Let There Be Sight!
A Celebration of Convergent Evolution
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"Once is an instance. Twice may be an accident.
But three times or more 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**). Finally, with Simon Conway Morris's book, *Life's Solution* (published in autumn 2003), and Richard Dawkins's book, *The Ancestor's Tale* (2004) convergent evolution is on the rise of biological concern and application once again.

Simon 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.

Richard Dawkins, zoologist, highlights convergent evolution in the final chapter of his book, *The Ancestor's Tale*:

> It seems that life, at least as we know it on this planet, is almost indecently eager to evolve eyes. We can confidently predict that a statistical sample of reruns [of evolutionary life on Earth] would culminate in eyes. And not just eyes, but compound eyes like those of an insect, a prawn, or a trilobite, and camera eyes like ours or a squid's, with color vision and mechanisms for fine-tuning the focus and the aperture. Also very probably parabolic reflector eyes like those of a limpet, and pinhole eyes like those of Nautilus, the latter-day ammonite-like mollusc in its floating coiled shell. And if there is life on other planets around the universe, it is a good bet that there will also be eyes, based on the same range of optical principles as we know on this

> planet. There are only so many ways to make an eye, and life as we know it may well have found them all. (page 588)
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> Like any zoologist, I can search my mental database of the animal kingdom and come up with an estimated answer to questions of the form: 'How many times has X evolved independently?' It would make a good research project, to do the counts more systematically. Presumably some Xs will come up with a 'many times' answer, as with eyes, or 'several times', as with echolocation. Others 'only once' or even 'never', although I have to say it is surprisingly difficult to find examples of these. And the difference could be interesting. I suspect that we'd find certain potential evolutionary pathways which life is 'eager' to go down. Other pathways have more 'resistance'. (page 590)

What follows is (1) some quotations from Simon Conway Morris's 2003, and (2) 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.

Quotations by Simon Conway Morris

Quotations are drawn from *Life's Solution: Inevitable Humans in a Lonely Universe,* by Simon Conway Morris (2003, Cambridge University Press).

p. xii definition of convergence: "the recurrent tendency of biological organization to arrive at the same solution to a particular need."

p. 283. "It is now widely thought that the history of life is little more than a contingent muddle punctuated by disastrous mass extinctions that in spelling the doom of one group so open the doors of opportunity to some other mob of lucky-chancers. The innumerable accidents of history and the endless concatenation of whirling circumstances make any attempt to find a pattern to the evolutionary process a ludicrous exercise. Rerun the tape of the history of life, as S. J. Gould would have us believe, and the end result will be an utterly different biosphere. . . Yet, what we know of evolution suggests the exact reverse: convergence is ubiquitous and the constraints of life make the emergence of the various biological properties very probable, if not inevitable."

p. 285. "My thesis is that both the extent and the importance of convergence have been consistently underestimated."

p. 297. "If convergent evolution is an eternal return to the attractors of functionality, then we cannot be surprised if history repeats itself."

p. 309. "This approach posits the existence of something analogous to attractors, by which evolutionary trajectories are channeled towards stable nodes of functionality. . . It is my suspicion that such a research program might reveal a deeper fabric to biology in which Darwinian evolution remains central as the agency, but the nodes of occupation are effectively predetermined from the Big Bang.

p. 329. “the exuberance of biological diversity, but the ubiquity of evolutionary convergence.”

UPDATE: **Simon Conway Morris wrote a seminal paper** on evolutionary convergence (23 pages PDF) in **2009**, **“The Predicability of Evolution: Glimpses into a Post-Darwinian World”** and this is vital reading for all those interested in evolutionary convergence and deep homologies.

