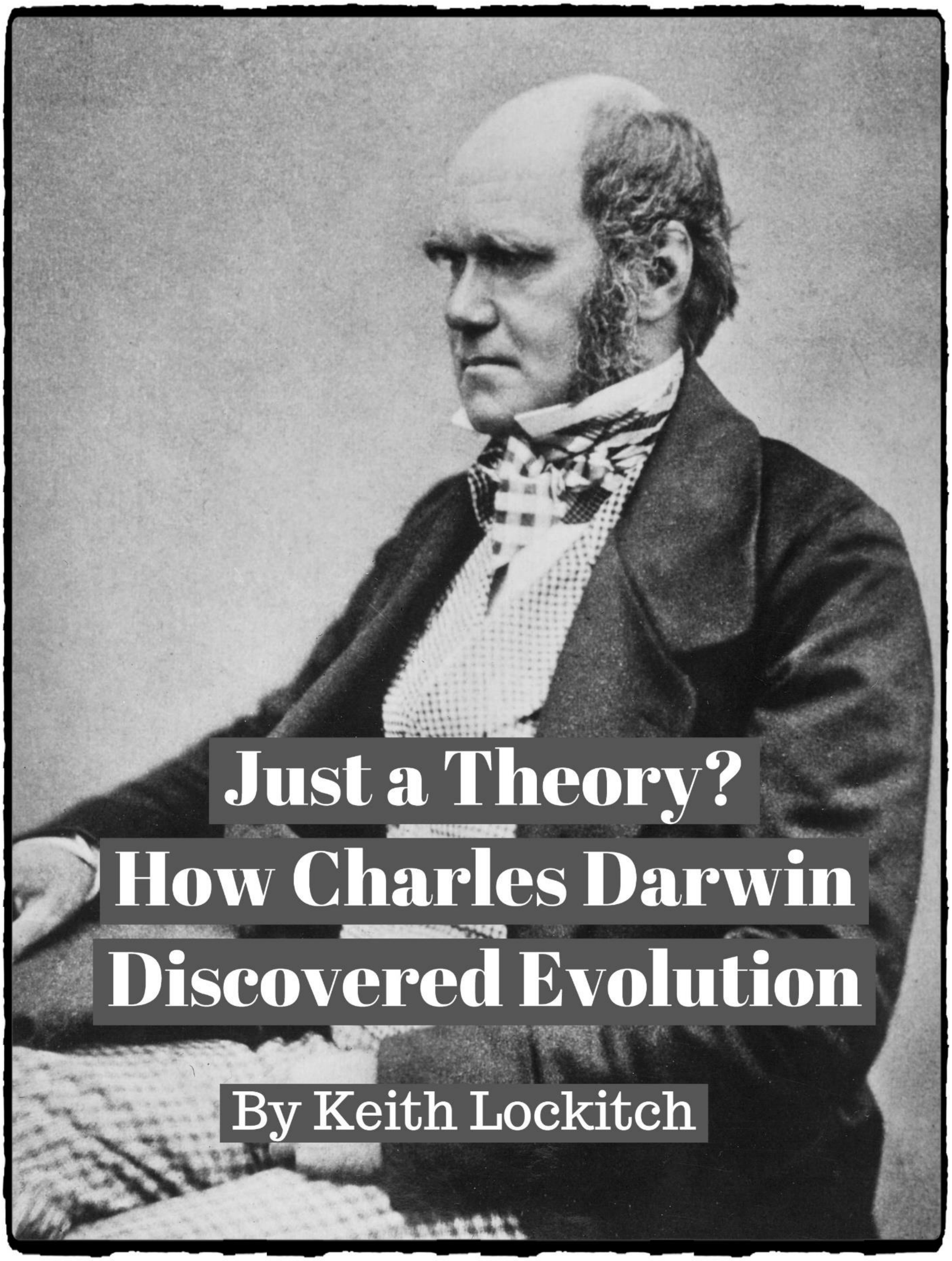

Just a Theory? How Charles Darwin Discovered Evolution

By Keith Lockitch

According to a recent Gallup poll, 40 percent of Americans believe in creationism, agreeing most closely with the view that "God created human beings pretty much in their present form at one time within the last 10,000 years or so." By contrast, only 22 percent agree most closely with the view that "Human beings have developed over millions of years from less advanced forms of life, but God had no part in this process."[1]

Such widespread rejection of the theory of evolution is fueled in part by the notion that evolution is "just a theory." This is the idea that evolution is just a speculative hypothesis—on a par with the biblical creation myth—with little-to-no basis in hard, scientific evidence.

The first thing to note about this claim is that it is simply not true—but even worse than the falsehood of the just-a-theory claim is the fact that it represents a grave injustice. To declare that evolution is "just a theory" is to suggest that Charles Darwin was "just a theorist"—that he was some sort of armchair scientist, spinning out scientific guesses in a vacuum instead of drawing his ideas from careful observations of nature. The just-a-theory allegation implies that Darwin formulated his theory without ever getting his hands dirty. But the truth is: *Darwin got his hands dirty*.

Darwin's theory of evolution by natural selection is the product of a monumental, lifelong effort to collect and integrate mountains of factual evidence. He developed it only after assembling and reflecting on a large body of compelling observations and data. And he devoted his entire life to finding and gathering facts and arguments supporting the theory, and to considering every possible objection and implication.

In this article, we'll explore Darwin's life and work, focusing on the process that he went through to amass and organize the enormous volume of evidence that he used to develop and validate his theory.

Darwin's Early Life and Education (1809–1831)

Charles Robert Darwin was born February 12, 1809, in Shrewsbury, England, just northwest of Birmingham. He was born into Jane Austen's England; *Pride and Prejudice* would be published just four years later. His father, Robert Darwin, was a wealthy doctor; and his mother, Susannah, was the daughter of the pottery magnate Josiah Wedgwood.

Charles Darwin grew up on a country estate and had ample opportunity to develop his early interest in the world of nature. In addition to the surrounding woods and the nearby river, the estate had a large greenhouse for him to explore, and his mother had a collection of fancy pigeons that she kept as pets. As a young boy he began collecting all sorts of things: shells, rocks, insects, bird's eggs, and more. He would collect plant specimens and try to identify them. By the age of ten, he had developed the habit of wandering off for hours to go bird watching or insect hunting.

Darwin was not a very hardworking student. He was completely uninterested in the classical education he received at the local school and did only the bare minimum of work necessary to get by. His father decided that Charles should follow in his own footsteps and become a doctor, so at the age of sixteen Charles was sent off to Scotland to Edinburgh University to study at its world-renowned medical school.

At university, Darwin was also an indifferent student—at least when it came to the classes in medicine he was taking. But he was interested in such activities as taking excursions to the Scottish coast to collect specimens of marine animals. He did not enjoy his anatomy classes, but just for fun he took private lessons in taxidermy.

One incident that occurred in his first year at Edinburgh basically put the writing on the wall regarding his career as a doctor. As a medical student he was required to observe surgical operations, which, in 1825, were far from the relatively safe and anesthetized affairs of today. One that he attended, on a small child, was so gruesome that he left in horror and never again set foot in an operating theater.

