Humbled by Evolution

Understanding the history and diversity of life inspires awe and wonder.

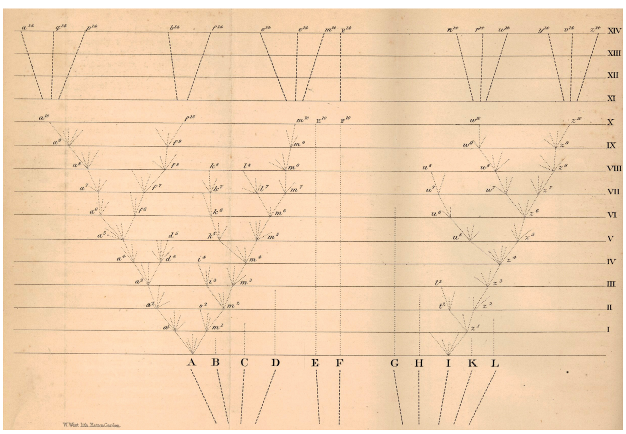
Lee Alan Dugatkin and Carl T. Bergstrom

Geology speaks to vast stretches of time and the very structure of the planet; physics explores even deeper time and broader spatial scales, from tiny quarks to stars, solar systems, and galaxies of unimaginable size and scope. These fields are humbling. But understanding the history, diversity, and connectedness of life, using a device—the human brain—that has been shaped by those very same forces, is outright vertiginous.

As the coauthors of an evolution textbook heading into its fourth edition, we spend a lot of time poring over scientific journals, reading and synthesizing material on a subject that, between the two of us, we've studied for more than 70 years. Ever since we were students, we have been amazed at the power of evolutionary biology to explain the history and diversity of life on Earth over the past 3.5 billion years. Still, being amazed is not the same thing as being humbled; more and more these days, we find ourselves humbled as well by the process of evolution.

The Same Simple Rules

Swim amidst teeming shoals of fish, with sharks cruising below, jellies pulsating in the water, giant clams gaping, nudibranchs flouncing past delicate-limbed shrimp, and an octopus exploring the crevices of the coral reef. Or watch a murmuration of starlings folding and unfolding dynamic patterns in the sky, as crickets begin to chirp in the gathering dusk. Watch the great migration of wildebeests, zebras, and antelope across the Serengeti, as hundreds of thousands of large ungulates shake the very earth, with predators lurking on the flanks. Look into a microscope at the translucent protoplasmic world in a drop of pond water: amoebas oozing, rotifers whirling, paramecia with thousands of beating cilia rowing across the surface of the slide.



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Charles Darwin included a sketch of a hypothetical phylogenic tree in *On the Origin of Species*, even though there was no understanding of genetics at that point. Time runs from past to present from the bottom to the top of the figure.

Now consider this: All of these living things, with their extraordinary capacities, are a result of the same simple rules operating over billions of years. All arose through natural selection, which requires only three basic conditions. First, selection requires *variation*: individuals differ. Variation is universal in our world. Second, it requires *inheritance*: Individuals reproduce, and offspring tend to resemble their parents. Third, selection requires *differential success*: Variation must somehow translate into differential survival, differences in reproductive success, or both. Given these three conditions, everything else follows inescapably. Natural selection will shape organisms that are better and better at producing offspring that survive and thrive. The result: organisms that are better and better adapted to their environments.

A Single Common Code

Charles Darwin unveiled his grand theory of evolution in his 1859 book *On the Origin of Species*. You might be surprised to know that this 500-page book contained only a single figure: a sketch of a hypothetical phylogenetic tree (*see figure at left*). This diagram, which traces historical relationships among living things, illustrates the core idea underlying an extraordinary extrapolation. Darwin knew that diverse varieties of domesticated animals—breeds of pigeons, for example—had been derived from a common ancestor over the span

QUICK TAKE

Understanding the process of evolution can be humbling because of its power to explain the history and diversity of life on Earth over the past 3.5 billion years.

