Notes on the evolutionary history of life

By Chris Wright

Reading *A New History of Life: The Radical New Discoveries about the Origins and Evolution of Life on Earth* (2016), by Peter Ward and Joe Kirschvink. A great book, so dense with information I have to take notes in order not to forget everything.

For almost a billion years the early Earth, largely molten, was bombarded by meteorites and comets, as well as ultraviolet radiation. An environment not exactly hospitable to life. It seems that the oldest fossil is from 3.4 billion years ago, of bacteria that needed the element sulfur to live and died if exposed to oxygen. (Related bacteria exist today.) The world was much hotter than today, with air composed of the (to us) toxic gases methane, carbon dioxide, ammonia, and hydrogen sulfide.

There have been many hypotheses for where and how life began. One possibility is that scalding deep-sea vents provided its environment. "The vents emit chemicals that are appropriate for the evolution of life, such as hydrogen sulfide, methane, and ammonia amid lots of hot water. The vent chemistry would be largely decoupled from the atmosphere, and thus the evolution of life could have taken place independent of the atmosphere. This removed the problem that the Earth's atmosphere at the time was not chemically correct to form life. But the so-called vent origin had its own problems. How could RNA, that highly unstable molecule, have formed in the vents, with their high temperatures and pressures?"

Another possibility is that RNA (which can form DNA) may have originated in desert conditions. "RNA is a very fragile molecule, large and complicated, and thus very easily destroyed. Water attacks and breaks up the nucleic acid polymers (strings of smaller molecules) that make up RNA." So maybe a dry environment would be more promising. The problem is that Earth's surface at this time was pretty much entirely ocean. But what about Mars? Mars never had planet-covering oceans, but it did have large bodies of water, which are necessary in order to form the borate minerals that are needed to stabilize RNA. It also had other advantages over Earth. So maybe life came here on meteorites from Mars.

Experiments have shown that meteorites can come here from Mars without being heat-sterilized, meaning life could have survived the journey. A large impact on Mars could easily have hurled life-bearing meteorites onto Earth. This is the scenario the authors favor.

Anyway, here's how the chapter on the beginning of life ends:

> The two major components necessary for life are a cell that can reproduce itself and some sort of molecule that can carry information, as well as performing chemical catalysis (changing conditions so that a chemical reaction that would not otherwise occur does take place because of the action

of the catalyst being present)… Cells and RNA [may have] evolved as a single unit—double-walled cells of fat with small RNA nucleotides within them grew by obtaining more fat and more nucleotides, which could have passed through gaps in the fat of the cell wall, whereas the larger linked nucleotides of the interior would be too large to pass out of the walls. The material available on the early Earth necessary to make the protocells were chemicals that would have combined to form fatty (lipid) molecules, which themselves would readily link together to form sheets and then spheres.

…The earliest life might have been composed of cells with very porous cell walls, allowing the swapping of whole genomes, a process known as horizontal gene transfer. But there came a time when the cell systems went from ephemeral to permanent. This is the point that biologist Carl Woese called the "Darwinian threshold." It is the point where species, in something approaching the modern sense, can be recognized, and when natural selection—evolution in other words—takes over. Natural selection favored more functionally complex, integrated cells than simpler precursors, and they flourished at the expense of the simpler modular varieties.

Modern Earth life was born when the radical changing of genes stopped. Some who study the evolution of the first life, such as Carl Woese, believe that arriving at this grade of organization is the most important event in all of evolutionary history. Yet those first cells were surely not alone, for there were probably ecosystems packed with all manners of complex chemical assemblages that had at least some life aspects. We can think of a giant zoo of the living, the near living, and the evolving toward living. What would that zoo contain? Lots of nucleic acid creatures of many kinds, things no longer existing and having no name because of this. We can imagine complicated chemical amalgamations that have been roughly defined as RNA-protein organisms, RNA-DNA organisms, DNA-RNA-protein creatures, RNA viruses, DNA viruses, lipid protocells, protein protocells. And all these huge menageries of the living and near living would have existed in one thriving, messy, competing ecosystem—the time of life's greatest diversity on Earth, perhaps 3.9 to 4.0 GA (billion years ago), but with our new view being that it was later rather than sooner. Natural selection whittled what might have been a thousand really different kinds of life down to one.

So, sometime in the middle of the Archean period (which lasted from 4.2 billion to 2.5 billion years ago) various life forms appeared, somehow. Much of early life used methane for food, but eventually cyanobacteria evolved, which were the first oxygenic photosynthesizing organisms. "Some of their descendants were enslaved by other organisms, and now serve us all as the green light-gathering organelles in plants and other algae. Every plant on Earth now has tiny 'capsules' that evolved from those first cyanobacteria, but are now 'endosymbiosis' slaves doing the bidding of the multicellular plant." Over hundreds of millions of years, these oxygen-producing cyanobacteria radically changed the composition of the atmosphere. This is the Great Oxygenation Event.

