the whole series is one in 10 to the 13th power. If so, the chances against our evolutionary emergence were ten trillion to one. Clearly, the emergence of intelligent life on this planet must have been either staggeringly improbable or driven by an external Providence. Or so it might seem — and so many people have argued.

I doubt it, because I doubt the numbers. It is always hard to make statistical arguments about the history of life, because we have a sample size of one: life on this planet. But what we can do is to see whether any of these events have happened more than once in that history. If we can find multiple occurrences — what are called evolutionary parallels — then we can assume that the story of human evolution exemplifies patterned regularities in the evolutionary process, and that something like this series of events would have been likely to have happen sooner or later: at least more likely than one chance in ten-to-the-thirteenth.

Let's take a look at the parallelisms in animal lineages other than our own. We've already noted that the first two items are general themes of the Cambrian radiation. I would go further and say that anywhere in the universe where life evolves, some organisms are eventually going to stumble upon the cheap and dirty strategy of eating other organisms. Once this happens, the chase is on. And that makes it very likely — I think inevitable — that some organisms will develop preferred directions of movement, and therefore have a head end and tail end and bilateral symmetry. So for the first two items on this list, we have a probability of one — not of point oh-one, as our first calculations suggest.

The internal skeleton seems chancier. Most non-chordates don't have one, and the ones that do, like starfish and sea urchins, don't look very much like plausible human ancestors. But there is one invertebrate group that has evolved its own sort of notochord along with a very fishlike way of life—namely, squids.

[SLIDE—CEPHALOPOD SHELL EVOLUTION] √

The octopus-squid group of molluscs evolved from animals with a coiled external shell, like that of the surviving chambered nautilus. Squids have reduced that shell to an internal stiffening rod of a bone-like substance, which does much the same job as a notochord or vertebral column.

[SLIDE—SQUID ANATOMY] √

The rod is shown here in pink. Squids have also added some other skeletal elements, including cartilage in these fins and a box of cartilage surrounding the brain. For jaws, they have a parrot-like beak and a rasping tongue. They have big image-forming eyes very much like a vertebrate's—

[SLIDE—SQUID BRAIN] √

—attached to a well-developed brain. In short, squid are poised to take over if fish suddenly become extinct. They give us some reason to think that the evolution of fish-like fast-swimming predators, with eyes and brains and spines and skulls, was not a billion-to-one improbability.

Jaws and predation on large prey, the fifth key innovation on our list, are another sure bet in the evolutionary lottery. These organs and habits have been evolved in dozens of other animal lineages. I just pointed out the birdlike beaks of squid and octopus—

[SLIDE—NEREIS HEAD] √

—and we see other sorts of prey-catching and -shredding apparatus around the mouth in annelids—

[SLIDE—SAGITTA] √

—and in arrow worms—

[SLIDE—B/W ANOMALOCARIS] √

—and in our old friend Anomalocaris from the Burgess shale, and so on and on, to say nothing—

[SLIDE—GRASSHOPPER] √

—of the complicated mouthparts we see in insects. And the case of insects reminds us that our next item—the conquest of land, and the evolution of eggs that could be laid on land—was another sure bet. At least eight different lines of animals, including molluscs, three phyla of worms, and several arthropod groups, crawled onto land and started laying eggs there alongside the vertebrates.

[SLIDE—CRAB] √

And this story isn't over. There are still things coming out of the sea and learning to breathe the air and compete for a place on dry land.

[SLIDE—MESOZOIC O^2 LEVELS] √

The next key innovation in our lineage was warm blood and small size, and the maternal care of helpless offspring that goes with these things. This complex of traits isn't a sure bet, but we know it wasn't wildly improbable, either, because birds evolved the same complex. Some people have suggested that the evolution of warm blood in birds and mammals was a response to the lowering of Triassic oxygen levels, and was therefore an unpredictable event driven by the happenstances of climate change. I doubt it, because the birds and their relatives probably didn't evolve warm blood and feathers until after the end of the Triassic, by which time oxygen levels were back up to about what they are today.

