Jerry A. Coyne

Why Evolution is True

'Compelling…masterful…outstandingly good.'
Richard Dawkins, *TLS*

OXFORD LANDMARK SCIENCE

Jerry Coyne is a professor in the Department of Ecology and Evolution at the University of Chicago, where he specializes in evolutionary genetics. His research focuses on the origin of new species, using the fruit fly (*Drosophila*) as model organism. A former student of the distinguished Harvard geneticist Richard Lewontin, Coyne has taught evolutionary biology for more than 25 years, and has contributed frequently to the public debate concerning evolution and creationism. He has published widely in research journals and is the author, with Allen Orr, of *Speciation*, now the standard academic text in the subject. He was elected Fellow of the American Academy of Arts and Sciences in 2007.

Praise for *Why Evolution is True*

'Evolution is true… Coyne displays it for us in a way that no objective reader could fail to find compelling… Coyne's knowledge of evolutionary biology is prodigious, his deployment of it as masterful as his touch is light… *Why Evolution is True* is outstandingly good.'

Richard Dawkins, *TLS*

'*Why Evolution is True* is the book I was hoping would be written someday: an engaging and accessible account of one of the most important ideas ever conceived by mankind. The book is a stunning achievement, written by one of the world's leading evolutionary biologists. Coyne has produced a classic—whether you are an expert or novice in science, a friend or foe of evolutionary biology, reading *Why Evolution is True* is bound to be an enlightening experience.'

Neil Shubin, author of *Your Inner Fish*

'An indispensable book: the single, accessible volume that makes the case for evolution. Jerry Coyne has given us an utterly fascinating, lucid, and beautifully written account of our place in the natural world. If you want to better understand your kinship with the rest of life, this book is the place to start.'

Sam Harris, author of *The End of Faith*
and *Letter to a Christian Nation*

'For anyone who wishes a clear, well-written explanation of evolution by one of the foremost scientists working on the subject, *Why Evolution is True* should be your choice.' **E.O. Wilson**

'Its ignorant opponents like to say that the process of evolution by natural selection is 'only a theory.' (That's how they prove their ignorance.) Jerry Coyne shows with elegance and rigor that it is a hypothesis that meets and withstands all tests, and strengthens itself as a theory thereby. One could almost say that it had the distinct merit of being true.' **Christopher Hitchens**

'Evolution is the foundation of modern biology, and in *Why Evolution is True,* Jerry Coyne masterfully explains why. From the vast trove of evidence of evolution scientists have gathered, Coyne has carefully selected some of the most striking examples and explained them with equal parts grace and authority.'

Carl Zimmer, author of *Microcosm: E. coli* and the *New Science*

'Coyne gives a clear and engaging overview of what evolution is, and how it works.' ***BBC Focus***

'Scholarly, yet delightfully readable account… A pleasure to read.' ***Current Biology***

'If you want a direct response to creationism, then Jerry Coyne's recent book *Why Evolution is True* is your book.' ***Financial Times***

'A lucidly brilliant account of evolutionary theory… It is a model of expository clarity and intellectual rigor… Coyne shows science carefully, responsibly, testably, profoundly at work on the glory that is the natural world. It starts with no prejudices but is open and self-critical. What you see in Coyne's account is science as the enterprise that seeks to understand, and always stands ready to revise itself in the face of contrary evidence.' **A.C. Grayling, barnesandnoble.com**

'Coyne's book is just what we needed in this bicentennial year to anchor Darwin where he belongs. It is calm, clear, detailed and utterly convincing.' **Nigel Hawkes, *The Times***

'*Why Evolution is True* succeeds in being fully accessible to any reader who has even a vague idea of what DNA is… it is a book that needed to be written and needs to be read… One of the very best and most important books on evolution for broad audiences in at least 50 years.' **Douglas J. Futuyma, *Trends in Ecology and Evolution***

'[Coyne] has been a leader in our understanding of the genetic changes that occur when species are formed. His primary object in writing this book is to present the incontrovertible evidence that evolution is a physical fact of the history of life on Earth … In this he is entirely successful.'

Richard C. Lewontin, *New York Review of Books*

'Lucid, thorough, and eminently readable, this book is a delight from start to finish.'

The Scotsman

'A masterfully concise reinstating of [Darwin's] big idea.'

Times Higher Education

'Jerry A. Coyne [is] among the leading evolutionary geneticists of his generation … *Why Evolution is True* is designed to present the evidence in an accessible way and thus to convince those who might otherwise be seduced by the blandishments of creationists … [Coyne] has offered Darwin a splendid birthday present.'