"[T]he evolution of the cyanobacteria was the most profound biological event on this planet (even more so than the evolution of the eukaryotic cell, and then multicellular life)."

One major consequence of all this production of oxygen and consumption of carbon dioxide was the first Snowball Earth event, which may have lasted 100 million years or so. This would have been around 2.3 billion years ago. The majority of life died out, but cyanobacteria survived, probably in local hot springs. Only after volcanic activity had released enough greenhouse gases could this frozen period come to an end. When it did, the cyanobacteria multiplied in numbers "almost incomprehensible" because the oceans, having been submerged under ice for so long, had loaded up on nutrients from hydrothermal vents. So there were further massive increases in the amount of oxygen in Earth's atmosphere, until it was "supersaturated" in oxygen (because there weren't yet organisms capable of breathing it, as animals do). Finally oxygen-breathing eukaryotes appeared around 2 billion years ago, restoring some balance to the atmosphere. They used mitochondria, which had originally been independent bacteria, as sources of energy—which relied on oxygen.

It took a very long time, though, for common multicellular life to evolve. Why? For a billion years or more there wasn't enough oxygen to support animal life (even though, it seems, many millions of years earlier there had been more than enough, when there weren't any oxygen-breathing organisms around at all). The reason is that there was an overabundance of sulfur-using bacteria, which relied on a type of photosynthesis that doesn't split water apart or produce oxygen. They populated most of the ocean, and after dying, their rotting bodies would have used up many of the oxygen molecules being emitted by other bacteria. After hundreds of millions of years these sulfur-consuming bacteria largely (though not entirely) died out for various complicated reasons, making possible levels of oxygen that could support animal life.

But there were already primitive multicellular organisms around, going back to 2 billion or more years ago. *Grypania*, for example, were bacteria that seem to have lived as "colonies" of cells, held together and bound by membranes. Multicellular plants evolved over a billion years ago, "species probably looking very much like the green and red algae found on any seashore." But it isn't until about 600 MA (million years ago) that fossils of true animals appear in abundance.

A summary:

> Here is a view of a shallow sea bottom, some 1 billion years ago: Kelp-like plants and green algae wave in the currents, as do shimmering mats of rainbow-hued microbial life, multicolored sheaths of the softest chiffon covering all of the sunlit portions of the bottom. Stromatolites peak out from the bottom sheaths, large to small domes and hummocks punching upward out of the microbial sheaths. The water is thick with life, single celled to multicellular. There is nary an animal anywhere on the planet…
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> In the oceans a revolution was brewing a billion years ago, while on land there may already have been a vast biomass of life: the ever-resourceful microbes, invading first ponds and swamps, but ultimately covering wetlands, bogs, and anywhere that was exposed to sun, had a least a modicum of water, and might get windblown dust with enough phosphates and nitrates to allow these tiny, single-celled plantlike microbes to grow their land-covering tarps of green snot. Life, colonizing the land in exuberance…

But then a second Snowball Earth episode occurred, from 717 to 635 million years ago, once again extinguishing most life. This second episode may have been caused primarily by the movement and tectonic activity of continents. The supercontinent Rodinia began to split apart, which substituted an abundance of maritime climates for formerly arid ones. This created the potential for increased chemical weathering of silicate rock minerals, which causes a reduction of carbon dioxide levels in the atmosphere. And thus a reduction of temperature.

In addition, the new (single-celled) plant species spreading over the land about 750 MA may have sucked up so much carbon dioxide that the Earth significantly cooled.

Whatever the cause, the huge masses of snow and ice that resulted shut out most sunlight and led to the loss of nutrients like iron, phosphates, and nitrates. But over millions of years, volcanoes and hot springs produced small warm bodies of open water, in which organisms could thrive. "Evolution works best on small, isolated populations. Thousands of these small marine and even freshwater refuges would have been evolutionary incubators, using the principle of 'genetic bottlenecks' (where tiny populations, when isolated, can quickly evolve because of their small number of genes). In this way, protozoa, those small single-celled eukaryotes, may have evolved into many different kinds of metazoans—animals. With the release of the snowball conditions, caused by the eventual buildup of greenhouse gases from all of those active volcanoes, there would have been rapid melting of the ice, as well as a rapid release of these thousands of new evolutionary experiments."

So Snowball Earth ironically fostered conditions necessary for the future rapid evolution of complex organisms. This is even more likely because it's known that many organisms respond to environmental stress by wholesale reorganization of their genomes. And Snowball Earth was certainly stressful.

The Ediacaran period, the last period before the start of the Paleozoic Era, began 635 million years ago and saw the beginning of truly complex and large multicellular life. Perhaps even animal life. Tiny wormlike creatures with *bilateral symmetry* appeared around 600 MA, and they apparently evolved into many of the larger Ediacarans, which colonized the world. These were soft-bodied, sexually reproducing, virtually immobile creatures that lasted until 540 million years ago, when they were wiped out by the animals, including predators, of the Cambrian explosion. Some of them were like fronds, some like worms, some like soft discs, etc. They don't seem to have any obvious evolutionary descendants.