All living things are the result of the same set of simple rules operating over that extended time frame, and all life encodes information the same way, using one ubiquitous genetic code.

Even the smallest of changes can produce adaptive benefits, although evolution sometimes produces forms that work just well-enough, affected by locked-in historical legacies.

Alexander Coke Smith

Bar-headed geese (*Anser indicus*) live in Tibet for most of the year, but they migrate in winter across the Himalayas, flying over mountains at altitudes of more than 6,000 meters, where the oxygen pressure drops perilously low. These geese have a genetic mutation that allow their hemoglobin to better bind oxygen. Such tiny tweaks in genetic instructions, when favored by natural selection, illustrate the vast and humbling scope of evolution.

of decades or centuries. Based on his deep knowledge of natural history, he speculated that the same process had unfolded on a far grander scale over billions of years, and thus all living things are descended from one or a few common ancestors. (Explorer and naturalist Alfred Russel Wallace independently chanced upon the same insight around the same time.)

It is difficult to sufficiently stress just how bold an extrapolation this conclusion represented. Darwin conjectured that the macroscale patterns that characterize the vast diversity of life arise from the same microscale processes that we can observe occurring in a single woodland or meadow over the course of our lifetimes. This position is a radically *uniformitarian* reading of the history of life. Much as physicists conjecture that the laws of physics are the same everywhere in space-time, Darwin imagined that the history of life has been governed not by cataclysmic acts of creation and destruction, but rather by the very same ecological processes we can observe occurring today.

Darwin made this proposal in the absence of even a rudimentary understanding of genetics. And in doing so, he put himself way out on a limb. He knew that if all living things had a single common ancestor, they would all have to share the same molecular basis, right down to how they transmit information across generations and how that information is interpreted to create cells, tissues, and bodies.

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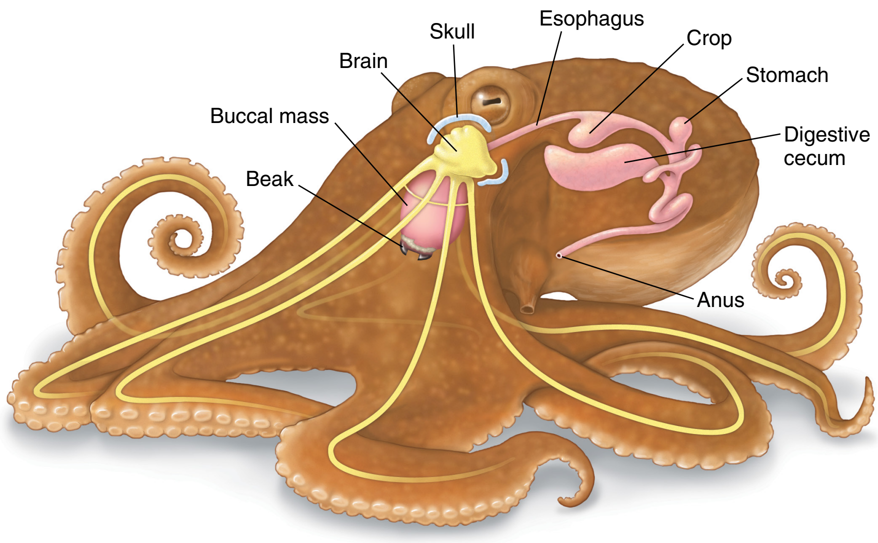
When Darwin published *On the Origin of Species*, no one had any idea whether this conjecture was true—but his intellectual courage paid off. Today, we know that the genetic code is ubiquitous. All living things encode information in the same way—as sequences of nucleotides making up DNA molecules. These sequences serve as instructions for creating proteins. Three-nucleotide blocks, known as *codon triplets*, specify one of 20 amino acids. Those amino acids are strung together in sequence as the building blocks of all proteins in all organisms.

