Was Darwin Wrong? By David Quammen

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Evolution by natural selection, the central concept of the life's work of Charles Darwin, is a theory. It's a theory about the origin of adaptation, complexity, and diversity among Earth's living creatures. If you are skeptical by nature, unfamiliar with the terminology of science, and unaware of the overwhelming evidence, you might even be tempted to say that it's "just" a theory. In the same sense, relativity as described by Albert Einstein is "just" a theory. The notion that Earth orbits around the sun rather than vice versa, offered by Copernicus in 1543, is a theory. Continental drift is a theory. The existence, structure, and dynamics of atoms? Atomic theory. Even electricity is a theoretical construct, involving electrons, which are tiny units of charged mass that no one has ever seen. Each of these theories is an explanation that has been confirmed to such a degree, by observation and experiment, that knowledgeable experts accept it as fact. That's what scientists mean when they talk about a theory: not a dreamy and unreliable speculation, but an explanatory statement that fits the evidence. They embrace such an explanation confidently but provisionally—taking it as their best available view of reality, at least until some severely conflicting data or some better explanation might come along.

The rest of us generally agree. We plug our televisions into little wall sockets, measure a year by the length of Earth's orbit, and in many other ways live our lives based on the trusted reality of those theories.

Evolutionary theory, though, is a bit different. It's such a dangerously wonderful and far-reaching view of life that some people find it unacceptable, despite the vast body of supporting evidence. As applied to our own species, *Homo sapiens,* it can seem more threatening still. Many fundamentalist Christians and ultraorthodox Jews take alarm at the thought that human descent from earlier primates contradicts a strict reading of the Book of Genesis. Their discomfort is paralleled by Islamic creationists such as Harun Yahya, author of a recent volume titled *The Evolution Deceit,* who points to the six-day creation story in the Koran as literal truth and calls the theory of evolution "nothing but a deception imposed on us by the dominators of the world system." The late Srila Prabhupada, of the Hare Krishna movement, explained that God created "the 8,400,000 species of life from the very beginning," in order to establish multiple tiers of reincarnation for rising souls. Although souls ascend, the species themselves don't change, he insisted, dismissing "Darwin's nonsensical theory."

Other people too, not just scriptural literalists, remain unpersuaded about evolution. According to a Gallup poll drawn from more than a thousand telephone interviews conducted in February 2001, no less than 45 percent of responding U.S. adults agreed that "God created human beings pretty much in their present form at one time within the last 10,000 years or so." Evolution, by their lights, played no role in shaping us.

Only 37 percent of the polled Americans were satisfied with allowing room for both God and Darwin—that is, divine initiative to get things started, evolution as the creative means. (This view, according to more than one papal pronouncement, is compatible with Roman Catholic dogma.) Still fewer Americans, only 12 percent, believed that humans evolved from other life-forms without any involvement of a god.

The most startling thing about these poll numbers is not that so many Americans reject evolution, but that the statistical breakdown hasn't changed much in two decades. Gallup interviewers posed exactly the same choices in 1982, 1993, 1997, and 1999. The creationist conviction—that God alone, and not evolution, produced humans—has never drawn less than 44 percent. In other words, nearly half the American populace prefers to believe that Charles Darwin was wrong where it mattered most.

Why are there so many antievolutionists? Scriptural literalism can only be part of the answer. The American public certainly includes a large segment of scriptural literalists—but not *that* large, not 44 percent. Creationist proselytizers and political activists, working hard to interfere with the teaching of evolutionary biology in public schools, are another part. Honest confusion and ignorance, among millions of adult Americans, must be still another. Many people have never taken a biology course that dealt with evolution nor read a book in which the theory was lucidly explained. Sure, we've all heard of Charles Darwin, and of a vague, somber notion about struggle and survival that sometimes goes by the catchall label "Darwinism." But the main sources of information from which most Americans have drawn their awareness of this subject, it seems, are haphazard ones at best: cultural osmosis, newspaper and magazine references, half-baked nature documentaries on the tube, and hearsay.