Summing up:

> In the time between about 635 and 550 million years ago, a whole new category of organisms had evolved, ones with internal water-filled spaces that could act as an internal or hydrostatic skeleton, as well as creatures with muscles, nerves, specialized sensory cells, germ cells, connective tissue cells, and the ability to secrete precipitated skeletal hard parts. Animals or not, the Ediacarans were the first on Earth to evolve skeletons, albeit nonmineralized. Skeletons allow for the attachment of muscles, and muscles allow locomotion. Locomotion then creates other needs that continue to drive the evolution of ever more complexity. Once moving, an animal needs sensory information to find food and mates, as well as to avoid predators. Sensory information needs a brain to process it. All of these developments were intertwined, and were triumphs of the eukaryotic metazoan revolution, which is really what happened near the end of the Proterozoic.

Then, of course, was the Cambrian explosion, when all the current animal phyla appeared. It was apparently a result, at least in part, of oxygen levels finally growing high enough by 550 or 540 million years ago. The iconic fossils of this time are the trilobites, arthropods with three body sections, fairly complex eyes, limbs, and large size. Even two or three feet long. But trilobites weren't the first animals: they appeared around 520 million years ago, well after the first tiny fossilized exoskeletons from about 545 MA. There were also brachiopods, echinoderms, mollusks, sponges, and cnidarians (the latter two may have been present among the Ediacarans), but the arthropods were the most successful and numerous animals of the Cambrian.

The authors have a fascinating discussion of what I've always found to be a central problem with Darwinism, namely that it can't really explain the origin of *novelty*. "The radical breakthroughs—be it the appearance of wings, legs for land, segmentation in arthropods, or even large size, the hallmark of the Cambrian explosion—could not stand up to stories about many and sudden [random] mutations all working in concert to somehow radically change an organism." Exactly. But apparently this problem has been solved in recent years, which, if true, strikes me as a theoretical development of the first importance. Commenting on Sean Carroll's 2005 book *Endless Forms Most Beautiful*, they list four "secrets to innovation." First is to "work with what is already present." It isn't always necessary to build new equipment; it's easier to work with what's already given. The second and third are multifunctionality and redundancy.

> Multifunctionality first is using an already present morphology or physiology to take over some second function in addition to that for which it was first evolved. Redundancy, on the other hand, is when some structure is composed of several parts that complete some function. If one of these can be then co-opted for some new kind of job, while the remaining parts are still able to function as before, there is in place a clear path for innovation that is far easier to use than the total de novo formation of some entirely novel morphology from scratch. Cephalopod swimming and respiration are like this. Cephalopods routinely pump huge quantities of water over their gills, and like many invertebrates used separated "tubes" or designated channels for water coming in and water being expelled, to ensure that oxygen-rich water is not rebreathed. But with minor morphological "tinkering" with this excurrent tube, a powerful new means of locomotion came about. Breathing and moving could now take place using the same amount of energy by utilizing the same volume of water for respiration and movement.

The fourth "secret" is modularity. Animals built of segments, including to an extent vertebrates, are composed of modules. Limbs branching off arthropod segments have been modified into feeding, mating, locomotion, and other functions, while vertebrates' digits have been used to walk on land, to swim, and to fly.

But more interesting than these four "secrets to innovation" is the research on the genetic "switches" that tell various parts of the body when and where to grow. The old view was that if new animals come into existence, it must mean there are new genes. Surely a sponge or a jellyfish must have fewer genes than the more complex arthropods! Wouldn't the common ancestor of all arthropod groups have had to add new genes to those that were present in the sponges and jellyfish? No: all that was necessary was to use the already existing genes in different ways. In fact, "ten different Hox genes were all that were necessary to utterly change and diversify the arthropods." Incredibly, the thousands or millions of different kinds of arthropod morphologies all evolved using the same toolkit of ten genes. Frankly, I don't fully understand this part. But I'll quote some passages anyway:

> One of the great discoveries [of the recent 'evolutionary development' field] is that the exact sequence of different body regions on an arthropod from its head to midregion to abdomen are lined up first on chromosomes in the same geographic pattern, and then on the developing embryo itself…
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> …The old idea that some gene or genes of an arthropod coded for the construction of a leg is false. The Hox genes make proteins. These proteins then become the means of starting and stopping the growth of particular regions of a developing embryo. Some of these proteins are concerned with making specific kinds of appendages. If those Hox gene proteins are somehow moved to different geographic regions on the developing embryo, the product that is produced will move as well. In this way a leg that was formerly in one part of the body might suddenly be found in a totally new place—if, however, the Hox gene protein was somehow moved to the corresponding place on the embryo long before the leg was formed. Innovation came from shifting the geographic places or "zones" on an embryo that a specific Hox gene protein could be found in.

