

DENNIS R. TRUMBLE

# THE WAY OF SCIENCE

Finding  
TRUTH AND MEANING  
in a Scientific Worldview



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# PREFACE

*The universe is not only queerer than we suppose, but queerer than we can suppose.*

—J. B. S. HALDANE,  
*POSSIBLE WORLDS AND OTHER PAPERS* (1927)

This book, in all probability, should never have been written. And you should not be reading it now. These are not statements of moral principle but of scientific fact. Everything we have come to know about this universe—the way matter interacts, planets take shape, and life evolves—suggests that we owe our existence to a wildly improbable series of events that started off with a bang some 13.7 billion years ago.<sup>1</sup> Unlikely as it seems, twentieth-century science has shown that ours is a universe governed by fixed physical laws riding atop a churning sea of quantum uncertainty, a place where many things are predictable (up to a point) but nothing is preordained. Simply put, the best evidence now suggests that most things in this universe exist not because they have to but because they happen to—and this, dear reader, includes you and me.

Goodness knows this is not the sort of thing that rests easily upon the human mind, and it's been rolling around in mine for quite some time now. For me the wheels started turning when I first learned about the “Big Bang” theory back in grade school during the height of the space race. Thanks to Sputnik and the Cold War, science education in America had suddenly become a national priority and was being promoted with patriotic zeal at every grade level. Keeping pace with the Soviets meant that we couldn't start learning too soon, and so my second-grade science teacher, trooper that she was, did her best to explain to her wide-eyed students the latest scientific evidence for how the universe began and how incredibly old it was. And like most of my classmates I was duly impressed.

But contrary to what Miss Jackson had intended, the thing that struck me most was not the tremendous age of the universe but its incredible youth. The suggestion that the entire universe and all its contents were once packed into a space smaller than an atom was surprising enough, but that it should be only ten to twenty billion years old (as was the best estimate at the time) was something I simply couldn't imagine. A two with ten zeros; was that all? And what was there before that? Nothing? To me this was the most outlandish thing I had ever heard—and I was a firm believer in

Santa Claus at the time.

Little did I know how perfectly ordinary this would all seem next to the bizarre world of quantum physics, a surreal reveal that most schools, my own included, happily saved for twelfth-grade physics class. If the Big Bang theory pressed the boundaries of believability at a time in my life when the idea of flying reindeer seemed plausible enough, this quantum business was really pushing things now that my childhood naïveté had given way to the ecumenical skepticism of teen adolescence. Though I was never one to doubt the sincerity of my teachers, to my mind the assertion that quantum-scale objects behave like both waves of energy and particles of matter had all the trappings of a practical joke. How could any one thing, no matter how small, be two different things at once? It made no sense, like Santa and Rudolph writ small. What made even less sense (if such a thing was possible) was the claim that these tiny entities were not always bound by the same cause-and-effect rules we see everywhere in the “regular world,” and will, from time to time and for no particular reason, disappear from one place and show up in another. Virtual particles, antimatter, quantum tunneling: surely our physics teacher was having us on, if not for his own amusement then perhaps to test the limits of our credulity.

But this was no joke. Strange as it seems, the current scientific thinking—based on no small amount of evidence—is that events that occur at the quantum level are not just thoroughly weird but completely spontaneous, which is to say they have no actual cause. And to be clear, the evidence is not that we simply don't *know* what the causes are, it's that there *are no* quantum causes, material or otherwise.<sup>2</sup> Needless to say, these observations run counter to every instinct we have regarding the way the world works. And the implications are profound. For example, if the theory of quantum uncertainty is true—and again, all evidence points in that direction—it means that at the bottom of it all there are no grandiose plans, no whys or wherefores, no rhyme or reason: only chance encounters and random events. This implies, at the very least, that if you are looking for meaning in this world it is best not to look too closely because at the most fundamental level of the physical universe the gods really do appear to be playing dice.<sup>3</sup>

Of course, just because there is chaos at the quantum level doesn't mean that higher levels of existence can't be more rigidly structured or even deliberately orchestrated. For all we know the gods could be playing craps in the cellar and chess in the penthouse. But what does the smart money say?

Well, if the rules of Vegas have anything to teach us in this regard, it's that the gratuitous goings-on in the subatomic realm can have no bearing on the human condition so long as “what happens at the quantum level stays at the quantum level.” That much, at

least, we can take to the bank. But what does it buy us? Quite a lot actually, because this one axiom effectively reduces the problem of cosmic indeterminacy to a single key question: *Do random quantum effects ever “bubble to the surface” in ways that make the unfolding of the larger cosmos fundamentally unpredictable?* In other words, do the things that happen at the quantum level always stay at the quantum level?

Admittedly, the prospect that any single quantum event would have any effect at all on the world at large seems extremely unlikely given what we know about the kinetics of super-small particles. Consider the large-scale impact of individual air molecules, for example. At the molecular level the air around us is positively seething with activity, nearly as frantic and unpredictable as the quantum foam itself. Yet owing to the impossibly large number of molecules involved and their incredibly small size, the state of any one particular molecule has no appreciable effect on the atmosphere as a whole. Individual gas particles may behave erratically, but the air itself is perfectly predictable, acting in strict accordance with the laws that govern the behavior of gases everywhere. And the same can be said for those molecules found on land and at sea. Even the largest molecules are, energetically speaking, much too small to influence anything in the world at large in any meaningful way. So by virtue of direct comparison one might reasonably conclude that if the actions of individual molecules make no real difference in human terms, then the activities that go on at the subatomic level, no matter how random or bizarre, must count for even less. Thus, according to the rules of deductive logic the world in which we live would figure to be safely insulated from the bedlam below by impenetrable barriers of size and scale, just as common sense (and our druthers) would have it.

As reliable as this train of logic might seem, however, the trail of evidence does not lead us to the same destination. On the contrary, based on empirical science we now know that certain quantum events can have surprisingly profound and far-reaching effects on the macroscopic world in general and the living world in particular.

The biological impact of nuclear radioactivity is a classic case in point. Scientists have known for decades that a *single* gamma ray can damage DNA in such a way as to produce something called a “point mutation,” a one-letter change in our genetic code that, if poorly placed, can lead to cell death, diseases like sickle-cell anemia, and most forms of cancer.<sup>4</sup> While all these maladies are cause for concern, radiogenic cancers are especially worrisome due to the fact that the average human body is a cooperative of some eighty trillion cells, any one of which can turn cancerous if its genetic instructions are altered in just the right way. The good news is that it generally takes ten to twenty of these mutations to override

the security mechanisms that normally prevent our cells from multiplying out of control. The bad news is that these tiny errors tend to accumulate as we age, and with some 560 sextillion ( $5.6 \times 10^{23}$ ) human cells living in the world today, there is sure to be a sizeable number of these cells, perhaps tens or even hundreds of millions at any given time, that are just a hair's breadth away from malignancy. Combine this with the fact that our bodies are constantly being bombarded by gamma radiation from naturally occurring sources like radium and potassium-40 (commonly found in soil, water, meats, and high-potassium foods), and you can bet your life that someone somewhere in the world will develop cancer within the next few minutes, or hours at most, for no other reason than an unstable atom somewhere on Earth (or beyond) randomly emitted a high-energy photon that just happened to land in the wrong place at the wrong time.

Whatever else we may learn about the finer workings of the universe, this one fact alone should convince us that the barrier between the quantum world and our own is imperfect at best and that the “regular” world is not quite as regular as it seems. On the surface the universe we inhabit may appear orderly even to the point of orchestration, but deep down things are not so tidy. We now know, for better or worse, that there is a fundamental uncertainty in nature that belies our anthropocentric inclinations, an elemental randomness that is at once the destroyer of worlds and the creator of all things. Like the proverbial butterfly that stirs the air in Brazil one day only to trigger a tornado in Texas three weeks later, the ripples that radiate from the quantum realm are occasionally absorbed by the larger universe in ways that nudge the course of cosmic events toward unpredictable ends. And as the butterfly metaphor aptly suggests, the forces of serendipity extend far beyond the quantum level, touching everything from the evolution of life on Earth to the very formation of the Earth itself. Indeed, both computer models and real-world experiments have demonstrated conclusively that the tiniest change in the initial state of any complex system can lead to monumental changes down the line.<sup>5</sup> It is therefore quite possible, if not all but certain, that part of the reason you are reading this now is because somewhere in the depths of time a dinosaur sneezed.

That such strange and inexplicable things should be going on everywhere, and right under our noses, seemed perfectly ridiculous to me back in high school and in many ways still does. Thirty-three years and four engineering degrees later, I'm still not quite sure what to make of it all and can sympathize with those who find the vagaries of quantum indeterminacy and Chaos Theory a hard pill to swallow. To paraphrase a scientist whose work figures prominently in the pages to follow: to suppose that the Earth and everything we see around us arose through accidental processes aimed at no

particular outcome seems, I freely confess, absurd in the highest possible degree. Despite all the success that scientists have had in uncovering the secrets of nature—successes visibly borne out by the technologies of our age—there is no denying that the current scientific account of the universe defies all commonsense notions about how the world works, including the popular perception that there is agency in nature and that we are all somehow *meant* to be here.

And therein lies the problem. In the space of just a few generations science has all but shattered our most cherished notions about what it means to be human while at the same time giving rise to technologies that make the continued belief in these notions more and more dangerous. To say that human history is rapidly becoming, as H. G. Wells put it, “*a race between education and catastrophe*,” is no exaggeration.<sup>6</sup> In some ways our species has grown up too fast, racing from adolescence to adulthood without allowing ourselves the time to adjust our thinking accordingly. But adjust we must—and not just for our sake. Ignorance of what science has to teach us about the world and ourselves might not bring human civilization to an apocalyptic end, but it is certainly the biggest threat to our continued development as an enlightened species, especially where our sense of moral responsibility toward our fellow travelers, human *and* nonhuman, is concerned.

My reason for writing this book is to make the case that scientific rationality and critical thinking are not only good for our physical well-being but also good for the soul—and essential to our achieving the kind of global stewardship worthy of our spiritual aspirations. Although science makes no claim to knowledge that is absolute, the scientific process has proven to be far and away the most open, direct, and dependable way there is to tell truth from fiction. And there has never been a time when making that distinction has been more important. Now more than ever we need to recognize that scientific literacy and critical thinking are not just tools for professional scientists; they are basic life skills, as vital to our personal and intellectual growth as reading, writing, and arithmetic. And contrary to popular belief, the fundamentals of scientific inquiry and critical thinking are concepts that lie well within the bounds of the average intellect. The fact that so many people don't really “get” how science works is a failure of our education system, not our students. Our failure as scientists and educators to talk about science in ways that everyone can understand might not account for all the muddled thinking surrounding issues like evolution and global warming, but it certainly adds to the confusion regarding the reliability of scientific information in general. What's more, the demotic misapprehension of science *as a way of knowing* poses a serious threat to the future

of all democratic societies, which rely on the participation of a rational, literate citizenry for their maintenance. That normal scientific uncertainty can be so easily exploited to undermine the legitimacy of real scientific knowledge is a sure sign that we have been failing our children in this regard for some time now. And if we can't even agree on what is true, we will never agree on what threats we face as a global civilization, much less what to do about them.

As critical as the understanding of science is from a global perspective, the benefits don't stop there. The scientific worldview also offers something that many people might not expect: a profound sense of wonder, connectedness, and yes, even optimism. Far from providing a cold and sterile outlook on the nature of things, the scientific method is actually responsible for more wondrous revelations about our world and our selves than any sacred text you can name, not the least of which is the knowledge that all life on Earth is connected through the bonds of common descent. Indeed, what science has revealed about the nature of humankind—how great the similarities and trivial the differences—is knowledge that completely destroys all claims to intellectual, racial, or ethnic superiority. Anyone who truly understands the science of evolution would no more look upon their fellow human beings with categorical disdain than they would kill an animal for sport.

Of course there is more to life than simply understanding our true place in the grand scheme of things. Facts without feelings are cold comfort at best, and we all deserve better. But if the best we can do is fool ourselves into believing ridiculous falsehoods about the world and our selves, where is the meaning—or the morality—in that? Happily, the evidence suggests that human beings on the whole are capable of a great deal more. The main thing that stands in the way in most cases, apart from the nostalgia we feel for the simple answers of simpler times, is the fear that the scientific outlook is emotionally impoverished and spiritually bankrupt. After all, in a dispassionate mindscape ruled by facts and reason alone, what room is there for passion, poetry, and love?

It's a fair question, but those who worry that a purely objective scientific worldview would provide poor sustenance in a world hungry for love are missing an important point. You might not know it by reading the daily newspapers, but there is no lack of love in the world. Love is everywhere and comes in an encouraging number of forms. Romantic love, love for our children, love of nature, love of god, love of country, love of community, love of family and friends—even our pets can, and often do, stir our deepest affections. Love is as plentiful as it is powerful. Unfortunately, love without understanding is a volatile thing. The plain truth is, we need

both...and if we are ever to rise above our parochial passions, it is on the rungs of the latter where we must begin our ascent. After all, genuine concern for the welfare of others, especially those unfamiliar to us, begins not with feelings of love but with pangs of sympathy.

If there is a single message I would like readers to take away from this book, it's that science is far more accessible—and a lot less scary—than people realize. Contrary to popular belief, the scientific outlook is not only something that most everyone can understand on an intellectual level; it is also as emotionally satisfying as any faith-based philosophy you can imagine. Indeed, despite all fears to the contrary, scientists are finding that moral truths and personal meaning are not merely the stuff of religious doctrine; these are tangible realities that can be discovered through an honest examination of ourselves and of the world around us. I like to think this is what Darwin meant when he wrote, “*There is grandeur in this view of life.*”<sup>7</sup> And at a time when a shared scientific outlook is so desperately needed yet so rarely sought, there has never been a more urgent need to reaffirm his hopeful vision.

# INTRODUCTION

# TRUTH AND CONSEQUENCES

*Innocence about science is the worst crime today.*

—SIR CHARLES PERCY SNOW

When one thinks about science and what it's good for, the first thing that usually comes to mind are the myriad benefits of modern technology—and understandably so. These days it's hard to imagine our lives without electric lights, automobiles, radio, television, cell phones, microwave ovens, personal computers, and the Internet. Not to mention the host of medical advances that now allow us to enjoy these creature comforts longer than ever before. Air travel, antibiotics, refrigeration, radar imaging, vaccines, lasers, digital electronics...the list of technological marvels borne of scientific discovery is as extensive as it is impressive. But there is another benefit of science and the scientific method that, while less obvious, may ultimately prove to be far more important in the long run: namely, the ability to look beyond our preconceptions and see the world and ourselves in a truer light.

Coming from a working scientist this might seem a tad self-indulgent—another case of someone with a hammer approaching every problem as if it were a nail. And I admit there may be some measure of truth to that. Like most people, the more I learn about something—whether it's science, art, music, or just about anything else—the more important it seems. It's a common affliction. We all have our biases when it comes to the things we feel are important, and the things we know best are the things we tend to value most. For this reason alone every scientist can be expected to extol the virtues of scientific literacy just as historians tout the importance of historical literacy, artists endorse artistic literacy, and Microsoft promotes computer literacy. But while all forms of literacy are important in their own right, there are good reasons for listing scientific literacy among the most essential of modern-day skills. The surprising thing—and what I hope to convey in this book—is that these reasons have less to do with advancing our ability to solve emerging technological challenges than establishing an informed, rational foundation for our moral attitudes and behavior.

What makes the understanding of science indispensable from a moral perspective might not be obvious at first glance, but on closer

inspection the connection is inescapable. In fact, the link between scientific knowledge and moral reasoning is so fundamental it can be summed up in a single sentence: *In order to have a true sense of right and wrong one must first know what is true.* You don't have to be a professor of ethics to know that basing our moral concerns on false precepts is probably a bad idea. Everyone understands this on some level, just as every educated person understands that false beliefs have led ordinary people to do some extraordinarily horrific things in times past. In Mesoamerica, for example, rituals involving human sacrifice were once performed on a routine basis in order to appease gods that every sane human being now agrees existed only in the imagination of the faithful.<sup>1</sup> These days everyone familiar with this chapter of human history understands that the religious beliefs of the Incas, Mayans, and Aztecs were tragically misguided and that, because of those beliefs, hundreds of thousands of people were systematically tortured and killed for no real reason at all.

Certainly had the Aztecs understood the world the way we understand it today things would have been very different, especially for those on the receiving end of the sacrificial blade. But, fundamentally speaking, things are not so different now as we would like to think. The fact is, we are still, some five hundred years and one scientific revolution later, largely governed by hand-me-down beliefs for which there is no rational justification. And like the Aztecs, many of us still treat those beliefs as though the world depends on them. Unfortunately, history teaches that things tend to get ugliest when people fail to temper their beliefs with the simple understanding that they might actually be wrong. Racism, sexism, religious inquisitions, the slave trade, “holy” wars, the Holocaust, and a long list of genocides past and present are all examples of what can happen when people silence the better angels of their nature with gratuitous moral certainties. Indeed, the instant our beliefs become set in stone we lose the ability to recognize—and thus learn from—our mistakes, at which point all intellectual progress ceases and our ability to think for ourselves withers away.

