FISH OUT OF WATER

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Miletus was a strategically important Ionian Greek trading center on the western shore of Anatolia, where meandered the river of that name into the sea. Miletus had been Minoan, then Hittite, then Mycenean Greek, and was mentioned by Homer in the Iliad. By the 8th century BCE, it was one of the several major Ionian cities of Asia Minor, and had a considerable maritime empire. The architectural remains indicate that it was a very handsome city of white marble set on the shores of the blue Aegean. It was well placed for the flow of ideas as well as commerce, and the Ionian Greeks by the 7th century BCE were probably the cultural and intellectual leaders of the Greek world, and were not burdened with humility, as Herodotus wrote a century later:

> So long as they remained free of painful foreign oppression, they had taken to living in continental luxury beyond their needs. They went around the forum clad in purple vestments, prompt to boast of their condition, vain of their well-oiled and scented coiffure.

Cyrus's troops would appear in 494 BCE, but in the 6th and 7th centuries BCE, they were unthreatened and secure.

Until then the natural phenomena of the earth and cosmos were assumed to be completely in the hands of a pantheon sometimes noble, sometimes cruel, often capricious, metamorphic and anthropomorphic, just as they were portrayed in the bardic recitations of Hesiod and Homer. The Ionian men of affairs though were serious thinkers and began to look for less mythic explanations of nature, explanations based on universal and endurable principles which could be made comprehensible by rational human thought.

The Milesians can be said to be the first philosophers, in the vanguard of the Presocratics.. Thales was the eldest but I would judge his pupil **Anaximander**, born in 610 BCE, to have been the most influential of these proto-scientists. He wrote the first prose book on nature. Only a fragment remains, but there are many quotations from its content in the works of Aristotle and Theophrastus. His was the metaphysical and abstract idea of the "apeiron," a boundless entity from which all the life and substance of the universe originated and to which it returned cyclically. He was the first astronomer, and mapped the universe, a geocentric one of course. He said that the stars and planets had full circular orbits, and that the earth floated unsupported in space. He was the first Greek to map the known world, and he led a Milesian expedition to start a colony on the Black Sea at Apollonia. He made scientific explanations of weather and introduced the sundial to Ionia.

But the most interesting to me of **Anaximander**'s speculations concerned the origin of living things. Having observed fossil seashells on dry land, he concluded that the world at some time must have been covered by water, and that life must have come from the seas. He said that scaly fish-like creatures arose from the wet element as it was being evaporated by the sun, and that they gave rise to all animals including man. Although Anaximander could hardly be called a proto-Darwinian, it was implicit that there was a process of evolution from an earlier form of aquatic life to the fish, and from fish to man. This was a bold departure from classical religious ideas of genesis, and it is a tribute to the open-minded tolerance of the Ionians that he was not stoned in the public square, but instead honored with a statue there. After all, it was not many decades later that his fellow Ionian Anaxagoras was imprisoned and threatened with death in Athens for stating that the sun was a metallic orb, and not the Chariot of Helios. Fortunately his friend Pericles had his sentence reduced to banishment.

Though mainly intuitive, **Anaximander**'s theory of life's origin is remarkably in tune with contemporary biology. He leaves large gaps though in his story, having nothing to say about the fish's aquatic ancestors or about the process of evolving from fish to man. Thanks to our own scientific pantheon of the last three centuries, to many brilliant paleontologists and molecular biologists of our time, to genomic mapping of many species, and isotopic dating of the earth's ancient rocks, we can now attempt to partially fill in those gaps.

We can begin 4.6 billion years ago when a supernova exploded, initiating the collapse of a molecular hydrogen cloud. The center of this rotating galactic cloud condensed, initiating hydrogen-helium nuclear fusion, and thus was formed our sun. In its surrounding nebular disc (Swedenborg, Kant, Laplace), matter coalesced to form the planets, first the big gassy ones like Jupiter and then the smaller rocky ones like Earth and Mars, at about 4 and a half billion years ago. The earth was then molten, with an iron core, and it would be another 500 million years before it cooled to its present temperature. When only about 30,000,000 years old our planet was struck by another one (theoretically named Theia), dislodging the large piece of crust and mantle which formed the moon. The impact gave the earth the 23.5 degree tilt, which is responsible for our seasons, and produced enough heat to remelt what solidification had occurred in the surface crust. There was intense volcanic and seismic activity, and steam, methane, and hydrogen sulfide poured into the early atmosphere from the fractured crust. Impacting comets and asteroids brought water to the earth, and by 4.2 billion years ago the oceans had begun to form. The earth's new atmosphere now contained water vapor, ammonia, nitrogen, methane, and CO2, certainly not one that would support today's life. Not yet punished enough, the infant earth was struck, at about 3.9 billion years ago, by another intense bombardment of planetesimals and asteroids. The moon still bears the visible cratered scars of this.

