

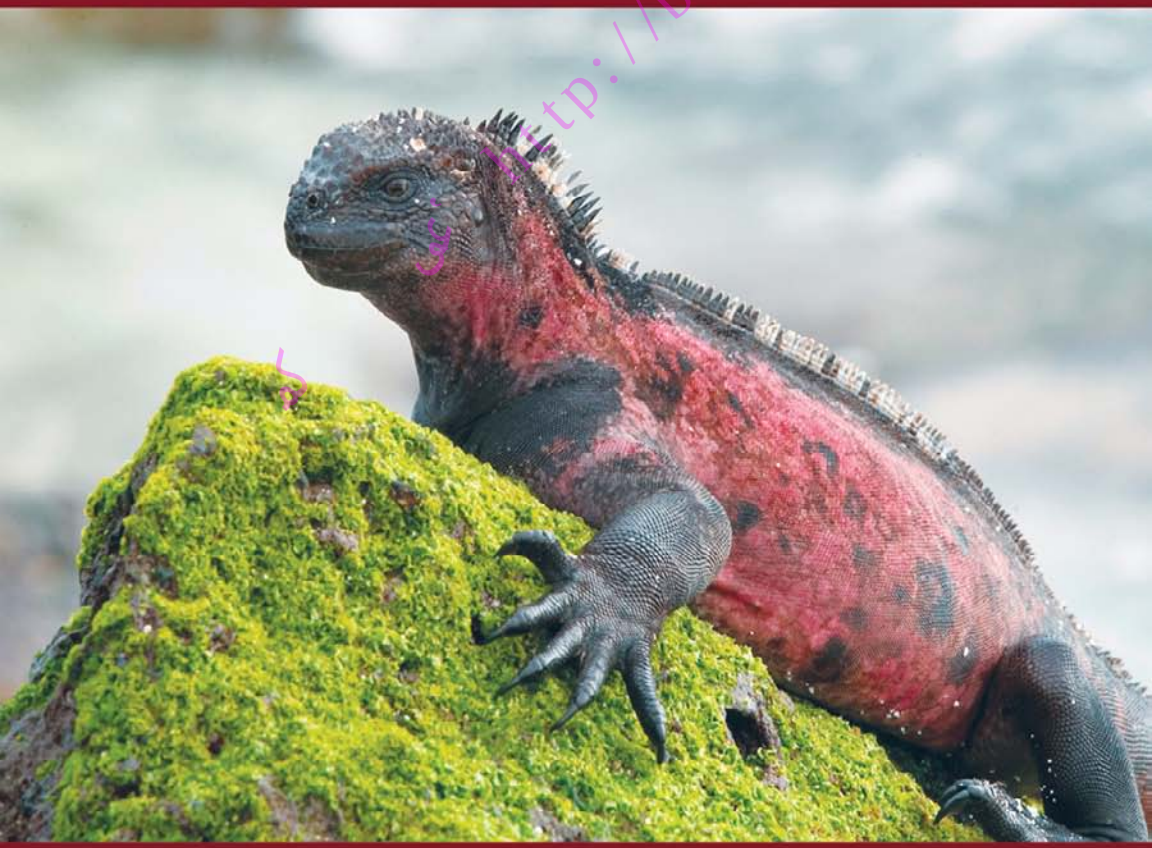
GENETICS &
EVOLUTION



# EVOLUTION

## *The History of Life on Earth*

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RUSS HODGE




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GENETICS & EVOLUTION



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RUSS HODGE

FOREWORD BY NADIA ROSENTHAL, PH.D.

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This book is dedicated to the memory of my grandparents, E. J. and Mabel Evens and Irene Hodge, to my parents, Ed and Jo Hodge, and especially to my wife, Gabi, and my children—Jesper, Sharon, and Lisa—with love.



**EVOLUTION: The History of Life on Earth**

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"I say that it touches a man that his blood is sea water and his tears are salt, that the seed of his loins is scarcely different from the same cells in a seaweed, and that of stuff like his bones coral is made. I say that the physical and biologic law lies down with him, and wakes when a child stirs in the womb, and that the sap in a tree, uprushing in the spring, and the smell of the loam, where the bacteria bestir themselves in darkness, and the path of the sun in the heaven, these are facts of first importance to his mental conclusions, and that a man who goes in no consciousness of them is a drifter and a dreamer, without a home or any contact with reality."

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—from *An Almanac for Moderns: A Daybook of Nature*
by Donald Culross Peattie
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# Foreword

It hits everyone differently, but the feeling of infectious curiosity is unmistakable. My own obsession with biology sprung, unexpectedly, out of an early passion for art. My epiphany at fifteen was sparked as much by the recurring themes in nature that I had been trying to capture in paint as by the biological information I was gobbling up at school, fed to me by an inspired teacher. I soon became convinced that studying the living world would satisfy my curiosity more than painting ever could.

Reading Russ Hodge's book reminds me of the excitement of those early days in my own discovery of evolution. It is a challenging, fascinating account: engaging narratives of the men and women with open eyes who struggled to reconcile their religious faith in a story that did not fit the facts they were uncovering in the fossils dug out from shales and cliffs of foreign shores, or even in their own backyards. Against a backdrop of our own relatively brief human history, the immense scale of geological time embedded in those rocks was a real conceptual impediment to these thinkers. To grasp the gradual emergence of life-forms, they had to wrestle with the presumptions of the day, that organisms spontaneously could appear fully formed, rather than evolve from a previous version. These people were courageous, real explorers of the unknown and reading their stories reminds me of the reasons I became obsessed with biology in the first place. Reading about them can help today's students experience for themselves the excitement of scientific exploration, and to appreciate how profoundly the work of yesterday's scientists affects the quality of our lives today. In trying to predict what new insights we will gain through biology in the course our own lifetimes, it's helpful to put oneself in the shoes of someone who did not yet know what DNA was, yet somehow imagined the ways genes might work from pure observation of his natural surroundings. I still thrill when

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I read of Wallace's solitary epiphany of evolutionary process in the Pacific islands, and still wince at the principles of evolution wrongly applied to human racial segregation. These are the tales this book tells.

The story of evolutionary discovery shows us as members of modern society how important it is to gain at least a basic grasp of scientific knowledge. The original concept of natural selection, so controversial that both of its founders hesitated for years to publish it, could have been readily tested with access to today's information and technology we now take for granted. What Darwin wouldn't have given for one of our state-of-the-art gene sequencing machines that provides us with an entire human DNA sequence in a day! The scientific opportunities in front of us have never been more exciting, but also raise controversial questions. Our own personal genetic data will soon be available, giving us a chance to chart our private evolution in a way never before possible. But more information can always be misused, and as a society it's critical that we engage with current scientific issues that will shape the future. To deal with the challenges of today's science, we must be armed with at least a general understanding of the concepts underlying the advances that brought us to this point in history.

These are the sensible reasons why studying the story of evolution matters. But the real reason is less practical. As the physicist Brian Greene describes it, science gives us a new perspective, and it allows us to travel from confusion to understanding in a manner that's precise, predictive, and reliable. To him, doing physics is a transformation that actually feels empowering and emotional. As a student I was lucky to have a teacher who made me feel that way about biology before I knew very much about it. To be able to think through and grasp the explanations that reveal how life formed on earth is a precious human experience that you do not have to be a scientist to enjoy.

Evolution is often viewed as an isolated topic that sometimes shows up in the news as a controversial challenge to biblical accounts of creation. But the study of evolution actually provides us with a new dimension of experience, giving us a

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language to connect our own history as a species to our present lives, and enriching our encounters with the natural world around us. *Evolution: The History of Life on Earth* will open those new dimensions and teach you the basics of the language while taking you on a great human adventure. It captures the drama of the struggle with religious belief, and that epiphany of insight that is at the core of scientific discovery. It will convince you that evolution matters.

—Nadia Rosenthal, Ph.D.
Head of Outstation,
European Molecular Biology Laboratory
Rome, Italy

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# Preface

In laboratories, clinics, and companies around the world, an amazing revolution is taking place in our understanding of life. It will dramatically change the way medicine is practiced and have other effects on nearly everyone alive today. This revolution makes the news nearly every day, but the headlines often seem mysterious and scary. Discoveries are being made at such a dizzying pace that even scientists, let alone the public, can barely keep up.

The six-volume Genetics and Evolution set aims to explain what is happening in biological research and put things into perspective for high-school students and the general public. The themes are the main fields of current research devoted to four volumes: *Evolution, The Molecules of Life, Genetic Engineering,* and *Developmental Biology*. A fifth volume is devoted to *Human Genetics,* and the sixth, *The Future of Genetics,* takes a look at how these sciences are likely to shape science and society in the future. The books aim to fill an important need by connecting the history of scientific ideas and methods to their impact on today's research. *Evolution,* for example, begins by explaining why a new theory of life was necessary in the 19th century. It goes on to show how the theory is helping create new animal models of human diseases and is shedding light on the genomes of humans, other animals, and plants.

Most of what is happening in the life sciences today can be traced back to a series of discoveries made in the mid-19th century. Evolution, cell biology, heredity, chemistry, embryology, and modern medicine were born during that era. At first these fields approached life from different points of view, using different methods. But they have steadily grown closer, and today they are all coming together in a view of life that stretches from single molecules to whole organisms, complex interactions between species, and the environment.

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The meeting point of these traditions is the cell. Over the last 50 years biochemists have learned how DNA, RNA, and proteins carry out a complex dialogue with the environment to manage the cell's daily business and to build complex organisms. Medicine is also focusing on cells: Bacteria and viruses cause damage by invading cells and disrupting what is going on inside. Other diseases—such as cancer or Alzheimer's disease—arise from inherent defects in cells that we may soon learn to repair.

This is a change in orientation. Modern medicine arose when scientists learned to fight some of the worst infectious diseases with vaccines and drugs. This strategy has not worked with AIDS, malaria, and a range of other diseases because of their complexity and the way they infiltrate processes in cells. Curing such infectious diseases, cancer, and the health problems that arise from defective genes will require a new type of medicine based on a thorough understanding of how cells work and the development of new methods to manipulate what happens inside them.

Today's research is painting a picture of life that is much richer and more complex than anyone imagined just a few decades ago. Modern science has given us new insights into human nature that bring along a great many questions and many new responsibilities. Discoveries are being made at an amazing pace, but they usually concern tiny details of biochemistry or the functions of networks of molecules within cells that are hard to explain in headlines or short newspaper articles. So the communication gap between the worlds of research, schools, and the public is widening at the worst possible time. In the near future young people will be called on to make decisions—large political ones and very personal ones—about how science is practiced and how its findings are applied. Should there be limits on research into stem cells or other types of human cells? What kinds of diagnostic tests should be performed on embryos or children? How should information about a person's genes be used? How can privacy be protected in an age when everyone carries a readout of his or her personal genome on a memory card? These questions will be difficult to answer, and

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decisions should not be made without a good understanding of the issues.

I was largely unaware of this amazing scientific revolution until 12 years ago, when I was hired to create a public information office at one of the world's most renowned research laboratories. Since that time I have had the great privilege of working alongside some of today's greatest researchers, talking to them daily, writing about their work, and picking their brains about the world that today's science is creating. These books aim to share those experiences with the young people who will shape tomorrow's science and live in the world that it makes possible.

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# Acknowledgments

This book would not have been possible without the help of many people. First I want to thank the dozens of scientists with whom I have worked over the past 12 years, who have spent a great amount of time introducing me to the world of molecular biology. In particular I thank Volker Wiersdorff, Patricia Kahn, Eric Karsenti, Thomas Graf, Nadia Rosenthal, and Walter Birchmeier. My agent, Jodie Rhodes, was instrumental in planning and launching the project. Frank Darmstadt, executive editor at Facts On File, kept things on track and made great contributions to the quality of the text. Sincere thanks go as well to the Production and Art departments for their invaluable contributions. I am very grateful to Beth Oakes for locating the photographs for the entire set. Finally, I thank my family for all their support. That begins with my parents, Ed and Jo Hodge, who somehow figured out how to raise a young writer, and extends to my wife, Gabi, and children, Jesper, Sharon, and Lisa, who are still learning how to live with one.

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# Introduction

If each of us lived for tens of millions of years, the world would seem like a much different place. We would witness the birth and death of mountain ranges and the steady drift of continents; ice ages would pass like brief storms. New creatures would appear, undergo amazing transformations, and vanish again. Our short life spans offer only snapshots of these processes. But imagination and science give us the unique ability to take new perspectives. We can discover the height of a mountain without climbing it, using surveying instruments, a few basic facts, and the rules of geometry. We cannot go back in time, but experiments can be used to analyze the formation of geological layers and measure the age of the Earth. And we can take a similar approach to the study of life.

In the 19th century Charles Darwin, Alfred Russel Wallace, and their contemporaries were faced with a set of puzzles about life that had no scientific explanation. Why did the Earth hold so many species—thousands of types of beetles alone, many of which differed only in tiny details? Why did each continent have a unique set of animals, and what was the meaning of *fossils*? Why did the bones of a dolphin's fin look so similar to those in a human's hand? Why did different strata of rocks contain different fossils? Darwin and Wallace found answers by imagining what the Earth would look like over hundreds of millions of years.

Their solution, the theory of *evolution,* is based on three main principles—*heredity, variation,* and *natural selection*—that people have been aware of for a long time and can be observed anywhere, from exotic tropical rain forests to our own backyards. The huge breakthrough of Darwin and Wallace was to explain how these processes work together to produce new species. Evolution provided the first scientific system to investigate the origins and relationships of living creatures, and today it serves as

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a grand unifying theory that explains facts that cannot really be accounted for in any other way. The goal of this book is to demonstrate why the theory was necessary, to describe it as clearly as possible, to show how it has been received by society, and to explain the central role that it plays in today's science. Another theme of the book is the immense impact that evolution has had on society.

Most books on evolution focus on the *theory* itself, or the life and ideas of Charles Darwin, or the history of life on Earth. Few of them explain what evolutionary theory means in today's science, in fields such as modern medicine. Nearly all of the books that do are written for college students or specialists. There is a need for a book that shows how these aspects of the theory fit together, at a level that can be understood by high-school students and the general public. *Evolution* aims to fill that niche.

The first chapter sets the stage by describing how people understood the world in the early 19th century, showing some of the historical influences on the ideas of Darwin and Wallace, and explaining why a central theory was necessary to explain what scientists were discovering about life. Chapter 2 recounts how the personal experiences and observations of Darwin and Wallace led to their theories. The third chapter explains the theory itself and discusses its enormous impact on society. It was accepted quickly by most scientists, and it encouraged philosophers and industrialists to look at human culture in terms of evolution; some of them hoped to use it to change society. Most of these attempts failed because people misunderstood the theory, or used it as an excuse to promote political or racist agendas.

The birth of genetic science in the early 1900s and the discovery that genes were made of DNA in the 1950s opened a new era in evolutionary science. Chapter 4 describes how evolution and *genetics* began to flow together in the early 20th century, creating modern biology. Chapter 5 shows how the discovery of the double-helical structure of DNA instantly brought the science of evolution to the level of molecules and the chemistry of cells. The final chapter gives some examples of the crucial

role that evolutionary theory has played in research in the age of *genomes.*

Very little of what biologists do today would make sense if life had not evolved in the way Darwin and Wallace proposed. Within science, the major aspects of the theory are no longer seriously debated. And whereas most people throughout the world, major religions, and even the Pope have embraced evolution, it is still a topic that divides society, in the United States more than in most other countries. It is possible to heal this rift, but the process has to start with a very clear understanding of what evolution means and what it does not. Evolution is easy to misunderstand, and then it can easily be misused to promote political or other agendas. History shows that using science in this way can lead down a very dangerous road. By showing where the theory came from, how it developed, and how it is driving modern science, this book aims to help clarify some of these issues.