## **REASONABLE DOUBT**

Given the none-too-subtle lessons of human history, one would think that the perils of faith-based reasoning would be something that every human being would take great pains to avoid. Instead, billions of people continue to eschew the scientific outlook in favor of the same sorts of inherited beliefs that inspired the Aztecs to casually eviscerate their fellow human beings. How is this possible?

The simplest, and perhaps most charitable, explanation is that

people of faith imagine that their particular belief system is somehow more valid and/or less harmful than the discredited beliefs of the ancients. Unfortunately for everyone, the evidence suggests otherwise. While it is true that ritualistic human sacrifice is now largely a thing of the past, people the world over continue to be harassed, injured, and even killed in reprisal for offenses committed against one deity or another, including such make-believe crimes as blasphemy, homosexuality, lewd behavior (women), apostasy, idolatry, and practicing witchcraft. There are even certain places in the world where expressing belief in anything other than the prevailing faith of the region is not just dangerous, it's practically suicidal.

And the damage doesn't stop there, for although the cost of in-group dogmatic thinking would figure to come mostly at the expense of perceived outsiders, the sectarian faithful pay a price that is just as steep. To be clear, this is not to suggest that there are no practical benefits to living among like-minded individuals who share a similar outlook on life, even if that outlook is not particularly rational. There are, in fact, plenty of practical advantages to be gained through the practice of conformist thinking, and there is no denying that, on the whole, they have served humanity extremely well up to now. The problem, however, is that modern technology has now pressed us to the point where global cooperation is an absolute must, and arbitrary dogmatic beliefs are the perfect impediment to consensus building between groups of people that, for reasons bound to history, happen not to share the same subjective take on reality. Indeed, while evidence-based worldviews tend to converge upon a single objective version of reality that can be revised as new information comes to light, faith-based worldviews can assume any form imaginable and brook no compromise. Needless to say, these are not the best conditions for fostering cooperation of any sort, much less the global kind. Worse still, because dogmatic beliefs often couch conflicting interpretations of reality in terms of eternal punishment and reward, the tension created by competing dogmas can be brutally intense, as demonstrated by the extreme expressions of sectarian violence that pepper the news with depressing regularity.

Of course, the ill effects of dogmatic thinking are not always so overt. People who preach nonviolence while condemning the "evils" of condom use and stem cell research, for instance, are more subtle in their methods but no less harmful. The truth is, these pious individuals, well meaning though they may be, add mightily to the excess of misery in the world by facilitating the spread of preventable diseases among the faithful and delaying the development of effective cell-based treatments for devastating diseases like cancer, diabetes, heart failure, neurological disorders,

and Alzheimer's. But again, the damage doesn't stop there. Religious taboos against blood transfusions and the practice of faith healing are thought to be responsible for dozens of preventable deaths every year in the United States alone, infants and children chief among them.

The depths of this travesty were recently plumbed in a paper published in the journal *Pediatrics*, in which researchers examined cases of 172 American children who died between 1975 and 1995 and were denied medical treatment due to the religious beliefs of their parents.<sup>2</sup> One fatality cited in the report was a two-year-old girl who choked on a bite of banana for nearly an hour while “her parents frantically called other members of [their] religious circle for prayer.” Another was a twelve-year-old who was kept out of school for seven months “while the primary osteogenic sarcoma [tumor] on her leg grew to a circumference of 41 inches” before her death. Overall the study found that 140 of these youngsters had a 90 percent chance of survival if standard medical care had been provided, meaning that 126 children lost their lives as a direct result of their parents' inability to evaluate truth claims in accordance with the evidence. This same failing is also why many parents, despite all evidence, are now refusing to vaccinate their children for fear of autism, giving the viruses that cause polio and measles (among others) a second chance at life—and another stab at our kids.<sup>3</sup>

As painful as it is to contemplate the senseless deaths of these young innocents, however, we must also bear in mind that the little children are not the only ones to suffer for “their” faith. Less lethal (usually) but just as pernicious are the faith-based assumptions that oblige hundreds of millions of women today to live as second-class citizens purely because of their sex. If the mass of men live lives of quiet desperation, how much more desperate are the lives of those women born in subjugation to the faith of their fathers? Likewise, the caste system in India, an enduring corruption of the Hindu faith, continues to condemn tens of millions of Indian citizens to lives of abject poverty despite government efforts to outlaw caste-based discrimination.

These are but a few of the demons of our lesser nature unleashed by our blind allegiance to traditional beliefs. Many more, too numerous to mention, are let loose on the world every day as people move heaven and earth to justify beliefs that play to their prejudices but defy all reason. And for all their subtlety, the ill effects are painfully obvious. So even if the long history of faith-based atrocities—ritualized murders, genocides, inquisitions, subjugations, holy wars, 9/11, the whole lot—were somehow secreted away in an effort to conceal the dark side of unthinking belief, the glaring facts of modern-day life should nonetheless make it blindingly obvious to every educated person on the planet that

basing our moral sense on anything other than tangible reality is fraught with the worst kind of danger.

And yet, despite mountains of evidence attesting to the unrivaled power of the scientific method to separate fact from fantasy, the idea that science might offer the most accurate account of the human condition, and thus provide the best measure of our moral obligations, is a notion that few people are prepared to even consider, much less accept. The question is why.

## **A FAILURE TO COMMUNICATE**

Part of the problem is that the scientific process *as a way of knowing* is a concept that is not widely understood outside the scientific community; a situation that makes it difficult, if not impossible, for scientists to communicate counterintuitive theories like evolution and the Big Bang in a way that nonscientists will find convincing. Fortunately, this “failure to communicate” has less to do with the intellectual acumen of the general public than the way we teach science. In truth, people are far more capable of understanding science than they realize. The main reason they tend not to is because the scientific method—arguably the single most important intellectual tool we have to bestow upon our children—has been given short shrift in science classrooms in deference to a longsome list of isolated facts that students are expected to memorize in order to pass their exams. This mind-numbing approach to science education, apart from being deadly dull, has proven disastrous from a scientific literacy standpoint in that most students manage to retain reams of scientific information (for a time) but learn very little about critical thinking and evidence-based problem solving in the process.

There are several reasons why this should worry us. Not only does this “poor man's science” impose an impoverished view of the world on people who might otherwise come to appreciate the “*grandeur in this view of life*”—a grave injustice in itself—it also paves the way for a host of other, more tangible, problems. For starters, our failure to provide our children with a proper science education, and the BS detection skills that come part and parcel, sets them up for a lifetime of exploitation by those with more education than scruples. This might not bother the quacks and charlatans of the world, but it should. Why? Because the concentration of critical thinking skills in the hands of a select few not only makes for a shyster's paradise; it also seriously retards the decision-making ability of local communities, nation-states, and humanity as a whole. This is bad news for everyone no matter where they live or

what they do, especially at a time when swift and concerted efforts are needed to address looming global threats presented by nuclear proliferation, biodiversity loss, and climate change (to name just three). As for self-governing republics like the United States, this situation is doubly precarious because without critical thinking skills voters cannot begin to fulfill their responsibility as stewards of a free and democratic society. Worst of all, our failure to promote critical thinking skills from the earliest grade levels undermines our ability as rational human beings to examine old assumptions in the light of new evidence and adjust our thinking accordingly, the very thing that makes intellectual and moral progress possible.

Of course, I am not the first to have noticed this gaping hole in our public education system. Many prominent scientists, including such luminaries as Albert Einstein and Carl Sagan, have written at length of their own struggles to overcome the same type of stultifying teaching practices that many youngsters face today. And thousands of reform-minded educators across the country have been quick to voice similar concerns. In the summer of 2010, for example, a committee of the National Research Council on K–12 science education in US schools released a draft framework for improved science standards in which they acknowledge:

*There is widespread recognition that too often standards are long lists of detailed and disconnected facts, reinforcing the criticism that the U.S. science curriculum tends to be ‘a mile wide and an inch deep.’ Not only is such an approach alienating to young people, but it can also leave students with fragmented elements of knowledge and little sense of the intellectual and creative achievements of science or its explanatory coherence.<sup>4</sup>*

Wading ankle-deep through the shallows of scientific knowledge without the tools to navigate deeper waters, it is easy to see how students might come away feeling frustrated and uninspired with little or no sense of how science—or the world—really works. Why wouldn't they? From the narrow viewpoint imposed by current instruction methods, science is made to look less like a path to self-discovery than an odd collection of trivial facts amassed by an equally odd collection of brainiac scientists; not exactly the best attitude to cultivate if our goal is to build an inclusive, enlightened society. Indeed, one of the great ironies of our time is the fact that, while we live in a society increasingly dependent upon science and technology for its maintenance, hardly anyone outside the scientific profession understands how science works in general or how scientists work in particular. If this situation is not yet a crisis in the most literal sense of the term, it soon will be. To quote Carl Sagan: “*This is a prescription for disaster. We might get away with it for a*

*while, but sooner or later this combustible mixture of ignorance and power is going to blow up in our faces.”<sup>5</sup>*

At this point you might be wondering: If the situation is really so dire, why aren't more scientists following Sagan's lead and joining efforts to stem the tide of scientific illiteracy? Why, with so much at stake, is there no concerted effort among American scientists to make science education a top national priority? What's holding them back?

As much as I would like to offer a nobler explanation (excuse?) for this apparent lack of concern from the scientific community, the main culprits in this crime of dispassion are, in fact, the usual suspects: time and money. Although job satisfaction polls indicate that most scientists are very happy with their career choice, the fact remains that doing science for a living can be as exhausting as it is rewarding. Gone are the days when scientists were mostly men of means who could afford to dabble in the empirical arts at their leisure. Today, science is an intensely competitive profession where time spent promoting science education is time lost in the struggle to keep the cycle of research, publication, and fund raising from grinding to an ignominious halt. So while few working scientists doubt the importance of a science-savvy citizenry, many consider public outreach efforts to be a luxury they simply cannot afford.

There is also the possibility, distasteful as it is to admit, that some small portion of the scientific community might not be especially eager to level the scientific playing field to such a degree. After all, viewed from the halls of academia, the dark cloud of scientific illiteracy is not without its silver lining. Oddly enough, the feelings of inadequacy and intimidation that many people experience when talking about science has been something of a public relations bonanza for researchers who, through no fault of their own, tend to receive a generous amount of respect and admiration due to the perceived perplexity of their craft. Apart from being extremely flattering, the enhanced reputation that scientists enjoy amid the present rash of science phobia has proven extremely useful in securing public funds for scientific research, which, trust me, is no small benefit. Thus, viewed from the narrow standpoint of professional pride and career advancement, the current epidemic of scientific illiteracy looks like a pretty good deal for working scientists.

Increasingly, however, gaining scientific prestige at the expense of common scientific literacy smacks of a Faustian bargain in that the lack of scientific understanding among nonscientists creates a serious barrier to the type of rational public discourse and consensus-building that is needed to address humanity's most pressing problems. And in the long run this is an extremely bad deal for everyone, scientists included. So whatever personal incentives

there might be pressing in the opposite direction, my guess is that most of my scientific colleagues would gladly trade their status as card-carrying members of the intellectual elite for a society replete with critical thinkers. The dangers of rampant scientific illiteracy in modern times are simply too obvious—and too frightening—for even the most self-serving scientist to ignore.

But while instilling a broad appreciation for the scientific process is a cause that virtually every scientist can support in principle, achieving that goal will take more than mere lip service from those of us who do science for a living. Moral support is all well and good, but in order to bring critical thinking to the forefront of human discourse working scientists will have to become actively involved in demystifying the scientific process and convincing the public that *their own* understanding of the fundamentals of science is of critical importance to the continued well-being of not just themselves and their loved-ones but of every sentient being on the planet.

The main goal of this book is to help advance this cause by explaining, in the context of Darwinian evolution, what science is, what it is not, and why it is important that everyone understands the difference. But more than that, it is meant to remind researchers that their responsibility as working scientists does not stop at the laboratory door. Part of our job—and not the least part—is to promote the public understanding of science from the earliest grade levels through mentoring, educational outreach, and any other means at our disposal. We need to convince youngsters that understanding science is not only easy and fun; it is the key to unlocking life's greatest mysteries and realizing our fullest potential as both compassionate human beings and thoughtful stewards of a fragile planet.

Unfortunately, the gap between science and society cannot be bridged with the alacrity that circumstances demand without convincing a sizeable portion of grownups as well, and it's easy to see how the halting nature of the scientific process might be disconcerting to those adults who stand outside the scientific profession. After all, classroom science has for generations been largely about parsing time-honored experiments and established facts, which can make the entire scientific enterprise seem remarkably neat and precise. It's a flattering portrayal to be sure, but this is not how science really works. Real science involves untried experiments and unknown unknowns that render the process a lot messier than most people realize. Indeed, the inherent vagaries of empiricism—the residue of those hidden variables that prevent any single scientific experiment from being definitive in the most common sense of the term—are a constant source of frustration for scientists and nonscientists alike, especially where the complexities

of biology and medicine are concerned. Add to the mix suspicions of statistical chicanery that have persisted since the days of Samuel Clemens (*lies, damned lies, and statistics*) and the occasional high-profile case of scientific fraud, and it's easy to see how the credibility of science might suffer in the minds of those who were never taught how transparent and ultimately self-correcting the scientific process really is.<sup>6</sup>

## GETTING PERSONAL

Whatever doubts people may have about the technical *bona fides* of the scientific process, however, they pale in comparison to worries over what might happen should the scientific outlook ever become so commonplace as to empty the pews. And this, it seems to me, is where the ultimate challenge lies. It is one thing to teach people how science works from an intellectual standpoint. It is quite another to get them to stare, unblinking, at the things they fear most while at the same time lowering their defenses. This is a lot to ask of anyone, much less everyone. Life is challenging enough without adding more uncertainty to the mix. And science, unlike religion, offers no guarantees.

The good news is that once you understand what science has discovered about the true nature of the human condition, you realize that many of our worst fears about the scientific worldview are largely, if not entirely, unfounded. Consider the issue of morality for example. One of the biggest dangers ascribed to the broad acceptance of the matter-of-fact worldview that science affords is that it would strip away all incentives toward moral behavior and, in so doing, lead straight to social chaos. This concern is perhaps best distilled in a quote that Jean-Paul Sartre attributed to Dostoyevsky in *The Brothers Karamazov* wherein Ivan Karamazov claims, “*If God did not exist, all things would be permitted.*”<sup>7</sup> Admittedly, if this were true it would be a good reason to think twice about teaching children to calibrate their beliefs strictly in proportion to the evidence (the logic being that it is better to live in blissful ignorance than painful enlightenment). In truth, however, worldwide health and crime statistics suggest nothing of the sort and, if anything, imply just the opposite. There is, in fact, no positive correlation between the proportion of religious believers and societal health—a finding that doubtless comes as no surprise to the hundreds of millions of good, honest people currently living exemplary lives without the benefit of religious belief. Moreover, there is a large and growing body of evidence in the scientific literature indicating that our sense of right and wrong is an inherent

feature of our mental makeup—and that of many other species besides.<sup>8</sup> In short, science has shown in no uncertain terms that morality is something we come by naturally; an empathic instinct that can be either nurtured and developed or starved and stunted. It need not be imposed from the outside by threats of reprisal in this life or the next. Thanks to science, we now understand that we are better than that.

But even if there were a strong positive link between morality and religiosity, there would still be no reason to abandon the scientific outlook purely on religious grounds because, contrary to popular belief, there is nothing inherently anti-religious about science. It may sound counterintuitive, but science holds no *a priori* prohibitions against the kinds of things that religious people tend to believe—even the really crazy stuff. The scientific process can only confirm or refute; it does not define or limit what is possible ahead of time. If what you believe is true, you can rest assured that science will not prove you wrong. If, on the other hand, what you believe is not true, then you should ask yourself: what is it, exactly, that I am holding on to? A hope? A dream? And at what expense?

Perhaps even more disconcerting to religious thinkers than the social ramifications of widespread rationalist thinking is the fear that the scientific outlook is too reality-bound to provide the same sense of hope and meaning traditionally derived from less empirical ways of looking at the world. But this assumes that the practice of calibrating one's beliefs in proportion to the evidence means rejecting the possibility that there is much more to this world than meets the eye, and nothing could be further from the truth. Nobody understands the limits of human knowledge better than scientists. Any scientist worthy of the title would not hesitate to acknowledge that our understanding of the cosmos, while vastly improved these last few centuries, is far from perfect and probably always will be. No matter how much we learn about our universe there will always be mysteries that lie beyond the power of science to unravel entirely, fundamental things we can never know for sure. What came before the Big Bang, for example, is one nut that scientists will probably never crack, which leaves open a whole host of fact-friendly possibilities for the spiritually minded to intelligently explore.