Philip Kitcher, *Wall Street Journal*

WHY EVOLUTION IS TRUE

Jerry A. Coyne

OXFORD
UNIVERSITY PRESS

OXFORD
UNIVERSITY PRESS
Great Clarendon Street, Oxford OX2 6DP
Oxford University Press is a department of the University of Oxford.
It furthers the University's objective of excellence in research, scholarship,
and education by publishing worldwide in
Oxford New York
Auckland Cape Town Dar es Salaam Hong Kong Karachi
Kuala Lumpur Madrid Melbourne Mexico City Nairobi
New Delhi Shanghai Taipei Toronto
With offices in
Argentina Austria Brazil Chile Czech Republic France Greece
Guatemala Hungary Italy Japan Poland Portugal Singapore
South Korea Switzerland Thailand Turkey Ukraine Vietnam
Oxford is a registered trade mark of Oxford University Press
in the UK and in certain other countries

First published 2009
First published in paperback 2010

British Library Cataloguing in Publication Data
Data available
Library of Congress Cataloging in Publication Data
Coyne, Jerry A., 1949–
Why evolution is true / Jerry A. Coyne.
p. cm.
Includes bibliographical references and index.
ISBN 978–0–19–923084–6
1. Evolution (Biology) I. Title.
QH366.2.C74 2009b
576.8—dc22 2008042122
Typeset by SPI Publisher Services, Pondicherry, India
Printed in Great Britain
on acid-free paper by
CPI Antony Rowe, Chippenham, Wiltshire
ISBN 978–0–19–923084–6 (Hbk.)
978–0–19–923085–3 (Pbk.)
1 3 5 7 9 10 8 6 4 2

For Dick Lewontin

il miglior fabbro

CONTENTS

PREFACE

December 20, 2005. Like many scientists on that day, I awoke feeling anxious. John Jones III, a federal judge in Harrisburg, Pennsylvania, was due to issue his ruling in the case of *Kitzmiller et al. vs. Dover Area School District et al.* It had been a watershed trial, and Jones's judgment would decide how American schoolchildren would learn about evolution.

The educational and scientific crisis had begun modestly enough, when administrators of the Dover, Pennsylvania, school district met to discuss which biology textbooks to order for the local high school. Some religious members of the school board, unhappy with the current text's adherence to Darwinian evolution, suggested alternative books that included the biblical theory of creationism. After heated wrangling, the board passed a resolution requiring biology teachers at Dover High to read the following statement to their ninth-grade classes:

> The Pennsylvania Academic Standards require students to learn about Darwin's Theory of Evolution and eventually to take a standardized test of which evolution is a part. Because Darwin's Theory is a theory, it continues to be tested as new evidence is discovered. The Theory is not a fact. Gaps in the Theory exist for which there is no evidence. . . . Intelligent design is an explanation of the origin of life that differs from Darwin's view. The reference book, *Of Pandas and People*, is available for students to see if they would like to explore this view in an effort to gain an understanding of what intelligent design actually involves. As is true with any theory, students are encouraged to keep an open mind.

This ignited an educational firestorm. Two of the nine school board members resigned, and all the biology teachers refused to read the statement to their classes, protesting that "intelligent design" was religion rather than science. Since offering religious instruction in public schools violates the United States Constitution, eleven outraged parents took the case to court.

The trial began on September 26, 2005, lasting six weeks. It was a colorful affair, justifiably billed as the "Scopes Trial of our century," after the famous 1925 trial in which high school teacher John Scopes, from Dayton, Tennessee, was convicted for teaching that humans had evolved. The national press descended on the sleepy town of Dover, much as it had eighty years earlier on the even sleepier town of Dayton. Even Charles Darwin's great-great-grandson, Matthew Chapman, showed up, researching a book about the trial.

By all accounts it was a rout. The prosecution was canny and well prepared, the defense lackluster. The star scientist testifying for the defense admitted that his definition of "science" was so broad that it could include astrology. And in the end, *Of Pandas and People* was shown to be a put-up job, a creationist book in which the word "creation" had simply been replaced by the words "intelligent design."

But the case was not open and shut. Judge Jones was a George W. Bush appointee, a devoted churchgoer, and a conservative Republican—not exactly pro-Darwinian credentials. Everyone held their breath and waited nervously.

Five days before Christmas, Judge Jones handed down his decision—in favor of evolution. He didn't mince words, ruling that the school board's policy was one of "breathtaking inanity," that the defendants had lied when claiming they had no religious motivations, and, most importantly, that intelligent design was just recycled creationism:

> It is our view that a reasonable, objective observer would, after reviewing both the voluminous record in this case, and our narrative, reach the inescapable conclusion that ID is an interesting theological argument, but that it is not science. . . . In summary, the [school board's]

> disclaimer singles out the theory of evolution for special treatment, misrepresents its status in the scientific community, causes students to doubt its validity without scientific justification, presents students with a religious alternative masquerading as a scientific theory, directs them to consult a creationist text [*Of Pandas and People*] as though it were a science resource, and instructs students to forego scientific inquiry in the public school classroom and instead to seek out religious instruction elsewhere.

Jones also brushed aside the defense's claim that the theory of evolution was fatally flawed:

> To be sure, Darwin's theory of evolution is imperfect. However, the fact that a scientific theory cannot yet render an explanation on every point should not be used as a pretext to thrust an untestable alternative hypothesis grounded in religion into the science classroom to misrepresent well-established scientific propositions.