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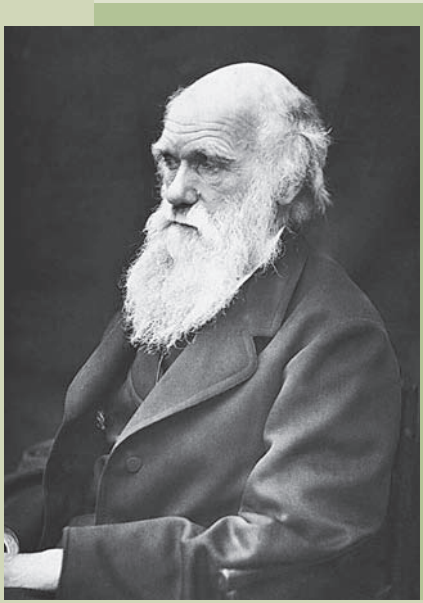
# 1

# A World without Evolution

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In the middle of the 19th century Charles Darwin (1809–89) and Alfred Russel Wallace (1823–1913), living on opposite sides of the globe, simultaneously proposed a completely new theory of life on Earth that contradicted what nearly everyone had believed until then. The theory answered a number of questions that had puzzled scientists for a long time. To understand evolution, it is helpful to understand what people believed before its discovery, and why previous views of life were neither adequate nor scientific.

Charles Darwin in 1869, 10 years after the publication of *On the Origin of Species (University of Brunel)*



For centuries the goal of most research in the Western world had been to support the biblical account of

the universe. The religious movement called *natural theology,* also known as *intelligent design,* studied the world and its *species* with the goal of proving the existence of God. Yet a completely new way of understanding the universe was developing, one based on careful observations, hypotheses, predictions, and experimental testing. The Bible did not offer a complete description of the world and there were intense debates about how it should be interpreted. Amateur scientists of the early 19th century believed that understanding the laws of nature might fill in some of the gaps. A theory of life was necessary for the same reasons that the Earth was no longer seen as the center of the universe and geologists had begun to suspect that the planet was very ancient. This chapter explains the origins of the idea of evolution and how it relates to the development of a scientific method of understanding the world.

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## CREATION, RELIGIONS, AND THE AGE OF THE EARTH

The world seems so mysterious and wonderful that people have always believed that gods created it. For the Australian aborigines, the world originated during an era called the "Dreamtime," when ancestral beings wandered the Earth and created humans out of bundled, shapeless bits of nature. A Scandinavian myth tells how animals and humans formed from the sweat of a sleeping god called Ymir.

Starting in about 700 B.C.E., the philosophers of ancient Greece began creating a new view of the world. They believed that laws that could be revealed through careful observation governed the universe. As well as proposing that the Earth was round and that substances were composed of tiny particles called atoms, they developed new ideas about the origins of life. After studying fossils, Anaximander (610–546 B.C.E.) claimed that all life arose from the sea, and that fishlike creatures moved onto land where they gave birth to humans and other animals. Greek science was still more descriptive and philosophical than experimental; it usually did not involve clear hypotheses that

could be tested in a systematic way. But these early thinkers valued careful observation over dogmas and the theology of the past, and their goal was to reveal the underlying principles or laws that governed the natural world.

Judeo-Christian beliefs about the origins of life are recounted in Genesis, the first book of the Bible, which tradition attributes to the prophet Moses. This story dominated attitudes about nature and culture in the Western world and deeply influenced how society received the ideas of Darwin and Wallace.

The Bible states that God created the universe over a six-day period, in several steps. On the second day God created the "firmament" (the Earth), and on the third day dry land appeared, along with grasses and plants. On the fourth day God made the Sun, Moon, and stars, and on the fifth "every living creature that moves," with the exception of human beings (created on the sixth day). After each act of creation, in the words of the King James Version of the Bible, "God saw that it was good." This has been interpreted to mean that everything in creation was perfect, with no hint that natural forces might alter them. So any new theory that proposed changes in species contradicted a long religious tradition.

Evidence of the "goodness" of God's works could be found everywhere. Plants and animals depended on each other and seemed well-designed for their environments: Animals were fast enough to catch their prey; eagles' eyes were sharp enough to spot mice from high in the air. When it became legal and morally acceptable to study anatomy in the late Renaissance, physicians discovered a world within the human body far more intricate than the most complex man-made machine, one that surely must have been designed by an intelligent creator. This was stated eloquently by Colin Maclaurin (1698–1746), one of Sir Isaac Newton's students and a strong promoter of the scientific method at the University of Edinburgh, Scotland: "The plain argument for the existence of the Deity. . . . is from the evident contrivance and fitness of things for one another, which we meet with throughout all parts of the universe. . . . No person, for example, that knows the principles of optics and the structure of the eye, can believe that it was formed without skill

in that science." The thinkers of the 18th century had no other explanation for how these things could have come about.

Passages in the Bible predicted that the world would last only 6,000 years, which was a powerful motivation for scholars to try to work out the exact date of creation—everyone wanted to be prepared for the end of the world. The early Christian scholars Julius Africanus (writing in 221 C.E.) and Bishop Eusebius of Caesaria (about 80 years later) based their calculations on biblical passages giving the ages of the first man and all of his descendents down to Moses. They arrived at a date of about 4,000 years before the birth of Christ. In 1650, the Calvinist Bishop James Ussher published a new set of calculations in a 2,000-page book called *Annals of the Old Testament, Deduced from the First Origins of the World.* He concluded that Creation began at nightfall before Sunday, October 23, 4004 B.C.E. Many other scholars followed his example and made chronologies based on the Bible. Even the great physicist Sir Isaac Newton (1643–1727), who had strong mystical beliefs in ancient prophecies, made a chronology that placed creation at about the same time.

Knowing the age of the planet was essential to the development of a science of life. A 6,000-year-old Earth gives very little time for change. When geologists such as James Hutton (1726–97) began to suspect that the Earth might be thousands or millions of times older than this, they opened the door to new ways of thinking about the origins of species. Like mountain ranges, they might have arisen through a gradual process, following laws that were still at work in the natural world.

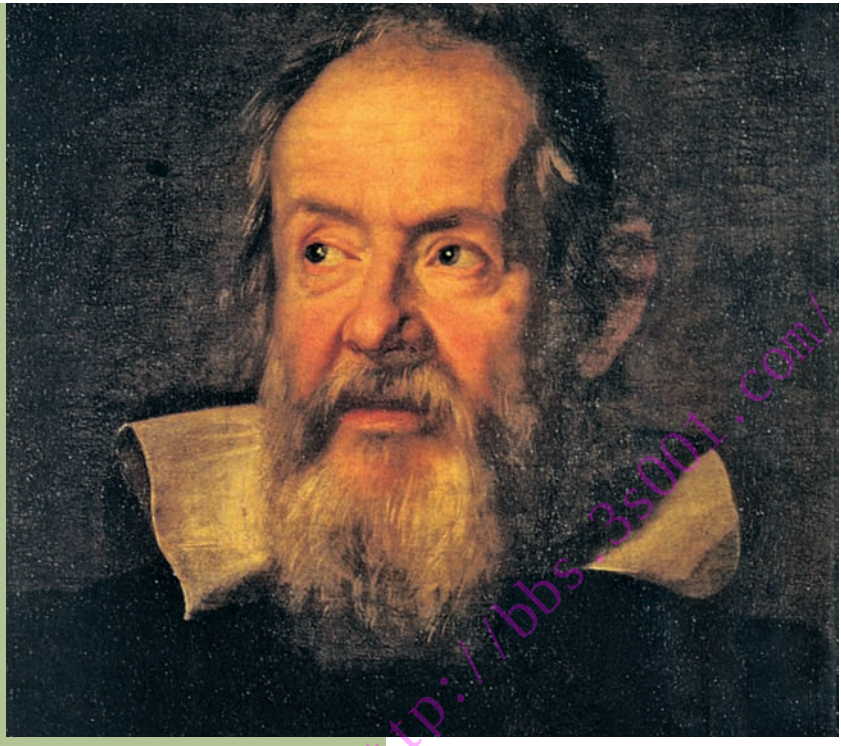
## ASTRONOMY AND PHYSICS POSE MAJOR CHALLENGES TO CHURCH DOCTRINES

The careful study of the sky began thousands of years ago as sailors learned to navigate using patterns of stars as reference points. Modern astronomy traces its roots back to about 1500, when the Polish scientist Nicolaus Copernicus (1473–1543) pro-

posed a radical new theory that the Earth and other planets of our solar system orbited the Sun. In doing so, he moved the Earth out of the center of creation, just as evolution would later take away humans' central status in the living world. Martin Luther said of Copernicus that "the fool wishes to reverse the entire science of astronomy! But as sacred Scripture tells us, Joshua commanded the Sun to stand still, and not the Earth!"

In itself a revolving Earth might not have been a serious issue for the church even though it contradicted Scripture. Keen observers of nature had already discovered natural phenomena that seemed to contradict the Bible—for example, the book of Leviticus claims that locusts and grasshoppers have four legs, although they are insects with six. In the Middle Ages, scholars rediscovered the writings of the Greek philosopher Aristotle (384–322 B.C.E.) which contradicted many doctrines of the church. But Aristotle's belief in a single powerful god could be useful, so Thomas Aquinas (1225–74) and other theologians managed to import many of his ideas into Christianity. They also left things out. Aristotle did not, for example, believe in creation—he thought that the universe had existed forever. He also believed that existing species could become new ones over time.

Several of Aristotle's ideas about astronomy became recognized as official Church doctrines. He claimed that nothing in the heavens farther away than the Moon could ever change, and that the stars were embedded in a set of 22 crystalline spheres that rotated above the Earth in complex patterns. He concluded that the Earth had a spherical shape, because different stars could be seen if one traveled to the north or south. But he also believed that it occupied the center of the universe. He explains his reasoning in the book *On the Heavens,* written in 350 B.C.E.: "Any body endowed with weight, of whatever size, moves towards the center. Clearly it will not stop when its edge touches the center. The greater quantity must prevail until the body's center occupies the center. . . . Now it makes no difference whether we apply this to a clod or common fragment of earth or to the Earth as a whole. . . . Therefore Earth in motion, whether in a mass or in fragments, necessarily continues to



Portrait of Galileo *(Justus Sustermans, 1597–1681)*

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move until it occupies the center equally every way, the less being forced to equalize itself by the greater owing to the forward drive of the impulse."

While the system of spheres seemed to account for the behavior of most of the night sky, it offered no explanation for comets or two supernovae (exploding stars) that suddenly appeared in the late 16th and early 17th centuries. Careful measurements showed that these strange objects lay far beyond the Moon. Another of Aristotle's doctrines stated that things could only orbit the Earth, not any other heavenly body—which would cause a problem when Galileo Galilei (1564–1642) plotted the orbits of Jupiter's moons.

As a professor at the university in Padua, Italy, Galileo taught that human observation and reason should be trusted over scriptures and ancient authorities when trying to answer

certain questions about the world. The approach disturbed not only leaders of the church, but also Galileo's fellow professors. Galileo complained about his colleagues in a letter to fellow astronomer Johannes Kepler: "What do you think of the foremost philosophers of this University? In spite of my oft-repeated efforts and invitations, they have refused, with the obstinacy of a glutted adder, to look at the planets or Moon or my telescope." Scholars and clerics had no interest in the telescope because they assumed that nothing in human experience could possibly contradict the Scriptures; if this seemed to happen, it merely proved that human senses and understanding were flawed, or that Satan was using reason to lead people astray. The same arguments are used today to ignore discoveries in biology.

Galileo did not intend to call God's existence into question; he did not believe that science could contradict faith, but rather that studying nature would increase people's appreciation of God's work. He strongly felt, however, that the Church should update its views of nature. His findings and experiments revealed "natural laws" that could be described through mathematics. He might have received a fair hearing but for a terrible political blunder; in his book *A Dialogue on the Two World Systems,* he ridiculed the Church's point of view rather than approaching it with respect. Although the Pope had been a good friend of Galileo when the two men were younger, Urban VIII could not tolerate a direct insult, and the astronomer was sentenced to house arrest.

Newton followed up Galileo's work with mathematical descriptions of the laws of mechanics. His explanation of gravity has been called the discovery of the first "natural law." Newton's work established a method for the investigation of the world that forms the basis of all modern sciences. Observations should yield hypotheses; these can be used to make predictions that can be tested in experiments by anyone. If the results do not uphold a theory, it must be discarded. Other scientists would apply this method to geology and finally to the origins of life. Like Galileo, Newton saw no contradiction between science and religion as he laid the groundwork for modern science. He was a deeply religious man who strongly believed in

God and creation. In fact, most of his writings are devoted to alchemy, mysticism, and religion.

One of Newton's principles states that in a vacuum, an object set in motion continues to travel in a straight line forever, unless disturbed by another force. This is vital to understanding gravity's effect on the planets, and it influenced how people thought about God's relationship to the world. The creator did not have to constantly intervene to make sure that the universe functioned: Instead, he might have put into place the initial state of the world and laws to keep it running.

The Frenchman René Descartes (1596–1650) also made major contributions to the development of the scientific method. Descartes was willing to call everything into question, building a logical system of philosophy that supported the evidence of the senses over authority. He pondered what the world would be like if the smallest parts of our bodies (meaning something like atoms) behaved according to Newton's laws: If the positions and velocities of all the particles in the universe at any given point in time were known, as well as the forces acting on them, one might be able to predict everything in the future. Yet this did not mean that humans were simply machines; the soul and the body were separate things, he claimed, and an eternal soul could not arise from simpler components. It could only have been created by something more perfect than itself, and Descartes believed this proved that an eternal, all-powerful deity had to exist.

## GEOLOGISTS POSTULATE AN ANCIENT EARTH

Mountains and landscapes seem permanent until a monstrous wave carries away a coastline, a volcano spouts fire, or cities are buried under thick layers of ash and stone. One of Plato's dialogues describes how the fabled city of Atlantis sank beneath the sea. Such terrible events imprint themselves into the memory of a culture, spawning superstitions and legends. In the 18th century, Newton's scientific method inspired a new generation

of scientists to observe the world beneath their feet as closely as astronomers had scanned the skies.

It is probably no great surprise that the University of Edinburgh, in Scotland, became a center for geology. Edinburgh sits on the rim of an ancient volcano, so evidence of the powers that formed the Earth were as close as a glance out the classroom window. Colin Maclaurin, a young student of Newton's, obtained an influential teaching position there thanks to Newton's recommendation. In his classes he strongly advocated the scientific method of careful observations, theory building, and experimentation. Students were encouraged to try the method on everything: stars, chemistry, farming, and the Earth itself. Edinburgh became one of the most progressive universities of its day, with excellent faculties of medicine and science. Charles Darwin first attended the university there, and his older brother, his father, and his grandfather Erasmus, one of the most radical and brilliant thinkers of his day, all got their degrees there.

James Hutton enrolled at the university and was immediately initiated into the scientific method of Newton and Maclaurin. He wrote: "We must not allow ourselves ever to reason without proper data, or to fabricate a system of apparent wisdom in the folly of a hypothetical delusion." Hutton became a brilliant agriculturalist who developed methods that improved British farming while cultivating a passionate hobby, investigating the makeup of the Earth. His interest in chemistry and minerals were a great help as he studied the composition of rocks and thought about how the planet had formed.