In his second year at *medical* school, he signed up for a number of classes on . . . geology and natural history. He studied techniques for preserving and labeling plant and animal specimens for collection and analysis, techniques that, as one biography points out, are "completely useless for anyone seriously intending to practice medicine."[2]

Darwin joined a natural history society and, with friends he made there, went on geological expeditions and trips to the coast to muck around in tidal pools. One of these friends was Robert Grant, a lecturer from the university who was a world-renowned expert on marine invertebrates. Under Grant's tutelage, Darwin learned how to dissect and analyze organisms, and he made original contributions of his own to Grant's research on primitive marine creatures.

Darwin continued his medical studies for a while, but his heart was clearly elsewhere, and, once again, he did only the bare minimum necessary to get by. At the end of his second year at Edinburgh, he gave up on medicine and left the university without a degree.

At this point, Charles's father was getting a bit frustrated. His father was not going to let him squander his inheritance pursuing fruitless hobbies; he decided that if Charles was not going to be a doctor, then he needed to do something else that would at least be respectable. If Charles did not want to continue with medicine, then he would have to study for the church and plan for a life as a respectable country clergyman. So Charles was sent off to Cambridge to study divinity—which he did with about as much enthusiasm as he had done medicine. What really interested him at Cambridge was collecting beetles, which was all the rage at the time, and his obsession with building and studying his beetle collection was the beginning of a lifelong interest in entomology.

In spite of Robert Darwin's most sincere efforts to shape his son's future, there was no denying that what Charles was really passionate about was natural science. He did complete his bachelor's degree in divinity; he spent the required three years at Cambridge and, by cramming like crazy in his third year, he managed to pass his final exams. But he spent most of his time during those three years pursuing his other interests.

He became friends with a botany professor by the name of John Henslow and took three years worth of botany classes from him (not exactly essential for an Anglican priest in training). Henslow encouraged him to read a six-volume book by the scientific explorer Alexander von Humboldt describing Humboldt's travels and scientific discoveries in South America. This really fired up Darwin, and it planted the idea in his mind of setting off around the world and exploring the flora and fauna of exotic lands.

Darwin also began studying with Adam Sedgwick, a prominent field geologist and professor of geology at Cambridge. Recognizing young Darwin's talent and enthusiasm, Sedgwick took him under his wing. He took Darwin on expeditions and taught him the rigorous techniques of geological fieldwork (again, not exactly a critical skillset for the priesthood).

By the time Darwin graduated from Cambridge with his degree in divinity, he was, as one biography put it, "thoroughly versed in botany and entomology, had more than a smattering of zoology, knew how to prepare and preserve specimens, [and] was an expert field geologist who had been taught his trade by one of the Vice-Presidents of the Geological Society of London."[3]

In other words, when Darwin left for home to begin preparing for his career in the church, he was thoroughly trained and ready . . . for a career *as a scientist*. And the big question he faced was: What was he going to do with all that training?

The Voyage of the Beagle (1831–1836)

Fortunately for Darwin, and for the rest of mankind, the perfect opportunity arose. On the recommendation of Professor Henslow, who had contacts in the British Admiralty, Darwin was invited to accompany the captain of the HMS *Beagle*, which was being sent to conduct a survey of coastal South America. On December 27, 1831, the *Beagle* set sail on what would end up being a five-year voyage circumnavigating the globe.

The journey gave Darwin an unparalleled opportunity to immerse himself in the work of making detailed, firsthand, scientific observations of nature. He was invited on board partly to serve as a gentleman companion to the captain and partly to serve as the ship's naturalist. And in those days, the job of the ship's naturalist was to conduct a systematic, scientific analysis of the regions visited on the journey—to observe and study the flora and fauna, to collect plant, animal, and geological specimens, and so on.

At various points of the voyage, Darwin left the ship and set off inland, sometimes for months at a time, before rejoining the *Beagle* and sailing on to the next port of call. He collected exotic beetles in the jungles of Brazil; he gathered seashells and sponges and corals from the coast of Patagonia (what is now Argentina); he collected specimens of birds and tortoises from the Galapagos Islands, west of Ecuador.

Darwin amassed a huge collection of specimens, which he shipped back to England in crate after crate. Just as importantly, he filled notebook after notebook with his scientific observations—on the geology of the regions he explored, and on the plant and animal species he encountered.

One often sees images of Darwin as an old, bearded, Victorian gentleman, and it is tempting to think of him as a sedentary scholar, sitting in his armchair and philosophizing about nature. But the Darwin that one encounters upon reading about the *Beagle* voyage depicts exactly the opposite image: He is a vigorous, almost swashbuckling young man, tramping off into the Brazilian jungle with his notebook and his shotgun.

With his own hands, he dug out of cliff walls fossils of ancient creatures the size of horses. He hunted for his own supper almost as much as for biological specimens—eating, for example, such delicacies as roasted armadillo. On one occasion, he had eaten half of a large ostrich-like bird when he suddenly realized that it was an unusual species that hadn't been described before. So he packed up the rest of the roast to ship home with his other specimens! Darwin was *not* an armchair scientist; he did not just theorize in a library, shut off from the world outside. He was an active observer of nature who traveled to the far corners of the world gathering facts and who got his hands dirty, *literally*.

By the time Darwin returned to England after five years' traveling the world, he had amassed a wealth of factual data. One biography summarizes his haul as follows: He had "1383 pages of geology notes, 368 pages of zoology notes, a catalogue of 1529 species in spirits and 3907 labeled skins, bones and miscellaneous specimens, as well as a live baby tortoise from the Galapagos Islands."[4]

Darwin had already sent parts of his 770-page diary home, and they were already being circulated among England's scientific elite, who were eager to embrace him as one of their own.

But in addition to his notes and his specimens, and the respect these won for him among scientists, Darwin got an unexpected benefit from his travels: The *Beagle* voyage helped him to find his true calling in life. It set him on the path to engaging in the work that would occupy the rest of his days—indeed, the work that would eventually bring about a major revolution in science.

Before he had even set foot back on the shores of England, Darwin had formulated a new plan for his future. After five years of single-mindedly pursuing scientific discovery, the notion of going home and settling down in a church parsonage was simply out of the question. He was determined to forge a career for himself as a gentleman scientist.

It is important to recognize that the mass of notes and specimens that Darwin had accumulated were not completed scientific discoveries; they were just the raw material for scientific discovery. Darwin understood perfectly well that that raw material had to be processed, studied, digested—converted into useful products, which for a scientist means scientific papers, lectures, treatises. For Darwin to return home and do nothing with the fruits of his scientific harvest would render his collection a heap of junk and his five-year journey a waste of time and effort.

Upon his return, and with his father's support—both moral and, more importantly, financial—Darwin set to work. His first order of business was to find a home for his collection and to delegate the detailed analysis of his specimens to experts in different fields. Darwin's education had exposed him to broad areas of natural science, but to fully and properly reap the fruits of his *Beagle* findings, he would have to farm out parts of the work to specialists who were highly trained in particular areas.