But scientific truth is decided by scientists, not by judges. What Jones had done was simply prevent an established truth from being muddled by biased and dogmatic opponents. Nevertheless, his ruling was a splendid victory for American schoolchildren, for evolution, and indeed for science itself.

All the same, it wasn't a time to gloat. This was certainly not the last battle that we would have to fight to keep evolution from being censored in the schools. During more than twenty-five years of teaching and defending evolutionary biology, I've learned that creationism is like the inflatable roly-poly clown I played with as a child: when you punch it, it briefly goes down, but then pops back up. And while the Dover trial is an American story, creationism isn't a uniquely American problem. Creationists—who aren't necessarily Christians—are establishing footholds in other parts of the world, especially the United Kingdom, Australia, and Turkey. The battle for evolution seems never-ending. And the battle is part of a wider war, a war between rationality and superstition. What is at stake is nothing less than science itself and all the benefits it offers to society.

The mantra of evolution's opponents, whether in America or elsewhere, is always the same: "The theory of evolution is in crisis." The implication is that there are some profound observations about nature that conflict with Darwinism. But evolution is far more than a "theory," let alone a theory in crisis. Evolution is a fact. And far from casting doubt on Darwinism, the evidence gathered by scientists over the past century and a half supports it completely, showing that evolution happened, and that it happened largely as Darwin proposed, through the workings of natural selection.

This book lays out the main lines of evidence for evolution. For those who oppose Darwinism purely as a matter of faith, no amount of evidence will do—theirs is a belief not based on reason. But for the many who find themselves uncertain, or who accept evolution but are not sure how to argue their case, this volume gives a succinct summary of why modern science recognizes evolution as true. I offer it in the hope that people everywhere may share my wonder at the sheer explanatory power of Darwinian evolution, and may face its implications without fear.

Any book on evolutionary biology is necessarily a collaboration, for the field enfolds areas as diverse as paleontology, molecular biology, population genetics, and biogeography; and no one person could ever master them all. I am grateful for the help and advice of many colleagues who have patiently instructed me and corrected my errors. These include Richard Abbott, Spencer Barrett, Andrew Berry, Deborah Charlesworth, Peter Crane, Mick Ellison, Rob Fleischer, Peter Grant, Matthew Harris, Jim Hopson, David Jablonski, Farish Jenkins, Emily Kay, Philip Kitcher, Rich Lenski, Mark Norell, Steve Pinker, Trevor Price, Donald Prothero, Steve Pruett-Jones, Bob Richards, Callum Ross, Doug Schemske, Paul Sereno, Neil Shubin, Janice Spofford, Douglas Theobald, Jason Weir,

Steve Yanoviak, and Anne Yoder. I apologize to those whose names have been inadvertently omitted, and exculpate all but myself for any remaining errors. I am especially grateful to Matthew Cobb, Naomi Fein, Hopi Hoekstra, and Brit Smith, who read and critiqued the entire manuscript. The book would have been substantially poorer without the hard work and artistic acumen of the illustrator, Kalliopi Monoyios. Finally, I am grateful to my agent, John Brockman, who agreed that people needed to hear the evidence for evolution, and to my editor at Oxford University Press, Latha Menon, for her unflagging help, advice, and support.

INTRODUCTION

Darwin matters because evolution matters. Evolution matters because science matters. Science matters because it is the preeminent story of our age, an epic saga about who we are, where we came from, and where we are going.

—Michael Shermer

Among the wonders that science has uncovered about the universe in which we dwell, no subject has caused more fascination and fury than evolution. That is probably because no majestic galaxy or fleeting neutrino has implications that are as personal. Learning about evolution can transform us in a deep way. It shows us our place in the whole splendid and extraordinary panoply of life. It unites us with every living thing on the Earth today and with myriads of creatures long dead. Evolution gives us the true account of our origins, replacing the myths that satisfied us for thousands of years. Some find this deeply frightening, others ineffably thrilling.

Charles Darwin, of course, belonged to the second group, and expressed the beauty of evolution in the famous final paragraph of the book that started it all—*On the Origin of Species* (1859):

> There is grandeur in this view of life, with its several powers, having been originally breathed into a few forms or into one; and that, whilst this planet has gone cycling on according to the fixed law of gravity, from so simple a beginning endless forms most beautiful and most wonderful have been, and are being, evolved.

But there is even more cause for wonder. For the *process* of evolution—natural selection, the mechanism that drove the first naked, replicating molecule into the diversity of millions of fossil and living forms—is a mechanism of staggering simplicity and beauty. And only those who understand it can experience the awe that comes with realizing how such a straightforward process could yield features as diverse as the flower of the orchid, the wing of the bat, and the tail of the peacock. Again in *The Origin*, Darwin—imbued with Victorian paternalism—described this feeling:

> When we no longer look at an organic being as a savage looks at a ship, as something wholly beyond his comprehension; when we regard every production of nature as one which has had a long history; when we contemplate every complex structure and instinct as the summing up of many contrivances, each useful to the possessor, in the same way as any great mechanical invention is the summing up of the labour, the experience, the reason, and even the blunders of numerous workmen; when we thus view each organic being, how far more interesting—I speak from experience—does the study of natural history become!

