A Short History of Nearly Everything

By Bill Bryson

Despite declining catches,

New England fishermen continue to receive state and federal tax incentives

that encourage them— in

some cases all but compel them— to acquire bigger boats and to harvest the

seas more intensively.

Today fishermen of Massachusetts are reduced to fishing the hideous

hagfish, for which there is a

slight market in the Far East, but even their numbers are now falling.

We are remarkably ignorant of the dynamics that rule life in the sea. While

marine life is poorer than

it ought to be in areas that have been overfished, in some naturally

impoverished waters there is far

more life than there ought to be. The southern oceans around Antarctica

produce only about 3

percent of the world’s phytoplankton— far too little, it would seem, to

support a complex ecosystem,

and yet it does. Crab-eater seals are not a species of animal that most of us

have heard of, but they

may actually be the second most numerous large species of animal on Earth,

after humans. As many

as fifteen million of them may live on the pack ice around Antarctica. There are also perhaps two million Weddel seals, at least half a million emperor penguins, and maybe as many as four million Adélie penguins. The food chain is thus hopelessly top heavy, but somehow it works. Remarkably no one knows how.

All this is a very roundabout way of making the point that we know very little about Earth's biggest system. But then, as we shall see in the pages remaining to us, once you start talking about life, there is a great deal we don't know, not least how it got going in the first place.

19 **THE RISE OF LIFE**

IN 1953, STANLEY Miller, a graduate student at the University of Chicago, took two flasks— one containing a little water to represent a primeval ocean, the other holding a mixture of methane, ammonia, and hydrogen sulphide gases to represent Earth's early atmosphere— connected them with rubber tubes, and introduced some electrical sparks as a stand-in for

lightning. After a few days, the
water in the flasks had turned green and yellow in a hearty broth of amino acids, fatty acids, sugars,
and other organic compounds. “If God didn’t do it this way,” observed Miller’s delighted supervisor,
the Nobel laureate Harold Urey, “He missed a good bet.”
Press reports of the time made it sound as if about all that was needed now was for somebody to give
the whole a good shake and life would crawl out. As time has shown, it wasn’t nearly so simple.
Despite half a century of further study, we are no nearer to synthesizing life today than we were in
1953 and much further away from thinking we can. Scientists are now pretty certain that the early
atmosphere was nothing like as primed for development as Miller and Urey’s gaseous stew, but
rather was a much less reactive blend of nitrogen and carbon dioxide. Repeating Miller’s
experiments with these more challenging inputs has so far produced only one fairly primitive amino

acid. At all events, creating amino acids is not really the problem. The problem is proteins.

Proteins are what you get when you string amino acids together, and we need a lot of them. No one really knows, but there may be as many as a million types of protein in the human body, and each one is a little miracle. By all the laws of probability proteins shouldn't exist. To make a protein you need to assemble amino acids (which I am obliged by long tradition to refer to here as "the building blocks of life") in a particular order, in much the same way that you assemble letters in a particular order to spell a word. The problem is that words in the amino acid alphabet are often exceedingly long. To spell collagen, the name of a common type of protein, you need to arrange eight letters in the right order. But to make collagen, you need to arrange 1,055 amino acids in precisely the right sequence. But— and here's an obvious but crucial point— you don't make it. It makes itself, spontaneously, without direction, and this is where the unlikelihoods come in.

The chances of a 1,055-sequence molecule like collagen spontaneously self-assembling are, frankly, nil. It just isn’t going to happen. To grasp what a long shot its existence is, visualize a standard Las Vegas slot machine but broadened greatly— to about ninety feet, to be precise— to accommodate 1,055 spinning wheels instead of the usual three or four, and with twenty symbols on each wheel (one for each common amino acid).*35 How long would you have to pull the handle before all 1,055 symbols came up in the right order? Effectively forever. Even if you reduced the number of spinning wheels to two hundred, which is actually a more typical number of amino acids for a protein, the odds against all two hundred coming up in a prescribed sequence are 1 in 10260 (that is a 1 followed by 260 zeroes). That in itself is a larger number than all the atoms in the universe.

Proteins, in short, are complex entities. Hemoglobin is only 146 amino acids long, a runt by protein standards, yet even it offers 10190 possible amino acid combinations, which is why it took the Cambridge University chemist Max Perutz twenty-three years— a career, more or less— to unravel it.

For random events to produce even a single protein would seem a stunning improbability— like a whirlwind spinning through a junkyard and leaving behind a fully assembled jumbo jet, in the colorful simile of the astronomer Fred Hoyle.

Yet we are talking about several hundred thousand types of protein, perhaps a million, each unique and each, as far as we know, vital to the maintenance of a sound and happy you. And it goes on from there. A protein to be of use must not only assemble amino acids in the right sequence, but then must engage in a kind of chemical origami and fold itself into a very specific shape. Even having achieved this structural complexity, a protein is no good to you if it can’t reproduce itself, and proteins can’t.

For this you need DNA. DNA is a whiz at replicating— it can make a copy of itself in seconds— but

can do virtually nothing else. So we have a paradoxical situation. Proteins can’t exist without DNA,

and DNA has no purpose without proteins. Are we to assume then that they arose simultaneously

with the purpose of supporting each other? If so: wow.

And there is more still. DNA, proteins, and the other components of life couldn’t prosper without

some sort of membrane to contain them. No atom or molecule has ever achieved life independently.

Pluck any atom from your body, and it is no more alive than is a grain of sand. It is only when they

come together within the nurturing refuge of a cell that these diverse materials can take part in the

amazing dance that we call life. Without the cell, they are nothing more than interesting chemicals.

But without the chemicals, the cell has no purpose. As the physicist Paul Davies puts it, “If everything needs everything else, how did the community of molecules ever arise in the first place?"

It is rather as if all the ingredients in your kitchen somehow got together and baked themselves into a cake— but a cake that could moreover divide when necessary to produce more cakes. It is little wonder that we call it the miracle of life. It is also little wonder that we have barely begun to understand it.

So what accounts for all this wondrous complexity? Well, one possibility is that perhaps it isn't quite— not quite— so wondrous as at first it seems. Take those amazingly improbable proteins. The wonder we see in their assembly comes in assuming that they arrived on the scene fully formed. But what if the protein chains didn't assemble all at once? What if, in the great slot machine of creation, some of the wheels could be held, as a gambler might hold a number of promising cherries? What if, in other words, proteins didn't suddenly burst into being, but evolved.

Imagine if you took all the components that make up a human being— carbon, hydrogen, oxygen, and so on— and put them in a container with some water, gave it a vigorous stir, and out stepped a completed person. That would be amazing. Well, that's essentially what Hoyle and others (including many ardent creationists) argue when they suggest that proteins spontaneously formed all at once.

They didn't— they can't have. As Richard Dawkins argues in The Blind Watchmaker, there must have been some kind of cumulative selection process that allowed amino acids to assemble in chunks. Perhaps two or three amino acids linked up for some simple purpose and then after a time bumped into some other similar small cluster and in so doing "discovered" some additional improvement.

Chemical reactions of the sort associated with life are actually something of a commonplace. It may be beyond us to cook them up in a lab, à la Stanley Miller and Harold Urey,

but the universe does it
readily enough. Lots of molecules in nature get together to form long chains called polymers. Sugars
constantly assemble to form starches. Crystals can do a number of lifelike things— replicate, respond
to environmental stimuli, take on a patterned complexity. They've never achieved life itself, of
course, but they demonstrate repeatedly that complexity is a natural, spontaneous, entirely
commonplace event. There may or may not be a great deal of life in the universe at large, but there is
no shortage of ordered self-assembly, in everything from the transfixing symmetry of snowflakes to
the comely rings of Saturn.

So powerful is this natural impulse to assemble that many scientists now believe that life may be
more inevitable than we think— that it is, in the words of the Belgian biochemist and Nobel laureate
Christian de Duve, "an obligatory manifestation of matter, bound to arise wherever conditions are

appropriate." De Duve thought it likely that such conditions would be encountered perhaps a million times in every galaxy.

Certainly there is nothing terribly exotic in the chemicals that animate us. If you wished to create another living object, whether a goldfish or a head of lettuce or a human being, you would need really only four principal elements, carbon, hydrogen, oxygen, and nitrogen, plus small amounts of a few others, principally sulfur, phosphorus, calcium, and iron. Put these together in three dozen or so combinations to form some sugars, acids, and other basic compounds and you can build anything that lives. As Dawkins notes: "There is nothing special about the substances from which living things are made. Living things are collections of molecules, like everything else."

The bottom line is that life is amazing and gratifying, perhaps even miraculous, but hardly impossible— as we repeatedly attest with our own modest existences. To be sure, many of the details of life’s beginnings remain pretty imponderable. Every scenario you have ever read concerning the conditions necessary for life involves water— from the “warm little pond” where Darwin supposed life began to the bubbling sea vents that are now the most popular candidates for life’s beginnings— but all this overlooks the fact that to turn monomers into polymers (which is to say, to begin to create proteins) involves what is known to biology as “dehydration linkages.” As one leading biology text puts it, with perhaps just a tiny hint of discomfort, “Researchers agree that such reactions would not have been energetically favorable in the primitive sea, or indeed in any aqueous medium, because of the mass action law.” It is a little like putting sugar in a glass of water and having it become a cube.

It shouldn’t happen, but somehow in nature it does. The actual chemistry of all this is a little arcane for our purposes here, but it is enough to know that if you make monomers

wet they don’t turn into
polymers— except when creating life on Earth. How and why it happens then and not otherwise is
one of biology’s great unanswered questions.

One of the biggest surprises in the earth sciences in recent decades was the discovery of just how
early in Earth’s history life arose. Well into the 1950s, it was thought that life was less than 600
million years old. By the 1970s, a few adventurous souls felt that maybe it went back 2.5 billion
years. But the present date of 3.85 billion years is stunningly early. Earth’s surface didn’t become
solid until about 3.9 billion years ago.

“We can only infer from this rapidity that it is not ‘difficult’ for life of bacterial grade to evolve on
planets with appropriate conditions,” Stephen Jay Gould observed in the New York Times in 1996.

Or as he put it elsewhere, it is hard to avoid the conclusion that “life, arising as soon as it could, was
chemically destined to be.”

Life emerged so swiftly, in fact, that some authorities think it must have had help— perhaps a good

deal of help. The idea that earthly life might have arrived from space has a surprisingly long and

even occasionally distinguished history. The great Lord Kelvin himself raised the possibility as long

ago as 1871 at a meeting of the British Association for the Advancement of Science when he

suggested that “the germs of life might have been brought to the earth by some meteorite.” But it

remained little more than a fringe notion until one Sunday in September 1969 when tens of

thousands of Australians were startled by a series of sonic booms and the sight of a fireball streaking

from east to west across the sky. The fireball made a strange crackling sound as it passed and left

behind a smell that some likened to methylated spirits and others described as just awful.

The fireball exploded above Murchison, a town of six hundred people in the Goulburn Valley north of Melbourne, and came raining down in chunks, some weighing up to twelve pounds. Fortunately, no one was hurt. The meteorite was of a rare type known as a carbonaceous chondrite, and the townspeople helpfully collected and brought in some two hundred pounds of it. The timing could hardly have been better. Less than two months earlier, the Apollo 11 astronauts had returned to Earth with a bag full of lunar rocks, so labs throughout the world were geared up— indeed clamoring— for rocks of extraterrestrial origin.

The Murchison meteorite was found to be 4.5 billion years old, and it was studded with amino acids— seventy-four types in all, eight of which are involved in the formation of earthly proteins. In late 2001, more than thirty years after it crashed, a team at the Ames Research Center in California announced that the Murchison rock also contained complex strings of sugars called polyols, which had not been found off the Earth before.

A few other carbonaceous chondrites have strayed into Earth's path since— one that landed near Tagish Lake in Canada's Yukon in January 2000 was seen over large parts of North America— and they have likewise confirmed that the universe is actually rich in organic compounds. Halley's comet, it is now thought, is about 25 percent organic molecules. Get enough of those crashing into a suitable place— Earth, for instance— and you have the basic elements you need for life.

There are two problems with notions of panspermia, as extraterrestrial theories are known. The first is that it doesn't answer any questions about how life arose, but merely moves responsibility for it elsewhere. The other is that panspermia sometimes excites even the most respectable adherents to levels of speculation that can be safely called imprudent. Francis Crick, codiscoverer of the structure of DNA, and his colleague Leslie Orgel have suggested that Earth was "deliberately seeded with life by intelligent aliens," an idea that Gribbin calls "at the very fringe of scientific respectability"— or, put another way, a notion that would be considered wildly lunatic if not voiced by a Nobel laureate.

Fred Hoyle and his colleague Chandra Wickramasinghe further eroded enthusiasm for panspermia by suggesting that outer space brought us not only life but also many diseases such as flu and bubonic plague, ideas that were easily disproved by biochemists. Hoyle— and it seems necessary to insert a reminder here that he was one of the great scientific minds of the twentieth century— also once suggested, as mentioned earlier, that our noses evolved with the nostrils underneath as a way of keeping cosmic pathogens from falling into them as they drifted down from space.

Whatever prompted life to begin, it happened just once. That is the most extraordinary fact in biology, perhaps the most extraordinary fact we know. Everything that has ever lived, plant or animal, dates its beginnings from the same primordial twitch. At some point in an unimaginably distant past some little bag of chemicals fidgeted to life. It absorbed some nutrients, gently pulsed, had a brief existence. This much may have happened before, perhaps many times. But this ancestral packet did something additional and extraordinary: it cleaved itself and produced an heir. A tiny bundle of genetic material passed from one living entity to another, and has never stopped moving since. It was the moment of creation for us all. Biologists sometimes call it the Big Birth.

"Wherever you go in the world, whatever animal, plant, bug, or blob you look at, if it is alive, it will use the same dictionary and know the same code. All life is one," says Matt Ridley. We are all the result of a single genetic trick handed down from generation to generation nearly four billion years, to such an extent that you can take a fragment of human genetic instruction, patch it into a faulty yeast cell, and the yeast cell will put it to work as if it were its own. In a very real sense, it is its own.

The dawn of life— or something very like it— sits on a shelf in the office of a friendly isotope geochemist named Victoria Bennett in the Earth Sciences building of the Australian National University in Canberra. An American, Ms. Bennett came to the ANU from California on a two-year contract in 1989 and has been there ever since. When I visited her, in late 2001, she handed me a modestly hefty hunk of rock composed of thin alternating stripes of white quartz and a gray-green material called clinopyroxene. The rock came from Akilia Island in Greenland, where unusually ancient rocks were found in 1997. The rocks are 3.85 billion years old and represent the oldest marine sediments ever found.

“We can’t be certain that what you are holding once contained living organisms because you’d have to pulverize it to find out,” Bennett told me. “But it comes from the same deposit where the oldest

life was excavated, so it probably had life in it.” Nor would you find actual

fossilized microbes,

however carefully you searched. Any simple organisms, alas, would have

been baked away by the

processes that turned ocean mud to stone. Instead what we would see if we

crunched up the rock and

examined it microscopically would be the chemical residues that the

organisms left behind— carbon

isotopes and a type of phosphate called apatite, which together provide

strong evidence that the rock

once contained colonies of living things. “We can only guess what the

organism might have looked

like,” Bennett said. “It was probably about as basic as life can get— but it

was life nonetheless. It

lived. It propagated.”

And eventually it led to us.

If you are into very old rocks, and Bennett indubitably is, the ANU has long

been a prime place to

be. This is largely thanks to the ingenuity of a man named Bill Compston,

who is now retired but in
the 1970s built the world's first Sensitive High Resolution Ion Micro
Probe— or SHRIMP, as it is
more affectionately known from its initial letters. This is a machine that
measures the decay rate of
uranium in tiny minerals called zircons. Zircons appear in most rocks apart
from basalts and are
extremely durable, surviving every natural process but subduction. Most of
the Earth's crust has
been slipped back into the oven at some point, but just occasionally— in
Western Australia and
Greenland, for example— geologists have found outcrops of rocks that have
remained always at the
surface. Compston's machine allowed such rocks to be dated with
unparalleled precision. The
prototype SHRIMP was built and machined in the Earth Science
department's own workshops, and
looked like something that had been built from spare parts on a budget, but it
worked great. On its
first formal test, in 1982, it dated the oldest thing ever found— a

4.3-billion-year-old rock from

Western Australia.

“It caused quite a stir at the time,” Bennett told me, “to find something so important so quickly with

brand-new technology.”

She took me down the hall to see the current model, SHRIMP II. It was a big heavy piece of

stainless-steel apparatus, perhaps twelve feet long and five feet high, and as solidly built as a deepsea

probe. At a console in front of it, keeping an eye on ever-changing strings of figures on a screen,

was a man named Bob from Canterbury University in New Zealand. He had been there since 4 A.M.,

he told me. SHRIMP II runs twenty-four hours a day; there’s that many rocks to date. It was just

after 9 A.M. and Bob had the machine till noon. Ask a pair of geochemists how something like this

works, and they will start talking about isotopic abundances and ionization levels with an enthusiasm

that is more endearing than fathomable. The upshot of it, however, was that the machine, by

bombarding a sample of rock with streams of charged atoms, is able to detect subtle differences in

the amounts of lead and uranium in the zircon samples, by which means the age of rocks can be

accurately adduced. Bob told me that it takes about seventeen minutes to read one zircon and it is

necessary to read dozens from each rock to make the data reliable. In practice, the process seemed to

involve about the same level of scattered activity, and about as much stimulation, as a trip to a

laundromat. Bob seemed very happy, however; but then people from New Zealand very generally

do.

The Earth Sciences compound was an odd combination of things— part offices, part labs, part

machine shed. “We used to build everything here,” Bennett said. “We even had our own

glassblower, but he’s retired. But we still have two full-time rock crushers.” She caught my look of mild surprise. “We get through a lot of rocks. And they have to be very carefully prepared. You have to make sure there is no contamination from previous samples— no dust or anything. It’s quite a meticulous process.” She showed me the rock-crushing machines, which were indeed pristine, though the rock crushers had apparently gone for coffee. Beside the machines were large boxes containing rocks of all shapes and sizes. They do indeed get through a lot of rocks at the ANU.

Back in Bennett’s office after our tour, I noticed hanging on her wall a poster giving an artist’s colorfully imaginative interpretation of Earth as it might have looked 3.5 billion years ago, just when life was getting going, in the ancient period known to earth science as the Archaean. The poster showed an alien landscape of huge, very active volcanoes, and a steamy, copper-colored sea beneath a harsh red sky. Stromatolites, a kind of bacterial rock, filled the shallows in the foreground. It didn’t look like a very promising place to create and nurture life. I asked her if the painting was accurate.

"Well, one school of thought says it was actually cool then because the sun was much weaker." (I later learned that biologists, when they are feeling jocose, refer to this as the "Chinese restaurant problem"— because we had a dim sun.) "Without an atmosphere ultraviolet rays from the sun, even from a weak sun, would have tended to break apart any incipient bonds made by molecules. And yet right there"— she tapped the stromatolites— "you have organisms almost at the surface. It's a puzzle."

"So we don't know what the world was like back then?"

"Mmmm," she agreed thoughtfully.

"Either way it doesn't seem very conducive to life."

She nodded amiably. "But there must have been something that suited life. Otherwise we wouldn't be here."

It certainly wouldn't have suited us. If you were to step from a time machine

into that ancient
Archaean world, you would very swiftly scamper back inside, for there was no more oxygen to
breathe on Earth back then than there is on Mars today. It was also full of noxious vapors from
hydrochloric and sulfuric acids powerful enough to eat through clothing and blister skin. Nor would
it have provided the clean and glowing vistas depicted in the poster in Victoria Bennett's office. The
chemical stew that was the atmosphere then would have allowed little sunlight to reach the Earth's
surface. What little you could see would be illumined only briefly by bright and frequent lightning
flashes. In short, it was Earth, but an Earth we wouldn't recognize as our own.

Anniversaries were few and far between in the Archaean world. For two billion years bacterial
organisms were the only forms of life. They lived, they reproduced, they swarmed, but they didn't
show any particular inclination to move on to another, more challenging

level of existence. At some
point in the first billion years of life, cyanobacteria, or blue-green algae, learned to tap into a freely
available resource— the hydrogen that exists in spectacular abundance in water. They absorbed water
molecules, supped on the hydrogen, and released the oxygen as waste, and in so doing invented
photosynthesis. As Margulis and Sagan note, photosynthesis is “undoubtedly the most important
single metabolic innovation in the history of life on the planet”— and it was invented not by plants
but by bacteria.

As cyanobacteria proliferated the world began to fill with O_2 to the consternation of those organisms
that found it poisonous— which in those days was all of them. In an anaerobic (or a non-oxygenusing)
world, oxygen is extremely poisonous. Our white cells actually use oxygen to kill invading
bacteria. That oxygen is fundamentally toxic often comes as a surprise to those of us who find it so

convivial to our well-being, but that is only because we have evolved to exploit it. To other things it is a terror. It is what turns butter rancid and makes iron rust. Even we can tolerate it only up to a point. The oxygen level in our cells is only about a tenth the level found in the atmosphere.

The new oxygen-using organisms had two advantages. Oxygen was a more efficient way to produce energy, and it vanquished competitor organisms. Some retreated into the oozy, anaerobic world of bogs and lake bottoms. Others did likewise but then later (much later) migrated to the digestive tracts of beings like you and me. Quite a number of these primeval entities are alive inside your body right now, helping to digest your food, but abhorring even the tiniest hint of $O2$. Untold numbers of others failed to adapt and died.

The cyanobacteria were a runaway success. At first, the extra oxygen they produced didn’t accumulate in the atmosphere, but combined with iron to form ferric oxides, which sank to the

bottom of primitive seas. For millions of years, the world literally rusted— a phenomenon vividly

recorded in the banded iron deposits that provide so much of the world's iron ore today. For many

tens of millions of years not a great deal more than this happened. If you went back to that early

Proterozoic world you wouldn't find many signs of promise for Earth's future life. Perhaps here and

there in sheltered pools you'd encounter a film of living scum or a coating of glossy greens and

browns on shoreline rocks, but otherwise life remained invisible.

But about 3.5 billion years ago something more emphatic became apparent. Wherever the seas were

shallow, visible structures began to appear. As they went through their chemical routines, the

cyanobacteria became very slightly tacky, and that tackiness trapped microparticles of dust and sand,

which became bound together to form slightly weird but solid structures— the stromatolites that were featured in the shallows of the poster on Victoria Bennett's office wall. Stromatolites came in various shapes and sizes. Sometimes they looked like enormous cauliflowers, sometimes like fluffy mattresses (stromatolite comes from the Greek for "mattress"), sometimes they came in the form of columns, rising tens of meters above the surface of the water— sometimes as high as a hundred meters. In all their manifestations, they were a kind of living rock, and they represented the world's first cooperative venture, with some varieties of primitive organism living just at the surface and others living just underneath, each taking advantage of conditions created by the other. The world had its first ecosystem.

For many years, scientists knew about stromatolites from fossil formations, but in 1961 they got a real surprise with the discovery of a community of living stromatolites at Shark Bay on the remote northwest coast of Australia. This was most unexpected— so unexpected, in fact, that it was some years before scientists realized quite what they had found. Today, however, Shark Bay is a tourist attraction— or at least as much of a tourist attraction as a place hundreds of miles from anywhere much and dozens of miles from anywhere at all can ever be. Boardwalks have been built out into the bay so that visitors can stroll over the water to get a good look at the stromatolites, quietly respiring just beneath the surface. They are lusterless and gray and look, as I recorded in an earlier book, like very large cow-pats. But it is a curiously giddying moment to find yourself staring at living remnants of Earth as it was 3.5 billion years ago. As Richard Fortey has put it: “This is truly time traveling, and if the world were attuned to its real wonders this sight would be as well-known as the pyramids of Giza.” Although you’d never guess it, these dull rocks swarm with life, with an estimated (well, obviously estimated) three billion individual organisms on every square yard of rock. Sometimes when you look carefully you can see tiny strings of bubbles rising to the surface as they give up their oxygen. In two billion years such tiny exertions raised the level of oxygen in Earth's atmosphere to 20 percent, preparing the way for the next, more complex chapter in life's history.

It has been suggested that the cyanobacteria at Shark Bay are perhaps the slowest-evolving organisms on Earth, and certainly now they are among the rarest. Having prepared the way for more complex life forms, they were then grazed out of existence nearly everywhere by the very organisms whose existence they had made possible. (They exist at Shark Bay because the waters are too saline for the creatures that would normally feast on them.)

One reason life took so long to grow complex was that the world had to wait until the simpler organisms had oxygenated the atmosphere sufficiently. "Animals could not summon up the energy to work," as Fortey has put it. It took about two billion years, roughly 40 percent of Earth's history, for

oxygen levels to reach more or less modern levels of concentration in the atmosphere. But once the

stage was set, and apparently quite suddenly, an entirely new type of cell arose— one with a nucleus

and other little bodies collectively called organelles (from a Greek word meaning "little tools"). The

process is thought to have started when some blundering or adventuresome bacterium either invaded

or was captured by some other bacterium and it turned out that this suited them both. The captive

bacterium became, it is thought, a mitochondrion. This mitochondrial invasion (or endosymbiotic

event, as biologists like to term it) made complex life possible. (In plants a similar invasion produced

chloroplasts, which enable plants to photosynthesize.)

Mitochondria manipulate oxygen in a way that liberates energy from foodstuffs. Without this niftily

facilitating trick, life on Earth today would be nothing more than a sludge of simple microbes.

Mitochondria are very tiny— you could pack a billion into the space occupied by a grain of sand—

but also very hungry. Almost every nutriment you absorb goes to feeding them.

We couldn’t live for two minutes without them, yet even after a billion years mitochondria behave as

if they think things might not work out between us. They maintain their own DNA. They reproduce

at a different time from their host cell. They look like bacteria, divide like bacteria, and sometimes

respond to antibiotics in the way bacteria do. In short, they keep their bags packed. They don’t even

speak the same genetic language as the cell in which they live. It is like having a stranger in your

house, but one who has been there for a billion years.

The new type of cell is known as a eukaryote (meaning “truly nucleated”), as contrasted with the old

type, which is known as a prokaryote (“prenucleated”), and it seems to have arrived suddenly in the

fossil record. The oldest eukaryotes yet known, called Grypania, were discovered in iron sediments
in Michigan in 1992. Such fossils have been found just once, and then no more are known for 500
million years.

Compared with the new eukaryotes the old prokaryotes were little more than “bags of chemicals,” in
the words of the geologist Stephen Drury. Eukaryotes were bigger— eventually as much as ten
thousand times bigger— than their simpler cousins, and carried as much as a thousand times more
DNA. Gradually a system evolved in which life was dominated by two types of form— organisms
that expel oxygen (like plants) and those that take it in (you and me).

Single-celled eukaryotes were once called protozoa (“pre-animals”), but that term is increasingly
disdained. Today the common term for them is protists. Compared with the bacteria that had gone
before, these new protists were wonders of design and sophistication. The simple amoeba, just one

cell big and without any ambitions but to exist, contains 400 million bits of genetic information in its DNA— enough, as Carl Sagan noted, to fill eighty books of five hundred pages.

Eventually the eukaryotes learned an even more singular trick. It took a long time— a billion years or so— but it was a good one when they mastered it. They learned to form together into complex multicellular beings. Thanks to this innovation, big, complicated, visible entities like us were possible. Planet Earth was ready to move on to its next ambitious phase.

But before we get too excited about that, it is worth remembering that the world, as we are about to see, still belongs to the very small.

20 **SMALL WORLD**

IT'S PROBABLY NOT a good idea to take too personal an interest in your microbes. Louis Pasteur, the great French chemist and bacteriologist, became so preoccupied with them that he took to peering critically at every dish placed before him with a magnifying glass, a habit that presumably

did not win him many repeat invitations to dinner.