The Earth's outer crust contains many thin layers of rock, or strata, stacked on top of each other. They can be seen along any stretch of highway where rock has been blasted away. Strata come in a particular order and tell a story, like the pages of a book lying facedown on a table: The deepest layers are the oldest, laid down the earliest, and higher layers represent successively more recent eras. This idea was first proposed by Niels Stensen (1638–86), a Danish physician and world traveler. Working in Florence for the Medici family, the patrons of Galileo a few decades earlier, Stensen (also called Nicolaus Steno)

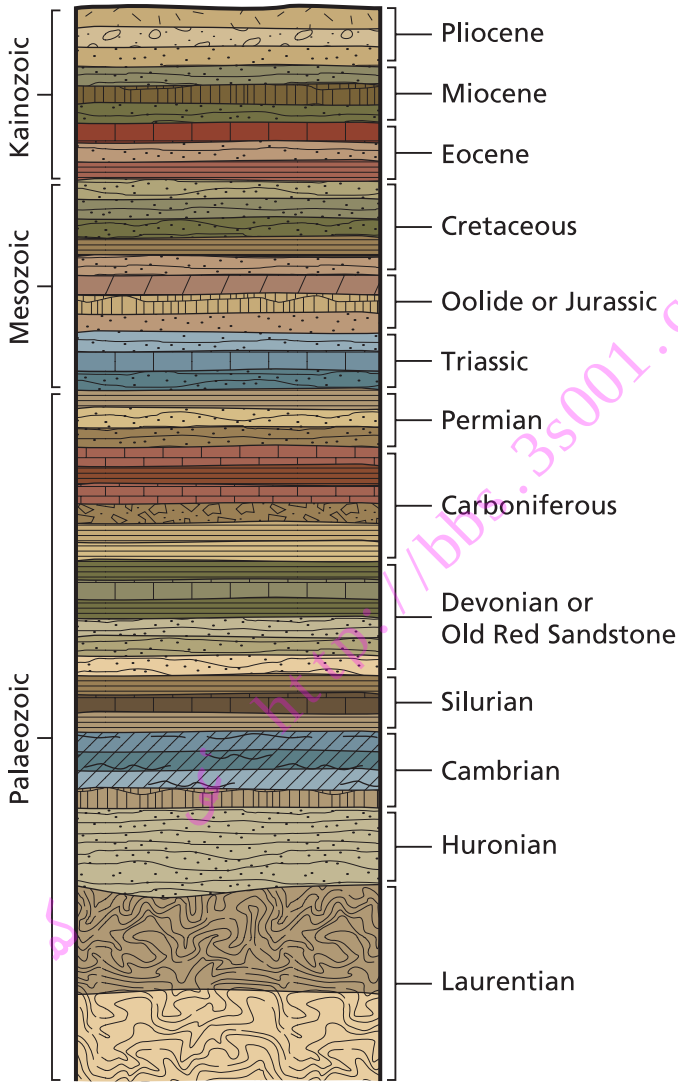
classified rocks into several types based on the processes that created them. His masterpiece, *De solido intra solidum naturalizer contento dissertationis prodromus,* or *Prodromus* for short, written in 1669, introduced new principles of geology, such as the idea that strata were originally lain down flat. The fact that some now aimed upward or appeared broken was due to later movements of the Earth. This had implications for time because it implied that different parts of a single stratum, even if spread over a large area, formed at the same time. Stensen concluded that strange triangular objects found in some of the strata were fossilized sharks' teeth. This led him to propose that strata contained a record of different eras of life.

A hundred years later, when James Hutton enrolled at the University of Edinburgh, Stensen's ideas were still not commonly accepted. If the world had sprung whole from the mind of a Creator in an instant, there was no pressing need to examine the Earth's crust for signs that it had been formed by a dynamic process. Except for a few notable events, such as volcanic eruptions, earthquakes, and the great flood of the Bible, scientists assumed that the world had always been close to the way they knew it now.

Hutton carefully studied the strata and the types of rocks he encountered while on walking tours through much of Scotland and England; the patterns he found made him begin to think seriously about time. Strata could be used as a great clock. Knowing how long it took each layer to form would provide a scientific means of dating the Earth.

Most rocks were sedimentary; erosion brought loose material into lakes or oceans, where it filtered to the bottom and hardened over time through heat or pressure. This usually happened to large, flat layers, which explained why Hutton found the same strata spread out over a large region, in the same

*(opposite page)* By the mid-19th century geologists had worked out the major geological periods in the history of the Earth and assembled diagrams like this one showing strata in their historical order. Each layer contained a unique set of fossils, which helped biologists understand how the types and forms of life had changed over immense stretches of geological time.




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order. Yet a layer found on the surface in one place might be found far up on the side of a cliff in another, demonstrating that the Earth's crust had undergone numerous major upheavals. To

capture the whole story, it would be necessary to assemble a complete and logical record of the order of strata in Britain.

This immense project was undertaken by the British surveyor William Smith (1769–1839) and a group of assistants. Smith made enormous, wall-sized maps of Great Britain that he colored in painstakingly by hand, giving each type of rock its own color. As he carried out this work, Smith came across the same phenomenon that Stensen had seen—each layer contained its own unique collection of fossils. This meant that fossils could be used to identify and compare strata where only a few layers were exposed, or in ambiguous cases. It also raised a huge question: Why did each layer contain different fossils? The answer lay in the connection between geological and biological time. Life on Earth had undergone major changes.

A great problem now facing geology was the question of how rocks lying at the bottom of the sea had made their way hundreds or even thousands of feet into the air. Intent on fitting the new findings to the Bible, German scientist Abraham Werner (1749–1817) proposed that strata and different types of rocks were created as the waters receded after the biblical flood. This was the accepted explanation in Edinburgh and elsewhere, but Hutton knew that erosion alone could not explain everything he was observing. Throughout England and Scotland he had seen evidence of incredible forces that seemed to have been generated from below, forcing strata upwards, bending and cracking them. If the level of the sea had simply dropped, he argued, all the strata seen in mountains and cliffs would still run parallel to the ground.

Granite was a key to resolving the debate. Veins of this stone could be seen running through sedimentary rocks. Werner claimed that granite veins were created by fluids seeping downward and then mineralizing. During field trips throughout Scotland, Hutton became convinced that granite started off as an intensely hot liquid that then burst upward in veinlike patterns.

Hutton now had a set of ideas that could be used to begin linking strata to time. Sediments formed slowly, so immense stretches of time must have been required to create them. Hut-



Hutton's unconformity. This rock formation in Scotland provided evidence for Hutton's hypotheses about the age of the Earth and the processes by which different types of rocks had arisen. *(Farnham Geological Society)*

ton had to let go of the chronologies of Ussher and others, relying instead on observations and logic. The Earth, he realized, must be at least many millions of years old, and it had experienced cycle upon cycle of sedimentation and upheaval.

While many scientists agreed with his analyses of how rocks formed, and the idea that volcanic activity and underground heat could thrust huge masses of rock upward, the idea that this had happened over many repeating cycles contradicted the biblical account of history. Genesis spoke of one flood, not hundreds or thousands. Hutton needed better evidence to support his claims. During an excursion to a windswept region of the Scottish coast, he discovered a set of strata that seemed to tell the whole story. Several layers had formed on top of each other, had then been thrust upward by heat and pressure from below, and were finally covered by new layers.

Hutton published his ideas in 1795 in a huge, three-volume work called *An Investigation of the Principles of Knowledge and of the Progress of Reason.* His ideas might have had more impact, but the book had 2,139 pages and even his well-meaning colleagues found it hard to read. Mathematics professor John Playfair (1748–1819), who accompanied Hutton on some of his excursions, wrote: "The great size of the book, and the obscurity which may justly be objected to many parts of it, have probably prevented it from being received as it deserves." Playfair helped ensure Hutton's place in history by summarizing the geologist's ideas in a book of his own, called *Illustrations of the Huttonian Theory of the Earth,* published in 1802. One of the readers would be a young Scottish geologist of the next generation, Charles Lyell (1797–1875).

## THE "NEW GEOLOGY": LYELL AND DARWIN

In the early 19th century, Hutton's hypothesis that the surface of the Earth had been reshaped by natural forces over long periods of time—possibly including the biblical flood—had spread among the scientific community. But *creationists* still had the upper hand on most of the field of geology. Lyell, who would later become one of Charles Darwin's closest friends and a strong supporter of evolution, would change that. He became convinced of Hutton's theories through careful studies of volcanoes in Scotland and France, excursions that gave him even more radical ideas.

Lyell proposed that a volcanic event could simultaneously raise masses of land and depress surrounding areas, perhaps as much as hundreds of feet. He found evidence of such events in Italy. Such upheavals could significantly alter a coastline, quickly making freshwater lakes of areas that had been ocean and vice versa. That, in turn, would explain why fossils of freshwater and ocean creatures could be found in alternating strata. Lyell presented his ideas on the formation of the Earth's surface in a series of books entitled *Principles of Geology,* published in the 1830s. Robert FitzRoy (1805–65), captain of the *Beagle,* gave

Charles Darwin the first volume as a present when the young naturalist joined the ship's crew. The second volume was published as the *Beagle* was en route and Darwin had it shipped to himself in South America. By that time Lyell was thinking even more widely, even speculating about how species might change over time.

His ideas had a strong influence on Darwin, even though the young man had been warned about Lyell by his geology professor. Christ's College in Cambridge, where Darwin enrolled after leaving Edinburgh, was still in the grip of traditionalists who wanted science to serve religion. Darwin took geology courses under professor Adam Sedgwick (1785–1873), who took him on field trips through Great Britain. Once Darwin found a fossil shell in a fairly recent layer of gravel—where it should not have been, according to Smith's rules of the connections between fossils and strata. He rushed it to Sedgwick, who was not impressed. The shell had gotten there by accident. "Nothing before had ever made me thoroughly realize, though I had read various scientific books, that science consists in grouping facts so that general laws or conclusions may be drawn from them," Darwin wrote. It was precisely what he would do in formulating the theory of evolution, many years later.

Sedgwick gave him an assignment: a 70-mile (112-km) walking tour in which he was to report on the arrangement of a particular stratum of rock in the northern part of Wales. Darwin returned with evidence that overturned a common hypothesis about the formation of that particular layer. The excitement of discovering new facts and fitting them into theory was a turning point in his life, again pushing Darwin toward geology. Later, when he was one of the first modern Europeans to witness an earthquake and tsunami firsthand, he had the necessary background to understand their importance for geological science.

## THE PROBLEM OF FOSSILS

The 18th century and its great expeditions across the globe brought along a fever of collecting in England—the rich prided



Shrimp fossil from the Cretaceous period *(Mila Zinkova)*

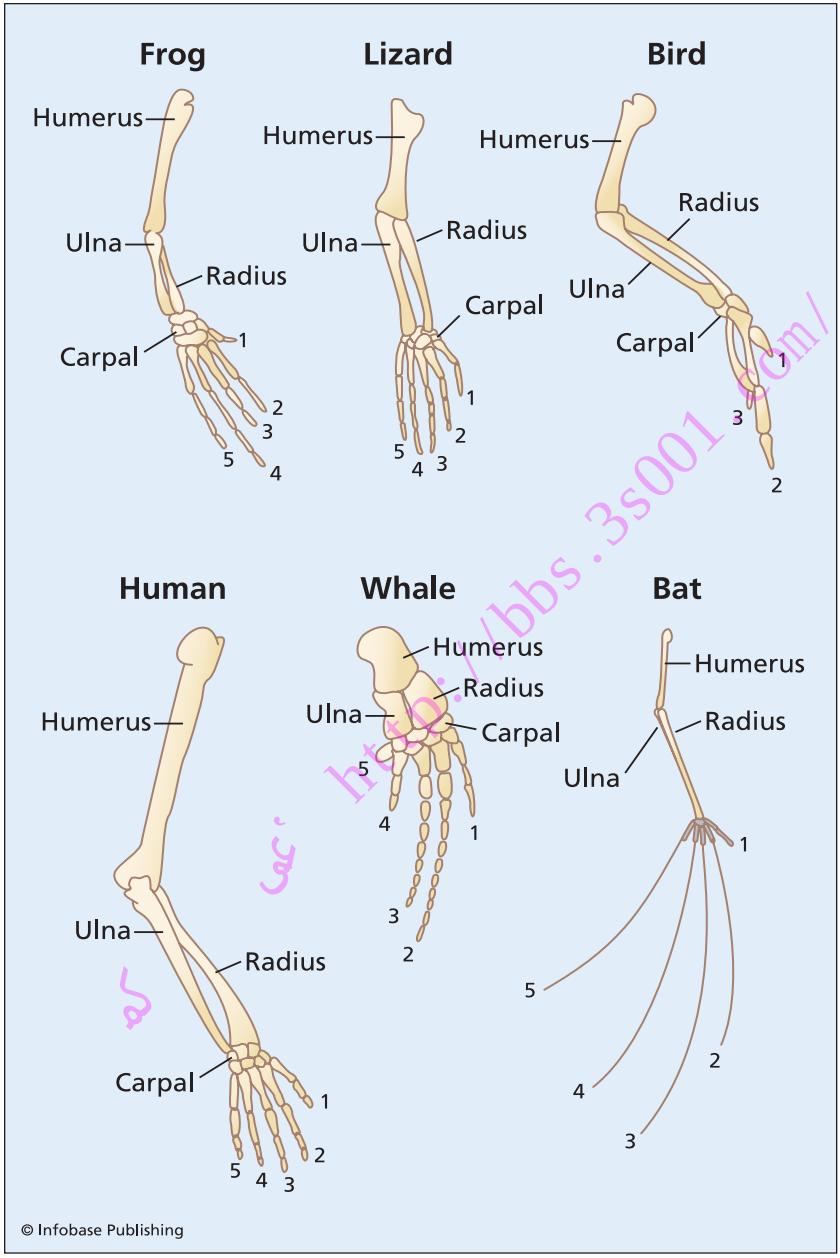
themselves on gathering exotic birds, butterflies, plants, and perhaps most mysterious of all, fossils. Curiosity-seekers and scientists learned to identify the strata where fossils were likely to be found, collected them, and sold them to collectors. Part of the attraction lay in the fact that no one knew what they were. They clearly resembled strange plants and animals that had somehow turned to stone—but how could that happen?

The Frenchman Georges Cuvier (1769–1832) had a brilliant insight into the nature of fossils by noticing the strong connection between an animal's diet and its anatomy. The bodies of living carnivores were entirely designed to capture and devour animal prey, he wrote, and this gave them a structure entirely different than that of plant-eating animals. Fossil animals should obey the same principles, so Cuvier began an intensive study of

the new finds. He became an expert of looking at single teeth or fragments of bones and drawing conclusions about their origins. He also discounted stories of mythical beasts, such as mermaids, by showing that they violated this principle of integrity. In 1817 he published a major book called *The Animal Kingdom,* in which he stated, "Every organized individual forms an entire system of its own, all the parts of which mutually correspond, and concur to produce a certain definite purpose."

Cuvier's ideas and his encyclopedic knowledge of anatomy throughout the animal kingdom won him wide international recognition. Yet he was focusing on just one part of a much larger picture, and this brought him into conflict with colleagues such as Jean-Baptiste Lamarck (1744–1829) and Étienne Geoffroy Saint-Hilaire (1772–1844). Geoffroy had helped Cuvier obtain a position at the National Museum of Natural History in Paris; the two became friends and wrote articles together. But over time Geoffroy had become interested in a different aspect of animal anatomy: the similarities between species. He discovered, for example, that fish have a structure similar to the wishbone of birds—why? Its functions in the bird—to support the stresses of flying—were unnecessary in fish. Geoffroy found an explanation: "It is known that nature works constantly with the same materials. She is ingenious to vary only the forms. . . . One sees her tend always to cause the same elements to reappear, in the same number, in the same circumstances, and with the same connections."

This principle led Geoffroy to some amazing insights, such as the fact that the bones that allowed fish to breathe were highly similar to the inner ear of mammals. Modern scientists recognize this as a fundamental component of how evolution works; nature builds on what is already there, and the great diversity of life stems from a much smaller number of structures that have been adapted in different organisms. Geoffroy took this much farther, proposing that all animals are built on a single mold, made different because the various parts have been stretched or rearranged. So far he was only talking about the *vertebrates*—animals with spines—but he was about to make a much bolder move and claim that the same principles held for




*invertebrates* such as mollusks and insects. They were so different, he understood, because insects lived "within their bones," whereas vertebrae lived "outside of them." It took the develop-

*(opposite page)* Careful anatomical studies of living animals and fossils at the beginning of the 19th century revealed unexpected homologies—parallel structures in different organisms that are usually arranged in the same way and perform similar functions. Before the theory of evolution there was no scientific way to understand such parallels. These diagrams reveal homologies between the limbs of tetrapods ranging from humans to bats to whales.

ment of molecular biology in the 20th century to prove that Geoffroy was right. This sounds like evolution, but Geoffroy had not understood that the forms represented a historical process—the ancient family relationships between animals. He was grouping facts but did not have a general principle by which to understand them.