It could be, for example, that the universe we see today is just the latest in an infinite series of cyclic events in which sentient beings like ourselves are recycled along with the heavens. If this is true—and there is no evidence to prove that it isn't—then the life we are experiencing now may be just the latest in an endless string of lives, each one a completely independent existence with an entirely fresh beginning. So far as science can tell, our conscious selves may have been around before, in one form or another, in some distant

past and may eventually come around again in the far future. This vision of the cosmos might, in fact, represent the best of all possible worlds in that it avoids the world-weariness that is bound to overtake and consume any intelligent being condemned to live continuously and forever. And that goes double for eternal beings living under what most people would consider to be “heavenly” conditions, bereft of dangers to avoid, problems to solve, and challenges to overcome. (One might also wonder in passing exactly what sort of “meaning” there is to be gained from such an idyllic existence.)

If you are convinced that there can be no meaning without permanency—a sentiment I do not share but can certainly understand—there must be dozens of ways to envision our eternal continuance that are perfectly compatible with the current scientific understanding of the cosmos. We need not resort to the cosmology of the Iron Age to imagine ourselves to be a lasting part of something far greater than ourselves. We simply need to acknowledge what we already know (that is to say, what science has revealed thus far) and consider the possibilities. This, to my mind, makes the continued belief in an eternal, judgmental, punishment-metering overlord—for which there is not a smidgen of compelling evidence—not only pointless but perfectly perverse given the demonstrable downsides.

The point is that we don't have to pretend to be certain about beliefs we cannot defend in order to live full, meaningful lives. Just because there are many things about our world that we don't fully understand doesn't mean we must deny the things we *do* understand in order to preserve our sense of purpose and meaning. It simply isn't necessary. Knowing that the universe was not created specifically for our benefit need not diminish our collective or individual sense of self-worth. The plain fact that we are here, that life exists at all, is proof positive that something wonderful is going on here. It might not be what we expected, but that doesn't make it any less meaningful. If anything, knowing how fragile and fleeting we really are—and not knowing for sure what may or may not come after—makes life all the more precious.

This is why a healthy dose of doubt is one of the best gifts any parent can give to their children, for it is doubt that causes us to hesitate, to stop and think. Doubt can't keep us from making mistakes, of course, but it *can* keep us from compounding them to the point where others are made to suffer as a consequence. Indeed, the surest way to turn an honest mistake into something sinister is to wield it with unyielding certainty. As fallible human beings we not only have the right to express uncertainty about claims backed by little or no evidence; we have an *obligation* to do so, not only to challenge the dictates of others but to reinforce the habit of

questioning our own assumptions about the way things are.

Not only is the willingness to question our every belief the only real way forward in an intellectual sense, it is the only way to ensure that the mistakes we make in interpreting the nature of things are not compounded by the kind of dogmatic certainties that serve to validate prejudices, silence the conscience, and keep people from thinking deeply and critically about the things that matter most. Although science teaches that in principle we can never be one hundred percent certain about anything, we can be reasonably sure that Aztec priests harbored no serious doubts about their core beliefs as they tore the beating hearts from the chests of their still-conscious victims. Likewise, seventeenth-century scientists, secure in the knowledge that animals were mere “automatons” lacking both sensation and self-awareness, would casually nail dogs to boards by their four paws and flay them open while still conscious in order to study the circulation of the blood.<sup>9</sup>

Looking back, these acts seem about as horrifying and unconscionable as any we can imagine. And yet, these people never intended to be cruel. Nor were they aware of the intense and gratuitous suffering being delivered at their hands. On the contrary, they were all acting in good faith, supremely confident that what they were doing was the right thing. The fact that they didn't understand what they were *really* doing may excuse the crime, but it does nothing to lessen the misery that resulted from their abject certainty. If we ever hope to bring this type of horrific, well-meaning behavior to an end we must first resolve to stop pretending to be sure of things that no human being can be sure about. We must learn to embrace the uncertainty of life and face the realities that face us, or risk repeating the same unwitting atrocities for the remainder of our tenure here on Earth. It sounds daunting I know, but, as I hope to show in the pages to follow, there is much more to be gained than lost in freeing ourselves from our most cherished certainties, be they religious, scientific, or otherwise.

## **BETWEEN THE COVERS**

This book, at its heart, is my response to a growing “crisis of faith,” a situation that threatens to derail our development as a sane and sensible species. Everything from the modern creationist movement to the increasing role of religion in politics speaks to our failure as a society to secure the blessings of rational discourse for ourselves and for our posterity. The good news is that it doesn't have to be this way. Far from being the sole province of scientists and academicians, critical thinking is a skill that can, and indeed must,

be taught to every child from the earliest grade levels. Now more than ever we must arm our children with the wherewithal to think for themselves, teaching them how to tell proof from propaganda, rational beliefs from superstition, and objective reality from abject fantasy. Only then will the prevailing culture of dogmatic thinking and the hostility it inspires give way to an era of responsible global stewardship, a time when all decisions great and small are based on demonstrable facts and not just wishful thinking.

Although it is hard to imagine a topic more compelling than this, the trick, as always, is in the telling. And like any true-life drama, this story cannot be told to any meaningful effect without first setting the stage. After all, as wondrous and inspiring as our journey of scientific self-discovery has been, one cannot truly appreciate the astonishing things that science has revealed about the human condition without first understanding what it is about science that makes it worthy of our trust. People are smart, but they face a cacophony of conflicting claims that are not always easy to resolve by common sense alone. Scientific evidence is all well and good, but experience teaches that things are not always as they seem, and even the “experts” don't always interpret the same data in the same way. So with all the controversy swirling around those areas where scientific knowledge challenges conventional wisdom, how can we be sure that scientific ways of knowing are more reliable than traditional tenets, time-honored social doctrines, scriptural teachings, or even our own base intuitions?

[Part 1](#) of this book, *From So Simple a Beginning*, attempts to answer this question in the context of what is easily the most emotionally charged scientific theory of our time: the evolution of species. By examining the way in which Darwin arrived at his theory of natural selection and his struggle to come to terms with what his research had revealed, I hope to make clear not only how the scientific process works in principle but also how scientists work in practice to, however haltingly, arrive at the truth despite their own preconceptions. To underscore the importance of knowing both what science is and what it is *not*, I also describe how evolutionary opponents have—sometimes unwittingly and sometimes not—turned the scientific process on its head in order to preserve many of those same cherished preconceptions.

The second section, *Science for Everyone*, explains why scientific ways of thinking do not come naturally to the human mind (hence the need for universal science education) and challenges the popular belief that science is too difficult for the general public to understand. The take-home message here is that scientific literacy and critical thinking are not just tools of the scientific trade. Like reading and writing, the ability to evaluate empirical evidence and adjust our views accordingly are essential life skills that can, with

sufficient effort, be mastered by most everyone.

This is easier said than done of course, and if there is one major stumbling block that scientists and educators tend to overlook when it comes to promoting the public understanding of science, it's the simple fact that getting at the truth of things isn't always at the top of everyone's agenda. In fact, when it comes to certain “big picture” questions, honest inquiry tends to rank rather low on our list of priorities, as the perceived need to preserve hopeful beliefs about the world (and ourselves) often trumps our desire to know what's *really* going on. This is why, by and large, you cannot reason someone out of a position they didn't reason themselves into. For many people of faith the issue isn't about determining which beliefs are true and which are false but, rather, deciding which beliefs are good and which are bad. Thus, from an educational perspective it is important to understand that if someone really wants—or feels the need—to believe something, no amount of evidence or clever argumentation is going to dissuade them because the truth is not what truly interests them most. In the end what people really want is a worldview they can live with, not knowledge they might prefer to live without. If this is true, then the only realistic way to loosen our collective grip on our most dangerous delusions is for rationalist thinkers to (somehow) convince people of faith that (1) the traditional beliefs they assume to be both good and necessary are, in fact, neither, and (2) the objective reality that science has revealed is not nearly as dark and gloomy as commonly thought.

With this realization in mind, [part 3](#), *Transcending Faith*, challenges readers to reexamine the common conviction that, right or wrong, the benefits of unthinking faith are worth the cost. Being realistic, this is a topic I approach with some trepidation, as there are literally billions of people—family and friends included—who take no small comfort in their religious convictions. It's hard to put a value on those things that give us peace of mind, no matter what their source. And while there is certainly something to be said for pursuing the truth for truth's sake, it would be cruel to rob anyone of their fondest hopes and dreams merely to chasten them with the cold, hard realities of the “real” world. This, however, is not my intention. Instead, what I hope to do here is convince readers that the damage we inflict upon one another in the service of our most durable and divisive myths is wholly unnecessary in light of what science has revealed about the world and our place in it. The truth is, the marvels of the “real” world as revealed by science are far more inspiring—and more liberating—than anything we have ever imagined for ourselves.

The final chapters, grouped under the Adamsian heading *Life, the Universe, and Everything*, explore the “big picture” implications that stem from the current body of scientific knowledge, including

what it means to be human in a universe that didn't know we were coming. Here the reader will find more questions than answers, but perhaps it's only fitting that a book rooted in science should lead to more puzzles in the end. And there are plenty left to be solved. For example, given what we know about our fortuitous rise from the swirling dustbin of creation, what are the odds that there are other advanced civilizations out there contemplating the cosmos along with us? Are we alone? And if our fragile planet really is, as some suggest, a singular “*bastion of animals in a sea of microbe-infested worlds*,” what would that mean to us?<sup>10</sup> Is there significance to be found in being a part of something so rare and precious? And what about the long view? Does the fact that we live in a universe with an expiration date make our existence ultimately pointless, or does life's true meaning transcend mere permanency?

These are but a few of the “big questions” that modern science has given us the opportunity to ponder in an informed way for the very first time; the ones that really matter. We may never find the answers to all our questions about life, the universe, and everything, but one thing seems clear enough: if these questions matter, then so must we.

PART I

# **FROM SO SIMPLE A BEGINNING**

**Evolution and the Scientific Process**

# CHAPTER 1

## THE DISSENT OF MAN

*Sit down before fact as a little child, be prepared to give up every preconceived notion, follow humbly wherever or whatever abysses nature leads, or you will learn nothing.*

—THOMAS H. HUXLEY, LETTER OF REPLY TO  
CHARLES KINGSLEY (SEPTEMBER 23, 1860)

When you stop to think about it, the enormous body of knowledge that we humans have come to appreciate in our brief stint on this planet is really quite remarkable. Our species, *Homo sapiens*, having branched from our hominid lineage a mere two thousand centuries ago, has far outstripped the cognitive capacity of every other earthly life form that has ever existed. We alone have come to understand the immensity of the universe, the workings of the stars and planets, and the forces that drive the seasons and turn night into day. Only humankind has managed to grasp the nature of the elements, the unity of matter and energy, the activities of the cell, and the function of the heart. These and countless other insights have, through the power of observation and reason, all become the exclusive province of the human mind.

Even more impressive is the stunning rapidity with which so many of nature's secrets have yielded to the ceaseless probings of humanity. Cave paintings and archaeological artifacts aside, the whole of recorded human history spans a surprisingly short period of time—fewer than five thousand years. And yet the vast majority of human knowledge has accumulated over an era much briefer still; a nascent epoch measured in mere *centuries*. Indeed, practically everything we've come to know about the natural world can be traced to the Renaissance and the formal adoption of what is now known as the scientific method. This objective approach to scientific inquiry, freed from the age-old compulsion to reconcile observation with preconceived worldviews, led quickly to the dissolution of numerous long-established and firmly entrenched beliefs that had effectively stymied scientific progress for nearly two thousand years. Chief among these doctrines were the geocentric astronomical system of Ptolemy and the Aristotelian conception of gravity and motion. Once these tenacious tenets were finally dispatched in the sixteenth century by the likes of

Copernicus, Kepler, and Galileo, the flood gates were opened. As suddenly as the dropping of Sir Isaac's apple, the modern era of free scientific inquiry and technological advancement had begun, promising to elevate humankind to heights scarcely imagined—perhaps even to know the mind of God.

As one discovery led inexorably to the next, however, the underlying assumptions that had buttressed our ancestors' views of creation since time immemorial came increasingly into doubt, creating a surge of societal angst that lingers to this day. Being plucked from our celebrated position at the center of the universe was bad enough, but then to suffer the indignity of evolution! The irony was piercing. It seemed the more enlightened we became, the more sanctified by intellect and reason, the further our status as unique, eternal beings was undermined. Could it be that man, in truth, was simply the latest in a long line of ephemeral animal species culled from the primordial seas by the forces of natural selection? Was it really possible that human beings, who had come to dominate the Earth and its creatures so completely, were actually *related* to these beasts?

To most people of the Victorian era this notion seemed perfectly absurd and, as such, was summarily dismissed as the idle ruminations of the academic fringe. To the scientific community, however, the body of evidence unearthed by the diggings of one Charles Darwin was not so easily ignored. Indeed, the voluminous observations that Darwin amassed in his 1859 opus *The Origin of Species* had clearly provided the best evidence to date that life in all its complexity had evolved from simpler forms and that the forces of change were still at work.<sup>1</sup> But that was the least of it. What really caused scientists to sit up and take notice was that Darwin had for the first time tied the evolutionary process to a scientifically viable mechanism of biological adaptation—something he called “descent with modification.”

## **DARWIN'S DANGEROUS IDEA**

Though the implications of Darwin's thesis were both provocative and far reaching, *The Origin of Species* might have emerged largely unnoticed beyond the cloistered walls of academia had its author not already published a popular tome on his *Journal of Researches* some two decades earlier.<sup>2</sup> As it was, word that Darwin was finally ready to publish his “big book on species” created something of a stir among the English book-buying public...so much so, in fact, that the original printing of 1,250 copies sold out to booksellers in a single day. Despite its popular appeal, however—or perhaps

because of it—a massive groundswell of resistance had already begun to take shape by the time the second edition was released just six weeks later. If Darwin had hoped to forestall his detractors with a surfeit of supporting evidence, he could harbor the fantasy no longer. The theory of evolution by means of natural selection, no matter how logical in construct or well supported by physical proof, was not about to go unchallenged.

Predictably, it was the clergy who spearheaded the backlash of opposition. But theirs were not the only voices raised in protest. Joining in the chorus were a goodly number of scientists who, for reasons known only to God, felt obliged to defend the long-standing supposition that all life forms had been created *de novo* in their present form. But to be fair, even the unchurched had every reason to be skeptical at first. After all, in the 2,500-year-history of Western philosophical thought, the fixity of species had scarcely been questioned, much less seriously challenged. Like begets like, that was the natural order among all living things. People beget people, swine beget swine, and tulips beget tulips—it was that obvious. And besides, unlike the ministerial dictates on celestial mechanics that had long stood in opposition to astronomical observations, there had never been a compelling reason to doubt the teachings of the church in *this* regard. No one, for example, had ever witnessed a cow begetting anything but another cow, and chicken eggs, when they hatched, never yielded anything apart from a chick. But perhaps more importantly, the idea of a perfect and unchanging natural world had, by Darwin's time, become more than just a provincial belief borne of cultural norms. It had also gained a large measure of scientific legitimacy, thanks to the 1735 publication of *Systema Naturae*, a seminal treatise on natural order in which Swedish botanist Carl Linnaeus introduced his scheme for classifying organisms according to their physical similarities, a scientific discipline known nowadays as taxonomy.<sup>3</sup>

The Linnaean system, still the basis for most taxonomic classifications used in biology today, was created under the explicit assumption that each class, order, family, and species of animal and plant in existence had remained unaltered since the world was new. Although the facts now speak strongly against this hypothesis, from a scientific perspective this was a perfectly legitimate place for the young Linnaeus to start, given the dearth of paleontologic (fossil) evidence at his disposal and the complete lack of genetic, embryologic, and biochemical clues available at the time. All in all, it was the kind of mistake that good scientists make all the time, and like all good scientists Linnaeus was not opposed to amending his hypotheses in deference to newfound facts. Indeed, as more information slowly came to light, Carl von Linné (as he would later come to be known) would ultimately abandon his original

contention that species were fixed and would conclude instead that some—if not most—species had arisen *after* the creation of the world through the process of hybridization. He was, after all, the first to propose that whales be grouped with cows, mice, and other quadrupeds. Still, as the son of a Lutheran minister, there were certain ideological lines that Linnaeus was not prepared to cross; time-honored beliefs that would ultimately blind him to the possibility that these changes might, in fact, be an open-ended process devoid of divine direction.

But while Linnaeus's work did cast a long shadow over all those who followed in his wake, Darwin's dilemma did not stem from just one man's narrow interpretation of an incomplete dataset. Linnaeus had simply advanced what Darwin had reason to believe was a false hypothesis, and the dissolution of false hypotheses is what ultimately pushes scientific knowledge forward. Linnaeus had done his part and Darwin was doing his, just as scientists were supposed to do. The problem was, the immutability of species was no ordinary hypothesis. This was a scientific paradigm with biblical backing; a theory that people very much wanted to believe. Thus, contrary to the base principles of scientific inquiry, the “fixity of species” hypothesis had in the minds of many come to assume the mantle of essential truth—an unassailable tenet that stood beyond all questioning. As a consequence, Darwin found himself not merely challenging a long-standing scientific conjecture but casting doubt upon a cherished article of faith. Pressing ahead meant that he would have to tread lightly and have plenty of proof to back his claims.

