EVIDENCE

of

EVOLUTION

photography by SUSAN MIDDLETON *text by* MARY ELLEN HANNIBAL

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ABRAMS, NEW YORK

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Opposite: Nature has been a careful couturier in the case of the butterfly; the four stages of metamorphosis between embryo and adult provide staging areas for developmental pathways to invent, elaborate, and organize features like eyespots, bands, and colors.

INTRODUCTION

Why do butterfly wings have so many different patterns, and if a snake is a reptile and an eel a fish, why do they look so similar? A hundred and fifty years ago, Charles Darwin addressed these questions with the publication of his seminal work, *On the Origin of Species*. In it, Darwin posited the theory of evolution based on natural selection as the answer. He proposed that descent with modification over time leads to new forms of life. According to his theory, butterflies gradually adopted traits such as wing patterning in service of eluding predators and attracting a mate. Similarly, both snakes and eels have capitalized on one of nature's most successful body plans, which works by land and by sea. Flexing, undulating, burrowing, and moving in and out of tight spaces—the sleek form facilitates swimming, whether in water or through grass. Today, most scientists would say that evidence of evolution is all around us; that as the central mechanism of life there is no way to understand the world without it. And science is now engaged with studying evolution as never before, because understanding the hows and whys of the Earth's history is the foundation for understanding our future, and ensuring that we will indeed have one. Modern scientists use techniques Darwin never dreamed of to parse out the story of life, grinding genetic material and entering its data into computer programs to yield the secrets encoded in DNA. But they are equally reliant on tradition that Darwin knew well—taxonomy.

Taxonomy—from the Greek *taxis*, "arrangement," and *nomos*, "law"—is nothing less than the classification of all living things, a vast and ever-increasing filing system. By identifying and naming species, scientists place them in relation to other organisms and thus define patterns of evolution, or systematics. And the first step in determining what exactly an organism is, and where it belongs in relation to other organisms, is to "collect" it. Specimen in hand, scientists can begin to compare it to others of its apparent kind by examining its morphology, or physical traits.

Thus do specimens in natural history museums inform the long conversation and drive the discovery process of science. Millions upon millions of them; beetles, butterflies, tortoises, birds, and fossils of everything from bacteria to dinosaurs, lie in temperature-controlled trays on enormous metal compactors, hidden from public view behind the dioramas and the exhibits (or sequestered on another floor)—scientists continue to collect a mind-boggling array of the treasures of life. Tiny ants are fastidiously mounted, along with documentation in minuscule script. Fish and reptiles are suspended in alcohol, the jar lids screwed on tight. Other specimens are simply tucked away, neatly, like sweaters in a drawer. These various displays are ways of preserving information.

Yet, confronted with more than two million beetle specimens alone at the California Academy of Sciences in San Francisco, where the photographs for this book were made, one might very well ask, "When is it enough?" And indeed, in our conservation-minded world, especially among scientists whose ultimate goal is the full appreciation of their subject, care is taken not to over-collect. Gone are the days when explorers stuffed as many tortoises as they could into the holds of their ships. But based on physical examples, how many would it take to represent the human being? You would certainly need one of each sex of every race, and all the combinations found in the world thereof, to say nothing of body types, blood types, hair and eye color differences, and so on. And if you wanted to understand exactly how *Homo sapiens* came to look and behave the way we do now, you would have to have examples from every previous incarnation of our species. Still, our individual experience of being human goes well beyond our body type, race, sex, and place in time. Taxonomists strive to develop broad, deep collections that will together create an accurate picture of nature and its relationships, but they must balance this quest with ecologically responsible practices.

All a far cry from the antecedents of today's natural history museums, which can be traced to the private "curiosity cabinets" of the seventeenth and eighteenth centuries. For hundreds of years thereafter, amateur collectors amassed souvenirs, both beautiful and strange; it was not unusual for an opulent domicile in sixteenth- and seventeenth-century Western Europe to house the equivalent of its own museum. (Even today, personal collections arrive at the doors of natural history museums, and sometimes these have valuable components: unexpected fossils, for example, or a prime example of indigenous art.) Peter the Great of Russia was one of the first to display his, in 1710; the collection included the pickled heads of his lover and his wife's lover. Now that says something about *Homo sapiens*.

At the same time, early scholars sought to identify, describe, and connect the links among organisms to create a vast hierarchy and re-create the Great Chain of Being. The Royal Society established the unifying principle of modern scientific institutions in 1660 based on Francis Bacon's idea that separate collected objects could be compared and analyzed toward "the knowledge of causes." *Cause* is a persistent bone of cultural, if not scientific, contention; though nobody knows why, or precisely how, life on Earth was instigated, a very detailed history of how it has progressed is being ever more deeply established. The relationships among even drastically disparate organisms, the genealogies that connect the most ancient organisms with groups alive today, is evolution.

