Let There Be Sight!
A Celebration of Convergent Evolution
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"Once is an instance. Twice may be an accident.
But three or more times makes a pattern." — Diane Ackerman, 1993

THE LATE STEPHEN JAY GOULD popularized an understanding of evolution that focused on the role of randomness and chance. "Rewind the tape" (of evolution), he would say, and imagine the whole process unfolding from the start once again: everything would be different.

At one level, this interpretation is indisputably true: DNA sequences surely would be different; indeed, there might well be a genetic template other than DNA. But at another level, the level that matters to me and surely to many others, the central issue is whether there would be "trees" reaching into the sky and plump "fruits" beckoning mobile creatures to swallow them and thus carry their progeny on a journey. What matters is whether there would be swimming and flying and running and slithering expressions of life, and even whether there would be a form who, like us, would come to know and celebrate the 13 billion year story of the universe.

For all except perhaps the last possibility, the best answer is an unqualified Yes! We can have confidence in this conclusion, based on the fact that these forms and lifeways have independently evolved, time and again, during the actual 3.8 billion year epic story of life on Earth. This propensity, this drive, for life to evolve in the same ways in unrelated lineages is known as *convergent* or *parallel* evolution (also, *homoplasy*). Birds and bats and insects and pterosaurs have wings not because a common ancestor had wings but because wings independently, convergently, evolved multiple times in very distinctive lineages.

Something indeed is going on in evolution. It is not just "one damn thing after another." The visible results of natural selection and other shaping processes are by no means best characterized as a random pageant of form and function. Whether examples of convergence owe to the inward pull of form (developmental biology) or to the push of Earth itself (ecology; "life rediscovering the same synergies," as Peter Corning speaks of it), we can count on particular forms and lifeways to develop — time and again.

The Inevitability of Emergence

Convergence is a sign of the inevitability of emergence. That is, because complex forms and functions have evolved on multiple occasions, we can surmise that the Universe / Divine Creativity easily produces wonders of the living world that seem miraculous to our sensibilities. We can discern that the "lesser" (simple forms) can in fact yield the "greater" (complex forms) — even if scientists have not yet figured out the genetic shifts and other steps by which such evolutionary "leaps" actually take place.

Whether or not something like humans would develop "if the tape were rewound" is not the central concern for those of us who love Life. For me, it is comforting to know that Earth is determined that there be trees, that there be eyes to see trees, that there be songs sung in trees to greet the dawn and other songs sung to greet the twilight.

An awe of the power and performance of convergent evolution profoundly shaped the worldviews of great biologists of the past (notably, Charles Darwin and Julian Huxley) and is beginning to do so again today (John Maynard Smith, Richard Dawkins, Simon Conway Morris, Mark McMenamin). But convergent evolution is not yet a big part of biological teaching at any level of schooling or for the general public.

It is time for this to change. What follows is an annotated list of examples of convergent evolution. Please use this list in whatever ways you wish (and hotlink it to your own websites). And do let me know of other examples so that I can expand and improve what is offered here.

Two New Books on Convergence

In October 2003, Simon Conway Morris's book, *Life's Solution: Inevitable Humans in a Lonely Universe,* was published by Cambridge University Press. In email correspondence with me, Professor Conway Morris wrote that evolutionary convergence is central to his book. He continues:

> Something is indeed going on in Evolution. My book has a number of aims, but one of the most important is to show that humanoid intelligence is an evolutionary inevitability, as are tools, bipedality, agriculture, colour vision (including trichromacy), advanced social systems: *all* are convergent.

Conway Morris, a paleontologist, contributed the cover story "Convergence" for the 16 November 2002 issue of *New Scientist* magazine. There he wrote:

> When you examine the tapestry of evolution you see the same patterns emerging over and over again. Gould's idea of rerunning the tape of life is not hypothetical; it's happening all around us. And the

> result is well known to biologists — evolutionary convergence. . . When convergence is the rule, you can rerun the tape of life as often as you like and the outcome will be much the same. Convergence means that life is not only predictable at a basic level; it also has a direction.