Evolution is both a beautiful concept and an important one, more crucial nowadays to human welfare, to medical science, and to our understanding of the world than ever before. It's also deeply persuasive—a theory you can take to the bank. The essential points are slightly more complicated than most people assume, but not so complicated that they can't be comprehended by any attentive person. Furthermore, the supporting evidence is abundant, various, ever increasing, solidly interconnected, and easily available in museums, popular books, textbooks, and a mountainous accumulation of peer-reviewed scientific studies. No one needs to, and no one should, accept evolution merely as a matter of faith.

Two big ideas, not just one, are at issue: the evolution of all species, as a historical phenomenon, and natural selection, as the main mechanism causing that phenomenon. The first is a question of what happened. The second is a question of how. The idea that all species are descended from common ancestors had been suggested by other thinkers, including Jean-Baptiste Lamarck, long before Darwin published *The Origin of Species* in 1859. What made Darwin's book so remarkable when it appeared, and so influential in the long run, was that it offered a rational explanation of how evolution must occur. The same insight came independently to Alfred Russel Wallace, a young naturalist doing fieldwork in the Malay Archipelago during the late 1850s. In historical annals, if not in the popular awareness, Wallace and Darwin share the kudos for having discovered natural selection.

The gist of the concept is that small, random, heritable differences among individuals result in different chances of survival and reproduction—success for some, death without offspring for others—and that this natural culling leads to significant changes in shape, size, strength, armament, color, biochemistry, and behavior among the descendants. Excess population growth drives the competitive struggle. Because less successful competitors produce fewer surviving offspring, the useless or negative variations tend to disappear, whereas the useful variations tend to be perpetuated and gradually magnified throughout a population.

So much for one part of the evolutionary process, known as anagenesis, during which a single species is transformed. But there's also a second part, known as speciation. Genetic changes sometimes accumulate within an isolated segment of a species, but not throughout the whole, as that isolated population adapts to its local conditions. Gradually it goes its own way, seizing a new ecological niche. At a certain point it becomes irreversibly distinct—that is, so different that its members can't interbreed with the rest. Two species now exist where formerly there was one. Darwin called that splitting-and-specializing phenomenon the "principle of divergence." It was an important part of his theory, explaining the overall diversity of life as well as the adaptation of individual species.

This thrilling and radical assemblage of concepts came from an unlikely source. Charles Darwin was shy and meticulous, a wealthy landowner with close friends among the Anglican clergy. He had a gentle, unassuming manner, a strong need for privacy, and an extraordinary commitment to intellectual honesty. As an undergraduate at Cambridge, he had studied halfheartedly toward becoming a clergyman himself, before he discovered his real vocation as a scientist. Later, having established a good but conventional reputation in natural history, he spent 22 years secretly gathering evidence and pondering arguments—both for and against his theory—because he didn't want to flame out in a burst of unpersuasive notoriety. He may have delayed, too, because of his anxiety about announcing a theory that seemed to challenge conventional religious beliefs—in particular, the Christian beliefs of his wife, Emma. Darwin himself quietly renounced Christianity during his middle age, and later described himself as an agnostic. He continued to believe in a distant, impersonal deity of some sort, a greater entity that had set the universe and its laws into motion, but not in a personal God who had chosen humanity as a specially favored species. Darwin avoided flaunting his lack of religious faith, at least partly in deference to Emma. And she prayed for his soul.