Darwin's theory that all of life was the product of evolution, and that the evolutionary process was driven largely by natural selection, has been called the greatest idea that anyone ever had. But it is more than just a good theory, or even a beautiful one. It also happens to be true. Although the idea of evolution itself was not original to Darwin, the copious evidence he mustered in its favor convinced most scientists and many educated readers that life had indeed changed over time. This took only about ten years after *The Origin* was published in 1859. But for many years thereafter, scientists remained skeptical about Darwin's key innovation: the theory of natural selection. Indeed, if ever there was a time when Darwinism was "just a theory," or was "in crisis," it was the latter half of the nineteenth century, when evidence for the mechanism of evolution was not clear, and the means by which it worked—genetics—was still obscure. This was all sorted out in the first few decades of the twentieth century, and since then the evidence for both evolution and

natural selection has continued to mount, crushing the scientific opposition to Darwinism. While biologists have revealed many phenomena that Darwin never imagined—how to discern evolutionary relationships from DNA sequences, for one thing—the theory presented in *The Origin of Species* has, in the main, held up steadfastly. Today scientists have as much confidence in Darwinism as they do in the existence of atoms, or in microorganisms as the cause of infectious disease.

Why then do we need a book that gives the evidence for a theory that long ago became part of mainstream science? After all, nobody writes books explaining the evidence for atoms, or for the germ theory of disease. What is so different about evolution?

Nothing—and everything. True, evolution is as solidly established as any scientific fact (it is, as we will learn, more than "just a theory"), and scientists need no more convincing. But things are different outside scientific circles. To many, evolution gnaws at their sense of self. If evolution offers a lesson, it seems to be that we're not only related to other creatures, but, like them, also the product of blind and impersonal evolutionary forces. If humans are just one of many outcomes of natural selection, maybe we aren't so special after all. You can understand why this doesn't sit well with many people who think that we came into being in a different way from other species, as the special goal of a divine intention. Does our existence have any purpose or meaning that distinguishes us from other creatures? Evolution is also thought to erode morality. If, after all, we are simply beasts, then why not *behave* like beasts? What can keep us moral if we're nothing more than monkeys with big brains? No other scientific theory produces such *angst*, or such psychological resistance.

It's clear that this resistance stems largely from religion. You can find religions without creationism, but you never find creationism without religion. Many religions not only deem humans as special, but deny evolution by asserting that we, like other species, were objects of an instantaneous creation by a deity. While many religious people have found a way to accommodate evolution with their spiritual beliefs, no

such reconciliation is possible if one adheres to the literal truth of a special creation. That is why opposition to evolution is so strong in the United States and Turkey, where fundamentalist beliefs are pervasive.

Statistics show starkly how resistant we are to accepting the plain scientific fact of evolution. Despite incontrovertible evidence for evolution's truth, year after year polls show that Americans are depressingly suspicious about this single branch of biology. In 2006, for example, adults in thirty-two countries were asked to respond to the assertion, "Human beings, as we know them, developed from earlier species of animals," by answering whether they considered it true, false, or were unsure. Now, this statement is flatly true: as we will see, genetic and fossil evidence shows that humans descend from a primate lineage that split off from our common ancestor with the chimpanzees roughly seven million years ago. And yet only 40 percent of Americans—four in ten people—judge the statement true (down 5 percent from 1985). This figure is nearly matched by the proportion of people who say it's false: 39 percent. And the rest, 21 percent, are simply unsure.

This becomes even more remarkable when we compare these statistics to those from other Western countries. Of the thirty-one other nations surveyed, only Turkey, rife with religious fundamentalism, ranked lower in accepting evolution (25 percent accept, 75 percent reject). Europeans, on the other hand, score much better, with over 80 percent of French, Scandinavians, and Icelanders seeing evolution as true. In Japan, 78 percent of people agree that humans evolved. Imagine if America ranked next to last among countries accepting the existence of atoms! People would immediately go to work improving education in the physical sciences.

And evolution gets bumped down even further when it comes to deciding not whether it's true, but whether it should be taught in the public schools. Nearly two-thirds of Americans feel that if evolution is taught in the science classroom, creationism should be as well. Only 12 percent—one in eight people—think that evolution should be taught without mentioning a creationist alternative. Perhaps the "teach all

sides" argument appeals to the American sense of fair play, but to an educator it's truly disheartening. Why teach a discredited, religiously based theory, even one widely believed, alongside a theory so obviously true? It's like asking that shamanism be taught in medical school alongside Western medicine, or astrology be presented in psychology class as an alternative theory of human behavior. Perhaps the most frightening statistic is this: despite legal prohibitions, nearly one in eight American high school biology teachers admits to presenting creationism or intelligent design in their classroom as a valid scientific alternative to Darwinism. (This may not be surprising given that one in six teachers believes that "God created human beings pretty much in their present form within the past 10,000 years").