So…but how do these shifts happen? How does the organism, or the set of Hox genes, 'know' when it's time for some innovation, time to change things around? Presumably there's some sort of interaction with the environment, some environmental trigger for novelty. But the authors don't go into this subject in any depth.

Anyway, their suggestions are tantalizing, and I'll have to do some more reading on this topic. Epigenetics is surely relevant to all this.

The Cambrian ended 485 million years ago with a mass extinction (but a "minor" one that killed less than 50 percent of species). Oxygen levels had increased, and now, during the Ordovician, there was a new explosion of diversity. Coral reefs appeared, benefiting from the higher oxygen levels, and have remained one of the most significant and diverse of all ecosystems. Life spread to environments that had been poorly populated, such as freshwater lakes and both deep and shallow regions of the sea. It may be that the late Cambrian extinctions actually made possible all this new vitality: "[They] acted like gasoline on the open fire of diversification, perhaps, in that those forms that were less adaptive died out, opening the way for new innovation and new species in the same manner that ridding a garden of weeds leads to a rapid proliferation of new growth from the nonweeded." Many of the primitive and inefficient evolutionary designs from earlier were replaced, as competition killed off the less fit.

The biggest winners in the Ordovician were animals that lived in colonies, such as corals, bryozoans, and sponges. This was a new adaptation that hadn't really been present during the Cambrian. The Ordovician period ended 444 million years ago with the first of the "big five" mass extinctions, probably caused by a "little ice age" and falling sea levels that destroyed habitats.

In this period and through the Silurian, Devonian, and Carboniferous, plants and animals invaded the land. Lichens, fungi, and sheets of green microbes were on the land even a billion years ago, but it wasn't until about 475 million years ago that aquatic green algae began the evolutionary changes that would allow them to get nutrients and reproduce on land. And it wasn't until 50 million years later that the fossil record shows clear remains of plants with roots and stems—but no leaves yet. It took yet another 40 million years (around 385 MA) for plants with true leaves to appear. But then change was more rapid: by 360 MA, trees were up to 25 feet tall and forests almost completely covered the world.

This plant invasion utterly changed the nature of the land and the atmosphere. All the sand dunes and dust storms started to disappear as roots held the grit and dust of the land in place. Thicker soil formed as plants died and rotted, and "the ragged, rocky landscape that had always been Earth began to soften." By the late Devonian, atmospheric oxygen levels had shot up to 30 or 35 percent (compared to 21 percent today). And these oxygen levels allowed limbed, lungless fish to climb out of the sea and survive the hundreds of thousands of years it took to evolve an efficient, air-breathing lung.

In order for the green algal group, the Charophyceae, to come onto land it had to protect itself from desiccation. This may have been done by coating itself in the same sort of cuticle that covers its reproductive zygotes. But the cuticle cut off easy access to carbon dioxide (which, in water, had been simply absorbed across the cell wall), so it had to evolve many small holes called stomata that allowed the entry of carbon dioxide. Modern plants still have these. Meanwhile, stems evolved so that plants could grow upright and access more light in an environment where there was competition between many low-growing plants.

But why did it take tens of millions of years for leaves to appear? It seems that plants evolved the genetic toolkit to assemble leaves but then had to wait a long time to actually use them, because carbon dioxide levels were too high. The problem is that high CO_2 levels mean a very warm planet. The stomata that let CO_2 in also let water out, a process that cools the plant. In a hot climate, a lot of cooling is needed, which means a lot of stomata. But there was so much CO_2 that *few* stomata were needed to absorb sufficient carbon dioxide. A large leaf with few stomata would cause the plant to overheat to the point of death, so, in short, leaves couldn't appear until the planet was cooler. This began to happen as deeper roots evolved for stability and access to nutrients and water: deeper roots increased the chemical weathering of silicate rocks, which drew CO_2 out of the atmosphere and cooled the climate. So the land became full of plant life that animals could eat, as the atmosphere was full of oxygen for them to breathe. It was time for the next big step.

Arthropods were well-adapted to be the first on land, since their exoskeletons could protect them from desiccation. But they still had to evolve proper respiratory structures. The pioneers certainly had less efficient such structures than later species, but air can diffuse across the body wall of very small land animals, so this was a help. What the first land spiders and scorpions evolved was a book lung, so called because of its resemblance to the pages of a book. ("A series of flat plates within the body have blood flowing between the leaves. Air enters the book lungs through a series of openings in the carapace.") It seems that proto-scorpions with water gills came onto land 430 million years ago (perhaps scavenging on dead animals that had washed up onto beaches), followed by millipedes and insects 10 and 20 million years later. Flying insects existed 330 million years ago, by which time oxygen levels had reached modern-day levels and were climbing to record heights.