> “There he challenges fellow biologists to move past the assumption that there is no logic to the bifurcations within the Tree of Life from which the “twigs” of existing species emerged. Indeed, he foresees huge breakthroughs fully consistent with the darwinian paradigm if this research program is undertaken: “In conclusion, the emphasis on a vast Darwinian Tree with innumerable terminations (the twigs) has blinded us to the possibility that the points of bifurcation are much more determined than at first appears. Support for this view will emerge from other lines of enquiry, such as the nature of major transitions, the concept of innateness and inherency, and the problems with so-called deep homology. . . . This view is emphatically not in conflict with theDarwinian formulations, but looks beyond them to enquire what deeper organizational principles underpin evolution.”

NOTE: 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).

Kevin Kelly, co-founder of *Wired* Magazine offers this lesson drawn from his studies of convergent evolution:

> . . . a hundred, or thousand, cases of isolated significant convergent evolution suggest something else at work. Some other force pushes the self-organization of evolution towards recurring solutions. A different dynamic besides the lottery of natural selection steers the course of evolution so that it can reach a remote unlikely destination more than once. It is not a supernatural force, but a fundamental dynamic as simple in its core as evolution itself.
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> Evolution is driven toward certain recurring and inevitable forms by two forces of convergence:
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> 1) The negative constraints cast by the laws of geometry and physics, which limit the scope of life's possibilities. And,

2) The positive constraints produced by the complexity of interlinked genes and metabolic pathways, which generates a few repeating new possibilities.

These two dynamics create a push in evolution that gives it a direction. Both of these forces continue to operate in the technium as well. The two dynamics shape the inevitabilities of technology.

Kelly then goes on to explore these two forces toward convergence in a 13,000 word essay posted on his personal blog, The Technium:

http://www.kk.org/thetechnium/archives/2009/04/ordained-becomi.php

A Celebration of Convergent Evolution

1. Vertebrate Forms

NOTE: About 20% of the examples described in this document were drawn directly from Simon Conway Morris's book; the rest Connie Barlow collected from years-worth of reading scientific journals with an eye to detect examples of evolutionary convergence.

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. In 2009 Simon Conway-Morris wrote, "independently several groups of theropods [a clade of dinosaurs] took to the air. The emergence of a "bird" seems, therefore, to be inevitable."

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. The first gliding mammal, *Volaticotheium antiquius*, is known to science from a 125 million year old fossil found in China. It is the single representative of its own order. Although it looked a lot like a flying squirrel, it was not an ancestor of squirrels. Thus, mammals began experimenting with aerial life about the same time as birds first took to the skies.

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.

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. Across phyla, the hawkmoths remarkably converge on the hummingbird form.

Woodpeckers – Amazing adaptations to allow birds to peck wood with force and without injury to their brains evolved independently in true woodpeckers and the "woodpeckers" (vangids) of Madagascar. Within the American woodpeckers, the small Downy Woodpecker and medium-size Hairy Woodpecker are unrelated, but have converged on strikingly similar plumage pattern and coloration.

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. As well, as of 2009, the majority view of the origin of the cheetah form both in Africa and in North America (going extinct around 13,000 years ago) is that they are of distinct evolutionary lineages; thus the "cheetah" form evolved twice.

The "horse" form – A horselike form with a hoof on a single enlarged (middle) toe evolved not only in North America among the true horses (beginning 50 million years ago), but also independently among the (now-extinct) liptotern mammals in South America. Some early camels of North America evolved heads and bodies that strikingly resembled the horse form, while maintaining the cleft hoof formed from digits three and four. That same cattle-like hoof also independently evolved in South America among the notoungulates.

The "beaver" form – In 2006, a fossil 164 million years old was unearthed in China that showed that a mammal with webbed feet and a flattened tail had evolved way back then. *Castorocauda* belonged to a dead-end lineage called mammliaforms that branched off near the base of the mammal family tree. While it had the tail and feet of a beaver, it had the carnivorous teeth of a seal (for hunting fish), and likely the habits of a platypus.

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.