Thus ended the appropriately named Hadean eon, which was followed by the Archaean 3.8 billion years ago. The earth had now cooled enough to allow the formation of the crust, which, along with the outer solid layer of the mantle, floated on the inner viscous layer of the mantle. At first only a few small protocontinents appeared on the watery earth, but they would later enlarge to form the drifting tectonic continental plates, which have continued to wander the globe's surface, coalescing, colliding, subducting, separating to this day, moving at about a centimeter a year. Do we on the San Andreas fault need to be reminded of this?

Life began at the dawn of the Archaean eon. How, despite intense scientific study, is still an uncertainty and may forever elude the grasp of human intellect. Darwin thought it might self-assemble from simple chemical elements "in some warm pond." Some have proposed that it came from outer space, and indeed organic compounds have been found in the dust of comets and in meteorites. Solutions of simple carbon and nitrogen compounds subjected in the laboratory to strong electrical currents have produced a variety of amino acids, but nothing approaching the complexity of life. More recently attention has been focused on RNA, the elder brother of DNA, which has been seen to catalyze its own formation, and could also carry the genetic instructions for replication.

The common ancestor of us all was undoubtedly a bacterium or its early microbial cousin, an Archaean. We think of it as simple, but in its one cell it contained all the structural, enzymatic and genetic machinery needed for its survival and reproduction. And this cell structure remains the basic template for all life since. Single celled microbes were the only form of life for another three billion years, and even today are the most abundant, stable, and essential of living organisms. Bacteria are well known to us, but Archea are a separate and more recently recognized domain of microbial life, and many are capable of living in extreme conditions—in the boiling heat of volcanic vents or in the depths of Antarctic ice floes. All these microbes were prokaryotes—they had no cell nucleus and their proteins and DNA floated rather loosely in their cytoplasmic soup. They reproduced by binary fission, simple splitting in two—quick, but with little opportunity for genetic variation. And since they lived in an atmosphere of CO2, N2, methane, H2S, NH4, the early bacteria had to survive on a metabolism which was anaerobic, not needing oxygen. As time went by however, two changes essential to our very existence would occur—the microbial production of oxygen and the development of the eukaryotic cell.

Bacterial growth became inhibited by dwindling supplies of carbon in the earth. There was plenty of it, however, in atmospheric CO2, and so there evolved a cellular process for capturing carbon from the air and converting it to sugar. Since it required energy from the photons of sunlight it is called photosynthesis. Quite fortuitously and unteleologically, the waste product of this reaction was oxygen, which at first was readily taken up by the reduced minerals, iron especially, of the earth, producing the red iron bands in rocks which we see in the Painted Desert of Arizona. Eventually though the earth became saturated with oxygen, and it began to be freely discharged into the air, causing a gradual increase in atmospheric oxygen. This oxygen was, however, fatal to anaerobic bacteria, causing the first great extinction, or the "great oxygen catastrophe," about 2 billion years ago. Oxygen-using, or aerobic bacteria then, however, evolved and the effect was profound. Life previously had been energetically limited, and now there was an enormous increase in the supply of free energy. Aerobic metabolism produced 20-30 times the energy of anaerobic, and so there was a great invigoration of the processes of life.

The other great gift of atmospheric oxygen was the formation of the ozone layer n the upper atmosphere, which absorbed 95% of the solar UV irradiation, and without which terrestrial life would have been impossible. The major photosynthetic organisms, the oxygen producers, were the cyanobacteria who lived in all the waters of the earth and in many places produced thick bacterial mats called stromatolites. They, and more advanced green plants, are still the major source of oxygen in our atmosphere, and also capture nitrogen for use in protein synthesis.