Sadly, anti-evolutionism, often thought to be a peculiarly American problem, is now spreading to other countries, including Germany and the United Kingdom. In the UK, a 2006 poll by the BBC asked 2,000 people to describe their view of how life formed and developed. While 48 percent accepted the evolutionary view, 39 percent opted for either creationism or intelligent design, and 13 percent didn't know. More than 40 percent of the respondents thought that either creationism or intelligent design should be taught in school science classes. That isn't so different from the statistics for America. And some schools in the UK do present intelligent design as an alternative to evolution, an educational tactic illegal in the United States. With evangelical Christianity gaining a foothold in mainland Europe, and Muslim fundamentalism spreading through the Middle East, creationism follows in their wake. As I write, Turkish biologists are fighting a rearguard action against well-funded and vociferous creationists in their own country. And—the ultimate irony—creationism has even established a foothold on the Galápagos archipelago. There, on the very land that symbolizes evolution, the iconic islands that inspired Darwin, a Seventh-day Adventist school dispenses undiluted creationist biology to children of all faiths.

Aside from its conflict with fundamentalist religion, much confusion and misunderstanding surrounds evolution because of a simple lack of

awareness of the weight and variety of evidence in its favor. Doubtless some simply aren't interested. But the problem is more widespread than this: it's a lack of information. Even many of my fellow biologists are unacquainted with the many lines of evidence for evolution, and most of my university students, who supposedly learned evolution in high school, come to my courses knowing almost nothing of this central organizing theory of biology. In spite of the wide coverage of creationism and its recent descendant, intelligent design, the popular press gives almost no background on why scientists accept evolution. No wonder, then, that many people fall prey to the rhetoric of creationists and their deliberate mischaracterizations of Darwinism.

Although Darwin was the first to compile evidence for the theory, since his time scientific research has uncovered a stream of new examples showing evolution in action. We are observing species splitting into two, and finding more and more fossils capturing change in the past—dinosaurs that have sprouted feathers, fish that have grown limbs, reptiles turning into mammals. In this book I weave together the many threads of modern work in genetics, paleontology, geology, molecular biology, anatomy, and development that demonstrate the "indelible stamp" of the processes first proposed by Darwin. We will examine what evolution is, what it is not, and how one tests the validity of a theory that inflames so many.

We will see that while recognizing the full import of evolution certainly requires a profound shift in thinking, it does not inevitably lead to the dire consequences that creationists always paint when trying to dissuade people from Darwinism. Accepting evolution needn't turn you into a despairing nihilist, or rob your life of purpose and meaning. It won't make you immoral, or give you the sentiments of a Stalin or Hitler. Nor must it promote atheism, for enlightened religion has always found a way to accommodate the advances of science. In fact, understanding evolution should surely deepen and enrich our appreciation of the living world and our place in it. The truth—that we, like lions, redwoods, and frogs, all resulted from the slow replacement of one gene by another, each step conferring a tiny reproductive advantage—is surely more satisfying

than the myth that we were suddenly called into being from nothing. As so often happens, Darwin put it best:

> When I view all beings not as special creations, but as the lineal descendants of some few beings which lived long before the first bed of the Cambrian system was deposited, they seem to me to become ennobled.

CHAPTER 1

WHAT IS EVOLUTION?

A curious aspect of the theory of evolution is that everybody thinks he understands it.

—Jacques Monod

If anything is true about nature, it is that plants and animals seem intricately and almost perfectly designed for living their lives. Squids and flatfish change color and pattern to blend in with their surroundings, becoming invisible to predator and prey. Bats have radar to home in on insects at night. Hummingbirds, which can hover in place and change position in an instant, are far more agile than any human helicopter, and have long tongues to sip nectar lying deep within flowers. And the flowers they visit also appear designed—to use hummingbirds as sex aids. For, while the hummingbird is busy sipping nectar, the flower attaches pollen to its bill, enabling it to fertilize the next flower that the bird visits. Nature resembles a well-oiled machine, with every species an intricate cog or gear.

What does all this seem to imply? A master mechanic, of course. This conclusion was most famously expressed by the eighteenth-century English philosopher William Paley. If we came across a watch lying on the ground, he said, we would certainly recognize it as the work of a watchmaker. Likewise, the existence of well-adapted organisms and their

intricate features surely implied a conscious, celestial designer—God. Let's look at Paley's argument, one of the most famous in the history of philosophy:

> 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; that, if the different parts had been differently shaped from what they are, if a different size from what they are, or placed after any other manner, or in any other order than that in which they are placed, either no motion at all would have been carried on in the machine, or none which would have answered the use that is now served by it. . . . Every indication of contrivance, every manifestation of design, which existed in the watch, exists in the works of nature; with the difference, on the side of nature, of being greater and more, and that in a degree which exceeds all computation.

The argument Paley put forward so eloquently was both commonsensical and ancient. When he and his fellow "natural theologians" described plants and animals, they believed that they were cataloging the grandeur and ingenuity of God manifested in his well-designed creatures.

Darwin himself raised the question of design—before disposing of it—in 1859.