Also, see two publications on convergence by Mark McMenamin:
• McMenamin, M. A. S. 2003 [in press]. *The Omega Files: Convergence, Reflectors and Evolutionary Change.* Meanma Press, South Hadley, Mass.
• McMenamin, M. A. S. 2000. "Out of the shadows." [Book review of Simon Conway Morris, *The Crucible of Creation: The Burgess Shale and the Rise of Animals*]. *Notes and Records of the Royal Society of London*, v. 54, n. 3., p. 407-408.

A fascinating essay on evolutionary convergence, especially discussion of the parallel anatomical details for intelligence of the vertebrate and the squid, is:

• "The Probability of Human Origins," by Matt Cartmill, Professor of Biological Anthropology and Anatomy, Duke University. The Essay is published in *When Worlds Converge: What Science and Religion Tell Us About the Story of the Universe and Our Place in It,* edited by Clifford N. Matthews, Mary Evelyn Tucker, and Philip Hefner (2002, Open Court).

A Celebration of Convergent Evolution

1. Vertebrate Forms

Vultures – Huge soaring birds that feed on carrion developed independently in the Eastern and Western Hemispheres. In the east, vultures evolved from hawks and eagles. In the west, vultures and condors (including the extinct teratorns of the Pleistocene, with 12-foot wingspans) evolved from storks and ibises. The different heritages mean that, while Old World vultures can grasp flesh by curling their clawed toes, New World vultures lack this ability.

Hovering nectar feeders – The hummingbirds of the Western Hemisphere, some of Hawaii's distinctive honeycreepers, and some sunbirds of the Old World tropics have converged on very similar adaptations of form for nectar feeding.

Flight - Birds, bats, and flying foxes (the "fruit bats" of Indonesia) have all independently evolved wings from their forelimbs for powered flight. So did the pterosaurs ("flying dinosaurs") of the Mesozoic Era.

Gliders – Passive flight, or gliding, has developed independently in squirrels, Australian marsupial mammals, lizards that glide by way of skin flaps stretched between fore and hind legs, the flying snake of Borneo which flattens its rib to widen the belly, Asian and Central American tree frogs that each evolved huge webbed feet for gliding from one tree to the next, and, of course, "flying" fish.

Flightless birds on islands – The pigeon and rail families have, time and again, devolved flightless forms on many of the world's islands, where there are no large mammals that might prey upon them. The dodo (from pigeon stock) is perhaps the most famous example, having evolved on Mauritius Island in the Indian Ocean. Even flies have lost wings on small, remote islands where a gust of wind could carry them out to sea.

Giant flightless vegetarian birds – A number of bird lineages have become very large, flightless vegetarians. This form evolved independently on several continents and the larger islands. The ostriches of Africa, the rheas of South America, the emus of Australia, along with the moa of New Zealand (extinct 600 years ago), and the giant "elephant birds" of Madagascar (extinct 1000 years ago) each evolved independently from rail ancestors. Genyornis of Australia (extinct 30,000 years ago) is thought to have evolved from duck ancestors.

Giant flightless carnivorous birds – Throughout most of the Cenozoic, flightless "terror birds" of South America joined marsupial "cats" as top predators on that isolated continent. These terror birds stood 10 feet tall and looked like miniature T. rexes with eagle-like bills. North America independently evolved its own terror bird, *Diatryma*, very early in the Cenozoic, during the Eocene. When the Isthmus of Panama joined the two continents 3 million years ago, South America's *Titanis* terror bird came north and thrived in what is now the southern United States until well into the Ice Ages.