It need not be so. There is no reason, in principle, that other genetic codes couldn't work—or why there would even have to be a genetic code at all. The information necessary for life could be transmitted in other ways. Indeed, a recent study by geneticists Sawsan Wehbi, Joanna Masel, and their colleagues at the University of Arizona, suggests that, at least very early on in the evolution of life, such alternative codes might very well have existed. Why the universal genetic code that has encoded life for billions of years became ubiquitous at some point deep in the evolutionary past is not yet understood. What we do know is that because of their shared evolutionary history, bacteria, fungi, plants, animals,



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Evolution sometimes produces systems that don't seem to be the most efficient, even though they work well enough. For example, in cephalopods, the brain wraps around the esophagus. The path of evolution is subject to what's called *historical contingency*: The directions that were taken in the past limit the sorts of changes that are possible in the present.

and even viruses all are built by instructions created using the same code.

Evolution Attends to Small Details

Even a *point mutation*—the tiniest of tweaks in the genetic instructions—can produce new evolutionary innovation. Consider two closely related species of geese. One, the greylag goose (*Anser anser*), resides year-round on the plains of India. The other, the bar-headed goose (*Anser indicus*), lives much of the year in Tibet, but migrates across the Himalayas to spend winters in India. Then it flies back to Tibet in the spring. This trip is no ordinary migration; to cross the world's highest mountain range, bar-headed geese cruise at altitudes in excess of 6,000 meters, where the oxygen pressure is very low. In these geese, but not in greylag geese, a point mutation in the hemoglobin protein in blood led to the substitution of an amino acid called proline by another amino acid called alanine. This small change matters, because this point mutation allows bar-headed geese to better bind oxygen during their migrations, and so has been favored over evolutionary time by natural selection.

In a case of what is called *convergent evolution*, something very similar has happened in the evolutionary history of Andean geese (*Chloephaga melanoptera*). These birds also spend long periods of time in a low-oxygen environment, but rather than the Himalayas, they navigate the Andes in South America. Andean geese have a point mutation in their hemoglobin protein that changes the amino acid leucine to serine, which also increases the ability to bind oxygen. To get a sense of just how small a tweak these sorts of point mutations are, keep in mind that bird genomes have roughly a billion locations where such a point mutation could occur: A change of one in a billion opens the door for evolutionary innovation. So in two different species, each facing a similar problem, natural selection found a comparable solution in the form of a single nucleotide change. These sorts of small genetic changes, each of which make organisms better suited to their world, when magnified across the tree of life and over evolutionary time, help explain the diversity of life.

Good Enough to Get By

With these high-altitude geese, we see an example of how the process of natural selection shapes organisms to their environments. But organisms from bacteria to humans are also riddled with traits that they'd be better off without. How is that possible? How can the same evolutionary processes that crafted the octopus eye, the remarkable ability of plants to turn sunlight into energy, and an ant's ability to follow chemical trails that are only molecules wide, also produce a respiratory system that results in tens of thousands of people choking to death every year? The answer to that question centers on the role of *historical contingency*.

The basic reason that humans choke is that the route that air takes through our nasal cavity to the trachea and into the lungs intersects with the route that food and water traverse through the mouth to the esophagus and into the stomach. But, it's not as if natural selection has stood by silently in the face of such odd architecture. The epiglottis, a flap of tissue that functions as a trapdoor over the larynx and trachea, has evolved as a partial work-around to this problem. When we breathe, the epiglottis rises and allows air into the lungs. When we swallow, the epiglottis is closed, preventing food and water from entering the trachea and lungs. That trapdoor system mostly works, but not well enough to prevent all those cases of mortality due to choking. Why hasn't natural selection produced a much simpler system whereby the airway doesn't intersect the path of food and water? How did we end up with the mess of a system that we have? To answer that conundrum, we need to dig deep into evolutionary history.