He had his fossil specimens studied by a leading expert in comparative anatomy, his mammals cataloged by the museum curator of the London Zoological Society, his reptiles examined by a zoology professor at King's College, and his plants studied by a team of botanists. He delegated the study of his birds to an expert ornithologist who discovered, much to Darwin's surprise, that the birds he had brought back from the Galapagos Islands—which he thought composed a fairly diverse collection—were in fact almost all different species of the common finch.

Darwin himself undertook the work of writing up his geological findings. At this point in his life, Darwin considered himself to be primarily a geologist, not a biologist, and his main priority was reporting the geological observations he had made on his travels.

At the same time, he was positively brimming with questions raised by his observations, questions in the field of biology as much as in that of geology. The most important question that captured his attention was one of the most important mysteries of Darwin's day: the mystery of the origin of species.

Evolution Before Darwin

At the time of Darwin's return to England in 1836, the question of how all the various living species originated was ripe for serious scientific consideration.

About a century earlier, Carl von Linnaeus had introduced the modern system of biological classification, organizing all living species into nested groups of genus, order, class, and so on. Linnaeus's system is based on a hierarchy of similarities and differences among the species, and forms a branching, tree-like structure that looks curiously like a family tree.

In Linnaeus's day, however, this similarity to a family tree would have been regarded as only a curious coincidence. Few would have suspected that all living species are actually related to each other in the same way in which you are related to your second (and 102nd) cousins. The prevailing view was, of course, the creationist view that each species was formed independently by a special act of miraculous creation.

Furthermore, it was generally held that species are immutable, unchanging. After all, the book of Genesis describes all living creatures as reproducing "after their kind," meaning that the offspring resemble the parents. The commonly held view was that species might be capable of a certain amount of variation but only within tightly circumscribed limits. The notion that, say, birds and reptiles are distant cousins on a single family tree is one that most people would have found absurd.

On the other hand, speculation along the lines of evolution went back to ancient Greece. A handful of thinkers before Darwin had put forward the idea that species *are* related—that life began in some primitive form and then gradually changed, transforming by some mechanism, and branching out into all the diverse species alive today. In fact, Darwin's own grandfather, Erasmus Darwin, was one such thinker; in the 1790s he wrote a book called *Zoonomia* that included a vague hypothesis about the evolutionary origin of species.

The most influential theory of evolution before Charles Darwin's was put forward by French biologist Jean Baptiste Lamarck in the first two decades of the nineteenth century. Lamarck proposed that species are not unique, independent creations but are the modified, transformed descendants of other species. He took seriously the family-tree-like structure suggested by the Linnaean system and proposed a theory to explain how species change.

As a young man, Charles Darwin read Lamarck's writings and was impressed by a couple of points. For one thing, Lamarck was seeking *natural* as opposed to *supernatural* explanations. Darwin recognized a pressing need to see biology as a field governed by scientific law—just as physics, astronomy, and chemistry had come to be seen. Later, in *Origin of Species*, Darwin would praise Lamarck by saying that he did "the eminent service of arousing attention to the probability of all change in the organic, as well as in the inorganic, world being the result of law and not of miraculous interposition."[5]

Darwin was also impressed by some of the evidence that Lamarck tried to bring to bear on the subject, evidence showing that species are not always markedly different from each other. In some groups of organisms there is an almost continuous variation in characteristics among different species in a group, which makes it plausible to view them as the gradually modified descendants of a common ancestor, rather than as a number of independently created species.

Although Darwin found certain valuable elements in Lamarck's evolutionary theory, he was not impressed with Lamarck's proposal for the causal mechanism driving evolutionary change. Lamarck held that changes occur as a result of organisms striving to be better adapted to their environment; this striving causes slight changes in their characteristics, which are then passed on to their offspring and build up over generations. Lamarck's classic example of this is a giraffe stretching up to the leaves on branches just out of reach. Striving to reach the higher leaves stretches the giraffe's neck slightly and it then produces baby giraffes with slightly longer necks. If this were to continue generation after generation, one could explain the transformation of a giraffe ancestor with a normal-sized neck into the modern giraffe.

The problem with Lamarck's explanation is that it simply is not true that characteristics acquired during an organism's life are passed on in reproduction. If you were to dye your hair green or lose an arm in an accident, you would not expect to then have a baby with green hair or a missing arm.

Darwin was also, as one would expect, aware of his grandfather's writings on evolution, which are strikingly similar to those of Lamarck. Erasmus Darwin was quite famous in his day, and his writings were part of the family lore. Charles had read *Zoonomia* as a young man and rather admired it. But neither Erasmus Darwin nor Lamarck had a fully convincing argument for evolution. Their works were too speculative and insufficiently supported by evidence and facts. In his autobiography, Charles Darwin writes that upon reading *Zoonomia* for a second time, he was "much disappointed, the proportion of speculation being so large to the facts given."[6]

Hence, when Darwin set sail around the world, he was, like almost every other scientist in his day, a firm believer in "special creation." He was aware of evolutionary thinking but held the commonly accepted view that each species was created independently of every other species. At the same time, however, he was becoming aware of other developments in early nineteenth-century science that would prove to be highly suggestive of evolution.

In geology, scientists had reached the conclusion that the major features of the earth are the result of slow, gradual changes built up over long periods of time. They had thrown out the attempt to explain earth's geology by means of supernatural cataclysms such as Noah's flood. But the geologist Charles Lyell had gone further and thrown out the appeal to cataclysms as such. In his *Principles of Geology*, he argued that even the largest-scale effects in geology, such as the raising of massive mountain ranges or the carving out of deep canyons, are the result not of massive, catastrophic events but of small-scale, everyday processes acting over unimaginably long time scales.

On board the *Beagle*, Darwin read the first volume of Lyell's three-volume treatise, which had been published in 1830. From his geological observations during the voyage, Darwin saw the truth of Lyell's views writ large on the very rocks themselves. As he set about collecting plant and animal specimens, the Lyellian idea of incremental changes accumulated over vast ages was at the forefront of Darwin's mind.

Darwin's travels around the world and his hard work as a naturalist revealed to him new facts about life on earth. As noted above, he brought home a vast array of specimens collected from all over the globe. When he returned home and studied his collections and reflected on his findings, a host of questions arose in his mind that challenged his creationist views.

For example, why should two regions that have almost identical physical conditions be inhabited by completely different forms of life? Consider the Galapagos Islands, off the coast of South America, and the Cape Verde Islands, off the coast of Africa—both of which Darwin visited. Both are volcanic archipelagos off the west coast of a large continent; they are extremely similar in every aspect of their environmental conditions: climate, height, size, the volcanic nature of their soil, and so on. Yet the species native to these islands are completely different.

On the premise of special creation, one might expect the opposite to be true. If God designed each creature to be perfectly adapted to its environment, then one would expect that places with identical environmental conditions would be inhabited by identical species. But that is not what one finds.