The "cat" form – This is one of the most exciting examples of convergent evolution, because the distinct lineages of "cats" look so similar in many details. The only family of cat alive today is family Felidae, so all the cats of the world share a common ancestral cat ancestor; they are not in themselves examples of convergent evolution. Rather, we find convergence when felid cats are compared with extinct creatures who looked strikingly like them. Family Felidae evolved in Eurasia some 20 million years ago, but before then, some 40 million years ago, Eurasia evolved and (then sent to North America across the Bering Land Bridge) cat look-alikes from Family Nimravidae. Nimravids were so catlike that, in addition to their skeletal and dental features, they independently evolved retractable claws. Meanwhile, the cat form evolved independently in South America among marsupial mammals. Remarkably, all three cat lineages (felids, nimravids, and marsupial thymacosmilids) produced strikingly similar forms of sabertooth (or dirk-tooth) cats, with bodies built for pouncing, not running, and with frighteningly long upper canines (as well as a single powerful slicing tooth at the back of each jaw, instead of crushing molars). *Smilodon* is the best known example among the felids of Pleistocene North America, *Barbourofelis* is the sabertooth nimravid, and *Thylacosmilus* is the sabertooth marsupial of South America.

The "horse" form – A horselike form with a hoof on a single enlarged toe evolved not only in North America among the true horses (beginning 50 million years ago), but also independently among the (now-extinct) notoungulate mammals in South America. Some early camels of North America evolved heads and bodies that strikingly resembled the horse form.

Australian marsupial v. placental mammals – Australia, as in isolated continent, evolved a number of forms among its marsupial mammals that are (or were) uncannily similar to squirrels, moles, cats, rabbits, and wolverines of the Northern Hemisphere.

Porcupine, armadillo, and anteater forms – America's porcupine is a recent immigrant from South America, having come north just 3 million years ago when the Isthmus of Panama joined the two continents. Protective spines have independently evolved in other mammal lineages too: the African "porcupine", Australia's spiny echidna (a monotreme mammal), and the European hedgehog. South American armadillos and Asian pangolins independently evolved their body armor. South American and African anteaters are also independently evolved.

Armored animals with spiked tails – The tank-like ankylosaurs (dinosaurs) with their dangerous tails tipped in massive spikes looked amazingly like the glyptodont mammals (family Edentata) of the late Cenozoic of South America.

Horned snouts – Weapons of modified hair or bone evolved independently on the snouts of several lineages of dinosaurs (most famously the ceratopsians, like Triceratops), as well as the rhinos and the brontotheres of the Cenozoic.

Billed snouts – The duck-billed dinosaurs (hadrosaurs) are aptly named. Even more strikingly convergent with ducks is the bill and webbed feet of an Australian monotreme mammal: the duck-billed platypus.

Hippo form – A Miocene rhinoceros of North America evolved a squat, aquatic, hippo-like form, even though rhinos (Order Perissodactyla, odd-numbers of toes) are unrelated to hippos (Order Artiodactyla, even numbers of toes).

Dolphin form – Ichthyosaurs (marine reptiles) of the Mesozoic (250 million to 90 million years ago) looked strikingly like mammalian porpoises.

Whale form – Mosasaurs were the whales of the Mesozoic, but they evolved from lizards and are closely related to living monitor lizards (including the Komodo Dragon).

Diving duck form – Hesperornithoforme reptiles were the diving "ducks" of the Cretaceous. The evolved not only lobed feet like grebes but also the placement of the legs so far toward the hind end that they could not walk on land.

Crocodile form – The phytosaurs of the Triassic were unrelated to true crocodilians, and yet they evolved long, narrow, toothy snouts just like crocodiles.

Pig form – The large-headed, pig-snouted, hoofed form of mammal evolved independently as true pigs in Eurasia (Family Suidae) and as peccaries in North America (Family Tayasuidae). Another mammal lineage, the Enteledonts, evolved some gigantic piglike forms in North America during the Oligocene.

Ground sloth form – Slow-moving, large, well-defended by claws, and whose paunch suggests a diet based on high intake of plant roughage, the ground sloth form evolved not only in South America mammals of the Cenozoic, but also in the dinosaur *Nothronychus*, who was a resident of North America 90 million years ago.

Chameleon-like eyes – sand lances (fish) and chameleons (lizards) both evolved eyes that move independently of one another. One eye is kept fixed, while the other jerkily moves, scanning for prey. In both the chameleon and sand lance, it is the cornea rather than the lens that provides most of the focusing, as the cornea is flexed by its own muscle. Corneal focus allows the animal to gauge distance using just one eye.