As Darwin prepared to publish his thesis, he was very much aware of the maelstrom he was about to unleash, this despite the fact that biological evolution was an idea that had already been bandied about for quite some time. The Greek philosopher Anaximander of Miletus (610–545 BCE) was among the first to broach the subject, having deduced, quite correctly, that humans had evolved from fishlike aquatic creatures that had somehow adapted to life on dry land.<sup>4</sup> For reasons lost to history, however, his proposal never grew legs and was all but forgotten until the Italian Renaissance when philosopher Lucilio Vanini finally revived the notion of human evolution in 1616, suggesting that humans descended from apes.<sup>5</sup> Unfortunately, the revival was short-lived, as the outspoken theorist was burned as a heretic just three years later. Still, despite this discomfiting reception, speculation concerning the evolution of species persisted and was widely discussed—albeit discreetly—in scientific circles even as a young Charles Darwin set sail as an unpaid naturalist on the British survey ship *H.M.S. Beagle* in December of 1831.

Upon his return to England, Darwin's five years of field work

studying the flora and fauna of Africa, South America, and the Galápagos archipelago quickly coalesced into a singular insight of immense importance: namely, that *natural selection* was the driving force behind the evolution of all living things. It finally made sense: a random variant within a population would, in time, become more prevalent if environmental conditions were to favor that particular characteristic. An elongation of the beak, a thickening of the fur, a flap of skin tucked between the toes, a bony protuberance here and there: just about any arbitrary nonconformity could do the trick under the right circumstances. Even the slightest competitive advantage might act to enhance survival, yield more offspring, and increase the prevalence of a particular trait among individuals of a species. And once a population had changed enough to become reproductively isolated from its progenitors, taxonomists would come to recognize these individuals as members of a new and separate species, similar yet distinct. String enough of these speciation events together and only the faintest similarities would survive from one end of the chain to the other; a situation that, in the prescientific era, provided the perfect pretext for humans to distance themselves from their animal kin.

At last, a self-consistent explanation for the evolution of species had been pieced together from the shards of evidence available to pre-genomic scientists. But was the public ready to hear it? Reaction to the publication of *Vestiges of the Natural History of Creation* in 1844 suggested to Darwin that they might not be.<sup>6</sup> Indeed, just as he was putting the finishing touches on a detailed sketch of his thesis, *Vestiges* author Robert Chambers had unwittingly given Darwin a sobering glimpse at the kind of reception his ideas were likely to receive. And it was quite an eyeful. Darwin could hardly help but notice the vitriol that Chambers had inspired with his suggestion that the Earth and its inhabitants had not been created all at once but had instead evolved gradually through a vast sequence of incremental changes. Although the author had cited evidence both copious and credible to support his conclusions, the idea that the creation process had taken considerably longer than biblical literalists had assumed did not play well with traditionalist thinkers. But this was nothing compared to the righteous indignation that greeted Chambers's proposition that humankind had, on a geological time scale, emerged quite recently as a transmutation of the great apes. Many people had taken this final assertion as a personal affront and were not shy about voicing their displeasure. Fortunately, these were gentler times and no one had sought to put the author's feet to the fire—at least not in the literal sense.

Still, it was easy to see why Chambers had chosen to publish *Vestiges* anonymously. It had taken more than a dozen generations

for people to fully digest the idea of an itinerant Earth circumnavigating its parent star, and by all indications most folks had little appetite for a second course of scientific revelation, especially one so unpalatable as the evolution of species. So despite having a 231-page treatise already in hand—a landmark essay that explained how natural selection might act to cull new species from existing varieties—Darwin hesitated. For better or worse the stormy politics of evolution had stayed his hand, redoubling his want to test every aspect of natural selection to the greatest possible extent before releasing his findings to a vexed and volatile public. This combination of diligence and trepidation had proved so viscous a mix, in fact, that it would ultimately prevent Darwin from publishing his theory for another fifteen years. Until, that is, he received a parcel from Alfred Russel Wallace.

## **GREAT MINDS...**

For ten years prior, Wallace had worked in the Amazon and Malay archipelago as a collector of exotic specimens for European buyers and in the course of his travels had ample opportunity to study the stunning variety of flora and fauna to be found there. He, like Darwin, had harbored a long-standing interest in the causes of organic evolution and had surmised in a sudden flash of recognition that the proliferation of plants and animals might very well operate under principles that parallel the economic checks and balances described by Thomas Malthus in his *Essay on the Principle of Population* (1798).<sup>7</sup> Like a bolt out of the blue, both men were struck by Malthus's observation that plants and animals naturally produce far more offspring than can possibly survive and thus create intense competition among siblings for limited resources. This singular insight, in concert with emerging geological evidence that spoke to the immense age of the Earth, raised the prospect that the tremendous diversity of modern species might, in fact, be the residue of innumerable varieties struggling over untold eons to survive amid shifting environmental conditions.

Excited over his breakthrough, which had come to him in dramatic fashion during a two-week bout with malaria, Wallace wasted little time. As soon as he was well enough, Wallace penned a brief essay on what he called the “*progression and continued divergence of varieties from their parent species*” and sent it off to Darwin, a man he knew through prior correspondence to be interested in “the species question.” With it he included a brief note asking Darwin to review the manuscript and, if he thought it worthy, forward it to Charles Lyell, whose *Principles of Geology*

had also figured prominently in his thinking.<sup>8</sup>

Darwin was stunned. Wallace had summarized his 1844 essay with such precision that he could scarcely imagine writing a better outline himself. The similarities were indeed uncanny, and though on some level Darwin must have been pleased to receive so clear an affirmation of his secreted theory, he was understandably pained to surrender ownership of his life's work and agonized over what to do next. True to his patrician upbringing, Darwin's first impulse was to stand aside and cede priority to Wallace, who, despite having started a distant second, was obviously prepared to publish first. On the other hand, Charles Lyell and botanist Joseph Hooker had for years urged Darwin to make public a sketch of his original essay and were resolute in their insistence that Darwin should now issue an abstract of his own to preserve the precedence that was rightfully his.<sup>9</sup> Still, Darwin worried that doing so might seem petty and underhanded given the circumstances, writing to Lyell in a letter dated June 25: "*I shd be extremely glad now to publish a sketch of my general views in about a dozen pages or so. But I cannot persuade myself that I can do so honorably.... I would far rather burn my whole book than that he or any man shd think that I had behaved in a paltry spirit.*"<sup>10</sup>

For Darwin, however, the issue of precedence would soon be eclipsed by more pressing concerns, as his infant son Charles—not yet nineteen months old—had recently taken ill with scarlet fever and was growing sicker by the day. Knowing that several children in the village of Downe had already died in the wake of the contagion, Darwin was consumed with worry and could think of little else, confessing to Hooker that under the circumstances it was "miserable in [him] to care at all about priority."<sup>11</sup> Conflicted and heartsick, Darwin soon lost all interest in what now seemed to him a trifling affair and was content to have his "two best & kindest friends" settle the matter in whatever way they thought fair.

Because they couldn't be sure that Wallace had not already sent a copy of his monograph elsewhere for publication, Lyell and Hooker felt obliged to act quickly. Their solution, though contrived primarily to preserve Darwin's priority, was perhaps as fair a compromise as could be struck under the circumstances. The plan was to credit both men by presenting a brief sketch of Darwin's original 1844 essay together with Wallace's monograph to the distinguished members of the Linnaean Society, who were scheduled to meet in London the following week. Sadly, by the time word of the arrangement reached Darwin, he and his wife Emma were arranging for the funeral of their son and preparing to move the other children out of Downe until the contagion had passed. "*I have just read your letter, & see you want papers at once. I am*

*quite prostrated & can do nothing but I send Wallace & my abstract of abstract [sic] of letter to Asa Gray, which gives most imperfectly only the means of change & does not touch on reasons for believing species do change. I daresay all is too late. I hardly care about it.”*<sup>12</sup>

On July 1, 1858, Charles and Emma Darwin buried their son in the parish churchyard. Later that same day, unread by Darwin and unbeknownst to Wallace, their shared accounting for the transmutation of species was formally announced to the world, effectively serving to solidify the mounting slurry of taxonomic data into a concrete science held firm by the mortar of natural selection. Here for the first time scientists were presented a self-consistent hypothesis regarding the actual *means* by which complex organisms might evolve from simpler forms—an idea supported by an abundance of evidence that could be put to the test.

If Darwin had been expecting to raise a row, however, he would have to wait. Taken completely unawares by this last-minute addition to the agenda, the twenty-five members of the Linnaean Society in attendance that evening had little opportunity to form a considered opinion of the work and so, perhaps wisely, offered very few comments at meeting's end. It would, in fact, take some time for the implications of Darwin's theory to sink in, as evidenced by the remarks made by society president Thomas Bell in an address delivered the following May. He (now famously) opined that the prior year's meetings had not “*been marked by any of those striking discoveries which at once revolutionize, so to speak, the department of science in which they bear.*”<sup>13</sup> In the end, of course, Bell's words could not have rung less true.

Although the significance of Darwin's proposal had managed to elude the Linnaeans in the short term, publication of the *Origin of Species* some seventeen months later had just about everyone talking, scientists and laymen alike. Passions ran high as the debate quickly reached a fevered pitch, igniting yet another skirmish in the ongoing battle between reason and sentiment.

But try as they might, the truth of evolution would never truly be tested by the loud and spirited objections that chimed steadily from church pulpits. Nor would it be undermined by the impassioned opposition of biblically minded naturalists like Richard Owen, whose storied debates with T. H. Huxley (a.k.a. Darwin's bulldog) were to become the stuff of legend. Indeed, the veracity of evolution via natural selection would not—and, indeed, *could* not—be challenged by those who simply rejected the notion out of hand, as their inability (or plain refusal) to faithfully weigh the evidence effectively stripped them of all authority to judge the matter.

Thus, at the end of the day the most intense and exacting examination of evolutionary theory would come not from Darwin's

most vociferous critics but would be administered by a group far more demanding: his scientific colleagues. Like all scientific hypotheses, the evolution of species by natural selection would either stand on its own merits or fall beneath the uncompromising scrutiny of the scientific method.

## THE RULES OF REASON

The thing that makes the scientific method so formidable is the fact that, like nature itself, it knows no prejudice nor is swayed by the wants of human sensibilities. Known also as the *method of inductive reasoning*, this approach to scientific inquiry—first brought to prominence in the sixteenth century by English philosopher Francis Bacon—relies entirely on the systematic use of observation and experimentation to separate fact from fiction.<sup>14</sup> Observations are used to formulate hypotheses (working assumptions) from which predictions are made and tested. Hypotheses that do not agree with observation or fail to yield accurate predictions regarding the phenomenon in question are abandoned without regard to pedigree or the power of its proponents. Only those hypotheses that consistently agree with observation rise to the level of scientific theory, a term strictly defined as *an explanation for some aspect of the natural world that is well supported by observed facts and tested hypotheses*. Because any given hypothesis can be tested by others, there is simply no place for an ill-conceived proposition to hide. Unless the proposed hypothesis consistently conforms to the available evidence, it will inevitably be discarded and replaced by a more tenable alternative, no matter how distasteful or counterintuitive that alternative might seem.

Of course, there have been and continue to be scientists who mistakenly feel their mission is to validate rather than test their hypotheses, never seriously considering the possibility that their personal intuition might actually be flawed. Indeed, this all-too-human tendency has led many a researcher to misinterpret and, on occasion, even falsify data in order to support a viewpoint they “know” to be correct. Fortunately, no faulty hypothesis can remain propped up by such self-serving scientific practices for long. Anyone who has ever attended a scientific conference or suffered the slings and arrows of the peer review process knows full well the enthusiasm scientists bring to the task of correcting the errors of their colleagues. Scientists, after all, tend not only to be highly accomplished but can be extremely competitive as well, each seeking to make their mark by exploring new avenues of research or, more often, extending established paths of inquiry beyond their

current scope. The impetus to make right the occasional mistakes of their fellow scientists is strengthened further by the realization that any accomplishment they themselves might hope to achieve will rely heavily on the integrity of prior work in their particular field of research. It is therefore in their best interest not only to ensure that data produced by their contemporaries are reliable, but also to question more established theories when new information brings them to doubt.

This routine and systematic reappraisal of accepted scientific theory is arguably the single most important facet of modern science and is the very aspect that distinguishes this method of critical thinking from other less reliable ways of viewing the world. Because there can, by definition, be no such thing as scientific dogma, all theories are subject to revision or outright rejection in light of fresh evidence gathered using the increasingly powerful probes delivered into the hands of latter-day researchers. Hypotheses previously confirmed against relatively coarse data from early experiments may, after all, prove to be only partly correct when examined under more exacting circumstances.

Such was the case when astronomers found, to their surprise, that the orbit of Mercury differed ever so slightly from the path predicted by Newton's universal law of gravitation; a most venerated scientific theory indeed!<sup>15</sup> It was this small but consistent aberration that first led scientists to reexamine the Newtonian laws of physics and ultimately recognize the phenomenon as evidence in support of Einstein's notion of special relativity—an idea accorded the rank of “theory” only after extensive experimental confirmation, of course. In all fairness to Sir Isaac, however, it must be said that although his formulations were not perfectly correct, they *were* perfectly consistent with the observations of the day and, in the end, proved accurate enough to land twelve men on the moon. Newton may have been wrong, but he was wrong for all the right reasons.

Be that as it may, the plain fact that the theories of no less an authority than Isaac Newton—perhaps the single most celebrated scientist and mathematician in history—can be questioned in the face of contrary evidence speaks volumes regarding the integrity of the scientific method. Through countless such episodes we have come to realize that even the most exacting research performed by brilliant scientists can, on occasion, be misinterpreted owing to the myriad possible hypotheses that can be formulated to explain a given phenomenon. Scientists as a rule try to select the most parsimonious explanation for a given set of observations in accordance with the guiding principle called *Ockham's Razor*, wherein a minimum number of assumptions are invoked to forge a working hypothesis. This approach offers a considerable advantage to scientists in that the simplest theories are generally the easiest to

disprove, thus leading to more rapid dissolution of erroneous precepts. By exposing their mistakes quickly, researchers minimize time spent chasing down false leads and thus improve their chances of uncovering some elusive facet of nature. When the simplest explanations prove wanting, layers of complexity are added to the hypothesis until theory and observation are reconciled once again. It is only through this painstaking process of trial and error that an increasingly accurate sense of how the world *actually* works has finally begun to emerge above the flotsam of myth, superstition, and received wisdom that has heretofore passed for real knowledge.

Modern science, in short, has become a self-correcting enterprise wherein all things are considered but only the theories that work endure. That is precisely why the exciting prospect of procuring limitless clean energy from cold fusion was ultimately abandoned: Despite all efforts, results from early positive experiments could not be reproduced.<sup>16</sup> This also explains how bizarre theories like quantum mechanics and general relativity have come to be widely accepted despite their seemingly outlandish consequences. As strange as they seem, these theories continue to accurately predict experimental outcomes and so have earned our grudging acceptance.

A playwright of substantial repute once penned the lines: “*There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy.*”<sup>17</sup> Thanks to the scientific method, we are finally beginning to understand the prescience of Shakespeare's words. It turns out that fact really *is* stranger than fiction, and it is only through careful, reasoned inquiry that we have begun to unravel the whole of nature's mysteries, a world that would otherwise have remained forever hidden from our animal senses. No wonder biologist E. O. Wilson touts the scientific method as “*demonstrably the most powerful instrument hitherto created by the human mind.*”<sup>18</sup> It simply won't allow us to fool ourselves despite our strong penchant for doing so.

## **THE NATURE OF EVIDENCE AND THE EVIDENCE OF NATURE**

Such was the daunting challenge that faced the untried hypothesis of Darwin and Wallace as their fellow naturalists set about to test their new idea. If complex animal and plant species truly evolved as a consequence of natural selection, they reasoned, traces of this gradual transformation process must surely exist. But where to look?

Darwin himself supplied an impressive volume of supportive evidence with the publication of *The Origin of Species*, wherein he detailed dozens upon dozens of instances where the “transmutation of species” seemed manifest. His principal inspiration was the natural laboratory that was the Galápagos archipelago, located some six hundred miles off the Ecuadorian coast. There, among the isolated micro-environments of this island group, Darwin documented numerous animal species that looked similar to those he had observed on the South American mainland, yet were surprisingly distinct in detail and numerous in variety.