Furthermore, compare the Galapagos Islands with the South American mainland. In this case, the environmental conditions of the islands are completely different from those of the mainland—and yet the species on the islands are dramatically similar to the mainland species. As Darwin later wrote: "There is nothing in the conditions of life, in the geological nature of the islands, in their height or climate . . . which resembles closely the conditions of the South American coast: in fact, there is a considerable dissimilarity in all these respects."[7] And still, he finds,

> the naturalist, looking at the inhabitants of these volcanic islands in the Pacific, distant several hundred miles from the continent, yet feels that he is standing on American land. Why should this be so? Why should the species which are

> supposed to have been created in the Galapagos Archipelago, and nowhere else, bear so plain a stamp of affinity to those created in America?[8]

Again, on the premise of special creation, one would expect the opposite. One would expect regions with dramatically different environmental conditions to be inhabited by dramatically different species. But that is not what one finds.

What these facts suggested to Darwin was that the island species were *related* to their mainland counterparts. He envisioned volcanic islands rising out of the ocean entirely bereft of life and then being populated by colonists from the nearest coastal mainland—the Galapagos Islands by species from South America, the Cape Verde Islands by species from Africa. Breeding in isolation from their relatives on the mainland, the descendants of the colonists gradually transform and adapt to the island conditions of their new home. Ultimately, they evolve into completely new species, but continue to bear an uncanny resemblance to the species on the nearest mainland—which is exactly what one finds.

Darwin assembled and reflected on a host of facts like these from the field of biogeography, the study of the geographical distribution of living creatures. These observations raised crucial questions in his mind and got him thinking along evolutionary lines.

Consider another example: the fossil species that Darwin had unearthed in South America. These turned out to be similar in many ways to currently existing South American animals. But they were also clearly not members of currently existing species. For instance, he had found fossils of giant, extinct species of rodent, armadillo, llama, and sloth—and they were similar, but not identical, to modern species of South American rodents, armadillos, llamas, and sloths.

Why did these extinct species die out? And when were the new species "created"? More curiously, why would the earlier existing species in a given region be so similar to those living there now? That is, why do the fossil rodents of South America resemble modern South American rodents more than they do, say, European rodents or African rodents?

Again, on the premise of special creation, these questions have no answers. Darwin's observations suggest that modern creatures are the evolved descendants of earlier ones. The South American fossil species resemble modern South American species because they are actually related to them; they are the literal ancestors of the modern forms.

These kinds of questions and considerations convinced Darwin that evolution, or "transmutation" as he called it then, might shed some light on the origin of species and was an idea worth exploring further.

In July 1837, just nine months after his return from his travels, Darwin opened a fresh notebook and wrote a single word on the title page: *Zoonomia*. Using a notebook expressly dedicated—in homage to his grandfather—to contemplating organic transmutation, he began, as he put it, "patiently accumulating and reflecting on all sorts of facts"[9] related to the origin of species.

It is important to note that at the time Darwin began his research on evolution, he was busy with many projects. Recall that his main order of business was to supervise the analysis of his *Beagle* collections and to write up the results for publication. This was a huge effort that required delegating and coordinating the work of a whole team of specialist scientists.

The years immediately following Darwin's return to England in 1836 were incredibly productive. Darwin describes them as "the most active ones which I ever spent."[10] He was editing his travel journal for publication; he was writing technical papers and presenting them before scientific societies in London; he was writing up his geological findings of the *Beagle* voyage; he was overseeing the publication of a set of volumes on the zoological findings of the *Beagle* voyage (the analyses of the animal specimens he collected were being written up as a series of expert reports); and, in 1838, he proposed to his cousin, Emma Wedgwood, whom he married in January 1839.

Clearly, Darwin had a lot on his mind. But all the while he was filling up notebook after notebook on the "transmutation" of species—collecting facts, anecdotes, questions, arguments—and thinking about them deeply. One biography reports that he was so obsessed with this work that he even took time on his wedding day to open one of his species notebooks to record Uncle Wedgwood's "views on turnips."[11]

Evidence of "Transmutation"

Like Lamarck, Darwin began to take seriously the family-tree-like structure suggested by the Linnaean system. On the theory of evolution, this structure is an actual genealogy, an actual family tree—and thinking of it that way helped to explain a host of curious facts.

For instance, people had long noticed that the bones in the forelimbs of all vertebrate animals have a common structure. This is hard to explain on the premise that they are all independently created species. But on the premise that they all inherited that bone structure from a common ancestor, it makes perfect sense. As Darwin was later to ask: "What can be more curious than that the hand of a man, formed for grasping, that of a mole for digging, the leg of the horse, the paddle of the porpoise, and the wing of the bat, should all be constructed on the same pattern, and should include the same bones, in the same relative positions?"[12] Darwin collected and considered a host of facts like these from the field of comparative anatomy—and found a ready explanation for them in terms of the evolutionary family tree.

Or consider the phenomenon of rudimentary organs, such as the human appendix, or the wings of flightless birds. Darwin also knew of species of beetles whose wings are not only incapable of flight but lie under wing cases that are completely sealed shut. How can "intelligent design" explain such utterly useless organs? A typical explanation in Darwin's day was that rudimentary organs are included to complete the "symmetry" of God's plan, to which Darwin replied in his notebook: "What bosch!!"[13]

But on the premise that species are the modified descendants of earlier species, one can explain rudimentary organs as the remnants of organs that once were functional but are no longer. For example, beetles living on small and exposed islands would be in danger of being blown out to sea if they retained the power of flight. Evolution, Darwin realized, would act over time to gradually shrink the wings and render them harmless. And they certainly cannot pose a danger if they are safely sealed away under a wing case that cannot open.

Darwin collected myriad facts and posed a host of questions on the phenomenon of rudimentary organs. The winner of them all, arguably, is: "Why do men have nipples?" Pondering this question, Darwin contemplated the possibility that the distant ancestor of all mammals was a species of hermaphrodite; that is, a species possessing both male and female sexual organs. Perhaps, he mused, male nipples are just remnants of female anatomy, vestiges of the process by which an ancestral hermaphrodite species evolved into a species with separated sexes.

Darwin also pursued the subject of domestic breeding. Recall the prevailing view in his day that species possessed a limited capacity for change, that transmutation could occur only within tight limits. But if the correct explanation for the origin of all species is evolution from common ancestral forms, then species would have to be capable, given enough time, of almost unlimited change.

So Darwin sought the expertise of farmers and horticulturalists to explore the limits of organic variation. After all, one goal of expert breeders is to modify plants and animals in order to bring out desirable qualities—woollier sheep or hardier strains of wheat. Darwin began quizzing everyone he met who knew anything about domestic breeding. He spoke to gamekeepers, zookeepers, gardeners; he spoke to friends and relatives who managed their country estates; he spoke to fanciers who bred exotic varieties of pigeon; he even quizzed his London hairdresser, who was interested in pedigree dogs. He began reading magazines and manuals of all kinds on the cultivation of pigs and poultry and potatoes and more.

It is worth pausing here to reflect on just how radical Darwin's actions were for a scientist in his day. Other "natural philosophers" contemplating such lofty questions as the origin of species would perhaps not have been as likely to step out of the ivory tower and into the barnyard. But Darwin was eager to follow the evidence wherever it led him—even if it led him to the pigpen or the fancy pigeon club.