2. FORMS ACROSS PHYLA

Multicellularity – Single-celled eukaryotes of a number of lineages evolved distinctive forms of multicellularity. Multicellularity is believed to have been independently invented by ancestors of these lineages: animals, fungi, red algae, green algae, brown algae, slime molds.

Eyes – In his 1995 book, *River Out of Eden*, Richard Dawkins estimates that image-forming eyes have independently evolved 40 to 60 times. Genetic analysis has since reduced the estimate of independent origins, but it is nevertheless striking how different the compound eyes of insects are from the single-lensed eyes of vertebrates, and how similar the eyes of octopi and squid are to our own. Because photoreceptors reside on the inner side of the retina in those mollusks, yet on the outer side in vertebrates, we can be sure that such differences signal deeply independent origins. At least nine distinct design principles are evident in the total range of eyes: pinhole eyes, two kinds of camera-lens eyes (vertebrate and octopus), curved reflector ("satellite dish") eyes, along with several kinds of compound, multi-lensed eyes.

Beaks – Parrotlike beaks have evolved independently in birds, ceratopsian dinosaurs (e.g., Triceratops), and even marine mollusks: squid and octopus. It is a wondrous experience to purchase a small, whole squid at a fish market and search for the hidden beak.

Brains – Prof. Mark McMenamin hypothesizes that some ediacaran creatures that pre-dated animals, and that thus existed before the Cambrian Period, were on the verge of developing animal-like sensory organs and brains.

Ultrasonic hearing – Bats and whales evolved sonar techniques for detecting prey and obstacles in darkness. In defense against predatory bats, some night-flying moths and a nocturnal tropical butterfly evolved the ability to "hear" ultrasonic (high frequency) clicks. Some developed hearing sensors near their mouthparts, others on the thorax, still others on the wing.

Clamlike shells – Phylum Mollusca (clams and oysters) and Phylum Brachiopoda (brachiopods or lampshells, most of which are extinct but which were the dominant bivalves of the Paleozoic) independently invented paired shells for protection. The anatomy of their soft body parts is so dissimilar, however, that they are regarded as separate, independently evolved phyla. Indeed, biologists conclude that clams are more closely related to earthworms than they are to brachiopods.

PLANT FORMS

Tree form – Multiple lineages have independently evolved a growth form of a single woody stem, with branching beginning a distance above the ground. There is no dispute that Paleozoic tree forms of club mosses, horsetails, and seed plants (cycads and gymnosperms) evolved independently. Some evolutionary theorists conclude that the flowering plant lineage began entirely herbaceous, having lost the capacity to become trees, then later re-evolved arborescence in many different lineages.

Palmlike trees – The distinctive tree form of flowering palm trees (with a single, apical growing point and pith rather than wood in the stem) is outwardly similar to that of the completely unrelated cycads (Jurassic origin), and of the even older tree ferns, which first developed this form in the Paleozoic and did so in a variety of ways. (Both cycads and tree ferns are still alive, found in the tropics/subtropics.

Cactus form – Cactus plants, family Cactaceae, are native to the western hemisphere. Prickly pear (genus *Opuntia*) cactus is now found in many deserts of the Old World and Australia, having been introduced there by humans or their livestock, but they are not native to those lands. All species of true Cactus are native to North and South America. Rather, in the eastern hemisphere, family Euphorbiaceae evolved many species that are strikingly convergent with cacti down to the very details of their succulent, prickly forms.

Bilateral flowers – Many families of flowering plants produce flowers with a distinct up-down orientation (violets, orchids, peas). Such bilateral forms have independently evolved in many lineages. The bilateral form (sometimes supplemented by colorful lines that serve as "nectar guides") fine-tunes the placement of the pollen-bearing and pollen-receiving structures such that pollination prospects are enhanced. Some bilateral flowers (orchids) have independently evolved structures that achieve pollination by tricking male wasps into thinking they have found a female wasp abdomen to copulate with.

United petals – Petals uniting into a single bell shape (blueberries, Ericaceae) or tube (several families, see next entry) have evolved independently at least 10 times.