Of all the island inhabitants documented in his field notes, the most celebrated are the bird species that have come to bear his name. There were, by his count, nine distinct varieties of finches living among the islands, each with beak structures and feeding habits remarkably fine-tuned to exploit the variety of food sources at their disposal (thirteen species are now known to inhabit the archipelago). This unexpected, if not unprecedented, observation prompted Darwin to remark in a carefully worded journal passage: “*Seeing this gradation and diversity of structure in one small, intimately related group of birds, one might really fancy that from an original paucity of birds in the archipelago, one species had been taken and modified for different ends.*”<sup>19</sup>

Modern evidence now suggests that these species are all descended from a single mainland variety called the Blue-black Grassquit (*volatinia jacarina*), which made its way to the island group some one hundred thousand years ago.<sup>20</sup> Because the arrival of new species was rare, these granivorous birds happened upon a landscape relatively free of competitors and were thus able to proliferate without constraint. As the population grew, random variations among individuals allowed some birds to exploit uncommon beak shapes by tapping food sources unavailable to others of their kind. The slow accumulation of small anatomic changes, fueled by the slight reproductive advantages they conferred, eventually allowed this single ancestor species to form distinct subpopulations, each inhabiting a unique ecological niche that had previously been unoccupied. Ground finches, for instance, developed heavy beaks ideal for crushing seeds, while cactus finches evolved longer bills suited for probing prickly pears for insects and fruit. Likewise, the arboreal lifestyle of the tree finch was made possible by virtue of its sharpened beak, which it uses to grasp wood-boring insects. Perhaps the most startling incarnation of this adaptive process, however, resides with the Sharpbeaked Ground Finch—a species found on several islands in the northwest corner of the archipelago. Known also as the Vampire Finch, these birds use their narrow bills to pierce the skin of boobies to feed on their blood. This curious behavior was first observed by an

American expedition in 1964 and is thought to be an adaptive variant of the symbiotic feeding habits of ground finches that routinely pluck parasitic insects from the plumage of these large seabirds.<sup>21</sup>

Despite the copious attention afforded these dusky little birds over the years, they were by no means the only Galápagos residents to exhibit such stark environmental conformities. Darwin also gathered evidence of this same adaptive process in a large number of other species unique to this island group. Among these were marine iguanas, large lizards like those on the continent that climb trees and eat leaves. In the Galápagos where such vegetation was sparse, these animals instead fed exclusively on algae growing along the rocky shoreline and had developed the peculiar ability to “sneeze” salt through a gland connected to their nostrils—an important adaptation to life in and around the saltwater sea.<sup>22</sup> And then there were cormorants: fish-eating seabirds similar to those routinely found skimming over the rivers and coastal waters of the mainland. These particular birds had lost the power of flight in exchange for superior swimming skills afforded by their more streamlined bodies, the ability to escape predation through the air being of little importance on these insular islands. There were also giant tortoises seen to resemble their continental cousins in most every respect save for their enormous size. Darwin found that these creatures had become so finely tuned to their local environs that the vice-governor of the islands claimed he could tell which island an individual tortoise occupied simply by the shape and pattern of its shell.<sup>23</sup> Those that lived on islands with relatively lush ground vegetation were easily identified by the leading edge of their shells, which were gently curved just above the neck. Tortoises from more arid regions, however, had longer necks and a saddle-shaped upper shell that allowed them to extend their heads almost vertically upward to snare the hard-to-reach vegetation endemic to these drier climes.

These and scores of similar observations linking physical form to both habitat and ancestry are what first led Darwin to suspect that organic beings may indeed change over time, as had been suggested near the turn of the century by Jean-Baptiste Lamarck and Darwin's paternal grandfather Erasmus. “*Why,*” Darwin wondered, “*should the species which are supposed to have been created on the Galápagos Archipelago, and nowhere else, bear so plain a stamp of affinity to those created in America?*”<sup>24</sup> This was especially puzzling in light of the geological and environmental conditions prevalent on these islands, which stood in stark contrast to those found on the South American coast. Darwin also wondered why the plants and animals of the Galápagos should bear so little

resemblance to those of the Cape de Verde archipelago, which share a similar climate and occupy islands of like size, elevation, and volcanic origin. Instead, these islands were populated by inhabitants of a kind most similar to those found in Africa, its parent continent. Of these observations Darwin remarked: “*I believe this grand fact can receive no sort of explanation on the ordinary view of independent creation; whereas on the view here maintained, it is obvious that the Galapagos Islands would be likely to receive colonists, whether by occasional means of transport or by formerly continuous land, from America; and the Cape de Verde Islands from Africa; and that such colonists would be liable to modifications;—the principle of inheritance still betraying their original birthplace.*”<sup>25</sup>

Still, Darwin realized that evidence of this sort—tantalizing though it was—would simply be viewed as an interesting quirk of creation were it not supported by compelling evidence that speciation not only *can* occur but actually *has* occurred and continues to reshape creatures to this day. To that end, he spent years compiling facts, performing experiments, and corresponding with naturalists of all stripes, not in a single-minded effort to confirm his hypothesis but rather to *test* it to the fullest possible extent. Like any good scientist, Darwin would not champion such a revolutionary idea based on a single line of circumstantial evidence, no matter how suggestive. After all, being a former divinity student, he too had embraced the traditional theological viewpoint regarding the immutability of species and was slow to believe what the evidence seemed to be suggesting. And so, before Darwin would consider sharing his ideas with the world, he would first have to convince *himself* beyond all rational doubt that species really had evolved over time, and that natural selection was the cause.

## CHAPTER 2

# A GRAIN IN THE BALANCE

*My mind seems to have become a kind of machine for grinding general laws out of large collections of facts.*

—CHARLES DARWIN,  
*THE AUTOBIOGRAPHY OF CHARLES DARWIN* (1887)

In the twenty-three years that separated the return of the *Beagle* from the publication of *The Origin of Species*, Darwin examined his hypothesis with a critical eye, weighing every reasonable argument that could be leveled against it. Indeed, in a profession where ideas tended to be exchanged rather liberally, his approach to this work was far more circumspect than was the norm. But he had reason to be cautious. Darwin knew full well that the evolution of species—like the voyage of the *Beagle* itself—was a perilous proposition, and he was not about to launch his theory before inspecting it from stem to stern. If there was a flaw in his thinking he was determined to find it before he set sail.

## WEIGHING THE EVIDENCE

Darwin began his two-hundred-thousand-word “abstract” with a detailed treatise describing variations (or breeds) known to arise among domesticated species due to selection pressures exerted by their human handlers. Having meticulously confirmed the power of artificial selection to alter the character of both plants and animals—a notion already widely accepted—Darwin could find no logical reason why the principle of selection should not also act in nature where competition for limited resources was both fierce and unrelenting. From this reasoned premise he then went on to recount numerous instances of variability known to exist among individuals and species in the economy of nature and to explain how a “struggle for existence” is necessarily brought about by the geometric rate of reproduction endemic to all organic beings. His argument, stated in the simplest possible terms, was that because many more individuals are born than can possibly survive, only those best suited to local living conditions would endure long enough to

reproduce and so perpetuate their kind. That extremely small variations among individuals could ultimately decide a species' fate was a logical corollary. Darwin expressed it this way: “*A grain in the balance will determine which individuals will live and die,—which variety of species shall increase in number, and which shall decrease, or finally become extinct.*”<sup>1</sup>

Having thus established a legitimate means by which speciation might occur in nature, Darwin continued his apollonian appraisal of the evidence, citing example after example to illustrate how natural laws conspire to create variation among individuals and govern animal instincts, all the while lamenting his inability to present all the evidence at his disposal for want of space. He likewise demonstrated—again citing numerous well-documented cases—how sterility among hybrids is neither uniform nor universal, undermining the popular notion that sterility was a property bestowed upon intercrossed species in order to keep them distinct. That observations showed breeding restrictions to be an incidental result of acquired physiologic differences was an important point in favor of natural selection, for had it been otherwise, the sterility of hybrids could not be adequately explained, as it offers no advantage for survival. Darwin's conclusions regarding the true nature of hybridism also carried with it the broad and somewhat surprising implication that there is, in fact, *no fundamental distinction between species and varieties*. According to the best evidence, what Linnaeus had assumed were creatures formed from separate acts of creation were really just variations on a single theme—extreme variations, to be sure, but variations nonetheless.

In the best tradition of scientific inquiry, Darwin formulated a number of predictions based on the assumed veracity of his hypothesis in order to test it still further, performing what was in effect an important series of reality checks. One obvious consequence of descent with modification was that members of the same taxonomic class (mammals, for instance) should share homologous structures, that is, body parts that resemble each other in their basic organization. Nature, it turned out, was replete with such evidence, as examples surfaced from every corner of the plant and animal kingdoms. Citing an exhaustive, if not exhausting, list of conspicuous anatomic similarities found in virtually every class of living organism, Darwin added: “*What can be more curious than that the hand of man, formed for grasping, that of a mole for digging, the leg of the horse, the paddle of the porpoise, and the wing of the bat, should all be constructed on the same pattern, and should include the same bones, in the same relative positions?*”<sup>2</sup> The ubiquity of such homologous structures, obvious to any observer who cared to examine the anatomic evidence, had in Darwin's view added a rather sizeable grain in the balance favoring

natural selection. But the weighing had only just begun.

Darwin examined his thesis still further through the lens of embryology, where the measured process of descent with modification could be expected to leave an indelible mark. Based on the fact that inherited variations often intervene late in fetal development, Darwin recognized that embryos of separate species, if truly born of common descent, should bear some resemblance to their common ancestor. The forelimbs of an ancestral species, for instance, might well be adapted through a long succession of discrete modifications to act as fins in one descendant, wings in another, and hands in a third. Each adaptation, however, must occur relatively late in fetal development so as to preserve those early embryonic cells upon which all subsequent development depends—these cells, in essence, forming the bottom members of a biological house of cards previously arranged to optimum advantage. Because even slight changes to these base structures would likely prove disastrous, few early alterations are ever propagated. On the other hand, the further an embryo develops, the less sensitive it becomes to small perturbations, and the more likely it is that random variations will be tolerated. Under the presumed guidance of random variation and natural selection, embryos of related species can therefore be expected to adopt similar growth patterns until profitable mutations intervene, adding more and more novel features to the adult forms through the course of successive generations.

And so another important reality check for natural selection had been devised. In order for Darwin's suspicions to be confirmed, developing embryos had to be found to embody the less modified characteristics of their ancient ancestors, making embryos of related species difficult to distinguish from one another. “*A better proof of this,*” Darwin wrote, “*cannot be given, than a circumstance mentioned by [Louis] Agassiz, namely, that having forgotten to ticket the embryo of some vertebrate animal, he cannot now tell whether it be that of a mammal, bird, or reptile.*”<sup>3</sup> Indeed, the fact that early embryos of air-breathing vertebrates all develop two-chambered hearts, six pairs of aortic arches, and gill slits—features characteristic of adult fish—could scarcely provide better substantiation of their common aquatic origin. Modern embryologists not only continue to confirm this relationship in ever finer detail, but have now established the order in which these life forms must have emerged, starting with vertebrate fishes and progressing to amphibians, reptiles, and finally mammals and birds. And so with another prediction confirmed, another grain was added to the balance, tilting the scale still further in favor of Darwin's thesis.

Because it stood to reason that certain features important to

ancestral creatures should, due to selection pressures, wither and eventually disappear from modern forms for which they hold no particular advantage, the existence of vestigial organs (remnants of structures inherited from progenitor organisms) was yet another marker employed by Darwin to test the veracity of his hypothesis. Once again the evidence proved plentiful, appearing in a wide assortment of guises: the absence of eyes among cave-dwelling fish and insects that were otherwise identical to their open-air cousins; the rudimentary wings of island birds no longer drawn to the air; the vestiges of the pelvic girdle and hind limbs in whales and snakes; and transient tooth buds found in bird embryos, to name but a few. Scientists would later discover dozens of similar biological relics in human beings, including remnants of a tail (caudal vertebrae), atrophied muscles formerly used to rotate the ears, and a rudimentary third eyelid (nictitating membrane) still found fully formed in cats and other land vertebrates. “*Nature*,” Darwin concluded, “*may be said to have taken pains to reveal, by rudimentary organs and by homologous structures, her scheme of modification, which it seems we wilfully will not understand.*”<sup>4</sup>

In the end, however, even Darwin failed to fully appreciate the power of natural selection to cull superfluous anatomic structures. Having no hard information regarding the true mechanism of inheritance—a shortcoming he readily admitted—Darwin supposed the agent of change to be long-term disuse as first proposed by Lamarck. In this he was mistaken. The advent of modern genetics has since shown the real culprit to be genetic variation, changes in gene function that result from factors including sexual recombination and rare copying errors (mutations) that sometimes occur during cell division. Natural selection acts to retain those genes that confer a competitive advantage and remove those that do not. All biological structures that help an animal improve reproductive success are therefore maintained or improved upon, whereas nonessential organs are gradually reduced until the costs of maintaining them become insignificant or they take on another function altogether, like the vestigial wings that penguins now use as flippers.

Not all mutations that occur at the genetic level have physiologic consequences, however. Random copying errors of single base pairs located along non-coding lengths of chromosomes remain selectively neutral and so tend to accumulate slowly—if not steadily—over time. As one might expect, the utility of this phenomenon has not been lost on modern researchers, who, despite variations in mutation rates within and between different groups of organisms, have discovered ways to use this portion of the genome as a reasonably accurate “molecular clock” to estimate when related species diverged from their last common ancestor.<sup>5</sup> Darwin,

however, was obliged to look for less subtle clues regarding the passage of time: evidence that the Earth itself was old enough to allow natural selection sufficient time to forge countless species from a single primordial replicator by way of innumerable intermediate links.

## SO MUCH TO DO...

“*The belief that species were immutable productions,*” Darwin allowed, “*was almost unavoidable as long as the history of the world was thought to be of short duration.*”<sup>6</sup> And given the common wisdom of the day, the evolution of species could hardly have seemed less likely. By Darwin's own admission the plodding process of natural selection ought to have required many millions of years—if not hundreds of millions—to do its work. But everyone already “knew” that the Earth was no more than a few thousand years old, and they had it on very good authority...or so they thought.

The conviction that all the ages of the Earth had seen fewer than three hundred generations of man was based on a literal interpretation of the Bible and had been bolstered by the popular teachings of biblical scholar James Ussher (1581–1656).<sup>7</sup> By counting backward through an improbably precise chronology of the Old Testament, Ussher had determined that creation had commenced at sunset on the evening of October 22, 4004 BCE. How could such biological diversity now in existence possibly have evolved on a planet scarcely six thousand years old? Conventional wisdom suggested that there had simply not been enough time for complex creatures to have evolved this way—not by a long shot.

Long before the publication of *The Origin of Species*, however, geologists from across the globe had already amassed hard evidence to the contrary. Among the most respected of these early earth scientists was Lyell himself, whose *Principles of Geology* had accompanied Darwin aboard the *Beagle* at the behest of his friend and mentor John Henslow.<sup>8</sup> A creationist like nearly all other mineralogists of the time, Henslow had encouraged his former student to study the text and consider its contents, but he warned Darwin against taking Lyell's unorthodox views too seriously. Still, Darwin was instantly struck by what he called “*the wonderful superiority of Lyell's manner of treating geology,*” and soon began to question his own long-held belief that a single global flood was sufficient to explain the multifaceted features that covered the earth.<sup>9</sup>

Although Archbishop Ussher had obviously taken great pains to compile a cogent chronicle of earthly events based on human history and holy writ, the one thing he had apparently failed to examine was the Earth itself. Those who did were quick to discover that the Earth had its own story to tell, a narrative etched in stone that belied the teachings embraced by the orthodoxy. Among the first to give voice to Earth's stratified crust was surveyor William Smith, who, while supervising the digging of the Somerset Coal Canal between 1794 and 1799, noticed that an invariant sequence of rock strata existed across the whole of England, each stratum containing “*organized fossils peculiar to itself.*”<sup>10</sup> The plain fact that these layers of sedimentary rock had been slowly deposited one on top of another proved to be of profound importance to geologists, providing important clues regarding the antiquity of the planet and the creatures it had harbored. It was this compelling line of evidence that both Lyell and Darwin would cite to refute the claims of catastrophists that the young Earth and its inhabitants had remained unaltered since their inception, save for the ravages of the great flood.

Drawing on Lyell's meticulous methodologies and his own considerable talents as a field scientist, Darwin had set about gathering geological data at every landfall during his famous round-the-world voyage, each overland excursion providing a welcome respite from the rhythmic ocean swells he had quickly come to dread. Working feverishly, as if to steady the *Beagle* beneath the ballast of his finds, Darwin collected voluminous plant and animal specimens with every expedition, together with a wealth of information regarding the geological formations that marked each landscape. Having gathered marine fossils high atop the Andes and witnessed firsthand the power of earthquakes to lift the land several feet at a time, he soon became convinced that the layered sediment found across the globe had indeed been deposited gradually with the slow rise and fall of the continents as Lyell had argued, the exposed land being reclaimed by the sea in granular increments by wind, rain, and surf, only to rise again through the periodic release of subterranean forces. The enormous height attained by former sea beds; the immense thickness of the Paleozoic strata of Great Britain (over 57,000 feet); seaside cliffs carved from erosion processes advancing far beneath the pale of human perception—all stood in testament to the unimaginable length of time the Earth had endured before the advent of mankind.