The distinctive mammalian features: the modern crushing molar and the intricate configuration of the tiny bones of the middle ear — Until recently, these complicated anatomical structures limited to mammals were assumed to have evolved just once. But beginning in 1997 new fossil discoveries in the Southern Hemisphere inclined some researchers to posit independent evolution of the same structures multiple times. [*Science News*, 8 March 2008, pp. 154–56]

Bipedal hoppers – Rodents repeatedly evolved this form of nocturnal "kangaroo-rat" form, but not yet in the deserts of South America and Australia. Michael Mares predicts that someday this form will evolve in those places as well. South America did evolve a now-extinct marsupial that was strongly convergent with North America's kangaroo rat. Many extinct South American marsupials (argyrolagids) echoed the rodents, who would later invade from the North.

Mole-like forms – This subterranean form of powerful digging forelimbs, rudimentary eyes, and small size independently evolved in 3 taxonomic orders, 11 families, and across 150 genera of marsupial and placental mammals.

Burrowing lizards – with reduced limbs and a snakelike appearance evolved independently at least 8 times.

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 anteaters and the pangolin and aardvark of the Old World independently evolved the toothless tube-mouth structure with long tongue ideally suited for raiding the homes of ants and termites.

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.

Prehensile tails – Tails that can curve around and grasp a branch like a supplementary arm evolved independently in New World monkeys (including spider, howler, and woolly monkeys) and among these unrelated South American vertebrates: kinkajous, porcupines, tree-aneaters, marsupial opposums, and the salamander *Bolitoglossa*. Beyond South America, prehensile tails also evolved among some pangolins, tree rats, skinks and chameleons.

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. In 2010, a PNAS paper reported that beaks evolved at least five times in theropod dinosaurs and, of course, independently within ceratopsian and hadrosaur dinosaurs, too.

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. More recently, grebes and loon evolved striking similarities, independently.

Pike form – Fusiform, sit-and-strike hunting styles that converged on the pike form evolved independently in a half dozen fish lineages.

Eel form – Eel-like forms evolved independently in the North American brook lamprey, neotropical eels, and the African spiny eel.

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.

Trichromatic color vision (blue, green, red) – is unusual in mammals, yet it evolved independently in our own ancestors and other apes, Old World monkeys, howler monkeys of the New World, and some Australian marsupials.

Inflatable penis – Mammals and turtles independently evolved penises that stiffen by hydrostatic inflation. Some mammals also independently evolved a penis bone, a baculum.

Muscles - In 2013 the genome of a member of the animal lineage Ctenophora was finally sequenced — and what a surprise! The "**comb jellies**" (which look somewhat like jellyfish, but lack stinging cells) now wrest the title of most primitive form of animal from sponges. Convergent evolution coupled with devolution were the reasons that sponges had for so long been assumed to be the most primitive living animal. Devolution: Even though sponges lack neurons, their genome indicates that their ancestors used to have a nerve net like a jellyfish, but it devolved away from being expressed in actual sponge bodies. Convergent evolution: The genes that code for muscles in comb jellies (sponges lack muscles) are very distinct from the genes that code for muscles in jellyfish and other animals. Hence, muscles independently emerged in comb jellies: an example of convergent evolution at the base of animal life!

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. A 2010 science article states that, of just the life forms alive today, multi-cellularity arose independently (that means, "convergently") at least 17 times.