Lungs arose very early in primitive fish as a pouch that trapped gas bubbles, providing these fish with additional oxygen. Fish took in air through the mouth to fill these pouches, so the pouches needed to be connected to the mouth, and thus to the digestive passageway. For primitive fish, there was no choking risk because lungs were only a backup to the gills as the primary source of oxygen. So far, so good. But, later in vertebrate evolution, when life moved to land, gills were lost, and lungs became the only source of oxygen. That's where the trouble began. Because lungs evolved as an extension of the esophagus rather than a separate organ system, during the process of embryonic development, lungs are formed from the esophageal tissue, and so our breathing apparatus cannot readily be decoupled from the feeding apparatus from which it arose. As a result of this historical contingency, we choke at far too high a frequency. This argument applies to other mammals as well, but humans are particularly at risk because the morphological changes that have occurred as speech evolved have exacerbated the risk of choking in our own species.

Historical contingency and the problem of choking show, among other things, that natural selection can't look into the future. When lungs were just a backup system for acquiring oxygen in primitive fish, there was no way for natural selection to act as if many millions of years later they would become the primary system. Selection works on variation present in the here and now. One consequence of this path dependence can be Rube Goldberg machine–like constructions that would make an engineer cringe. Yet they work, well enough at least. Otherwise they wouldn't be here.

We humans don't have it as bad as octopuses and squids. In these animals, their brains wrap around their esophagi, so that each bite of food must pass through the middle of their brains. Most of the time, this crazy architecture operates just fine, but one large piece of food that can't navigate the system can have disastrous consequences.

Evolution Everywhere

So far, we've taken an Earth-centric approach to the power of evolution to shape life. But one thing that makes understanding evolution so humbling is that it's not just life on Earth to which the rules apply. If life exists elsewhere in the universe, natural selection likely operates on it there as well. Although this claim might sound astonishing, it is one that NASA gives considerable credence. NASA's Exobiology Program—which, it is worth noting, used to be called the Exobiology and Evolutionary Biology Program—is tasked with studying "the origin, evolution, distribution, and future of life in the universe." As part of that grand quest to understand possible life on other celestial bodies, NASA funds research that looks at how natural selection operates in the most extreme environments on Earth, as a proxy for how life might evolve elsewhere in the cosmos.

Deep-sea hydrothermal vents are about as extreme an environment as you'll find anywhere on Earth. Temperatures at some of these sites, such as the Von Damm vents, 2,300 meters below the surface near Grand Cayman in the Caribbean, can reach more than 200 degrees Celsius. Deep-sea hydrothermal vents are home to sulfide-rich compounds belched from giant "black smokers," natural chimneys rising 20 meters above their bases, which form over magma chambers beneath the seafloor. These sulfide-rich substances interact with iron-laden waters on the ocean floor, creating compounds that may have played a role in the early formation of life. Bacteria abound near these vents, and the oxidation of hydrogen sulfide by chemosynthesis, as opposed to photosynthesis, is one key chemical energy source for them.

Funded in part by NASA's Exobiology Program, Harvard University's Alief Moulana and his team sequenced the genome of bacteria in the genus *Sulfurovum* at two deep-sea hydrothermal vent sites: the Von Damm vents and others near the Axial Seamount in the Pacific Ocean. When it came to the chunk of the genome associated with basic survival—DNA replication, metabolism, cell growth, and cell structure—*Sulfurovum* looked similar at both vent sites. Some things are so fundamental to life that natural selection favors them far and wide. But selection has also acted in important ways on other *Sulfurovum* genes. At the Von Damm vents, for example, the amount of phosphate—a key nutrient for energy production in these inhospitable environments—is severely limited relative to that at the Axial Seamount vents. And at the Von Damm vent, natural selection has acted to increase the frequency of genes associated with the acquisition and retention of phosphate. But this shift does not come without cost: When bacteria scavenge for phosphate, they sometimes take up arsenic. And, lo and behold, natural selection on *Sulfurovum* at the Von Damm vent has also led to a means of breaking down the arsenic that may be picked up as a byproduct of searching for phosphate.