In 1859 he finally delivered his revolutionary book. Although it was hefty and substantive at 490 pages, he considered *The Origin of Species* just a quick-and-dirty "abstract" of the huge volume he had been working on until interrupted by an alarming event. (In fact, he'd wanted to title it *An Abstract of an Essay on the Origin of Species and Varieties Through Natural Selection,* but his publisher found that insufficiently catchy.) The alarming event was his receiving a letter and an enclosed manuscript from Alfred Wallace, whom he knew only as a distant pen pal. Wallace's manuscript sketched out the same great idea—evolution by natural selection—that Darwin considered his own. Wallace had scribbled this paper and (unaware of Darwin's own evolutionary thinking, which so far had been kept private) mailed it to him from the Malay Archipelago, along with a request for reaction and help. Darwin was horrified. After two decades of painstaking effort, now he'd be scooped. Or maybe not quite. He forwarded Wallace's paper toward publication, though managing also to assert his own prior claim by releasing two excerpts from his unpublished work. Then he dashed off *The Origin,* his "abstract" on the subject. Unlike Wallace, who was younger and less meticulous, Darwin recognized the importance of providing an edifice of supporting evidence and logic.

The evidence, as he presented it, mostly fell within four categories: biogeography, paleontology, embryology, and morphology. Biogeography is the study of the geographical distribution of living creatures—that is, which species inhabit which parts of the planet and why. Paleontology investigates extinct life-forms, as revealed in the fossil record. Embryology examines the revealing stages of development (echoing earlier stages of evolutionary history) that embryos pass through before birth or hatching; at a stretch, embryology also concerns the immature forms of animals that metamorphose, such as the larvae of insects. Morphology is the science of anatomical shape and design. Darwin devoted sizable sections of *The Origin of Species* to these categories.

Biogeography, for instance, offered a great pageant of peculiar facts and patterns. Anyone who considers the biogeographical data, Darwin wrote, must be struck by the mysterious clustering pattern among what he called "closely allied" species—that is, similar creatures sharing roughly the same body plan. Such closely allied species tend to be found on the same continent (several species of zebras in Africa) or within the same group of oceanic islands (dozens of species of honeycreepers in Hawaii, 13 species of Galápagos finch), despite their species-by-species preferences for different habitats, food sources, or conditions of climate. Adjacent areas of South America, Darwin noted, are occupied by two similar species of large, flightless birds (the rheas, *Rhea americana* and *Pterocnemia pennata),* not by ostriches as in Africa or emus as in Australia. South America also has agoutis and viscachas (small rodents) in terrestrial habitats, plus coypus and capybaras in the wetlands, not—as Darwin wrote—hares and rabbits in terrestrial habitats or beavers and muskrats in the wetlands. During his own youthful visit to the Galápagos, aboard the survey ship *Beagle,* Darwin himself had discovered three very similar forms of mockingbird, each on a different island.

Why should "closely allied" species inhabit neighboring patches of habitat? And why should similar habitat on different continents be occupied by species that aren't so closely allied? "We see in these facts some deep organic bond, prevailing throughout space and time," Darwin wrote. "This bond, on my theory, is simply inheritance." Similar species occur nearby in space because they have descended from common ancestors.

Paleontology reveals a similar clustering pattern in the dimension of time. The vertical column of geologic strata, laid down by sedimentary processes over the eons, lightly peppered with fossils, represents a tangible record showing which species lived when. Less ancient layers of rock lie atop more ancient ones (except where geologic forces have tipped or shuffled them), and likewise with the animal and plant fossils that the strata contain. What Darwin noticed about this record is that closely allied species tend to be found adjacent to one another in successive strata. One species endures for millions of years and then makes its last appearance in, say, the middle Eocene epoch; just above, a similar but not identical species replaces it. In North America, for example, a vaguely horselike creature known as *Hyracotherium* was succeeded by *Orohippus,* then *Epihippus,* then *Mesohippus,* which in turn were succeeded by a variety of horsey American critters. Some of them even galloped across the Bering land bridge into Asia, then onward to Europe and Africa. By five million years ago they had nearly all disappeared, leaving behind *Dinohippus,* which was succeeded by *Equus,* the modern genus of horse. Not all these fossil links had been unearthed in Darwin's day, but he captured the essence of the matter anyway. Again, were such sequences just coincidental? No, Darwin argued. Closely allied species succeed one another in time, as well as living nearby in space, because they're related through evolutionary descent.