Eyes – In his 1995 book, *River Out of Eden*, (and again in his 2004 book *Ancestor's Tale*) Richard Dawkins cites estimates that image-forming eyes have independently evolved 40 to 60 times, using a total of 9 very different optical forms. It is striking how different the compound eyes of insects are from the single-lensed eyes of vertebrates, and how similar the **camera-like 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. Compound eyes have evolved independently in ostracods v. crablike crustaceans, as well as among annelid worms (sabellids), and bivalve mollusks. Camera-like eyes have evolved not only in vertebrates and octopuses, but independently in jumping spiders, some snails, alciopid polychaete worms, cubozoan jellyfish, and backward looking eyes of coral reef shrimp. Finally, while many single-celled protists have photosensitive eyespots, single-celled dinoflagellates have a lens in their eye spot! NOTE: Genetic evidence suggests that the basic chemistry of a "photoreceptor" (like the "eye" dot on Euglena) evolved well before multicellularity; thus all animals that have vision share the same genetic code for building the basic photoreceptors. Nevertheless, the diversity of organs that use photoreceptors is evidence of multiple instances of independent and sometimes convergent evolution. Note: The genetic rudiments that later evolve into eyes and other convergent body forms sometimes evidence "**deep homology**". A 2009 paper is an excellent review, and uses the question about convergent evolution of eyes (from jellyfish to vertebrates) as one key example: "Deep Homoogy and the Origins of Evolutionary Novelty," by Neil Shubin et al.

Note: **Simon Conway Morris** disputes the significance of "deep homology", using eyes as a key example, in his 2009 paper on evolutionary convergence (23 pages PDF): **"The Predicability of Evolution: Glimpses into a Post-Darwinian World"**

Hovering nectar feeders - The flight patterns of sphinx moths, which are hovering nectar feeders, are strikingly convergent with that of hummingbirds.

Hydrostatic stiffening of extremities – Eye stalks in snails, legs of spiders, penises in turtles and mammals, and the whole body of earthworms are held firm and moved by hydrostatic pressure.

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.

Swim bladders – Buoyant badders of gas that can be regulated according to position in the water column were independently evolved in fishes (swim bladders), female octopus of *Ocythoe* genus, and siphonorphore jellyfish (e.g., Portuguese man-of-war).

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 (echolocation)– Bats (several times) 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. Among living birds we find two that nest in dark caves that each independently evolved echolcation: the South American oilbird and Asian cave swiftlets .

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.

Eusociality – This is a remarkable form of behavioral convergence, in which organisms live in colonies in which only one female is reproductive, and the remaining individuals are divided into several castes that all work together in a cohesive, coordinate way. In addition to bees, termites, and ants, some gall thrips and certain beetles live this way. In coral reef shrimps, eusociality has evolved independently three times. Mole rats evolved in the mammals independently twice, and some voles live in eusocial societies. See "The Evolution of Eusociality," Nowak et al. 2010

Venomous sting: The ability to inject poison hypodermically through a sharp-pointed tube has evolved at least 10 times independently: jellyfish, spiders, scorpions, centipedes, various insects, cone shell mollusks, snakes, stingrays, stonefish, the male duckbill platypus, and stinging nettles.

Venomous bite: Venomous snakes use a channeled groove in their fangs to direct the flow of venom. So do some living and extinct mammals: Two rare species of solendons (rat-size mammals in Haiti and Cuba) have this same kind of groove for venom delivery along the backside of their canine teeth. And a 60 million year old fossil mammal, *Bisonalveus browni*, has the same kind of grooved canine. Male duckbilled platypuses have venomous spurs on their hind feet, but they produce venom only during breeding season.

Song generated by scraping: Insects (notably, crickets) have evolved external devices on appendages that, by rhythmic scraping at very fast rates, produce lovely tones audible to the human ear. A bird of the Ecuadorian forest, the club-winged manakin, has evolved a lead primary wing feather whose central vein is rapidly scraped across the underside of the veins of the other primary feathers on the wing, producing a tone like that made by a violin.

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.

Flower Petals – Genetic analysis post 2000 has shown that petals independently evolved a number of times in different plant lineages. (see NYT: 09/07/09 "Where Did All the Flowers Come From?")

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.

Other plant toxins – Many plants have independently evolved cyanogenic glycosides or proteinase inhibitor toxins to deter herbivores.

Deadly skin poisons – Evolved independently in poison-dart frogs of South America and two New Guinea birds. The crested auklet has skin poisons strikingly similar to those found in defensive glands of heteropteran insects.