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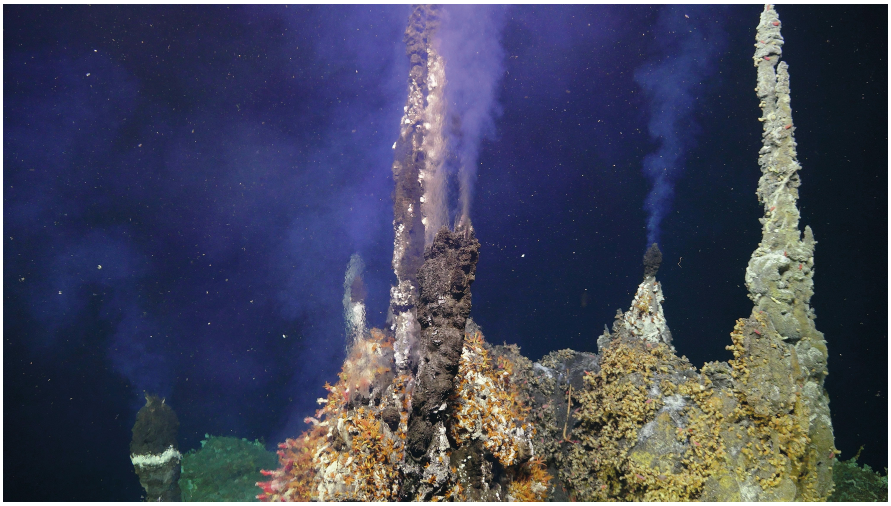
If natural selection acts 2,300 meters below the surface of the ocean, at temperatures of more than 200 degrees, on organisms who glean their energy in a way that is fundamentally different from the rest of life on our planet, then the notion that natural selection acts the same everywhere in the universe all of a sudden sounds far less speculative.

Recovering from Disaster

One of Darwin's profound insights was that much of the evolutionary change responsible for the current diversity and form of living things occurs on a local scale in response to local conditions. But from time to time over the past half billion years, catastrophic events have had enormous effects on the course of evolution. At least five times over this period, a huge swath of life on the planet has been wiped out during a mass extinction, and evolutionary change has proceeded afterward at an accelerated rate. The most famous of these mass extinctions occurred 65 to 66 million years ago, during the transition between the Cretaceous and Paleogene periods; this event is often called the K–Pg mass extinction (after the German words for these periods). Half of the genera present before the end of the Cretaceous period, including all the nonavian dinosaurs, were wiped out entirely during this event.

Even before scientists were able to work out the when, where, and how, geological evidence suggested that at least one huge asteroid, roughly 10 kilometers wide, crashed into the Earth at the time. The impact explosion triggered unimaginable tsunamis, and also caused vast amounts of particulate matter to shoot into the atmosphere. That matter eventually spread around the globe and blocked out sunlight, stopping photosynthesis in its tracks. Without plants synthesizing food from sunlight, the food chain collapsed, and mass extinction ensued. In the late 1980s and early 1990s, geologists found the impact site, deep underwater in the Yucatán Peninsula of Mexico. The Chicxulub crater is the right size and age. It has very high levels of iridium, an element found in abundance on asteroids but rarely on Earth. And the crater contains rock with mineralogical signatures of a massive collision.

Humbling as it is to recognize that an extraterrestrial object is capable of wiping out such a large chunk of life on the planet, what is arguably more humbling is the recovery of life around the crater after the asteroid



UW/NSF-OOI/WHOI-ROV *Jason*

Deep-sea hydrothermal vents, such as this one located on the Axial Seamount about 480 kilometers off the coast of Oregon, produce natural chimneys called "black smokers," which emit high-temperature substances created by subterranean magma fields. The bacteria living at these vents have evolved varying abilities to bind trace levels of the chemicals they need for life, and to break down toxins, depending on what is emitted at the specific location.

struck. Using a core sample from hundreds of meters below the seafloor near the crater, a team led by geochemist Kliti Grice at Australia's Curtin University, together with collaborators from the United States and Europe, have found that, within hours of impact, ocean water would have flooded the crater, and tsunamis striking nearby would have deposited organic debris and single-celled organisms into the crater. Within months, algae, unicellular cyanobacteria, dinoflagellates, numerous species of sulfur-oxidizing bacteria, and perhaps land plants, began colonizing the Chicxulub crater. Other work suggests that, within a matter of years, wormlike burrowing animals were present. Soon, at least from an evolutionary perspective, full-blown ecosystems were in place. And that's at the incredibly inhospitable site of an asteroid collision. The same sort of recovery was going on at a global scale, although the speed at which it occurred differed from place to place.