> How have all those exquisite adaptations of one part of the organization to another part, and to the conditions of life, and of one distinct organic being, been perfected? We see these beautiful coadaptations most plainly in the woodpecker and missletoe; and only a little less plainly in the humblest parasite which clings to the hairs of a quadruped or feathers of a bird; in the structure of the beetle which dives though the water; in the plumed seed which is wafted by the gentlest breeze; in short, we see beautiful adaptations everywhere and in every part of the organic world.

Darwin had his own answer to the conundrum of design. A keen naturalist, who originally studied to be a minister at Cambridge University (where, ironically, he occupied Paley's former rooms), Darwin well knew the seductive power of arguments like Paley's. The more one learns about

plants and animals, the more one marvels at how well their designs fit their ways of life. What could be more natural than inferring that this fit reflects *conscious* design? Yet Darwin looked beyond the obvious, suggesting—and supporting with copious evidence—two ideas that forever dispelled the idea of deliberate design. Those ideas were evolution and natural selection. He was not the first to think of evolution—several before him, including his own grandfather Erasmus Darwin, floated the idea that life had evolved. But Darwin was the first to use data from nature to convince people that evolution was true, and his idea of natural selection was truly novel. It testifies to his genius that the concept of natural theology, accepted by most educated Westerners before 1859, was vanquished within only a few years by a single 500-page book. *On the Origin of Species* turned the mysteries of life's diversity from mythology into genuine science.

So what is "Darwinism"?[1] This simple and profoundly beautiful theory, the theory of evolution by natural selection, has been so often misunderstood, and even on occasion maliciously misstated, that it is worth pausing for a moment to set out its essential points and claims. We'll be coming back to these repeatedly as we consider the evidence for each.

In essence, the modern theory of evolution is easy to grasp. It can be summarized in a single (albeit slightly long) sentence: Life on Earth evolved gradually beginning with one primitive species—perhaps a self-replicating molecule—that lived more than 3.5 billion years ago; it then branched out over time, throwing off many new and diverse species; and the mechanism for most (but not all) of evolutionary change is natural selection.

When you break that statement down, you find that it really consists of six components: evolution, gradualism, speciation, common ancestry, natural selection, and nonselective mechanisms of evolutionary change. Let's examine what each of these parts means.

The first is the idea of *evolution* itself. This simply means that a species undergoes genetic change over time. That is, over many generations a species can evolve into something quite different, and those differences are based on changes in the DNA, which originate as mutations. The

species of animals and plants living today weren't around in the past, but are descended from those that lived earlier. Humans, for example, evolved from a creature that was ape-like, but not identical to modern apes.

Although all species evolve, they don't do so at the same rate. Some, like horseshoe crabs and gingko trees, have barely changed over millions of years. The theory of evolution does not predict that species will constantly be evolving, or how fast they'll change when they do. That depends on the evolutionary pressures they experience. Groups like whales and humans have evolved rapidly, while others, like the coelacanth "living fossil," look almost identical to ancestors that lived hundreds of millions of years ago.

The second part of evolutionary theory is the idea of *gradualism*. It takes many generations to produce a substantial evolutionary change, such as the evolution of birds from reptiles. The evolution of new features, like the teeth and jaws that distinguish mammals from reptiles, does not occur in just one or a few generations, but usually over hundreds or thousands—even millions—of generations. True, some change can occur very quickly. Populations of microbes have very short generations, some as brief as twenty minutes. This means that these species can undergo a lot of evolution in a short time, accounting for the depressingly rapid rise of drug resistance in disease-causing bacteria and viruses. And there are many examples of evolution known to occur within a human lifetime. But when we're talking about really *big* change, we're usually referring to change that requires many thousands of years. Gradualism does not mean, however, that each species evolves at an even pace. Just as different species vary in how fast they evolve, so a single species evolves faster or slower as evolutionary pressures wax and wane. When natural selection is strong, as when an animal or plant colonizes a new environment, evolutionary change can be fast. Once a species becomes well adapted to a stable habitat, evolution often slows down.

The next two tenets are flip sides of the same coin. It is a remarkable fact that while there are many living species, all of us—you, me, the elephant, and the potted cactus—share some fundamental traits. Among

these are the biochemical pathways that we use to produce energy, our standard four-letter DNA code, and how that code is read and translated into proteins. This tells us that every species goes back to a single common ancestor, an ancestor who had those common traits and passed them on to its descendants. But if evolution meant only gradual genetic change within a species, we'd have only one species today—a single highly evolved descendant of the first species. Yet we have many: well over ten million species inhabit our planet today, and we know of a further quarter million as fossils. Life is diverse. How does this diversity arise from one ancestral form? This requires the third idea of evolution: that of *splitting*, or, more accurately, *speciation*.