Cuvier felt that Geoffroy Saint-Hilaire was going too far in drawing parallels between vertebrates and invertebrates. If animals had similar body plans, he felt, it was only because their bodies functioned in similar ways. The two men held a public debate on the issue. Most of those who attended believed that Cuvier won. But the debate was skirting the real issue. In a way both men were right and both were wrong, but there was no way to unify their positions without a theory of evolution.

Cuvier was equally interested in geology. In the regions around Paris he discovered traces of numerous cycles of rising and receding oceans, signs of ancient catastrophes that had occurred over very long periods of time. Marine fossils were sandwiched between layers containing the remains of land plants and animals, including monstrous creatures that no longer seemed to exist anywhere. This was obviously troubling to religious thinkers, who came up with ingenious theories: Fossils might somehow form themselves out of structures in the soil, the way that trees grow from seeds. Most scientists still believed in *spontaneous generation,* the idea that simple organisms such as worms or flies could arise by themselves out of rotting meat and other food. Until Pasteur disproved the idea, it did not seem so strange that animallike forms should somehow crystallize, all by themselves.

Reverend William Buckland (1784–1856), an avid fossil collector in Oxford and the first person to publish a scientific

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description of a dinosaur, waged a lifetime campaign to prove that the fossils in strata confirmed the order in which animals were created in the Bible; fish and lizards were created before mammals, for example. He believed that the creation story could be saved if biblical days were reinterpreted as much longer "creative epochs." When he became the first professor of geology at Oxford he gave a speech subtitled, "The Connexion between Religion and Geology Explained." It was a reaction against an increasing appreciation of the ideas of Hutton and Lyell about geological time and was well-received by conservative colleagues.

But Buckland could not explain alternating phases of sea- and ocean-living creatures, and no one knew what to make of monstrous dinosaurs. When he became director of Britain's largest museum, the Ashmolean, he invited Georges Cuvier to have a look at the fossils in the collection. Cuvier stated that at least one of the dinosaur specimens came from a land-living lizard that ate plants and was more than 40 feet long. Buckland could not fit this into his religious view of the world and waited many years to annouce the discovery of the first land-based dinosaur.

Buckland's situation was typical of most researchers of his time; many excellent scientists were desperately trying to reconcile new discoveries in their fields with the Bible's description of creation. But the tide was turning. Most serious geologists and paleontologists were moving away from a strict interpretation of the Bible, and the idea that animals could become extinct suggested that new types might also be born. Now that the Earth was thought to be very old, the stage was set for supposing that species might change over immense periods of time.

## JEAN-BAPTISTE LAMARCK AND THE TRANSMUTATION OF SPECIES

Georges Cuvier's older colleague Jean-Baptiste-Pierre-Antoine de Monet, chevalier de Lamarck (1744–1829) is a curious figure of history who is remembered best for being wrong; his name

## Erasmus Darwin and the "Living Filament"

Erasmus Darwin (1731–1802)—physician, inventor, poet, philosopher, writer, and grandfather of Charles—was an eccentric and brilliant doctor who studied the animal world and thought deeply about life. In the second half of the 18th century he started to ponder fossils, coming to the conclusion that living species had descended from simpler forms of life. Part of his inspiration came from the work of Georges-Louis Leclerc, comte de Buffon (1707–88).

Buffon had fled France to escape arrest after an impetuous love affair and a duel. In England he discovered Newton's methods of doing science and began thinking about life in a new way. When he finally returned to France, he established a research center and began working on a 44-volume encyclopedia called *Natural History* that would be published between 1749 and 1778 and cause a scandal. Not only did he promote the idea of an ancient Earth, but he also proposed that species had changed over time. The Catholic Church condemned him, calling him an atheist and burning his books.

While Cuvier had emphasized the features of animals that fit them to their lifestyles, Buffon focused on strange features that did not seem to have any logic at all. Animals were far from perfect, he wrote, citing many examples of poor design. Pigs, for example, had toes that did not touch the ground. This made no sense unless they had been inherited from earlier forms of animals in which the toes functioned. All mammals had similar limbs, in fact; could they have had a common ancestor? The Church was enraged by his work, but Buffon was not about to suffer the fate of Galileo; he wrote in a slippery style and built

*(continues)*





*(continued)*

in an "escape clause." Facts and observations might seem to lead to logical conclusions, he wrote, but only a person who had never read the Bible would believe them. Everyone else, of course, would understand the truth.

The debate between Cuvier and Buffon raised two issues that would have to be solved by any scientific theory of life: first, each type of animal shares features with many other species, and second, that each is adapted to its own environment. Erasmus Darwin tried to expand on Buffon's ideas. At the end of the 18th century he published a major book called the *Zoonomia* in which he wrote the following:

> In the great length of time since the Earth began to exist, perhaps millions of ages before the commencement of the history of mankind, would it be too bold to imagine that all warm-blooded animals have arisen from one living filament, which THE GREAT FIRST CAUSE [sic] endowed with animality, with the power of acquiring new parts, attended with new propensities, directed by irritations, sensations, volitions and associations; and thus possessing the faculty of continuing to improve by its own inherent activity, and of delivering down those improvements by generation to its posterity, world without end!

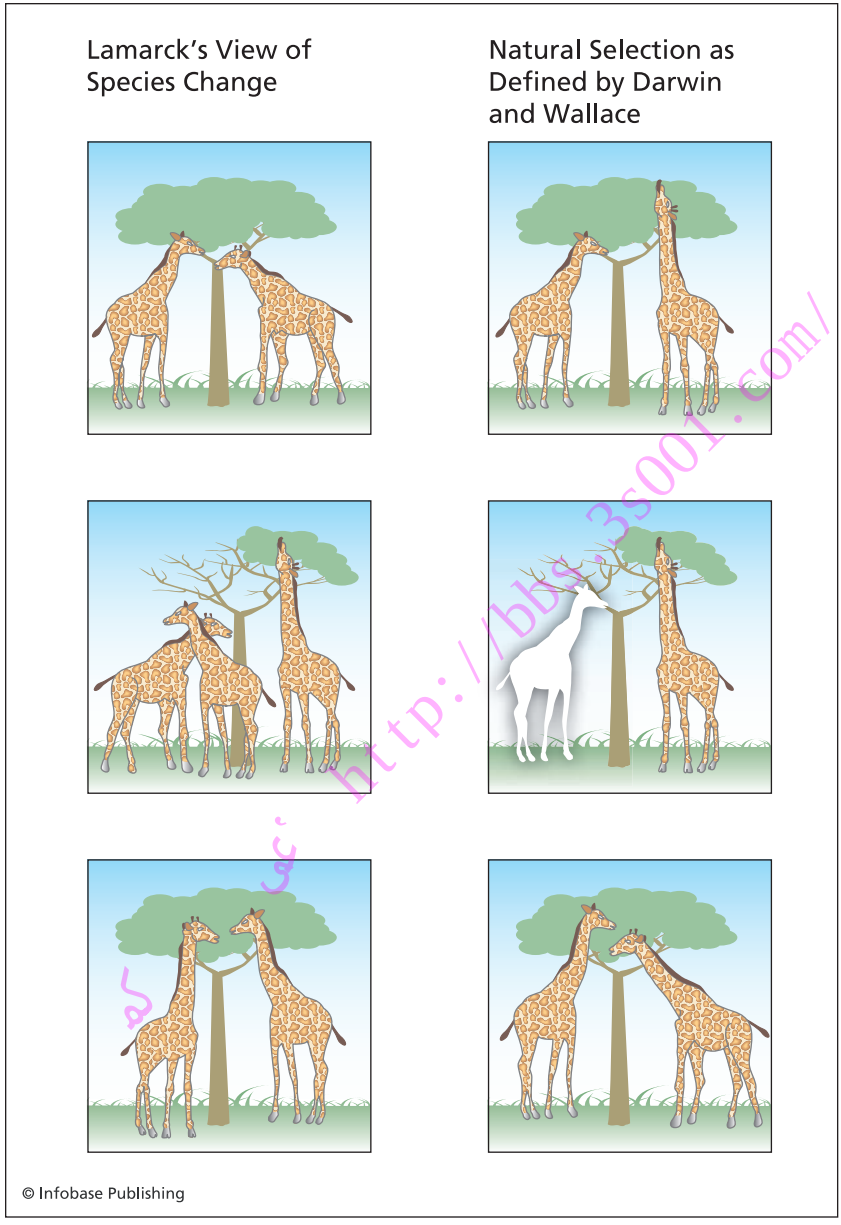
The beginning of the text sounds like an evolutionist's account of the descent of life from an ancient, very simple "filament." But the end of the passage shows that Erasmus Darwin, like other thinkers of his time, fundamentally misunderstood heredity. Many found Erasmus's philosophy attractive, but he could not back it up with facts, and besides, in the wake of the French Revolution, the society of Great Britain was wary of radical new ideas.

usually appears as a footnote to the story of Charles Darwin and evolution. Lamarck made the famous claim that giraffes got their long necks by stretching for the most luscious leaves, high in the treetops. He believed that each generation passed its slightly elongated neck to the next, finally achieving the towering height of today's animals. Lamarck's assumptions were wrong, but his theory that species could transform themselves was extremely influential.

Lamarck was influenced by the ideas of Buffon, whom he knew, and drew on Cuvier's ideas that species' bodies had functions connected to their environments and lifestyles. He also knew of Erasmus Darwin's work, and was influenced by the *"Great Chain of Being,"* a philosophy stretching back to the ancient Greek philosopher Aristotle. This system claimed that life formed a ladder from very primitive to extremely advanced organisms, with every species trying to move upward and improve itself. Higher and lower rungs represented greater and lesser levels of perfection. Man, with his ability to reason, held the top position, just below the gods. As organisms strived to move upward, they acquired new forms and behavior. Lamarck believed that they could somehow pass these characteristics along to their young. In doing so, he made two mistakes: He saw evolution as a process of improvement, and he believed that lifetime experiences and learning somehow entered an organism's hereditary information.

One might think that Cuvier and Lamarck, working in the same museum, might have found a way to unite their discoveries into a single, more powerful system. Instead, they became bitter rivals. Cuvier regarded Lamarck's ideas as ridiculous; animals' organs were obviously already "in tune" with each other and could not—or should not—change through use. There was no evidence, he claimed, that transformations of species had ever happened. (If he had talked to farmers and animal breeders, he might have thought differently.)

Lamarck's ideas addressed serious questions about the relationships between species while offering a way to keep humans at the pinnacle of creation, a step below God. It was a type of wishful thinking that was appealing to both progressive social




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thinkers and those who wished to justify slavery. One could interpret it to mean that different human races occupied different rungs on the ladder of perfection, where higher forms ought to

(opposite page) Differences between Lamarck's and Darwin's ideas of species change. Left: According to Lamarck, animals' needs and desires could change their behavior, which could produce inheritable changes in their bodies. Giraffes, for example, would need to stretch to reach high leaves when they had eaten all the low ones, causing their necks (and those of their offspring) to become longer. Right: Darwin's natural selection works differently. A population of giraffes will naturally have a few animals with longer necks. If only they can get food, they will survive to pass along genes for long necks to their offspring. Giraffes that are not tall enough die out. The entire species may become extinct if the population does not have much variety, and none of the animals can obtain food.

have dominion over lower ones. Darwin's theory would overturn this idea, but even today, some people misunderstand evolution by thinking it means that species improve themselves, for example by supposing that intelligence "had to evolve." This probably reflects a long history of confusion between Lamarck's ideas and those of Charles Darwin.

A simple experiment could have disproved Lamarck's concept of the inheritance of acquired traits, and several decades later, the German biologist August Weismann (1834–1914) performed it. He cut off the tails of mice for generation after generation. No matter how long he did so, none of his animals gave birth to a litter of mice lacking tails. The experiment has been repeated by many other scientists and has always led to the same conclusion.

## NATURAL THEOLOGY AND "INTELLIGENT DESIGN"

At the beginning of the 19th century, most theologians and scientists still hoped that new discoveries could be reconciled with religion and the Bible, but it was becoming harder. A theologian named William Paley (1743–1805) hoped to bring science back on the right track, laying the groundwork for a religious movement that is known today as "intelligent design." *Natural Theology, or Evidences of the Existence and Attributes of the Deity*

*Collected from the Appearances of Nature,* the title of Paley's 1802 book, sums up its thesis: The aim of science, in Paley's mind, should be to prove the existence of God. Since God created the universe, whatever scientists discovered should strengthen the case for His existence. If science presented what appeared to be contradictions, it would be because science or human understanding had not yet progressed far enough to completely decipher God's design. Paley's book begins with the following famous watchmaker analogy:

> Suppose I had found a watch upon the ground, and it should be enquired how the watch happened to be in that place. . . . When we come to inspect the watch, we perceive . . . that its several parts are framed and put together for a purpose, e.g. that they are so formed and adjusted as to produce motion, and that motion so regulated as to point out the hour of the day . . . the inference, we think, is inevitable; that the watch must have had a maker; that there must have existed . . . an artificer or artificers who formed it for the purposes, which we find it actually to answer; who comprehended its construction, and designed its use.

The same thing, Paley wrote, held true for everything in the natural world. Pain existed so that people would take care of their bodies, and so that they would feel good when it stopped. Even night, he claimed, had been designed to an exact length—to fit humans' need for a certain amount of sleep!

Paley was in his way a very scientifically minded man, and his book contains careful observations of how things in nature fit each other, which he interpreted as evidence for the existence of God. Yet as attractive as Paley's arguments were to some, he had a great number of critics. There was no guarantee (except for his personal belief in God) that scientific discoveries would not one day contradict scriptures. And in a way, natural theology was planting the seeds of its own demise. It encouraged men of religion to pursue science; some of them eventually discovered things that undermined their faith.



Proponents of the religious philosophy "intelligent design" have used the pocketwatch as an analogy for living creatures for several hundred years. *(Empire Jewelers)*

The argument for intelligent design reminded some of the character Doctor Pangloss in Voltaire's novel *Candide.* Pangloss preaches that "this is the best of all possible worlds," and uses twisted logic to cope with anything that does not seem perfect. His pupil Candide, forced out of a comfortable home and into the harsh world, does everything he can to hold on to this notion, but finally he has to admit that things might not be so perfect after all. Something similar happened when scientists scrutinized nature. The design of human teeth, for example, left much to be desired—especially in an age before anesthetics and modern dentistry. To be fair, Paley was not necessarily claiming

that everything was good, or even that it was perfect—but that it was designed. That required a Designer.

Intelligent design also ran up against a straightforward, well-known fact: people already knew that extremely complex structures such as the eye could arise "by themselves" from much simpler origins. This happens in every embryo, which grows from a single cell. To get around this problem, Paley had to turn the watch in his analogy into a miraculous instrument which could somehow build and reproduce itself. It would have to contain an entire inner world of "lathes, files and other tools." The fact that such a watch had never existed did not matter, Paley wrote; at some point, there had to have been a powerful master Creator to make it, just as Descartes claimed that the eternal soul could only have stemmed from a more perfect being.

Natural theology is important because it shows how serious the conflict between religion and science was becoming. Science of the early 19th century was an easy target for Paley and his followers, because new hypotheses were still based on attractive ideas rather than facts. As long as there was no real scientific alternative to the Bible's account of the origins of life, natural theology could still hold its own. Its adherents hoped to turn the clock back and steer science away from Newton's methods, but they were reasonable enough to keep their eyes open and appreciate scientific discoveries.

The approach might have seemed scientific at the time, but it is completely different from how science is practiced today. Paley started from the premise of a God responsible for creating the universe, and in his mind, nothing would ever demolish this hypothesis. It made science into something like a baseball game whose outcome is decided before the first inning; the purpose of playing is to ensure that the right team wins. If things start to go wrong, umpires have to step in and change the rules. Today's scientists are not at liberty to bend facts any way they like; it is always possible for theories or hypotheses to be demolished by the results of experiments. That has happened over and over again, even regarding hypotheses within the field of evolution.