In fact, there is no point in trying to hide from your bacteria, for they are on and around you always,

in numbers you can’t conceive. If you are in good health and averagely diligent about hygiene, you

will have a herd of about one trillion bacteria grazing on your fleshy plains— about a hundred

thousand of them on every square centimeter of skin. They are there to dine off the ten billion or so

flakes of skin you shed every day, plus all the tasty oils and fortifying minerals that seep out from

every pore and fissure. You are for them the ultimate food court, with the convenience of warmth

and constant mobility thrown in. By way of thanks, they give you B.O.

And those are just the bacteria that inhabit your skin. There are trillions more tucked away in your

gut and nasal passages, clinging to your hair and eyelashes, swimming over the surface of your eyes,

drilling through the enamel of your teeth. Your digestive system alone is

host to more than a hundred
trillion microbes, of at least four hundred types. Some deal with sugars, some with starches, some
attack other bacteria. A surprising number, like the ubiquitous intestinal spirochetes, have no
detectable function at all. They just seem to like to be with you. Every human body consists of about
10 quadrillion cells, but about 100 quadrillion bacterial cells. They are, in short, a big part of us.

From the bacteria's point of view, of course, we are a rather small part of them.

Because we humans are big and clever enough to produce and utilize antibiotics and disinfectants, it
is easy to convince ourselves that we have banished bacteria to the fringes of existence. Don't you
believe it. Bacteria may not build cities or have interesting social lives, but they will be here when
the Sun explodes. This is their planet, and we are on it only because they allow us to be.

Bacteria, never forget, got along for billions of years without us. We couldn’t survive a day without

them. They process our wastes and make them usable again; without their

diligent munching nothing

would rot. They purify our water and keep our soils productive. Bacteria

synthesize vitamins in our

gut, convert the things we eat into useful sugars and polysaccharides, and go

to war on alien

microbes that slip down our gullet.

We depend totally on bacteria to pluck nitrogen from the air and convert it

into useful nucleotides

and amino acids for us. It is a prodigious and gratifying feat. As Margulis

and Sagan note, to do the

same thing industrially (as when making fertilizers) manufacturers must heat

the source materials to

500 degrees centigrade and squeeze them to three hundred times normal

pressures. Bacteria do it all

the time without fuss, and thank goodness, for no larger organism could

survive without the nitrogen

they pass on. Above all, microbes continue to provide us with the air we

breathe and to keep the

atmosphere stable. Microbes, including the modern versions of cyanobacteria, supply the greater part of the planet's breathable oxygen. Algae and other tiny organisms bubbling away in the sea blow out about 150 billion kilos of the stuff every year.

And they are amazingly prolific. The more frantic among them can yield a new generation in less than ten minutes; Clostridium perfringens, the disagreeable little organism that causes gangrene, can reproduce in nine minutes. At such a rate, a single bacterium could theoretically produce more offspring in two days than there are protons in the universe. "Given an adequate supply of nutrients, a single bacterial cell can generate 280,000 billion individuals in a single day," according to the Belgian biochemist and Nobel laureate Christian de Duve. In the same period, a human cell can just about manage a single division.

About once every million divisions, they produce a mutant. Usually this is bad luck for the mutant—

change is always risky for an organism— but just occasionally the new bacterium is endowed with
some accidental advantage, such as the ability to elude or shrug off an attack of antibiotics. With this
ability to evolve rapidly goes another, even scarier advantage. Bacteria share information. Any
bacterium can take pieces of genetic coding from any other. Essentially, as Margulis and Sagan put
it, all bacteria swim in a single gene pool. Any adaptive change that occurs in one area of the
bacterial universe can spread to any other. It's rather as if a human could go to an insect to get the
necessary genetic coding to sprout wings or walk on ceilings. It means that from a genetic point of
view bacteria have become a single superorganism— tiny, dispersed, but invincible.
They will live and thrive on almost anything you spill, dribble, or shake loose. Just give them a little
moisture— as when you run a damp cloth over a counter— and they will bloom as if created from

nothing. They will eat wood, the glue in wallpaper, the metals in hardened paint. Scientists in Australia found microbes known as Thiobacillus concretivorans that lived in— indeed, could not live without— concentrations of sulfuric acid strong enough to dissolve metal. A species called Micrococcus radiophilus was found living happily in the waste tanks of nuclear reactors, gorging itself on plutonium and whatever else was there. Some bacteria break down chemical materials from which, as far as we can tell, they gain no benefit at all.

They have been found living in boiling mud pots and lakes of caustic soda, deep inside rocks, at the bottom of the sea, in hidden pools of icy water in the McMurdo Dry Valleys of Antarctica, and seven miles down in the Pacific Ocean where pressures are more than a thousand times greater than at the surface, or equivalent to being squashed beneath fifty jumbo jets. Some of them seem to be practically indestructible. Deinococcus radiodurans is, according to the

Economist, “almost immune to radioactivity.” Blast its DNA with radiation, and the pieces immediately reform “like the scuttling limbs of an undead creature from a horror movie.”

Perhaps the most extraordinary survival yet found was that of a Streptococcus bacterium that was recovered from the sealed lens of a camera that had stood on the Moon for two years. In short, there are few environments in which bacteria aren’t prepared to live. “They are finding now that when they push probes into ocean vents so hot that the probes actually start to melt, there are bacteria even there,” Victoria Bennett told me.

In the 1920s two scientists at the University of Chicago, Edson Bastin and Frank Greer, announced that they had isolated from oil wells strains of bacteria that had been living at depths of two thousand feet. The notion was dismissed as fundamentally preposterous— there was nothing to live on at two thousand feet— and for fifty years it was assumed that their samples had been contaminated with

surface microbes. We now know that there are a lot of microbes living deep

within the Earth, many

of which have nothing at all to do with the organic world. They eat rocks or,

rather, the stuff that’s in

rocks— iron, sulfur, manganese, and so on. And they breathe odd things

too— iron, chromium,

cobalt, even uranium. Such processes may be instrumental in concentrating

gold, copper, and other

precious metals, and possibly deposits of oil and natural gas. It has even

been suggested that their

tireless nibblings created the Earth’s crust.

Some scientists now think that there could be as much as 100 trillion tons of

bacteria living beneath

our feet in what are known as subsurface lithoautotrophic microbial

ecosystems— SLiME for short.

Thomas Gold of Cornell has estimated that if you took all the bacteria out of

the Earth’s interior and

dumped it on the surface, it would cover the planet to a depth of five feet. If

the estimates are correct,

there could be more life under the Earth than on top of it.

At depth microbes shrink in size and become extremely sluggish. The liveliest of them may divide no more than once a century, some no more than perhaps once in five hundred years. As the Economist has put it: “The key to long life, it seems, is not to do too much.” When things are really tough, bacteria are prepared to shut down all systems and wait for better times. In 1997 scientists successfully activated some anthrax spores that had lain dormant for eighty years in a museum display in Trondheim, Norway. Other microorganisms have leapt back to life after being released from a 118-year-old can of meat and a 166-year-old bottle of beer. In 1996, scientists at the Russian Academy of Science claimed to have revived bacteria frozen in Siberian permafrost for three million years. But the record claim for durability so far is one made by Russell Vreeland and colleagues at West Chester University in Pennsylvania in 2000, when they announced that they had resuscitated

250-million-year-old bacteria called Bacillus permians that had been trapped

in salt deposits two

thousand feet underground in Carlsbad, New Mexico. If so, this microbe is

older than the continents.

The report met with some understandable dubiousness. Many biochemists

maintained that over such

a span the microbe's components would have become uselessly degraded

unless the bacterium

roused itself from time to time. However, if the bacterium did stir

occasionally there was no

plausible internal source of energy that could have lasted so long. The more

doubtful scientists

suggested that the sample may have been contaminated, if not during its

retrieval then perhaps while

still buried. In 2001, a team from Tel Aviv University argued that B.

permians were almost identical

to a strain of modern bacteria, Bacillus marismortui, found in the Dead Sea.

Only two of its genetic

sequences differed, and then only slightly.

“Are we to believe,” the Israeli researchers wrote, “that in 250 million years B. permians has accumulated the same amount of genetic differences that could be achieved in just 3–7 days in the laboratory?” In reply, Vreeland suggested that “bacteria evolve faster in the lab than they do in the wild.”

Maybe.

It is a remarkable fact that well into the space age, most school textbooks divided the world of the living into just two categories— plant and animal. Microorganisms hardly featured. Amoebas and similar single-celled organisms were treated as proto-animals and algae as proto-plants. Bacteria were usually lumped in with plants, too, even though everyone knew they didn’t belong there. As far back as the late nineteenth century the German naturalist Ernst Haeckel had suggested that bacteria deserved to be placed in a separate kingdom, which he called Monera, but the idea didn’t begin to

catch on among biologists until the 1960s and then only among some of them. (I note that my trusty
American Heritage desk dictionary from 1969 doesn't recognize the term.) Many organisms in the visible world were also poorly served by the traditional division. Fungi, the
group that includes mushrooms, molds, mildews, yeasts, and puffballs, were nearly always treated as
botanical objects, though in fact almost nothing about them— how they reproduce and respire, how
they build themselves— matches anything in the plant world. Structurally they have more in common
with animals in that they build their cells from chitin, a material that gives them their distinctive
texture. The same substance is used to make the shells of insects and the claws of mammals, though
it isn't nearly so tasty in a stag beetle as in a Portobello mushroom. Above all, unlike all plants, fungi
don't photosynthesize, so they have no chlorophyll and thus are not green. Instead they grow directly
on their food source, which can be almost anything. Fungi will eat the sulfur

off a concrete wall or the decaying matter between your toes— two things no plant will do. Almost the only plantlike quality they have is that they root.

Even less comfortably susceptible to categorization was the peculiar group of organisms formally called myxomycetes but more commonly known as slime molds. The name no doubt has much to do with their obscurity. An appellation that sounded a little more dynamic— “ambulant self-activating protoplasm,” say— and less like the stuff you find when you reach deep into a clogged drain would almost certainly have earned these extraordinary entities a more immediate share of the attention they deserve, for slime molds are, make no mistake, among the most interesting organisms in nature.

When times are good, they exist as one-celled individuals, much like amoebas. But when conditions grow tough, they crawl to a central gathering place and become, almost miraculously, a slug. The slug is not a thing of beauty and it doesn't go terribly far— usually just from the bottom of a pile of leaf litter to the top, where it is in a slightly more exposed position— but for millions of years this may well have been the niftiest trick in the universe.

And it doesn't stop there. Having hauled itself up to a more favorable locale, the slime mold transforms itself yet again, taking on the form of a plant. By some curious orderly process the cells reconfigure, like the members of a tiny marching band, to make a stalk atop of which forms a bulb known as a fruiting body. Inside the fruiting body are millions of spores that, at the appropriate moment, are released to the wind to blow away and become single-celled organisms that can start the process again.

For years slime molds were claimed as protozoa by zoologists and as fungi by mycologists, though most people could see they didn't really belong anywhere. When genetic testing arrived, people in lab coats were surprised to find that slime molds were so distinctive and peculiar that they weren’t directly related to anything else in nature, and sometimes not even to each other.

In 1969, in an attempt to bring some order to the growing inadequacies of classification, an ecologist from Cornell University named R. H. Whittaker unveiled in the journal Science a proposal to divide life into five principal branches— kingdoms, as they are known— called Animalia, Plantae, Fungi, Protista, and Monera. Protista, was a modification of an earlier term, Protoctista, which had been suggested a century earlier by a Scottish biologist named John Hogg, and was meant to describe any organisms that were neither plant nor animal.

Though Whittaker’s new scheme was a great improvement, Protista remained ill defined. Some taxonomists reserved it for large unicellular organisms— the eukaryotes— but others treated it as the kind of odd sock drawer of biology, putting into it anything that didn’t fit

anywhere else. It included
(depending on which text you consulted) slime molds, amoebas, and even seaweed, among much
else. By one calculation it contained as many as 200,000 different species of organism all told.

That’s a lot of odd socks.

Ironically, just as Whittaker’s five-kingdom classification was beginning to find its way into
textbooks, a retiring academic at the University of Illinois was groping his way toward a discovery
that would challenge everything. His name was Carl Woese (rhymes with rose), and since the mid-
1960s— or about as early as it was possible to do so— he had been quietly studying genetic
sequences in bacteria. In the early days, this was an exceedingly painstaking process. Work on a
single bacterium could easily consume a year. At that time, according to Woese, only about 500
species of bacteria were known, which is fewer than the number of species you have in your mouth.

Today the number is about ten times that, though that is still far short of the 26,900 species of algae, 70,000 of fungi, and 30,800 of amoebas and related organisms whose biographies fill the annals of biology.

It isn’t simple indifference that keeps the total low. Bacteria can be exasperatingly difficult to isolate and study. Only about 1 percent will grow in culture. Considering how wildly adaptable they are in nature, it is an odd fact that the one place they seem not to wish to live is a petri dish. Plop them on a bed of agar and pamper them as you will, and most will just lie there, declining every inducement to bloom. Any bacterium that thrives in a lab is by definition exceptional, and yet these were, almost exclusively, the organisms studied by microbiologists. It was, said Woese, “like learning about animals from visiting zoos.”

Genes, however, allowed Woese to approach microorganisms from another angle. As he worked,

Woese realized that there were more fundamental divisions in the microbial world than anyone
suspected. A lot of little organisms that looked like bacteria and behaved like bacteria were actually
something else altogether— something that had branched off from bacteria a long time ago. Woese
called these organisms archaebacteria, later shortened to archaea.
It has be said that the attributes that distinguish archaea from bacteria are not the sort that would
quicken the pulse of any but a biologist. They are mostly differences in their lipids and an absence of
something called peptidoglycan. But in practice they make a world of difference. Archaeans are
more different from bacteria than you and I are from a crab or spider. Singlehandedly Woese had
discovered an unsuspected division of life, so fundamental that it stood above the level of kingdom
at the apogee of the Universal Tree of Life, as it is rather reverentially known.
In 1976, he startled the world— or at least the little bit of it that was paying

attention— by redrawing

the tree of life to incorporate not five main divisions, but twenty-three.

These he grouped under three

new principal categories— Bacteria, Archaea, and Eukarya (sometimes

spelled Eucarya)— which he

called domains.

Woese's new divisions did not take the biological world by storm. Some

dismissed them as much

too heavily weighted toward the microbial. Many just ignored them. Woese,

according to Frances

Ashcroft, "felt bitterly disappointed." But slowly his new scheme began to

catch on among

microbiologists. Botanists and zoologists were much slower to admire its

virtues. It's not hard to see

why. On Woese's model, the worlds of botany and zoology are relegated to

a few twigs on the

outermost branch of the Eukaryan limb. Everything else belongs to

unicellular beings.

"These folks were brought up to classify in terms of gross morphological

similarities and

differences," Woese told an interviewer in 1996. "The idea of doing so in terms of molecular sequence is a bit hard for many of them to swallow." In short, if they couldn't see a difference with their own eyes, they didn't like it. And so they persisted with the traditional five-kingdom division— an arrangement that Woese called "not very useful" in his milder moments and "positively misleading" much of the rest of the time. "Biology, like physics before it," Woese wrote, "has moved to a level where the objects of interest and their interactions often cannot be perceived through direct observation."

In 1998 the great and ancient Harvard zoologist Ernst Mayr (who then was in his ninety-fourth year and at the time of my writing is nearing one hundred and still going strong) stirred the pot further by declaring that there should be just two prime divisions of life— "empires" he called them. In a paper published in the Proceedings of the National Academy of Sciences, Mayr

said that Woese's findings
were interesting but ultimately misguided, noting that "Woese was not trained as a biologist and
quite naturally does not have an extensive familiarity with the principles of classification," which is
perhaps as close as one distinguished scientist can come to saying of another that he doesn't know
what he is talking about.

The specifics of Mayr's criticisms are too technical to need extensive airing here— they involve
issues of meiotic sexuality, Hennigian cladification, and controversial interpretations of the genome
of Methanobacterium thermoautrophicum, among rather a lot else— but essentially he argues that
Woese's arrangement unbalances the tree of life. The bacterial realm, Mayr notes, consists of no
more than a few thousand species while the archaean has a mere 175 named specimens, with perhaps
a few thousand more to be found— "but hardly more than that." By contrast, the eukaryotic realm—

that is, the complicated organisms with nucleated cells, like us— numbers already in the millions. For
the sake of “the principle of balance,” Mayr argues for combining the simple bacterial organisms in a
single category, Prokaryota, while placing the more complex and “highly evolved” remainder in the
empire Eukaryota, which would stand alongside as an equal. Put another way, he argues for keeping
things much as they were before. This division between simple cells and complex cells “is where the
great break is in the living world.”
The distinction between halophilic archaeans and methanosarcina or between flavobacteria and
gram-positive bacteria clearly will never be a matter of moment for most of us, but it is worth
remembering that each is as different from its neighbors as animals are from plants. If Woese’s new
arrangement teaches us anything it is that life really is various and that most of that variety is small,
unicellular, and unfamiliar. It is a natural human impulse to think of

evolution as a long chain of

improvements, of a never-ending advance toward largeness and

complexity— in a word, toward us.

We flatter ourselves. Most of the real diversity in evolution has been

small-scale. We large things are

just flukes— an interesting side branch. Of the twenty-three main divisions

of life, only three—

plants, animals, and fungi— are large enough to be seen by the human eye,

and even they contain

species that are microscopic. Indeed, according to Woese, if you totaled up

all the biomass of the

planet— every living thing, plants included— microbes would account for at

least 80 percent of all

there is, perhaps more. The world belongs to the very small— and it has for

a very long time.

So why, you are bound to ask at some point in your life, do microbes so

often want to hurt us? What

possible satisfaction could there be to a microbe in having us grow feverish

or chilled, or disfigured

with sores, or above all expire? A dead host, after all, is hardly going to provide long-term

hospitality.

To begin with, it is worth remembering that most microorganisms are

neutral or even beneficial to

human well-being. The most rampantly infectious organism on Earth, a

bacterium called Wolbachia,

doesn’t hurt humans at all— or, come to that, any other vertebrates— but if

you are a shrimp or worm

or fruit fly, it can make you wish you had never been born. Altogether, only

about one microbe in a

thousand is a pathogen for humans, according to National Geographic—

though, knowing what some

of them can do, we could be forgiven for thinking that that is quite enough.

Even if mostly benign,

microbes are still the number-three killer in the Western world, and even

many less lethal ones of

course make us deeply rue their existence.

Making a host unwell has certain benefits for the microbe. The symptoms of

an illness often help to

spread the disease. Vomiting, sneezing, and diarrhea are excellent methods

of getting out of one host
and into position for another. The most effective strategy of all is to enlist the help of a mobile third
party. Infectious organisms love mosquitoes because the mosquito’s sting delivers them directly to a
bloodstream where they can get straight to work before the victim’s defense mechanisms can figure
out what’s hit them. This is why so many grade-A diseases— malaria, yellow fever, dengue fever,
encephalitis, and a hundred or so other less celebrated but often rapacious maladies— begin with a
mosquito bite. It is a fortunate fluke for us that HIV, the AIDS agent, isn’t among them— at least not
yet. Any HIV the mosquito sucks up on its travels is dissolved by the mosquito’s own metabolism.

When the day comes that the virus mutates its way around this, we may be in real trouble.

It is a mistake, however, to consider the matter too carefully from the position of logic because
microorganisms clearly are not calculating entities. They don’t care what

they do to you any more
than you care what distress you cause when you slaughter them by the millions with a soapy shower
or a swipe of deodorant. The only time your continuing well-being is of consequence to a pathogen
is when it kills you too well. If they eliminate you before they can move on, then they may well die
out themselves. This in fact sometimes happens. History, Jared Diamond notes, is full of diseases
that "once caused terrifying epidemics and then disappeared as mysteriously as they had come." He
cites the robust but mercifully transient English sweating sickness, which raged from 1485 to 1552,
killing tens of thousands as it went, before burning itself out. Too much efficiency is not a good
thing for any infectious organism.

A great deal of sickness arises not because of what the organism has done to you but what your body
is trying to do to the organism. In its quest to rid the body of pathogens, the immune system

sometimes destroys cells or damages critical tissues, so often when you are unwell what you are feeling is not the pathogens but your own immune responses. Anyway, getting sick is a sensible response to infection. Sick people retire to their beds and thus are less of a threat to the wider community. Resting also frees more of the body's resources to attend to the infection.

Because there are so many things out there with the potential to hurt you, your body holds lots of different varieties of defensive white cells— some ten million types in all, each designed to identify and destroy a particular sort of invader. It would be impossibly inefficient to maintain ten million separate standing armies, so each variety of white cell keeps only a few scouts on active duty. When an infectious agent— what's known as an antigen— invades, relevant scouts identify the attacker and put out a call for reinforcements of the right type. While your body is manufacturing these forces,

you are likely to feel wretched. The onset of recovery begins when the troops finally swing into
action.
White cells are merciless and will hunt down and kill every last pathogen they can find. To avoid
extinction, attackers have evolved two elemental strategies. Either they strike quickly and move on
to a new host, as with common infectious illnesses like flu, or they disguise themselves so that the
white cells fail to spot them, as with HIV, the virus responsible for AIDS, which can sit harmlessly
and unnoticed in the nuclei of cells for years before springing into action.
One of the odder aspects of infection is that microbes that normally do no harm at all sometimes get
into the wrong parts of the body and "go kind of crazy," in the words of Dr. Bryan Marsh, an
infectious diseases specialist at Dartmouth–Hitchcock Medical Center in Lebanon, New Hampshire.
"It happens all the time with car accidents when people suffer internal injuries. Microbes that are

normally benign in the gut get into other parts of the body— the bloodstream, for instance— and cause terrible havoc.”

The scariest, most out-of-control bacterial disorder of the moment is a disease called necrotizing fasciitis in which bacteria essentially eat the victim from the inside out, devouring internal tissue and leaving behind a pulpy, noxious residue. Patients often come in with comparatively mild complaints— a skin rash and fever typically— but then dramatically deteriorate. When they are opened up it is often found that they are simply being consumed. The only treatment is what is known as “radical excisional surgery”— cutting out every bit of infected area. Seventy percent of victims die; many of the rest are left terribly disfigured. The source of the infection is a mundane family of bacteria called Group A Streptococcus, which normally do no more than cause strep throat.

Very occasionally, for reasons unknown, some of these bacteria get through the lining of the throat

and into the body proper, where they wreak the most devastating havoc.

They are completely

resistant to antibiotics. About a thousand cases a year occur in the United

States, and no one can say

that it won't get worse.

Precisely the same thing happens with meningitis. At least 10 percent of

young adults, and perhaps

30 percent of teenagers, carry the deadly meningococcal bacterium, but it

lives quite harmlessly in

the throat. Just occasionally— in about one young person in a hundred

thousand— it gets into the

bloodstream and makes them very ill indeed. In the worst cases, death can

come in twelve hours.

That's shockingly quick. "You can have a person who's in perfect health at

breakfast and dead by

evening," says Marsh.

We would have much more success with bacteria if we weren't so profligate

with our best weapon

against them: antibiotics. Remarkably, by one estimate some 70 percent of

the antibiotics used in the
developed world are given to farm animals, often routinely in stock feed, simply to promote growth
or as a precaution against infection. Such applications give bacteria every opportunity to evolve a
resistance to them. It is an opportunity that they have enthusiastically seized.
In 1952, penicillin was fully effective against all strains of staphylococcus bacteria, to such an extent
that by the early 1960s the U.S. surgeon general, William Stewart, felt confident enough to declare:
“The time has come to close the book on infectious diseases. We have basically wiped out infection
in the United States.” Even as he spoke, however, some 90 percent of those strains were in the
process of developing immunity to penicillin. Soon one of these new strains, called Methicillin-
Resistant Staphylococcus Aureus, began to show up in hospitals. Only one type of antibiotic,
vancomycin, remained effective against it, but in 1997 a hospital in Tokyo reported the appearance

of a strain that could resist even that. Within months it had spread to six other Japanese hospitals. All over, the microbes are beginning to win the war again: in U.S. hospitals alone, some fourteen thousand people a year die from infections they pick up there. As James Surowiecki has noted, given a choice between developing antibiotics that people will take every day for two weeks or antidepressants that people will take every day forever, drug companies not surprisingly opt for the latter. Although a few antibiotics have been toughened up a bit, the pharmaceutical industry hasn't given us an entirely new antibiotic since the 1970s.

Our carelessness is all the more alarming since the discovery that many other ailments may be bacterial in origin. The process of discovery began in 1983 when Barry Marshall, a doctor in Perth, Western Australia, found that many stomach cancers and most stomach ulcers are caused by a bacterium called Helicobacter pylori. Even though his findings were easily

tested, the notion was so
radical that more than a decade would pass before they were generally
accepted. America’s National
Institutes of Health, for instance, didn’t officially endorse the idea until 1994.
“Hundreds, even
thousands of people must have died from ulcers who wouldn’t have,”
Marshall told a reporter from
Forbes in 1999.

Since then further research has shown that there is or may well be a bacterial
component in all kinds
of other disorders— heart disease, asthma, arthritis, multiple sclerosis,
several types of mental
disorders, many cancers, even, it has been suggested (in Science no less),
obesity. The day may not
be far off when we desperately require an effective antibiotic and haven’t
got one to call on.

It may come as a slight comfort to know that bacteria can themselves get
sick. They are sometimes
infected by bacteriophages (or simply phages), a type of virus. A virus is a
strange and unlovely

entity— “a piece of nucleic acid surrounded by bad news” in the memorable phrase of the Nobel laureate Peter Medawar. Smaller and simpler than bacteria, viruses aren’t themselves alive. In isolation they are inert and harmless. But introduce them into a suitable host and they burst into busyness— into life. About five thousand types of virus are known, and between them they afflict us with many hundreds of diseases, ranging from the flu and common cold to those that are most invidious to human well-being: smallpox, rabies, yellow fever, ebola, polio, and the human immunodeficiency virus, the source of AIDS.

Viruses prosper by hijacking the genetic material of a living cell and using it to produce more virus. They reproduce in a fanatical manner, then burst out in search of more cells to invade. Not being living organisms themselves, they can afford to be very simple. Many, including HIV, have ten genes or fewer, whereas even the simplest bacteria require several thousand.

They are also very tiny,
much too small to be seen with a conventional microscope. It wasn't until 1943 and the invention of
the electron microscope that science got its first look at them. But they can do immense damage.
Smallpox in the twentieth century alone killed an estimated 300 million people.
They also have an unnerving capacity to burst upon the world in some new and startling form and
then to vanish again as quickly as they came. In 1916, in one such case, people in Europe and
America began to come down with a strange sleeping sickness, which became known as encephalitis
lethargica. Victims would go to sleep and not wake up. They could be roused without great difficulty
to take food or go to the lavatory, and would answer questions sensibly—they knew who and where
they were— though their manner was always apathetic.
However, the moment they were permitted to rest, they would sink at once back into deepest slumber

and remain in that state for as long as they were left. Some went on in this manner for months before dying. A very few survived and regained consciousness but not their former liveliness. They existed in a state of profound apathy, “like extinct volcanoes,” in the words of one doctor. In ten years the disease killed some five million people and then quietly went away. It didn’t get much lasting attention because in the meantime an even worse epidemic— indeed, the worst in history— swept across the world.

It is sometimes called the Great Swine Flu epidemic and sometimes the Great Spanish Flu epidemic, but in either case it was ferocious. World War I killed twenty-one million people in four years; swine flu did the same in its first four months. Almost 80 percent of American casualties in the First World War came not from enemy fire, but from flu. In some units the mortality rate was as high as 80 percent.

Swine flu arose as a normal, nonlethal flu in the spring of 1918, but somehow over the following
months— no one knows how or where— it mutated into something more severe. A fifth of victims
suffered only mild symptoms, but the rest became gravely ill and often died. Some succumbed
within hours; others held on for a few days.

In the United States, the first deaths were recorded among sailors in Boston in late August 1918, but
the epidemic quickly spread to all parts of the country. Schools closed, public entertainments were
shut down, people everywhere wore masks. It did little good. Between the autumn of 1918 and
spring of the following year, 548,452 people died of the flu in America. The toll in Britain was
220,000, with similar numbers dead in France and Germany. No one knows the global toll, as
records in the Third World were often poor, but it was not less than 20 million and probably more
like 50 million. Some estimates have put the global total as high as 100

million.