Embryology too involved patterns that couldn't be explained by coincidence. Why does the embryo of a mammal pass through stages resembling stages of the embryo of a reptile? Why is one of the larval forms of a barnacle, before metamorphosis, so similar to the larval form of a shrimp? Why do the larvae of moths, flies, and beetles resemble one another more than any of them resemble their respective adults? Because, Darwin wrote, "the embryo is the animal in its less modified state" and that state "reveals the structure of its progenitor."

Morphology, his fourth category of evidence, was the "very soul" of natural history, according to Darwin. Even today it's on display in the layout and organization of any zoo. Here are the monkeys, there are the big cats, and in that building are the alligators and crocodiles. Birds in the aviary, fish in the aquarium. Living creatures can be easily sorted into a hierarchy of categories—not just species but genera, families, orders, whole kingdoms—based on which anatomical characters they share and which they don't.

All vertebrate animals have backbones. Among vertebrates, birds have feathers, whereas reptiles have scales. Mammals have fur and mammary glands, not feathers or scales. Among mammals, some have pouches in which they nurse their tiny young. Among these species, the marsupials, some have huge rear legs and strong tails by which they go hopping across miles of arid outback; we call them kangaroos. Bring in modern microscopic and molecular evidence, and you can trace the similarities still further back. All plants and fungi, as well as animals, have nuclei within their cells. All living organisms contain DNA and RNA (except some viruses with RNA only), two related forms of information-coding molecules.

Such a pattern of tiered resemblances—groups of similar species nested within broader groupings, and all descending from a single source—isn't naturally present among other collections of items. You won't find anything equivalent if you try to categorize rocks, or musical instruments, or jewelry. Why not? Because rock types and styles of jewelry don't reflect unbroken descent from common ancestors. Biological diversity does. The number of shared characteristics between any one species and another indicates how recently those two species have diverged from a shared lineage.

That insight gave new meaning to the task of taxonomic classification, which had been founded in its modern form back in 1735 by the Swedish naturalist Carolus Linnaeus. Linnaeus showed how species could be systematically classified, according to their shared similarities, but he worked from creationist assumptions that offered no material explanation for the nested pattern he found. In the early and middle 19th century, morphologists such as Georges Cuvier and Étienne Geoffroy Saint-Hilaire in France and Richard Owen in England improved classification with their meticulous studies of internal as well as external anatomies, and tried to make sense of what the ultimate source of these patterned similarities could be. Not even Owen, a contemporary and onetime friend of Darwin's (later in life they had a bitter falling out), took the full step to an evolutionary vision before *The Origin of Species* was published. Owen made a major contribution, though, by advancing the concept of homologues—that is, superficially different but fundamentally similar versions of a single organ or trait, shared by dissimilar species.

For instance, the five-digit skeletal structure of the vertebrate hand appears not just in humans and apes and raccoons and bears but also, variously modified, in cats and bats and porpoises and lizards and turtles. The paired bones of our lower leg, the tibia and the fibula, are also represented by homologous bones in other mammals and in reptiles, and even in the long-extinct bird-reptile *Archaeopteryx.* What's the reason behind such varied recurrence of a few basic designs? Darwin, with a nod to Owen's "most interesting work," supplied the answer: common descent, as shaped by natural selection, modifying the inherited basics for different circumstances.

Vestigial characteristics are still another form of morphological evidence, illuminating to contemplate because they show that the living world is full of small, tolerable imperfections. Why do male mammals (including human males) have nipples? Why do some snakes (notably boa constrictors) carry the rudiments of a pelvis and tiny legs buried inside their sleek profiles? Why do certain species of flightless beetle have wings, sealed beneath wing covers that never open? Darwin raised all these questions, and answered them, in *The Origin of Species.* Vestigial structures stand as remnants of the evolutionary history of a lineage.

Today the same four branches of biological science from which Darwin drew—biogeography, paleontology, embryology, morphology—embrace an ever growing body of supporting data. In addition to those categories we now have others: population genetics, biochemistry, molecular biology, and, most recently, the whiz-bang field of machine-driven genetic sequencing known as genomics. These new forms of knowledge overlap one another seamlessly and intersect with the older forms, strengthening the whole edifice, contributing further to the certainty that Darwin was right.