The vertebrate transition to land is a complicated story. The famous *Tiktaalik*, which was a fish with a flattened head and sturdy interior bones and limb-like fins with which it could prop itself up in shallow water, may have been an ancestor of the amphibians that lived their whole adult lives on land. It existed about 375 million years ago. (The Devonian, from 416 to 359 MA, has been called the Age of Fish.) More generally, the rhipidistians, lobe-finned fish some of which still exist (such as the living fossils called coelacanths), appear to have been the ancestors of the first amphibians. Still-living lungfish shed light on the transition from gill to lung.

It's possible that the first amphibians evolved about 400 million years ago, although the first tetrapod bone fossils (as opposed to tracks) are 360 million years old. *Ichthyostega*, from around this time, was a genus that was a kind of proto-amphibian, which like several other similar genuses existed soon after the devastating late Devonian mass extinction (caused by a drop in atmospheric oxygen that created widespread anoxia in the seas). It didn’t lead to an evolutionary radiation of amphibians, however; within a few million years, it and the other pioneering tetrapods for some reason disappeared. It wasn’t until 340 or 330 million years ago that amphibians were widespread. *Pederpes*, from about 350 MA, may have been the first true amphibian, since it had the legs necessary for land life.

In short, “The evidence at hand suggests that the evolution of the amphibian grade of organization, essentially a fish that came on land, may have taken place twice, or even three times, the first being some 400 million years ago as evidenced by the Valentia footprints as well as the *Tiktaalik* fossil discovery, and the second some 360 million years ago, and the last some 350 million years ago.”

Moving on…the next really interesting ‘phase’ of life is the time when giants reigned, during the Carboniferous and the first half of the Permian periods. Between 320 and 260 MA, atmospheric oxygen reached the highest levels in Earth’s history, making possible huge arthropods (and amphibians). Dragonflies with 30-inch wingspans, spiders with 18-inch legs, six- or seven-feet-long millipedes and scorpions. But why was there so much oxygen? “When a great deal of organic matter is buried, oxygen levels go up.” In fact, 90 percent of the Earth’s coal deposits are found in rocks of the time period mentioned a moment ago. The Carboniferous was the time of forest burial “on a spectacular scale” (as trees were spreading to new areas)—as well as the burial of plankton, which produced huge amounts of both oxygen and carbon at the bottom of oceans. Another piece of the puzzle is that

> …[b]ack in the Carboniferous, many or perhaps all of the bacteria that decompose wood were not yet present, with the key to this the seeming inability of microbes to break down the main structural component of wood, the material lignin. Trees would fall and not decompose back then. Eventually sediment would cover the undecomposed trees, and ‘reduced’ carbon was buried in the process. With all of these trees (and the plankton in the seas) producing oxygen through photosynthesis, and very little of this new oxygen being used to decompose the rapidly growing and falling forests, oxygen levels began to rise.

Eventually you got massive arthropods as a result.

It was also in this time that reptiles evolved, which, unlike amphibians, laid amniotic eggs. (They didn’t have to lay eggs in water.) This was around 310 MA or earlier. Fairly soon thereafter, “three great stocks of reptiles had diverged from one another to become independent groups: one [synapsids] that gave rise to mammals, a second [anapsids] to turtles, and a third [diapsids] to the other reptilian groups [such as dinosaurs, lizards, snakes, etc.]—and to the birds."

Regarding mammals, the authors suggest, somewhat whimsically, that there were three "ages" of mammals. First was during the Permian, the heyday of therapsids: technically these weren't mammals, but they were close, as you can see from pictures on Google. For instance, their legs weren't so splayed out to the side as in modern lizards but were under the trunk of the body, making possible a more upright position. Also, the therapsids were probably warm-blooded. They included the cynodonts, which gave rise to modern mammals. Second was the time between the late Triassic and the end of the Cretaceous, when small mammals lived in the shadow of the dinosaurs, usually creeping around at night, in burrows or in trees. Third was the real "age of mammals," after the mass extinction that decimated the dinosaurs. –So mammals have been quite resilient. At least until *homo sapiens* emerged, a species that may well kill off most mammals in the next century or two.

And then, 252 million years ago, occurred the greatest of all mass extinctions, the Permian extinction. About 90 percent of species were snuffed out. The extinction itself, or at least the most deadly phase of it, may have lasted no more than 60,000 years. Trilobites were killed off, though they had been declining for a long time.

What caused the cataclysm? First, colossal volcanic eruptions in Siberia likely ejected large amounts of CO_2 into the atmosphere, causing global warming, as acid aerosols blocked out sunlight and caused acid rain. The Wikipedia article on the event notes that massive coal beds may also have ignited, which could have released more than 3 trillion tons of carbon. To make things even worse, all this emission of carbon could have led to severe anoxia in the oceans, which would have permitted sulfate-reducing bacteria to thrive. Huge amounts of hydrogen sulfide would have poisoned the water and bubbled up into the atmosphere. Bad enough in itself, this would have weakened or destroyed the ozone layer, exposing much of the life that remained to fatal levels of UV radiation. And so on. It was a pretty hellish time.