In an attempt to devise a vaccine, medical authorities conducted tests on volunteers at a military prison on Deer Island in Boston Harbor. The prisoners were promised pardons if they survived a battery of tests. These tests were rigorous to say the least. First the subjects were injected with infected lung tissue taken from the dead and then sprayed in the eyes, nose, and mouth with infectious aerosols. If they still failed to succumb, they had their throats swabbed with discharges taken from the sick and dying. If all else failed, they were required to sit open-mouthed while a gravely ill victim was helped to cough into their faces.

Out of— somewhat amazingly— three hundred men who volunteered, the doctors chose sixty-two for the tests. None contracted the flu— not one. The only person who did grow ill was the ward doctor, who swiftly died. The probable explanation for this is that the epidemic had passed through the

prison a few weeks earlier and the volunteers, all of whom had survived that visitation, had a natural
immunity.

Much about the 1918 flu is understood poorly or not at all. One mystery is how it erupted suddenly,
all over, in places separated by oceans, mountain ranges, and other earthly impediments. A virus can
survive for no more than a few hours outside a host body, so how could it appear in Madrid,
Bombay, and Philadelphia all in the same week?

The probable answer is that it was incubated and spread by people who had only slight symptoms or
none at all. Even in normal outbreaks, about 10 percent of people have the flu but are unaware of it
because they experience no ill effects. And because they remain in circulation they tend to be the
great spreaders of the disease.

That would account for the 1918 outbreak's widespread distribution, but it still doesn't explain how
it managed to lay low for several months before erupting so explosively at

more or less the same

time all over. Even more mysterious is that it was primarily devastating to

people in the prime of life.

Flu normally is hardest on infants and the elderly, but in the 1918 outbreak

deaths were

overwhelmingly among people in their twenties and thirties. Older people

may have benefited from

resistance gained from an earlier exposure to the same strain, but why the

very young were similarly

spared is unknown. The greatest mystery of all is why the 1918 flu was so

ferociously deadly when

most flus are not. We still have no idea.

From time to time certain strains of virus return. A disagreeable Russian

virus known as H1N1

caused severe outbreaks over wide areas in 1933, then again in the 1950s,

and yet again in the 1970s.

Where it went in the meantime each time is uncertain. One suggestion is that

viruses hide out

unnoticed in populations of wild animals before trying their hand at a new

generation of humans. No

one can rule out the possibility that the Great Swine Flu epidemic might once again rear its head.

And if it doesn’t, others well might. New and frightening viruses crop up all the time. Ebola, Lassa, and Marburg fevers all have tended to flare up and die down again, but no one can say that they aren’t quietly mutating away somewhere, or simply awaiting the right opportunity to burst forth in a catastrophic manner. It is now apparent that AIDS has been among us much longer than anyone originally suspected. Researchers at the Manchester Royal Infirmary in England discovered that a sailor who had died of mysterious, untreatable causes in 1959 in fact had AIDS. But for whatever reasons the disease remained generally quiescent for another twenty years.

The miracle is that other such diseases haven’t gone rampant. Lassa fever, which wasn’t first detected until 1969, in West Africa, is extremely virulent and little understood. In 1969, a doctor at a Yale University lab in New Haven, Connecticut, who was studying Lassa fever came down with it.

He survived, but, more alarmingly, a technician in a nearby lab, with no direct exposure, also
contracted the disease and died.

Happily the outbreak stopped there, but we can’t count on such good fortune always. Our lifestyles
invite epidemics. Air travel makes it possible to spread infectious agents across the planet with
amazing ease. An ebola virus could begin the day in, say, Benin, and finish it in New York or
Hamburg or Nairobi, or all three. It means also that medical authorities increasingly need to be
acquainted with pretty much every malady that exists everywhere, but of course they are not. In
1990, a Nigerian living in Chicago was exposed to Lassa fever on a visit to his homeland, but didn’t
develop symptoms until he had returned to the United States. He died in a Chicago hospital without
diagnosis and without anyone taking any special precautions in treating him, unaware that he had

one of the most lethal and infectious diseases on the planet. Miraculously, no one else was infected.

We may not be so lucky next time.

And on that sobering note, it's time to return to the world of the visibly living.

21 **LIFE GOES ON**

IT ISN'T EASY to become a fossil. The fate of nearly all living organisms— over 99.9 percent of them— is to compost down to nothingness. When your spark is gone, every molecule you own will be nibbled off you or sluiced away to be put to use in some other system. That's just the way it is.

Even if you make it into the small pool of organisms, the less than 0.1 percent, that don't get devoured, the chances of being fossilized are very small.

In order to become a fossil, several things must happen. First, you must die in the right place. Only about 15 percent of rocks can preserve fossils, so it's no good keeling over on a future site of granite.

In practical terms the deceased must become buried in sediment, where it can leave an impression,

like a leaf in wet mud, or decompose without exposure to oxygen, permitting the molecules in its

bones and hard parts (and very occasionally softer parts) to be replaced by dissolved minerals,

creating a petrified copy of the original. Then as the sediments in which the fossil lies are carelessly

pressed and folded and pushed about by Earth's processes, the fossil must somehow maintain an

identifiable shape. Finally, but above all, after tens of millions or perhaps hundreds of millions of

years hidden away, it must be found and recognized as something worth keeping.

Only about one bone in a billion, it is thought, ever becomes fossilized. If that is so, it means that the

complete fossil legacy of all the Americans alive today— that's 270 million people with 206 bones

each— will only be about fifty bones, one quarter of a complete skeleton. That's not to say of course

that any of these bones will actually be found. Bearing in mind that they can be buried anywhere

within an area of slightly over 3.6 million square miles, little of which will

ever be turned over,

much less examined, it would be something of a miracle if they were.

Fossils are in every sense

vanishingly rare. Most of what has lived on Earth has left behind no record

at all. It has been

estimated that less than one species in ten thousand has made it into the

fossil record. That in itself is

a stunningly infinitesimal proportion. However, if you accept the common

estimate that the Earth has

produced 30 billion species of creature in its time and Richard Leakey and

Roger Lewin's statement

(in The Sixth Extinction) that there are 250,000 species of creature in the

fossil record, that reduces

the proportion to just one in 120,000. Either way, what we possess is the

merest sampling of all the

life that Earth has spawned.

Moreover, the record we do have is hopelessly skewed. Most land animals,

of course, don't die in

sediments. They drop in the open and are eaten or left to rot or weather down to nothing. The fossil record consequently is almost absurdly biased in favor of marine creatures. About 95 percent of all the fossils we possess are of animals that once lived under water, mostly in shallow seas.

I mention all this to explain why on a gray day in February I went to the Natural History Museum in London to meet a cheerful, vaguely rumpled, very likeable paleontologist named Richard Fortey.

Fortey knows an awful lot about an awful lot. He is the author of a wry, splendid book called Life: An Unauthorised Biography, which covers the whole pageant of animate creation. But his first love is a type of marine creature called trilobites that once teemed in Ordovician seas but haven't existed for a long time except in fossilized form. All shared a basic body plan of three parts, or lobes— head, tail, thorax— from which comes the name. Fortey found his first when he was a boy clambering over rocks at St. David's Bay in Wales. He was hooked for life.

He took me to a gallery of tall metal cupboards. Each cupboard was filled with shallow drawers, and

each drawer was filled with stony trilobites— twenty thousand specimens in all.

"It seems like a big number," he agreed, "but you have to remember that millions upon millions of

trilobites lived for millions upon millions of years in ancient seas, so twenty thousand isn't a huge

number. And most of these are only partial specimens. Finding a complete trilobite fossil is still a big

moment for a paleontologist."

Trilobites first appeared— fully formed, seemingly from nowhere— about 540 million years ago, near

the start of the great outburst of complex life popularly known as the Cambrian explosion, and then

vanished, along with a great deal else, in the great and still mysterious Permian extinction 300,000 or

so centuries later. As with all extinct creatures, there is a natural temptation to regard them as failures, but in fact they were among the most successful animals ever to live. Their reign ran for 300 million years— twice the span of dinosaurs, which were themselves one of history's great survivors.

Humans, Fortey points out, have survived so far for one-half of 1 percent as long.

With so much time at their disposal, the trilobites proliferated prodigiously. Most remained small, about the size of modern beetles, but some grew to be as big as platters. Altogether they formed at least five thousand genera and sixty thousand species— though more turn up all the time. Fortey had recently been at a conference in South America where he was approached by an academic from a small provincial university in Argentina. "She had a box that was full of interesting things— trilobites that had never been seen before in South America, or indeed anywhere, and a great deal else. She had no research facilities to study them and no funds to look for more. Huge parts of the world are still unexplored."

"In terms of trilobites?"

"No, in terms of everything."

Throughout the nineteenth century, trilobites were almost the only known forms of early complex life, and for that reason were assiduously collected and studied. The big mystery about them was their sudden appearance. Even now, as Fortey says, it can be startling to go to the right formation of rocks and to work your way upward through the eons finding no visible life at all, and then suddenly "a whole Profallotaspis or Elenellus as big as a crab will pop into your waiting hands." These were creatures with limbs, gills, nervous systems, probing antennae, "a brain of sorts," in Fortey's words, and the strangest eyes ever seen. Made of calcite rods, the same stuff that forms limestone, they constituted the earliest visual systems known. More than this, the earliest trilobites didn't consist of just one venturesome species but dozens, and didn't appear in one or two locations but all over.

Many thinking people in the nineteenth century saw this as proof of God's handiwork and refutation of Darwin's evolutionary ideals. If evolution proceeded slowly, they asked, then how did he account for this sudden appearance of complex, fully formed creatures? The fact is, he couldn't.

And so matters seemed destined to remain forever until one day in 1909, three months shy of the fiftieth anniversary of the publication of Darwin's On the Origin of Species, when a paleontologist named Charles Doolittle Walcott made an extraordinary find in the Canadian Rockies.

Walcott was born in 1850 and grew up near Utica, New York, in a family of modest means, which became more modest still with the sudden death of his father when Walcott was an infant. As a boy Walcott discovered that he had a knack for finding fossils, particularly trilobites, and built up a collection of sufficient distinction that it was bought by Louis Agassiz for

his museum at Harvard for
a small fortune— about $70,000 in today’s money. Although he had barely a high school education
and was self taught in the sciences, Walcott became a leading authority on trilobites and was the first
person to establish that trilobites were arthropods, the group that includes modern insects and
crustaceans.

In 1879 he took a job as a field researcher with the newly formed United States Geological Survey
and served with such distinction that within fifteen years he had risen to be its head. In 1907 he was
appointed secretary of the Smithsonian Institution, where he remained until his death in 1927.

Despite his administrative obligations, he continued to do fieldwork and to write prolifically. “His
books fill a library shelf,” according to Fortey. Not incidentally, he was also a founding director of
the National Advisory Committee for Aeronautics, which eventually became the National

Aeronautics and Space Agency, or NASA, and thus can rightly be considered the grandfather of the space age.

But what he is remembered for now is an astute but lucky find in British Columbia, high above the little town of Field, in the late summer of 1909. The customary version of the story is that Walcott, accompanied by his wife, was riding on horseback on a mountain trail beneath the spot called the Burgess Ridge when his wife’s horse slipped on loose stones. Dismounting to assist her, Walcott discovered that the horse had turned a slab of shale that contained fossil crustaceans of an especially ancient and unusual type. Snow was falling— winter comes early to the Canadian Rockies— so they didn’t linger, but the next year at the first opportunity Walcott returned to the spot. Tracing the presumed route of the rocks’ slide, he climbed 750 feet to near the mountain’s summit. There, 8,000 feet above sea level, he found a shale outcrop, about the length of a city

block, containing an
unrivaled array of fossils from soon after the moment when complex life burst forth in dazzling
profusion— the famous Cambrian explosion. Walcott had found, in effect, the holy grail of
paleontology. The outcrop became known as the Burgess Shale, and for a long time it provided "our
sole vista upon the inception of modern life in all its fullness," as the late Stephen Jay Gould
recorded in his popular book Wonderful Life.

Gould, ever scrupulous, discovered from reading Walcott's diaries that the story of the Burgess
Shale's discovery appears to have been somewhat embroidered— Walcott makes no mention of a
slipping horse or falling snow— but there is no disputing that it was an extraordinary find.

It is almost impossible for us whose time on Earth is limited to a breezy few decades to appreciate
how remote in time from us the Cambrian outburst was. If you could fly backwards into the past at

the rate of one year per second, it would take you about half an hour to reach the time of Christ, and

a little over three weeks to get back to the beginnings of human life. But it would take you twenty

years to reach the dawn of the Cambrian period. It was, in other words, an extremely long time ago,

and the world was a very different place.

For one thing, 500-million-plus years ago when the Burgess Shale was formed it wasn’t at the top of

a mountain but at the foot of one. Specifically it was a shallow ocean basin at the bottom of a steep

cliff. The seas of that time teemed with life, but normally the animals left no record because they

were soft-bodied and decayed upon dying. But at Burgess the cliff collapsed, and the creatures

below, entombed in a mudslide, were pressed like flowers in a book, their features preserved in

wondrous detail.

In annual summer trips from 1910 to 1925 (by which time he was seventy-five years old), Walcott excavated tens of thousands of specimens (Gould says 80,000; the normally unimpeachable fact

checkers of National Georgraphic say 60,000), which he brought back to Washington for further

study. In both sheer numbers and diversity the collection was unparalleled. Some of the Burgess

fossils had shells; many others did not. Some were sighted, others blind. The variety was enormous,

consisting of 140 species by one count. “The Burgess Shale included a range of disparity in

anatomical designs never again equaled, and not matched today by all the creatures in the world’s

oceans,” Gould wrote.

Unfortunately, according to Gould, Walcott failed to discern the significance of what he had found.

“Snatching defeat from the jaws of victory,” Gould wrote in another work, Eight Little Piggies,

“Walcott then proceeded to misinterpret these magnificent fossils in the deepest possible way.” He

placed them into modern groups, making them ancestral to today’s worms,

jellyfish, and other
creatures, and thus failed to appreciate their distinctness. “Under such an interpretation,” Gould
sighed, “life began in primordial simplicity and moved inexorably, predictably onward to more and
better.”

Walcott died in 1927 and the Burgess fossils were largely forgotten. For nearly half a century they
stayed shut away in drawers in the American Museum of Natural History in Washington, seldom
consulted and never questioned. Then in 1973 a graduate student from Cambridge University named
Simon Conway Morris paid a visit to the collection. He was astonished by what he found. The fossils
were far more varied and magnificent than Walcott had indicated in his writings. In taxonomy the
category that describes the basic body plans of all organisms is the phylum, and here, Conway
Morris concluded, were drawer after drawer of such anatomical singularities— all amazingly and

unaccountably unrecognized by the man who had found them.

With his supervisor, Harry Whittington, and fellow graduate student Derek Briggs, Conway Morris spent the next several years making a systematic revision of the entire collection, and cranking out one exciting monograph after another as discovery piled upon discovery. Many of the creatures employed body plans that were not simply unlike anything seen before or since, but were bizarrely different. One, Opabinia, had five eyes and a nozzle-like snout with claws on the end. Another, a disc-shaped being called Peytoia, looked almost comically like a pineapple slice. A third had evidently tottered about on rows of stilt-like legs, and was so odd that they named it Hallucigenia.

There was so much unrecognized novelty in the collection that at one point upon opening a new drawer Conway Morris famously was heard to mutter, “Oh fuck, not another phylum.”

The English team’s revisions showed that the Cambrian had been a time of

unparalleled innovation
and experimentation in body designs. For almost four billion years life had dawdled along without
any detectable ambitions in the direction of complexity, and then suddenly, in the space of just five
or ten million years, it had created all the basic body designs still in use today. Name a creature, from
a nematode worm to Cameron Diaz, and they all use architecture first created in the Cambrian party.

What was most surprising, however, was that there were so many body designs that had failed to
make the cut, so to speak, and left no descendants. Altogether, according to Gould, at least fifteen
and perhaps as many as twenty of the Burgess animals belonged to no recognized phylum. (The
number soon grew in some popular accounts to as many as one hundred—far more than the
Cambridge scientists ever actually claimed.) “The history of life,” wrote Gould, “is a story of
massive removal followed by differentiation within a few surviving stocks,

not the conventional tale
of steadily increasing excellence, complexity, and diversity.” Evolutionary success, it appeared, was
a lottery.

One creature that did manage to slip through, a small wormlike being called Pikaia gracilens, was
found to have a primitive spinal column, making it the earliest known ancestor of all later
vertebrates, including us. Pikaia were by no means abundant among the Burgess fossils, so goodness
knows how close they may have come to extinction. Gould, in a famous quotation, leaves no doubt
that he sees our lineal success as a fortunate fluke: “Wind back the tape of life to the early days of
the Burgess Shale; let it play again from an identical starting point, and the chance becomes
vanishingly small that anything like human intelligence would grace the replay.”

Gould’s book was published in 1989 to general critical acclaim and was a great commercial success.

What wasn’t generally known was that many scientists didn’t agree with Gould’s conclusions at all, and that it was all soon to get very ugly. In the context of the Cambrian, “explosion” would soon have more to do with modern tempers than ancient physiological facts.

In fact, we now know, complex organisms existed at least a hundred million years before the Cambrian. We should have known a whole lot sooner. Nearly forty years after Walcott made his discovery in Canada, on the other side of the planet in Australia, a young geologist named Reginald Sprigg found something even older and in its way just as remarkable.

In 1946 Sprigg was a young assistant government geologist for the state of South Australia when he was sent to make a survey of abandoned mines in the Ediacaran Hills of the Flinders Range, an expanse of baking outback some three hundred miles north of Adelaide. The idea was to see if there were any old mines that might be profitably reworked using newer technologies, so he wasn’t studying surface rocks at all, still less fossils. But one day while eating his lunch, Sprigg idly overturned a hunk of sandstone and was surprised— to put it mildly— to see that the rock's surface was covered in delicate fossils, rather like the impressions leaves make in mud. These rocks predated the Cambrian explosion. He was looking at the dawn of visible life.

Sprigg submitted a paper to Nature, but it was turned down. He read it instead at the next annual meeting of the Australian and New Zealand Association for the Advancement of Science, but it failed to find favor with the association's head, who said the Ediacaran imprints were merely "fortuitous inorganic markings"— patterns made by wind or rain or tides, but not living beings. His hopes not yet entirely crushed, Sprigg traveled to London and presented his findings to the 1948 International Geological Congress, but failed to excite either interest or belief. Finally, for want of a better outlet, he published his findings in the Transactions of the Royal

Society of South Australia.

Then he quit his government job and took up oil exploration.

Nine years later, in 1957, a schoolboy named John Mason, while walking through Charnwood Forest in the English Midlands, found a rock with a strange fossil in it, similar to a modern sea pen and exactly like some of the specimens Sprigg had found and been trying to tell everyone about ever since. The schoolboy turned it in to a paleontologist at the University of Leicester, who identified it at once as Precambrian. Young Mason got his picture in the papers and was treated as a precocious hero; he still is in many books. The specimen was named in his honor Chamia masoni.

Today some of Sprigg's original Ediacaran specimens, along with many of the other fifteen hundred specimens that have been found throughout the Flinders Range since that time, can be seen in a glass case in an upstairs room of the stout and lovely South Australian Museum in Adelaide, but they don’t attract a great deal of attention. The delicately etched patterns are rather faint and not terribly arresting to the untrained eye. They are mostly small and disc-shaped, with occasional, vague trailing ribbons. Fortey has described them as “soft-bodied oddities.”

There is still very little agreement about what these things were or how they lived. They had, as far as can be told, no mouth or anus with which to take in and discharge digestive materials, and no internal organs with which to process them along the way. “In life,” Fortey says, “most of them probably simply lay upon the surface of the sandy sediment, like soft, structureless and inanimate flatfish.” At their liveliest, they were no more complex than jellyfish. All the Ediacaran creatures were diploblastic, meaning they were built from two layers of tissue. With the exception of jellyfish, all animals today are triploblastic.

Some experts think they weren’t animals at all, but more like plants or fungi. The distinctions

between plant and animal are not always clear even now. The modern sponge spends its life fixed to
a single spot and has no eyes or brain or beating heart, and yet is an animal. “When we go back to
the Precambrian the differences between plants and animals were probably even less clear,” says
Fortey. “There isn’t any rule that says you have to be demonstrably one or the other.”

Nor is it agreed that the Ediacaran organisms are in any way ancestral to anything alive today
(except possibly some jellyfish). Many authorities see them as a kind of failed experiment, a stab at
complexity that didn’t take, possibly because the sluggish Ediacaran organisms were devoured or
outcompeted by the lither and more sophisticated animals of the Cambrian period.

“There is nothing closely similar alive today,” Fortey has written. “They are difficult to interpret as
any kind of ancestors of what was to follow.”

The feeling was that ultimately they weren’t terribly important to the development of life on Earth.

Many authorities believe that there was a mass extermination at the

Precambrian–Cambrian

boundary and that all the Ediacaran creatures (except the uncertain jellyfish)

failed to move on to the

next phase. The real business of complex life, in other words, started with

the Cambrian explosion.

That's how Gould saw it in any case.

As for the revisions of the Burgess Shale fossils, almost at once people

began to question the

interpretations and, in particular, Gould's interpretation of the interpretations.

"From the first there

were a number of scientists who doubted the account that Steve Gould had

presented, however much

they admired the manner of its delivery," Fortey wrote in Life. That is

putting it mildly.

"If only Stephen Gould could think as clearly as he writes!" barked the

Oxford academic Richard

Dawkins in the opening line of a review (in the London Sunday Telegraph)

of Wonderful Life.

Dawkins acknowledged that the book was “unputdownable” and a “literary tour-de-force,” but accused Gould of engaging in a “grandiloquent and near-disingenuous” misrepresentation of the facts by suggesting that the Burgess revisions had stunned the paleontological community. “The view that he is attacking— that evolution marches inexorably toward a pinnacle such as man— has not been believed for 50 years,” Dawkins fumed.

And yet that was exactly the conclusion to which many general reviewers were drawn. One, writing in the New York Times Book Review, cheerfully suggested that as a result of Gould’s book scientists “have been throwing out some preconceptions that they had not examined for generations. They are, reluctantly or enthusiastically, accepting the idea that humans are as much an accident of nature as a product of orderly development.”

But the real heat directed at Gould arose from the belief that many of his conclusions were simply mistaken or carelessly inflated. Writing in the journal Evolution, Dawkins attacked Gould's assertions that "evolution in the Cambrian was a different kind of process from today" and expressed exasperation at Gould's repeated suggestions that "the Cambrian was a period of evolutionary 'experiment,' evolutionary 'trial and error,' evolutionary 'false starts.' . . . It was the fertile time when all the great 'fundamental body plans' were invented. Nowadays, evolution just tinkers with old body plans. Back in the Cambrian, new phyla and new classes arose. Nowadays we only get new species!"

Noting how often this idea— that there are no new body plans— is picked up, Dawkins says: "It is as though a gardener looked at an oak tree and remarked, wonderingly: 'Isn't it strange that no major new boughs have appeared on this tree for many years? These days, all the new growth appears to be at the twig level.' "

"It was a strange time," Fortey says now, "especially when you reflected that this was all about

something that happened five hundred million years ago, but feelings really did run quite high. I

joked in one of my books that I felt as if I ought to put a safety helmet on before writing about the

Cambrian period, but it did actually feel a bit like that."

Strangest of all was the response of one of the heroes of Wonderful Life, Simon Conway Morris, who

startled many in the paleontological community by rounding abruptly on Gould in a book of his own,

The Crucible of Creation. The book treated Gould "with contempt, even loathing," in Fortey's

words. "I have never encountered such spleen in a book by a professional," Fortey wrote later. "The

casual reader of The Crucible of Creation, unaware of the history, would never gather that the

author's views had once been close to (if not actually shared with) Gould's."

When I asked Fortey about it, he said: "Well, it was very strange, quite shocking really, because

Gould's portrayal of him had been so flattering. I could only assume that Simon was embarrassed.

You know, science changes but books are permanent, and I suppose he regretted being so irremediably associated with views that he no longer altogether held. There was all that stuff about 'oh fuck, another phylum' and I expect he regretted being famous for that."

What happened was that the early Cambrian fossils began to undergo a period of critical reappraisal.

Fortey and Derek Briggs— one of the other principals in Gould's book— used a method known as cladistics to compare the various Burgess fossils. In simple terms, cladistics consists of organizing organisms on the basis of shared features. Fortey gives as an example the idea of comparing a shrew and an elephant. If you considered the elephant's large size and striking trunk you might conclude that it could have little in common with a tiny, sniffing shrew. But if you compared both of them with a lizard, you would see that the elephant and shrew were in fact built to

much the same plan. In
essence, what Fortey is saying is that Gould saw elephants and shrews where they saw mammals.

The Burgess creatures, they believed, weren’t as strange and various as they appeared at first sight.

“They were often no stranger than trilobites,” Fortey says now. “It is just that we have had a century
or so to get used to trilobites. Familiarity, you know, breeds familiarity.”

This wasn’t, I should note, because of sloppiness or inattention. Interpreting the forms and
relationships of ancient animals on the basis of often distorted and fragmentary evidence is clearly a
tricky business. Edward O. Wilson has noted that if you took selected species of modern insects and
presented them as Burgess-style fossils nobody would ever guess that they were all from the same
phylum, so different are their body plans. Also instrumental in helping revisions were the discoveries
of two further early Cambrian sites, one in Greenland and one in China, plus more scattered finds,

which between them yielded many additional and often better specimens. The upshot is that the Burgess fossils were found to be not so different after all. Hallucigenia, it turned out, had been reconstructed upside down. Its stilt-like legs were actually spikes along its back.

Peytoia, the weird creature that looked like a pineapple slice, was found to be not a distinct creature but merely part of a larger animal called Anomalocaris. Many of the Burgess specimens have now been assigned to living phyla— just where Walcott put them in the first place. Hallucigenia and some others are thought to be related to Onychophora, a group of caterpillar-like animals. Others have been reclassified as precursors of the modern annelids. In fact, says Fortey, “there are relatively few Cambrian designs that are wholly novel. More often they turn out to be just interesting elaborations of well-established designs.” As he wrote in his book Life: “None was as strange as a present day barnacle, nor as grotesque as a queen termite.”

So the Burgess Shale specimens weren't so spectacular after all. This made them, as Fortey has
written, "no less interesting, or odd, just more explicable." Their weird body plans were just a kind
of youthful exuberance— the evolutionary equivalent, as it were, of spiked hair and tongue studs.
Eventually the forms settled into a staid and stable middle age.

But that still left the enduring question of where all these animals had come from— how they had
suddenly appeared from out of nowhere.

Alas, it turns out the Cambrian explosion may not have been quite so explosive as all that. The
Cambrian animals, it is now thought, were probably there all along, but were just too small to see.

Once again it was trilobites that provided the clue— in particular that seemingly mystifying
appearance of different types of trilobite in widely scattered locations around the globe, all at more
or less the same time.

On the face of it, the sudden appearance of lots of fully formed but varied creatures would seem to

enhance the miraculousness of the Cambrian outburst, but in fact it did the opposite. It is one thing to

have one well-formed creature like a trilobite burst forth in isolation— that really is a wonder— but to

have many of them, all distinct but clearly related, turning up simultaneously in the fossil record in

places as far apart as China and New York clearly suggests that we are missing a big part of their

history. There could be no stronger evidence that they simply had to have a forebear— some

grandfather species that started the line in a much earlier past.

And the reason we haven't found these earlier species, it is now thought, is that they were too tiny to

be preserved. Says Fortey: "It isn't necessary to be big to be a perfectly functioning, complex

organism. The sea swarms with tiny arthropods today that have left no fossil record." He cites the

little copepod, which numbers in the trillions in modern seas and clusters in shoals large enough to turn vast areas of the ocean black, and yet our total knowledge of its ancestry is a single specimen found in the body of an ancient fossilized fish.