[SLIDE—NYCTICEBUS] √

Primate origins— that is, the shift of small mammals into a life of visually-directed predation in the trees — were also a good bet. Trees themselves are a sure thing. Anywhere in the universe where there are photosynthetic plants whose growth is limited by the available sunlight, we can expect to find them competing by casting shadows on each other. A tree is a plant adapted to casting shadows on its shorter neighbors. So trees and forests were an inevitable outcome of the plants' conquest of land. And where there are trees, there will eventually be small herbivores climbing in them and eating off them; and so we can expect that small arboreal predators will eventually evolve to eat the herbivores.

[SLIDE—CERCARTETUS] √

And this has happened more than once on this planet — for example, among several groups of marsupials.

[SLIDE—CHAMELEON] √

Even some lizards have evolved primate-like visual predation and grasping extremities.

[SLIDE—EULEMUR/ADAPIS X-RAYS] √

How about the evolution of big brains in the higher primates? Again, we see lots of parallels. Loring Brace pointed out long ago that monkeys are a sort of mammalian parrot — noisy, bright-colored, gregarious, intelligent diurnal fruit-eaters living up in the trees in the tropics. And if we step back and look at the bigger picture, we see that mammalian brains have been gradually getting larger ever since the dinosaurs went away—not just in monkeys, but in many other lines as well. This slide compares x-rays of the skull of a modern lemur from Madagascar with a 40-million-year-old fossil relative of about the same size. The colored areas represent the brain. You can see what a difference 40 million years has made. I could show you similar data for many other orders of mammals. We're not sure why so many mammals (and also birds) have been slowly getting smarter, but it seems that intelligence must be advantageous in a great many different ways of life. Brain enlargement isn't always inevitable, but it clearly isn't an unlikely chance event restricted to the human lineage. There are selection pressures driving it in all sorts of warm-blooded vertebrates.

[SLIDE—ORANG] √

Ape-like arboreality also has its parallels in other lineages. Tree-dwelling animals rarely get very big, because of the obvious dangers involved in falling. But those that do grow big move cautiously through the trees, hanging underneath branches for greater security. Ape-like habits and anatomy have evolved in at least four different primate lineages (two of them extinct)—

[SLIDE—SLOTH] √

—and we see something very similar in a different mammalian order among the sloths of South and Central America.

What about human bipedality? Here we find no real parallels among other primates, or indeed any other mammals. But striding bipedalism was one of the key adaptations underlying the whole radiation of dinosaurs—

[SLIDE—OSTRICHES] √

—including their modern representatives. Who knows what might have emerged from an additional sixty million years of evolution of warm-blooded dinosaurs with functional, grasping forelimbs? If it hadn't been for that asteroid, we might have seen a world populated by intelligent bipeds—covered with feathers; and attending learned meetings to argue about why no large mammals ever evolved.

But this is fantasy, and the asteroid impact is a fact. And you might argue, as many people have argued, that without that asteroid, human beings would never have evolved. For Stephen Gould and many others who champion the unpredictability of history, the impact event at the end of the Age of Reptiles has become something of an icon, demonstrating beyond any shadow of doubt that the race is not always to the swift, nor the battle to the strong, and that the course of evolution is governed by a kind of ontological randomness that pervades the history of the world. Who could have known that the asteroid would strike? And without that knowledge, who could have predicted that human beings would step forth on the world's stage?

This is a seductive argument, but I think it is philosophically mistaken. And in this particular case, I think it is grounded in a misleading habit of thought about large body size.

[SLIDE—VELOCIRAPTOR EATING MULTITUBERCULATE] √

We like to say that dinosaurs were the dominant land animals of the Mesozoic. Why do we say that? Well, because they were big. Mammals couldn't compete with dinosaurs at large body size. The poor mammals crept about under the feet of the dinosaurs, trembling at the thunder of their footsteps, and occasionally getting snapped up and eaten. Doesn't that mean that the dinosaurs were dominant? Isn't that what we mean by domination?

Well, it does if we think about individuals—about big guys and little guys getting into fights in bars. But this is a mistake. The important fact here, in terms of ultimate survival, is that the dinosaurs couldn't compete with mammals at the other end of the size spectrum.

[SLIDE—SMALLEST DINO, COMPSOGNATHUS]

True, there were no very large mammals at the end of the Cretaceous. But there were also no very small dinosaurs. This is the smallest dinosaur ever found. Adults were about the size of a house cat or a large chicken. But this was a hundred times as big as the average mammal of the period. And in the long run, small size makes for survival and large size makes for extinction.