Look at figure 1, which shows a sample evolutionary tree that illustrates the relationships between birds and reptiles. We've all seen these, but let's examine one a bit more closely to understand what it really

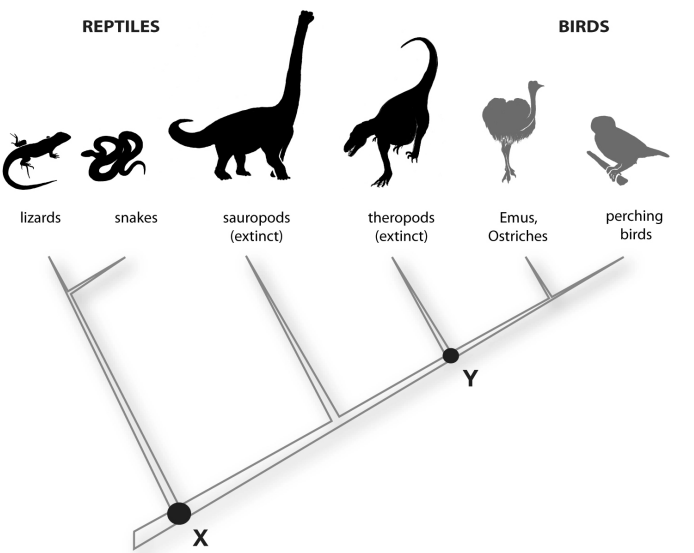

FIGURE 1. An example showing common ancestors in reptiles. X and Y are species that were the common ancestors between later-evolved forms.

means. What exactly happened when node X, say, split into the lineage that leads to modern reptiles like lizards and snakes on the one hand and to modern birds and their dinosaurian relatives on the other? Node X represents a *single ancestral species*, an ancient reptile, that split into two descendant species. One of the descendants went on its own merry path, eventually splitting many times and giving rise to all dinosaurs and modern birds. The other descendant did the same, but produced most modern reptiles. The common ancestor X is often called the "missing link" between the descendant groups. It is the genealogical connection between birds and modern reptiles—the intersection you'd finally reach if you traced their lineages all the way back. There's a more recent "missing link" here, too: node Y, the species that was the common ancestor of bipedal meat-eating dinosaurs like *Tyrannosaurus rex* (all now extinct) and modern birds. But although common ancestors are no longer with us, and their fossils nearly impossible to document (after all, they represent but a single species out of thousands in the fossil record), we can sometimes discover fossils closely related to them, species having features that show common ancestry. In the next chapter, for example, we'll learn about the "feathered dinosaurs" that support the existence of node Y.

What happened when ancestor X split into two separate species? Nothing much, really. As we'll see later, speciation simply means the evolution of different groups that can't interbreed—that is, groups that can't exchange genes. What we would have seen had we been around when this common ancestor began to split is simply two populations of a single reptilian species, probably living in different places, beginning to evolve slight differences from one another. Over a long time, these differences gradually grew larger. Eventually the two populations would have evolved sufficient genetic difference that members of the different populations could not interbreed. (There are many ways this can happen: members of different animal species may no longer find each other attractive as mates or, if they do mate with each other, the offspring could be sterile. Different plant species can use different pollinators or flower at different times, preventing cross-fertilization.)

Millions of years later, and after more splitting events, one of the descendant dinosaur species, node Y, itself split into two more species, one eventually producing all the bipedal, carnivorous dinosaurs and the other producing all living birds. This critical moment in evolutionary history—the birth of the ancestor of all birds—wouldn't have looked so dramatic at the time. We wouldn't have seen the sudden appearance of flying creatures from reptiles, but merely two slightly different populations of the same dinosaur, probably no more different than members of diverse human populations are today. All the important changes occurred thousands of generations after the split, when selection acted on one lineage to promote flight and on the other to promote the traits of bipedal dinosaurs. It is only in retrospect that we can identify species Y as the common ancestor of *T. rex* and birds. These evolutionary events were slow, and seem momentous only when we arrange in sequence all the descendants of these diverging evolutionary streams.

But species don't *have* to split. Whether they do depends, as we'll see, on whether circumstances allow populations to evolve enough differences that they are no longer able to interbreed. The vast majority of species—more than 99 percent of them—go extinct without leaving any descendants. Others, like gingko trees, live millions of years without producing many new species. Speciation doesn't happen very often. But each time one species splits into two, it doubles the number of opportunities for *future* speciation, so the number of species can rise exponentially. Although speciation is slow, it happens sufficiently often, over such long periods of history, that it can easily explain the stunning diversity of living plants and animals on Earth.

Speciation was so important to Darwin that he made it the title of his most famous book. And that book did give some evidence for the splitting. The only diagram in the whole of *The Origin* is a hypothetical evolutionary tree resembling figure 1. But it turns out that Darwin didn't really explain how new species arose, for, lacking any knowledge of genetics, he never really understood that explaining species means explaining barriers to gene exchange. Real understanding of how speciation occurs

began only in the 1930s. I'll have more to say about this process, which is my own area of research, in chapter 7.