"The Cambrian explosion, if that's the word for it, probably was more an increase in size than a sudden appearance of new body types," Fortey says. "And it could have happened quite swiftly, so in that sense I suppose it was an explosion." The idea is that just as mammals bided their time for a hundred million years until the dinosaurs cleared off and then seemingly burst forth in profusion all over the planet, so too perhaps the arthropods and other triploblasts waited in semimicroscopic anonymity for the dominant Ediacaran organisms to have their day. Says Fortey: "We know that mammals increased in size quite dramatically after the dinosaurs went—though when I say quite abruptly I of course mean it in a geological sense. We're still talking millions of years."

Incidentally, Reginald Sprigg did eventually get a measure of overdue credit.

One of the main early
genera, Spriggina, was named in his honor, as were several species, and the whole became known as
the Ediacaran fauna after the hills through which he had searched. By this time, however, Sprigg's
fossil-hunting days were long over. After leaving geology he founded a successful oil company and
eventually retired to an estate in his beloved Flinders Range, where he created a wildlife reserve. He
died in 1994 a rich man.

22 **GOOD-BYE TO ALL THAT**

WHEN YOU CONSIDER it from a human perspective, and clearly it would be difficult for us to do
otherwise, life is an odd thing. It couldn't wait to get going, but then, having gotten going, it seemed
in very little hurry to move on.

Consider the lichen. Lichens are just about the hardiest visible organisms on Earth, but among the
least ambitious. They will grow happily enough in a sunny churchyard, but they particularly thrive in

environments where no other organism would go— on blowy mountaintops and arctic wastes,
wherever there is little but rock and rain and cold, and almost no competition. In areas of Antarctica
where virtually nothing else will grow, you can find vast expanses of lichen— four hundred types of
them— adhering devotedly to every wind-whipped rock.
For a long time, people couldn’t understand how they did it. Because lichens grew on bare rock
without evident nourishment or the production of seeds, many people— educated people— believed
they were stones caught in the process of becoming plants. “Spontaneously, inorganic stone becomes
living plant!” rejoiced one observer, a Dr. Homschuch, in 1819.
Closer inspection showed that lichens were more interesting than magical. They are in fact a
partnership between fungi and algae. The fungi excrete acids that dissolve the surface of the rock,
freeing minerals that the algae convert into food sufficient to sustain both. It is not a very exciting

arrangement, but it is a conspicuously successful one. The world has more than twenty thousand
species of lichens.
Like most things that thrive in harsh environments, lichens are slow-growing. It may take a lichen
more than half a century to attain the dimensions of a shirt button. Those the size of dinner plates,
writes David Attenborough, are therefore “likely to be hundreds if not thousands of years old.” It
would be hard to imagine a less fulfilling existence. “They simply exist,” Attenborough adds,
“testifying to the moving fact that life even at its simplest level occurs, apparently, just for its own
sake.”
It is easy to overlook this thought that life just is. As humans we are inclined to feel that life must
have a point. We have plans and aspirations and desires. We want to take constant advantage of all
the intoxicating existence we’ve been endowed with. But what’s life to a lichen? Yet its impulse to

exist, to be, is every bit as strong as ours— arguably even stronger. If I were told that I had to spend decades being a furry growth on a rock in the woods, I believe I would lose the will to go on.

Lichens don’t. Like virtually all living things, they will suffer any hardship, endure any insult, for a moment’s additional existence. Life, in short, just wants to be. But— and here’s an interesting point— for the most part it doesn’t want to be much.

This is perhaps a little odd because life has had plenty of time to develop ambitions. If you imagine the 4,500-billion-odd years of Earth’s history compressed into a normal earthly day, then life begins very early, about 4 A.M., with the rise of the first simple, single-celled organisms, but then advances no further for the next sixteen hours. Not until almost 8:30 in the evening, with the day five-sixths over, has Earth anything to show the universe but a restless skin of microbes. Then, finally, the first sea plants appear, followed twenty minutes later by the first jellyfish and the

enigmatic Ediacaran
fauna first seen by Reginald Sprigg in Australia. At 9:04 P.M. trilobites swim onto the scene,
followed more or less immediately by the shapely creatures of the Burgess Shale. Just before 10 P.M.
plants begin to pop up on the land. Soon after, with less than two hours left in the day, the first land
creatures follow.
Thanks to ten minutes or so of balmy weather, by 10:24 the Earth is covered in the great
carboniferous forests whose residues give us all our coal, and the first winged insects are evident.
Dinosaurs plod onto the scene just before 11 P.M. and hold sway for about three-quarters of an hour.
At twenty-one minutes to midnight they vanish and the age of mammals begins. Humans emerge one
minute and seventeen seconds before midnight. The whole of our recorded history, on this scale,
would be no more than a few seconds, a single human lifetime barely an instant. Throughout this

greatly speeded-up day continents slide about and bang together at a clip that seems positively

reckless. Mountains rise and melt away, ocean basins come and go, ice sheets advance and

withdraw. And throughout the whole, about three times every minute, somewhere on the planet there

is a flashbulb pop of light marking the impact of a Manson-sized meteor or one even larger. It’s a

wonder that anything at all can survive in such a pummeled and unsettled environment. In fact, not

many things do for long.

Perhaps an even more effective way of grasping our extreme recentness as a part of this 4.5-billionyear-

old picture is to stretch your arms to their fullest extent and imagine that width as the entire

history of the Earth. On this scale, according to John McPhee in Basin and Range, the distance from

the fingertips of one hand to the wrist of the other is Precambrian. All of complex life is in one hand,

“and in a single stroke with a medium-grained nail file you could eradicate human history."

Fortunately, that moment hasn't happened, but the chances are good that it will. I don't wish to interject a note of gloom just at this point, but the fact is that there is one other extremely pertinent quality about life on Earth: it goes extinct. Quite regularly. For all the trouble they take to assemble and preserve themselves, species crumple and die remarkably routinely. And the more complex they get, the more quickly they appear to go extinct. Which is perhaps one reason why so much of life isn't terribly ambitious.

So anytime life does something bold it is quite an event, and few occasions were more eventful than when life moved on to the next stage in our narrative and came out of the sea.

Land was a formidable environment: hot, dry, bathed in intense ultraviolet radiation, lacking the buoyancy that makes movement in water comparatively effortless. To live on land, creatures had to

undergo wholesale revisions of their anatomies. Hold a fish at each end and it sags in the middle, its
backbone too weak to support it. To survive out of water, marine creatures needed to come up with
new load-bearing internal architecture— not the sort of adjustment that happens overnight. Above all
and most obviously, any land creature would have to develop a way to take its oxygen directly from
the air rather than filter it from water. These were not trivial challenges to overcome. On the other
hand, there was a powerful incentive to leave the water: it was getting dangerous down there. The
slow fusion of the continents into a single landmass, Pangaea, meant there was much, much less
coastline than formerly and thus much less coastal habitat. So competition was fierce. There was also
an omnivorous and unsettling new type of predator on the scene, one so perfectly designed for attack
that it has scarcely changed in all the long eons since its emergence: the shark. Never would there be

a more propitious time to find an alternative environment to water.

Plants began the process of land colonization about 450 million years ago, accompanied of necessity

by tiny mites and other organisms that they needed to break down and recycle dead organic matter

on their behalf. Larger animals took a little longer to emerge, but by about 400 million years ago

they were venturing out of the water, too. Popular illustrations have encouraged us to envision the

first venturesome land dwellers as a kind of ambitious fish— something like the modern mudskipper,

which can hop from puddle to puddle during droughts— or even as a fully formed amphibian. In fact,

the first visible mobile residents on dry land were probably much more like modern wood lice,

sometimes also known as pillbugs or sow bugs. These are the little bugs (crustaceans, in fact) that

are commonly thrown into confusion when you upturn a rock or log.

For those that learned to breathe oxygen from the air, times were good. Oxygen levels in the

Devonian and Carboniferous periods, when terrestrial life first bloomed, were as high as 35 percent
(as opposed to nearer 20 percent now). This allowed animals to grow remarkably large remarkably
quickly.

And how, you may reasonably wonder, can scientists know what oxygen levels were like hundreds
of millions of years ago? The answer lies in a slightly obscure but ingenious field known as isotope
geochemistry. The long-ago seas of the Carboniferous and Devonian swarmed with tiny plankton
that wrapped themselves inside tiny protective shells. Then, as now, the plankton created their shells
by drawing oxygen from the atmosphere and combining it with other elements (carbon especially) to
form durable compounds such as calcium carbonate. It's the same chemical trick that goes on in (and
is discussed elsewhere in relation to) the long-term carbon cycle— a process that doesn't make for
terribly exciting narrative but is vital for creating a livable planet.

Eventually in this process all the tiny organisms die and drift to the bottom of the sea, where they are
slowly compressed into limestone. Among the tiny atomic structures the plankton take to the grave
with them are two very stable isotopes— oxygen-16 and oxygen-18. (If you have forgotten what an
isotope is, it doesn't matter, though for the record it's an atom with an abnormal number of
neutrons.) This is where the geochemists come in, for the isotopes accumulate at different rates
depending on how much oxygen or carbon dioxide is in the atmosphere at the time of their creation.

By comparing these ancient ratios, the geochemists can cunningly read conditions in the ancient
world— oxygen levels, air and ocean temperatures, the extent and timing of ice ages, and much else.

By combining their isotope findings with other fossil residues— pollen levels and so on— scientists
can, with considerable confidence, re-create entire landscapes that no human eye ever saw.

The principal reason oxygen levels were able to build up so robustly throughout the period of early
terrestrial life was that much of the world's landscape was dominated by giant tree ferns and vast
swamps, which by their boggy nature disrupted the normal carbon recycling process. Instead of
completely rotting down, falling fronds and other dead vegetative matter accumulated in rich, wet
sediments, which were eventually squeezed into the vast coal beds that sustain much economic
activity even now.

The heady levels of oxygen clearly encouraged outsized growth. The oldest indication of a surface
animal yet found is a track left 350 million years ago by a millipede-like creature on a rock in
Scotland. It was over three feet long. Before the era was out some millipedes would reach lengths
more than double that.

With such creatures on the prowl, it is perhaps not surprising that insects in the period evolved a trick that could keep them safely out of tongue shot: they learned to fly. Some took to this new means of locomotion with such uncanny facility that they haven't changed their techniques in all the time since. Then, as now, dragonflies could cruise at up to thirty-five miles an hour, instantly stop, hover, fly backwards, and lift far more proportionately than any human flying machine. "The U.S. Air Force," one commentator has written, "has put them in wind tunnels to see how they do it, and despaired." They, too, gorged on the rich air. In Carboniferous forests dragonflies grew as big as ravens. Trees and other vegetation likewise attained outsized proportions. Horsetails and tree ferns grew to heights of fifty feet, club mosses to a hundred and thirty.

The first terrestrial vertebrates— which is to say, the first land animals from which we would derive— are something of a mystery. This is partly because of a shortage of relevant fossils, but partly also because of an idiosyncratic Swede named Erik Jarvik whose odd

interpretations and
secretive manner held back progress on this question for almost half a century. Jarvik was part of a
team of Scandinavian scholars who went to Greenland in the 1930s and 1940s looking for fossil fish.
In particular they sought lobe-finned fish of the type that presumably were ancestral to us and all
other walking creatures, known as tetrapods.
Most animals are tetrapods, and all living tetrapods have one thing in common: four limbs that end in
a maximum of five fingers or toes. Dinosaurs, whales, birds, humans, even fish— all are tetrapods,
which clearly suggests they come from a single common ancestor. The clue to this ancestor, it was
assumed, would be found in the Devonian era, from about 400 million years ago. Before that time
nothing walked on land. After that time lots of things did. Luckily the team found just such a
creature, a three-foot-long animal called an Ichthyostega. The analysis of the fossil fell to Jarvik,

who began his study in 1948 and kept at it for the next forty-eight years. Unfortunately, Jarvik refused to let anyone study his tetrapod. The world's paleontologists had to be content with two sketchy interim papers in which Jarvik noted that the creature had five fingers in each of four limbs, confirming its ancestral importance.

Jarvik died in 1998. After his death, other paleontologists eagerly examined the specimen and found that Jarvik had severely miscounted the fingers and toes— there were actually eight on each limb— and failed to observe that the fish could not possibly have walked. The structure of the fin was such that it would have collapsed under its own weight. Needless to say, this did not do a great deal to advance our understanding of the first land animals. Today three early tetrapods are known and none has five digits. In short, we don't know quite where we came from.

But come we did, though reaching our present state of eminence has not of course always been straightforward. Since life on land began, it has consisted of four megadynasties, as they are sometimes called. The first consisted of primitive, plodding but sometimes fairly hefty amphibians and reptiles. The best-known animal of this age was the Dimetrodon, a sail-backed creature that is commonly confused with dinosaurs (including, I note, in a picture caption in the Carl Sagan book Comet). The Dimetrodon was in fact a synapsid. So, once upon a time, were we. Synapsids were one of the four main divisions of early reptilian life, the others being anapsids, euryapsids, and diapsids.

The names simply refer to the number and location of small holes to be found in the sides of their owners' skulls. Synapsids had one hole in their lower temples; diapsids had two; euryapsids had a single hole higher up.

Over time, each of these principal groupings split into further subdivisions, of which some prospered and some faltered. Anapsids gave rise to the turtles, which for a time,

perhaps a touch improbably,
appeared poised to predominate as the planet's most advanced and deadly species, before an
evolutionary lurch let them settle for durability rather than dominance. The synapsids divided into
four streams, only one of which survived beyond the Permian. Happily, that was the stream we
belonged to, and it evolved into a family of protomammals known as therapsids. These formed
Megadynasty 2.

Unfortunately for the therapsids, their cousins the diapsids were also productively evolving, in their
case into dinosaurs (among other things), which gradually proved too much for the therapsids.

Unable to compete head to head with these aggressive new creatures, the therapsids by and large
vanished from the record. A very few, however, evolved into small, furry, burrowing beings that
bided their time for a very long while as little mammals. The biggest of them grew no larger than a

house cat, and most were no bigger than mice. Eventually, this would prove their salvation, but they would have to wait nearly 150 million years for Megadynasty 3, the Age of Dinosaurs, to come to an abrupt end and make room for Megadynasty 4 and our own Age of Mammals.

Each of these massive transformations, as well as many smaller ones between and since, was dependent on that paradoxically important motor of progress: extinction. It is a curious fact that on Earth species death is, in the most literal sense, a way of life. No one knows how many species of organisms have existed since life began. Thirty billion is a commonly cited figure, but the number has been put as high as 4,000 billion. Whatever the actual total, 99.99 percent of all species that have ever lived are no longer with us. “To a first approximation,” as David Raup of the University of Chicago likes to say, “all species are extinct.” For complex organisms, the average lifespan of a species is only about four million years— roughly about where we are now. Extinction is always bad news for the victims, of course, but it appears to be a good thing for a dynamic planet. “The alternative to extinction is stagnation,” says Ian Tattersall of the American Museum of Natural History, “and stagnation is seldom a good thing in any realm.” (I should perhaps note that we are speaking here of extinction as a natural, long-term process. Extinction brought about by human carelessness is another matter altogether.)

Crises in Earth’s history are invariably associated with dramatic leaps afterward. The fall of the Ediacaran fauna was followed by the creative outburst of the Cambrian period. The Ordovician extinction of 440 million years ago cleared the oceans of a lot of immobile filter feeders and, somehow, created conditions that favored darting fish and giant aquatic reptiles. These in turn were in an ideal position to send colonists onto dry land when another blowout in the late Devonian period gave life another sound shaking. And so it has gone at scattered intervals through history. If most of these events hadn't happened just as they did, just when they did, we almost certainly wouldn't be here now.

Earth has seen five major extinction episodes in its time— the Ordovician, Devonian, Permian, Triassic, and Cretaceous, in that order— and many smaller ones. The Ordovician (440 million years ago) and Devonian (365 million) each wiped out about 80 to 85 percent of species. The Triassic (210 million years ago) and Cretaceous (65 million years) each wiped out 70 to 75 percent of species. But the real whopper was the Permian extinction of about 245 million years ago, which raised the curtain on the long age of the dinosaurs. In the Permian, at least 95 percent of animals known from the fossil record check out, never to return. Even about a third of insect species went— the only occasion on which they were lost en masse. It is as close as we have ever come to total obliteration.

“It was, truly, a mass extinction, a carnage of a magnitude that had never troubled the Earth before,”

says Richard Fortey. The Permian event was particularly devastating to sea creatures. Trilobites

vanished altogether. Clams and sea urchins nearly went. Virtually all other marine organisms were

staggered. Altogether, on land and in the water, it is thought that Earth lost 52 percent of its

families— that’s the level above genus and below order on the grand scale of life (the subject of the

next chapter)— and perhaps as many as 96 percent of all its species. It would be a long time— as

much as eighty million years by one reckoning— before species totals recovered.

Two points need to be kept in mind. First, these are all just informed guesses. Estimates for the

number of animal species alive at the end of the Permian range from as low as 45,000 to as high as

240,000. If you don’t know how many species were alive, you can hardly specify with conviction the

proportion that perished. Moreover, we are talking about the death of species, not individuals. For

individuals the death toll could be much higher— in many cases, practically total. The species that

survived to the next phase of life's lottery almost certainly owe their existence to a few scarred and

limping survivors.

In between the big kill-offs, there have also been many smaller, less well-known extinction

episodes— the Hemphillian, Frasnian, Famennian, Rancholabrean, and a dozen or so others— which

were not so devastating to total species numbers, but often critically hit certain populations. Grazing

animals, including horses, were nearly wiped out in the Hemphillian event about five million years

ago. Horses declined to a single species, which appears so sporadically in the fossil record as to

suggest that for a time it teetered on the brink of oblivion. Imagine a human history without horses, without grazing animals.

In nearly every case, for both big extinctions and more modest ones, we have bewilderingly little idea of what the cause was. Even after stripping out the more crackpot notions there are still more theories for what caused the extinction events than there have been events. At least two dozen potential culprits have been identified as causes or prime contributors: global warming, global cooling, changing sea levels, oxygen depletion of the seas (a condition known as anoxia), epidemics, giant leaks of methane gas from the seafloor, meteor and comet impacts, runaway hurricanes of a type known as hypercanes, huge volcanic upwellings, catastrophic solar flares.

This last is a particularly intriguing possibility. Nobody knows how big solar flares can get because we have only been watching them since the beginning of the space age, but the Sun is a mighty engine and its storms are commensurately enormous. A typical solar flare—

something we wouldn't

even notice on Earth— will release the energy equivalent of a billion

hydrogen bombs and fling into

space a hundred billion tons or so of murderous high-energy particles. The

magnetosphere and

atmosphere between them normally swat these back into space or steer them

safely toward the poles

(where they produce the Earth's comely auroras), but it is thought that an

unusually big blast, say a

hundred times the typical flare, could overwhelm our ethereal defenses. The

light show would be a

glorious one, but it would almost certainly kill a very high proportion of all

that basked in its glow.

Moreover, and rather chillingly, according to Bruce Tsurutani of the NASA

Jet Propulsion

Laboratory, "it would leave no trace in history."

What all this leaves us with, as one researcher has put it, is "tons of

conjecture and very little

evidence." Cooling seems to be associated with at least three of the big

extinction events— the

Ordovician, Devonian, and Permian— but beyond that little is agreed, including whether a particular episode happened swiftly or slowly. Scientists can't agree, for instance, whether the late Devonian extinction— the event that was followed by vertebrates moving onto the land— happened over millions of years or thousands of years or in one lively day.

One of the reasons it is so hard to produce convincing explanations for extinctions is that it is so very hard to exterminate life on a grand scale. As we have seen from the Manson impact, you can receive a ferocious blow and still stage a full, if presumably somewhat wobbly, recovery. So why, out of all the thousands of impacts Earth has endured, was the KT event so singularly devastating? Well, first it was positively enormous. It struck with the force of 100 million megatons. Such an outburst is not easily imagined, but as James Lawrence Powell has pointed out, if you exploded one Hiroshimasized bomb for every person alive on earth today you would still be about a billion bombs short of

the size of the KT impact. But even that alone may not have been enough to

wipe out 70 percent of

Earth’s life, dinosaurs included.

The KT meteor had the additional advantage— advantage if you are a

mammal, that is— that it

landed in a shallow sea just ten meters deep, probably at just the right angle,

at a time when oxygen

levels were 10 percent higher than at present and so the world was more

combustible. Above all the

floor of the sea where it landed was made of rock rich in sulfur. The result

was an impact that turned

an area of seafloor the size of Belgium into aerosols of sulfuric acid. For

months afterward, the Earth

was subjected to rains acid enough to burn skin.

In a sense, an even greater question than that of what wiped out 70 percent

of the species that were

existing at the time is how did the remaining 30 percent survive? Why was

the event so irremediably

devastating to every single dinosaur that existed, while other reptiles, like snakes and crocodiles,

passed through unimpeded? So far as we can tell no species of toad, newt, salamander, or other

amphibian went extinct in North America. "Why should these delicate creatures have emerged

unscathed from such an unparalleled disaster?" asks Tim Flannery in his fascinating prehistory of

America, Eternal Frontier.

In the seas it was much the same story. All the ammonites vanished, but their cousins the nautiloids,

who lived similar lifestyles, swam on. Among plankton, some species were practically wiped out—

92 percent of foraminiferans, for instance— while other organisms like diatoms, designed to a similar

plan and living alongside, were comparatively unscathed.

These are difficult inconsistencies. As Richard Fortey observes: "Somehow it does not seem

satisfying just to call them 'lucky ones' and leave it at that." If, as seems entirely likely, the event

was followed by months of dark and choking smoke, then many of the insect survivors become

difficult to account for. “Some insects, like beetles,” Fortey notes, “could

live on wood or other

things lying around. But what about those like bees that navigate by sunlight

and need pollen?

Explaining their survival isn’t so easy.”

Above all, there are the corals. Corals require algae to survive and algae

require sunlight, and both

together require steady minimum temperatures. Much publicity has been

given in the last few years

to corals dying from changes in sea temperature of only a degree or so. If

they are that vulnerable to

small changes, how did they survive the long impact winter?

There are also many hard-to-explain regional variations. Extinctions seem to

have been far less

severe in the southern hemisphere than the northern. New Zealand in

particular appears to have come

through largely unscathed even though it had almost no burrowing creatures.

Even its vegetation was

overwhelmingly spared, and yet the scale of conflagration elsewhere

suggests that devastation was
global. In short, there is just a great deal we don’t know.
Some animals absolutely prospered— including, a little surprisingly, the turtles once again. As
Flannery notes, the period immediately after the dinosaur extinction could well be known as the Age
of Turtles. Sixteen species survived in North America and three more came into existence soon after.
Clearly it helped to be at home in water. The KT impact wiped out almost 90 percent of land-based
species but only 10 percent of those living in fresh water. Water obviously offered protection against
heat and flame, but also presumably provided more sustenance in the lean period that followed. All
the land-based animals that survived had a habit of retreating to a safer environment during times of
danger— into water or underground— either of which would have provided considerable shelter
against the ravages without. Animals that scavenged for a living would also have enjoyed an

advantage. Lizards were, and are, largely impervious to the bacteria in rotting carcasses. Indeed, often they are positively drawn to it, and for a long while there were clearly a lot of putrid carcasses about.

It is often wrongly stated that only small animals survived the KT event. In fact, among the survivors were crocodiles, which were not just large but three times larger than they are today. But on the whole, it is true, most of the survivors were small and furtive. Indeed, with the world dark and hostile, it was a perfect time to be small, warm-blooded, nocturnal, flexible in diet, and cautious by nature— the very qualities that distinguished our mammalian forebears. Had our evolution been more advanced, we would probably have been wiped out. Instead, mammals found themselves in a world to which they were as well suited as anything alive.

However, it wasn't as if mammals swarmed forward to fill every niche. "Evolution may abhor a vacuum," wrote the paleobiologist Steven M. Stanley, "but it often takes a long time to fill it." For perhaps as many as ten million years mammals remained cautiously small. In the early Tertiary, if you were the size of a bobcat you could be king.

But once they got going, mammals expanded prodigiously— sometimes to an almost preposterous degree. For a time, there were guinea pigs the size of rhinos and rhinos the size of a two-story house.

Wherever there was a vacancy in the predatory chain, mammals rose (often literally) to fill it. Early members of the raccoon family migrated to South America, discovered a vacancy, and evolved into creatures the size and ferocity of bears. Birds, too, prospered disproportionately. For millions of years, a gigantic, flightless, carnivorous bird called Titanis was possibly the most ferocious creature in North America. Certainly it was the most daunting bird that ever lived. It stood ten feet high, weighed over eight hundred pounds, and had a beak that could tear the head off pretty much

anything that irked it. Its family survived in formidable fashion for fifty

million years, yet until a

skeleton was discovered in Florida in 1963, we had no idea that it had ever

existed.

Which brings us to another reason for our uncertainty about extinctions: the

paltriness of the fossil

record. We have touched already on the unlikelihood of any set of bones

becoming fossilized, but the

record is actually worse than you might think. Consider dinosaurs. Museums

give the impression that

we have a global abundance of dinosaur fossils. In fact, overwhelmingly

museum displays are

artificial. The giant Diplodocus that dominates the entrance hall of the

Natural History Museum in

London and has delighted and informed generations of visitors is made of

plaster— built in 1903 in

Pittsburgh and presented to the museum by Andrew Carnegie. The entrance

hall of the American

Museum of Natural History in New York is dominated by an even grander

tableau: a skeleton of a
large Barosaurus defending her baby from attack by a darting and toothy Allosaurus. It is a
wonderfully impressive display— the Barosaurus rises perhaps thirty feet toward the high ceiling—
but also entirely fake. Every one of the several hundred bones in the display is a cast. Visit almost
any large natural history museum in the world— in Paris, Vienna, Frankfurt, Buenos Aires, Mexico
City— and what will greet you are antique models, not ancient bones.

The fact is, we don’t really know a great deal about the dinosaurs. For the whole of the Age of
Dinosaurs, fewer than a thousand species have been identified (almost half of them known from a
single specimen), which is about a quarter of the number of mammal species alive now. Dinosaurs,
bear in mind, ruled the Earth for roughly three times as long as mammals have, so either dinosaurs
were remarkably unproductive of species or we have barely scratched the surface (to use an

irresistibly apt cliché).

For millions of years through the Age of Dinosaurs not a single fossil has yet been found. Even for

the period of the late Cretaceous— the most studied prehistoric period there is, thanks to our long

interest in dinosaurs and their extinction— some three quarters of all species that lived may yet be

undiscovered. Animals bulkier than the Diplodocus or more forbidding than tyrannosaurus may have

roamed the Earth in the thousands, and we may never know it. Until very recently everything known

about the dinosaurs of this period came from only about three hundred specimens representing just

sixteen species. The scantiness of the record led to the widespread belief that dinosaurs were on their

way out already when the KT impact occurred.

In the late 1980s a paleontologist from the Milwaukee Public Museum, Peter Sheehan, decided to

conduct an experiment. Using two hundred volunteers, he made a painstaking census of a welldefined, but also well-picked-over, area of the famous Hell Creek formation in Montana. Sifting meticulously, the volunteers collected every last tooth and vertebra and chip of bone— everything that had been overlooked by previous diggers. The work took three years. When finished they found that they had more than tripled the global total of dinosaur fossils from the late Cretaceous. The survey established that dinosaurs remained numerous right up to the time of the KT impact. “There is no reason to believe that the dinosaurs were dying out gradually during the last three million years of the Cretaceous,” Sheehan reported.

We are so used to the notion of our own inevitability as life’s dominant species that it is hard to grasp that we are here only because of timely extraterrestrial bangs and other random flukes. The one thing we have in common with all other living things is that for nearly four billion years our ancestors have managed to slip through a series of closing doors every time we needed them to.

Stephen Jay Gould expressed it succinctly in a well-known line: “Humans are here today because our particular line never fractured— never once at any of the billion points that could have erased us from history.”

We started this chapter with three points: Life wants to be; life doesn’t always want to be much; life from time to time goes extinct. To this we may add a fourth: Life goes on. And often, as we shall see, it goes on in ways that are decidedly amazing.