Lacking the wherewithal to actually date the banded deposits that to his mind so clearly marked the passing ages, Darwin was obliged to rely on measured rates of erosion and sedimentation to formulate a reasoned estimate regarding the passage of time. Facts concerning the stately pace of sediment deposition; the astounding

depth of the layered strata; the complete smoothing of rocky faults displaced thousands of feet upward: all were offered as evidence of a landscape that had been sculpted not over thousands or even millions but hundreds of millions of years. Indeed, the lengthy retreat of seaside cliffs located along the southeastern shores of England, themselves a by-product of the most recent strata formation, was alone estimated to have taken over three hundred million years. “*The consideration of these facts,*” Darwin wrote, “*impresses my mind almost in the same manner as does the vain endeavour to grapple with the idea of eternity.*”<sup>11</sup>

Darwin was similarly impressed by the coral colonies that had come to form giant rings, called barrier reefs, around many of the Pacific islands he had visited and that occasionally stood by themselves in the open sea. Charles Lyell had proposed that these isolated, sea-bound communities were simply the result of coral growing along the rims of extinct volcanoes that just happened to lie at a depth compatible with coral life (roughly thirty fathoms at most). For Darwin, however, the more he studied these enormous structures—some of them hundreds of feet thick—the more convinced he became that this simple explanation would not suffice at all. In fact, Darwin devoted an entire book to the study of coral reefs (1842) in which he proposed that these structures were built up slowly over vast periods of time. Darwin, in his typical matter-of-fact style, distilled his thinking like this: “*The facts stand thus;—there are many large tracts of ocean, without any high land, interspersed with reefs and islets, formed by the growth of those kinds of corals, which cannot live at great depths; and the existence of these reefs and low islets, in such numbers and at such distant points, is quite inexplicable, excepting on the theory, that the bases on which the reefs first became attached, slowly and successively sank beneath the level of the sea, whilst the corals continued to grow upwards.*”<sup>12</sup> What Darwin couldn't know for sure, of course, was precisely how long it took for the seabed to subside the many hundreds of feet necessary to account for his observations. Still, there were plenty of clues pointing to the protracted pace of the process, and Darwin was keen to examine them all. In the case of atolls with shallow lagoons, for example, Darwin reasoned that “*if the theory be worth considering [we are] required to admit, that the subsidence has not exceeded in rate the filling up of the interior spaces by the growth of the corals living there, and by the accumulation of sediment. As this filling up must take place very slowly within barrier-reefs lying far from the land, and within atolls which are of large dimensions and which have open lagoons with very few reefs, we are led to conclude that the subsidence thus counter-balanced, must have been slow in an extraordinary*

degree.”<sup>13</sup>

While no better equipped than Darwin to fathom this stupendous span of time, modern geologists have nonetheless continued to measure its passing with increasing accuracy, employing techniques that were all but inconceivable a century ago. Building upon the 1896 discovery of Antoine Henri Becquerel regarding the natural radioactivity of uranium, scientists have measured the rate at which unstable elements “decay” and have used this information to determine when objects containing these isotopes were first formed. Because nuclear decay processes are exponential, scientists routinely express its progress in terms of the time it takes for half a given sample to transform into its daughter element—its half-life. Nuclides with extremely long half-lives such as uranium-238 (4.5 billion years) and rubidium-87 (48.8 billion years) have been used in recent years to date everything from terrestrial stones and minerals to meteorites and moon rocks, with results as consistent as they are humbling. The age of the solar system as gleaned from extraterrestrial materials currently clocks in at an astonishing 4.55 billion years.<sup>14</sup> The oldest earthy rocks found so far have fixed the minimum age of our planet's crust at 3.8 billion years, time enough for even so deliberate a process as natural selection to run its course, fleshing out a seemingly infinite variety of life forms from the most humble of beginnings.

## A LAYERED LEDGER

Fortunately, the Earth's crust has proven to be much more than a simple stack of barren strata marking the passage of time. These banded layers of sediment also contain what is perhaps the most compelling evidence of all regarding the history of life on Earth—the fossilized remains of its former inhabitants. Unlike many of Darwin's more forward-thinking hypotheses, his views regarding the biological relevance of the fossil record happily placed him in good company. Leonardo da Vinci (1452–1519) was the first in modern times to recognize fossils as the remnants of past life forms and was likewise convinced that a single flood could not account for their distribution, noting that *“if the shells [found in mountainous regions] had been carried by the muddy deluge they would have been mixed up, and separated from each other amidst the mud, and not in regular steps and layers...as we see them now in our time.”*<sup>15</sup>

Yet despite Leonardo's insights, the persistent view of fossils as mere “sports of nature” remained largely unchallenged until 1665,

the year British physicist and inventor Robert Hooke published *Micrographia*, a detailed record of his observations using a compound microscope of his own devising.<sup>16</sup> The first person to train a microscope on fossilized specimens, Hooke reported seeing stark similarities between petrified wood, fossil shells, and their biological counterparts, concluding that organic materials steeped in mineral-rich water could slowly be rendered solid with microscopic deposits, an incremental process that quite literally turned them to stone. This notion was also advanced five years later in a singular work titled *La Vana Speculazione Disingannata dal Senso* (Vain Speculation Undeceived by Sense), wherein Agostino Scilla argued for the organic origin of fossils.<sup>17</sup> Together with Danish anatomist Niels Stensen, Scilla would also correctly divine the source of objects widely known as *glossopetrae* or “tongue stones,” thought for centuries to be the tongues of serpents turned to stone by Saint Paul. Stensen and Scilla were the first to recognize *glossopetrae* for what they really were: petrified shark teeth, much to the dismay of those who had come to rely on their mystical powers to cleanse the body of toxins.

That fossils were the remnants of organic beings had thus come to be widely accepted in Darwin's time, yet the full measure of their significance had scarcely begun to be appreciated. Constrained by the notion that creatures deemed good by their creator would surely not be allowed to perish from the earth, many scholars felt obliged to shoe-horn the fossil record into their preordained worldview rather than accept the evidence at face value. Some simply assumed fossils to be the ancient remains of known species. Fossil mammoths discovered in Italy, for instance, were held to be the bones of elephants used by Hannibal to traverse the Alps. Others hoped these fantastic creatures might eventually be found alive in uncharted regions of the world, as did Thomas Jefferson, who dispatched Lewis and Clark into the American wilderness expecting to discover mastodons and seven-foot beavers among the native fauna. (Ironically, it seems the Native Americans who had long occupied that territory—the “noble savages” of the untamed West—not only knew about such things as fossils but had the insight to recognize them as the remains of creatures no longer in existence.)<sup>18</sup>

As the vast expanse of unexplored territories slowly dwindled behind the advancing borders of civilization, a growing menagerie of unique fossil species began to surface, effectively extinguishing any prospect of finding these exotic creatures still alive. More and more it seemed extinction was the only tenable explanation for their curious absence. The final nail (as it were) was delivered in the early nineteenth century by French anatomist Georges Cuvier, who

painstakingly assembled the petrified remains of numerous large land animals never seen in the flesh by modern humans, including the giant ground sloth, Irish Elk, and flying reptiles called pterosaurs. Drawing on the fossil discoveries and oral traditions of Native Americans recorded by European colonists, Cuvier reasoned that it was quite unlikely that so conspicuous a creature as a mastodon or a giant sloth would escape the attention of *“the nomadic peoples who move ceaselessly around the continent in all directions and who themselves recognize that the creatures no longer exist.”*<sup>19</sup>

Confronted with the reality of prehistoric life forms and the expanding list of “terrible lizards” known to have populated the continents, creationists were obliged to turn once again to the great flood and other cataclysmic events to preserve the precept of animal immutability in the face of their extinction, apparently deciding that the dinosaurs and their cohorts must have had it coming. But far from being a liability to be explained away, the extinction of species in Darwin's view was simply a logical result of competition: an unavoidable consequence of descent with modification through natural selection. As Darwin explained it: *“The theory of natural selection is grounded on the belief that each new variety and ultimately each new species, is produced and maintained by having some advantage over those with which it comes into competition; and the consequent extinction of less-favored forms almost inevitably follows.”*<sup>20</sup> In essence then, the continued discovery of bygone life forms, many unearthed by scientists steadfastly opposed to Darwin's position, delivered yet another grain of evidence in its support. For had the fossil record been plumbed without producing evidence of the extinctions that were so plainly mandated by natural selection, his entire argument would have collapsed. Instead, each fresh discovery of an extinguished variety simply fortified the notion that species were at least ephemeral, if not subject to gradual change.

The principal challenge Darwin faced in the latter regard was to determine whether hard, physical evidence of the transmutation of species was indeed present in the fossil record, formulating perhaps the most definitive, clear-cut test ever to be leveled against his thesis. Because it was inconceivable that such clues would be absent from the fossil record given the assumed reality of evolution, a dearth of evidence in this area alone would be sufficient to undermine the entire notion of natural selection and send both Darwin and Wallace back to the proverbial drawing board. No such revisitation would be necessary, however, as Darwin found among the sediment precisely what a seasoned geologist would know to expect: isolated snap-shots of organisms preserved against tremendous odds through a series of extremely fortuitous events.

Rather than blithely searching for a complete series of specimens to document the fine gradations leading from one species to the next, Darwin was careful to anticipate the fragmented state of the fossil record and was equally diligent in clarifying this key point to his readers, dedicating an entire chapter of *The Origin of Species* to the imperfection of the geological record.

“All geological facts,” he explained,

*tell us plainly that each area has undergone numerous slow oscillations of level, and apparently these oscillations have affected wide spaces. Consequently, formations rich in fossils and sufficiently thick and extensive to resist subsequent degradation, may have been formed over wide spaces during periods of subsidence, but only where the supply of sediment was sufficient to keep the sea shallow and to embed and preserve the remains before they had time to decay. On the other hand, as long as the bed of the sea remained stationary, thick deposits could not have been accumulated in the shallow parts, which are the most favorable to life. Still less could this have happened during the alternate periods of elevation; or, to speak more accurately, the beds which were then accumulated will have been destroyed by being upraised and brought within the limits of the coast-action [erosion].... Thus the geological [fossil] record will almost necessarily be rendered intermittent.*<sup>21</sup>

Having thus effectively disarmed those who would view gaps in the fossil record as evidence of celestial tinkering, Darwin turned his attention toward those rare specimens that had managed to survive the vicissitudes of fossil formation and preservation long enough to catch the eye of paleontologists. Despite the obvious limitations of studying such a paltry and fragmented sample, Darwin nonetheless found that those fossils that *had* been examined fit neatly between the taxonomic classifications of existing species, noting that the combination of living and extinct forms yielded a much more complete series than either one alone. This conclusion was further supported by the fact that fossil remains from each stratum were commonly found to exhibit characteristics intermediate to those contained in formations above and below owing to their central position in the chain of descent. Observations by the most accomplished paleontologists of the day regarding fossil classification and links to existing species were also cited as independent confirmation of these facts, including the many fossil links reported by Owen and Cuvier.

Today, paleontologists continue to add to the fossil record, expanding their digs to sample every corner of the globe. Through their efforts, millions of additional specimens have been recovered and analyzed using increasingly sophisticated techniques to determine their age, origin, and ancestry. The oldest known fossils now date to the Precambrian era (3.5 billion years ago) and describe

cyanobacteria that are credited with oxygenating the early atmosphere and making complex animal life possible. Progressively younger strata have reliably yielded organisms increasingly similar to modern forms, beginning with the sea-dwelling invertebrates of the Cambrian epoch and culminating with more familiar creatures exhumed from the uppermost layers of rock. The long series of species leading to modern horses constitutes perhaps the most complete set of intermediate forms described to date, their earliest documented ancestor (*Hyracotherium*) standing just ten to twenty inches at the shoulder and sporting four toes on each front foot. Hundreds of other transitional forms have also been described linking fish to amphibians, amphibians to reptiles and mammals, reptiles to birds, and most recently, mammals to whales. What's more, of the countless fossils unearthed in the history of paleontology, no specimen has yet been found to contradict the precept of descent with modification that is the hallmark of natural selection—not a single one. Nature, it seems, has taken pains to chronicle the long history of life on earth through a layered ledger of fossilized entries, adding more weight to the balance favoring Darwin's hypothesis with each new find.

## FRESH GRAINS FOR THE BALANCE

After exhausting every credible means to disprove his thesis, Darwin finally outlined his work in a 230-page essay that he then shelved in 1844 together with detailed instructions for its publication in the event of his death, perhaps planning to exercise the same strategy used by Copernicus to avoid the societal repercussions that he felt were sure to come. In the fifteen years that followed, he would continue gathering data and corresponding with scientific colleagues until ultimately compelled to release a greatly expanded (albeit still incomplete) version in the wake of Alfred Wallace's paper on the same subject. Darwin would later supplement his book with several more volumes, making good on his promise (threat?) to provide in future works “*a long catalog of dry facts*” in order to “*treat the subject properly.*”<sup>22</sup>

But it was more than just the copious compilation of specifics that caused *The Origin of Species* to hold such sway. It was also the reserved, objective manner in which these many facts were presented that ultimately rendered Darwin's arguments so persuasive and so frustratingly difficult to discredit. Not one to rely on fiery prose or emotional entreaties to help carry his arguments, Darwin chose instead to simply let the facts speak for themselves, packaged as they were in a construct of logical consistency and

delivered through the vehicle of dispassionate discourse. Indeed, Darwin's commonsense arguments were so clear and convincing that scores of evolutionary skeptics were soon slapping their collective foreheads in sudden recognition of what they now took to be obvious. This sentiment was distilled most effectively by famed biologist T. H. Huxley, who, upon reading *The Origin of Species* remarked “*how extremely stupid of me not to have thought of that!*”<sup>23</sup>

For over 150 years now, scientists and scholars the world over have continued to examine evolutionary processes through every means at their disposal, employing ever more powerful tools to access worlds of information far beyond the reach of earlier scientists.<sup>24</sup> The mechanism of inheritance, for instance, which had thoroughly eluded Darwin and his contemporaries, is now known to be centered around long-chained molecules of DNA (deoxyribonucleic acid), which serve as the master instruction set for all multi-cellular organisms on earth. Four different chemical bases, called nucleotides, form the backbone of these molecules and work in pairs to both encode a “blueprint” for the organism and allow for the copying and transcribing of this information. Innumerable experiments have shown how changes in nucleotide sequencing can influence protein production, cell function, and even the physical characteristics of an entire organism. Scientists are even beginning to catalog the location and function of individual genes by comparing the genomes of stricken individuals to healthy subjects. Discovering the origin of human disease, however, is not the only end to which genomic sequencing has been applied; this powerful technique has also been used to reconfirm the veracity of evolution and help trace its course.

Genetic information spanning hundreds of species from microbes and plants to primates and humans have now been collected and analyzed with eye-opening results. From a purely biochemical perspective, all living things have been found to be stunningly similar. Every creature from *E. coli* to *H. sapiens* uses DNA as its base genetic material, with the exception of certain viruses that employ a similar molecule called RNA (ribonucleic acid). Just as natural selection mandates, species that appear closely related based on anatomical similarities—dogs and cats, for example—exhibit similar gene sequences whereas those less intimately associated, like dogs and dogwoods, share proportionally fewer genetic links. This relationship has not only led to more accurate taxonomic groupings; it has also been used to determine actual divergence times by calibrating the rate of random nucleotide substitutions against the fossil record. These myriad studies have coalesced into an orderly phylogenetic map tracing the 3.5-billion-year history of all life on earth; a map that remains entirely

consistent with the precept of evolution via descent with modification and utterly inexplicable under the pretense of special creation.

As modern-day science continues to teach us more about ourselves and the world we inhabit, surprising details regarding the mechanisms that drive evolution and shape its outcome continue to surface.<sup>25</sup> Natural selection is now known to act by decreasing genetic variation within a population through a combination of environmental pressures, sexual selection, and genetic drift. What Darwin described as “variation under nature” is currently thought to be the compounded effects of random mutations, chromosomal recombination, and gene flow from neighboring populations. The curious geographical distribution of species is now understood to have resulted from the separation of a solitary primordial land mass: a supercontinent called Pangaea that slowly drifted apart, forcing resident species to evolve in isolation. What's more, the fossil record suggests that modern species have also been shaped by at least five major and a dozen or more minor extinction events brought about by such disparate causes as glaciation, volcanic activity, fluctuations in sea level, and asteroid impact. Add to these the immense number of chance events that have undoubtedly influenced the survival of individual organisms and discrete populations, and one begins to appreciate the difficulties facing those charged with tracing the convoluted evolutionary pathways that define the history of life on earth.

The course of evolution, it turns out, is more tortuous than even Darwin could have imagined, combining elements of structured processes and accidents of chance to yield a complex biological system unique to our planet. The grains of evidence, now too numerous to count, will likely be sifted for decades if not centuries to come before the nuances of evolution are completely understood, but the reality of evolution itself is now as well-established as any other fact in science. Like the accumulation of multi-colored flecks in an impressionist painting, each new discovery has added a little more definition to the portrait of life, bringing the intricacies of the human condition slowly into focus. The broad picture first sketched by Darwin and Wallace, however, has remained true to form. Even as the complex process of evolution gains more facets, straining our comprehension with its tangled paths and delighting us with its intricate mechanisms, the words of geneticist Theodosius Dobzhansky hold true now more than ever before: “*Nothing in biology makes sense except in the light of evolution.*”<sup>26</sup>

## CHAPTER 3

# ONE LONGSOME ARGUMENT

*Unthinking faith is a curious offering to be made to the creator of the human mind.*

—JOHN A. HUTCHINSON,  
*FAITH, REASON, AND EXISTENCE* (1956)

Charles Darwin liked to describe *The Origin of Species* as “one long argument,” but his extensive treatise in support of biological evolution now seems painfully brief compared to the argument that has followed in its wake.<sup>1</sup> Indeed, never in the history of science has a more prolonged and passionate debate dogged the heels of a theory so thoroughly researched and repeatedly validated. Still, despite all evidence to the contrary, a large portion of the world's population continues to cling to the belief that human beings are fundamentally different from all other life forms and that our origins are unique. It's a lovely sentiment to be sure, but how is it that so many people continue to be drawn to this thoroughly discredited notion?