We now have entered the Proterazoic eon (2.5 billion years ago) and by 2 billion years ago the prokaryocytes were joined by the eukaryotes, a more complex organism in which the genetic material, DNA, is packaged in a membrane and becomes the cell nucleus. They were probably formed by the fusion of an archaean and another prokaryotic bacterium. The eukaryote is to the prokaryote what the iPhone 3G is to the old iPod—bigger, much more complex and versatile (many more "applications," and the ability to communicate with other cells.) It had compartmentalized the various cell functions in organelles, the most important of which are the mitochondria, the energy-producing engines of the cell. It is now known that the mitochondria were once free living bacteria that had been ingested by a larger eukaryote, and instead of being a meal, lived on happily within the host cell forever, in a condition of endosymbiosis. Thus, we, who are eukaryotes, like all forms of life visible to the naked eye, are descendants of two microbial progenitors.

Enkaryotes also introduced sexual reproduction. Not only could cells then divide clonally by simple mitosis, but they could divide meiotically to produce gametes of the two sexes, each containing a thorough mix of parental genes. The genetic deck was now well shuffled before it was dealt, and this generated the genetic variation which allowed natural selection to work its wonders, and was the foundation for the creation of all following species. We can raise our glasses to Bangiomorpha pubescens, a red algae living 1.2 billion years ago, who was the first to reproduce sexually and to become multicellular, but he or she was a plant so we can't claim her as an ancestor. Although many eukaryotes are still present in great abundance as unicellular protists, it was finally they who were able to become multicellular plants and animals, in whom cells became differentiated in form and function.

Though life remained largely unicellular and exclusively aquatic for the rest of the proterozoic, the imprints of a variety of soft-bodied animals probably living about 600 million years ago were found in Russia (the Vendian) and Australia (Ediocaran) and elsewhere. Little can be known of their connection to later animal life except, that they were apparently multicellular.

Multicellular life took off in the Cambrian period which initiated our own eon, the Phanerozoic, at 544 million years ago. There seemed at that time to be an "explosion" in the variety of life, with the appearance of thousands of new animals, early representatives of most of today's phyla in a brief 5 million years. This is a period of great interest to the paleontologists, as animals of that period had become able to extract calcium from sea water and to produce shells and exoskeletons, which could be preserved in rocks as fossils. Fossils from the Burgess Shale in the Canadian Rockies were especially abundant and well preserved. The Trilobites, early arthropods, were most prominent. The sharp-clawed anomalocaris was among the first predators. But the six foot sea scorpion (Pterygatus) would have made frolicking in the surf a risky business. But of all the thousands of Cambrian fossils only one chordate, Pikakia, can we claim as ancestral.

We are now about 4 billion years from our starting point, and at about 500 million years ago are entering the Ordovician period. The largest continent, Gondwana, was moving over the South Pole. There was a rapidly increasing diversity of marine fauna and flora, with the appearance of jawless fishes (lampreys), the first vertebrates. The Ordovician ended at 440 million years ago with mass extinction in which about 70% of extant species were lost, probably from extensive global glaciation. There has always been a continuum of small extinctions punctuated by mass extinctions every 100,000,000 years or so, and about 97% of species that ever lived are now extinct. A good record for intelligent design? However, the big extinctions were probably the result of severe environmental disasters more than of poor adaptation. Though not very happy for the extinct, these episodes did open niches for new species, and thus have accelerated evolution. Nature does abhor a vacuum. It is an ill extinction that blows no one good.

And so to the Devonian 410 million years ago—the age of the fishes. First came the jawed fishes, armor-plated first, then scaled. Then there were the cartilaginous sharks and rays, followed by our more immediate ancestors, the bony fish or Osteichthyes, who were tremendously successful, becoming, and remaining, the largest class of vertebrates, with 26,000 species of all sizes, forms, and numbers. They often had a versatile organ which could be a swim bladder (preferred by deep water fishes) or an air-breathing lung (preferred by our ancestors.) The latter group, the lungfish often ventured into shallow fresh water streams and ponds, which occasionally evaporated to a depth where air-breathing was necessary. So the lungfish adapted, and, finding the water sometimes too shallow to swim in, their fins gradually became sturdy enough to be used to propel them along the muddy bottom. But there was then a gap in the fossil record, between these lobe-finned fishes and the existing fossils of early amphibians, who were the first true four-footed tetrapods.