23 **THE RICHNESS OF BEING**

HERE AND THERE in the Natural History Museum in London, built into recesses along the underlit corridors or standing between glass cases of minerals and ostrich eggs and a century or so of other productive clutter, are secret doors— at least secret in the sense that there is nothing about them to attract the visitor’s notice. Occasionally you might see someone with the distracted manner and

interestingly willful hair that mark the scholar emerge from one of the doors and hasten down a
corridor, probably to disappear through another door a little further on, but this is a relatively rare
event. For the most part the doors stay shut, giving no hint that beyond them exists another— a
parallel— Natural History Museum as vast as, and in many ways more wonderful than, the one the
public knows and adores.

The Natural History Museum contains some seventy million objects from every realm of life and
every corner of the planet, with another hundred thousand or so added to the collection each year,
but it is really only behind the scenes that you get a sense of what a treasure house this is. In
cupboards and cabinets and long rooms full of close-packed shelves are kept tens of thousands of
pickled animals in bottles, millions of insects pinned to squares of card, drawers of shiny mollusks,
bones of dinosaurs, skulls of early humans, endless folders of neatly pressed

plants. It is a little like

wandering through Darwin’s brain. The spirit room alone holds fifteen miles

of shelving containing

jar upon jar of animals preserved in methylated spirit.

Back here are specimens collected by Joseph Banks in Australia, Alexander

von Humboldt in

Amazonia, Darwin on the Beagle voyage, and much else that is either very

rare or historically

important or both. Many people would love to get their hands on these

things. A few actually have.

In 1954 the museum acquired an outstanding ornithological collection from

the estate of a devoted

collector named Richard Meinertzhagen, author of Birds of Arabia, among

other scholarly works.

Meinertzhagen had been a faithful attendee of the museum for years, coming

almost daily to take

notes for the production of his books and monographs. When the crates

arrived, the curators

excitedly jimmied them open to see what they had been left and were

surprised, to put it mildly, to

discover that a very large number of specimens bore the museum's own labels. Mr. Meinertzhagen,
it turned out, had been helping himself to their collections for years. It also explained his habit of
wearing a large overcoat even during warm weather.

A few years later a charming old regular in the mollusks department—"quite a distinguished
gentleman," I was told— was caught inserting valued seashells into the hollow legs of his Zimmer
frame.

"I don't suppose there's anything in here that somebody somewhere doesn't covet," Richard Fortey
said with a thoughtful air as he gave me a tour of the beguiling world that is the behind-the-scenes
part of the museum. We wandered through a confusion of departments where people sat at large
tables doing intent, investigative things with arthropods and palm fronds and boxes of yellowed
bones. Everywhere there was an air of unhurried thoroughness, of people being engaged in a gigantic

endeavor that could never be completed and mustn't be rushed. In 1967, I had read, the museum
issued its report on the John Murray Expedition, an Indian Ocean survey, forty-four years after the
expedition had concluded. This is a world where things move at their own pace, including a tiny lift
Fortey and I shared with a scholarly looking elderly man with whom Fortey chatted genially and
familiarly as we proceeded upwards at about the rate that sediments are laid down.

When the man departed, Fortey said to me: "That was a very nice chap named Norman who's spent
forty-two years studying one species of plant, St. John's wort. He retired in 1989, but he still comes
in every week."

"How do you spend forty-two years on one species of plant?" I asked.

"It's remarkable, isn't it?" Fortey agreed. He thought for a moment. "He's very thorough
apparently." The lift door opened to reveal a bricked-over opening. Fortey looked confounded.

“That’s very strange,” he said. “That used to be Botany back there.” He punched a button for another floor, and we found our way at length to Botany by means of back staircases and discreet trespass through yet more departments where investigators toiled lovingly over once-living objects. And so it was that I was introduced to Len Ellis and the quiet world of bryophytes—mosses to the rest of us.

When Emerson poetically noted that mosses favor the north sides of trees (“The moss upon the forest bark, was pole-star when the night was dark”) he really meant lichens, for in the nineteenth century mosses and lichens weren’t distinguished. True mosses aren’t actually fussy about where they grow, so they are no good as natural compasses. In fact, mosses aren’t actually much good for anything.

“Perhaps no great group of plants has so few uses, commercial or economic, as the mosses,” wrote Henry S. Conard, perhaps just a touch sadly, in How to Know the Mosses and Liverworts, published

in 1956 and still to be found on many library shelves as almost the only attempt to popularize the
subject.

They are, however, prolific. Even with lichens removed, bryophytes is a busy realm, with over ten
thousand species contained within some seven hundred genera. The plump and stately Moss Flora of
Britain and Ireland by A. J. E. Smith runs to seven hundred pages, and Britain and Ireland are by no
means outstandingly mossy places. “The tropics are where you find the variety,” Len Ellis told me.

A quiet, spare man, he has been at the Natural History Museum for twenty-seven years and curator
of the department since 1990. “You can go out into a place like the rain forests of Malaysia and find
new varieties with relative ease. I did that myself not long ago. I looked down and there was a
species that had never been recorded.”

“So we don’t know how many species are still to be discovered?”

“Oh, no. No idea.”

You might not think there would be that many people in the world prepared to devote lifetimes to the study of something so inescapably low key, but in fact moss people number in the hundreds and they feel very strongly about their subject. “Oh, yes,” Ellis told me, “the meetings can get very lively at times.”

I asked him for an example of controversy.

“Well, here’s one inflicted on us by one of your countrymen,” he said, smiling lightly, and opened a hefty reference work containing illustrations of mosses whose most notable characteristic to the uninstructed eye was their uncanny similarity one to another. “That,” he said, tapping a moss, “used to be one genus, Drepanocladus. Now it’s been reorganized into three: Drepanocladus, Wamstorfia, and Hamatacoulis.”

“And did that lead to blows?” I asked perhaps a touch hopefully.

“Well, it made sense. It made perfect sense. But it meant a lot of reordering of collections and it put all the books out of date for a time, so there was a bit of, you know, grumbling."

Mosses offer mysteries as well, he told me. One famous case— famous to moss people anyway—

involved a retiring type called Hyophila stanfordensis, which was discovered on the campus of

Stanford University in California and later also found growing beside a path in Cornwall, on the

southwest tip of England, but has never been encountered anywhere in between. How it came to

exist in two such unconnected locations is anybody's guess. "It's now known as Hennediella

stanfordensis," Ellis said. "Another revision."

We nodded thoughtfully.

When a new moss is found it must be compared with all other mosses to make sure that it hasn't

been recorded already. Then a formal description must be written and illustrations prepared and the

result published in a respectable journal. The whole process seldom takes less than six months. The twentieth century was not a great age for moss taxonomy. Much of the century's work was devoted to untangling the confusions and duplications left behind by the nineteenth century.

That was the golden age of moss collecting. (You may recall that Charles Lyell's father was a great moss man.) One aptly named Englishman, George Hunt, hunted British mosses so assiduously that he probably contributed to the extinction of several species. But it is thanks to such efforts that Len Ellis's collection is one of the world's most comprehensive. All 780,000 of his specimens are pressed into large folded sheets of heavy paper, some very old and covered with spidery Victorian script. Some, for all we knew, might have been in the hand of Robert Brown, the great Victorian botanist, unveiler of Brownian motion and the nucleus of cells, who founded and ran the museum's botany department for its first thirty-one years until his death in 1858. All the specimens are kept in

lustrous old mahogany cabinets so strikingly fine that I remarked upon them.
“Oh, those were Sir Joseph Banks’s, from his house in Soho Square,” Ellis said casually, as if
identifying a recent purchase from Ikea. “He had them built to hold his specimens from the
Endeavour voyage.” He regarded the cabinets thoughtfully, as if for the first time in a long while. “I
don’t know how we ended up with them in bryology,” he added.

This was an amazing disclosure. Joseph Banks was England’s greatest botanist, and the Endeavour
voyage— that is the one on which Captain Cook charted the 1769 transit of Venus and claimed
Australia for the crown, among rather a lot else— was the greatest botanical expedition in history.

Banks paid £10,000, about $1 million in today’s money, to bring himself and a party of nine
others— a naturalist, a secretary, three artists, and four servants— on the three-year adventure around
the world. Goodness knows what the bluff Captain Cook made of such a velvety and pampered

assemblage, but he seems to have liked Banks well enough and could not but admire his talents in
botany— a feeling shared by posterity.

Never before or since has a botanical party enjoyed greater triumphs. Partly it was because the
voyage took in so many new or little-known places— Tierra del Fuego, Tahiti, New Zealand,
Australia, New Guinea— but mostly it was because Banks was such an astute and inventive collector.

Even when unable to go ashore at Rio de Janeiro because of a quarantine, he sifted through a bale of
fodder sent for the ship's livestock and made new discoveries. Nothing, it seems, escaped his notice.

Altogether he brought back thirty thousand plant specimens, including fourteen hundred not seen
before— enough to increase by about a quarter the number of known plants in the world.

But Banks's grand cache was only part of the total haul in what was an almost absurdly acquisitive
age. Plant collecting in the eighteenth century became a kind of international

mania. Glory and wealth alike awaited those who could find new species, and botanists and adventurers went to the most incredible lengths to satisfy the world's craving for horticultural novelty. Thomas Nuttall, the man who named the wisteria after Caspar Wistar, came to America as an uneducated printer but discovered a passion for plants and walked halfway across the country and back again, collecting hundreds of growing things never seen before. John Fraser, for whom is named the Fraser fir, spent years in the wilderness collecting on behalf of Catherine the Great and emerged at length to find that Russia had a new czar who thought he was mad and refused to honor his contract. Fraser took everything to Chelsea, where he opened a nursery and made a handsome living selling rhododendrons, azaleas, magnolias, Virginia creepers, asters, and other colonial exotica to a delighted English gentry.

Huge sums could be made with the right finds. John Lyon, an amateur botanist, spent two hard and dangerous years collecting specimens, but cleared almost $200,000 in today’s money for his efforts.

Many, however, just did it for the love of botany. Nuttall gave most of what he found to the Liverpool Botanic Gardens. Eventually he became director of Harvard’s Botanic Garden and author of the encyclopedic Genera of North American Plants (which he not only wrote but also largely typeset).

And that was just plants. There was also all the fauna of the new worlds—kangaroos, kiwis, raccoons, bobcats, mosquitoes, and other curious forms beyond imagining. The volume of life on Earth was seemingly infinite, as Jonathan Swift noted in some famous lines:

So, naturalists observe, a flea
Hath smaller fleas that on him prey;
And these have smaller still to bite ’em;
And so proceed ad infinitum.

All this new information needed to be filed, ordered, and compared with what was known. The world was desperate for a workable system of classification. Fortunately there was a man in Sweden who stood ready to provide it.

His name was Carl Linné (later changed, with permission, to the more aristocratic von Linné), but he is remembered now by the Latinized form Carolus Linnaeus. He was born in 1707 in the village of Råshult in southern Sweden, the son of a poor but ambitious Lutheran curate, and was such a sluggish student that his exasperated father apprenticed him (or, by some accounts, nearly apprenticed him) to a cobbler. Appalled at the prospect of spending a lifetime banging tacks into leather, young Linné begged for another chance, which was granted, and he never thereafter wavered from academic distinction. He studied medicine in Sweden and Holland, though his passion became the natural world. In the early 1730s, still in his twenties, he began to produce catalogues of the

world's plant and animal species, using a system of his own devising, and

gradually his fame grew.

Rarely has a man been more comfortable with his own greatness. He spent

much of his leisure time

penning long and flattering portraits of himself, declaring that there had

never "been a greater

botanist or zoologist," and that his system of classification was "the greatest

achievement in the

realm of science." Modestly he suggested that his gravestone should bear the

inscription Princeps

Botanicorum, "Prince of Botanists." It was never wise to question his

generous self-assessments.

Those who did so were apt to find they had weeds named after them.

Linnaeus's other striking quality was an abiding— at times, one might say, a

feverish—

preoccupation with sex. He was particularly struck by the similarity between

certain bivalves and the

female pudenda. To the parts of one species of clam he gave the names

vulva, labia, pubes, anus,

and hymen. He grouped plants by the nature of their reproductive organs and endowed them with an arrestingly anthropomorphic amorousness. His descriptions of flowers and their behavior are full of references to “promiscuous intercourse,” “barren concubines,” and “the bridal bed.” In spring, he wrote in one oft-quoted passage:

Love comes even to the plants. Males and females . . . hold their nuptials . . . showing by their sexual organs which are males, which females. The flowers’ leaves serve as a bridal bed, which the Creator has so gloriously arranged, adorned with such noble bed curtains, and perfumed with so many soft scents that the bridegroom with his bride might there celebrate their nuptials with so much the greater solemnity. When the bed has thus been made ready, then is the time for the bridegroom to embrace his beloved bride and surrender himself to her.

He named one genus of plants Clitoria. Not surprisingly, many people thought him strange. But his system of classification was irresistible. Before Linnaeus, plants were given names that were expansively descriptive. The common ground cherry was called Physalis amno ramosissime ramis angulosis glabris foliis dentoserratis. Linnaeus lopped it back to Physalis angulata, which name it still uses. The plant world was equally disordered by inconsistencies of naming. A botanist could not be sure if Rosa sylvestris alba cum rubore, folio glabro was the same plant that others called Rosa sylvestris inodora seu canina. Linnaeus solved the puzzlement by calling it simply Rosa canina. To make these excisions useful and agreeable to all required much more than simply being decisive. It required an instinct— a genius, in fact— for spotting the salient qualities of a species.

The Linnaean system is so well established that we can hardly imagine an alternative, but before Linnaeus, systems of classification were often highly whimsical. Animals might be categorized by whether they were wild or domesticated, terrestrial or aquatic, large or small, even whether they were thought handsome and noble or of no consequence. Buffon arranged his animals by their utility to man. Anatomical considerations barely came into it. Linnaeus made it his life's work to rectify this deficiency by classifying all that was alive according to its physical attributes. Taxonomy— which is to say the science of classification— has never looked back.

It all took time, of course. The first edition of his great Systema Naturae in 1735 was just fourteen pages long. But it grew and grew until by the twelfth edition— the last that Linnaeus would live to see— it extended to three volumes and 2,300 pages. In the end he named or recorded some 13,000 species of plant and animal. Other works were more comprehensive— John Ray's three-volume Historia Generalis Plantarum in England, completed a generation earlier, covered no fewer than 18,625 species of plants alone— but what Linnaeus had that no one else

could touch were
consistency, order, simplicity, and timeliness. Though his work dates from the 1730s, it didn’t
become widely known in England until the 1760s, just in time to make Linnaeus a kind of father
figure to British naturalists. Nowhere was his system embraced with greater enthusiasm (which is
why, for one thing, the Linnaean Society has its home in London and not Stockholm).

Linnaeus was not flawless. He made room for mythical beasts and “monstrous humans” whose
descriptions he gullibly accepted from seamen and other imaginative travelers. Among these were a
wild man, Homo ferus, who walked on all fours and had not yet mastered the art of speech, and
Homo caudatus, “man with a tail.” But then it was, as we should not forget, an altogether more
credulous age. Even the great Joseph Banks took a keen and believing interest in a series of reported
sightings of mermaids off the Scottish coast at the end of the eighteenth

century. For the most part,

however, Linnaeus's lapses were offset by sound and often brilliant

taxonomy. Among other

accomplishments, he saw that whales belonged with cows, mice, and other

common terrestrial

animals in the order Quadrupedia (later changed to Mammalia), which no

one had done before.

In the beginning, Linnaeus intended only to give each plant a genus name

and a number—

Convolvulus 1, Convolvulus 2, and so on— but soon realized that that was

unsatisfactory and hit on

the binomial arrangement that remains at the heart of the system to this day.

The intention originally

was to use the binomial system for everything— rocks, minerals, diseases,

winds, whatever existed in

nature. Not everyone embraced the system warmly. Many were disturbed by

its tendency toward

indelicacy, which was slightly ironic as before Linnaeus the common names

of many plants and

animals had been heartily vulgar. The dandelion was long popularly known

as the “pissabed”
because of its supposed diuretic properties, and other names in everyday use included mare’s fart,
naked ladies, twitch-ballock, hound’s piss, open arse, and bum-towel. One or two of these earthy
appellations may unwittingly survive in English yet. The “maidenhair” in maidenhair moss, for
instance, does not refer to the hair on the maiden’s head. At all events, it had long been felt that the
natural sciences would be appreciably dignified by a dose of classical renaming, so there was a
certain dismay in discovering that the self-appointed Prince of Botany had sprinkled his texts with
such designations as Clitoria, Fornicata, and Vulva.
Over the years many of these were quietly dropped (though not all: the common slipper limpet still
answers on formal occasions to Crepidula fornicata) and many other refinements introduced as the
needs of the natural sciences grew more specialized. In particular the system was bolstered by the

gradual introduction of additional hierarchies. Genus (plural genera) and species had been employed by naturalists for over a hundred years before Linnaeus, and order, class, and family in their biological senses all came into use in the 1750s and 1760s. But phylum wasn't coined until 1876 (by the German Ernst Haeckel), and family and order were treated as interchangeable until early in the twentieth century. For a time zoologists used family where botanists placed order, to the occasional confusion of nearly everyone.*36

Linnaeus had divided the animal world into six categories: mammals, reptiles, birds, fishes, insects, and "vermes," or worms, for everything that didn't fit into the first five. From the outset it was evident that putting lobsters and shrimp into the same category as worms was unsatisfactory, and various new categories such as Mollusca and Crustacea were created. Unfortunately these new classifications were not uniformly applied from nation to nation. In an attempt to reestablish order,

the British in 1842 proclaimed a new set of rules called the Stricklandian Code, but the French saw

this as highhanded, and the Société Zoologique countered with its own conflicting code. Meanwhile,

the American Ornithological Society, for obscure reasons, decided to use the 1758 edition of

Systema Naturae as the basis for all its naming, rather than the 1766 edition used elsewhere, which

meant that many American birds spent the nineteenth century logged in different genera from their

avian cousins in Europe. Not until 1902, at an early meeting of the International Congress of

Zoology, did naturalists begin at last to show a spirit of compromise and adopt a universal code.

Taxonomy is described sometimes as a science and sometimes as an art, but really it’s a

battleground. Even today there is more disorder in the system than most people realize. Take the

category of the phylum, the division that describes the basic body plans of all organisms. A few phyla are generally well known, such as mollusks (the home of clams and snails), arthropods (insects and crustaceans), and chordates (us and all other animals with a backbone or protobackbone), though things then move swiftly in the direction of obscurity. Among the latter we might list Gnathostomulida (marine worms), Cnidaria (jellyfish, medusae, anemones, and corals), and the delicate Priapulida (or little "penis worms"). Familiar or not, these are elemental divisions. Yet there is surprisingly little agreement on how many phyla there are or ought to be. Most biologists fix the total at about thirty, but some opt for a number in the low twenties, while Edward O. Wilson in The Diversity of Life puts the number at a surprisingly robust eighty-nine. It depends on where you decide to make your divisions— whether you are a "lumper" or a "splitter," as they say in the biological world.

At the more workaday level of species, the possibilities for disagreements are even greater. Whether a species of grass should be called Aegilops incurva, Aegilops incurvata, or Aegilops ovata may not be a matter that would stir many nonbotanists to passion, but it can be a source of very lively heat in the right quarters. The problem is that there are five thousand species of grass and many of them look awfully alike even to people who know grass. In consequence, some species have been found and named at least twenty times, and there are hardly any, it appears, that haven't been independently identified at least twice. The two-volume Manual of the Grasses of the United States devotes two hundred closely typeset pages to sorting out all the synonymies, as the biological world refers to its inadvertent but quite common duplications. And that is just for the grasses of a single country.

To deal with disagreements on the global stage, a body known as the

International Association for

Plant Taxonomy arbitrates on questions of priority and duplication. At intervals it hands down

decrees, declaring that Zauschneria californica (a common plant in rock gardens) is to be known

henceforth as Epilobium canum or that Aglaothamnion tenuissimum may now be regarded as

conspecific with Aglaothamnion byssoides, but not with Aglaothamnion pseudobyssoides. Normally

these are small matters of tidying up that attract little notice, but when they touch on beloved garden

plants, as they sometimes do, shrieks of outrage inevitably follow. In the late 1980s the common

chrysanthemum was banished (on apparently sound scientific principles) from the genus of the same

name and relegated to the comparatively drab and undesirable world of the genus Dendranthema.

Chrysanthemum breeders are a proud and numerous lot, and they protested to the real if improbablesounding

Committee on Spermatophyta. (There are also committees for Pteridophyta,

Bryophyta,
and Fungi, among others, all reporting to an executive called the Rapporteur-Général; this is truly an institution to cherish.) Although the rules of nomenclature are supposed to be rigidly applied, botanists are not indifferent to sentiment, and in 1995 the decision was reversed. Similar adjudications have saved petunias, euonymus, and a popular species of amaryllis from demotion, but not many species of geraniums, which some years ago were transferred, amid howls, to the genus Pelargonium. The disputes are entertainingly surveyed in Charles Elliott's The Potting-Shed Papers.

Disputes and reorderings of much the same type can be found in all the other realms of the living, so keeping an overall tally is not nearly as straightforward a matter as you might suppose. In consequence, the rather amazing fact is that we don't have the faintest idea— "not even to the nearest order of magnitude," in the words of Edward O. Wilson— of the number of

things that live on our
planet. Estimates range from 3 million to 200 million. More extraordinary still, according to a report
in the Economist, as much as 97 percent of the world's plant and animal species may still await
discovery.

Of the organisms that we do know about, more than 99 in 100 are only sketchily described— "a
scientific name, a handful of specimens in a museum, and a few scraps of description in scientific
journals" is how Wilson describes the state of our knowledge. In The Diversity of Life, he estimated
the number of known species of all types— plants, insects, microbes, algae, everything— at 1.4
million, but added that that was just a guess. Other authorities have put the number of known species
slightly higher, at around 1.5 million to 1.8 million, but there is no central registry of these things, so
nowhere to check numbers. In short, the remarkable position we find ourselves in is that we don't

actually know what we actually know.

In principle you ought to be able to go to experts in each area of specialization, ask how many species there are in their fields, then add the totals. Many people have in fact done so. The problem is that seldom do any two come up with matching figures. Some sources put the number of known types of fungi at 70,000, others at 100,000— nearly half as many again. You can find confident assertions that the number of described earthworm species is 4,000 and equally confident assertions that the figure is 12,000. For insects, the numbers run from 750,000 to 950,000 species. These are, you understand, supposedly the known number of species. For plants, the commonly accepted numbers range from 248,000 to 265,000. That may not seem too vast a discrepancy, but it's more than twenty times the number of flowering plants in the whole of North America.

Putting things in order is not the easiest of tasks. In the early 1960s, Colin

Groves of the Australian

National University began a systematic survey of the 250-plus known species of primate. Oftentimes it turned out that the same species had been described more than once—sometimes several times—without any of the discoverers realizing that they were dealing with an animal that was already known to science. It took Groves four decades to untangle everything, and that was with a comparatively small group of easily distinguished, generally noncontroversial creatures. Goodness knows what the results would be if anyone attempted a similar exercise with the planet's estimated 20,000 types of lichens, 50,000 species of mollusk, or 400,000-plus beetles.

What is certain is that there is a great deal of life out there, though the actual quantities are necessarily estimates based on extrapolations— sometimes exceedingly expansive extrapolations. In a well-known exercise in the 1980s, Terry Erwin of the Smithsonian Institution saturated a stand of nineteen rain forest trees in Panama with an insecticide fog, then collected everything that fell into his nets from the canopy. Among his haul (actually hauls, since he repeated the experiment seasonally to make sure he caught migrant species) were 1,200 types of beetle. Based on the distribution of beetles elsewhere, the number of other tree species in the forest, the number of forests in the world, the number of other insect types, and so on up a long chain of variables, he estimated a figure of 30 million species of insects for the entire planet— a figure he later said was too conservative. Others using the same or similar data have come up with figures of 13 million, 80 million, or 100 million insect types, underlining the conclusion that however carefully arrived at, such figures inevitably owe at least as much to supposition as to science.

According to the Wall Street Journal, the world has “about 10,000 active taxonomists”— not a great number when you consider how much there is to be recorded. But, the

Journal adds, because of the cost (about $2,000 per species) and paperwork, only about fifteen thousand new species of all types are logged per year.

“It’s not a biodiversity crisis, it’s a taxonomist crisis!” barks Koen Maes, Belgian-born head of invertebrates at the Kenyan National Museum in Nairobi, whom I met briefly on a visit to the country in the autumn of 2002. There were no specialized taxonomists in the whole of Africa, he told me. “There was one in the Ivory Coast, but I think he has retired,” he said. It takes eight to ten years to train a taxonomist, but none are coming along in Africa. “They are the real fossils,” Maes added.

He himself was to be let go at the end of the year, he said. After seven years in Kenya, his contract was not being renewed. “No funds,” Maes explained.

Writing in the journal Nature last year, the British biologist G. H. Godfray noted that there is a chronic “lack of prestige and resources” for taxonomists everywhere. In consequence, “many species

are being described poorly in isolated publications, with no attempt to relate

a new taxon*37 to

existing species and classifications.” Moreover, much of taxonomists’ time

is taken up not with

describing new species but simply with sorting out old ones. Many,

according to Godfray, “spend

most of their career trying to interpret the work of nineteenth-century

systematicists: deconstructing

their often inadequate published descriptions or scouring the world’s

museums for type material that

is often in very poor condition.” Godfray particularly stresses the absence of

attention being paid to

the systematizing possibilities of the Internet. The fact is that taxonomy by

and large is still quaintly

wedded to paper.

In an attempt to haul things into the modern age, in 2001 Kevin Kelly,

cofounder of Wired magazine,

launched an enterprise called the All Species Foundation with the aim of

finding every living

organism and recording it on a database. The cost of such an exercise has been estimated at anywhere from $2 billion to as much as $50 billion. As of the spring of 2002, the foundation had just $1.2 million in funds and four full-time employees. If, as the numbers suggest, we have perhaps 100 million species of insects yet to find, and if our rates of discovery continue at the present pace, we should have a definitive total for insects in a little over fifteen thousand years. The rest of the animal kingdom may take a little longer.

So why do we know as little as we do? There are nearly as many reasons as there are animals left to count, but here are a few of the principal causes:

Most living things are small and easily overlooked. In practical terms, this is not always a bad thing. You might not slumber quite so contentedly if you were aware that your mattress is home to perhaps two million microscopic mites, which come out in the wee hours to sup on your sebaceous

oils and feast on all those lovely, crunchy flakes of skin that you shed as you doze and toss. Your
pillow alone may be home to forty thousand of them. (To them your head is just one large oily bonbon.)

And don't think a clean pillowcase will make a difference. To something on the scale of bed
mites, the weave of the tightest human fabric looks like ship's rigging. Indeed, if your pillow is six
years old— which is apparently about the average age for a pillow— it has been estimated that onetenth
of its weight will be made up of "sloughed skin, living mites, dead mites and mite dung," to
quote the man who did the measuring, Dr. John Maunder of the British Medical Entomology Center.

(But at least they are your mites. Think of what you snuggle up with each time you climb into a
motel bed.)*38 These mites have been with us since time immemorial, but they weren't discovered
until 1965.

If creatures as intimately associated with us as bed mites escaped our notice until the age of color

television, it’s hardly surprising that most of the rest of the small-scale world

is barely known to us.

Go out into a woods— any woods at all— bend down and scoop up a

handful of soil, and you will be

holding up to 10 billion bacteria, most of them unknown to science. Your

sample will also contain

perhaps a million plump yeasts, some 200,000 hairy little fungi known as

molds, perhaps 10,000

protozoans (of which the most familiar is the amoeba), and assorted rotifers,

flatworms,

roundworms, and other microscopic creatures known collectively as

cryptozoa. A large portion of

these will also be unknown.