He was right about evolution, that is. He wasn't right about *everything.* Being a restless explainer, Darwin floated a number of theoretical notions during his long working life, some of which were mistaken and illusory. He was wrong about what causes variation within a species. He was wrong about a famous geologic mystery, the parallel shelves along a Scottish valley called Glen Roy. Most notably, his theory of inheritance—which he labeled pangenesis and cherished despite its poor reception among his biologist colleagues—turned out to be dead wrong. Fortunately for Darwin, the correctness of his most famous good idea stood independent of that particular bad idea. Evolution by natural selection represented Darwin at his best—which is to say, scientific observation and careful thinking at its best.

Douglas Futuyma is a highly respected evolutionary biologist, author of textbooks as well as influential research papers. His office, at the University of Michigan, is a long narrow room in the natural sciences building, well stocked with journals and books, including volumes about the conflict between creationism and evolution. I arrived carrying a well-thumbed copy of his own book on that subject, *Science on Trial: The Case for Evolution.* Killing time in the corridor before our appointment, I noticed a blue flyer on a departmental bulletin board, seeming oddly placed there amid the announcements of career opportunities for graduate students. "Creation vs. evolution," it said. "A series of messages challenging popular thought with Biblical truth and scientific evidences." A traveling lecturer from something called the Origins Research Association would deliver these messages at a local Baptist church. Beside the lecturer's photo was a drawing of a dinosaur. "Free pizza following the evening service," said a small line at the bottom. Dinosaurs, biblical truth, and pizza: something for everybody.

In response to my questions about evidence, Dr. Futuyma moved quickly through the traditional categories—paleontology, biogeography—and talked mostly about modern genetics. He pulled out his heavily marked copy of the journal *Nature* for February 15, 2001, a historic issue, fat with articles reporting and analyzing the results of the Human Genome Project. Beside it he slapped down a more recent issue of *Nature,* this one devoted to the sequenced genome of the house mouse, *Mus musculus*. The headline of the lead editorial announced: "HUMAN BIOLOGY BY PROXY." The mouse genome effort, according to *Nature's* editors, had revealed "about 30,000 genes, with 99% having direct counterparts in humans."

The resemblance between our 30,000 human genes and those 30,000 mousy counterparts, Futuyma explained, represents another form of homology, like the resemblance between a five-fingered hand and a five-toed paw. Such genetic homology is what gives meaning to biomedical research using mice and other animals, including chimpanzees, which (to their sad misfortune) are our closest living relatives.

No aspect of biomedical research seems more urgent today than the study of microbial diseases. And the dynamics of those microbes within human bodies, within human populations, can only be understood in terms of evolution.

Nightmarish illnesses caused by microbes include both the infectious sort (AIDS, Ebola, SARS) that spread directly from person to person and the sort (malaria, West Nile fever) delivered to us by biting insects or other intermediaries. The capacity for quick change among disease-causing microbes is what makes them so dangerous to large numbers of people and so difficult and expensive to treat. They leap from wildlife or domestic animals into humans, adapting to new circumstances as they go. Their inherent variability allows them to find new ways of evading and defeating human immune systems. By natural selection they acquire resistance to drugs that should kill them. They evolve. There's no better or more immediate evidence supporting the Darwinian theory than this process of forced transformation among our inimical germs.

Take the common bacterium *Staphylococcus aureus,* which lurks in hospitals and causes serious infections, especially among surgery patients. Penicillin, becoming available in 1943, proved almost miraculously effective in fighting staphylococcus infections. Its deployment marked a new phase in the old war between humans and disease microbes, a phase in which humans invent new killer drugs and microbes find new ways to be unkillable. The supreme potency of penicillin didn't last long. The first resistant strains of *Staphylococcus aureus* were reported in 1947. A newer staph-killing drug, methicillin, came into use during the 1960s, but methicillin-resistant strains appeared soon, and by the 1980s those strains were widespread. Vancomycin became the next great weapon against staph, and the first vancomycin-resistant strain emerged in 2002. These antibiotic-resistant strains represent an evolutionary series, not much different in principle from the fossil series tracing horse evolution from *Hyracotherium* to *Equus.* They make evolution a very practical problem by adding expense, as well as misery and danger, to the challenge of coping with staph.