The first few million years of the Triassic weren't much better. Temperatures in the ocean were an incredible 110°F, and on the land they were around 140°. Not much could survive these temperatures. "The entire zone of the topics would have been devoid of animals, and complex life would have hung on only at high latitudes." But it was a paradise for sulfur-loving, oxygen-hating microbes.

Later in the Triassic, mammals and (especially) dinosaurs started to become more prominent—though it wasn't until the Jurassic that the Age of Dinosaurs arrived. But even before this, an amazingly diverse assemblage of life appeared:

> In some ways it was not unlike the Cambrian explosion—a slew of newly invented body plans filling up an empty world, just as the first animals rapidly evolved into the cornucopia of body plans that filled the seas after the extinction of the first animals, the Ediacarans. And like the great Cambrian explosion, many of the body plans of novelty turned out to be but short-term experiments, to be pushed into extinction by the competition and/or predation of better-designed organisms. There is no time period other than the Cambrian and Triassic in which such a diversity of new forms appeared.

The main reason is just that the world was so empty that virtually any new design would work, at least for a while. But the authors also suggest that times of low oxygen, like the Triassic, foster a diversity of new body plans. "Body plans were being evolutionarily modified by intense selective pressures, and dominant among these was the need to access sufficient oxygen to feed, breed, and compete in a low-oxygen world."

In the sea, "new stocks of bivalve mollusks took the place of the many extinct brachiopods, while a great diversification of ammonoids and nautiloids refilled the oceans with active predators. Fully a quarter of all the ammonites that ever lived have been found in Triassic rocks, a time interval that is only 10 percent of their total time existence on Earth… A new kind of coral, the scleractinians, began to build reefs, and many land reptiles returned to the sea." On land, therapsids diversified and competed with archosaurs and many kinds of reptiles. Dinosaurs emerged about 235 million years ago, but remained rather rare and small for over 30 million years.

In an atmosphere with little oxygen, certain adaptations evolved. To breathe as efficiently as possible, the ancestors of dinosaurs and birds adopted bipedalism. "By removing the quadruped stance, they were freed of the constraints of motion and lung function." Ancestors of mammals, on the other hand, evolved a secondary palate, which allows simultaneous eating and breathing. (The nasal cavity is separated from the oral cavity.) They also grew a new powerful set of muscles called the diaphragm, which allowed a more forceful system of inhaling and exhaling.

Meanwhile, many reptiles solved the problem of living in a hot, low-oxygenated world by returning to the cooler sea. (A high temperature entails a high metabolic rate—a high rate of using energy—which means the animal needs more oxygen to fuel the metabolic processes. Since there were low oxygen levels in the Triassic, one solution was to move to the relatively cool oceans.) Ichthyosaurs, placodonts (like large seals), eventually plesiosaurs, etc.

But then 200 million years ago there was another mass extinction, and the Triassic came to an end. Another volcanic event, probably, led to skyrocketing CO_2 levels and a lethal greenhouse effect. Every group except the saurischian dinosaurs either died out or got smaller over this period, which had the lowest oxygen levels of the last 500 million years. Why did the saurischians do better than the others, even expanding their numbers? The authors argue it's because they were "unique in possessing a highly septate lung (one with many tiny flaps to increase surface area) that was more efficient than the lungs of any other lineage… [I]n the very low oxygen world that occurred both before and after the Triassic-Jurassic mass extinction, this respiratory system conveyed great competitive advantages." The Age of Dinosaurs began.

It didn't start out very auspiciously, though:

> …At the beginning [of the Jurassic], it was a shattered world: a world again coming out of mass extinction; a world without coral reefs; a world where the dinosaurs were still few in number, species, and size; a world of such low oxygen that insects could barely fly, but to no matter, as no vertebrate flier could have caught them anyway.
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> By the end of the Jurassic the largest land animals of all time were common: dinosaurs were lords of all creation; tiny primitive birds and tinier primitive mammals hid in the lowest-rent districts in town. At the beginning the seas were so bare that stromatolites had made a comeback, and the larger fish and predators were few indeed.
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> By its end there was a veritable cornucopia of the most spectacular marine denizens to have ever populated the sea: long-necked reptilian plesiosaurs, dolphin-like ichthyosaurs, and splendid primitive fish—similar to the modern-day gar and sturgeon (both with strange body armor)—schooled among vast coral reefs and an ocean filled to exuberance with all manner of ammonites and their more squid-like relatives, the belemnites…

With regard to dinosaurs, the authors don't focus on well-known facts like that birds evolved from them (or, in fact, *are* them—dinosaurs still exist!) or that because of their dominance mammals "retreated in size and numbers to become a minor aspect of the land fauna." They're trying to write a *new* history of life, after all. So, in keeping with their overall argument that levels of carbon dioxide and oxygen have been some of the most important variables for life on this planet, they suggest that both dinosaur numbers and size increased as oxygen levels rose through the Jurassic and Cretaceous periods.