The most comprehensive handbook of microorganisms, Bergey’s Manual of

Systematic

Bacteriology, lists about 4,000 types of bacteria. In the 1980s, a pair of

Norwegian scientists, Jostein

Goksøyr and Vigdis Torsvik, collected a gram of random soil from a beech

forest near their lab in

Bergen and carefully analyzed its bacterial content. They found that this single small sample contained between 4,000 and 5,000 separate bacterial species, more than in the whole of Bergey's Manual. They then traveled to a coastal location a few miles away, scooped up another gram of earth, and found that it contained 4,000 to 5,000 other species. As Edward O. Wilson observes: "If over 9,000 microbial types exist in two pinches of substrate from two localities in Norway, how many more await discovery in other, radically different habitats?" Well, according to one estimate, it could be as high as 400 million.

We don't look in the right places. In The Diversity of Life, Wilson describes how one botanist spent a few days tramping around ten hectares of jungle in Borneo and discovered a thousand new species of flowering plant— more than are found in the whole of North America. The plants weren't hard to find. It's just that no one had looked there before. Koen Maes of the

Kenyan National

Museum told me that he went to one cloud forest, as mountaintop forests are known in Kenya, and in

a half hour “of not particularly dedicated looking” found four new species of millipedes, three

representing new genera, and one new species of tree. “Big tree,” he added, and shaped his arms as if

about to dance with a very large partner. Cloud forests are found on the tops of plateaus and have

sometimes been isolated for millions of years. “They provide the ideal climate for biology and they

have hardly been studied,” he said.

Overall, tropical rain forests cover only about 6 percent of Earth’s surface, but harbor more than half

of its animal life and about two-thirds of its flowering plants, and most of this life remains unknown

to us because too few researchers spend time in them. Not incidentally, much of this could be quite

valuable. At least 99 percent of flowering plants have never been tested for their medicinal properties. Because they can't flee from predators, plants have had to contrive chemical defenses, and so are particularly enriched in intriguing compounds. Even now nearly a quarter of all prescribed medicines are derived from just forty plants, with another 16 percent coming from animals or microbes, so there is a serious risk with every hectare of forest felled of losing medically vital possibilities. Using a method called combinatorial chemistry, chemists can generate forty thousand compounds at a time in labs, but these products are random and not uncommonly useless, whereas any natural molecule will have already passed what the Economist calls "the ultimate screening programme: over three and a half billion years of evolution."

Looking for the unknown isn't simply a matter of traveling to remote or distant places, however. In his book Life: An Unauthorised Biography, Richard Fortey notes how one ancient bacterium was found on the wall of a country pub "where men had urinated for generations"— a discovery that would seem to involve rare amounts of luck and devotion and possibly some other quality not specified.

There aren't enough specialists. The stock of things to be found, examined, and recorded very much outruns the supply of scientists available to do it. Take the hardy and little-known organisms known as bdelloid rotifers. These are microscopic animals that can survive almost anything. When conditions are tough, they curl up into a compact shape, switch off their metabolism, and wait for better times. In this state, you can drop them into boiling water or freeze them almost to absolute zero— that is the level where even atoms give up— and, when this torment has finished and they are returned to a more pleasing environment, they will uncurl and move on as if nothing has happened.

So far, about 500 species have been identified (though other sources say 360), but nobody has any

idea, even remotely, how many there may be altogether. For years almost all that was known about
them was thanks to the work of a devoted amateur, a London clerical worker named David Bryce
who studied them in his spare time. They can be found all over the world, but you could have all the
bdelloid rotifer experts in the world to dinner and not have to borrow plates from the neighbors.

Even something as important and ubiquitous as fungi— and fungi are both— attracts comparatively
little notice. Fungi are everywhere and come in many forms— as mushrooms, molds, mildews,
yeasts, and puffballs, to name but a sampling— and they exist in volumes that most of us little
suspect. Gather together all the fungi found in a typical acre of meadow and you would have 2,500
pounds of the stuff. These are not marginal organisms. Without fungi there would be no potato
blights, Dutch elm disease, jock itch, or athlete’s foot, but also no yogurts or beers or cheeses.

Altogether about 70,000 species of fungi have been identified, but it is thought the number could be as high as 1.8 million. A lot of mycologists work in industry, making cheeses and yogurts and the like, so it is hard to say how many are actively involved in research, but we can safely take it that there are more species of fungi to be found than there are people to find them.

The world is a really big place. We have been gulled by the ease of air travel and other forms of communication into thinking that the world is not all that big, but at ground level, where researchers must work, it is actually enormous— enormous enough to be full of surprises. The okapi, the nearest living relative of the giraffe, is now known to exist in substantial numbers in the rain forests of Zaire— the total population is estimated at perhaps thirty thousand— yet its existence wasn’t even suspected until the twentieth century. The large flightless New Zealand bird called the takahe had been presumed extinct for two hundred years before being found living in a rugged area of the country's South Island. In 1995 a team of French and British scientists in Tibet, who were lost in a snowstorm in a remote valley, came across a breed of horse, called the Riwoche, that had previously been known only from prehistoric cave drawings. The valley's inhabitants were astonished to learn that the horse was considered a rarity in the wider world.

Some people think even greater surprises may await us. "A leading British ethno-biologist," wrote the Economist in 1995, "thinks a megatherium, a sort of giant ground sloth which may stand as high as a giraffe . . . may lurk in the fastnesses of the Amazon basin." Perhaps significantly, the ethnobiologist wasn't named; perhaps even more significantly, nothing more has been heard of him or his giant sloth. No one, however, can categorically say that no such thing is there until every jungly glade has been investigated, and we are a long way from achieving that.

But even if we groomed thousands of fieldworkers and dispatched them to the farthest corners of the world, it would not be effort enough, for wherever life can be, it is. Life's extraordinary fecundity is amazing, even gratifying, but also problematic. To survey it all, you would have to turn over every rock, sift through the litter on every forest floor, sieve unimaginable quantities of sand and dirt, climb into every forest canopy, and devise much more efficient ways to examine the seas. Even then you would overlook whole ecosystems. In the 1980s, spelunkers entered a deep cave in Romania that had been sealed off from the outside world for a long but unknown period and found thirty-three species of insects and other small creatures— spiders, centipedes, lice— all blind, colorless, and new to science. They were living off the microbes in the surface scum of pools, which in turn were feeding on hydrogen sulfide from hot springs.

Our instinct may be to see the impossibility of tracking everything down as frustrating, dispiriting,
perhaps even appalling, but it can just as well be viewed as almost unbearably exciting. We live on a
planet that has a more or less infinite capacity to surprise. What reasoning person could possibly
want it any other way?
What is nearly always most arresting in any ramble through the scattered disciplines of modern
science is realizing how many people have been willing to devote lifetimes to the most sumptuously
esoteric lines of inquiry. In one of his essays, Stephen Jay Gould notes how a hero of his named
Henry Edward Crampton spent fifty years, from 1906 to his death in 1956, quietly studying a genus
of land snails in Polynesia called Partula. Over and over, year after year, Crampton measured to the
tiniest degree— to eight decimal places— the whorls and arcs and gentle curves of numberless
Partula, compiling the results into fastidiously detailed tables. A single line

of text in a Crampton table could represent weeks of measurement and calculation.

Only slightly less devoted, and certainly more unexpected, was Alfred C. Kinsey, who became famous for his studies of human sexuality in the 1940s and 1950s. But before his mind became filled with sex, so to speak, Kinsey was an entomologist, and a dogged one at that. In one expedition lasting two years, he hiked 2,500 miles to assemble a collection of 300,000 wasps. How many stings he collected along the way is not, alas, recorded.

Something that had been puzzling me was the question of how you assured a chain of succession in these arcane fields. Clearly there cannot be many institutions in the world that require or are prepared to support specialists in barnacles or Pacific snails. As we parted at the Natural History Museum in London, I asked Richard Fortey how science ensures that when one person goes there's someone ready to take his place.

He chuckled rather heartily at my naiveté. “I’m afraid it’s not as if we have substitutes sitting on the
bench somewhere waiting to be called in to play. When a specialist retires or, even more
unfortunately, dies, that can bring a stop to things in that field, sometimes for a very long while.”

“And I suppose that’s why you value someone who spends forty-two years studying a single species
of plant, even if it doesn’t produce anything terribly new?”

“Precisely,” he said, “precisely.” And he really seemed to mean it.

24 **CELLS**

IT STARTS WITH a single cell. The first cell splits to become two and the two become four and so
on. After just forty-seven doublings, you have ten thousand trillion (10,000,000,000,000,000) cells in
your body and are ready to spring forth as a human being.*39 And every one of those cells knows
exactly what to do to preserve and nurture you from the moment of conception to your last breath.

You have no secrets from your cells. They know far more about you than

you do. Each one carries a
copy of the complete genetic code— the instruction manual for your body— so it knows not only how
to do its job but every other job in the body. Never in your life will you have to remind a cell to keep
an eye on its adenosine triphosphate levels or to find a place for the extra squirt of folic acid that's
just unexpectedly turned up. It will do that for you, and millions more things besides.

Every cell in nature is a thing of wonder. Even the simplest are far beyond the limits of human
ingenuity. To build the most basic yeast cell, for example, you would have to miniaturize about the
same number of components as are found in a Boeing 777 jetliner and fit them into a sphere just five
microns across; then somehow you would have to persuade that sphere to reproduce.

But yeast cells are as nothing compared with human cells, which are not just more varied and
complicated, but vastly more fascinating because of their complex

interactions.

Your cells are a country of ten thousand trillion citizens, each devoted in some intensively specific way to your overall well-being. There isn't a thing they don't do for you. They let you feel pleasure and form thoughts. They enable you to stand and stretch and caper. When you eat, they extract the nutrients, distribute the energy, and carry off the wastes— all those things you learned about in junior high school biology— but they also remember to make you hungry in the first place and reward you with a feeling of well-being afterward so that you won't forget to eat again. They keep your hair growing, your ears waxed, your brain quietly purring. They manage every corner of your being.

They will jump to your defense the instant you are threatened. They will unhesitatingly die for you— billions of them do so daily. And not once in all your years have you thanked even one of them. So let us take a moment now to regard them with the wonder and appreciation they deserve.

We understand a little of how cells do the things they do— how they lay down fat or manufacture insulin or engage in many of the other acts necessary to maintain a complicated entity like yourself— but only a little. You have at least 200,000 different types of protein laboring away inside you, and so far we understand what no more than about 2 percent of them do. (Others put the figure at more like 50 percent; it depends, apparently, on what you mean by "understand.")

Surprises at the cellular level turn up all the time. In nature, nitric oxide is a formidable toxin and a common component of air pollution. So scientists were naturally a little surprised when, in the mid-1980s, they found it being produced in a curiously devoted manner in human cells. Its purpose was at first a mystery, but then scientists began to find it all over the place— controlling the flow of blood and the energy levels of cells, attacking cancers and other pathogens,

regulating the sense of smell,
even assisting in penile erections. It also explained why nitroglycerine, the well-known explosive,
soothes the heart pain known as angina. (It is converted into nitric oxide in the bloodstream, relaxing
the muscle linings of vessels, allowing blood to flow more freely.) In barely the space of a decade
this one gassy substance went from extraneous toxin to ubiquitous elixir.
You possess "some few hundred" different types of cell, according to the Belgian biochemist
Christian de Duve, and they vary enormously in size and shape, from nerve cells whose filaments
can stretch to several feet to tiny, disc-shaped red blood cells to the rod-shaped photocells that help
to give us vision. They also come in a sumptuously wide range of sizes—nowhere more strikingly
than at the moment of conception, when a single beating sperm confronts an egg eighty-five
thousand times bigger than it (which rather puts the notion of male conquest into perspective). On

average, however, a human cell is about twenty microns wide— that is about two hundredths of a
millimeter— which is too small to be seen but roomy enough to hold thousands of complicated
structures like mitochondria, and millions upon millions of molecules. In the most literal way, cells
also vary in liveliness. Your skin cells are all dead. It’s a somewhat galling notion to reflect that
every inch of your surface is deceased. If you are an average-sized adult you are lugging around
about five pounds of dead skin, of which several billion tiny fragments are sloughed off each day.

Run a finger along a dusty shelf and you are drawing a pattern very largely in old skin.

Most living cells seldom last more than a month or so, but there are some notable exceptions. Liver
cells can survive for years, though the components within them may be renewed every few days.

Brain cells last as long as you do. You are issued a hundred billion or so at birth, and that is all you are ever going to get. It has been estimated that you lose five hundred of them an hour, so if you have any serious thinking to do there really isn't a moment to waste. The good news is that the individual components of your brain cells are constantly renewed so that, as with the liver cells, no part of them is actually likely to be more than about a month old. Indeed, it has been suggested that there isn't a single bit of any of us— not so much as a stray molecule— that was part of us nine years ago. It may not feel like it, but at the cellular level we are all youngsters.

The first person to describe a cell was Robert Hooke, whom we last encountered squabbling with Isaac Newton over credit for the invention of the inverse square law. Hooke achieved many things in his sixty-eight years— he was both an accomplished theoretician and a dab hand at making ingenious and useful instruments— but nothing he did brought him greater admiration than his popular book

Microphagia: or Some Physiological Descriptions of Miniature Bodies Made by Magnifying

Glasses, produced in 1665. It revealed to an enchanted public a universe of the very small that was

far more diverse, crowded, and finely structured than anyone had ever come close to imagining.

Among the microscopic features first identified by Hooke were little chambers in plants that he

called “cells” because they reminded him of monks’ cells. Hooke calculated that a one-inch square

of cork would contain 1,259,712,000 of these tiny chambers— the first appearance of such a very

large number anywhere in science. Microscopes by this time had been around for a generation or so,

but what set Hooke’s apart were their technical supremacy. They achieved magnifications of thirty

times, making them the last word in seventeenth-century optical technology.

So it came as something of a shock when just a decade later Hooke and the other members of

London’s Royal Society began to receive drawings and reports from an unlettered linen draper in

Holland employing magnifications of up to 275 times. The draper's name was Antoni van Leeuwenhoek. Though he had little formal education and no background in science, he was a perceptive and dedicated observer and a technical genius.

To this day it is not known how he got such magnificent magnifications from simple handheld devices, which were little more than modest wooden dowels with a tiny bubble of glass embedded in them, far more like magnifying glasses than what most of us think of as microscopes, but really not much like either. Leeuwenhoek made a new instrument for every experiment he performed and was extremely secretive about his techniques, though he did sometimes offer tips to the British on how they might improve their resolutions.*40

Over a period of fifty years— beginning, remarkably enough, when he was already past forty— he made almost two hundred reports to the Royal Society, all written in Low Dutch, the only tongue of which he was master. Leeuwenhoek offered no interpretations, but simply the facts of what he had found, accompanied by exquisite drawings. He sent reports on almost everything that could be usefully examined— bread mold, a bee's stinger, blood cells, teeth, hair, his own saliva, excrement, and semen (these last with fretful apologies for their unsavory nature)—nearly all of which had never been seen microscopically before.

After he reported finding "animalcules" in a sample of pepper water in 1676, the members of the Royal Society spent a year with the best devices English technology could produce searching for the "little animals" before finally getting the magnification right. What Leeuwenhoek had found were protozoa. He calculated that there were 8,280,000 of these tiny beings in a single drop of water—more than the number of people in Holland. The world teemed with life in ways and numbers that no one had previously suspected.

Inspired by Leeuwenhoek's fantastic findings, others began to peer into microscopes with such
keenness that they sometimes found things that weren't in fact there. One respected Dutch observer,
Nicolaus Hartsoecker, was convinced he saw "tiny preformed men" in sperm cells. He called the
little beings "homunculi" and for some time many people believed that all humans— indeed, all
creatures— were simply vastly inflated versions of tiny but complete precursor beings. Leeuwenhoek
himself occasionally got carried away with his enthusiasms. In one of his least successful
experiments he tried to study the explosive properties of gunpowder by observing a small blast at
close range; he nearly blinded himself in the process.

In 1683 Leeuwenhoek discovered bacteria, but that was about as far as progress could get for the
next century and a half because of the limitations of microscope technology. Not until 1831 would
anyone first see the nucleus of a cell— it was found by the Scottish botanist

Robert Brown, that

frequent but always shadowy visitor to the history of science. Brown, who lived from 1773 to 1858,

called it nucleus from the Latin nucula, meaning little nut or kernel. Not until 1839, however, did

anyone realize that all living matter is cellular. It was Theodor Schwann, a German, who had this

insight, and it was not only comparatively late, as scientific insights go, but not widely embraced at

first. It wasn’t until the 1860s, and some landmark work by Louis Pasteur in France, that it was

shown conclusively that life cannot arise spontaneously but must come from preexisting cells. The

belief became known as the “cell theory,” and it is the basis of all modern biology.

The cell has been compared to many things, from “a complex chemical refinery” (by the physicist

James Trefil) to “a vast, teeming metropolis” (the biochemist Guy Brown). A cell is both of those

things and neither. It is like a refinery in that it is devoted to chemical activity on a grand scale, and

like a metropolis in that it is crowded and busy and filled with interactions

that seem confused and

random but clearly have some system to them. But it is a much more

nightmarish place than any city

or factory that you have ever seen. To begin with there is no up or down

inside the cell (gravity

doesn't meaningfully apply at the cellular scale), and not an atom's width of

space is unused. There

is activity everywhere and a ceaseless thrum of electrical energy. You may

not feel terribly electrical,

but you are. The food we eat and the oxygen we breathe are combined in the

cells into electricity.

The reason we don't give each other massive shocks or scorch the sofa when

we sit is that it is all

happening on a tiny scale: a mere 0.1 volts traveling distances measured in

nanometers. However,

scale that up and it would translate as a jolt of twenty million volts per meter,

about the same as the

charge carried by the main body of a thunderstorm.

Whatever their size or shape, nearly all your cells are built to fundamentally the same plan: they have
an outer casing or membrane, a nucleus wherein resides the necessary genetic information to keep
you going, and a busy space between the two called the cytoplasm. The membrane is not, as most of
us imagine it, a durable, rubbery casing, something that you would need a sharp pin to prick. Rather,
it is made up of a type of fatty material known as a lipid, which has the approximate consistency "of
a light grade of machine oil," to quote Sherwin B. Nuland. If that seems surprisingly insubstantial,
bear in mind that at the microscopic level things behave differently. To anything on a molecular
scale water becomes a kind of heavy-duty gel, and a lipid is like iron.

If you could visit a cell, you wouldn't like it. Blown up to a scale at which atoms were about the size
of peas, a cell itself would be a sphere roughly half a mile across, and supported by a complex
framework of girders called the cytoskeleton. Within it, millions upon

millions of objects— some the
size of basketballs, others the size of cars— would whiz about like bullets. There wouldn't be a place
you could stand without being pummeled and ripped thousands of times every second from every
direction. Even for its full-time occupants the inside of a cell is a hazardous place. Each strand of
DNA is on average attacked or damaged once every 8.4 seconds— ten thousand times in a day— by
chemicals and other agents that whack into or carelessly slice through it, and each of these wounds
must be swiftly stitched up if the cell is not to perish.
The proteins are especially lively, spinning, pulsating, and flying into each other up to a billion times
a second. Enzymes, themselves a type of protein, dash everywhere, performing up to a thousand
tasks a second. Like greatly speeded up worker ants, they busily build and rebuild molecules, hauling
a piece off this one, adding a piece to that one. Some monitor passing proteins and mark with a

chemical those that are irreparably damaged or flawed. Once so selected, the doomed proteins proceed to a structure called a proteasome, where they are stripped down and their components used to build new proteins. Some types of protein exist for less than half an hour; others survive for weeks. But all lead existences that are inconceivably frenzied. As de Duve notes, “The molecular world must necessarily remain entirely beyond the powers of our imagination owing to the incredible speed with which things happen in it.”

But slow things down, to a speed at which the interactions can be observed, and things don’t seem quite so unnerving. You can see that a cell is just millions of objects—lysosomes, endosomes, ribosomes, ligands, peroxisomes, proteins of every size and shape—bumping into millions of other objects and performing mundane tasks: extracting energy from nutrients, assembling structures, getting rid of waste, warding off intruders, sending and receiving messages, making repairs.

Typically a cell will contain some 20,000 different types of protein, and of these about 2,000 types

will each be represented by at least 50,000 molecules. “This means,” says Nuland, “that even if we

count only those molecules present in amounts of more than 50,000 each, the total is still a very

minimum of 100 million protein molecules in each cell. Such a staggering figure gives some idea of

the swarming immensity of biochemical activity within us.”

It is all an immensely demanding process. Your heart must pump 75 gallons of blood an hour, 1,800

gallons every day, 657,000 gallons in a year— that’s enough to fill four Olympic-sized swimming

pools— to keep all those cells freshly oxygenated. (And that’s at rest. During exercise the rate can

increase as much as sixfold.) The oxygen is taken up by the mitochondria. These are the cells’ power

stations, and there are about a thousand of them in a typical cell, though the number varies considerably depending on what a cell does and how much energy it requires.

You may recall from an earlier chapter that the mitochondria are thought to have originated as captive bacteria and that they now live essentially as lodgers in our cells, preserving their own genetic instructions, dividing to their own timetable, speaking their own language. You may also recall that we are at the mercy of their goodwill. Here's why. Virtually all the food and oxygen you take into your body are delivered, after processing, to the mitochondria, where they are converted into a molecule called adenosine triphosphate, or ATP.

You may not have heard of ATP, but it is what keeps you going. ATP molecules are essentially little battery packs that move through the cell providing energy for all the cell's processes, and you get through a lot of it. At any given moment, a typical cell in your body will have about one billion ATP molecules in it, and in two minutes every one of them will have been drained dry and another billion will have taken their place. Every day you produce and use up a volume of ATP equivalent to about half your body weight. Feel the warmth of your skin. That's your ATP at work.

When cells are no longer needed, they die with what can only be called great dignity. They take down all the struts and buttresses that hold them together and quietly devour their component parts.

The process is known as apoptosis or programmed cell death. Every day billions of your cells die for your benefit and billions of others clean up the mess. Cells can also die violently— for instance, when infected— but mostly they die because they are told to. Indeed, if not told to live— if not given some kind of active instruction from another cell— cells automatically kill themselves. Cells need a lot of reassurance.

When, as occasionally happens, a cell fails to expire in the prescribed manner, but rather begins to divide and proliferate wildly, we call the result cancer. Cancer cells are really just confused cells.

Cells make this mistake fairly regularly, but the body has elaborate mechanisms for dealing with it. It is only very rarely that the process spirals out of control. On average, humans suffer one fatal malignancy for each 100 million billion cell divisions. Cancer is bad luck in every possible sense of the term.

The wonder of cells is not that things occasionally go wrong, but that they manage everything so smoothly for decades at a stretch. They do so by constantly sending and monitoring streams of messages— a cacophony of messages— from all around the body: instructions, queries, corrections, requests for assistance, updates, notices to divide or expire. Most of these signals arrive by means of couriers called hormones, chemical entities such as insulin, adrenaline, estrogen, and testosterone that convey information from remote outposts like the thyroid and endocrine glands. Still other messages arrive by telegraph from the brain or from regional centers in a process called paracrine signaling. Finally, cells communicate directly with their neighbors to make sure their actions are coordinated.

What is perhaps most remarkable is that it is all just random frantic action, a sequence of endless encounters directed by nothing more than elemental rules of attraction and repulsion. There is clearly no thinking presence behind any of the actions of the cells. It all just happens, smoothly and repeatedly and so reliably that seldom are we even conscious of it, yet somehow all this produces not just order within the cell but a perfect harmony right across the organism. In ways that we have barely begun to understand, trillions upon trillions of reflexive chemical reactions add up to a mobile, thinking, decision-making you— or, come to that, a rather less reflective but still incredibly organized dung beetle. Every living thing, never forget, is a wonder of atomic engineering.

Indeed, some organisms that we think of as primitive enjoy a level of cellular organization that makes our own look carelessly pedestrian. Disassemble the cells of a sponge (by passing them through a sieve, for instance), then dump them into a solution, and they will find their way back together and build themselves into a sponge again. You can do this to them over and over, and they will doggedly reassemble because, like you and me and every other living thing, they have one overwhelming impulse: to continue to be.

And that's because of a curious, determined, barely understood molecule that is itself not alive and for the most part doesn't do anything at all. We call it DNA, and to begin to understand its supreme importance to science and to us we need to go back 160 years or so to Victorian England and to the moment when the naturalist Charles Darwin had what has been called "the

single best idea that
anyone has ever had"— and then, for reasons that take a little explaining,
locked it away in a drawer
for the next fifteen years.

25 DARWIN'S SINGULAR NOTION

IN THE LATE summer or early autumn of 1859, Whitwell Elwin, editor of
the respected British
journal the Quarterly Review, was sent an advance copy of a new book by
the naturalist Charles
Darwin. Elwin read the book with interest and agreed that it had merit, but
feared that the subject
matter was too narrow to attract a wide audience. He urged Darwin to write
a book about pigeons
instead. "Everyone is interested in pigeons," he observed helpfully.
Elwin's sage advice was ignored, and On the Origin of Species by Means of
Natural Selection, or the
Preservation of Favoured Races in the Struggle for Life was published in
late November 1859,
priced at fifteen shillings. The first edition of 1,250 copies sold out on the
first day. It has never been

out of print, and scarcely out of controversy, in all the time since— not bad going for a man whose principal other interest was earthworms and who, but for a single impetuous decision to sail around the world, would very probably have passed his life as an anonymous country parson known for, well, for an interest in earthworms.

Charles Robert Darwin was born on February 12, 1809,*41 in Shrewsbury, a sedate market town in the west Midlands of England. His father was a prosperous and well-regarded physician. His mother, who died when Charles was only eight, was the daughter of Josiah Wedgwood, of pottery fame.

Darwin enjoyed every advantage of upbringing, but continually pained his widowed father with his lackluster academic performance. “You care for nothing but shooting, dogs, and rat-catching, and you will be a disgrace to yourself and all your family,” his father wrote in a line that nearly always appears just about here in any review of Darwin’s early life. Although his inclination was to natural history, for his father's sake he tried to study medicine at Edinburgh University but couldn't bear the blood and suffering. The experience of witnessing an operation on an understandably distressed child— this was in the days before anesthetics, of course— left him permanently traumatized. He tried law instead, but found that insupportably dull and finally managed, more or less by default, to acquire a degree in divinity from Cambridge.

A life in a rural vicarage seemed to await him when from out of the blue there came a more tempting offer. Darwin was invited to sail on the naval survey ship HMS Beagle, essentially as dinner company for the captain, Robert FitzRoy, whose rank precluded his socializing with anyone other than a gentleman. FitzRoy, who was very odd, chose Darwin in part because he liked the shape of Darwin's nose. (It betokened depth of character, he believed.) Darwin was not FitzRoy's first choice, but got the nod when FitzRoy's preferred companion dropped out. From a twenty-first-century perspective the two men's most striking joint feature was their extreme youthfulness. At the time of sailing, FitzRoy was only twenty-three, Darwin just twenty-two.

FitzRoy's formal assignment was to chart coastal waters, but his hobby—passion really— was to seek out evidence for a literal, biblical interpretation of creation. That Darwin was trained for the ministry was central to FitzRoy's decision to have him aboard. That Darwin subsequently proved to be not only liberal of view but less than wholeheartedly devoted to Christian fundamentals became a source of lasting friction between them.

Darwin's time aboard HMS Beagle, from 1831 to 1836, was obviously the formative experience of his life, but also one of the most trying. He and his captain shared a small cabin, which can't have been easy as FitzRoy was subject to fits of fury followed by spells of simmering resentment. He and

Darwin constantly engaged in quarrels, some “bordering on insanity,” as Darwin later recalled.

Ocean voyages tended to become melancholy undertakings at the best of times— the previous

captain of the Beagle had put a bullet through his brain during a moment of lonely gloom— and

FitzRoy came from a family well known for a depressive instinct. His uncle, Viscount Castlereagh,

had slit his throat the previous decade while serving as Chancellor of the Exchequer. (FitzRoy would

himself commit suicide by the same method in 1865.) Even in his calmer moods, FitzRoy proved

strangely unknowable. Darwin was astounded to learn upon the conclusion of their voyage that

almost at once FitzRoy married a young woman to whom he had long been betrothed. In five years

in Darwin’s company, he had not once hinted at an attachment or even mentioned her name.