Darwin's investigations into domestic plants and animals gave him a great deal of data concerning variations among domestic species, and how those variations arose. He assembled and organized and reflected on these data as well as on others concerning variation in the wild.

Darwin assembled and reflected on a range of facts concerning the family-tree relationships of all creatures (the similarities and differences among organisms, such as the vertebrate hand bones or the rudimentary organs); he assembled and reflected on a range of facts concerning the fossil record; he assembled and reflected on a range of facts concerning biogeography, such as his Galapagos finches; he became, as he put it later, a "complete millionaire in odd and curious little facts."[14]

And as he put all these facts together, the outlines for a theory of evolution gradually took shape. He wrote to a friend that he had been working on a "delightful number of new views, which have been coming in, thickly and steadily, on the classification & affinities & instincts of animals—bearing on the question of species—note book after note book has been filled with facts which begin to group themselves *clearly* under sub-laws."[15]

As he assembled these facts and identified these "sub-laws," it became more and more plausible to him that all living species *are* actually related—and that evolutionary changes *have* occurred. What he had not yet worked out, however, was *how* those changes occurred. What was the causal mechanism driving evolution?

"A Theory by Which to Work"

The key to the discovery of the causal mechanism turned out to be his study of domestic breeding. He began to see domestic breeding and the cultivation of new or better varieties of plants and animals as analogous to how new varieties and species might arise in nature.

A breeder enhances a desirable quality in a breed by very carefully selecting individuals to breed together. By selecting only the best animals and breeding them together—or selecting the best fruits and cultivating only their seeds—man has improved and adapted his domestic species to suit his needs, sometimes transforming them greatly in the process.

What Darwin realized is that nature also exercises a kind of selection, and that its power of selection could also bring about great transformations. Its agent of selection is not the purposeful eye of the human breeder but the natural occurrences of disease, starvation, predation, death.

In September 1838, Darwin opened a book that had a profound impact on his thinking: *An Essay on the Principle of Population* by Thomas Malthus. Malthus's book was an attempt to identify the factors limiting human population growth. He used statistical arguments to calculate the rate at which people reproduce and to compare that to the rate at which the food supply could increase. The result was a bleak, doomsday prediction that population growth would outstrip food production, leading to mass starvation, disease, and war. (When environmentalists today wail about scarce resources and issue doomsday predictions of a "population bomb," they are sometimes criticized as being "Malthusian.")

Although Malthus's conclusions are false as applied to man (because reasoning minds make possible technological innovations that invalidate Malthus's assumed limits on the growth of food production),[16] Darwin realized that Malthus's arguments were extremely enlightening as applied to plants and animals. All living species produce many more offspring in each generation than can possibly survive; the struggle to survive is a fierce competition that most individuals will lose. Darwin saw that this would give rise to a kind of *natural selection* that is analogous to the selection exercised by breeders.

Darwin combined this Malthusian argument with the ideas he had already worked out concerning variation in nature and the family-tree relationships among living organisms. The result was an explanation for how evolution occurs: Organisms reproduce after their kind but with minor modifications—a certain degree of variation is always naturally occurring among individuals of the same species. Those variations will be passed on to the offspring of any individuals that survive to reproduce. But, as just noted, very few individuals will, in fact, survive to reproduce. The struggle for existence is fierce; every tiny little advantage matters; every little difference makes a difference. As Darwin explained it:

> As many more individuals of each species are born than can possibly survive; and, as consequently, there is a frequently recurring struggle for existence, it follows that any being, if it vary however slightly in any manner profitable to itself, under the complex and sometimes varying conditions of life, will have a better chance of surviving, and thus be naturally selected.[17]

Darwin saw that the unrelenting character of the struggle for existence would imply an unrelenting process driving greater and greater diversity and complexity in nature. As small changes accumulate over massive stretches of time, competition imposes a steady pressure forcing evolutionary change. More and more *diverse* forms of life arise as species evolve to fill all available niches in the economy of nature. And more and more *complex* forms of life arise as more intricate adaptations make possible more intricate means of survival.

Darwin was finally able to explain the origin of all the various forms of life that we find in nature, in all their wondrous complexity; natural selection was the final piece of the puzzle, the basic causal mechanism driving evolutionary change. His hard work had paid off. Within two years of returning from his travels, Darwin had found an explanation for the origin of species.

Perhaps most interesting about this period is how Darwin, himself, judged the status of the theory he had discovered. At this point, Darwin did *not* regard evolution as a proven theory.

He had assembled and integrated enough evidence to work out the essential elements of the theory, and he had identified a plausible causal mechanism that could explain how evolution occurs. But he knew that he still had a lot of work to do to prove all the details of the theory. At this point, Darwin regarded his theory as a solid working hypothesis, or, as he later put it in his autobiography, as "a theory by which to work."[18] But it was not yet a theory that he regarded as conclusively proven.

Consider this in light of the widespread attack on evolution as "just a theory." The careful objectivity with which Darwin assessed the cognitive status of his own work stands in such stark contrast to that utterly ignorant, knee-jerk dismissal of the theory. But polemics aside, it is interesting to consider how hard a scientist has to work even to come up with a good hypothesis—let alone to prove a fundamental theory. Darwin's two years of determined thinking were not the end of his work on evolution; they were just the beginning.

Darwin continued to work on evolution while forging ahead with his many other projects, which dragged on and on.

He spent ten years writing up his *Beagle* findings. After his travel journal was published in 1839, he started putting out volumes on his geological discoveries. In 1842, he published a study of the formation of coral reefs, based partly on research he did while the *Beagle* stopped at a coral atoll in the Indian Ocean. In 1844, he published his observations on the geology of the volcanic islands he visited, such as the Galapagos Islands and the Cape Verde Islands. And in 1846, he published his observations on the geology of South America.

Amidst all of this, he continued accumulating facts, considering objections, and developing his arguments on evolution. In 1842, he wrote a brief, 35-page abstract of the theory, which he expanded in 1844 into a 231-page "sketch." But he was still not yet ready to go public with it. He put the sketch in his desk drawer, with a note to his wife instructing her to arrange for its publication "in case of my sudden death."[19] And he continued gathering facts and developing his arguments.

By 1846, his geology books were done; he was almost finished with the *Beagle* work; and he was almost ready to turn his attention full-time to the "species question"—*almost* ready, because one more little piece of the *Beagle* work was left to complete.

On the coast of Chile in 1835, Darwin had collected a tiny and very unusual species of barnacle. It was a parasitic barnacle that made its way in the world by boring inside a conch shell and setting up home there. Darwin anticipated that he would write some short, scientific papers describing this new species. He wrote to a friend, saying, "I am going to begin some papers on the lower marine animals, which will last me some months, perhaps a year, & then I shall begin looking over my ten-year-long accumulation of notes on species."[20]

But he soon ran into a problem: In order to properly classify his one little barnacle species, he had to know something about the taxonomy of barnacles in general. And in 1846, the field of barnacle taxonomy (despite its obvious, inherent sexiness as an area of research) was in a state of complete chaos.