Hummingbird flowers – Red, scentless tubular flowers have independently evolved at least 80 times within 4 plant families to attract nectar-feeding birds (hummingbirds, honey eaters, sunbirds). Especially in Hawaii, the most remote islands in the world, an astonishing variety of families of plants have each evolved curved, red, tubular flowers, even if they have done that nowhere else on Earth.

Carrion-beetle flowers – Maroon or brownish flowers whose nectar smells like rotting meat have independently evolved in many lineages of plants to attract pollinators attracted to carrion. These carrion mimics include the American pawpaw (family Annonaceae), the giant Indonesian parasitic flower *Rafflesia*, and an African milkweed (*Stapelia gigantea*).

Fruits that develop underground – The peanut, a legume, bears flowers in the upper part of its branches. Following pollination, the flower stalk elongates, arches downward and pushes into the ground. Florida's endangered burrowing four o'clock does the same thing. For seed dispersal, Africa's *Cucumis humifructus* depends on aardvarks to find, dig up, and consume its deeply buried gourdlike fruit.

Thorns and prickles – Many lineages of plants have independently shaped nubs of branches into thorns or leaf cells into prickles. Strikingly convergent is the holly-like leaf of true hollies, some dry-adapted oaks, the low-growing Oregon grape shrubs, and even a South African cycad (nonflowering plant): *Encephalartos ferox*. All of these have herbivore-repelling, sharp prickles at the apices of pointy leaf lobes or variously around the leaf edge.

Sexual dimorphism – Nearly half of flowering plant families have independently evolved in some of their species reproductive systems in which pollen and ova are produced on separate male and female plants, rather than both within the same flower. Many plant genera within a single plant family have independently evolved this kind of sexuality. Examples of plants with distinct male and female forms include honey locust, holly, and hemp. Earlier, during the Mesozoic, gymnosperm trees (including conifers) independently invented sexual dimorphism, such as the ginkgo and the torreya.

Heterospory – The divergence of spores into two sexual types (big spores that develop into plants that produce female gametes and little spores that develop into plants that produce male gametes) evolved independently in Paleozoic ferns, club mosses, horsetails, and early seed plants (like cycads).

Fleshy fruit – fleshy, nutritious fruits that attract animal dispersers to swallow whole the embedded seeds and to defecate them distant from the parent plant have evolved many times not only among the flowering plants but also among gymnosperms (ginkgo and cycads).

Water transport systems – Systems of water conducting vessels in horsetails, club mosses, ferns, and gymnosperms evolved independently.

Wind pollination – Pines, grasses, and other distinctive plants independently evolved wind pollinated flower forms from ancestral insect-pollinated forms.

Wind dispersal of seeds – Dandelions, milkweed, cottonwood trees, and others independently evolved tufted seeds adapted for wind dispersal.

Nectar spurs – The columbines (genus *Aquilegia*) are one of several taxa of flowering plants that have independently evolved nectar spurs — tubular extensions of flowers that produce nectar at their base. A long tongue (butterfly or hummingbird) is needed to extract it.

BIOCHEMICALS

Hallucinogenic toxins - Plants as diverse as the peyotyl cactus and the ayahuasca vine converge on producing the same form of chemical toxin to deter predators. This LSD-like toxin is structurally similar to the neurotransmitter serotonin. Kingdom fungi discovers the same chemical adaptation in the psilocybin mushroom.

Antifreeze –Special proteins have evolved in some insects, plant (grasses), and Antarctic fishes that stick to ice crystals in supercooled water and prevent their further growth, which would otherwise damage cell structures.

C-4 photosynthesis – This biochemical pathway independently evolved at least 31 times in 18 different families of flowering plants during the past 8 million years, for a total of nearly 10,000 species of plants (4,600 grasses; 1,330 species of sedges Cyperaceae, and 1,600 dicots of various families). C-4 plants comprise the majority of grasses in tropical grasslands and in the American tallgrass prairie. Of the world's 33 grass species domesticated as cereals, 20 are drought-resistant C-4 species. These include: maize, sugarcane, sorghum, millet. The C-4 pathway (visible in the form of vascular bundles) optimizes the storage and transport of carbon dioxide in any environment in which carbon dioxide is in short supply. Such environments tend to be water stressed, as the plant closes down its pores (stomates) in an attempt to conserve water, thus limiting the amount of fresh carbon dioxide that can be taken in from the atmosphere. A coastal diatom has also been found to photosynthesize in this way.