Previous spread, left: Starfish are not fish, but echinoderms (from the Greek for "spiny skin"); their number of arms ranges from five to even more than the whopping twenty-four in this species. Tube feet cover the underside of their arms and have sticky suckers at their ends, which can be used for locomotion or to manipulate objects, including food. When it comes time for the starfish to eat, it simply everts its stomach over its prey and begins digesting.

Opposite: Moths seek camouflage when they rest, lying flat against a tree trunk or another obscuring surface. Butterflies fold their wings over their backs, hiding their glory. In contrast to most moths, which are drab, this atlas moth, *Attacus edwardsii*, displays a quiet beauty.

Overleaf: Amphibians, including these salamanders, frogs, and legless schistometopums, are found everywhere on Earth except in the Arctic. Because they bridge two worlds, land and water, and have highly permeable skin, they are good indicators of the health of an ecosystem.

HOW DOES LIFE WORK?

Most of us use the term "evolution" as synonymous with change, but the word is from the Latin *evolvere*, meaning "to unfold." Evolution is a series of relationships connecting all life on Earth at this moment and back through time, both a history and a picture of what comprises life now. We establish these relationships through various means, but tangibly through the evidence of specimens. An evolutionary biologist first determines exactly what a specimen is and where it fits within densely articulated classification systems. Most disciplines, like botany, use something called a dichotomous key to begin placing a specimen within a genus and to identify it further as a particular species.

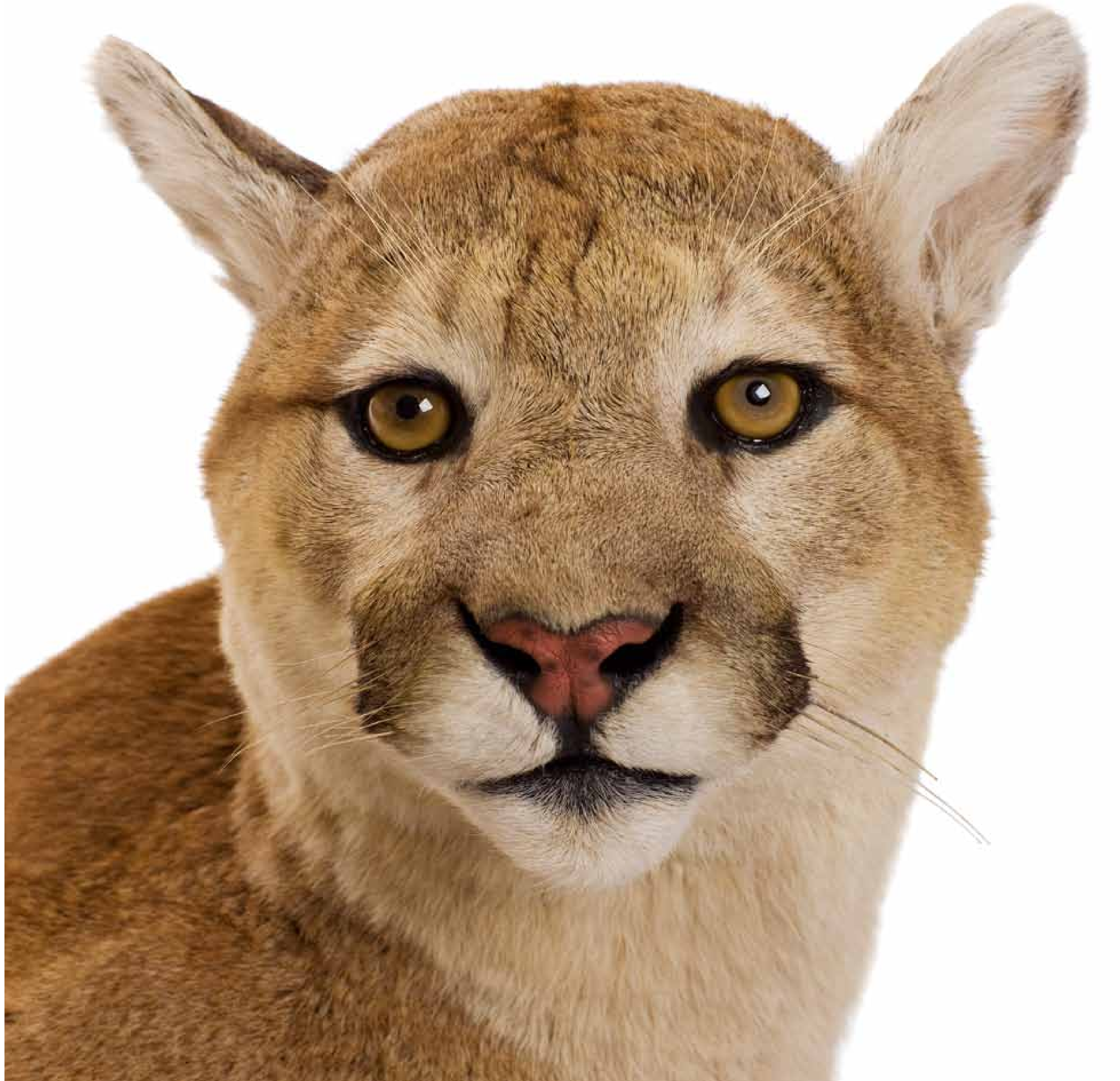
Dichotomous means "divided into two," and thus the key lays out a set of either/or questions that quickly sort the features of the specimen: Is a leaf evergreen or deciduous; does it have six lobes or four? These either/or questions get specific down to the chemical compounds found in the plant's metabolic pathways, down to the molecular structure of its DNA. Every answer helps determine where the specimen belongs, what it is related to, and its age. Sometimes, however, the scientist cannot fit all the details of a specimen into a previous picture and experiences the thrill of discovering something new. Once the identity of a specimen has been firmly determined, it takes its place in the vast jigsaw puzzle science is constructing to depict this unfolding of life on Earth.