Barnacles were originally thought to be a kind of mollusk, like clams or mussels. But it was discovered in 1830 that they are actually crustaceans, built on the same general body plan as crabs and shrimp. Zoologists had a pressing need for an up-to-date, systematic study of these misunderstood creatures.

Barnacles, Barnacles, Barnacles

Darwin began collecting other barnacle species. He wrote to colleagues requesting specimens, and he began the painstaking, delicate work of dissecting them and comparing their anatomy. Very quickly, the project got completely out of hand. Word got out on the barnacle-enthusiast grapevine that Darwin was on the job, and next thing he knew he was up to his eyeballs in barnacles; people from all over the world were sending him specimens. Collecting fossil barnacles as well as living species, he began grouping whole families, orders, and genera of barnacle.

Instead of a few short papers describing his one little friend from Chile, Darwin ended up undertaking the Herculean task of organizing and classifying the entire subclass *Cirripedia* (the scientific term for barnacles).

By 1852, his project of "some months" had been dragging on for six years. He wrote to his cousin saying: "I hate a barnacle as no man ever did before, not even a sailor in a slow moving ship."[21]

By 1853, he had been dissecting barnacles for seven years. At this time, four of his children were actually younger than seven years old, which means that all they ever knew him to do in his work life was sit hunched over his microscope studying barnacles. As one biography noted, they must have concluded that this is what all fathers do, because one of them asked about a neighbor's father: "Where does he do *his* barnacles?"[22]

By 1854, the project was completed at last. After eight years of intense labor, he was finally through with barnacles for good. The result was four technical monographs on *cirripedes*, which were published to great acclaim.

Darwin estimated that in the eight years he spent on the barnacle work, he lost about two years worth of working time to illness. He suffered from a mysterious health condition, which slowed his work considerably. Symptoms first appeared in the years just following his return from the voyage on the *Beagle* and continued intermittently until his death in 1882. He suffered from frequent stomach cramps and vomiting spells, he had headaches and all sorts of skin disorders, and for long periods of time he was able to work for only a couple of hours each day. The exact nature of Darwin's illness has been the subject of much scholarly debate, but it appears to have eluded scholars and remains somewhat of a mystery.

Even without the health delays, however, the barnacle project took far longer than Darwin had intended. He could be the patron saint of anyone who has begun a project only to see it expand out of control and become a monumental task taking way longer than anticipated. But, in the end, the barnacle work proved to be extremely useful to him.

For one thing, it was his public debut as a biologist, as opposed to a geologist (recall that prior to this work, his primary focus was on his geological discoveries from the *Beagle* voyage). The barnacle work expanded his expertise into the field of zoology, and the experience of working out in exhaustive detail the classification of an entire suborder of species gave him the knowledge and confidence to speak authoritatively on species.

More importantly, the barnacles provided crucial evidence for his theory of evolution.

Barnacles exhibit a large degree of natural variation, a key element of Darwin's theory. Natural selection can operate only if there are natural variations among individuals—natural variations that make a difference for survival and reproduction.

By systematically studying all of the barnacle species and comparing their bodily structures, he learned a great deal about the extent of variation in nature. As he said in a letter to a friend: "I have been struck . . . with the variability of every part in some slight degree of every species: when the same organ is *rigorously* compared in many individuals I always find some slight variability."[23]

Another piece of supporting evidence came from a set of surprising discoveries he made about barnacle reproduction. Barnacles are usually hermaphrodites (possessing both male and female reproductive organs). But in the course of his study, Darwin found a number of curious exceptions to this rule.

A number of barnacle species turned out to have two separate sexes, but the adult males were tiny, rudimentary organisms that live as parasites within the shell of the female. In some cases, Darwin found that each female had a collection of, as he put it, "little husbands"[24] that consisted of "mere bags of spermatozoa"[25] without even a mouth or stomach.

Other species Darwin found were even more curious. They were hermaphrodites, but also possessed a collection of tiny, parasitic males. The male organs of each hermaphrodite individual, though functional, were smaller than usual and were supplemented by the extra, "complemental" males.

What this proved is that, within a species, in addition to the fact that sexual identity can be mixed, the degrees of maleness and femaleness can vary. It is not true that a species is either fully hermaphroditic or composed of fully separate male and female sexes. As Darwin had long suspected, an initially hermaphroditic species can evolve by a continuous series of slight modifications into a species with separate sexes.

Indeed, in the end Darwin actually found a whole series of barnacle species displaying a graduated range of varying degrees of sexual differentiation. Darwin's notebook musings on the origin of male nipples had been validated in nature beyond his wildest imaginings. In great excitement, he wrote about all this to a friend: "I never sh[d]. have made this out, had not my species theory convinced me that an hermaphrodite species must pass into a bisexual species by insensibly small stages; & here we have it, for the male organs in the hermaphrodite are beginning to fail, & independent males already formed."[26]

The Origin of *The Origin*

Having completed his barnacle work at long last, Darwin emerged from the project with strong new evidence for his theory of species, and he was able finally—eighteen years after his return from the *Beagle* voyage—to turn his attention to evolution full-time.

Although he had been collecting evidence and reflecting on the arguments for and against his theory for years, he still had myriad details to consider and unresolved questions to explore.

For example, he had gathered large amounts of evidence about the distribution of plants and animals around the world, such as the facts concerning the Galapagos species; but in order to explain that distribution, he had to be able to explain how organisms could get from one place to another. How, for instance, could mainland plant species get to distant islands?

It occurred to him that seeds might simply float across the ocean. But when he asked his botanist friends about this, he was told that seeds are killed by salt water. On the other hand, it turned out that nobody he talked to had ever put them in salt water to see if that was true! So Darwin decided to try it. He launched into a series of experiments, floating seeds of all types in salt water. He kept them there for weeks at a time and then checked whether they would germinate.

To his surprise and delight, he found that the assumption that they would quickly die was simply false. He was able to grow plants from seeds that had been immersed in brine for twenty-eight days, and a colleague was able to do so after an even longer immersion. Using a nautical atlas, he calculated from the speed of various currents how far a seed could travel in the time available and found that it could go a distance of up to nine hundred miles, certainly far enough to account for the data he had collected. In addition to floating seeds, he tested a number of other methods of transport, including by birds. To get a sense of the lengths he went to in these inquiries, consider the following quotation from *The Origin of Species*, where he describes some of this work:

> I forced many kinds of seeds into the stomachs of dead fish, and then gave their bodies to fishing-eagles, storks and pelicans; these birds after an interval of many hours, either rejected the seeds in pellets or passed them in their excrement; and several of these seeds retained their power of germination.[27]

Other lines of evidence also required further development. Consider Darwin's argument from domestic breeding. To explore the similarities between natural selection and man's "artificial selection," he decided to study a particular domestic species in depth: domestic pigeons.

Recognizing the degree to which his immersion in barnacles enabled him to acquire expertise at taxonomical classification, he threw himself into the strange subculture of the fancy pigeon breeder to explore the power of domestic selection. He built an aviary at his house and began to acquire exotic breeds—at one point keeping almost ninety birds. He read treatises on pigeon breeding, hunting down references going back to ancient Rome and

Egypt. He had correspondents send him pigeon skins from India and Persia. He joined pigeon clubs and talked pigeon lore with an assortment of pigeon fanciers.