## MYSTERY LOVES COMPANY

Like most mystic mindsets, creationist beliefs are normally instilled at an early age, nurtured by well-meaning parents and sustained by religious organizations whose vested leaders are traditionally loath to amend church doctrine in the face of emergent scientific facts. Though seemingly antithetic to the inquisitive nature of our species, the rote acceptance of received wisdom has been a hallmark of human culture almost from the get-go, arising initially as a benign behavioral adaptation geared to promote the rapid transfer of communal survival skills to our young hominid forebears. It was only with the advent of modern civilization that this age-old habit finally began to outlive its usefulness and yield serious negative consequences, most notably by granting gratuitous momentum to all kinds of ill-conceived notions about how the world is “supposed” to work. Today, this surge of ideological inertia remains a surprisingly powerful force, pushing beliefs as impossibly anachronistic as

geocentrism and flat-earth cosmology past the ramparts of the enlightenment to foul the fringes of modern thought.<sup>2</sup>

Fortunately, unlike the veiled forces that impart momentum to particles of mass, the impulse that propels incongruous ideas from one generation to the next is fairly transparent at its base. After all, youngsters imprinted with self-flattering beliefs are understandably reluctant to amend them later in life owing to the special status and privileges they bestow. And once someone has grown accustomed to the hollow pleasures of this egocentric worldview, it's easy to see how these inflated beliefs would come to be shielded from the prickly barbs of reason by a panoply of family, friends, and other like-minded folks, all of whom harbor the same heart-warming yet inscrutable notions.

Although this perpetual pattern of natal indoctrination and communal reassurance does not begin to encompass the full psychosocial breadth of this phenomenon—especially where adult converts are concerned—it *does* go a long way toward explaining the inordinate longevity of creationist mythology and why so many intelligent, well-educated, and otherwise rational people appear unable to step back and examine certain beliefs with a critical eye. Because creationist beliefs are both deeply rooted and profoundly comforting, it isn't hard to understand why certain people feel compelled to enlist any and all means at their disposal to discredit Darwin's theory. Nor is it difficult to imagine the sense of frustration they must feel when repeatedly told by scientists that their arguments are fundamentally flawed.

The problem is, most folks—including many of the more learned among us—don't understand the basic workings of science well enough to appreciate how feeble the arguments against evolution really are. If they did, they would realize that the scientific process is not about gathering data to prove a favored hypothesis but instead involves the *testing of ideas against the totality of real-world observations*. Creationists turned amateur scientists almost always fail to grasp this essential scientific precept and so unwittingly launch from false premises all kinds of pseudoscientific arguments in support of special creation. In fact, if there's one reason why creationist critiques are so consistently misguided, it's that adherents generally presuppose that special creation is true and then sift the evidence for clues to support that supposition—a recipe for self-deception that stands in stark contrast to the scientific method, which mandates that fresh hypotheses be derived from *all* available evidence

Were this fundamental misconception to be extinguished in a sudden wave of scientific literacy, the illusory evidence that thinking creationists use to anchor their beliefs would be swept away in an instant, leaving precious little demand for the writings of

creation “scientists.” As it is, however, an ungodly amount of literature is being published by the sectarian faithful in a spirited attempt to preserve mankind's privileged place in the grand scheme of things. Whether knowingly or not, creationists of every stripe have come to rely on an assortment of pseudoscientific arguments to legitimize their efforts to unravel the fabric of evolutionary theory, hoping against hope that the extensive tapestry woven by eight generations of scientists might somehow dissolve with the tug of a few loose threads. Unfortunately, as the weave of evolutionary theory has continued to tighten and expand over the years, the number and variety of confused arguments in defense of creationism and intelligent design have risen to keep pace.

One popular tactic enlisted by creation “scientists” is the classic all-or-nothing argument wherein proponents claim that nothing in science can be known with confidence until every last detail is described with absolute certainty. Appealing largely to those unschooled in the scientific method, critics repeatedly point to such non-issues as gaps in the fossil record, poorly understood aspects of gene function, and the mystery of life's origins as reasons to view evolutionary theory as speculative or provisional.<sup>3</sup> What they fail to appreciate, of course, is that scientific theories are built solely upon evidence that is actually available for study and cannot be refuted by speculation regarding those clues that remain hidden. As long as a given theory remains consistent with observed phenomena and yields verifiable predictions, it must be considered a viable explanation regardless of what remains to be discovered. Hence, it is entirely irrelevant that gaps in the fossil record exist but vitally important that those fossils that *do* exist make sense in the context of evolution. A single hominid fossil found among the trilobites of the Burgess Shale, for instance, would immediately throw Darwin's theory into doubt. Likewise, the fact that certain aspects of molecular genetics remain to be fully described in no way negates the fact that the substantial amount that *is* known about gene function is entirely consistent with evolution as we understand it today.

Yet despite the proverbial admonition against doing so, many still choose to view the absence of evidence as evidence of absence and are all too eager to fill this fictional void with the narrative of their choosing. Indeed, this particular brand of *argumentum ad ignorantiam* has long been a mainstay for creationists looking to wedge their cosmology between the narrowing gaps of scientific knowledge (an increasingly difficult task). But issues of legitimacy aside, because this fallacy has sired so many specious claims over the years, it seems only fitting that the mother of all such “arguments to ignorance” should stem from the granddaddy of all biological data gaps: the evolution of single-celled life forms.

Because no physical body of evidence exists to document the very beginning of life on earth, this knowledge gap has proven a wildly popular (albeit wholly inappropriate) foil for those seeking to discredit evolutionary theory. In truth, the origin of life is an issue entirely separate from the origin of species, rendering this otherwise important question utterly irrelevant as far as the veracity of natural selection is concerned. Whether the first primitive life form arose from known physical processes or was somehow willed into being through means beyond our understanding, evidence that all life on earth descended from simple primordial beings remains just as compelling and the myth of independent creation just as untenable.

But even this slender refuge for intelligent design has slowly begun to evaporate under the light of modern scientific scrutiny. While earth's original life forms left no physical evidence for scientists to examine, several credible hypotheses regarding the spontaneous formation and assembly of self-replicating molecules have been proposed and tested. Laboratory experiments and astronomic observations suggest that key organic compounds were present in abundance shortly following earth's formation and that natural chemical affinities and mineral scaffolds may have acted in concert to produce the simplest of biochemical copying machines. In 1953, Stanley Miller became the first to demonstrate that amino acids and other organic molecules could have formed through chemical means in prebiotic oceans capped with an atmosphere of ammonia, methane, and hydrogen gas.<sup>4</sup> Although geochemists now question Miller's assumptions regarding the reducing power of the prebiotic atmosphere, reducing environments may well have existed in isolated pockets on the embryonic Earth (near volcanic vents, for instance).<sup>5</sup> What's more, many of these same organic compounds have also been found to exist among interstellar dust clouds and meteorites, suggesting life's building blocks may have also been delivered to Earth on the backs of icy comets and carbonaceous asteroids.<sup>6</sup>

Based on these and other findings, biochemists have proposed several plausible mechanisms by which these compounds may have coalesced of their own accord into the precursors of life. Experiments confirm that layered mineral deposits can attract, concentrate, and link organic molecules and that certain clays may function as scaffolding for assembling the molecular components of RNA.<sup>7</sup> Crystalline templates have also been proposed as possible means of primitive protein assembly, their mirror-image surface structure accounting for the curious predominance of "left-handed" amino acids found in all creatures living today. These and other minerals have also been shown to facilitate the sequence of chemical transformations needed to spark life, acting as sheltered

containers (feldspar), catalysts (magnetite), and iron sulfide reactants (pyrite). What's more, a complex mixture of organic compounds formed within simulated interstellar ices has recently been observed to spontaneously form cell-like vessels when immersed in water, providing yet another viable mechanism by which particles awash in a dilute prebiotic soup might have come to assemble themselves into crude cells.<sup>8</sup>

Although the precise sequence of events will never be known with absolute certainty, these and similar experiments strongly suggest that the earliest terrestrial life forms arose spontaneously in accordance with the known laws of nature. Biology professor Antonio Lazcano, in a recent essay in the journal *Science* summed it up nicely when he wrote:

*It is true that there is a huge gap in the current descriptions of the evolutionary transition between the prebiotic synthesis of biochemical compounds and the last common ancestor of all extant living beings. Even the unanticipated discovery in 1982...of catalytic RNA molecules (ribozymes), which can be loosely described as nucleic acids that simultaneously have characteristics of DNA and enzymes, has not closed this gap. Instead, that and related discoveries have led to a more precise definition of what should be understood as the origin of life. The origin of protein synthesis is still not understood, but the surprising conservation of widely distributed polypeptide sequences related to RNA metabolism has led my group and others to suggest that these sequences provide insights into an RNA/protein world that may have resulted from the interaction of ribozymes with amino acids, and that very likely preceded our familiar DNA/RNA/protein world. Our understanding of the origin and early stages of biological evolution still has major unsolved problems, but they are recognized by the scientific community as intellectual challenges, and not as requiring metaphysical explanations, as proponents of creationism would have it.<sup>9</sup>*

In short, everything we have come to understand about our world suggests that living creatures are a natural consequence of the laws that govern the physical universe, no more anomalous than the matter they comprise or the space they occupy. Still, despite all efforts to disseminate this hard-earned knowledge, a broad swath of creationist sentiment lingers on, fueled by well-worn arguments ranging from the philosophical and dogmatic to the confused and plain disingenuous. The good news is that the great majority of these objections quickly collapse under even the most cursory examination.

## **CREATION PSEUDOSCIENCE**

For starters, many of the “scientific” arguments for intelligent design invoke common misconceptions about how the physical world really works, as in the classic “watchmaker” argument wherein nature is assumed to act randomly and possess no organizational tendencies.<sup>10</sup> Given this false premise, it is a simple matter to show that complex molecular structures could never have formed by chance alone any more than a factory whirlwind could assemble a Mercedes from its component parts. But anyone with a basic understanding of chemistry knows full well that such analogies do not apply to atoms and molecules. If the physical sciences have taught us nothing else, it's that the world of the very small is surprisingly counterintuitive. Processes in the realm of the microscopic simply do not behave as one might expect based on our experience living on the macroscopic plane. Electric charges, energy barriers, and nuclear forces all dominate the realm of the minuscule and compel individual atoms to form stable chemical bonds with neighboring elements, blindly building molecular structures of every possible type and complexity that the laws of physical chemistry will allow.

Objects large enough to arouse our naked senses, on the other hand, behave quite differently. Because they exhibit no special affinity for one another, the scattered components of a disassembled watch will never coalesce of their own accord—the odds against such haphazard assemblies are simply too long. Nature, however, does not act without organizational tendencies, nor are living organisms randomly assembled. There is now ample reason to believe that simple unicellular life forms arose through processes endemic to the life-friendly universe we occupy and that more sophisticated beings slowly emerged from these modest beginnings. In truth, all complex organisms on Earth, including humans, begin life as single cells that multiply, differentiate, and ultimately mature to assume, with some variation, the form of its parent—all in strict accordance with the natural laws of biochemistry.

The contention that evolution somehow violates the second law of thermodynamics is another popular fiction that has endured through widespread confusion over a fundamental physical concept—in this case, thermodynamic entropy.<sup>11</sup> From an educational perspective this is especially disconcerting, as entropy permeates all aspects of human existence and is arguably one of the most basic of all the laws that govern our universe. Unfortunately, the scientific community has only added to the confusion by employing two seemingly incongruous definitions of entropy in their work, one being the traditional thermodynamic definition favored by chemists and the other a statistical interpretation preferred by physicists.<sup>12</sup> These two definitions are really just opposite sides of the same

phenomenological coin, however, and neither presents a problem with regard to biological evolution. Here's why.

Couched in the plainest possible terms, the thermodynamic definition of entropy simply states that energy tends to spread from areas where it is concentrated to areas where it is not. Although it is not widely recognized as such, this phenomenon is an integral part of our everyday experience and shapes our commonsense expectations. For example, because energy always flows from where it is concentrated to where it is more diffuse, we expect, say, a warm bottle of Gewürztraminer to chill when lowered into a bucket of ice water. In this instance, thermal energy will flow from the tepid wine to the surrounding fluid until both reach a common temperature and an energetic balance is achieved. Like the ice bucket and its contents, self-contained systems receiving no external energy will always experience a net increase in the diffusion of thermal energy, or a rise in thermodynamic entropy, resulting in lower energy gradients and less potential to do work.

In the field of statistical mechanics, entropy is defined in terms of probabilities and is used as a measure of the number of ways in which a given system of particles can be arranged. Unlike thermodynamic entropy, which defines energy distributions in terms of heat transfer, “statistical” entropy describes the probability that randomly distributed particles in a composite system will assume a certain configuration or organized pattern. Ordered systems with low entropy values may appear to the casual observer to contain discernible patterns, whereas high entropy systems seem more disorganized. Gas molecules distributed within a defined enclosure, for instance, are said to exhibit greater entropy when they are scattered than when they are grouped together. Why? Because although every possible pattern of molecules has an equal chance of occurring, there are a great many more ways to define a diffuse pattern than any given clumped arrangement and, as physicist Richard Feynman was keen to observe, statistical entropy is simply “the logarithm of that number of ways.”<sup>13</sup>

Despite the fact that thermodynamic and statistical entropy describe different aspects of the same phenomenon, many laymen—and a few scientists who really should know better—have come to confuse and intermingle the two, transforming the second law of thermodynamics into a fallacious “law of disorder” that purportedly explains why all material things break down over time and precludes the possibility that complex living organisms might spontaneously evolve from simpler forms.

This notion is not only mistaken; it is profoundly so. In this universe there are no physical laws that preclude the spontaneous formation of highly complex assemblages from less interesting beginnings. If there were, the stars themselves would never have

formed. The important thing to remember here is that entropy is a net sum game wherein only the *total* amount of disorder in a system must increase over time. This is why tiny fluctuations in the distribution of matter in the early universe were able to coalesce into pockets of highly ordered (low entropy) regions: As stars ignited and organized themselves into galaxies, other regions of the cosmos became less orderly in response, causing the net entropy of the universe as a whole to increase, all in keeping with the second law. Simply put, the fact that all complex systems will ultimately break down over countless eons as the laws of statistical mechanics demand does not mean that some interesting patterns can't take shape in the meantime.

Those who argue this point from a purely energetic standpoint are somewhat less confused but just as easily refuted. The fact that the amount of energy available to do work must always decrease in a closed system would indeed be a serious impediment to the evolution of life if our planet were isolated from all external energy sources. But one need look no further than our companion star to see that such is not the case. Energy is constantly being delivered to the thin shell of our biosphere both from above, in the form of sunlight, and below, via heat generated by Earth's radioactive core, providing ample energy to fuel the assembly of structured molecules. An important energetic leg-up is also gained by the fact that the entropy of certain *parts* of a system can, and often do, spontaneously decrease at the expense of even greater increases in adjacent regions, as with the formation of crystalline salts and snowflakes. Moreover, there are literally millions of chemical compounds including water, cholesterol, and DNA that carry *less* energy than the elements they contain (possessing “negative energies of formation,” in scientific parlance). In these cases, the second law of thermodynamics actually *favors* the impromptu formation of complex structured molecules due to their tendency to disperse energy as they coalesce.

Another threadbare canard spread by the creationist camp is that biological evolution is still not widely accepted within the scientific community, a ruse for which competing evolutionary hypotheses are offered up as evidence. The truth of the matter is quite the opposite. The fact that biologists support alternate hypotheses regarding specific evolutionary mechanisms no more challenges the reality of evolution than Einstein's relativistic views threatened the existence of gravity. Whether evolution proceeds in fits and starts as envisioned by the punctuated equilibrium model or progresses with more stately regularity, each competing hypothesis simply seeks to explain a certain aspect of evolution in a plausible way. The overarching framework of evolution itself, however, remains astonishingly consistent with the huge body of evidence

accumulated to date. Far from being the object of scientific debate, the evolution of species is actually no more, or less, than the collection of observed facts that these hypotheses are meant to explain. Gene flow, frequency dependence, and punctuated equilibrium are but three possible mechanisms put forward to explain the nature of this overarching phenomenon. Which, if any, of these hypotheses survives the test of time bears no influence on whether modern species are the product of biological evolution—the evidence in this regard, now comprising countless independent observations, is simply overwhelming. It is only the processes that drive the phenomenon of evolution that remain the object of scientific scrutiny.