The basic framework for understanding evolution is the fact that all living things have parents (mostly two, but not always). Darwin's terminology "descent with modification" refers to the fact that new variations in individuals result from transmission of traits, half contributed by a mother and half by a father. He was unaware of Gregor Mendel's work on inheritance of traits in pea plants, although the two men lived at the same time. Mendel identified how hereditary factors sort out and come back together; called genetics, this science is integral to the pattern Darwin identified.

Later work in the field showed that change occurs not only from new combinations of genes, but through a process known as genetic drift. Cells divide by replicating themselves, a copying process that is frequently imperfect. The copies end up being slightly different from their originals. Some scientists say the resulting mutation is caused by "mistakes" in genetic copying, but since there is no intention on the part of cells, it seems more accurate simply to say that "changes" are made during genetic copying. Change, whether effected through new combinations of genes or genetic drift, is fundamentally necessary to evolution, providing the raw materials for innovative forms. Over time, changes in a population's genetic makeup accumulate to the point that a species is effectively separate from its ancestors. One of the central goals of evolutionary biologists is to locate the point at which this divergence occurs.

Opposite: This Puma *concolor* was donated to the California Academy of Sciences by the U.S. Fish and Wildlife Service; it was likely given to this agency when it became illegal to hunt and mount endangered species. The puma is threatened by habitat loss.

Overleaf, left: Venus arose from a scallop shell, ordinarily the home of a bivalve, which propels itself away from predators by contracting its adductor muscle and clapping its two shells open and closed.



DARWIN AND THE GALÁPAGOS

Darwin's thought process was as slow as the tortoises that so influenced it, and as in the Aesop fable featuring the plodding beast, just as successful. Darwin did not publish his most famous work until he was fifty; he had ruminated upon and developed his ideas for more than a quarter of a century. A poster child for underachieving students everywhere (or at least for their parents, who are the ones holding out hope), Darwin was an unfocused youth prodded down various paths by his father. Historians find hints of his future direction in some of Darwin's early experiences; one of these is a taxidermy lesson he undertook while studying medicine at the University of Edinburgh. Reportedly revolted by the surgery he was supposed to perform, he quit; but the taxidermy, taught by a freed black slave who regaled Darwin with travel tales from the South American rain forest, beguiled him.

Darwin's father nudged him onto the professional path of a clergyman, which both perhaps saw as conducive to his love of the outdoors and his predilection for studying beetles—many gentlemen naturalists of the day were also men of the cloth. In 1831, when he was twenty-two, just before he was due to take his orders, Darwin instead took the opportunity to travel as gentleman's companion to Captain Robert FitzRoy, who was shortly to lead an expedition charting the coastline of South America (FitzRoy's eventual maps are highly accurate, and were used until World War II). The voyage was projected to last two years—it returned five years later. It was on this trip that Darwin famously visited the Galápagos Islands off the coast of Ecuador, a volcanic archipelago with a most intriguing population of flora and fauna. While he was intellectually curious and an inveterate observer all his life, virtually all of Darwin's paradigm-shifting thought can be traced to observations made on this trip and to subsequent reflection on the specimens he brought back. Thus did a fairly substantial "step out" by a waffling young man become the cornerstone of, arguably, the greatest scientific theory of all time.