To the rescue came Neil Shubin, Chicago paleontologist and author of the popular *Your Inner Fish*. He and associates studied the rocks of Ellsmere Island in the Canadian arctic, rocks which had been equatorial 380,000,000 years ago. They were looking for the transitional animals living between the lobe-finned fish and the known early amphibians. They found him, his fossilized head sticking out of a rock. He was a fish but with major differences. His head was flattened like an alligator, he had a movable neck, a sturdy rib cage, and his caudal fins contained a humerus, a radius and an ulna, just like ours. He was clearly a fish on the way to be a terrestrial tetrapod, clearly our ancestor, and just as predicted by **Anaximander**.

The first tetrapods were the amphibians, who fortunately made it to shore before the 20 million-year-later Devonian extinction, 375-360 million years ago. Great global forestation then began in the next, the Carboniferous, period, with a rise in atmospheric oxygen to 35% and a fall in CO_2 to less than a tenth of the Cambrian levels. Decaying vegetation produced the equatorial coal swamps which gave us the fossil fuels of today. The amphibians thrived in and near shallow water. They were mobile on land, but their reproductive style was still aquatic. Eggs were laid in water where they hoped for the sperm of a male passerby, and their hatchling tadpoles lived a dangerous life in water until their metamorphosis.

This was clearly not a well-designed plan for a fully terrestrial life. The problem was solved by the amniotic egg, in which there was an inner membrane, the amnion, producing a watery environment for the embryo, a yolk for its nourishment, and an outer shell, leathery or calcified, for protection. The egg can be praised not only for its contribution to human cuisine, but for its making possible the evolution of birds and mammals. Thus the riddle is answered—the egg definitely came before the chicken. And since the amniotic egg required internal fertilization it necessarily led to the heightened degree of parental physical intimacy which must be reckoned one of evolution's most felicitous events.

Our first amniote ancestor was a small lizard-like amphibian who lived about 340 million years ago. He was followed in the Permian era by a proliferation of reptile species, and a group of mammal-like reptiles called therapsids, who though egg-layers and probably cold-blooded, were more like mammals in size and shape, and at some time developed milk producing glands, the *sine qua non* of mammaldom. Some were carnivores, some herbivores, some quite large and seemed to have a good evolutionary prognosis when at about 250 million years ago the Permian ended with the mother of all extinctions. 96% of all marine and more than 70% of all terrestrial species vanished. There was heavy loss of plant life as well. There may have been many causes, but the major one was a prolonged series of immense volcanic eruptions in the Siberian Traps, which covered 2,000,000 square kilometers with a mile deep layer of molten lava, obliterated the sunlight, filled the air for years with dust, CO2, and H2S, and released methane from the melting polar ice. Recovery took at least 30 million years. All larger animal species were lost. Of the survivors, there were small mammal-like reptiles, the Cynodonts, who became nocturnal, insectivorous tree-dwellers. They were not major players in the Triassic world, but they were our ancestors. The larger reptiles were the big winners, and following the extinction at the end of the Triassic, the dinosaurs became the dominant animals of the land.

They ruled the roost for the next 150 million years, through the Jurasic, yes Jurasic Park, and the Cretaceous (205-60 million years ago). There were more than 1,000 species, herbivorous and carnivorous, from the size of a pigeon to the giant sauropods weighing more than 300,000 pounds. Sauroposeidon could stand at the door of your hotel and peer into your 6th floor window. Fossils indicate that they were abundantly present in all the terrestrial areas, as well as the sea and air. Our birds of today are truly avian dinosaurs, the descendants of the Therapods in whose ranks lived T. Rex. The musical trill of our present-day warbler is then but a derivative of the roar of

Tyrannosaurus. The dinosaurs were a vigorous flourishing fauna, and then 65 million years ago, in a geological wink, they were totally gone, survived only by the birds. This mass extinction, the cretaceous-tertiary, is now generally agreed to have been caused by the impact of a large asteroid near Chicxulub on the Yucatan peninsula. This was confirmed in 1980 by Luis Alvarez, Nobel prize physicist, and his geologist son Walter, both from UC Berkeley, when they identified a layer of iridium, an element found only in meteors, in a rock layer of exactly the right age. It is estimated that the colliding asteroid was six miles in diameter, and its crater 112 miles wide and that the strike released energy equivalent to 100,000,000 megatons of TNT, 2,000,000 times more powerful than the largest hydrogen bomb. It certainly caused immense worldwide volcanic and seismic activity and probably a tsunami 1000 feet high. There would have been an enormous ejection of steam and dust sufficient to cover the earth for several years. Sunlight on the earth's surface, and thus photosynthesis, would have been diminished drastically, reducing the plant life on which the dinosaurs depended. Smaller reptiles who could live on carrion and insects survived, as did most of the birds. And of course the mammals, small, insectivorous, and probably quite numerous, were able to survive, and to come down out of the trees into the sunlight, and in the dinosaur-free Tertiary period 65 million years ago underwent a period of massive evolutionary expansion, which has led them to dominate the terrestrial earth. Had not the Chicxulub impact occurred the dinosaurs might have lived on for another 100,000,000 years, and we might still be swinging in the trees, eating bugs and berries.