How to oxygenate blood – Vertebrates use iron (in hemoglobin molecules) to bind to oxygen for transit through the blood system. Crustaceans use copper in their blood molecules instead.

Bioluminescence - Symbiotic partnerships with light-emitting bacteria developed many times independently in deep-sea fish and in arthropods (fireflies, glow worms).

Biomineralization – The so-called "Cambrian Explosion" of early animals in the sea beginning 543 million years ago marks a time when multiple lineages of early animals (mollusks, brachiopods, arthropods, bryozoans, echinoderms, tube worms) simultaneously learned to secrete protective shells or carapaces out of organically made hard materials: mineral carbonates and organic chitins. Microscopic plankton in today's oceans include single-cell creatures whose ancestors independently invented elegant "shells" (or, "tests") made of silica (radiolarians and diatoms) or of carbonate (foraminiferans and calcareous algae).

Reef builders – Ever since colonial groups of bacteria began building stromatolites some 3.5 billion years ago, Earth has had marine life-forms that have built up rocky reefs. In the lower Cambrian various sponges evolved ways to build skeletons of calcium carbonate that fused into reefs (Archaeocyath sponges, and then stromatoporoid sponges). In fact, many groups of sponges independently evolved calcareous skeletons analogous to the later evolving corals. And several groups of anthozoan cnidarians (relatives of jellyfish) independently evolved reef building "corals," including those that dominate coral reefs today: scleratinian (photosynthetic) corals which originated in the Cenozoic. Seven taxonomic orders of corals independently invented reef-building capacities during the Paleozoic, of which the orders Rugosa and Tabulata were most widespread. Paleozoic bryozoans and calcareous algae also contributed to fossil reef structures. Even bivalves (rudist bivalves) built reefs. These rudists looked more like solitary corals than like bivalves. They were abundant in the Cretaceous, but accompanied the dinosaurs into extinction. Today, the bivalves that make reeflike structures are oysters.

Magnetite for orientation – Magnetically charged particles of magnetite for directional sensing have been found in salmon and rainbow trout, as well as in some butterflies, birds, and bacteria.

Hydrothermal vent adaptations – Particular lineages of mollusks and tube worms have independently evolved strategies to thrive alongside the hydrothermal vents of the deep sea, establishing symbiotic relationships with bacteria housed in their flesh or in special organs, such that the host animals no longer needed to consume food. Indeed, some of theme lost (devolved away) their mouths.

Lens material for eyes – Extinct trilobites fashioned lenses for their compound eyes by fostering the growth of a single calcite crystal in each tiny eye tube. This is a very different strategy from the soft bio-molecules used in vertebrate eyes.

FOOD AND NUTRIENT ACQUISITION

Ruminant forestomach – An organ to house cellulose-digesting bacteria in a friendly, alkaline environment before food is passed to the deadly, acidic juices of the stomach is a strategy independently invented by animals as diverse as the hoatzin bird and tree sloths of the Amazon, and by bovid mammals (deer, cattle) and colobus monkeys of the Old World.

Mycorrhizal associations of plants and fungi – More than 90% of living plants form associations with fungi in their roots. The plant supplies the fungus with sugar-rich food, while the fungus helps plants obtain mineral nutrients from the soil. A number of different fungal lineages have independently evolved this kind of association with plants. Western hemlock trees form mycorrhizal associations with more than 100 fungal species, while the fly agaric mushroom (*Amanita muscaria*) associates with at least 23 species of trees and shrubs.