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. "The snow flea antifreeze proteins have an entirely different composition from those of antifreezes that have been isolated from other insects, like the fire colored beetle, which has antifreeze proteins that are in turn different from those of the spruce budworm caterpillar. And all of these insect antifreezes are distinct from the kind that keeps Antarctic fish alive. Each animal's antifreeze is a separate evolutionary invention." (from NYT 1/18/10:) http://www.nytimes.com/2010/01/19/science/19creatures.html?ref=science

Silk – Spiders, silk moths, larval caddis flies, and the weaver ant *Oecophyll* all produce silken threads.

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 and many mollusks use copper (in hemocyanin molecules) to bind oxygen in their blood system instead. In July 2010, Jay Storz et al published findings that hemoglobin molecules evolved independently (convergently) in the jawless fishes (lampreys) and the jawed fishes ancestors of all the remaining vertebrates.

Bioluminescence - Symbiotic partnerships with light-emitting bacteria developed many times independently in deep-sea fish, jellyfish, 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). The phosphatic plates produced by barnacles are remarkably convergent in lamellate structure with the phosphatic bones of vertebrates.

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. A 2015 paper in *Nature Genetics* confirms that "Convergent evolution of the mycorrhizal habit in fungi occurred via the repeated evolution of a 'symbiosis toolkit', with reduced numbers of PCWDEs and lineage-specific suites of mycorrhiza-induced genes."

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!

C4 Photosynthesis – in which the first product of carbon fixing is a molecule containing 4 carbons instead of 3. This 4-carbon method evolved indepependently in different plant lineages and is an adaptation for higher temperature and drier environments.

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.

Evolution of carnivory from herbivorous ancestors – A stingless bee in South America, *Trigona hypogea*, has evolved carrion-feeding and predation from a nectar-and pollen-feeding ancestor. Are there other examples?

Evolution of herbivory from carnivorous ancestors – The four-legged ancestor of the whale group, Order Cetacea, is thought to have been carnivorous, and yet baleen whales evolved from the same ancestor as did killer whales. Some bats are insectivores, some are blood eaters (vampires), and some are fruit-and-nectar feeders. Granivorous birds (grain eaters), such as chickens, have evolved a gizzard to grind the grain.

Evolution of plankton feeding by large forms – Whale sharks and baleen whales (like the humpback and blue) independently evolved very sophisticated ways of maintaining huge vertebrate bodies on the food energy derived from sifting plankton from marine waters.

Praying mantis form – The praying mantis form of raptorial forelimb, prehensile neck, and extraordinary snatching speed has evolved not only in mantid insects but also independently in neuropteran insects (*Mantispa*) and rhachiberothidids. The resemblence among them is eerily the same.

The army ant syndrome – Marauding columns of invincible ants have evolved independently in several distinct lineages of ants.

Animal-algae symbioses - Among the so-called "invertebrates," corals are best-known for relying on photosynthetic algae in their tissues for producing sugars in a mutualistic way (although the algae either exit or get pushed out when the chemistry or temperature of the water puts the coral animals under stress: "bleaching.") In 2010, the journal *Nature* published a paper on the **first example of a vertebrate in symbiotic relationship with an alga**. In this case, the vertebrate utilizes the alga for ensuring a rich supply of oxygen. Spotted salamanders in the eastern USA carry a species of green alga in their oviducts; when a massive bundle of jelly is laid along with the eggs, each spherical casing around each embryo is provisioned with algae. When the embryo begins to generate metabolites, including carbon-dioxide, the algae population blooms and begins producing oxygen. In this way, the jelly that prevents dehydration between replenishing rainfalls in ephemeral spring ponds can do its job without interfering with the embryo's ability to obtain the oxygen that it requires for its 4-6 weeks inside the jelly mass. See "A Solar Salamander."