*Natural Theology* was so influential that it remained on the required readings list at many universities, even into the 20th century. It is a great irony that the man who would deal the strongest blow against Paley's life's work attended the same college where Paley's ideas ruled for so many years. It is an even greater irony that when Charles Darwin moved into the college in 1828, he was given the same rooms that William Paley had lived in a few decades before.

## LINNAEUS AND THE CLASSIFICATION OF LIFE

The 18th century has been called the "Age of Classifiers" because so many people were consumed with a passion for categorizing things, particularly living creatures. In every mound of horse dung and under the bark of every tree, new species of beetles might be found, and searching for them became a sport. Half the joy was the search; the rest was classifying and naming the new creature.

The preeminent classifier of the Enlightenment period was the eccentric Swede Carolus Linnaeus (1707–78), a professor and pastor. Linnaeus created one of the first exacting methods for classifying plant species. Whereas previous classification systems focused on flowers and leaves, Linnaeus zoomed in on the reproductive organs of plants (reflecting a personal preoccupation with the relationship between the sexes). Given the important role that sex plays in evolution, this turned out to be a good decision.

Linnaeus's system classifies species into groups based on the number of male organs—the *stamens;* the number of female *pistils* is used to describe subgroups. Linnaeus extended plant metaphors to thinking about people and societies, even describing his relationship with his wife in botanic terms. Such double entendres remained a style in the science of botany for decades afterward, even though Linneaus was criticized for turning botany into a mixture of science and romantic poetry.

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Linnaeus believed that species changed, not in the sense that new ones could arise, but that plants could become better attuned to their environments by drifting away from their original perfection. The Garden of Eden, he claimed, was a place of great harmony between all of its inhabitants. As plants, animals, and humans scattered across the globe, they somehow lost this harmony. It might be possible to bring it back, and Linnaeus tried to do this in experiments conducted in Sweden rather than Babylon. He proposed that his experiments could make the country into a new Eden—self-reliant, independent of foreign wares and trade—arguments which helped him win a great deal of money from the Swedish government.

He conducted thousands of experiments on plants sent back by collectors who had been dispersed across the globe, creating the beginning of a worldwide scientific network. Many of the specimens (and some of their collectors) died during the arduous voyages to Sweden; other plants perished because they had been brought to the wrong climate. Species, it turned out, were not as adaptable as Linnaeus thought—at least not with the methods he applied.

Linnaeus had a huge influence on biology. He inspired generations of young naturalists to collect specimens and attempt to classify the entire living world. People began to study the features of organisms carefully and scientifically, mapping them into a great system of life. At the time, they did not realize that by comparing and grouping things, they were also drawing a map of the family relationships between plants and animals. Linnaeus had a great influence on Darwin's grandfather Erasmus, an ardent "Linnaean" who wrote poems comparing the reproductive behavior of plants to a Tahitian marriage ceremony.

Another English naturalist of Erasmus's generation, Joseph Banks (1743–1820), was likewise a devoted follower of Linnaeus who discovered a great number of new plant and animal species while traveling with the explorer James Cook. On a scandalous trip to Tahiti, Banks had amorous adventures with the native women that made the headlines back home. Even so, upon returning to Great Britain, Banks was able to use his po-

litical connections to become appointed President of the Royal Society, England's most prestigious scientific group. He held on to that position for four decades and used it to increase government support for science. At the same time he developed an almost dictatorial control over opinions and theories. Banks's influence was felt for many years after his death—even into the early 1830s, as a ship called the *Beagle* was outfitted for a round-the-world voyage to further England's military, political, and scientific aims. Largely because of Banks's work, even military expeditions usually included a naturalist. Charles Darwin would be one of them.

## THOMAS MALTHUS AND THE THREAT OF OVERPOPULATION

To judge from the number of eggs that animals lay, it is a wonder that the Earth is not knee-deep in sea slugs, or smothered in mile-high anthills. Most species, including humans, produce far more offspring than are necessary to maintain a stable population. This was common knowledge in biology, but until the beginning of the 19th century, there was no theory to explain the forces that kept species in check. Thomas Malthus (1766–1834) changed that when he considered human population growth in *An Essay on Population,* written in 1798.

Born with a cleft lip and palate, Malthus led a sheltered childhood and was schooled at home by friends of his father, a wealthy scholar who knew some of France's most prominent philosophers and scientists. As an adult, Malthus first took a job as a country curate and was then offered a position as professor of history and political economy at Jesus College in Cambridge, England, in 1793. Like the natural sciences, the social sciences of Malthus's era were dominated by religious ideas: The ultimate goal of economics and politics should be to create a perfect, moral society.

In Malthus's day society was moving in a direction that seemed simultaneously promising and threatening. The industrial revolution was sweeping Europe. Technology and

industry ought to help bring people close to perfection, it was believed, but their effects on society were not all positive; there was a growing gap between the rich and the poor. Malthus was deeply aware of rising poverty and hoped that his studies of society would lead to a solution. Instead, what he learned gave him a pessimistic view of man's future. Human population, he observed, would always grow much faster than the production of food and other necessary resources. People reproduced in a "geometrical" pattern; every person who is born can have many more children. The food supply, on the other hand, grew in an "arithmetical" way, limited by realities such as the availability of land and labor and the productivity of plants. At some point, populations would outgrow their ability to feed themselves, and the consequence would inevitably be poverty, famine, wars, and disease. In a world without birth control, there was no obvious way to limit the birthrate except through "self-discipline," and Malthus did not hold out much hope of humans acquiring that. Even now in an age of convenient birth control, humanity has not curbed its growing population. Many modern thinkers echo Malthus's concerns. The huge public reaction to *The Population Bomb,* written by Paul Ehrlich in 1968, resembled how people responded to Malthus's essay.

Malthus's observations had a significant impact on politicians. Previously, an increasing population had been thought of only as a way to acquire more wealth, just as people might have more children so that they will be supported in their old age. Great Britain had passed "poverty laws" to attempt to adjust the standard of living between rich and poor, but some of the measures were actually encouraging poor families to have many more children. This was increasing the problem.

Malthus's essay was read several decades later by the young Charles Darwin and Alfred Wallace. One of their greatest accomplishments was to understand that the forces that keep human populations in check worked throughout nature and that their ultimate effect is to create new species. Both men said that Malthus's work provided an essential piece in solving the puzzle of the origin of new species.

The development of the scientific method and the thinkers of the 18th and early 19th centuries set the stage for evolution. Astronomers and physicists had discovered that the matter of the universe was governed by invisible forces that could be expressed as laws. Geologists claimed that the Earth and life were very old, and scientists had begun to hypothesize that species could change. What remained was to discover the hidden laws that, over huge periods of time, governed life—and possibly had created it in the first place.

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# 2

# Building the Foundations: The Voyages of Darwin and Wallace

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From the 16th century onward, English ships traveled to the far reaches of the globe on expeditions of discovery and colonization. Each expansion increased the wealth of the British Empire through trade and the exploitation of natural resources. The expeditions helped advance British science by bringing back exotic new plants, animals, and fossils for study. At the beginning of the 19th century, scientists often accompanied naval voyages in hopes of finding plants that could be sources of new foods and textiles or other valuable resources. Robert FitzRoy, captain of the British navy ship *Beagle,* wrote the following in his journal of an expedition to South America:

> There may be metal in many of the Fuegian mountains, and I much regret that no person in the vessel was skilled in mineralogy, or at all acquainted with geology. It is a pity that so good an opportunity of ascertaining the nature of the rocks and earths of these regions should have been almost lost. . . .

The next time he sailed, he took along a young geologist named Charles Darwin.

The fascination with nature also offered opportunities to young men like Alfred Wallace, willing to travel the globe in search of plants and animals for wealthy collectors and museums. Such voyages were full of danger and hardships. Wallace suffered from recurrent fevers; Darwin nearly died of dehydration, freezing, drowning, and disease. Throughout most of his life he suffered from a strange illness that may have been caused by a tropical parasite. Darwin's friend Joseph Hooker, who traipsed through the Himalayas for years on plant-seeking expeditions, was thrown into jail after crossing the border into Tibet in search of new species of rhododendrons.

These voyages were essential to developing the theory of evolution, partly because they were opportunities to observe species in habitats that had not yet been significantly altered by human activity. A great mystery surrounded the way plants and animals were spread across the globe; it was hard to understand why God had not simply put the same species everywhere. Explorations also provided the chance to observe humans in other types of relationships with nature, which might answer questions about the history and development of society. People were curious about the connection between technology and culture and whether certain forms of government were better than others. Would a perfect society come through advances in science, or should people try to return to a "state of nature" like the Garden of Eden? Conquerors and travelers found very few examples of these romantic ideals of paradise. At the same time, their own behavior made it hard to believe that technological progress would lead to a more moral society.

## THE VOYAGE OF THE *BEAGLE*

The *Beagle* was built in about 1820 and was one of several ships sent to South America during the late 1820s on surveying missions. The navy needed accurate maps of coastlines and harbors to protect British ports abroad and to navigate into new areas



HMS *Beagle* at Tierra del Fuego (Conrad Martens) from *The Illustrated Origin of Species* by Charles Darwin, abridged and illustrated by Richard Leakey *(Wikipedia)*

for trade. This was a huge task that would take years to accomplish. Lieutenant Robert FitzRoy was responsible for much of the mapping activity on the *Beagle.*

Two events during the *Beagle*'s original mission had a huge impact on her next voyage. The *Beagle*'s first captain, Pringle Stokes, committed suicide. A captain's job was hard and mostly administrative, a far cry from the image of a romantic figure standing on a windswept prow, charging into battle. He spent most of his time filling out paperwork and meting out punishments. To maintain authority he had to remain aloof from the crew, meaning years of loneliness. After the suicide, FitzRoy was given command of the ship.

The second incident involved the theft of a boat by natives of the Tierra del Fuego, the land at the southernmost tip of South America. While trying to recover the boat, FitzRoy and his men took two captives that they pressed into service as translators. FitzRoy decided to take the prisoners and two more Fuegians to England, where they could be educated. He promised to bring them home on the next surveying trip. He had in

mind a social experiment to see if "savages" could be civilized. If so, what they learned might help improve their society when they returned home. Once the ship returned to Great Britain, it looked as if FitzRoy would be unable to keep his promise, because plans for a follow-up voyage had been cancelled. In the end, an influential relative pulled strings with the Admiralty, and the survey was on the agenda again.

FitzRoy was a precise and scientific man and had the *Beagle* outfitted with the best possible equipment. He brought on board 22 elaborate timepieces, essential to making accurate maps and charts because they were the only method to measure the ship's longitude. The instrumentation was considered extravagant, so FitzRoy had to pay for much of it out of his own pocket. He even hoped to substitute the ship's iron cannons for brass guns, which would not interfere with the compasses, but his superiors would not agree. In the end, he bought the guns himself, smuggled them onto the ship, and threw the iron cannons overboard.

He also engaged extra personnel, including a technician to take care of the clocks and an artist to capture images of the voyage. Finally, he began looking for a scientist—preferably an educated person with whom he could have dinner. Members of FitzRoy's own family had been affected by madness and suicide, and he was concerned for his own mental health. An intelligent companion of his own social class on board might help him avoid the loneliness and fate of the *Beagle*'s former captain.

Darwin was only 22 years old when he received the invitation to accompany the *Beagle*'s surveying expedition, chiefly as a geologist. No one suspected that he was about to embark on one of the greatest adventures of scientific history. In many ways, he was an unlikely candidate to be offered the position and to achieve what he did. So far his studies had not been very successful; enrolled in medicine in Edinburgh, he found the normal courses tedious and dropped out. The invitation to join the *Beagle* expedition came in the middle of his studies of theology in Cambridge, where he was not doing much better.

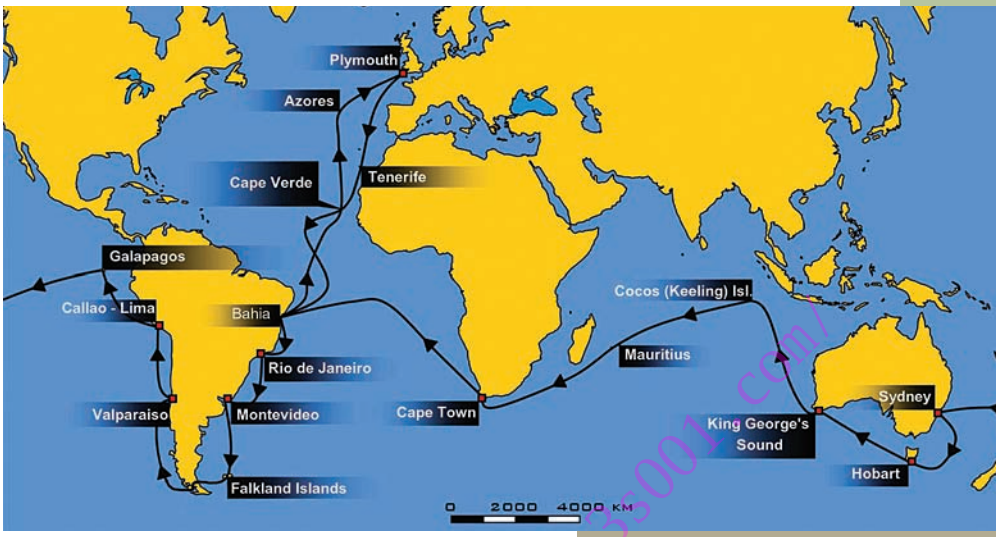
His father, Robert, was a wealthy doctor and financier who had been paying for his son's studies at the university in hopes

that Charles would finish a degree and settle into the comfortable life of a country pastor. It was a life that appealed to Charles, who was religious enough and knew that a pastor's duties could be easily combined with an interest in geology and nature. Robert hesitated to allow his son to go on the voyage, fearing he would never finish his studies. Charles wanted to go, although he admitted that he did not have the best qualifications to become a world-roving naturalist.

Yet some qualities made him exactly the right person at the right time. He had absorbed a lot of science while at Edinburgh through extracurricular activities. His time at the microscope and on geological excursions revealed a talent at research, self-discipline, and a seriousness that had been lacking in his studies. And he understood that science involved looking beyond appearances to understand the principles that lay underneath. Professors and friends strongly urged him to go on the voyage. Their combined support changed his father's mind, and the path was cleared for Darwin to change history.

Five years later, Darwin returned home far more mature, with a remarkable set of notes and specimens that would give him a solid footing for a career in science. The book that he published about his travels in 1839, *The Voyage of the Beagle,* is an abstract of much more detailed journals that he kept, recording observations and impressions of geological formations and life. At the same time the book is an adventure story with tales of wild horseback rides across plains and mountains, battles between colonial Spanish forces and natives in South America, and narrow escapes as Darwin nearly froze on mountaintops or died of thirst.

The book became an immediate best seller and is still required reading at universities throughout the world, though not directly because of evolution, which Darwin had not yet figured out at the time of publication. Instead, *The Voyage of the Beagle* is poised at a crucial turning point of science; its value lies in the snapshot it gives of how scientists understood the world just before evolution changed everything. To read it is like rereading a favorite mystery story and understanding all the clues long before the detective does. Darwin grasped much of what he




The route taken by the HMS *Beagle* from 1831–1836 *(Wikipedia)*

saw, and he had a good sense for key pieces of evidence, but he did not yet know how to assemble the elements into a complete scientific theory. His ideas were still dominated by the influence of natural theology and the cataloging spirit of Linnaeus. Yet a few years later at home, sorting through his collections, he would have answers to many of the questions that he posed on board.