This effort produced strong evidence in support of his theory. In the few centuries that people had been keeping pigeons, they had produced a variety of breeds that were so different that zoologists finding them in the wild would have classified them as different species—and some as even belonging to different genera. Yet, a number of lines of evidence established that they were all descended from a single pigeon species. This showed that, starting with small, naturally occurring variations among individuals in a single species, the careful selection of breeding pairs could magnify those variations into substantial differences.

If man could do this over a mere few hundred years, could there be any doubt of the power of natural selection to bring about, over the immense time scale of geological history, the diversity of forms that exist in nature? Whales and horses differ so greatly that it seems impossible that they could be descendants of a common ancestor. But if man, who can select breeding pairs based only on visually observable differences, can produce a wide variety of pigeon breeds in the blink of a geological eye, then surely over tens of millions of years natural selection, which acts on all characteristics—seen and unseen—that have bearing on survival and reproduction, could transform an ancient mammal species into both whale and horse.

Contemplating the "thousand intermediate forms"[28] that must have existed between such creatures as the otter and its land ancestor, Darwin wrote: "Opponents will say, show me them. I will answer yes, if you show me every step between bull Dog & Greyhound."[29]

The image of Darwin as an *experimental* scientist is as atypical as the image of Darwin as the *Beagle*'s resident Indiana Jones. Yet he conducted any experiment he thought was necessary and relevant to his theory. At one point, he even tickled aphids to see if he could get them to excrete nectar for him as they do for ants. There is no room in science (or in any area of thought, for that matter) for unfounded assertions. If something needs to be put to the experimental test, then a true scientist will engage accordingly, even if it means tickling insects or collecting fishy pelican poop.

Darwin spent a number of years conducting these sorts of experiments and filling in details on his theory. At long last, he was ready to pull together all the data and threads of evidence he had accumulated, and to arrange and organize his vast collection of facts.

He began writing a book, to be called *Natural Selection*, that would present the full, scientific case for his theory. He planned it to be a massive, multivolume tome, like Lyell's *Principles of Geology*—systematic and thorough, and replete with the full apparatus of scholarly discourse, including voluminous notes and references.

But almost two years into the writing, with ten chapters finished, Darwin's plans were completely overturned. On June 18, 1858, he received a letter from a young naturalist named Alfred Russel Wallace. Wallace had discovered independently the essential elements of the theory of evolution by natural selection, and he wrote to see what Darwin thought of it!

Darwin was shocked and distraught. Wallace had asked him to circulate the letter to other interested scientists, if he thought it worthy. Being intimately aware of the worthiness of the theory, Darwin felt obliged to send Wallace's letter to a scientific journal for immediate publication. And being the gentleman that he was, Darwin would not dream of doing otherwise, even though it would mean that Wallace would be forever credited with the major scientific discovery that had comprised Darwin's life's work.

Fortunately, the crisis was resolved amicably and to the satisfaction of all parties (a rare occasion in the history of scientific priority disputes). Friends arranged for the publication of Wallace's letter alongside excerpts from Darwin's unpublished writings, including his 1844 sketch. These were read before a meeting of the Linnaean Society on July 1, 1858, and published in its journal.

The incident, however, was a wake-up call to Darwin, who realized that he had better put out a book quickly presenting the details of the theory, rather than continue to labor on his large, technical treatise. In less than a year, he dashed off one of the immortal works in the history of science: *The Origin of Species*.

Conclusion

It is important to keep in mind that evolution by natural selection is a theory that pertains to all life on earth. To prove a fundamental truth concerning all life on earth requires a range of facts and evidence drawn from every part of the organic world. The scope of the evidence must be commensurate with the scope of the principle it supports—and evolution is one of *the* fundamental integrating principles of all biology.

To prove his theory, Darwin assembled and organized "long catalogues of facts."[30] He gathered evidence from all corners of the plant and animal kingdoms, and from all corners of the globe. He had correspondents all over the world who sent him specimens and answered questions on local flora and fauna. He drew on the most obvious and the most obscure facts, spanning all branches of life's family tree—from the smallest, microscopic organisms to the tallest trees and the largest whales, and from as far back in time as the fossil record went in his day.

The Origin of Species offers an impressive survey of the enormous scope and depth of knowledge that Darwin brought to bear on his theory. To get a sense of that scope and depth, consider the following brief laundry list of some of the kinds of facts he refers to in the book. At various points he bases arguments on, or draws conclusions from, facts concerning: the relative weights of the wing and leg bones in domestic versus wild ducks;[31] the fertility via self-fertilization of numerous species of hermaphrodite flower;[32] the differences in the method that different species of honeybee use in constructing their hives;[33] the sexual relations of snails and of earthworms;[34] the number of feathers in the tails of various breeds of domesticated pigeons, followed immediately in the same paragraph by observations on the root stems of different varieties of turnip and rutabaga;[35] the slave-making instincts of different species of ant[36]; the differences in the marine faunas of the eastern and western shores of South and Central America, which have "hardly a fish, shell, or crab in common";[37] the hooks on the ends of the branches of a species of bamboo in the Malay Archipelago;[38] the similarities in the embryos of a whole range of vertebrate animals, including birds, reptiles, and mammals;[39] the absence on remote oceanic islands of all mammals except bats, which can fly;[40] the rules governing the intercrossing of different varieties of cabbage, radish, and onion[41]; the reappearance of ancestral stripes on various breeds of horse, ass, and zebra.[42]

One could keep going with this list—and going and going. But the point should be clear. By the time Darwin published the *Origin*, he had assembled, organized, reflected on, and digested a vast body of factual evidence, and he had *integrated* that body of evidence into a fundamental principle of nature.

Darwin published *The Origin of Species* in 1859 and spent the rest of his life continuing to explore the foundations and the implications of his theory. The list of books that he wrote after the *Origin* reveals that although he wrote on a broad range of biological topics, all of his works have some bearing on evolution. For example, his 1862 book on orchids (*On the Various Contrivances by which British and Foreign Orchids are Fertilised by Insects*) grew directly out of his attempt to understand complex, interrelated adaptations such as the shape of the flower and the behavior of the insects that fertilize it—and why these would have arisen together by natural selection. His 1868 book on domesticated plants and animals (*The Variation of Animals and Plants under Domestication*) was the fruit of his labors in the pigeon clubs and barnyards. His 1871 book, *The Descent of Man, and selection in Relation to Sex*, was his application of his theory to human evolution. And so on.

Even his last book in 1881, which explains the work of earthworms in reconstituting the soil, is relevant to evolution insofar as it addresses the power of small effects, accumulated over time, to bring about important changes.

Having explored Darwin's life and work, and the stages by which he discovered and painstakingly validated the theory of evolution, one can readily see how unjust is the accusation that Darwin was an armchair theorist indulging in baseless speculation.