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. Rather than internal lungs, terrestrial arthropods independently invented for breathing systems of tubes (tracheids) not commingled with body fluids. Tracheal systems evolved independently in winged insects, isopod crustaceans, wood lice and their relatives, arachnids (spiders), and onychophorans (velvet "worms").

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

Parental care: Mammals, by definition, offer post-birth parental care because mother's suckle their young for at least a short period, and sometimes for an extended time. Birds will feed their young at the nest post-hatching, and sometimes extend this behavior after the young have fledged so that their offspring can learn to mimic their food gathering behaviors. In contrast, with the exception of some snakes brooding their eggs, we don't usually think of reptiles as extending parental care beyond hatching. The great exception are the crocodilians; mothers linger with their young not to feed them but to protect them—from other crocodilians. Some male fishes (and seahorses) are known to put an immense effort into guarding eggs (even newly hatched young). Most surprising is discovery of a 14 cm long squid off the coast of California, which guards the eggs that it lays at great depth for 3 months. 13 October 2012 issue of *New Scientist* reports that scorpions not only give birth to live young (rather than laying eggs), but that the young ride on the mother, as "the juveniles are unable to feed or defend themselves, or regulate their moisture levels."

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.

Parasitoid employment of viruses – Parasitoid wasps lay their eggs inside host caterpillars such that the young consume (and kill) the living caterpillar from the inside out. To prevent the caterpillar immune system from destroying the wasp eggs, the parent wasp injects viral particles along with the eggs, and these viruses disable the host immune system. This mutualistic symbiosis between parasitoid and virus is thought to have evolved independently no less than twice.

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.

Short-lived breeders - As humans, we tend to think of the juvenile phase as being short and preparatory for the "real" life of an organism: an adult. But in many unrelated insects, juvenile forms last a long time compared to the adult stage of mouthless breeders: cicada, silk moths, mayflies. Even in vertebrates, salmon die spectacularly after having worked their way upstream against rapids into streams where they lay eggs, deposit sperm, and then die. Bits of flesh are already rotting on their bodies as they writhe in the final dance of mating.

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.

Jet propulsion – Squids and scallops, although both mollusks, seem to have independently evolved very different ways of squeezing water through their bodies to power their movement through a fluid. Dragonfly larvae (aquatic at this stage) employ and anal jet to propel their movements. Modern jellyfish still use the same form of jet propulsion invented by their early ancestors—which ranks as the first example of jet propulsion in multicellular animals. [*Science News*, 23 February 2008. p. 122]

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.

Sleep as physiological necessity - convergent in mammals, several groups of insects (notably bees and the fly) as well as some jellyfish [refer to Simon Conway-Morris 2009].

Agriculture – Starting millions of years before the rise of human agriculture, some kinds of ants, termites, and ambrosia beetles began to cultivate and tend fungi for food. Today, these insects sow, fertilize, and weed their crops. Now a form of proto-agriculture has been discovered in fish. A damselfish, *Stegastes nigricans*, not only defends a territory in which red algae carpets a piece of reef; the damselfish actively "weeds" out invading species of algae by nipping out the newcomer, seimming outside its territory, and spitting it out. If a damselfish is removed from its algal rock, its preferred species of alga is quickly overwhelmed by other species, so it is likely that the association is mutualistic—the red alga, *Polysiphonia*, requires the help of the damselfish. In a 2011 issue of the journal *Nature*, researchers report that even **slime molds** (a form of social amoeba) engages in farming of bacteria: "the social amoeba *Dictyostelium discoideum* has a primitive farming symbiosis that includes dispersal and prudent harvesting of the crop."

STRANGE AND SOPHISTICATED ORGANS

Whirling rods for balance – Dipteran flies (like the common housefly) have little whirling drumsticks (halteres) on their backs that are used to maintain balance. Acting like gyroscopes, they detect angular accelerations. The halteres were evolved from the pair of hind wings in the dipteran ancestor. An unrelated group of insects, strepsipterans, evolved haltere-like organs, but from the ancestral fore-wings instead of the hind-wings. An African beetle has evolved its wing-cases into haltere-like organs, and a fourth example can be found in a group of hemipterans known as coccoideans (who produce swollen galls in plants).