Lichens – There are some 20,000 "species" of lichen, which are each cross-kingdom partnerships of fungi and algae, in which the fungus provides the substrate and holds the water, while the embedded cells of algae photosynthesize. Because each "species" of lichen is a genetically distinct combination of a single fungus with a single species of green alga or cyanobacterium (blue-green "alga" but really a eubacterium), the evidence is strong that each partnership evolved independently. This means that the lichen form has been discovered and rediscovered thousands of times!

Acquiring water by fat combustion – Camels are just one among many desert-adapted animals that manufacture their own supply of water by harvesting hydrogen atoms from fat reserves and combining those atoms with oxygen atoms that they breathe in from the air.

Parasitic plants – Plants that rely on host plants to gain their energy, water, and nutrients (e.g., Rafflesia, Orobanche) have reduced roots and leaves, and a substantial or entire loss of chlorophyll. This form of parasitism independently evolved in different plant families.

Insectivorous plants – Nitrogen-deficient, boggy soils have induced insectivory in plant taxa at least 7 distinct times. Plants evolve flypaper traps (sundew), spring traps (Venus fly trap), and pitcher traps in order to capture and digest insects to obtain scarce nitrogen.

LAND HO!
Emergence from Sea onto Land

Arthropods – Of the arthropods, the first to emerge onto land were the ancestors of millipedes 450 million years ago, followed by the ancestors of insects, spiders, scorpions, and mites.

Vertebrates – Fishes evolved lungs at least twice: the still-living lungfishes of Africa are aquatic, while the crossopterigian coelacanthes (of the deep sea) are "living fossils" whose ancestors spawned a divergent line of lunged fishes when the fishes were evolving amphibians. It appears that amphibians and reptiles may have emerged from the sea in distinctive lineages, rather than the latter evolving from the former. All were initially carnivores. Soon 4 lineages of early reptiles evolved plant-eating forms. Later, more than a dozen carnivorous lineages evolved adaptations that would enable them to feed on plants.

Air-breathing strategies – Insects evolved a "tracheid" system of internal tubes with multiple openings in order to oxygenate their cells. This is separate from their vascular system of blood that supplies foods, carries away wastes, etc. Vertebrates evolved lungs that oxygenate the blood, so oxygen is carried in the same vessel system as are energetic molecules (food) for the cells. The "choice" of insects to utilize a separate tracheid system for breathing seems to have limited their maximum size to not much bigger than a small mouse! Any larger, and an insect would not be able to sufficiently oxygenate its cells. The seagull size insects of the Carboniferous Period probably evolved because of far higher oxygen concentrations in the atmosphere during that time.

RETURN TO THE WATER

Mammals – On more than a dozen occasions, land-dwelling mammals have returned to make their living, either wholly or partly, in water. The ancestors of whales did it once, or possibly twice (the distinction between toothed v. baleen whales). Sirenians (dugong and manatee) made the return independently once. Hippos and polar bears, seals and sea lions, sea otters and beavers, a South American water marsupial related to opossum, along with Australia's duck-billed platypus have all partly made the return, continuing to bear their young on land. Tiny insectivore mammals (water shrews, an aquatic mole, and an aquatic Madagascan tenrec) have taken the plunge independently in four separate lineages.

Other animals – Turtles, as reptiles, evolved on land; even sea turtles still must return to land to lay their eggs. Aquatic turtles supplement air breathing by absorbing oxygen in water through the lining of their mouths, their hind-end cloaca, and softshell turtles by the skin covering the shell. Other partial returns include crocodilians, sea snakes, Galpagos marine iguanas, and many aquatic forms of beetles and other insects. Freshwater snails are wholly aquatic, but they arose from land snails, not marine snails, and continue to depend on breathing air. Water beetles and diving-bell spiders carry bubbles of air down with them.

Extinct reptiles – The distinctive lineages of reptiles of the Mesozoic that returned to the sea (before going extinct 65 million years ago) included whale-like mosasaurs (which descended from the same branch of lizards as Komodo dragons later did), dolphin-like ichthyosaurs, and long-necked plesiosaurs.

Penguins – The penguin form of cold waters of the Southern Hemisphere, was matched by the Great Auk of the northwest Atlantic (now extinct, owing to overhunting). Penguin and auk, flightless, both used their stubby wings to swim through the water, and walked clumsily on land in an upright posture.