Even after much of the slate of life had been wiped clean, evolution continued and diversity was created anew. Propelled by evolutionary forces, life finds a way.

We Are Not a Pinnacle

Being humbled by evolution means that, once and for all, we need to give up the notion that *Homo sapiens* is some sort of unique pinnacle of evolution, different in kind from all other lifeforms. For one thing, life on Earth got along perfectly well—and arguably better, given what is happening in the Anthropocene era—without us for more than 3.5 billion years. For another, if an asteroid hadn't crashed into the planet about 65 million years ago, opening the door for early mammals to adapt and radiate out to colonize new ecological niches, there'd likely be no primates, let alone humans. What's more, work on *hologenomes*—the genome of an organism and all of the genomes of all the microorganisms that it hosts, both internally and externally—has revealed that the majority of cells in a human are not human cells, but rather those of the bacteria and fungi that live in and on us. When one day we go extinct—which has been the fate of the vast majority of all species that have ever lived—*Homo sapiens* will go down as a tiny twig on the tree of life. None of these examples describe the legacy of a "pinnacle of evolution." Indeed, evolution doesn't have pinnacles.

Here's the thing: Not only are we not a pinnacle, we are not even unique. In the near evolutionary past, our planet was inhabited by a range of hominin species that rivals Tolkien's imaginary tales of Middle-earth. This *hominin clade* is composed of humans and extinct species more closely related to humans than to chimpanzees. Within the past 100,000 years, we *Homo sapiens* encountered and interacted with *Homo neanderthalensis*, *Homo luzonensis*, *Homo floresiensis*, Denisovans, and likely other species still to be discovered. Neanderthals disappeared only 40,000 years ago; Denisovans more recently still. There is little reason to think that *Homo sapiens* were fundamentally more advanced than some of these other hominin species; we were just subtly different. Like us, other hominins created elaborate tools, tailored clothing, cooked their food, buried their dead, and created art. Neanderthals and Denisovans very likely had spoken language. And sometimes, they mated with *Homo sapiens*.

These matings mattered. Think back to the bar-headed goose on the Tibetan plateau. Tibetan people, too, need to deal with low oxygen levels at high altitude, and many Tibetans carry a combination of genes that increases oxygen delivery by increasing blood flow. Evolutionary biologist Emilia Huerta-Sánchez, now at Brown University, and her colleagues set out to understand how that came to be. They first scanned data from the 1000 Genomes Project—an international collaboration that created a catalog of human genetic variation across ethnic groups—and then added in genomes from now-extinct members of the hominin clade. The only match to the genes associated with oxygen uptake found in the Tibetan population came from genome sequences of Denisovan hominins.

Denisovans are more closely related to Neanderthals than to modern humans, but they coexisted with other *Homo* lineages until about 30,000 years ago. And we know from other lines of evidence that Denisovans and *Homo sapiens* interbred in Asia about 40,000 years ago. The upshot of this interaction is that interbreeding with Denisovans provided *Homo sapiens* with genetic variation that proved to be adaptive in modern human groups that migrated to high altitudes.

Not all the mating that ancestral *Homo sapiens* engaged in with other *Homo* species turned out so well for contemporary humans. For example, a gene cluster found on human chromosome 3 is known to be a risk factor for respiratory failure in patients with acute symptoms brought on by COVID-19. When Nobel laureate Svante Pääbo and his colleague Hugo Zeberg, both at the Max Planck Institute for Evolutionary Anthropology in Germany, tapped into the 1000 Genomes Project, they found that this increased risk is the result of a genomic segment that made its way into the human genome through interbreeding with Neanderthals.