Darwin's first encounter with the *Beagle*'s captain went reasonably well. FitzRoy was only 26, but he had a commanding, all-knowing presence that fit well with his absolute rule of the ship. There were only a few nagging issues. The navy man held to a common theory of the time that said personality could be predicted by the shape of a person's nose and the bumps on his skull. "He doubted whether anyone with my nose could possess sufficient energy and determination for the voyage," Darwin wrote in his autobiography. "But I think he was afterwards well-satisfied that my nose had spoken falsely." For his part, Darwin was shocked at the tiny size of the cabin he would inhabit. He would have to sleep in a hammock above his working table, which put him barely two feet from the ceiling. Then during a three-day practice run aboard ship, he was violently

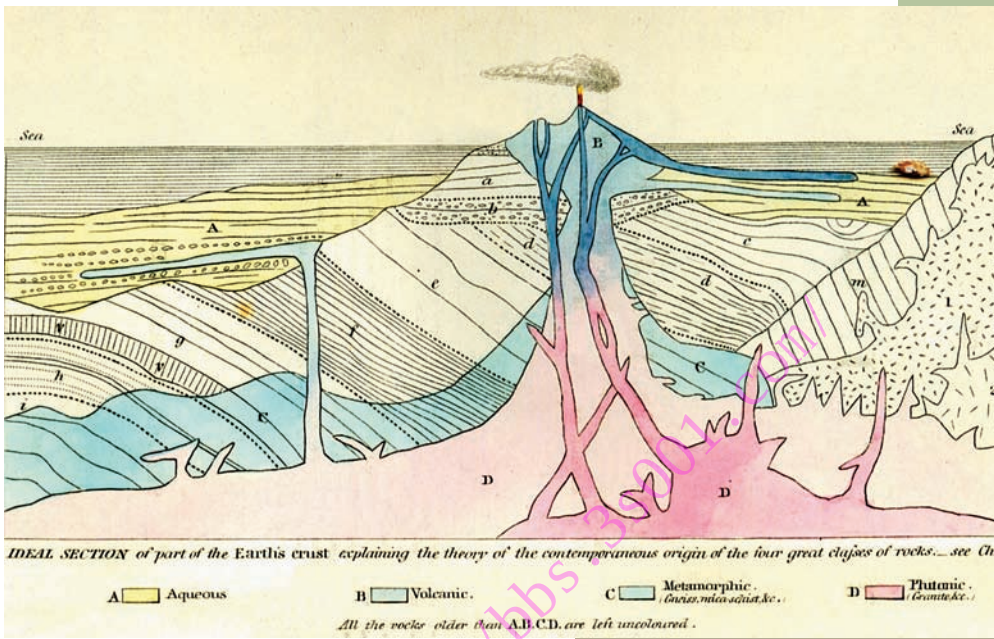
seasick. But nothing would make him turn back now. He was equally thrilled and terrified when, after numerous delays, the *Beagle* set sail on December 27, 1831.

FitzRoy and Darwin managed to get along well for five strenuous years, which contributed a great deal to Darwin's success. It was not always easy; Fitzroy could fly into a rage one day on an issue such as slavery (which Darwin opposed but the captain originally supported) and apologize the next. Darwin learned to make himself scarce when necessary, and for his part, FitzRoy often went out of his way to put Darwin ashore in interesting places. The two men grew fond of each other and after the voyage exchanged friendly letters—FitzRoy called Darwin "philos," for "philosopher," and teased him with details of his wedding plans; Darwin told stories of the wild welcoming parties on his arrival home.

## GEOLOGICAL DISCOVERIES, FOSSILS, AND EXTINCTIONS

During his five years on the *Beagle,* Darwin investigated everything: geological formations, the physical characteristics of plants and animals, the origins of coral, the social behavior of insects and other creatures, the backs of turtles, and the cultural clashes of South American natives and Europeans. One of the *Beagle*'s first stops was the island of St. Jago, 300 miles (480 km) off the coast of Africa. While strolling the beach, Darwin discovered a white layer of sediment about 30 feet (9 m) above the waterline. It was full of fossil oyster shells nearly identical to their present-day relatives, strewn along the beach below. He wondered about the age of the stratum and why it lay so high above the sea line. There were only two possibilities: The level of the ocean had dropped, or a force had pushed the land upward.

With this first landfall he had stepped into the middle of one of the major controversies of his time. Sedgwick, Darwin's geology professor in Cambridge, supported a *"catastrophe theory"* of geology that tried to align modern findings with the bibli-




The frontispiece from Charles Lyell's *Principles of Geology* (second American edition, 1857), showing the origins of different rock types *(Public domain)*

cal account of creation. It accepted that the Earth had been through major upheavals, but this had happened in a distant past, the days of creation and the great flood, a special time when unusual forces were at work. Sedgwick had warned Darwin away from the opposing camp, *"gradualism,"* promoted by Charles Lyell in the first volume of his *Principles of Geology*. Lyell maintained that the Earth behaved according to laws which had operated over vast stretches of time and that the forces at work in the present were basically the same that operated in the distant past. This was a simple extension of Newton's "rules of reasoning" for science. Researchers often have to make assumptions about things outside their direct experience. In such cases, a scientist should assume that things he cannot observe behave as the things he can observe do. Without clear evidence, one should not suppose that there has been a change in the laws of nature, that miracles happen, or that distant objects behave differently than those close at hand. Gradualism was an application of these

principles to geology, and evolution would apply them to the living world.

What Darwin saw on St. Jago supported Lyell's theories. The similarity of fossil oysters and the live creatures on the beach meant that the white layer was relatively recent. The layer was higher in some places and lower in others, but there were no signs of major cataclysmic events. Later Darwin was lying on the floor of a forest in Chile when he felt a massive earthquake, one which rocked the entire coast. The *Beagle* was in the harbor and quickly set sail for the major city of Concepción, 200 miles (360 km) to the north, to find the town and its cathedral in ruins. A massive tsunami had struck the coastline, killing thousands, tossing huge stones onto the shore, lifting great blocks of earth. All of these effects were obviously related, and Darwin tracked their source to volcanic activity off the coast. Comparing the new landscape to the old proved that the Earth could still experience cataclysmic forces; they were merely slumbering and could return at any time.

Almost immediately after the *Beagle*'s first stop in South America, Darwin began finding amazing fossils which raised a number of questions. Each continent contained a mixture of unique and shared species, but in some geological periods, certain animals did not appear at all. Other layers held bizarre forms of life that no human had ever seen and had never been mentioned in the Bible. One dinosaur discovered by Darwin would have been longer than the ship itself and had to be left behind.

Sometimes what he found in layers of rock bore almost no relation to present-day animals; other fossils were recognizable but strange. He sent home the bones of a rodent the size of a rhinoceros, anteaters as big as horses, and enormous cats. "It is impossible to reflect on the changed state of the American continent without the deepest astonishment," he wrote. "Formerly it must have swarmed with great monsters: now we find mere pygmies."

There was no clear reason why species should have disappeared. The Americas could obviously support vast numbers of animals. In just a few centuries, horses brought by the Spanish had produced hundreds of thousands of descendants. Darwin

suspected that extinctions might have something to do with the environment. Although he was not yet ready to follow these ideas to their logical conclusions, he was thinking along the right lines, raising issues like the tendency of species to produce too many offspring. "Every animal in a state of nature regularly breeds," Darwin wrote, "yet in a species long established, any *great* increase in numbers is obviously impossible, and must be checked by some means." Discovering the means was the crucial missing step to arriving at the theory of evolution. A crucial moment arrived much later in the voyage when he had the chance to observe a place that had remained almost completely undisturbed by humans—the Galápagos Islands.

## LIFE IN SPACE AND TIME

Through his observations of fossils and geology, Darwin realized that the animal populations of most regions changed significantly over time. He did not yet know that species themselves changed. Like many others, he regarded his grandfather's and Lamarck's ideas as interesting but unscientific. Many years later, in the preface to the first edition of *On the Origin of Species,* Darwin praised Lamarck for being one of the first modern scientists to suspect "that species, including man, are descended from other species. He first 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." On the other hand, Lamarck made serious mistakes: "He likewise believed in a law of progressive development; and as all the forms of life thus tend to progress, in order to account for the existence at the present day of simple productions, he maintains that such forms are now spontaneously generated." In other words, Lamarck made the mistake of believing that species changed by improving themselves. *Bacteria* and very simple organisms still existed because nature produced new ones from scratch.

Darwin was more influenced by the thinking of Lyell, whose books spoke of the relationship between species and

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their environments but had not proposed anything like evolution. Lyell strongly disagreed with Lamarck's views that one species could somehow transform itself into another or improve itself. The fossil record was incomplete and did not prove that life had become more complex over time, or that new species appeared. Lyell did believe that species could undergo a certain amount of adaptation to the places in which they lived. If they failed to do so, he pointed out, they might die off.

Everywhere the *Beagle* sailed, Darwin witnessed how completely species were dependent on each other and their environments. In the Straits of Magellan he pulled up strands of kelp—seaweed—which grew hundreds of feet from the ocean floor to the surface. An incredible number of species depended on this plant. In the roots alone he found small fish, shells, cuttlefish, crabs, sea eggs, starfish, and dozens of other species. Other parts of the plant hosted mollusks, crustaceans, and other animals. From region to region of the ocean the species changed, but kelp played an equally important role everywhere. Darwin described it as a "great aquatic forest." He wrote, "Amidst the leaves of this plant numerous species of fish live, which nowhere else could find food or shelter; with their destruction the many cormorants and other fishing birds, the otters, seals, and porpoises, would soon perish also." Even human populations might be affected.

On land, species were just as dependent on each other. But they were oddly distributed around the globe, and Darwin could think of no reason why a Creator would have given England a species of snail that plagued gardeners by feasting on their salads, while a nearly identical strain in South America had no taste for salad at all. Lyell suggested that each species had been created in a single place, and then spread as far as it could until running up against some natural boundary. The idea of natural barriers would also become important in evolution.

As the *Beagle* sailed up the western coast of South America, along the long western shore of Chile with its impressive chain of mountains, Darwin was about to discover signs of the deep underlying logic he had been looking for. Intent on finding more

evidence of the geological forces that had raised the mountains, he climbed into the Andes, ascending the western slope and coming down on the other side. The species on the east slope were quite different than those on the west. But they were remarkably similar to plants and animals he had seen much farther to the east, on the central plains of the continent.

Darwin suddenly realized that the high Andes formed a nearly total barrier between two zones of life. The western side was a small strip cramped between the mountains and the oceans; the eastern slope descended into plains that went on for thousands of miles. Absolute distances did not matter as much as barriers. Species could not cross the Andes, so they did not mix with each other. Those on the east had lots of room to spread. Simple geography, Darwin realized, could dictate which species inhabited a region. From the creationist point of view, there was no reason why this should be so. Everything could have lived everywhere.

Such thoughts occupied him intensely as the *Beagle* sailed onward toward the small group of islands called the Galápagos, a volcanic cluster of rocks several hundred miles off the west coast of South America. Other than a few traders and a small prison colony, the islands had never had any human habitants. Ships had been using them as a stopover point to take on water and huge tortoises that could feed dozens of men and could be kept alive for months in a ship's lower deck. Some of the islands were little more than craggy bits of volcanic rock; others sported lush tropical vegetation. But the unusual location between the cold currents of the south and the warmer waters of the north made the Galápagos home to a rich variety of other forms of life, from penguins and seals to flamingoes and tropical birds. Monstrous lizards and tortoises lived side by side.

Darwin was fascinated by several species of ugly iguanas with bizarre habits. Most of them were vegetarian. They lived on land but some dove into the sea for food. Darwin wondered if they swam between islands, some of which were separated by distances of 50 miles (80 km). He threw one iguana into the water over and over again, curious to see how comfortable it



Galápagos iguanas *(Wikipedia)*

was in the ocean (they generally disliked the water, diving in only when they had to eat). To find out about their diets, he brought animals on board the ship for dissections. This smelled so horrible that his shipmates forced him to move his operating room onto land.

The Galápagos were full of species of birds, lizards, and turtles so similar to each other that without careful study it was hard to tell them apart. The only difference between some of the 13 species of finches, for example, was the size and shapes of their beaks. Darwin regarded these things as simply odd until Nicholas Lawson, an Englishman watching over a small Ecuadorian prison colony, claimed that each of the Galápagos Islands had a unique collection of species with its own peculiar characteristics. Lawson could tell where any tortoise had come from based on the form of its shell—on one island tortoises had saddle-shaped shells, on another they were rounder and blacker. The evidence could be found in Lawson's own garden, where he used shells as flowerpots. This chance

remark would lead to a dramatic change in Darwin's thinking and it saved his collections; he had already begun to mix up specimens from several locations. It had never occurred to him that islands only about 50 or 60 miles (from 80 to 96 km) apart, within sight of each other, with similar climates and made of exactly the same types of rocks, might hold different inhabitants.

Darwin frantically began sorting out his collections and looking at the islands in a completely new way. The rest of his days on the Galápagos became a race to discover whether the pattern for the tortoises was also true for finches, iguanas, other animals, and plants. Later, he made charts and lists of species found in each location. Why did James Island have 38 species of plants found only in the Galápagos, and why did 33 of these species only exist on James Island? Why would each island contain so many wholly original species, even though it was so similar in climate and geology to the other islands? There had to be an extremely active "creative force" at work, he wrote, but he had no idea what it might be.

The Galápagos archipelago has been called "evolution's laboratory" because its special geographical situation simplified the problem of the development of new species to just a few variables. Similar processes were at work in the South American rain forests, but there the ecosphere was far too complex to grasp. The Galápagos were far from the mainland, so they were rarely influenced by the arrival of new species from the outside. At the same time, they were just far enough from each other to isolate some of their populations, which is a key factor in evolution.

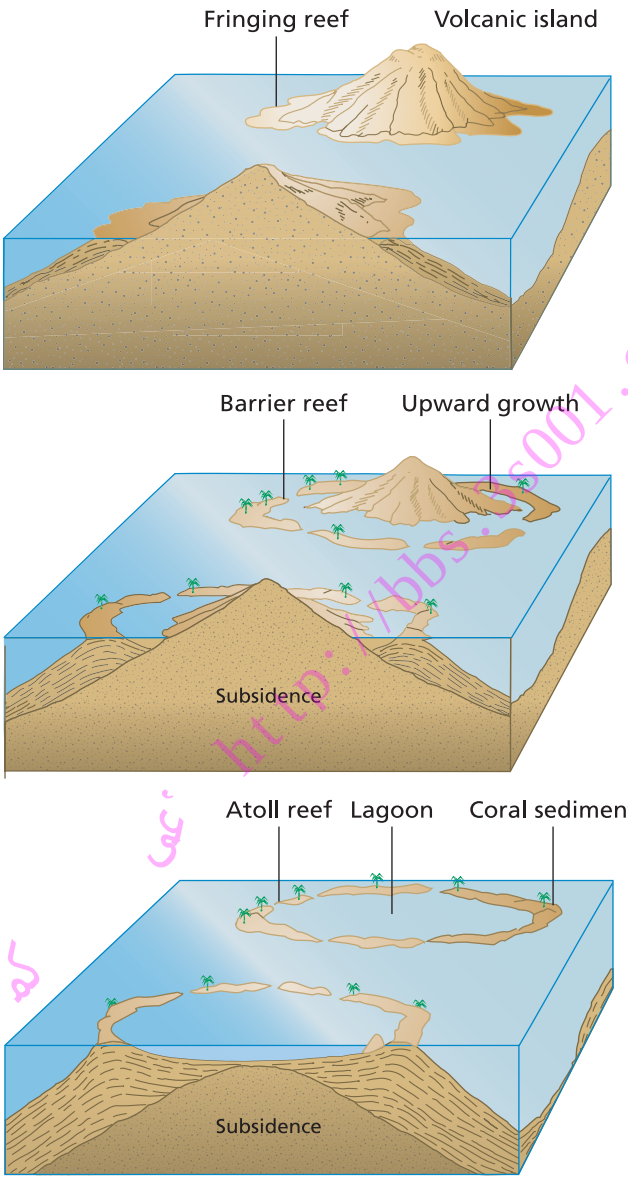
When the *Beagle* finally left the islands, its voyage had been under way for over four years. Darwin was becoming overwhelmed, but the pace of work did not let up. He would have the rest of his life to think; now it was necessary to collect as many facts and specimens as possible. He did not want to fall into the same trap as his grandfather, or Lamarck—building a beautiful theory that stood on philosophy, rather than facts. (His contemporaries later estimated that he possessed a hundred times as many facts as Lamarck had.)