Plants – Eel grass, genus *Zostera*, is a flowering plant that is now exposed to the air only during the lowest of low tides along the coast. It is an important food of other returnees: manatees and sea turtles.

LIFEWAYS

Brood parasitism – a hundred species of living birds in various families sneakily lay their eggs in the nests of birds of other species (brood parasitism).

Parasitism – Flowering plants that grow as "mistletoe" on and into the branches of trees and shrubs and obtain water, nutrients, and sometimes sugars from their hosts evolved the parasitic habit independently at least twice: family Loranthaceae (950 species) and family Viscaceae (365 species). All forms of parasitism, including root parasitism, has evolved independently at least 9 times among the flowering plants.

Parthenogenesis – Some lizards and insects have independently evolved the capacity for females to produce live young from unfertilized eggs. Some "species," in fact, are entirely female.

Male brooding of eggs – Some male fishes brood their young in their mouths; some frogs and insects on their backs. Male seahorses have a stomach pouch into which the females deposit eggs; these pouches buldge as the young grow, making the males look pregnant. Red phalarope (bird) females abandon their eggs to the male upon laying, seeking out yet another male to do the same for another set of eggs. Not surprisingly, male phalaropes are colored for camouflage, while the females bear flamboyant color.

Male mating calls – Frogs and katydids both make loud sounds, using similar strategies, to attract females for mating.

Camouflage – Walking sticks and the larvae of certain butterflies and moths independently invented twig-like camouflage. Lineages of praying mantids and winged moths independently evolved leaf-like forms. Various fishes, including seahorses, independently evolved elaborate appendages to blend in with floating Sargasso weed in the sea.

Mimicry of toxic animals – Toxic insects (monarch butterflies and cucumber beetles, for example) and venomous vertebrates (coral snakes) signal their toxicity to potential predators by being brightly colored in orange, red, or yellow, and often striped. Edible and nonvenomous lineages (e.g., Viceroy butterflies and king snakes) sometime mimic the dangerous varieties in order to deter predators.

Electrical detection of prey in murky water, and electrical defense – Electric eel of the Amazon and what else?

HUMAN CULTURE

Seafaring vessels and skills – Independently developed in many cultures.

Agriculture – Developed independently around the same time in the Eastern and Western hemispheres, some 8 to 11 thousand years ago. Evolved tens of millions of years earlier among ants who cultivate edible fungi on bits of leaves stored in underground chambers.

Writing – Independently invented, around the same time, in the Old and New Worlds.

The "Axial Age" – Around 500 B.C.E. Philosophical and religious thought blossomed in new ways in the Mediterranean (Hebraic Bible, early Greek Philosophy), in India (Buddhism), and in Asia (Confucianism, Taoism).

The calculus – Independently invented by Newton and Leibniz at almost exactly the same time.

Evolution by natural selection – Charles Darwin and Alfred Russel Wallace independently envisioned that the forms of life could have diverged from common ancestors and adapted to different lifeways by the natural ecological forces that determine who lives, who dies, and who produces the fittest offspring.

Recognizing the Great Story – In the 1930s and 40s, three remarkable people whose legacies have lived on made an understanding of the Great Story central to their worldviews: Physician and teacher Maria Montessori called it "the story of the universe." Conservationist and wilderness advocate Aldo Leopold called it: "the odyssey of evolution." Anthropologist and essayist Loren Eiseley called it: "the immense journey."

Celebrating the Great Story – Right around the turn of the millennium, "Great Story Beads" (called Earth Prayer beads by Gail Worcelo, Universe Story beads by Paula Hendrick) were independently created and promoted two, three, and possibly more times. In the 1980s and 1990s, various versions of ritualistically walking the 13 billion year timeline were independently created: The "Cosmic Walk" by Miriam McGillis (at Genesis Farm, New Jersey); the "Walk Through Time" by the Foundation for Global Community (Palo Alto, California); and "Sands of Time" by artist Chris Hardman of Sausalito, California.