In every other respect, however, the Beagle voyage was a triumph. Darwin experienced adventure enough to last a lifetime and accumulated a hoard of specimens sufficient to make his reputation and keep him occupied for years. He found a magnificent trove of giant ancient fossils, including the finest Megatherium known to date; survived a lethal earthquake in Chile; discovered a new species of dolphin (which he dutifully named Delphinus fitzroyi); conducted diligent and useful geological investigations throughout the Andes; and developed a new and much-admired theory for the formation of coral atolls, which suggested, not coincidentally, that atolls could not form in less than a million years— the first hint of his long-standing attachment to the extreme antiquity of earthly processes. In 1836, aged twenty-seven, he returned home after being away for five years and two days. He never left England again.

One thing Darwin didn't do on the voyage was propound the theory (or even a theory) of evolution.

For a start, evolution as a concept was already decades old by the 1830s.

Darwin’s own grandfather,
Erasmus, had paid tribute to evolutionary principles in a poem of inspired mediocrity called “The
Temple of Nature” years before Charles was even born. It wasn’t until the younger Darwin was back
in England and read Thomas Malthus’s Essay on the Principle of Population (which proposed that
increases in food supply could never keep up with population growth for mathematical reasons) that
the idea began to percolate through his mind that life is a perpetual struggle and that natural selection
was the means by which some species prospered while others failed. Specifically what Darwin saw
was that all organisms competed for resources, and those that had some innate advantage would
prosper and pass on that advantage to their offspring. By such means would species continuously
improve.

It seems an awfully simple idea— it is an awfully simple idea— but it explained a great deal, and

Darwin was prepared to devote his life to it. “How stupid of me not to have thought of it!” T. H.
Huxley cried upon reading On the Origin of Species. It is a view that has been echoed ever since.
Interestingly, Darwin didn’t use the phrase “survival of the fittest” in any of his work (though he did
express his admiration for it). The expression was coined five years after the publication of On the
Origin of Species by Herbert Spencer in Principles of Biology in 1864. Nor did he employ the word
evolution in print until the sixth edition of Origin (by which time its use had become too widespread
to resist), preferring instead “descent with modification.” Nor, above all, were his conclusions in any
way inspired by his noticing, during his time in the Galápagos Islands, an interesting diversity in the
beaks of finches. The story as conventionally told (or at least as frequently remembered by many of
us) is that Darwin, while traveling from island to island, noticed that the finches’ beaks on each

island were marvelously adapted for exploiting local resources— that on one island beaks were sturdy and short and good for cracking nuts, while on the next island beaks were perhaps long and thin and well suited for winkling food out of crevices— and it was this that set him to thinking that perhaps the birds had not been created this way, but had in a sense created themselves.

In fact, the birds had created themselves, but it wasn't Darwin who noticed it. At the time of the Beagle voyage, Darwin was fresh out of college and not yet an accomplished naturalist and so failed to see that the Galápagos birds were all of a type. It was his friend the ornithologist John Gould who realized that what Darwin had found was lots of finches with different talents. Unfortunately, in his inexperience Darwin had not noted which birds came from which islands. (He had made a similar error with tortoises.) It took years to sort the muddles out.

Because of these oversights, and the need to sort through crates and crates of other Beagle

specimens, it wasn't until 1842, six years after his return to England, that

Darwin finally began to

sketch out the rudiments of his new theory. These he expanded into a

230-page "sketch" two years

later. And then he did an extraordinary thing: he put his notes away and for

the next decade and a

half busied himself with other matters. He fathered ten children, devoted

nearly eight years to

writing an exhaustive opus on barnacles ("I hate a barnacle as no man ever

did before," he sighed,

understandably, upon the work's conclusion), and fell prey to strange

disorders that left him

chronically listless, faint, and "flurried," as he put it. The symptoms nearly

always included a terrible

nausea and generally also incorporated palpitations, migraines, exhaustion,

trembling, spots before

the eyes, shortness of breath, "swimming of the head," and, not surprisingly,

depression.

The cause of the illness has never been established, but the most romantic

and perhaps likely of the
many suggested possibilities is that he suffered from Chagas's disease, a lingering tropical malady
that he could have acquired from the bite of a Benchuga bug in South America. A more prosaic
explanation is that his condition was psychosomatic. In either case, the misery was not. Often he
could work for no more than twenty minutes at a stretch, sometimes not that. Much of the rest of his time was devoted to a series of increasingly desperate treatments— icy plunge
baths, dousings in vinegar, draping himself with "electric chains" that subjected him to small jolts of
current. He became something of a hermit, seldom leaving his home in Kent, Down House. One of
his first acts upon moving to the house was to erect a mirror outside his study window so that he
could identify, and if necessary avoid, callers.

Darwin kept his theory to himself because he well knew the storm it would cause. In 1844, the year
he locked his notes away, a book called Vestiges of the Natural History of

Creation roused much of
the thinking world to fury by suggesting that humans might have evolved from lesser primates
without the assistance of a divine creator. Anticipating the outcry, the author had taken careful steps
to conceal his identity, which he kept a secret from even his closest friends for the next forty years.
Some wondered if Darwin himself might be the author. Others suspected Prince Albert. In fact, the
author was a successful and generally unassuming Scottish publisher named Robert Chambers whose
reluctance to reveal himself had a practical dimension as well as a personal one: his firm was a
leading publisher of Bibles. Vestiges was warmly blasted from pulpits throughout Britain and far
beyond, but also attracted a good deal of more scholarly ire. The Edinburgh Review devoted nearly
an entire issue— eighty-five pages— to pulling it to pieces. Even T. H. Huxley, a believer in
evolution, attacked the book with some venom, unaware that the author was

a friend.*42

Darwin’s manuscript might have remained locked away till his death but for an alarming blow that arrived from the Far East in the early summer of 1858 in the form of a packet containing a friendly letter from a young naturalist named Alfred Russel Wallace and the draft of a paper, On the Tendency of Varieties to Depart Indefinitely from the Original Type, outlining a theory of natural selection that was uncannily similar to Darwin’s secret jottings. Even some of the phrasing echoed Darwin’s own. “I never saw a more striking coincidence,” Darwin reflected in dismay. “If Wallace had my manuscript sketch written out in 1842, he could not have made a better short abstract.”

Wallace didn’t drop into Darwin’s life quite as unexpectedly as is sometimes suggested. The two were already corresponding, and Wallace had more than once generously sent Darwin specimens that he thought might be of interest. In the process of these exchanges

Darwin had discreetly warned Wallace that he regarded the subject of species creation as his own territory. "This summer will make the 20th year (!) since I opened my first note-book, on the question of how & in what way do species & varieties differ from each other," he had written to Wallace some time earlier. "I am now preparing my work for publication," he added, even though he wasn't really. In any case, Wallace failed to grasp what Darwin was trying to tell him, and of course he could have no idea that his own theory was so nearly identical to one that Darwin had been evolving, as it were, for two decades.

Darwin was placed in an agonizing quandary. If he rushed into print to preserve his priority, he would be taking advantage of an innocent tip-off from a distant admirer. But if he stepped aside, as gentlemanly conduct arguably required, he would lose credit for a theory that he had independently propounded. Wallace's theory was, by Wallace's own admission, the result of a flash of insight;

Darwin’s was the product of years of careful, plodding, methodical thought. It was all crushingly

unfair.

To compound his misery, Darwin’s youngest son, also named Charles, had contracted scarlet fever

and was critically ill. At the height of the crisis, on June 28, the child died. Despite the distraction of

his son’s illness, Darwin found time to dash off letters to his friends Charles Lyell and Joseph

Hooker, offering to step aside but noting that to do so would mean that all his work, “whatever it

may amount to, will be smashed.” Lyell and Hooker came up with the compromise solution of

presenting a summary of Darwin’s and Wallace’s ideas together. The venue they settled on was a

meeting of the Linnaean Society, which at the time was struggling to find its way back into fashion

as a seat of scientific eminence. On July 1, 1858, Darwin’s and Wallace’s theory was unveiled to the world. Darwin himself was not present. On the day of the meeting, he and his wife were burying their son.

The Darwin–Wallace presentation was one of seven that evening— one of the others was on the flora of Angola— and if the thirty or so people in the audience had any idea that they were witnessing the scientific highlight of the century, they showed no sign of it. No discussion followed. Nor did the event attract much notice elsewhere. Darwin cheerfully later noted that only one person, a Professor Haughton of Dublin, mentioned the two papers in print and his conclusion was "that all that was new in them was false, and what was true was old."

Wallace, still in the distant East, learned of these maneuverings long after the event, but was remarkably equable and seemed pleased to have been included at all. He even referred to the theory forever after as "Darwinism." Much less amenable to Darwin's claim of priority was a Scottish

gardener named Patrick Matthew who had, rather remarkably, also come up with the principles of
natural selection— in fact, in the very year that Darwin had set sail in the Beagle. Unfortunately,
Matthew had published these views in a book called Naval Timber and Arboriculture, which had
been missed not just by Darwin, but by the entire world. Matthew kicked up in a lively manner, with
a letter to Gardener’s Chronicle, when he saw Darwin gaining credit everywhere for an idea that
really was his. Darwin apologized without hesitation, though he did note for the record: “I think that
no one will feel surprised that neither I, nor apparently any other naturalist, has heard of Mr.
Matthew’s views, considering how briefly they are given, and they appeared in the Appendix to a
work on Naval Timber and Arboriculture.”
Wallace continued for another fifty years as a naturalist and thinker, occasionally a very good one,
but increasingly fell from scientific favor by taking up dubious interests such

as spiritualism and the

possibility of life existing elsewhere in the universe. So the theory became,

essentially by default,

Darwin's alone.

Darwin never ceased being tormented by his ideas. He referred to himself as

"the Devil's Chaplain"

and said that revealing the theory felt "like confessing a murder." Apart from

all else, he knew it

deeply pained his beloved and pious wife. Even so, he set to work at once

expanding his manuscript

into a book-length work. Provisionally he called it An Abstract of an Essay

on the Origin of Species

and Varieties through Natural Selection— a title so tepid and tentative that

his publisher, John

Murray, decided to issue just five hundred copies. But once presented with

the manuscript, and a

slightly more arresting title, Murray reconsidered and increased the initial

print run to 1,250.

On the Origin of Species was an immediate commercial success, but rather

less of a critical one.

Darwin's theory presented two intractable difficulties. It needed far more time than Lord Kelvin was willing to concede, and it was scarcely supported by fossil evidence. Where, asked Darwin's more thoughtful critics, were the transitional forms that his theory so clearly called for? If new species were continuously evolving, then there ought to be lots of intermediate forms scattered across the fossil record, but there were not.*43 In fact, the record as it existed then (and for a long time afterward) showed no life at all right up to the moment of the famous Cambrian explosion.

But now here was Darwin, without any evidence, insisting that the earlier seas must have had abundant life and that we just hadn't found it yet because, for whatever reason, it hadn't been preserved. It simply could not be otherwise, Darwin maintained. "The case at present must remain inexplicable; and may be truly urged as a valid argument against the views here entertained," he allowed most candidly, but he refused to entertain an alternative possibility. By way of explanation he speculated— inventively but incorrectly— that perhaps the Precambrian seas had been too clear to lay down sediments and thus had preserved no fossils.

Even Darwin’s closest friends were troubled by the blitheness of some of his assertions. Adam Sedgwick, who had taught Darwin at Cambridge and taken him on a geological tour of Wales in 1831, said the book gave him “more pain than pleasure.” Louis Agassiz dismissed it as poor conjecture. Even Lyell concluded gloomily: “Darwin goes too far.”

T. H. Huxley disliked Darwin’s insistence on huge amounts of geological time because he was a saltationist, which is to say a believer in the idea that evolutionary changes happen not gradually but suddenly. Saltationists (the word comes from the Latin for “leap”) couldn’t accept that complicated organs could ever emerge in slow stages. What good, after all, is one-tenth of a wing or half an eye?

Such organs, they thought, only made sense if they appeared in a finished state.

The belief was surprising in as radical a spirit as Huxley because it closely recalled a very conservative religious notion first put forward by the English theologian William Paley in 1802 and known as argument from design. Paley contended that if you found a pocket watch on the ground, even if you had never seen such a thing before, you would instantly perceive that it had been made by an intelligent entity. So it was, he believed, with nature: its complexity was proof of its design.

The notion was a powerful one in the nineteenth century, and it gave Darwin trouble too. “The eye to this day gives me a cold shudder,” he acknowledged in a letter to a friend. In the Origin he conceded that it “seems, I freely confess, absurd in the highest possible degree” that natural selection could produce such an instrument in gradual steps.

Even so, and to the unending exasperation of his supporters, Darwin not only insisted that all change

was gradual, but in nearly every edition of Origin he stepped up the amount

of time he supposed

necessary to allow evolution to progress, which pushed his ideas

increasingly out of favor.

“Eventually,” according to the scientist and historian Jeffrey Schwartz,

“Darwin lost virtually all the

support that still remained among the ranks of fellow natural historians and

geologists.”

Ironically, considering that Darwin called his book On the Origin of Species,

the one thing he

couldn’t explain was how species originated. Darwin’s theory suggested a

mechanism for how a

species might become stronger or better or faster— in a word, fitter— but

gave no indication of how it

might throw up a new species. A Scottish engineer, Fleeming Jenkin,

considered the problem and

noted an important flaw in Darwin’s argument. Darwin believed that any

beneficial trait that arose in

one generation would be passed on to subsequent generations, thus strengthening the species.

Jenkin pointed out that a favorable trait in one parent wouldn’t become dominant in succeeding generations, but in fact would be diluted through blending. If you pour whiskey into a tumbler of water, you don’t make the whiskey stronger, you make it weaker. And if you pour that dilute solution into another glass of water, it becomes weaker still. In the same way, any favorable trait introduced by one parent would be successively watered down by subsequent matings until it ceased to be apparent at all. Thus Darwin’s theory was not a recipe for change, but for constancy. Lucky flukes might arise from time to time, but they would soon vanish under the general impulse to bring everything back to a stable mediocrity. If natural selection were to work, some alternative, unconsidered mechanism was required.

Unknown to Darwin and everyone else, eight hundred miles away in a tranquil corner of Middle

Europe a retiring monk named Gregor Mendel was coming up with the solution.

Mendel was born in 1822 to a humble farming family in a backwater of the Austrian empire in what
is now the Czech Republic. Schoolbooks once portrayed him as a simple but observant provincial
monk whose discoveries were largely serendipitous— the result of noticing some interesting traits of
inheritance while pottering about with pea plants in the monastery's kitchen garden. In fact, Mendel
was a trained scientist— he had studied physics and mathematics at the Olmütz Philosophical
Institute and the University of Vienna— and he brought scientific discipline to all he did. Moreover,
the monastery at Brno where he lived from 1843 was known as a learned institution. It had a library
of twenty thousand books and a tradition of careful scientific investigation.

Before embarking on his experiments, Mendel spent two years preparing his control specimens,
seven varieties of pea, to make sure they bred true. Then, helped by two

full-time assistants, he repeatedly bred and crossbred hybrids from thirty thousand pea plants. It was delicate work, requiring them to take the most exacting pains to avoid accidental cross-fertilization and to note every slight variation in the growth and appearance of seeds, pods, leaves, stems, and flowers.

Mendel knew what he was doing.

He never used the word gene— it wasn't coined until 1913, in an English medical dictionary— though he did invent the terms dominant and recessive. What he established was that every seed contained two "factors" or "elemente," as he called them— a dominant one and a recessive one— and these factors, when combined, produced predictable patterns of inheritance.

The results he converted into precise mathematical formulae. Altogether Mendel spent eight years on the experiments, then confirmed his results with similar experiments on flowers, corn, and other plants. If anything, Mendel was too scientific in his approach, for when he presented his findings at the February and March meetings of the Natural History Society of Brno in 1865, the audience of about forty listened politely but was conspicuously unmoved, even though the breeding of plants was a matter of great practical interest to many of the members.

When Mendel's report was published, he eagerly sent a copy to the great Swiss botanist Karl-Wilhelm von Nägeli, whose support was more or less vital for the theory's prospects. Unfortunately, Nägeli failed to perceive the importance of what Mendel had found. He suggested that Mendel try breeding hawkweed. Mendel obediently did as Nägeli suggested, but quickly realized that hawkweed had none of the requisite features for studying heritability. It was evident to him that Nägeli had not read the paper closely, or possibly at all. Frustrated, Mendel retired from investigating heritability and spent the rest of his life growing outstanding vegetables and studying bees, mice, and sunspots, among much else. Eventually he was made abbot.

Mendel’s findings weren’t quite as widely ignored as is sometimes suggested. His study received a glowing entry in the Encyclopaedia Britannica— then a more leading record of scientific thought than now— and was cited repeatedly in an important paper by the German Wilhelm Olbers Focke.

Indeed, it was because Mendel’s ideas never entirely sank below the waterline of scientific thought that they were so easily recovered when the world was ready for them.

Together, without realizing it, Darwin and Mendel laid the groundwork for all of life sciences in the twentieth century. Darwin saw that all living things are connected, that ultimately they “trace their ancestry to a single, common source,” while Mendel’s work provided the mechanism to explain how that could happen. The two men could easily have helped each other. Mendel owned a German edition of the Origin of Species, which he is known to have read, so he must have realized the applicability of his work to Darwin's, yet he appears to have made no effort to get in touch. And

Darwin for his part is known to have studied Focke's influential paper with its repeated references to

Mendel's work, but didn't connect them to his own studies.

The one thing everyone thinks featured in Darwin's argument, that humans are descended from apes,

didn't feature at all except as one passing allusion. Even so, it took no great leap of imagination to

see the implications for human development in Darwin's theories, and it became an immediate

talking point.

The showdown came on Saturday, June 30, 1860, at a meeting of the British Association for the

Advancement of Science in Oxford. Huxley had been urged to attend by Robert Chambers, author of

Vestiges of the Natural History of Creation, though he was still unaware of Chambers's connection

to that contentious tome. Darwin, as ever, was absent. The meeting was held at the Oxford

Zoological Museum. More than a thousand people crowded into the chamber; hundreds more were turned away. People knew that something big was going to happen, though they had first to wait while a slumber-inducing speaker named John William Draper of New York University bravely slogged his way through two hours of introductory remarks on “The Intellectual Development of Europe Considered with Reference to the Views of Mr. Darwin.” Finally, the Bishop of Oxford, Samuel Wilberforce, rose to speak. Wilberforce had been briefed (or so it is generally assumed) by the ardent anti-Darwinian Richard Owen, who had been a guest in his home the night before. As nearly always with events that end in uproar, accounts vary widely on what exactly transpired. In the most popular version, Wilberforce, when properly in flow, turned to Huxley with a dry smile and demanded of him whether he claimed attachment to the apes by way of his grandmother or grandfather. The remark was doubtless intended as a quip, but it came across as an icy challenge. According to his own account, Huxley turned to his neighbor and whispered, "The Lord hath delivered him into my hands," then rose with a certain relish. Others, however, recalled a Huxley trembling with fury and indignation. At all events, Huxley declared that he would rather claim kinship to an ape than to someone who used his eminence to propound uninformed twaddle in what was supposed to be a serious scientific forum. Such a riposte was a scandalous impertinence, as well as an insult to Wilberforce's office, and the proceedings instantly collapsed in tumult. A Lady Brewster fainted. Robert FitzRoy, Darwin's companion on the Beagle twenty-five years before, wandered through the hall with a Bible held aloft, shouting, "The Book, the Book." (He was at the conference to present a paper on storms in his capacity as head of the newly created Meteorological Department.) Interestingly, each side afterward claimed to have routed the other.

Darwin did eventually make his belief in our kinship with the apes explicit in The Descent of Man in 1871. The conclusion was a bold one since nothing in the fossil record supported such a notion. The only known early human remains of that time were the famous Neandertal bones from Germany and a few uncertain fragments of jawbones, and many respected authorities refused to believe even in their antiquity. The Descent of Man was altogether a more controversial book, but by the time of its appearance the world had grown less excitable and its arguments caused much less of a stir.

For the most part, however, Darwin passed his twilight years with other projects, most of which touched only tangentially on questions of natural selection. He spent amazingly long periods picking through bird droppings, scrutinizing the contents in an attempt to understand how seeds spread between continents, and spent years more studying the behavior of worms.

One of his experiments was to play the piano to them, not to amuse them but to study the effects on them of sound and vibration. He was the first to realize how vitally important worms are to soil fertility. “It may be doubted whether there are many other animals which have played so important a part in the history of the world,” he wrote in his masterwork on the subject, The Formation of Vegetable Mould Through the Action of Worms (1881), which was actually more popular than On the Origin of Species had ever been. Among his other books were On the Various Contrivances by Which British and Foreign Orchids Are Fertilised by Insects (1862), Expressions of the Emotions in Man and Animals (1872), which sold almost 5,300 copies on its first day, The Effects of Cross and Self Fertilization in the Vegetable Kingdom (1876)— a subject that came improbably close to Mendel’s own work, without attaining anything like the same insights— and his last book, The Power of

Movement in Plants. Finally, but not least, he devoted much effort to

studying the consequences of

inbreeding— a matter of private interest to him. Having married his own

cousin, Darwin glumly

suspected that certain physical and mental frailties among his children arose

from a lack of diversity

in his family tree.

Darwin was often honored in his lifetime, but never for On the Origin of

Species or Descent of Man.

When the Royal Society bestowed on him the prestigious Copley Medal it

was for his geology,

zoology, and botany, not evolutionary theories, and the Linnaean Society

was similarly pleased to

honor Darwin without embracing his radical notions. He was never knighted,

though he was buried

in Westminster Abbey— next to Newton. He died at Down in April 1882.

Mendel died two years

later.

Darwin's theory didn't really gain widespread acceptance until the 1930s and 1940s, with the

advance of a refined theory called, with a certain hauteur, the Modern

Synthesis, combining

Darwin’s ideas with those of Mendel and others. For Mendel, appreciation

was also posthumous,

though it came somewhat sooner. In 1900, three scientists working

separately in Europe

rediscovered Mendel’s work more or less simultaneously. It was only

because one of them, a

Dutchman named Hugo de Vries, seemed set to claim Mendel’s insights as

his own that a rival made

it noisily clear that the credit really lay with the forgotten monk.

The world was almost ready, but not quite, to begin to understand how we

got here— how we made

each other. It is fairly amazing to reflect that at the beginning of the

twentieth century, and for some

years beyond, the best scientific minds in the world couldn’t actually tell

you where babies came

from.

And these, you may recall, were men who thought science was nearly at an end.

26 **THE STUFF OF LIFE**

IF YOUR TWO parents hadn't bonded just when they did— possibly to the second, possibly to the nanosecond— you wouldn't be here. And if their parents hadn't bonded in a precisely timely manner, you wouldn't be here either. And if their parents hadn't done likewise, and their parents before them, and so on, obviously and indefinitely, you wouldn't be here.

Push backwards through time and these ancestral debts begin to add up. Go back just eight generations to about the time that Charles Darwin and Abraham Lincoln were born, and already there are over 250 people on whose timely couplings your existence depends. Continue further, to the time of Shakespeare and the Mayflower Pilgrims, and you have no fewer than 16,384 ancestors earnestly exchanging genetic material in a way that would, eventually and miraculously, result in you.

At twenty generations ago, the number of people procreating on your behalf has risen to 1,048,576.

Five generations before that, and there are no fewer than 33,554,432 men and women on whose devoted couplings your existence depends. By thirty generations ago, your total number of forebears— remember, these aren't cousins and aunts and other incidental relatives, but only parents and parents of parents in a line leading ineluctably to you— is over one billion (1,073,741,824, to be precise). If you go back sixty-four generations, to the time of the Romans, the number of people on whose cooperative efforts your eventual existence depends has risen to approximately 1,000,000,000,000,000,000, which is several thousand times the total number of people who have ever lived.

Clearly something has gone wrong with our math here. The answer, it may interest you to learn, is that your line is not pure. You couldn't be here without a little incest—

actually quite a lot of incest—
albeit at a genetically discreet remove. With so many millions of ancestors in your background, there
will have been many occasions when a relative from your mother's side of the family procreated
with some distant cousin from your father's side of the ledger. In fact, if you are in a partnership now
with someone from your own race and country, the chances are excellent that you are at some level
related. Indeed, if you look around you on a bus or in a park or café or any crowded place, most of
the people you see are very probably relatives. When someone boasts to you that he is descended
from William the Conqueror or the Mayflower Pilgrims, you should answer at once: "Me, too!" In
the most literal and fundamental sense we are all family.

We are also uncannily alike. Compare your genes with any other human being's and on average they
will be about 99.9 percent the same. That is what makes us a species. The tiny differences in that

remaining 0.1 percent— “roughly one nucleotide base in every thousand,” to quote the British
geneticist and recent Nobel laureate John Sulston— are what endow us with our individuality. Much
has been made in recent years of the unraveling of the human genome. In fact, there is no such thing
as “the” human genome. Every human genome is different. Otherwise we would all be identical. It is
the endless recombinations of our genomes— each nearly identical, but not quite— that make us what
we are, both as individuals and as a species.

But what exactly is this thing we call the genome? And what, come to that, are genes? Well, start
with a cell again. Inside the cell is a nucleus, and inside each nucleus are the chromosomes— fortysix
little bundles of complexity, of which twenty-three come from your mother and twenty-three
from your father. With a very few exceptions, every cell in your body— 99.999 percent of them,
say— carries the same complement of chromosomes. (The exceptions are

red blood cells, some
immune system cells, and egg and sperm cells, which for various
organizational reasons don't carry
the full genetic package.) Chromosomes constitute the complete set of
instructions necessary to
make and maintain you and are made of long strands of the little wonder
chemical called
deoxyribonucleic acid or DNA— "the most extraordinary molecule on
Earth," as it has been called.

DNA exists for just one reason— to create more DNA— and you have a lot
of it inside you: about six
feet of it squeezed into almost every cell. Each length of DNA comprises
some 3.2 billion letters of
coding, enough to provide 103,480,000,000 possible combinations,
"guaranteed to be unique against
all conceivable odds," in the words of Christian de Duve. That's a lot of
possibility— a one followed
by more than three billion zeroes. "It would take more than five thousand
average-size books just to
print that figure," notes de Duve. Look at yourself in the mirror and reflect

upon the fact that you are

beholding ten thousand trillion cells, and that almost every one of them

holds two yards of densely

compacted DNA, and you begin to appreciate just how much of this stuff

you carry around with you.

If all your DNA were woven into a single fine strand, there would be enough

of it to stretch from the

Earth to the Moon and back not once or twice but again and again.

Altogether, according to one

calculation, you may have as much as twenty million kilometers of DNA

bundled up inside you.

Your body, in short, loves to make DNA and without it you couldn't live.

Yet DNA is not itself

alive. No molecule is, but DNA is, as it were, especially unalive. It is

"among the most nonreactive,

chemically inert molecules in the living world," in the words of the

geneticist Richard Lewontin.

That is why it can be recovered from patches of long-dried blood or semen

in murder investigations

and coaxed from the bones of ancient Neandertals. It also explains why it

took scientists so long to
work out how a substance so mystifyingly low key— so, in a word, lifeless— could be at the very
heart of life itself.

As a known entity, DNA has been around longer than you might think. It was discovered as far back
as 1869 by Johann Friedrich Miescher, a Swiss scientist working at the University of Tübingen in
Germany. While delving microscopically through the pus in surgical bandages, Miescher found a
substance he didn’t recognize and called it nuclein (because it resided in the nuclei of cells). At the
time, Miescher did little more than note its existence, but nuclein clearly remained on his mind, for
twenty-three years later in a letter to his uncle he raised the possibility that such molecules could be
the agents behind heredity. This was an extraordinary insight, but one so far in advance of the day’s
scientific requirements that it attracted no attention at all.