Mineralized hairs for balance – Statocysts are grains of mineral attached to fine hairs that give sensitivity to gravity. Statocysts have evolved independently and repeatedly in organisms as diverse as jellyfish, crabs, cephalopods, and even single-cell ciliates. In vertebrates, statocysts have evolved into otoconia mineral grains in the inner ear.

Electrical detection of prey or defense - In murky water, electric sensing to detect prey (e.g. saltwater sharks and freshwater paddlefish) and electrogeneration for defense (torpedo ray, electric "eel" of the Amazon, African mormyrid fish) have evolved many times. Electric generation comes from organs that independently evolved to resemble a stack of gelatinous disks, with interprenetrating stalks. Duck-billed platypuses (monotreme mammals who live in freshwaters of Australia) also are sensitive to electric fields, as is the star-nosed mole. The huge flattened rostrum of the extinct trilobite *Reedocalymene* also suggests much earlier development of electric sensing in a Paleozoic saltwater arthropod.

Sophisticated hearing devices – The way mosquitoes hear (the Johnston's organ) is amazingly similar to the way that mammals hear, yet the process is independently evolved. The tympanal ear found more generally in insects is convergent with the eardrum of mammals.

High-pitched ultrasound – The concave-eared torrent frog of China (*Amolops tormotus*), differs from other frogs in that it uses high-pitched sound (including ultrasound, higher than humans can hear) in its mating call. Because it lives by raging rivers, this unusual ability may have evolved to be heard despite the low roar of river habitat. Bats, of course, use ultrasound, but this is the first occurrence of ultrasound in an amphibian.

Long-frequency infrasound communication – Elephants, whales, and humans (e.g., submarines) all independently invented and effectively use transmittal and reception of exceptionally long-frequency sound waves for communication over great distances.

Mammalian ear structure – The tiny bones in the middle ear of mammals (stapes, incus, and malleus) are now believed to have evolved independently at least twice, given the still-reptilian-like ear configuration implied in a well-preserved jaw of a monotreme (egg-laying mammal), *Teinolophos trusleri*, dated at 115 mya.

Infrared focused vision - The ability to see longer wavelengths than "visible" light has independently evolved in crotalid snakes (rattlesnakes), pythons, vampire bats, and wood-boring wasps and fire beetles.

External scrotum for holding testicles - Testicles are retained within the body in all monotremes, but marsupial mammals and placental mammals long ago evolved major lineages with external scrotal sacs. Among the placentals, however, the Afrotheres (elephants, mammoths, manatees, aardvarks) never developed a scrotum. Their ancient lineage split from the rest of mammals before a scrotum developed. Among those living placental lineages that do have scrotal sacs (primates, cats, dogs, bears, and all hoofed mammals), some have de-evolved scrotal sacs and the testicles once again reside within the body: hedgehogs, moles, rhinos and tapirs, hippopotamuses, dolphins and whales, some seals and walruses, and scaly anteaters). Apparently, sperm production adapted to cooler ideal temperatures in scrotal mammals — rather than the scrotum evolving in order for sperm to receive cooler temperatures. The the fitness value of a scrotum (despite its dangerous placement) may have something to do with sexual selection -- rather than natural selection. Like a peacock's tail, a dangling set indicates to a female that this male is so fit it can protect its dangling treasure. Alternatively is "the galloping hypothesis" — that the rigors of galloping wreak havoc in the plumbing of a combined sperm, prostate, and urine system that lacks sphincter valves. For a superb discussion of this as-yet contentious scientific mystery, see a 2013 essay by Liam Drew: "The Scrotum Is Nuts."

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.