THE MYSTERY OF MYSTERIES

Darwin sent back specimens and descriptions from the Galápagos to scholars and scientists in London, who were also intrigued with what he found there, and they accepted him into their company as an established naturalist upon his return. Even before *On the Origin of Species*, he published papers pondering the provenance of these organisms and helped to build interest in the Galápagos. Prominent natural history museums and private collectors began more routinely to go to the islands to see, and collect, for themselves.

For years, Darwin and a coterie of friends and colleagues mulled over what they called the "mystery of mysteries," the origin of species. At the center of this question is the key to life on Earth and what makes it work. The tortoises, lizards, birds, fishes, and plants brought back by Darwin were different from those found anywhere else, yet distinctly related to South American life-forms. How could they be both different and the same?

THE SANDS OF TIME

Every organism is uniquely adapted to the physical forces that shape its environment. Birds, fish, and insects all use hydro- or aerodynamic strategies to cope with the vagaries of their world. Sand dollars perfectly illustrate this story of adaptation. Sand dollars live relatively close to the shore in big colonies in almost all oceans, where the action of waves and currents is turbulent and strong, and they have evolved a multitude of strategies for staying put. It is one of nature's deceptions that the sand dollar's clinging grasp on the sand looks natural and passive, because it is a model of hydrodynamic engineering and works tremendously hard to stay where it is—amazingly, without expending much energy.

Sand dollars' flattened shape helps them resist both lift and drag, as they burrow themselves into the sand in defense against the flow of water above them, and when young they increase their weight by taking in granules of magnetite selected from the sand around them. As sand dollars mature, they build permanent weight belts, pillars of calcite between their upper and lower surfaces. The sand dollar's low central dome not only helps it to burrow, but gives it a low profile, to reduce drag. But the sand dollar's shape generates lift in the same way an airplane wing does: As fluid flows over a wing, pressure under it increases relative to the region above it, pushing the wing, and therefore the entire airplane, upward. What is good for a plane, however, is bad for a sand dollar. So shallow depressions on the sand dollar's underside provide channels to dissipate sand and water pressing from below; excess flow is then directed to indentations on the margin, where it disperses the lift forces without upending the sand dollar. In some species, the indentations along the margin have become very deep, making it easier and quicker for the pressure of the water to pass upward and zero out the lift.

A sand dollar wants to stay in place because here is where it makes its living—in the sand. Eating it, to be exact. In the upper few millimeters of sediment on the bottom of the ocean, each sand grain is a veritable garden of nutrients, covered in diatoms and bacteria and other organic material that has drifted downward from the dynamic fish and plant activity going on throughout the ocean. The sand dollar thus makes use of nutrients that otherwise would remain unavailable to the overall ecology of the environment.

Again, belying its benign, childhood-evoking demeanor, the sand dollar has some major equipment tucked away in its test, which is the thickest part of its center. In *The History of Animals*, Aristotle correctly described the sand dollar's set of five convergent teeth, which he likened to "a horn lantern with the panes of horn left out"; this remarkable contraption at the center of the sand dollar's body has been called "Aristotle's lantern" or "lamp" ever since. The sand dollar's tube feet (an adult can have up to a million on its oral surface) have sticky suckers that pass sand in a bucket brigade from one to the next, until the grains reach the mouth, where Aristotle's lamp pulverizes them.

In the meantime, those tiny spines covering the sand dollar's body are doing their part. Mounted on miniscule ball-and-socket joints, they perform different tasks. The spines around the perimeter of the sand dollar are the longest and, in general, sweep sand to keep the way clear for the sand dollar to move and to prevent it from getting clogged up. The spines on the lower surface function as levers for movement; in perfect synchronism they swing in an arc and move the organism. On the top, club-shaped spines with expanded tips form a canopy to prevent sand from settling into the spaces between the spines.

So while the sand dollar is about evident stillness and staying put, the way it achieves this is through constant and complete motion. The sand dollar manipulates its environment, using its spines to jiggle the sand around it and make it move as if it were a liquid. Sand and water mixed form a solid, but if you have ever given a sand castle a gentle pat to tidy it and had it collapse in a heap, you have experienced what the sand dollar is up to—instigating "thixotropy," or liquefaction, which makes the combination of sand and water behave like a liquid when it is agitated.