A Final Puzzle

We are left with a final puzzle. Why should we—"a thin film of life on an obscure and solitary lump of rock and metal," to quote Carl Sagan—be able to apprehend the workings of the universe that fashioned us?

When it comes to fundamental physics, the answer may be that we cannot. Quantum theory is notoriously difficult to conceptualize. Theories such as supersymmetry, quantum loop gravity, and other recent developments are more difficult still. In these domains, the quantitative tools of science give us remarkable predictive power, but deep understanding is elusive. There is often little we can do beyond "shut up and calculate."

Given that our senses and our ways of thinking evolved by natural selection, our struggles with these subjects should be unsurprising. We are denizens of the Newtonian regime. We live out our lives on scales from millimeters to kilometers, milliseconds to decades. Some of the mechanics underlying our biology happen at smaller scales—DNA synthesis, transcription, and translation, for example—but these processes happen far from conscious control, and when we study them, they are often adequately approximated without resorting to quantum models.

We and our surroundings are large enough to behave according to classical physics; we move slowly enough that relativistic effects are negligible; the fields in which we operate are sufficiently weak that the complications associated with general relativity do not come into play. There is no evolutionary need for us to understand the quantum world or relativistic space-time. Our brains did not evolve to make sense of the extra six spatial dimensions that superstring theory demands, for example; they're folded up so minutely that we have no access to them, and there is nothing we can do with these extra dimensions.

Consider why our brains evolved in the first place. Brains evolved to control actuators—muscles, for example—that operate on a classical scale. Moreover, our brains and sensory systems literally evolved by natural selection to make us good at the things that natural selection favors: feeding, mating, avoiding predators, and so forth. At the risk of being a little too glib, our brains became well suited to the game we were playing: natural selection. To win, we evolved appropriately scaled sensory systems and a capacity for reasoning. With the help of a cumulative culture by which we learn, teach, and "stand on the shoulders of giants" (to paraphrase Isaac Newton), we can derive Newtonian mechanics, and we can understand the grand story of evolution.

So that's half an answer. But there is no reason for evolved creatures such as us to have any capacity to comprehend *deep time*, the notion of a process that plays out over a million or a billion years. Considerations of deep time are no more relevant to the decisions associated with an individual's reproductive success than are the structural composition of subatomic particles, the slowing of clocks near light speed, or the freezing-in of the Higgs field within an instant of the Big Bang.

The diversity of life arose not through some catastrophic process far in the distant past, but rather through the gradual action of the very same processes we observe ongoing today.

And yet we can and do make sense of deep time, at least conceptually, if not emotionally. Why? It comes back to the principle of uniformitarianism and Darwin's radical conjecture: The diversity of life arose not through some catastrophic process far in the distant past, but rather through the gradual action of the very same processes we observe ongoing today. Indeed, in the final paragraph of *On the Origin of Species,* Darwin returns to this theme with the image of an "entangled bank, clothed with many plants of many kinds, with birds singing on the bushes, with various insects flitting about, and with worms crawling through the damp earth." We might have been just as flummoxed trying to understand how all of this came to be as we are now when our Newtonian minds try to imagine the universe in the initial femtoseconds after the Big Bang. But we are not, because, as Darwin observes, the diverse and interconnected creatures of the entangled bank "have all been produced by laws acting around us."

We certainly are not the first to feel awed and humbled by process of biological evolution. It is difficult to study the field without experiencing these emotions. To this day, there may never have been a better expression of these emotions than the words that Darwin chose to conclude the first edition of *On the Origin of Species*: "There is grandeur in this view of life, with its several powers, having been originally breathed into a few forms or into one; and that, whilst this planet has gone circling on according to the fixed law of gravity, from so simple a beginning endless forms most beautiful and most wonderful have been, and are being, evolved."

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