The biologist Stephen Palumbi has calculated the cost of treating penicillin-resistant and methicillin-resistant staph infections, just in the United States, at 30 billion dollars a year. "Antibiotics exert a powerful evolutionary force," he wrote last year, "driving infectious bacteria to evolve powerful defenses against all but the most recently invented drugs." As reflected in their DNA, which uses the same genetic code found in humans and horses and hagfish and honeysuckle, bacteria are part of the continuum of life, all shaped and diversified by evolutionary forces.

Even viruses belong to that continuum. Some viruses evolve quickly, some slowly. Among the fastest is HIV, because its method of replicating itself involves a high rate of mutation, and those mutations allow the virus to assume new forms. After just a few years of infection and drug treatment, each HIV patient carries a unique version of the virus. Isolation within one infected person, plus differing conditions and the struggle to survive, forces each version of HIV to evolve independently. It's nothing but a speeded up and microscopic case of what Darwin saw in the Galápagos—except that each human body is an island, and the newly evolved forms aren't so charming as finches or mockingbirds.

Understanding how quickly HIV acquires resistance to antiviral drugs, such as AZT, has been crucial to improving treatment by way of multiple drug cocktails. "This approach has reduced deaths due to HIV by severalfold since 1996," according to Palumbi, "and it has greatly slowed the evolution of this disease within patients."

Insects and weeds acquire resistance to our insecticides and herbicides through the same process. As we humans try to poison them, evolution by natural selection transforms the population of a mosquito or thistle into a new sort of creature, less vulnerable to that particular poison. So we invent another poison, then another. It's a futile effort. Even DDT, with its ferocious and long-lasting effects throughout ecosystems, produced resistant house flies within a decade of its discovery in 1939. By 1990 more than 500 species (including 114 kinds of mosquitoes) had acquired resistance to at least one pesticide. Based on these undesired results, Stephen Palumbi has commented glumly, "humans may be the world's dominant evolutionary force."

Among most forms of living creatures, evolution proceeds slowly—too slowly to be observed by a single scientist within a research lifetime. But science functions by inference, not just by direct observation, and the inferential sorts of evidence such as paleontology and biogeography are no less cogent simply because they're indirect. Still, skeptics of evolutionary theory ask: Can we see evolution in action? Can it be observed in the wild? Can it be measured in the laboratory?

The answer is yes. Peter and Rosemary Grant, two British-born researchers who have spent decades where Charles Darwin spent weeks, have captured a glimpse of evolution with their long-term studies of beak size among Galápagos finches. William R. Rice and George W. Salt achieved something similar in their lab, through an experiment involving 35 generations of the fruit fly *Drosophila melanogaster.* Richard E. Lenski and his colleagues at Michigan State University have done it too, tracking 20,000 generations of evolution in the bacterium *Escherichia coli.* Such field studies and lab experiments document anagenesis—that is, slow evolutionary change within a single, unsplit lineage. With patience it can be seen, like the movement of a minute hand on a clock.

Speciation, when a lineage splits into two species, is the other major phase of evolutionary change, making possible the divergence between lineages about which Darwin wrote. It's rarer and more elusive even than anagenesis. Many individual mutations must accumulate (in most cases, anyway, with certain exceptions among plants) before two populations become irrevocably separated. The process is spread across thousands of generations, yet it may finish abruptly—like a door going slam!—when the last critical changes occur. Therefore it's much harder to witness. Despite the difficulties, Rice and Salt seem to have recorded a speciation event, or very nearly so, in their extended experiment on fruit flies. From a small stock of mated females they eventually produced two distinct fly populations adapted to different habitat conditions, which the researchers judged "incipient species."