Large animals are fragile. They're physically fragile, because of the square-cube law—for the same reason that big cartons of books break open more easily than small cartons. But they're also ecologically fragile. It is a reliable rule throughout the history of life that whenever there is an environmental catastrophe of any sort, the big animals—what we call the megafauna— will disappear and be replaced afterward by enlarged versions of some of the small animals.

Why are large animals ecologically fragile? For two reasons: they have fewer individuals per square mile than small animals, and they have fewer species as well. If a catastrophe wipes out 95% of the individuals in a species, or 95 of every 100 species, mice are far more likely to survive than elephants are. In the long run, the small things are the ones that survive. A wise Martian who came to Earth in the Jurassic would have looked around at all the tiny, trembling mammals — and noted the absence of tiny, trembling dinosaurs — and said, "Well, that's it, then; the mammals have won. It's just a matter of waiying for the next asteroid." If a similar asteroid hit the earth tomorrow, elephants and lions and giraffes would probably vanish away; but mice would survive if any mammals did.

Would we survive? I don't know. I'd like to think so. But if we didn't, and if subsequent evolution brought forth another species capable of composing symphonies and chalking up equations on blackboards, I would venture to predict that the composers and mathematicians of that successor species would have very large front teeth. Because among living mammals, it's the rodents, not the primates, that have achieved that dominion of the Kingdom of the Small that makes for immortality.

And what about that last trait on the list — human intelligence? Why hasn't that evolved in parallel? Here again, our preconceptions are blinding us to the facts— in this case, to the fact that humanlike intelligence <u>has</u> evolved in parallel in several lineages of other animals. I'm not thinking here about the celebrated experiments with Kanzi and other apes that show that chimpanzees are capable of picking up English without any training or rewards. Chimpanzee minds are very much like ours, though stupider. But that might not be a parallelism; it might be a shared inheritance from our common ancestor. No, I am thinking here of other lineages — parrots, for example. The last common ancestor of people and parrots was a primitive reptile that lived almost 300 million years ago. It looked like a giant salamander with scales. It had no more social skills or intelligence than a frog has. And yet 300 million years later, the minds of people and parrots have undergone so much convergent evolution that the two can be friends. They can enjoy each other's company, and groom each other, and understand and respond appropriately to each other's emotions. And experiments show that properly trained parrots can mean human words when they utter them, and understand what we mean when we say them. We see similar convergent evolution of mind, social intelligence, and protolanguage in many non-primate mammals as well. There are even rudiments of it in the squid-and-octopus group of molluscs.

I don't want to leave you with the impression that I think there is some sort of Bergsonian élan vital behind the history of life, pushing it in a human direction. Life pushes in all available directions at once. But some directions are more available than others; and the sequence of key innovations that led to the emergence of humanity follows some well-worn pathways, which more than one lineage has traced in parallel. The appearance of an animal something like ourselves was not a sure thing — humans are not as inevitable as trees — but it was <u>natural</u>. Something like us had a decent chance of coming into existence on this planet.

To an integrator like myself, this is a pleasing thought. It makes me feel more at home in the universe to know that creatures like us might be expected to emerge from the evolutionary process under the right circumstances. And this is also pleasing to me as a scientist trying to understand the world. The supposed uniqueness of the human condition, which some people think gives human life its significance, seems to me to be just another word for unintelligibility. After all, to explain something is to show that it fits some recurring pattern. If anything is truly unique, it is inexplicable. One of the peculiar gifts of our species is that we are better at discerning patterns than the other animals are. The singular glory of humanity is not our isolation from the order of nature, but our dawning comprehension of how we fit into it.

KEY INNOVATIONS IN HUMAN EVOLUTION

1. Heterotrophy (eating other organisms).
2. Bilateral symmetry.
3. Internal skeleton.
4. A head, with special sense organs and nerve centers.
5. Jaws and predation on large prey.
6. Paired fins/limbs.
7. Reptile–type egg, laid on land.
8. Small size + high metabolism (insulation, maternal care, etc.)
9. Arboreal visual predation.
10. Monkeylike brains and social intelligence.
11. Large size (and suspensory habits).
12. Bipedality.
13. Large brains, technology, and language.