It is notable that Darwin himself anticipated that accusation and answered it in his introduction to *The Origin of Species*. With his characteristic understatement and modesty, Darwin described his years of painstaking work developing his theory and then expressed the hope that his readers would not think he was too quick to accept his conclusions.

> When on board H.M.S. "Beagle" as naturalist, I was much struck with certain facts in the

> distribution of the inhabitants of South America, and in the geological relations of the present to the past inhabitants of that continent. These facts seemed to me to throw some light on the origin of species—that mystery of mysteries, as it has been called by one of our greatest philosophers. On my return home, it occurred to me, in 1837, that something might perhaps be made out on this question by patiently accumulating and reflecting on all sorts of facts which could possibly have any bearing on it. After five years' work I allowed myself to speculate on the subject, and drew up some short notes; these I enlarged in 1844 into a sketch of the conclusions, which then seemed to me probable: from that period to the present day I have steadily pursued the same object. I hope that I may be excused for entering on these personal details, as I have given them to show that I have not been hasty in coming to a decision.[43]

Indeed, he was not hasty.

And as careful as he was about assessing the status of his work, when he finally became convinced that his theory was true he was confident in expressing that conviction. By the time Darwin published his theory he was certain of its validity; he was, as he put it, "thoroughly convinced" by the vast body of evidence he had accumulated "that species have changed, and are still slowly changing by the preservation and accumulation of successive slight favorable variations."[44]

Today, 160 years after the publication of *Origin of Species*, the truth of Darwin's conclusions is rationally indisputable. Darwin's discoveries, as well as discoveries that were unimaginable in Darwin's day (such as those concerning the genetic mechanism of heredity and the structure and properties of DNA), have all been integrated into evolutionary theory and further attest to its validity.

Despite the fervent wishes of creationists, the facts leave no room for believing that evolution is "just a theory" or that Darwin was "just a theorist." On the contrary, the evidence demonstrates that Darwin was the quintessential hands-on scientist—and that his theory is true.[45]

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Endnotes

[1] https://news.gallup.com/poll/261680/americans-believe-creationism.aspx
[2] Michael White and John Gribbin, *Darwin: A Life in Science* (New York: Plume, 1997), 123.
[3] White and Gribbin, *Darwin*, 125–26.
[4] White and Gribbin, *Darwin*, 80.
[5] Charles Darwin, *The Origin of Species* (New York: Barnes and Noble Classics, 2004), 386.
[6] Charles Darwin, *The Autobiography of Charles Darwin: 1809–1882*, edited by Nora Barlow (New York: Norton, 1958), 49.
[7] Darwin, *The Origin of Species*, 316.
[8] Darwin, *The Origin of Species,* 316.
[9] Darwin, *The Origin of Species*, 11.
[10] Darwin, *Autobiography*, 82.
[11] Adrian Desmond and James Moore, *Darwin* (New York: Norton, 1991), 279.
[12] Darwin, *Origin of Species*, 343.
[13] Desmond and Moore, *Darwin*, 272.
[14] Desmond and Moore, *Darwin*, 324.
[15] Janet Browne, *Charles Darwin: Voyaging* (Princeton, NJ: Princeton University Press, 1995), 382.
[16] https://newideal.aynrand.org/new-book-challenges-fears-of-overpopulation-climate-change/
[17] Darwin, *Origin of Species*, 14.
[18] Darwin, *Autobiography*, 120.
[19] Browne, *Charles Darwin: Voyaging*, 446.
[20] Charles Darwin to J. D. Hooker, 2 October 1846, *The correspondence of Charles Darwin vol. 3: 1844–1846*. https://www.darwinproject.ac.uk/letter/DCP-LETT-1003.xml.
[21] White and Gribbin, *Darwin*, 178.
[22] Desmond and Moore, *Darwin*, 407.
[23] Browne, *Charles Darwin: Voyaging*, 514.
[24] Desmond and Moore, *Darwin*, 355.
[25] Desmond and Moore, *Darwin*, 357.
[26] Desmond and Moore, *Darwin*, 356.
[27] Darwin, *The Origin of Species*, 289.
[28] Desmond and Moore, *Darwin*, 248.
[29] Desmond and Moore, *Darwin*, 248.
[30] Darwin, *The Origin of Species*, 14.
[31] Darwin, *The Origin of Species*, 20.
[32] Darwin, *The Origin of Species*, 86–90.
[33] Darwin, *The Origin of Species*, 186–94.
[34] Darwin, *The Origin of Species*, 89.
[35] Darwin, *The Origin of Species*, 136.
[36] Darwin, *The Origin of Species*, 182–86.
[37] Darwin, *The Origin of Species*, 278.
[38] Darwin, *The Origin of Species*, 164–65.
[39] Darwin, *The Origin of Species*, 347–55.
[40] Darwin, *The Origin of Species*, 313–14.
[41] Darwin, *The Origin of Species*, 88–89.
[42] Darwin, *The Origin of Species*, 139–42.
[43] Darwin, *The Origin of Species*, 11.
[44] Darwin, *The Origin of Species*, 378.
[45] Readers interested in more rigorous and scholarly accounts of Darwin's life and work—especially in discussions of Darwin's inductive methodology—would benefit from the following works by James Lennox, emeritus professor of history and philosophy of science at the University of Pittsburgh:

- James Lennox, 'Darwin's Methodological Evolution', *Journal of the History of Biology*, 38/1 (March 2005), 85-99.
- James Lennox, 'From Darwin to Neo-Darwinism', chapter 5, in Sahotra Sarkar and Anya Plutynksi, eds. *A Companion to Philosophy of Biology*, Malden, MA: Blackwell Publishing Ltd., 2008.
- James Lennox, 'The Evolution of Darwinian Thought Experiments' and 'Thought Experiments in Evolutionary Biology Today', chapters 2 and 4 in W. J. Gonzalez (ed.), *Evolutionism: Present Approaches*, La Coruña: Netbiblio, 2009, 63-76, 109-120.
- James Lennox, 'Darwinian Thought Experiments: A Function for Just So Stories', in Tamara Horowitz, Gerald Massey, eds., *Thought Experiments in Science and Philosophy*, Savage, MD: Rowman and Littlefield, 1991, 173-196.
- James Lennox, "Darwinism", *The Stanford Encyclopedia of Philosophy* (Fall 2019 Edition), Edward N. Zalta (ed.), https://plato.stanford.edu/archives/fall2019/entries/darwinism
- A 2013 talk by Professor Lennox offers a fascinating overview of his work on these topics:
- "The Inductive Basis of Darwin's *Origin,*" Oslo Objectivist Conference, 2013. https://www.youtube.com/watch?v=6teGZ4ezAtM

I'm grateful to Professor Lennox for his assistance in selecting these references.

Readers interested in the relationship between evolutionary biology and the phenomenon of teleology (or goal-directedness) in nature may consult the following works:

- Harry Binswanger, *The Biological Basis of Teleological Concepts*, Los Angeles: ARI Press, 1990.
- James Lennox, 'Darwin and Teleology', Chapter 17 in Michael Ruse (ed.) *The Cambridge Encyclopedia of Darwin and Evolutionary Thought*. Cambridge: Cambridge University Press, 152-157.