No longer needing the protection of the night, these mammals became more boldly diurnal, and rapidly diversified into a vast variety of sizes, forms and habitats.

The advent of angiosperms, the flowering plants, produced lush forests and grassy savannahs, the latter supporting herds of hoofed ungulates and their predators. The 2- and 3-toed ungulates were the ancestors of all hoofed animals, wild and domestic, and it was an early such animal, related to the hippopotamus, who, about 50 million years ago, returned to the sea and whose descendants include the largest mammal of them all, the blue whale.

But let us return to the treetops where we find that those shrew-like insectivores have largely abandoned the egg and the marsupial pouch and have become placental, moving the amnion to a safer haven. One of these, a primate-like mammal, has the interesting scientific name "Purgatorius uno." We find that many of them have become pro-simian, wide-eyed and lemur-like, brachiating and jumping from limb to limb, probably adding fruit to the diet. They populated the world widely, and from some of them, monkeys evolved. Competitive pressure from the monkeys, predation, and cooling climate led to a decline in Prosimians, who retreated to Madagascar, and left the rest of the world to the anthropoids, first in Eurasia and later South America. By 25 million years ago the first apes, Proconsul, had evolved from the monkeys, and in turn were the ancestors of the gibbons and then the gorillas and chimpanzees. The ancestral lines of the chimpanzees and hominins (humans and related fossil species) diverged only about 6 million years ago, sharing with each other more than 95% of their DNA. The fossils of a large variety of hominins, living between 5 million and 1.8 million years ago, have been found, mostly in Africa, and as a group are known as the Australopithecines. They had given up knuckle-walking and become bipedal, and Lucy, the best known of this genus, had a cranium about 1/3 the size of modern man.

Homo erectus then lived from 1.8 million years ago until his extinction 300,000 years ago. He had fully upright posture, and was perhaps a more efficient walker than modern man—myself definitely included, demonstrating his walking prowess by trekking from Africa to Europe and Asia. He was a competent tool maker and, as the first to use fire, was the real Prometheus. Homo Neanderthalensis, descended from Homo Erectus, lived in Europe and the Middle East from 230,000 to 28,000 years ago. He was very heavy boned and muscular, and hunted large game, including the wooly rhinoceros. He shared 99% of his genome with Homo Sapiens and possessed the HOXP-2 gene which is linked to speech. Though he shared the land with Homo Sapiens, there is no evidence of interbreeding or combat between the two. His last remains were found in a cave on the Rock of Gibraltar, with no clear evidence for the cause of his extinction, which was surely a great loss for the NFL. Other archaic forms of Homo Sapiens had lived in Africa earlier, but modern man evolved by 160,000 years ago.

DNA studies now support the theory that 60,000-70,000 years ago there was a single migration out of Africa by a small band of Homo Sapiens, who had, some say, been greatly reduced in numbers by another near extinction event, an immense eruption of Mount Toba in Sumatra. They crossed the Red Sea, some going north to the Near East and Europe, and some east to Asia and Australia, eventually replacing the Neanderthals. Now they were the last surviving members of the Homo genus and had, for a time at least, inherited the earth. In just a few seconds of geological time beautiful paintings would appear on the cave walls at Lascaux, grain would grow in the fertile crescent, maize in the Yucatan, and in the agora of Miletus **Anaximander** would contemplate the origin of life, never knowing how many gaps he needed to fill. Had he known, would he regard our place in the world now as the result of a preordained, predictable ascent of a ladder to perfection? Or would he view it as the outcome of many contingent and fortuitous events like, for instance, the collision at Chicxulub? And would he wonder whether, if the spark of life were relit in a similarly vacant world, it would all turn out the same way again?

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