> …By the end of the Cretaceous (in the Campanian age, 84 to 72 million years ago) there are hundreds of times more dinosaurs than during the Triassic to late Jurassic. So what was the cause of this great increase? The relationship suggests that oxygen levels played a role in dictating dinosaur diversity. Through the late Triassic and first half of Jurassic, dinosaur numbers were both stable and low, as was atmospheric oxygen when compared to today's values. Gradually, oxygen rose in the Jurassic, hitting 15 to 20 percent in the latter part of the period. It is only then that the numbers of dinosaurs really began to increase. Oxygen levels steadily climbed through the Cretaceous, and so too did dinosaur numbers, with a great rise in dinosaur numbers found in the late Cretaceous, the true dinosaur heyday. The dramatic rise in oxygen at the end of the Jurassic was also the time that the sizes of dinosaurs increased, culminating in the largest-known dinosaurs appearing from the late Jurassic through the Cretaceous.

Other factors must have played a role too, such as the appearance of angiosperms (flowering plants) in the mid-Cretaceous, which created more plants and sparked an insect diversification. More resources became available in all ecosystems.

Another interesting observation is that dinosaurs, or at least many of them, had the same highly efficient air-sac system of breathing that birds do, and the same hollows in their bones in which the air sacs rested. (Birds are far more effective at extracting oxygen from air than mammals, and dinosaurs must have been too.) They were also warm-blooded, like birds: they could generate heat in their bodies without external heat sources.

The chapter on the Mesozoic oceans I don't find particularly gripping, so let's skip to the chapter on the extinction of the dinosaurs. This event, of course, was caused by an asteroid impact. It led to a several-month period of darkness from all the material thrown into the atmosphere, which was long enough to kill much of the plant life on Earth, including plankton. "With the death of the plants, disaster and starvation rippled upward through the food chains." In addition, for a number of years solar energy transmission to Earth was reduced through absorption by aerosols, which produced a decade of near-freezing temperatures in a world that had been largely tropical. More than half of species died out.

But now the mammals and birds had their chance to shine. The earliest-known mammals were tiny, shrew-sized things called morganucodontids, living about 210 million years ago in the late Triassic. "Much of mammalian success came from anatomical change, including the separation of the jaw and the ear bones, which allowed the skulls of later mammals to expand sideways and backward, a prerequisite for bigger brains. But the most important of all innovations was by the revolution of mammalian teeth. The upper and lower molars of morganucodontid jawbones interlocked, letting them slice their food into pieces." The two major groups of mammals today, marsupials and placentals, diverged 175 million years ago.

So all kinds of new and larger mammals were appearing after the K-T asteroid impact…until once again, 9 million years later, there was a mass extinction. A greenhouse event, such as we're experiencing today, known as the Paleocene-Eocene Thermal Maximum (PETM). It isn't clear what caused it, though it surely involved raised methane levels, but the actual event lasted 10,000 or 20,000 years and raised global temperatures by 5° to 8°Celsius. According to Wikipedia, this warm period lasted about 200,000 years. Among plants, the gymnosperms (conifers, etc.) disappeared…but then after it was all over they reappeared. Old insect species eventually came back to life too, after seemingly going extinct for a while. But the mammals that died out didn't return; instead, the PETM marked "the start of our modern-day mammalian fauna." For instance, many marsupials and carnivorous ungulates (hoofed mammals) went extinct, while, afterwards, more modern herbivorous ungulates and carnivores preying on them appeared.

Gradually the world cooled:

> From the Eocene to the start of the 23.5–5.3-million-year-ago Miocene epoch, the world slowly began to cool. At first, during the Eocene, this was almost imperceptible, and in fact there was a global tropical forest with crocodiles living inside the present-day Arctic Circle. But in the Oligocene this cooling accelerated, creating a different kind of major climate, and changing what had been a near uniform global climate to one with extreme seasonality. At the same time, giant continental ice sheets began to form on Antarctica, and probably Greenland as well. These swelling ice sheets caused a rapid and dramatic fall in sea level. At higher latitudes, forests gradually gave way in many places to grassland meadows and savannas…

This brings us, finally, to modern ecosystems. The primates, naturally, are the animals that interest us. They date well back into the Cretaceous, some of the earliest belonging to the lemur branch. The *Purgatorius* genus, luckily for us, survived the K-T extinction; by 45 million years ago, more advanced anthropoids (which today include monkeys, apes, and humans) existed in Asia. Ten million years later, smarter, larger, and more aggressive monkeys existed, such as *Catopithecus*, which "has a skull the size of a small monkey's, a relatively flat face, and is the first primate to sport the same arrangement of teeth humans have—two incisors, one canine, two premolars, and three molars."