After my visit with Douglas Futuyma in Ann Arbor, I spent two hours at the university museum there with Philip D. Gingerich, a paleontologist well-known for his work on the ancestry of whales. As we talked, Gingerich guided me through an exhibit of ancient cetaceans on the museum's second floor. Amid weird skeletal shapes that seemed almost chimerical (some hanging overhead, some in glass cases) he pointed out significant features and described the progress of thinking about whale evolution. A burly man with a broad open face and the gentle manner of a scoutmaster, Gingerich combines intellectual passion and solid expertise with one other trait that's valuable in a scientist: a willingness to admit when he's wrong.

Since the late 1970s Gingerich has collected fossil specimens of early whales from remote digs in Egypt and Pakistan. Working with Pakistani colleagues, he discovered *Pakicetus,* a terrestrial mammal dating from 50 million years ago, whose ear bones reflect its membership in the whale lineage but whose skull looks almost doglike. A former student of Gingerich's, Hans Thewissen, found a slightly more recent form with webbed feet, legs suitable for either walking or swimming, and a long toothy snout. Thewissen called it *Ambulocetus natans,* or the "walking-and-swimming whale." Gingerich and his team turned up several more, including *Rodhocetus balochistanensis,* which was fully a sea creature, its legs more like flippers, its nostrils shifted backward on the snout, halfway to the blowhole position on a modern whale. The sequence of known forms was becoming more and more complete. And all along, Gingerich told me, he leaned toward believing that whales had descended from a group of carnivorous Eocene mammals known as mesonychids, with cheek teeth useful for chewing meat and bone. Just a bit more evidence, he thought, would confirm that relationship. By the end of the 1990s most paleontologists agreed.

Meanwhile, molecular biologists had explored the same question and arrived at a different answer. No, the match to those Eocene carnivores might be close, but not close enough. DNA hybridization and other tests suggested that whales had descended from artiodactyls (that is, even-toed herbivores, such as antelopes and hippos), not from meat-eating mesonychids.

In the year 2000 Gingerich chose a new field site in Pakistan, where one of his students found a single piece of fossil that changed the prevailing view in paleontology. It was half of a pulley-shaped anklebone, known as an astragalus, belonging to another new species of whale.

A Pakistani colleague found the fragment's other half. When Gingerich fitted the two pieces together, he had a moment of humbling recognition: The molecular biologists were right. Here was an anklebone, from a four-legged whale dating back 47 million years, that closely resembled the homologus anklebone in an artiodactyls. Suddenly he realized how closely whales are related to antelopes.

This is how science is supposed to work. Ideas come and go, but the fittest survive. Downstairs in his office Phil Gingerich opened a specimen drawer, showing me some of the actual fossils from which the display skeletons upstairs were modeled. He put a small lump of petrified bone, no longer than a lug nut, into my hand. It was the famous astragalus, from the species he had eventually named *Artiocetus clavis.* It felt solid and heavy as truth.

Seeing me to the door, Gingerich volunteered something personal: "I grew up in a conservative church in the Midwest and was not taught anything about evolution. The subject was clearly skirted. That helps me understand the people who are skeptical about it. Because I come from that tradition myself." He shares the same skeptical instinct. Tell him that there's an ancestral connection between land animals and whales, and his reaction is: Fine, maybe. But show me the intermediate stages. Like Charles Darwin, the onetime divinity student, who joined that round-the –world voyage aboard the *Beagle* instead of becoming a country parson, and whose grand view of life on Earth was shaped by attention to small facts, Phil Gingerich is a reverant empiricist. He's not satisfied until he sees solid data. That's what excites his so much about pulling shale fossils out of the ground. In 30 years he has seen enough to be satisfied. For him, Gingerich said, it's "a spiritual experience."

"The evidence is there," he added. "It's buried in the rocks of ages."