Unencumbered by the rules of scientific inquiry, there are others who proclaim with total aplomb that evolution can never truly be validated until *major* speciation events (the transformation of land mammals into whales, for instance) are directly observed. In this case, what is ignored is the important fact that reliable scientific evidence is not limited to firsthand experience of real-time events but includes all forms of physical clues. The folly of this argument becomes evident when one considers that knowledge of galaxy formation, stellar composition, and subatomic particles would be impossible if researchers were to adopt similar rules of evidence across the whole of science. But why stop at the boundaries of academia? Imagine for a moment the chaos that would ensue within the criminal justice system if such an unreasonable burden of proof were placed on prosecutors! Indeed, as many jurors would no doubt attest, it is often the physical evidence that ultimately proves most reliable and compelling in a court of law, eclipsing even eyewitness accounts that can be tainted by errors of interpretation and outright deceit.

Beliefs maintained through the narrow interpretation of isolated facts or held in default against evidence not readily understood can be called any number of things, but “scientific” is certainly not one of them. As these few examples amply illustrate, the myriad approaches adopted by creation “scientists” in their attempts to undermine evolutionary theory are indeed quite creative but hardly scientific. As has been demonstrated time and again, evidence carefully sifted can be enlisted to endorse practically any supposition, so long as the preponderance of contrary clues is ignored and the rules of sound scientific practice are suspended. It is precisely this brand of exclusionary thinking that enables young earth devotees to dismiss mountains of physical evidence while defending their assertions with flawed assumptions such as constant population growth and the linear decay of Earth's magnetic field (both demonstrably false).<sup>14</sup> Likewise, partisans who claim that evolutionary processes have never actually been observed

inexplicably dismiss the scientific literature where such observations have been reported in abundance. In truth, physical adaptations to environmental pressures have been documented in *hundreds* of modern species from bacteria and fruit flies to birds, squirrels, and stickleback fish.<sup>15</sup> Even Darwin's own finches have been caught in the act of adaptation, thanks to decades of meticulous study spearheaded by Princeton biologists Peter and Rosemary Grant.

A full accounting of the ways in which the scientific method has been manipulated to promote creationist sentiment would doubtless occupy many volumes, but in no instance has a legitimate scientific case ever been made to countermand the notion that, as Darwin phrased it: “*from so simple a beginning endless forms most beautiful and most wonderful have been, and are being, evolved.*”<sup>16</sup>

## CHAPTER 4

# GRASPING AT STRAWS AND COMING TO GRIPS: HOW SCIENCE REALLY WORKS

*Great is the power of steady misrepresentation—but the history of science shows, how fortunately, this power does not long endure.*

—CHARLES DARWIN, *ORIGIN OF SPECIES*, 6TH EDITION (1872)

Living at a time when a rising tide of science and technology threatens to saturate every aspect of modern life, a growing number of latter-day creationists are opting to trim their sectarian sails and go with the scientific flow—a sudden change of tack that some observers may find difficult to fathom. On the surface this maneuver would seem to portend a surprisingly risky foray into the turbulent waters of scientific inquiry, the one place the captains of creationist lore have always been careful to avoid. But faced with a deluge of data that in recent decades has significantly deepened our understanding of the evolutionary process, it seems that steering clear of this technological tempest is no longer an option. Consequently, those bent on salvaging this leaky vessel now find themselves in increasingly dire straits, desperate to find some way—any way—to keep their beliefs afloat amid mounting waves of countermanding evidence. Perhaps it is not so surprising, then, to find so many creationist hangers-on clinging to the flotsam of intelligent design as they struggle to keep their heads above water the only way they can: by floating the contention that the findings of science, despite what scientists say, have not completely scuttled their worldview.

## DEAD RECKONING

Now more than ever, keeping creationist mythology on an even keel is proving to be a tricky proposition as the honest criticism of evolutionary theory has grown increasingly untenable in the face of what has become a veritable flood of confirmatory evidence.

Ultimately, this has forced the creationist faithful to become more and more “creative” in their defense of special creation, even to the point of stretching the truth from time to time. Indeed, in order to buoy their floundering arguments, creation “scientists” have found it necessary to muddy the waters time and again, clouding the issue with half-truths and misstatements regarding evolutionary processes and the scientists who study them.

Unfortunately, those ill-equipped to judge such matters are readily duped into accepting these absurd caricatures as accurate distillations of evolutionary thought and are often persuaded to reject the whole notion of biological evolution as a consequence. This is as unfortunate as it is unnecessary, for anyone with even a rudimentary understanding of modern evolutionary theory would know that evolution does not suggest that life arose from nothing or that complex organs like the eye emerged fully formed from haphazard mutations. Nor would they be fooled into thinking that evolution by natural selection is unscientific (not falsifiable), based on circular reasoning, or inconsistent with the molecular complexities of life. And they would certainly understand that our hominid ancestry does not suggest that we are descended from some modern form of primate.

This last misconception, silly as it is, has struck a chord with certain standup comics who, wittingly or not, have managed to prop up two straw men with a single shtick by quipping, “If humans descended from monkeys, why are there still monkeys?” To those unfamiliar with evolutionary theory this might seem like a fair question, but, in truth, this one-liner is doubly misleading in that it contains two glaring falsehoods, the most obvious being the very notion that mankind descended from monkeys. We did not. While modern-day monkeys are certainly among our closest living relatives, the hominid species that spawned *Homo sapiens* vanished long ago.

The other hidden fallacy here is only slightly less conspicuous and is brought to light with the realization that natural selection does not mandate that parent species immediately perish in the wake of newer forms. In other words, even if we *had* descended from monkeys, our status as contemporary creatures would present no contradiction with regard to descent with modification. One might just as well ask: If man came from dust, why is there still dust? It simply makes no sense. Ultimately, then, if there is any real humor to be found here—a remote possibility at best—it lies not in the joke itself but in the fact that it amuses only those people who don't really get it. To borrow another line from Hamlet: “*Though it make the unskillful laugh, [it] cannot help but make the judicious grieve.*”<sup>1</sup>

All kidding aside, perhaps the most laughable contention

promoted by the creationist camp to date—at least as far as working scientists are concerned—is that evolutionary thinking has hardened into a dogmatic, quasi-religious mindset held primarily on faith rather than empirical evidence. Many have expressed this sentiment over the years but few so skillfully as Berkeley law professor Phillip Johnson, who first presented the case against “Darwinism” in his 1992 book *Darwin on Trial*.<sup>2</sup> In keeping with other works of this genre, much of this volume is consumed by an expansive rendering of the standard all-or-nothing argument wherein the author attempts to dispatch much of what is currently understood about biological evolution by simply cataloging missing data and citing competing evolutionary hypotheses. What separates Johnson from the majority of his creationist cohorts, however, is his considerable talent as a professional litigator—skills that render his arguments more comprehensive, more persuasive, and slicker than most. These attributes are also what make his book the quintessential study of how scientific naïveté and clever argumentation can be combined to great effect to defend even the most improbable of conclusions.

Mindful of the need to maintain some pretense of scientific objectivity, Johnson begins by presenting what to the untrained eye might seem like an accurate distillation of the evidence for descent with modification, which he then systematically refutes point by point. In reality, however, his arguments are tainted by subtle bits of misinformation that appear with disturbing regularity throughout the text; straw men cleverly hidden amid a smattering of legitimate scientific findings. Samples of such debate-savvy chicanery, to cite but two, include the suggestion that living fossils (species that remain essentially unaltered for millions of years) are somehow inconsistent with natural selection and the declaration that Darwin himself had found the fossil evidence to be “*heavily against his theory*.”<sup>3</sup>

Although repeatedly professing an interest in “*what unbiased scientific investigation has to tell us about the story of life*,” the author's real take-home message is that we should hold biological evolution as a provisional hypothesis equal to all others until proof is rendered absolute, especially since natural selection has never actually been observed to produce anything so complex as a wing or an eye, and intermediates are “*hard to imagine*.”<sup>4</sup> Much harder to imagine, however, is evidence that Johnson might actually consider convincing. After all, even if such stark biological transformations were to occur right before our eyes, intermediates and all, one could always argue that modern-day evolution does not prove that these processes operated the same way in the past. Using these untenable standards Johnson would have us dismiss as unreliable all evolutionary evidence not readily envisioned or witnessed in real

time. To be consistent, however, we would also be obliged to regard atoms, black holes, and electromagnetic fields as unproven entities since none have been witnessed first-hand and each is devilishly difficult to envision. Taking his arguments at face value, it would seem that Professor Johnson has an awful lot to teach scientists regarding the rules of their own profession, the first and most important lesson being that there can never be enough evidence to prove a hypothesis you are unwilling to accept.

Still, prosaic as they are, these tired arguments would hardly be worth noting were they not prelude to a more pernicious sophistry with which Johnson ends his book—an artfully oblique diatribe in which the vagaries of semantics and philosophy are invoked in an effort to cleave evolution from its scientific moorings and cast it adrift among the raft of ancestral creation stories floated across the centuries.

Evidently undeterred by the shortcomings of his evidentiary arguments, Johnson marshals his prosecutorial acumen in these later chapters to draw attention away from the conclusive evidence supporting evolution, cajoling the scientifically naïve with a mind-numbing series of apocryphal aphorisms contrived to foster distrust of evolutionary theory in particular and the scientific community in general. That the author should resort to this brand of nebulous argumentation is not unexpected given the gossamer-thin foundations of his case. What is surprising, however, is the number of people who continue to be swayed by such deceptive language—not the least of which (apparently) is Professor Johnson himself.

Perhaps the most ludicrous of these falsehoods appears in a brief chapter titled *Darwinist Religion*, where the author casually dismisses descent with modification as just one more possible way to explain the diversity of life on Earth; a hypothetical guess based no more on tangible evidence than any other creation myth (!). Disregarding the physical evidence against which he had railed for better than a hundred pages, Johnson brashly soldiers on in an effort to convince his readers that evolution is really nothing more than “*an imaginative story about who we are and where we came from, which is to say it is a creation myth.*”<sup>5</sup> This being the case, one can only assume the professor holds similar disdain for the fanciful tales scientists have concocted about continental drift and the geologic processes that gave rise to the Himalayas. The plain truth is, all these phenomena—biological evolution, plate tectonics, and continental subduction—run so contrary to the universal illusion of global stasis that their existence was not even dreamt of until after the physical clues were slowly cobbled together. Indeed, if humans were capable of creating such “imaginative stories” through intuition alone, our ancient ancestors would have thought of them long ago. The reason no one did is because such things were, as

Johnson might phrase it, extremely “hard to imagine” in the absence of positive evidence. In truth, it is only with the accumulation of many consistent and oft-times surprising facts that the amazing history of our planet has come to be understood. So to suggest that the complex processes of biological evolution are simply products of the human imagination is incredibly naïve to say the least. Johnson further argues that the theory of evolution is not really scientific because phylogenetic mechanisms can be modified to accommodate any observation and are therefore untestable. Of necessity, he defends this allegation through an exceedingly sidelong approach, drawing fanciful parallels between Darwin's theory and those ideologies that historically have failed to meet the base standards of scientific legitimacy as framed by famed philosopher of science Karl Popper.

Popper, known best for his landmark treatise *The Logic of Scientific Discovery*, was among the first to formally define scientific hypotheses as those ideas susceptible to falsification by empirical observation and declared ideas compatible with any and all possible observations as being wholly subjective and unscientific.<sup>6</sup> Johnson would have his readers believe that Darwin's theory, like the ideas of Marx and Freud, falls beyond the purview of science because it presumably can be modified to accommodate *any* realizable observation—this despite the ease with which conclusive counterexamples can be produced.

Indeed, a modicum of thought quickly reveals any number of ways biological evolution could have been, and still can be, proven wrong. Proof that life forms have not changed appreciably over time, credible evidence that the earth is only a few thousand (or a few million) years old, lack of common genetic markers linking diverse species, finding modern animal species entombed within Precambrian rock; any of these observations would have eliminated natural selection as a possible means by which the rich diversity of life on earth was achieved. Intelligent design, on the other hand, bears no such burden of vulnerability since no matter what is observed, it can simply be said that it pleased the creator to make it so.

Knowing that biological evolution cannot be reconciled with just any set of observations, what does the plasticity of evolutionary theory really say about this body of knowledge and the researchers who test it? Does the formulation of *ad hoc* theorems in the face of fresh facts violate the rules of scientific inquiry as Johnson suggests? Do these fine, episodic adjustments really betray a concerted effort among scientists to promote evolution despite evidence to the contrary? In a word: no. What all this tweaking really indicates is that researchers are constantly checking the numerous hypotheses *about* evolution against observation and are

willing to amend these special theorems as new facts demand. After all, it would be unrealistic at best to suppose a pair of nineteenth-century naturalists could have devised a comprehensive accounting of how life works. If evolution seems to be a theory in flux, it is only because there is a lot more to the serendipitous saga of evolution than just biological variation and natural selection. Otherwise, scientists would have lost interest long ago. In reality, it is the details that keep evolutionary biologists up at night, vacillating between alternate explanations for a given set of observations, often working to obsession to illuminate just one small piece of this grand puzzle. So while evolutionary theory has indeed been expanded over the years to encompass newly emergent evidence, this activity does not betray a sinister plot hatched by the “scientific priesthood” to buoy a preconceived worldview but merely typifies the maturation of a scientific theory onto which multiple layers of complexity have been, and are being, added.

In truth, fresh hypotheses stripped to the bone by Ockham's Razor must often be fleshed out to accommodate the complexities of the real world. When, for example, aesthetic circular orbits were found wanting in their power to predict planetary positions, elliptical paths were eventually recognized as a better fit. And when finer measures revealed deviations from *this* expected course, more subtle elements like the gravitational interplay among planets and relativity were added to the mix to account for these tiny discrepancies.

This is the way complex scientific theories are forged. Working hypotheses don't have to be 100 percent correct to be useful; they need only fit the facts better than all other theorems. Allowed a moment of allegoric indulgence, one might fancy the gradual accumulation of empirical evidence as a form of selection pressure to which scientific theories must adapt over time. Within the confines of the scientific method, individual hypotheses, like individual species, survive only so long as a compatible environment persists. Once the environs of information change to favor a new theorem, extinction of the old becomes inevitable. How quickly depends only upon the degree to which the data field has been altered and the relative strength of rival hypotheses. In the face of clear contradictory evidence, nothing—not the antiquity of an idea or its appeal to human sentiment—can save a flawed hypothesis from extermination. In the harsh environment of science, only the fittest theories survive.

Among the most ambitious attacks launched in Johnson's ongoing campaign is his attempt to impugn the legitimacy of the scientific method itself. Here the author invokes the philosophical ruminations of David Hume to suggest that no collection of factual observations, no matter how extensive, can ever suffice to establish

the validity of a scientific theory.<sup>7</sup> This time, the semantic smokescreen centers on the erroneous assertion that in order to be valid, a scientific law must be irrefutably true—a condition, by the way, that flies in the face of the falsifiability criterion he had touted just pages earlier. What Johnson fails to acknowledge in this case is that the method of inductive reasoning does not presume to grant scientists the power to discern what is true in absolute terms but instead provides a systematic way to gauge the *odds* that something is true. To be sure, scientists cannot claim complete knowledge of anything with dogmatic certainty, but they *have* shown concepts like atoms, genes, cells, and star-centered solar systems to be demonstrably true while showing countless other ideas like geocentrism and the fixity of species to be manifestly false. As author and skeptic Michael Shermer recently observed: “*Superstring theory may be uncertain, but heliocentrism is not. Whether the history of life is best described by gradualism or punctuated equilibrium may still be in dispute, but the fact that life has evolved is not. The difference is one of probabilities...*”<sup>8</sup>

Arguing that all empirical knowledge is imperfect might make for engaging dinner conversation, but such philosophical truisms are not very useful in prosecuting our daily lives. In practice, all firsthand knowledge—everything we know without being told—is based on observation and inductive reasoning. Consciously or not, everyone relies on the informal application of scientific methodologies to judge how the world works. We all know from countless episodes of casual experimentation that nature exhibits certain broad consistencies that hold true time and again. No one has to tell us, for example, that unsupported objects tend to fall to the floor. We all know this from an untold number of personal experiments performed since infancy. This is how we learn to anticipate future events and determine what to expect from our environment. And even though superficial analyses of this sort can occasionally lead us to misinterpret the true nature of things, we are compelled to act on these presumptive truths because they have always been the most practicable way to survive in the real world. Formal scientific practices simply add rigor to everyday inductive processes in order to bring less obvious physical processes into sharper focus while stripping away the biases that come from our possessing biological senses tuned to narrow spatial dimensions and brief time frames. Pundits can always argue that absolute knowledge cannot be attained through the logic of induction, but we still play the odds as play we must—and there are plenty of safe bets out there. Of course, not all safe bets are as obvious as the persistent tug of gravity or the coming dawn, but considering the astounding confluence of evidence supporting Darwin's theory, the odds favoring evolution are for all practical purposes just as short.