His book on the *Beagle*'s voyage abandons the huge questions raised by the Galápagos very abruptly—practically in midsentence. But a seed had been planted in his mind: What was true in the Galápagos held for South America. A mountain range or a stretch of water could form a barrier to the spread of life. Very fine differences between species like finches—sometimes amounting to only a single feature—might be the rule rather than the exception. Darwin did not yet see the connection between small differences within a species and small differences between species, but he had begun to accept that organisms could become transformed and that the environment played an important role in this process.

Though he was eager to return to England, there were more stops to make—Australia, Tahiti, and the Cocos Islands. Darwin carefully observed reefs of coral so deep and massive that the ship could not locate the bottom on which they stood. Lyell had proposed that coral—huge colonies composed of billions of tiny creatures—stood on the rims of ancient volcanoes. Before ever seeing a reef, Darwin developed a different theory about their formation. The living parts of coral colonies always lay at a shallow depth in the ocean. As the land dropped or the ocean level rose, new animals built upward toward the surface, on the stony remains of their ancestors. If the opposite happened and the land rose, the height of the colony fell and they built outward. Thus a reef preserved a record of its own history: geological events and life combined to create living islands, ecospheres just as complex as kelp forests. Tiny organisms linked themselves in huge colonies to create vast, mountainlike islands that became habitats for thousands of other species. Everything was interdependent.

The voyage of the *Beagle* ended in 1836, and Darwin returned home. A huge amount of work faced him and a group of

*(opposite page)* Darwin was the first to understand that coral reefs are "living islands" built by organisms in response to changes in the environment. Most corals live in shallow waters, at depths less than 200 feet (60 m). When water rises (or the land sinks), coral grow upward; if the water level remains constant or sinks, the reef grows outward.




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experts that he had carefully selected to help; he had to preserve, catalog, and study thousands of specimens he had been sending home throughout the voyage. The ordeals of scrambling up

mountains to collect species were over, and an entirely new type of ordeal was about to begin.

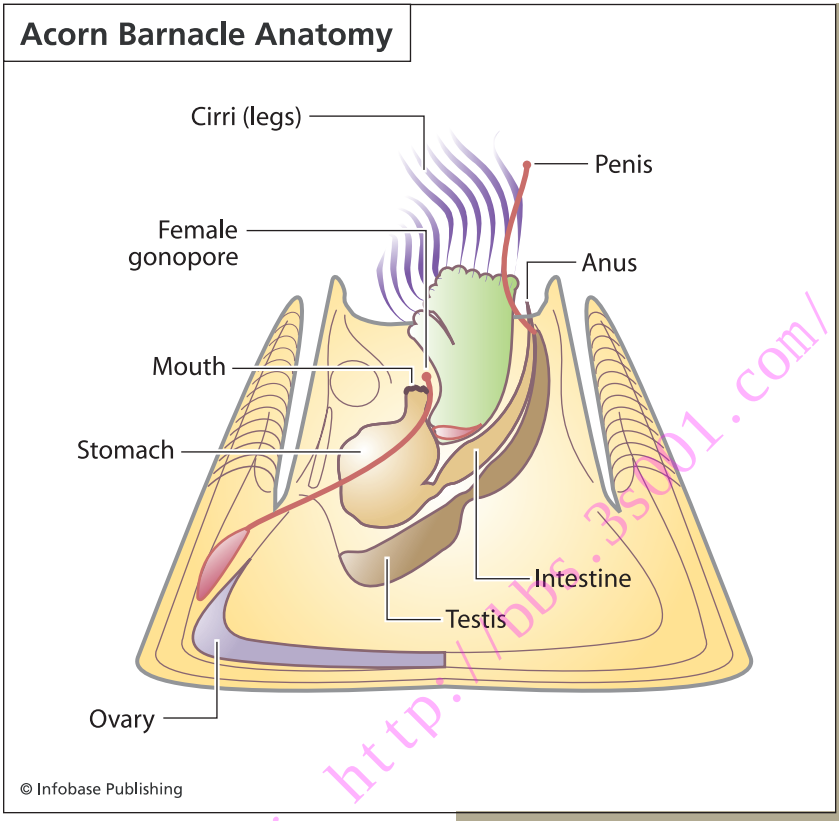
## BARNACLES AND EXPERIMENTS

By 1844, Charles Darwin had understood the basic principles of evolution and written a brief sketch of the theory. Then he locked the draft in a drawer in his study, composed a letter to his wife explaining what to do with it in case he died unexpectedly, and devoted himself to one of nature's oddest creatures: the barnacle, best known for the problems it causes when it glues itself to the hulls of ships.

He anticipated that dissecting, analyzing, and classifying the many different species of this creature would take months, perhaps a year. But as colleagues all over the world sent him specimens, he entered a bewildering labyrinth of classification that cost him nearly a decade of his life. The exhausting work was made more difficult by the appearance of serious health problems. His doctor ordered enforced rest and sent him off on cures where he was wrapped, mummylike, in wet sheets for hours on end.

The whole time the theory lay locked away, never even mentioned except for hints in cautious discussions with a small circle of friends, some of whom became frustrated with his hesitation in publishing it. Darwin knew he needed a reputation as the world expert on one topic to have any hope of his theory being taken seriously. He chose the barnacle because of the immense variety of specimens found across the world—including some fascinating examples he had personally collected during his voyage on the *Beagle.* The creatures were poorly understood; no one had ever thoroughly classified them. And a careful study might make or break his ideas on evolution.

He was amazed and confounded by the creatures' strangeness. Upon prying open the shell of a female, he discovered that the shell's interior was divided into compartments. These served as apartments for her tiny mates, male barnacles that would live their entire lives in the female body, never seeing




Studying the incredible variety of barnacles found throughout the world took Darwin eight years. The diversity of these strange animals gave him a close look at how natural selection works on varieties to create new species, adapted to a wide range of environments.

the world outside. They were much simpler creatures than the female—Darwin called them "bags of sperm"—and their only function was to perpetuate the species. What an incredible solution to the problem of finding a mate, he thought. The males were not alone; they were surrounded by newborn larvae and barnacles in other stages of development. It was like peering into a miniature ocean, a new world inside a shell.

The work on barnacles plunged Darwin deep into one of the most crucial aspects of evolutionary theory. Either what he found would confirm his ideas or somehow contradict them.

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The books he wrote about barnacles were two things at the same time: traditional works on anatomy and classification, and a reference for the future, a mass of evidence that would support evolution. There were thousands of types of barnacles alone. Which were distinct species, and how many were simply variants of the same type? Every type of barnacle he studied represented a new solution to the problem of how an organism could survive and reproduce within the possibilities offered by its environment.

Because each member of a species was slightly different, it was helpful to propose an *archetype*—a standard representative by which to measure all the others. He realized that this was really another question in disguise: He was really searching for the original type. Somewhere among all his specimens, he thought, might be one close to the ancestor of all the others, the first barnacle that had ever evolved. But how would a person know if he found it? His friend Joseph Hooker, climbing through the Himalayas, was having the same problems understanding varieties of rhododendrons and other plant specimens. Hooker knew that Darwin was getting close to a solution. By straightening out the family tree of barnacles, Darwin would be showing the way through a labyrinth of problems that other scientists would face time and time again with other organisms.

Nothing Darwin discovered in his work with barnacles contradicted his ideas about variation and natural selection. But a single species, even exhaustively studied, could not prove the theory, and it did not solve all the questions raised by evolution. For example, if all varieties of a plant descended from a single ancestor, there had to have been some way for them to spread throughout the world. Oceans and mountains might be too great a barrier.

Seeds might be carried by winds, in dirt clinging to the feet of birds, or carried along in their digestive tracts. Darwin needed to know if seeds could survive long voyages under these circumstances. He built aquariums in which he immersed seeds for weeks, retrieving them and then planting them; he did the same thing after extracting them from the droppings of birds and other animals. He found that they were able to withstand a wide variety of conditions. The experiments proved that life

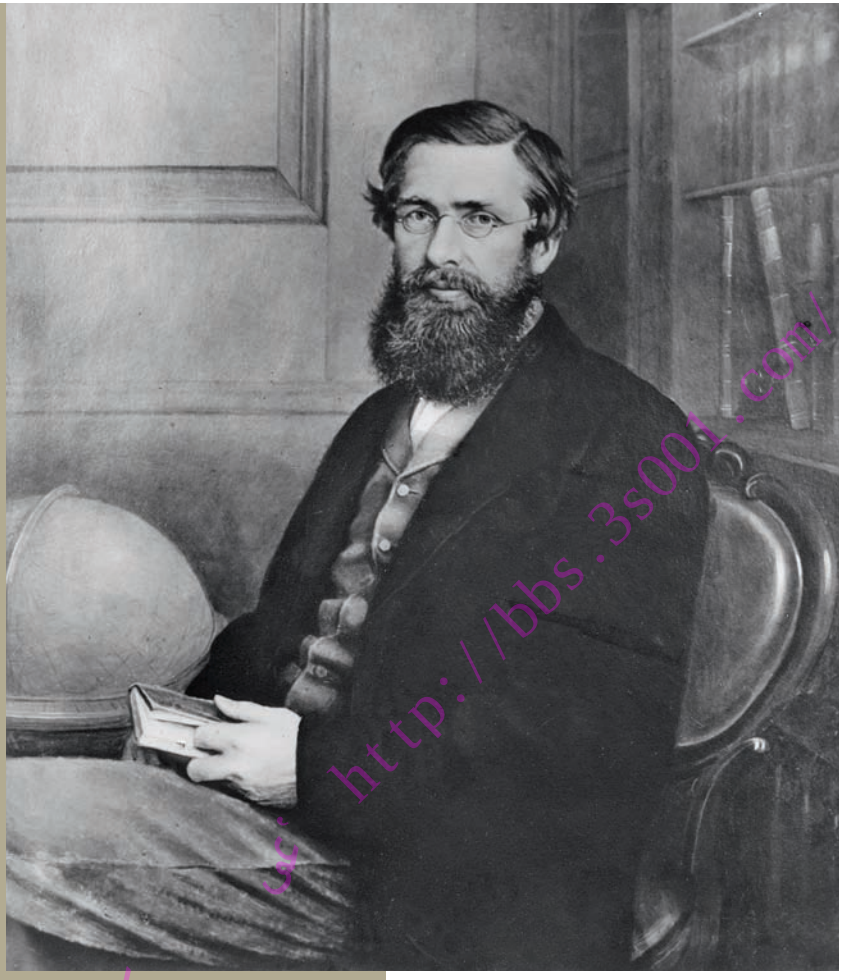
was amazingly resilient. Once it came to exist, he had no doubt it could find its way around the globe.

He also carried out intense studies of animal breeding and agriculture. If anyone ought to know about changes in species, he reasoned, it would be people who had spent their lives trying to improve crops or change the characteristics of horses, cows, sheep, dogs, and many other animals. A large section of his major work on evolution, *On the Origin of Species,* is devoted to breeding.

The weakest part of the theory was its explanation of how evolutionary changes could be transmitted from parent to child. Darwin carried out experiments on a wide variety of animals and plants, including over 40 species of peas, not knowing that at the same time a monk named Gregor Mendel was attacking the same problem with the same plant. They took very different approaches to the problem, with the result that Mendel discovered the laws that governed heredity, while Darwin learned almost nothing.

## ALFRED RUSSEL WALLACE IN THE SPICE ISLANDS

Alfred Russel Wallace (1823–1913) was 14 years younger than Darwin and came from a much different background. His father was a gentleman with a modest regular income, but Thomas Wallace had none of the ambitions, sense of business, or family wealth that had made Charles Darwin's father into a rich man. A series of bad investments brought the family into severe financial difficulties. Alfred and his brothers constantly had to work to supplement the family's income and support their own education. His father died when Wallace was 20; by that time the son had tried watchmaking, surveying, and teaching school. Along the way he studied and read a great deal, including the works on geology that had so strongly influenced Darwin, and developed a passion for collecting plants. He also met Henry Bates, a young naturalist his own age. The two began collecting beetles and butterflies together.



Alfred Russel Wallace, codiscoverer of the theory of evolution *(National Portrait Library)*

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After his father's death, Alfred made a living as a surveyor and moved to the town of Neath in Wales, where he became curator of a small museum and gave lectures on science. He continued his excursions into the countryside on surveying expeditions with one of his brothers and exchanged letters with Henry Bates, comparing the species they had found.

In 1845 he read a popular new book called the *Vestiges of the Natural History of Creation,* whose claims were so extravagant

and controversial that the author (Robert Chambers) published it anonymously. The work began by suggesting if the entire universe was ruled by natural laws like gravity, then species must be ruled by such laws, too. He included observations from Geoffroy Saint-Hilaire and Cuvier and attempted to wrap them all up in a theory of life. For example, Chambers wrote, "While the external forms of all these various animals are so different, it is very remarkable that the whole are, after all, variations of a fundamental plan, which can be traced as a basis throughout the whole, the variations being merely modifications of that plan to suit the particular conditions in which each particular animal has been designed to live."

The book suffered from the same weaknesses as previous theories, offering neither any real evidence nor a mechanism by which animals adapted to their environments. Chambers agreed with Erasmus Darwin and Lamarck that changes in species represented improvements. He went farther, claiming that humans were a part of the scheme; they, too, had arisen from "less perfect" forms of life. He saw no difficulty in reconciling this idea with religion: "if He, as appears, has chosen to employ inferior organisms as a generative medium for the production of higher ones, even including ourselves, what right have we, his humble creatures, to find fault?"

Because of the lack of evidence, Darwin and most scientists rejected the book's speculations. Wallace was more open-minded. Either the author was right or wrong, he wrote to Bates; what scientists ought to do was look for evidence either way. The way to do it might be to select one family of organisms and spend years studying it very carefully, hoping to arrive at a new theory of the origin of species. This was exactly what Darwin was doing with his barnacles.

There was money to be made overseas searching for new species and sending back specimens to museums and private collections. Inspired by Darwin's experiences aboard the *Beagle* and the adventures of other travelers, Wallace and Bates decided to head for the Amazon. After several months of preparation, the two men set off on a merchant ship for South America. They were determined and successful collectors. In the field,

Wallace possessed an almost infinite patience, once spending nearly a month in pursuit of a single beautiful species of butterfly. The men were able to sell enough specimens to collectors back home to make a living. After several months, for reasons that they never revealed, they split up. Wallace found a new partner in his younger brother Herbert, who sailed across the Atlantic to join him.

In spite of several near disasters—including an infection caused by an accidental gunshot wound and a near-fatal case of malaria—Wallace's first expedition abroad was a success. While most collectors were regarded as the "legmen" of museums and rich curiosity seekers, Wallace was seen as someone who also thought deeply about the central problems of science, and the respect he earned improved the reputation of collectors in general. The voyage had a heartbreaking ending because the ship that was to take him and the majority of his collections back to England burned and sank. Nearly everything was lost, including Wallace's journal and notes. It was a crushing blow, and he vowed not to travel abroad again. (He would not keep the promise for long.)

Back in England he was able to reconstruct enough of his notes to write two small books, one about species of palms and their uses among the natives of South America, and a second account of his travels. During this time he briefly met Darwin, but since the older scientist was not talking about his theories yet, and the younger man had not formulated any, they did not make a very strong impression on each other.

Like Darwin, Wallace had almost universal interests. Although his books did not match the literary quality of the *Voyage of the Beagle,* and scientists criticized him for a lack of rigor—partly due to losing most of his notes—he gained enough of a reputation to finance another trip. He decided to head for the Spice Islands, a labyrinth that stretches between Indonesia and Malaysia, which had never been thoroughly explored.