The hominids arrived five or six million years ago with the appearance of the famous Lucy and her kind, *Australopithecus afarensis*. The most important descendant of the early pre-Pleistocene hominids is the first member of our genus, *Homo habilis*, about 2.5 million years old. "This creature gave rise to *Homo erectus* about 1.5 million years ago, and *H. erectus* either gave rise to our species, *Homo sapiens*, directly about 200,000 years ago, or through an evolutionary intermediate known as *Homo heidelbergensis*. Our species has been further subdivided into a number of separate varieties. Some workers consider the Neanderthals to be a variety, while others interpret it as separate species, *Homo neanderthalensis*."

The first fairly modern *Homo sapiens* lived 200,000 years ago in Ethiopia. Soon this group migrated out of Africa and spread around the world, the different habitats leading to slightly different morphologies and physiologies among members of the same species.

Over the past 2.5 million years, because of orbital changes Earth has undergone, ice ages have repeatedly occurred, the more recent interglacial periods on average lasting about 11,000 years. They haven't been anything like Snowball Earth, but they've been cold enough. "As late as fourteen thousand years ago, the continental glaciers covering most of Canada and large portions of what is now the United States were still slowly melting under gradually rising temperatures." After the end of the last ice age, human populations began to increase markedly. By 10,000 years ago, humans had colonized all of the continents except Antarctica.

Meanwhile, in fact for the last 50,000 years, other changes were happening: the larger mammalian species were disappearing. For example, in the Late Pleistocene epoch of 15,000 to 12,000 years ago, a significant proportion of large mammals in North America went extinct. "At least thirty-five genera (and thus at least this number of species) became extinct. Six of these lived on elsewhere (such as the horse, which died out in North and South America but lived on in the Old World). The vast majority, however, died out. In fact, most belonged to a wide spectrum of taxonomic groups, being distributed across twenty-one families and seven orders." For thousands of years we've been in the midst of a tenth mass extinction. Which, of course, is accelerating now.

One reason for these extinctions may be that climatic changes have caused nutritious plants in North America and elsewhere, such as willow, aspen, and birch trees, to shrink in numbers and give way to the less nutritious spruce and alder groves. Another reason is probably that humans hunted species to extinction.

In South America, 15,000 to 10,000 years ago 46 genera went extinct. In Australia, earlier and over a longer period of time, 45 species of marsupials died out. Large reptiles also vanished, including a giant snake, a giant monitor lizard, a giant tortoise, etc. "The larger creatures that did survive were those capable of speed or those that had nocturnal habits." Africa was the continent least affected. "The loss of large mammalian genera in North America was 73 percent; in South America, 79 percent; in Australia, 86 percent; but in Africa, only 14 percent died out during the last hundred thousand years."

What does the future hold? The very long-term future isn't in doubt: life on Earth is doomed. The sun's energy output has been increasing for billions of years and will continue to do so. The sun won't become a red giant until about 7.5 billion years from now, but life will be long gone by then, maybe by half a billion years from now. The sun will just be too bright and energetic for organisms to survive here; in fact, oceans will evaporate (though after life disappears), and conditions will approach those on Venus.

Another problem is that CO_2 levels have been slowly but inexorably decreasing for at least a billion years. "The lowering levels are because of both life and plate tectonics: as more and more CO_2 is used to make the skeletons of organisms, especially in the oceans, CO_2 is consumed. If these skeletons stay in the oceans, the skeletally confined CO_2 (now in calcium carbonate) will recycle. But plate tectonics makes the continents ever larger, and an increasing amount of limestone, which is the grave of atmospheric CO_2, becomes locked to the continents as sedimentary deposits." The decrease of carbon dioxide won't lead to a colder planet, because the increase of the sun's intensity will utterly dwarf the cooling effects of diminishing CO_2. (Needless to say, carbon dioxide emissions from human activity will not stop the long-term trend of disappearing atmospheric CO_2.)

A low-CO_2 atmosphere will kill off photosynthetic organisms (which will, in turn, reduce oxygen levels). For a long time, plants will be able to adapt; there will even still be types of plants when carbon dioxide concentrations have dropped to as low as 10 ppm. "Eventually, however, even these last holdouts will die out." Phytoplankton will be devastated too, thus devastating all marine life. After all plants and animals have gone extinct, those hardy creatures the bacteria will still be around. Cyanobacteria, for instance. Meanwhile, the Earth will look more like it did early in its history: soils will blow away, leaving behind bare rock surfaces. The mechanical weathering of rock will build up an enormous volume of blowing sand, and the surface of the planet will become a giant series of dune fields.

It's a rather bleak future. It'll be as if life never existed. Everything that's happened—gone. No wonder people want to believe in God.

Anyway, there you have it. A summary of life's evolution. What humanity's future holds is anyone's guess, though personally I'm not very optimistic. Turning from this book to the political headlines of today is like turning one's gaze from the night's canopy of stars to a small mass of writhing maggots. The little things of the present are just so *little* compared to the grand sweep of life's history.

But we must press on, and try to influence the future using what we've learned from the past.