It stands to reason that if the history of life forms a tree, with all species originating from a single trunk, then one can find a common origin for every pair of twigs (existing species) by tracing each twig back through its branches until they intersect at the branch they have in common. This node, as we've seen, is their common ancestor. And if life began with one species and split into millions of descendant species through a branching process, it follows that every pair of species shares a common ancestor sometime in the past. Closely related species, like closely related people, had a common ancestor that lived fairly recently, while the common ancestor of more distantly related species, like that of distant human relatives, lived farther back in the past. Thus, the idea of *common ancestry*—the fourth tenet of Darwinism—is the flip side of speciation. It simply means that we can always look back in time, using either DNA sequences or fossils, and find descendant lineages fusing at their ancestors.

Let's examine one evolutionary tree, that of vertebrates (figure 2). On this tree I've put some of the features that biologists use to deduce evolutionary relationships. For a start, fish, amphibians, mammals, and reptiles all have a backbone—they are "vertebrates"—so they must have descended from a common ancestor that also had vertebrae. But within vertebrates, reptiles and mammals are united (and distinguished from fish and amphibians) by having an "amniotic egg"—the embryo is surrounded by a fluid-filled membrane called the amnion. So reptiles and mammals must have had a more recent common ancestor that itself possessed such an egg. But this group also contains two subgroups, one with species that all have hair, are warm-blooded, and produce milk (that is, mammals), and another with species that are cold-blooded, scaly, and produce watertight eggs (that is, reptiles). Like all species, these form a nested hierarchy: a hierarchy in which big groups of species whose members share a few traits are subdivided into smaller groups of species sharing more traits, and so on down to species, like black bears and grizzly bears, that share nearly all their traits.

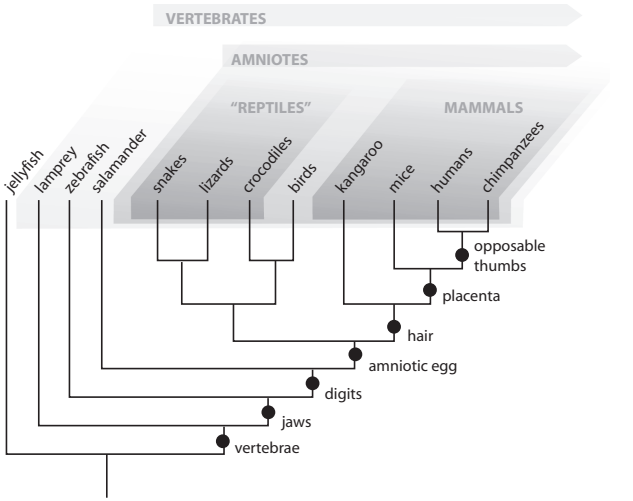

FIGURE 2. A phylogeny (evolutionary tree) of vertebrates, showing how evolution produces a heirarchical grouping of features, and thus of species containing these features. The dots indicate where on the tree each trait arose.

Actually, the nested arrangement of life was recognized long before Darwin. Starting with the Swedish botanist Carl Linnaeus in 1735, biologists began classifying animals and plants, discovering that they consistently fell into what was called a "natural" classification. Strikingly, different biologists came up with nearly identical groupings. This means that these groupings are not subjective artifacts of a human need to classify, but that they tell us something real and fundamental about nature. But nobody knew what that something was until Darwin came along, and showed that the nested arrangement of life is precisely what evolution predicts. Creatures with recent common ancestors share many traits, while those whose common ancestors lay in the distant past are more dissimilar. The "natural" classification is itself strong evidence for evolution.

Why? Because we don't see such a nested arrangement if we're trying to arrange objects that haven't arisen by an evolutionary process

of splitting and descent. Take cardboard books of matches, which I used to collect. They don't fall into a natural classification in the same way as living species. You could, for example, sort matchbooks hierarchically beginning with size, and then by country within size, color within country, and so on. Or you could start with the type of product advertised, sorting thereafter by color and then by date. There are many ways to order them, and everyone will do it differently. There is no sorting system that all collectors agree on. This is because rather than evolving, so that each matchbook gives rise to another that is only slightly different, each design was created from scratch by human whim.

Matchbooks resemble the kinds of creatures expected under a creationist explanation of life. In such a case, organisms would not have common ancestry, but would simply result from an instantaneous creation of forms designed *de novo* to fit their environments. Under this scenario, we wouldn't expect to see species falling into a nested hierarchy of forms that is recognized by all biologists.[2]

Until about thirty years ago, biologists used visible features like anatomy and mode of reproduction to reconstruct the ancestry of living species. This was based on the reasonable assumption that organisms with similar features also have similar genes, and thus are more closely related. But now we have a powerful new and independent way to establish ancestry: we can look directly at the genes themselves. By sequencing the DNA of various species and measuring how similar these sequences are, we can reconstruct their evolutionary relationships. This is done by making the entirely reasonable assumption that species having more similar DNA are more closely related—that is, their common ancestors lived more recently. These molecular methods have not produced much change in the pre-DNA-era trees of life: both the visible traits of organisms and their DNA sequences usually give the same information about evolutionary relationships.

The idea of common ancestry leads naturally to powerful and testable predictions about evolution. If we see that birds and reptiles group together based on their features and DNA sequences, we can predict that we should find common ancestors of birds and reptiles in the fossil