He established a base in western Borneo, which turned out to be a biological gold mine. During one two-week period he found an average of 24 new species of beetles every day. On




While traveling in the Spice Islands, Wallace discovered a natural barrier now known as the Wallace Line. Different species are found on either side. Even many birds, which could fly across, remain on one side of the line. Some of the islands separated by it are only about 35 miles (56 km) apart, but the water is very deep. The division between species on either side probably began when the water was more shallow and many of the islands (except those separated by the line) were connected by land.

a single day he found 34 entirely new species. He caught his first sight of an orangutan, whose eerie, manlike eyes and intelligence fascinated Europeans. The hard work of collecting was occasionally interrupted by sickness or rains, and whenever this happened, Wallace sat in his hut to think and write. When the rains stopped or the fever

subsided, he jumped into his boots and waded back into the forest, leaving his theoretical work until the next period of enforced immobility.

The incredible variety of highly similar species struck Wallace just as it had Darwin in the Galápagos, and he began making notes for a book to be called *The Organic Law of Change*—just as the Earth had to obey laws, so did species. In 1855 he wrote a paper called "On the Law Which Has Regulated the Introduction of Species," published in the *Annals and Magazine of Natural History*. In it he stated that species arose through gradual change. The evidence for this, he said, was that "every species has come into existence coincident both in time and space with a pre-existing closely allied species." Whatever the rules were by which species arose and changed, they were closely linked to space and time. Darwin read the paper but did not give it much attention. Wallace was not really saying anything that had not been stated before, and he certainly had not solved the central problem of identifying the mechanism by which new species could arise. If Darwin had read more closely, he might have sensed that Wallace was getting close to an answer.

Wallace discovered a biological barrier running through the Spice Islands. There were two cleanly divided ecospheres; species on one side never seemed to mingle with those of the other. This was the same phenomenon that had puzzled Darwin in the Andes and the Galápagos: Why had God put different species in different places? What was the role of physical barriers? In 1858, during a bout of malaria and theorizing, Wallace recalled having read Thomas Malthus's essay on population. He thought about how diseases, accidents, war, and famine kept human overpopulation from exploding. The answer came in the following flash of insight:

> These causes or their equivalents are continually acting in the case of animals also; and as animals usually breed much more rapidly than does mankind, the destruction every year from these causes must be enormous. Why do some die and some live? And the answer was clearly, that on the whole the best fitted live. From the effects

> of disease the most healthy escaped; from enemies, the strongest, the swiftest, or the most cunning; from famine, the best hungers or those with the best digestion; and so on.

Over the long term, changes of geography, climate, the food supply, and other factors would challenge organisms. The individuals best suited to the new circumstances would likely survive better, and after many generations this would produce new species. What seemed to be *adaptations* to their environments were simply the qualities that allowed them to survive.

In 1858 Wallace packed his new ideas into a paper called "On the Tendency of Varieties to Depart Indefinitely from the Original Type" and sent it off with a letter to Charles Darwin. The two had already been corresponding, and Wallace knew that Darwin was keenly interested in the laws underlying the development of species. In the letter he wrote that he hoped Darwin would find the idea original and helpful in solving the problem of species. He asked that his ideas be brought to the attention of Charles Lyell and other prominent scientists. Then Wallace packed his bags and boarded a boat bound for New Guinea, where he hoped to capture a living specimen of a rare creature called the Bird of Paradise.

Wallace's letter came as an enormous shock to Darwin. Although he had been working on evolution for almost fifteen years, he had not gone public with his ideas. Darwin had waited so long for several reasons. He had a good idea of what a furious controversy he would be setting off. The implications would be tremendous—for organized religion, but also personally. The Darwins' daughter, Annie, had died recently, and religion had been his wife's only consolation.

## THE THEORY IS MADE PUBLIC

Darwin knew he could not offer ironclad proof for evolution. Like a lawyer lacking a "smoking gun," the best he could do was to collect as much circumstantial evidence as possible, show that



## Who Really Discovered Evolution?

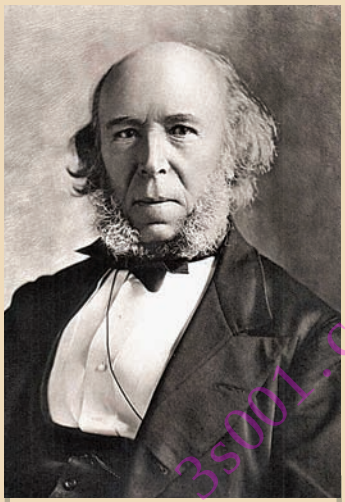
Things rarely turn out well when two or more scientists make the same discovery independently and almost simultaneously. Important discoveries not only help a scientist earn a place in history; they also have practical, personal benefits. They help researchers further their careers and obtain the freedom to pursue the questions they are most interested in. Charles Darwin and Alfred Russel Wallace might have waged a bitter fight over who should be named as the first discoverer of evolution. Instead, they developed a lifelong friendship and a close working relationship, evidence of each man's sense of integrity and honor.

Darwin helped get Wallace the credit he was due. Wallace did not try to grab the lion's share of the glory because he was a shy man; besides, he lacked the patience and discipline to spend years gathering thousands of facts to support the theory. At one point Wallace described Darwin as a "great General who can manoeuvre the largest army," whereas he considered himself good for "skirmishes or smaller campaigns"—unable to cope with the mass of details necessary to make a strong factual case for evolution.

Additionally, being known as the codiscoverer of a major theory was far more than Wallace had ever expected to accomplish. After years of virtually no recognition and a constant struggle to make a living—at one point, his entire livelihood depended on the survival of two rare birds—Wallace was suddenly propelled into the life of the scientific elite, as if he had suddenly become a movie star.

Both men recognized that their ideas owed a debt to many other scientists. After *On the Origin of Species* had been published, Darwin discovered that the idea of natural selection was not entirely new. In 1831, Patrick Matthew had described it in a book called *Naval Timber and Arboriculture;* a doctor named William Wells had discussed it in 1818, as had Henry Freke, an Irish physician, in 1851. Their

books had gone almost unnoticed by the scientific community, and neither Darwin nor Wallace had read them.



Herbert Spencer *(Smithsonian Institution Libraries)*

Another person who had come close was Herbert Spencer, a journalist and philosopher who coined the term *evolution* and used it to talk about social progress nearly a decade before Darwin and Wallace presented their theories to the public. Spencer was familiar with the ideas of Lamarck, Erasmus Darwin, and Robert Chambers and believed that the laws that ruled the natural world also applied to society. But he believed that changes in species and culture represented progress, and he had not proposed a theory of natural selection.

So many people were thinking along similar lines that if Darwin and Wallace had not come up with the theory, someone else surely would have. It might have been Thomas Henry Huxley (1825–95), one of Charles' relatives and a brilliant naturalist who had also traveled the world. When Huxley heard the theory he compared it to being struck by a lightning bolt—instantly recognizing it as the laws everyone had been looking for. He said, "How extremely stupid not to have thought of that!" He became one of evolution's staunchest supporters, calling himself "Darwin's bulldog," and helped win wide acceptance for the theory in the scientific community. He took on the battles that Darwin could not because of illness, his solitary nature, or the fact that there was too much scientific work to be done with the theory.



the theory was compatible with all the facts, and demonstrate that it could deal with problems and questions about life that no other theory addressed. He did this extremely thoroughly and methodically. But he had not rewritten his early outline because he was too busy collecting facts and he did not think anyone else was remotely close to his solution. Now Wallace was forcing his hand. If Darwin did not publish, two decades of work would be lost. If he did, he might look like a pirate who had stolen Wallace's work.

Depressed and unsure of what to do, Darwin asked Lyell for advice. His friend proposed a joint announcement of the theories at a meeting of a scientific group called the Linnaean Society. Darwin was unable to attend because another child, his infant son, had just died from scarlet fever. Wallace was still in Asia. Charles Lyell, with Joseph Hooker (back from the Himalayas), read the papers and added their statements of support. There was very little debate this first evening, because the ideas were too revolutionary and the audience needed time to think them through. But the world had now heard of evolution, and there was no going back.

Things would not remain quiet for long. The next year Darwin finished and published his book *On the Origin of Species,* which spelled out the theory in detail and presented an enormous amount of evidence in support of it. While the book itself did not take the theory to all of its logical conclusions—for example, it did not directly address the evolution of humans—the stakes were clear. Evolution surely applied to human beings, meaning it posed a threat to the Church's most treasured beliefs. Perhaps man was no longer a special creation of God, with divine characteristics. Perhaps he had descended from the apes, and was "just" an animal with some unique characteristics. Most of what scientists and the religious community had believed about life might be wrong.

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# 3

# The Theory and Society's Response

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At the end of the 1830s *The Voyage of the Beagle* was a state-of-the-art travel book for the old way of looking at life, full of sharp observations about the features, lives, and interactions of species. But they remained single facts; Darwin was not yet able to perceive the grand system that unified them and made sense of them. *On the Origin of Species,* 20 years later, served as a guidebook to an entirely new world. Columbus's return from America was likely the last time that a discovery had such a deep and sweeping impact on people's worldview. Columbus had turned the world into a sphere and opened up new lands for European exploration; Darwin's work opened human nature and all of life to scientific exploration.

The theory touched off ferocious debates within science, at public gatherings, in the newspapers, and in churches—it was not easy to integrate into worldviews that had been held for thousands of years. On the one hand, evolution was so simple "that anyone could misunderstand it," as the philosopher David Hull has ironically put it, but in other ways it was quite complex. Science could not yet cope with some of the basic issues it raised. *On the Origin of Species* was a research proposal, a report on a vast work in progress, with the potential of becoming a complete theory of life. It offered the first scientific

explanation of the history and distribution of organisms and replaced the notion of intelligent design with a set of natural laws.

Darwin purposefully left out two issues that everyone was interested in—the beginnings of life itself and the origin of humans (which he would address in another book, *The Descent of Man,* published many years later). He avoided the first topic because scientists did not know enough about microorganisms, the simplest and most ancient forms of life, to classify them or understand their evolution. As for the second, Darwin had not yet studied humans and primates with the intensity he had examined barnacles and other animals. Waiting to address human evolution might give people the time to get used to the theory, and time for scientists to collect further evidence. Wallace, on the other hand, did not hesitate to claim that human beings had arisen from earlier forms of life and had been shaped by natural selection. Ironically, he later changed his mind and began to believe that certain aspects of human beings could not be explained by natural selection. Darwin believed that Wallace was wrong about these questions, and nearly all of today's scientists agree. To understand why, it is necessary to look more deeply into what evolution said, what it did not, and what modern science has made of the theory.

## A RECIPE FOR NEW SPECIES

Evolution is based on a few straightforward principles. Its complexity comes from how these principles work together, the intricacy of life itself, and the fact that evolution nearly always takes place in environments where thousands of species are constantly interacting. The list below draws together the main points Darwin mapped out in *On the Origin of Species.* The real work of understanding evolution lies in appreciating the profound meaning of each of these points, its implications, and how the mechanisms work together.

The following ideas form the main theses of *On the Origin of Species* and all extend from the concepts of variation, heredity, and selection:

- Heredity. Organisms pass along most of their characteristics to their offspring.
- Variation. Within species there is a great deal of variation; individuals are neither identical to their parents nor to each other. Some of these variations are passed along to the next generation through heredity.
- Acquired characteristics are not inherited. An organism's makeup is the product of hereditary information from its parents and variations from other sources (today the reasons are known: Mutations and other types of errors creep in as *DNA* is copied). Learning or lifetime experiences may be passed along by teaching, but they do not directly enter the physical hereditary material that is passed along to an organism's offspring. The only exceptions that have been found are certain types of viruses or bacteria that inject new DNA into the genomes of their host. If the change affects egg or sperm cells, it may be passed down to the next generation.
- Reproductive advantages. Some individuals have more healthy offspring than other members of their species. A plant may produce more seeds, or an animal may have larger litters. Or a feature may help the organism survive long enough to reproduce. If an organism has more offspring, more of its *genes* will appear in the next generation. If its offspring also reproduce more, and this cycle of bias repeats long enough, the genes from one "family" will eventually dominate an entire species.
- Natural selection. In the long run, every successful species produces more offspring than can survive to adulthood. Environmental factors such as climate and predators play an important role in determining which will survive. Selection can be negative (for example, by eliminating organisms that have difficulties surviving and reproducing) or positive (increasing the number of descendants a particular organism has). Selection is a result of the interaction of the organism and the environment. For example, camouflage is often a good survival strategy, but it is only successful through a

combination of the organism's own color, background colors in the environment, and the sharpness of predators' eyes.

- Adaptations happen when natural selection works on variation that already exists within a species. Organisms do not change their hereditary material in order to survive; a characteristic already has to be present to undergo selection. Over time, if the environment remains stable (for example, if no new predators arrive), selection leads to a better "fit" between an organism and its environment.
- Natural selection works constantly, from the moment of conception to death. An organism has to survive each stage of its development as an embryo, birth, childhood, adolescence, and adulthood to pass along its genes to the next generation. After it has finished reproducing, it may help younger members of its species to survive, so natural selection may even influence organisms that are too old to reproduce. But in most cases its influence stops when organisms are no longer fertile. As a consequence, humans and other mammals have evolved immune systems that protect them from many threats that they face in the early parts of their lives—such as infectious diseases—but do not have defenses against "old-age" diseases like Alzheimer's.
- Natural selection can apply to any level within an organism, ranging from events within cells to the formation of tissues and behavior, if these features are hereditary. Even *altruistic* behavior (self-sacrifice) can undergo positive selection if it improves the chances that an organism's genes will survive in the next generation.
- Competition. Some varieties dominate an entire species very quickly, completely replacing other forms. This happens if they offer such major advantages to an organism's success and reproduction that over just a few generations, the genes that cause them spread through the entire population. This should not be confused with deliberate human competition. Organisms

may not be aware of it or want it to happen. And varieties that have less of an advantage do not always become extinct; they may make minor contributions to a species's *gene pool* for a long time, or even develop into new species.

- Isolation plays an important role in the development of new species. If two groups from the same species become separated, they will undergo different random variations and thus experience different types of natural selection. If the two environments are quite different, the pressures of selection will affect them in very different ways. But even when environments are almost identical, such as in the Galápagos Islands, populations that become separated usually follow different evolutionary pathways.
- Natural selection is not the only influence on species change. Accidents, random events, and other factors also play an important role.
- Evolution is nondirectional. It does not necessarily lead to more complex or more intelligent creatures. It does not make organisms "better" in any sense except that in the long term, if the environment stays stable, they tend to have more offspring.
- Strictly speaking, species do not adapt "to" an environment; they adapt because of it. Adaptation does not occur within one generation, as a response to existing conditions. The current population of every species is the result of selection in the past. So the features of modern humans are largely the product of the environment in which the species originated, and the hunter-gatherer lifestyle that *Homo sapiens* practiced throughout most of its history.

Taken together, these principles are responsible for the origins of new species. They can also work on nonliving systems, such as chemical substances that arose on the early Earth. Anything that reproduces imperfectly in an environment with limited resources is subject to evolution.



## Natural Selection versus Bottlenecks

Natural selection operates over many generations to give rise to new species. Over time the "fitness" of organisms increases because the environment favors those that are better equipped to survive and reproduce. Sometimes, however, an organism survives for unusual reasons, or simply because it is lucky. When an individual or a small group survives and the rest of the species dies out, due to a catastrophe or something else, scientists say that there has been a *bottleneck*. This is an unusual situation because it determines the entire future fate of the species. All of the characteristics of the survivors will be passed along to the next generation, not only features that would normally undergo positive or negative selection. So bottlenecks are usually exceptions to the way that natural selection normally works.

The following are some examples of how this happens:

1. About 75 years ago, yeast cells were taken from a moldy fig and brought into the laboratory to be used in the production of beer. Over decades, scientists repeatedly selected the cells that did the best job at fermentation and discarded the rest. Thus the yeast cells most commonly used in today's laboratory experiments have undergone many bottlenecks through "artificial selection."
2. In the late 18th century, a tsunami washed over a very low-lying Pacific island called Pingelap, killing about 900 of the island's 1,000 inhabitants. Most of the survivors belonged to the royal family. Centuries of inbreeding had given many of them a rare genetic form of color blindness called *monochromatism*. Their eyes have no cone cells, which

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