For most of the next half century the common assumption was that the

material— now called
deoxyribonucleic acid, or DNA— had at most a subsidiary role in matters of heredity. It was too
simple. It had just four basic components, called nucleotides, which was like having an alphabet of
just four letters. How could you possibly write the story of life with such a rudimentary alphabet?
(The answer is that you do it in much the way that you create complex messages with the simple dots
and dashes of Morse code— by combining them.) DNA didn't do anything at all, as far as anyone
could tell. It just sat there in the nucleus, possibly binding the chromosome in some way or adding a
splash of acidity on command or fulfilling some other trivial task that no one had yet thought of. The
necessary complexity, it was thought, had to exist in proteins in the nucleus.
There were, however, two problems with dismissing DNA. First, there was so much of it: two yards
in nearly every nucleus, so clearly the cells esteemed it in some important way. On top of this, it kept

turning up, like the suspect in a murder mystery, in experiments. In two studies in particular, one involving the Pneumonococcus bacterium and another involving bacteriophages (viruses that infect bacteria), DNA betrayed an importance that could only be explained if its role were more central than prevailing thought allowed. The evidence suggested that DNA was somehow involved in the making of proteins, a process vital to life, yet it was also clear that proteins were being made outside the nucleus, well away from the DNA that was supposedly directing their assembly.

No one could understand how DNA could possibly be getting messages to the proteins. The answer, we now know, was RNA, or ribonucleic acid, which acts as an interpreter between the two. It is a notable oddity of biology that DNA and proteins don't speak the same language. For almost four billion years they have been the living world's great double act, and yet they answer to mutually incompatible codes, as if one spoke Spanish and the other Hindi. To communicate they need a mediator in the form of RNA. Working with a kind of chemical clerk called a ribosome, RNA translates information from a cell's DNA into terms proteins can understand and act upon.

However, by the early 1900s, where we resume our story, we were still a very long way from understanding that, or indeed almost anything else to do with the confused business of heredity.

Clearly there was a need for some inspired and clever experimentation, and happily the age produced a young person with the diligence and aptitude to undertake it. His name was Thomas Hunt Morgan, and in 1904, just four years after the timely rediscovery of Mendel's experiments with pea plants and still almost a decade before gene would even become a word, he began to do remarkably dedicated things with chromosomes.

Chromosomes had been discovered by chance in 1888 and were so called

because they readily
absorbed dye and thus were easy to see under the microscope. By the turn of the twentieth century it
was strongly suspected that they were involved in the passing on of traits, but no one knew how, or
even really whether, they did this.

Morgan chose as his subject of study a tiny, delicate fly formally called Drosophila melanogaster,
but more commonly known as the fruit fly (or vinegar fly, banana fly, or garbage fly). Drosophila is
familiar to most of us as that frail, colorless insect that seems to have a compulsive urge to drown in
our drinks. As laboratory specimens fruit flies had certain very attractive advantages: they cost
almost nothing to house and feed, could be bred by the millions in milk bottles, went from egg to
productive parenthood in ten days or less, and had just four chromosomes, which kept things
conveniently simple.

Working out of a small lab (which became known inevitably as the Fly

Room) in Schermerhorn Hall

at Columbia University in New York, Morgan and his team embarked on a program of meticulous

breeding and crossbreeding involving millions of flies (one biographer says billions, though that is

probably an exaggeration), each of which had to be captured with tweezers and examined under a

jeweler's glass for any tiny variations in inheritance. For six years they tried to produce mutations by

any means they could think of— zapping the flies with radiation and X-rays, rearing them in bright

light and darkness, baking them gently in ovens, spinning them crazily in centrifuges— but nothing

worked. Morgan was on the brink of giving up when there occurred a sudden and repeatable

mutation— a fly that had white eyes rather than the usual red ones. With this breakthrough, Morgan

and his assistants were able to generate useful deformities, allowing them to track a trait through

successive generations. By such means they could work out the correlations between particular

characteristics and individual chromosomes, eventually proving to more or

less everyone’s

satisfaction that chromosomes were at the heart of inheritance.

The problem, however, remained the next level of biological intricacy: the

enigmatic genes and the

DNA that composed them. These were much trickier to isolate and

understand. As late as 1933,

when Morgan was awarded a Nobel Prize for his work, many researchers

still weren’t convinced that

genes even existed. As Morgan noted at the time, there was no consensus “as

to what the genes are—

whether they are real or purely fictitious.” It may seem surprising that

scientists could struggle to

accept the physical reality of something so fundamental to cellular activity,

but as Wallace, King,

and Sanders point out in Biology: The Science of Life (that rarest thing: a

readable college text), we

are in much the same position today with mental processes such as thought

and memory. We know

that we have them, of course, but we don't know what, if any, physical form they take. So it was for
the longest time with genes. The idea that you could pluck one from your body and take it away for
study was as absurd to many of Morgan's peers as the idea that scientists today might capture a stray
thought and examine it under a microscope.

What was certainly true was that something associated with chromosomes was directing cell
replication. Finally, in 1944, after fifteen years of effort, a team at the Rockefeller Institute in
Manhattan, led by a brilliant but diffident Canadian named Oswald Avery, succeeded with an
exceedingly tricky experiment in which an innocuous strain of bacteria was made permanently
infectious by crossing it with alien DNA, proving that DNA was far more than a passive molecule
and almost certainly was the active agent in heredity. The Austrian-born biochemist Erwin Chargaff
later suggested quite seriously that Avery's discovery was worth two Nobel

Prizes.

Unfortunately, Avery was opposed by one of his own colleagues at the

institute, a strong-willed and

disagreeable protein enthusiast named Alfred Mirsky, who did everything in

his power to discredit

Avery’s work— including, it has been said, lobbying the authorities at the

Karolinska Institute in

Stockholm not to give Avery a Nobel Prize. Avery by this time was sixty-six

years old and tired.

Unable to deal with the stress and controversy, he resigned his position and

never went near a lab

again. But other experiments elsewhere overwhelmingly supported his

conclusions, and soon the

race was on to find the structure of DNA.

Had you been a betting person in the early 1950s, your money would almost

certainly have been on

Linus Pauling of Caltech, America’s leading chemist, to crack the structure

of DNA. Pauling was

unrivaled in determining the architecture of molecules and had been a

pioneer in the field of X-ray

crystallography, a technique that would prove crucial to peering into the heart of DNA. In an exceedingly distinguished career, he would win two Nobel Prizes (for chemistry in 1954 and peace in 1962), but with DNA he became convinced that the structure was a triple helix, not a double one, and never quite got on the right track. Instead, victory fell to an unlikely quartet of scientists in England who didn’t work as a team, often weren’t on speaking terms, and were for the most part novices in the field.

Of the four, the nearest to a conventional boffin was Maurice Wilkins, who had spent much of the Second World War helping to design the atomic bomb. Two of the others, Rosalind Franklin and Francis Crick, had passed their war years working on mines for the British government— Crick of the type that blow up, Franklin of the type that produce coal.

The most unconventional of the foursome was James Watson, an American prodigy who had distinguished himself as a boy as a member of a highly popular radio program called The Quiz Kids (and thus could claim to be at least part of the inspiration for some of the members of the Glass family in Franny and Zooey and other works by J. D. Salinger) and who had entered the University of Chicago aged just fifteen. He had earned his Ph.D. by the age of twenty-two and was now attached to the famous Cavendish Laboratory in Cambridge. In 1951, he was a gawky twenty-threeyear-old with a strikingly lively head of hair that appears in photographs to be straining to attach itself to some powerful magnet just out of frame.

Crick, twelve years older and still without a doctorate, was less memorably hirsute and slightly more tweedy. In Watson’s account he is presented as blustery, nosy, cheerfully argumentative, impatient with anyone slow to share a notion, and constantly in danger of being asked to go elsewhere. Neither was formally trained in biochemistry.

Their assumption was that if you could determine the shape of a DNA molecule you would be able to see— correctly, as it turned out— how it did what it did. They hoped to achieve this, it would appear, by doing as little work as possible beyond thinking, and no more of that than was absolutely necessary. As Watson cheerfully (if a touch disingenuously) remarked in his autobiographical book The Double Helix, “It was my hope that the gene might be solved without my learning any chemistry.” They weren’t actually assigned to work on DNA, and at one point were ordered to stop it. Watson was ostensibly mastering the art of crystallography; Crick was supposed to be completing a thesis on the X-ray diffraction of large molecules.

Although Crick and Watson enjoy nearly all the credit in popular accounts for solving the mystery of DNA, their breakthrough was crucially dependent on experimental work done by their competitors, the results of which were obtained “fortuitously,” in the tactful words of the historian Lisa Jardine.

Far ahead of them, at least at the beginning, were two academics at King’s

College in London,

Wilkins and Franklin.

The New Zealand–born Wilkins was a retiring figure, almost to the point of

invisibility. A 1998 PBS

documentary on the discovery of the structure of DNA— a feat for which he

shared the 1962 Nobel

Prize with Crick and Watson— managed to overlook him entirely.

The most enigmatic character of all was Franklin. In a severely unflattering

portrait, Watson in The

Double Helix depicted Franklin as a woman who was unreasonable,

secretive, chronically

uncooperative, and— this seemed especially to irritate him— almost

willfully unsexy. He allowed

that she “was not unattractive and might have been quite stunning had she

taken even a mild interest

in clothes,” but in this she disappointed all expectations. She didn’t even use

lipstick, he noted in

wonder, while her dress sense “showed all the imagination of English blue-stocking adolescents."*44

However, she did have the best images in existence of the possible structure of DNA, achieved by means of X-ray crystallography, the technique perfected by Linus Pauling. Crystallography had been used successfully to map atoms in crystals (hence "crystallography"), but DNA molecules were a much more finicky proposition. Only Franklin was managing to get good results from the process, but to Wilkins's perennial exasperation she refused to share her findings.

If Franklin was not warmly forthcoming with her findings, she cannot be altogether blamed. Female academics at King's in the 1950s were treated with a formalized disdain that dazzles modern sensibilities (actually any sensibilities). However senior or accomplished, they were not allowed into the college's senior common room but instead had to take their meals in a more utilitarian chamber that even Watson conceded was "dingily pokey." On top of this she was being constantly pressed—

at times actively harassed— to share her results with a trio of men whose desperation to get a peek at them was seldom matched by more engaging qualities, like respect. “I’m afraid we always used to adopt— let’s say a patronizing attitude toward her,” Crick later recalled. Two of these men were from a competing institution and the third was more or less openly siding with them. It should hardly come as a surprise that she kept her results locked away.

That Wilkins and Franklin did not get along was a fact that Watson and Crick seem to have exploited to their benefit. Although Crick and Watson were trespassing rather unashamedly on Wilkins’s territory, it was with them that he increasingly sided— not altogether surprisingly since Franklin herself was beginning to act in a decidedly queer way. Although her results showed that DNA definitely was helical in shape, she insisted to all that it was not. To Wilkins’s presumed dismay and embarrassment, in the summer of 1952 she posted a mock notice around the

King’s physics
department that said: “It is with great regret that we have to announce the death, on Friday 18th July
1952 of D.N.A. helix. . . . It is hoped that Dr. M.H.F. Wilkins will speak in memory of the late
helix.”

The outcome of all this was that in January 1953, Wilkins showed Watson Franklin’s images,
“apparently without her knowledge or consent.” It would be an understatement to call it a significant
help. Years later Watson conceded that it “was the key event . . . it mobilized us.” Armed with the
knowledge of the DNA molecule’s basic shape and some important elements of its dimensions,
Watson and Crick redoubled their efforts. Everything now seemed to go their way. At one point
Pauling was en route to a conference in England at which he would in all likelihood have met with
Wilkins and learned enough to correct the misconceptions that had put him on the wrong line of

inquiry, but this was the McCarthy era and Pauling found himself detained at Idlewild Airport in
New York, his passport confiscated, on the grounds that he was too liberal of temperament to be
allowed to travel abroad. Crick and Watson also had the no less convenient good fortune that
Pauling's son was working at the Cavendish and innocently kept them abreast of any news of
developments and setbacks at home.

Still facing the possibility of being trumped at any moment, Watson and Crick applied themselves
feverishly to the problem. It was known that DNA had four chemical components— called adenine,
guanine, cytosine, and thiamine— and that these paired up in particular ways. By playing with pieces
of cardboard cut into the shapes of molecules, Watson and Crick were able to work out how the
pieces fit together. From this they made a Meccano-like model— perhaps the most famous in modern
science— consisting of metal plates bolted together in a spiral, and invited

Wilkins, Franklin, and the rest of the world to have a look. Any informed person could see at once that they had solved the problem. It was without question a brilliant piece of detective work, with or without the boost of Franklin's picture.

The April 25, 1953, edition of Nature carried a 900-word article by Watson and Crick titled "A Structure for Deoxyribose Nucleic Acid." Accompanying it were separate articles by Wilkins and Franklin. It was an eventful time in the world— Edmund Hillary was just about to clamber to the top of Everest while Elizabeth II was imminently to be crowned queen of England— so the discovery of the secret of life was mostly overlooked. It received a small mention in the News Chronicle and was ignored elsewhere.

Rosalind Franklin did not share in the Nobel Prize. She died of ovarian cancer at the age of just thirty-seven in 1958, four years before the award was granted. Nobel Prizes are not awarded

posthumously. The cancer almost certainly arose as a result of chronic

overexposure to X-rays

through her work and needn't have happened. In her much-praised 2002

biography of Franklin,

Brenda Maddox noted that Franklin rarely wore a lead apron and often

stepped carelessly in front of

a beam. Oswald Avery never won a Nobel Prize either and was also largely

overlooked by posterity,

though he did at least have the satisfaction of living just long enough to see

his findings vindicated.

He died in 1955.

Watson and Crick's discovery wasn't actually confirmed until the 1980s. As

Crick said in one of his

books: "It took over twenty-five years for our model of DNA to go from

being only rather plausible,

to being very plausible . . . and from there to being virtually certainly

correct."

Even so, with the structure of DNA understood progress in genetics was

swift, and by 1968 the

journal Science could run an article titled “That Was the Molecular Biology That Was,”
suggesting— it hardly seems possible, but it is so— that the work of genetics was nearly at an end.
In fact, of course, it was only just beginning. Even now there is a great deal about DNA that we
scarcely understand, not least why so much of it doesn’t actually seem to do anything. Ninety-seven
percent of your DNA consists of nothing but long stretches of meaningless garble— “junk,” or “noncoding
DNA,” as biochemists prefer to put it. Only here and there along each strand do you find
sections that control and organize vital functions. These are the curious and long-elusive genes.
Genes are nothing more (nor less) than instructions to make proteins. This they do with a certain dull
fidelity. In this sense, they are rather like the keys of a piano, each playing a single note and nothing
else, which is obviously a trifle monotonous. But combine the genes, as you would combine piano

keys, and you can create chords and melodies of infinite variety. Put all these genes together, and
you have (to continue the metaphor) the great symphony of existence known as the human genome.

An alternative and more common way to regard the genome is as a kind of instruction manual for the
body. Viewed this way, the chromosomes can be imagined as the book's chapters and the genes as
individual instructions for making proteins. The words in which the instructions are written are
called codons, and the letters are known as bases. The bases— the letters of the genetic alphabet—
consist of the four nucleotides mentioned a page or two back: adenine, thiamine, guanine, and
cytosine. Despite the importance of what they do, these substances are not made of anything exotic.

Guanine, for instance, is the same stuff that abounds in, and gives its name to, guano.

The shape of a DNA molecule, as everyone knows, is rather like a spiral staircase or twisted rope

ladder: the famous double helix. The uprights of this structure are made of a type of sugar called
deoxyribose, and the whole of the helix is a nucleic acid— hence the name “deoxyribonucleic acid.”
The rungs (or steps) are formed by two bases joining across the space between, and they can
combine in only two ways: guanine is always paired with cytosine and thiamine always with
adenine. The order in which these letters appear as you move up or down the ladder constitutes the
DNA code; logging it has been the job of the Human Genome Project.
Now the particular brilliance of DNA lies in its manner of replication. When it is time to produce a
new DNA molecule, the two strands part down the middle, like the zipper on a jacket, and each half
goes off to form a new partnership. Because each nucleotide along a strand pairs up with a specific
other nucleotide, each strand serves as a template for the creation of a new matching strand. If you
possessed just one strand of your own DNA, you could easily enough

reconstruct the matching side
by working out the necessary partnerships: if the topmost rung on one strand was made of guanine,
then you would know that the topmost rung on the matching strand must be cytosine. Work your
way down the ladder through all the nucleotide pairings, and eventually you would have the code for
a new molecule. That is just what happens in nature, except that nature does it really quickly— in
only a matter of seconds, which is quite a feat.

Most of the time our DNA replicates with dutiful accuracy, but just occasionally— about one time in
a million— a letter gets into the wrong place. This is known as a single nucleotide polymorphism, or
SNP, familiarly known to biochemists as a "Snip." Generally these Snips are buried in stretches of
noncoding DNA and have no detectable consequence for the body. But occasionally they make a
difference. They might leave you predisposed to some disease, but equally they might confer some

slight advantage— more protective pigmentation, for instance, or increased production of red blood
cells for someone living at altitude. Over time, these slight modifications accumulate in both
individuals and in populations, contributing to the distinctiveness of both.
The balance between accuracy and errors in replication is a fine one. Too many errors and the
organism can't function, but too few and it sacrifices adaptability. A similar balance must exist
between stability in an organism and innovation. An increase in red blood cells can help a person or
group living at high elevations to move and breathe more easily because more red cells can carry
more oxygen. But additional red cells also thicken the blood. Add too many, and "it's like pumping
oil," in the words of Temple University anthropologist Charles Weitz. That's hard on the heart. Thus
those designed to live at high altitude get increased breathing efficiency, but pay for it with higherrisk
hearts. By such means does Darwinian natural selection look after us. It also

helps to explain
why we are all so similar. Evolution simply won't let you become too different— not without
becoming a new species anyway.
The 0.1 percent difference between your genes and mine is accounted for by our Snips. Now if you
compared your DNA with a third person's, there would also be 99.9 percent correspondence, but the
Snips would, for the most part, be in different places. Add more people to the comparison and you
will get yet more Snips in yet more places. For every one of your 3.2 billion bases, somewhere on
the planet there will be a person, or group of persons, with different coding in that position. So not
only is it wrong to refer to "the" human genome, but in a sense we don't even have "a" human
genome. We have six billion of them. We are all 99.9 percent the same, but equally, in the words of
the biochemist David Cox, "you could say all humans share nothing, and that would be correct, too."

But we have still to explain why so little of that DNA has any discernible purpose. It starts to get a little unnerving, but it does really seem that the purpose of life is to perpetuate DNA. The 97 percent of our DNA commonly called junk is largely made up of clumps of letters that, in Ridley's words, "exist for the pure and simple reason that they are good at getting themselves duplicated."*45 Most of your DNA, in other words, is not devoted to you but to itself: you are a machine for reproducing it, not it for you. Life, you will recall, just wants to be, and DNA is what makes it so.

Even when DNA includes instructions for making genes— when it codes for them, as scientists put it— it is not necessarily with the smooth functioning of the organism in mind. One of the commonest genes we have is for a protein called reverse transcriptase, which has no known beneficial function in human beings at all. The one thing it does do is make it possible for retroviruses, such as the AIDS virus, to slip unnoticed into the human system.

In other words, our bodies devote considerable energies to producing a protein that does nothing that is beneficial and sometimes clobbers us. Our bodies have no choice but to do so because the genes order it. We are vessels for their whims. Altogether, almost half of human genes— the largest proportion yet found in any organism— don't do anything at all, as far as we can tell, except reproduce themselves.

All organisms are in some sense slaves to their genes. That's why salmon and spiders and other types of creatures more or less beyond counting are prepared to die in the process of mating. The desire to breed, to disperse one's genes, is the most powerful impulse in nature. As Sherwin B. Nuland has put it: "Empires fall, ids explode, great symphonies are written, and behind all of it is a single instinct that demands satisfaction." From an evolutionary point of view, sex is really just a reward mechanism to encourage us to pass on our genetic material.

Scientists had only barely absorbed the surprising news that most of our DNA doesn't do anything when even more unexpected findings began to turn up. First in Germany and then in Switzerland researchers performed some rather bizarre experiments that produced curiously unbizarre outcomes.

In one they took the gene that controlled the development of a mouse's eye and inserted it into the larva of a fruit fly. The thought was that it might produce something interestingly grotesque. In fact, the mouse-eye gene not only made a viable eye in the fruit fly, it made a fly's eye. Here were two creatures that hadn't shared a common ancestor for 500 million years, yet could swap genetic material as if they were sisters.

The story was the same wherever researchers looked. They found that they could insert human DNA into certain cells of flies, and the flies would accept it as if it were their own. Over 60 percent of

human genes, it turns out, are fundamentally the same as those found in fruit flies. At least 90
percent correlate at some level to those found in mice. (We even have the same genes for making a
tail, if only they would switch on.) In field after field, researchers found that whatever organism they
were working on— whether nematode worms or human beings— they were often studying essentially
the same genes. Life, it appeared, was drawn up from a single set of blueprints.

Further probings revealed the existence of a clutch of master control genes, each directing the
development of a section of the body, which were dubbed homeotic (from a Greek word meaning
"similar") or hox genes. Hox genes answered the long-bewildering question of how billions of
embryonic cells, all arising from a single fertilized egg and carrying identical DNA, know where to
go and what to do— that this one should become a liver cell, this one a stretchy neuron, this one a

bubble of blood, this one part of the shimmer on a beating wing. It is the hox genes that instruct them, and they do it for all organisms in much the same way.

Interestingly, the amount of genetic material and how it is organized doesn't necessarily, or even generally, reflect the level of sophistication of the creature that contains it. We have forty-six chromosomes, but some ferns have more than six hundred. The lungfish, one of the least evolved of all complex animals, has forty times as much DNA as we have. Even the common newt is more genetically splendorous than we are, by a factor of five.

Clearly it is not the number of genes you have, but what you do with them. This is a very good thing because the number of genes in humans has taken a big hit lately. Until recently it was thought that humans had at least 100,000 genes, possibly a good many more, but that number was drastically reduced by the first results of the Human Genome Project, which suggested a figure more like

35,000 or 40,000 genes— about the same number as are found in grass. That came as both a surprise
and a disappointment.
It won't have escaped your attention that genes have been commonly implicated in any number of
human frailties. Exultant scientists have at various times declared themselves to have found the
genes responsible for obesity, schizophrenia, homosexuality, criminality, violence, alcoholism, even
shoplifting and homelessness. Perhaps the apogee (or nadir) of this faith in biodeterminism was a
study published in the journal Science in 1980 contending that women are genetically inferior at
mathematics. In fact, we now know, almost nothing about you is so accommodatingly simple.
This is clearly a pity in one important sense, for if you had individual genes that determined height
or propensity to diabetes or to baldness or any other distinguishing trait, then it would be easy—
comparatively easy anyway— to isolate and tinker with them. Unfortunately,

thirty-five thousand

genes functioning independently is not nearly enough to produce the kind of

physical complexity

that makes a satisfactory human being. Genes clearly therefore must

cooperate. A few disorders—

hemophilia, Parkinson’s disease, Huntington’s disease, and cystic fibrosis,

for example— are caused

by lone dysfunctional genes, but as a rule disruptive genes are weeded out

by natural selection long

before they can become permanently troublesome to a species or population.

For the most part our

fate and comfort— and even our eye color— are determined not by

individual genes but by

complexes of genes working in alliance. That’s why it is so hard to work out

how it all fits together

and why we won’t be producing designer babies anytime soon.

In fact, the more we have learned in recent years the more complicated

matters have tended to

become. Even thinking, it turns out, affects the ways genes work. How fast a

man’s beard grows, for

instance, is partly a function of how much he thinks about sex (because thinking about sex produces a testosterone surge). In the early 1990s, scientists made an even more profound discovery when they found they could knock out supposedly vital genes from embryonic mice, and the mice were not only often born healthy, but sometimes were actually fitter than their brothers and sisters who had not been tampered with. When certain important genes were destroyed, it turned out, others were stepping in to fill the breach. This was excellent news for us as organisms, but not so good for our understanding of how cells work since it introduced an extra layer of complexity to something that we had barely begun to understand anyway.

It is largely because of these complicating factors that cracking the human genome became seen almost at once as only a beginning. The genome, as Eric Lander of MIT has put it, is like a parts list for the human body: it tells us what we are made of, but says nothing about

how we work. What’s
needed now is the operating manual— instructions for how to make it go. We are not close to that
point yet.

So now the quest is to crack the human proteome— a concept so novel that the term proteome didn’t
even exist a decade ago. The proteome is the library of information that creates proteins.

“Unfortunately,” observed Scientific American in the spring of 2002, “the proteome is much more
complicated than the genome.”

That’s putting it mildly. Proteins, you will remember, are the workhorses of all living systems; as
many as a hundred million of them may be busy in any cell at any moment. That’s a lot of activity to
try to figure out. Worse, proteins’ behavior and functions are based not simply on their chemistry, as
with genes, but also on their shapes. To function, a protein must not only have the necessary
chemical components, properly assembled, but then must also be folded into

an extremely specific
shape. “Folding” is the term that’s used, but it’s a misleading one as it suggests a geometrical
tidiness that doesn’t in fact apply. Proteins loop and coil and crinkle into shapes that are at once
extravagant and complex. They are more like furiously mangled coat hangers than folded towels.

Moreover, proteins are (if I may be permitted to use a handy archaism) the swingers of the biological
world. Depending on mood and metabolic circumstance, they will allow themselves to be
phosphorylated, glycosylated, acetylated, ubiquitinated, farneysylated, sulfated, and linked to
glycophosphatidylinositol anchors, among rather a lot else. Often it takes relatively little to get them
going, it appears. Drink a glass of wine, as Scientific American notes, and you materially alter the
number and types of proteins at large in your system. This is a pleasant feature for drinkers, but not
nearly so helpful for geneticists who are trying to understand what is going

on.

It can all begin to seem impossibly complicated, and in some ways it is impossibly complicated. But there is an underlying simplicity in all this, too, owing to an equally elemental underlying unity in the way life works. All the tiny, deft chemical processes that animate cells—the cooperative efforts of nucleotides, the transcription of DNA into RNA— evolved just once and have stayed pretty well fixed ever since across the whole of nature. As the late French geneticist Jacques Monod put it, only half in jest: "Anything that is true of E. coli must be true of elephants, except more so."

Every living thing is an elaboration on a single original plan. As humans we are mere increments—each of us a musty archive of adjustments, adaptations, modifications, and providential tinkerings stretching back 3.8 billion years. Remarkably, we are even quite closely related to fruit and vegetables. About half the chemical functions that take place in a banana are fundamentally the same

as the chemical functions that take place in you.

It cannot be said too often: all life is one. That is, and I suspect will forever prove to be, the most profound true statement there is.

PART VI **THE ROAD TO US**

27 **ICE TIME**

I had a dream, which was not all a dream.

The bright sun was extinguish'd, and the stars

Did wander . . .

— Byron, "Darkness"

IN 1815 on the island of Sumbawa in Indonesia, a handsome and long-quiescent mountain named Tambora exploded spectacularly, killing a hundred thousand people with its blast and associated tsunamis. It was the biggest volcanic explosion in ten thousand years— 150 times the size of Mount St. Helens, equivalent to sixty thousand Hiroshima-sized atom bombs.

News didn't travel terribly fast in those days. In London, The Times ran a small story— actually a letter from a merchant— seven months after the event. But by this time Tambora's effects were already being felt. Thirty-six cubic miles of smoky ash, dust, and grit had diffused through the atmosphere, obscuring the Sun's rays and causing the Earth to cool. Sunsets were unusually but blearily colorful, an effect memorably captured by the artist J. M. W. Turner, who could not have been happier, but mostly the world existed under an oppressive, dusky pall. It was this deathly dimness that inspired the Byron lines above.

Spring never came and summer never warmed: 1816 became known as the year without summer.

Crops everywhere failed to grow. In Ireland a famine and associated typhoid epidemic killed sixtyfive thousand people. In New England, the year became popularly known as Eighteen Hundred and Froze to Death. Morning frosts continued until June and almost no planted seed would grow. Short of fodder, livestock died or had to be prematurely slaughtered. In every way

it was a dreadful year—
almost certainly the worst for farmers in modern times. Yet globally the temperature fell by only
about 1.5 degrees Fahrenheit. Earth's natural thermostat, as scientists would learn, is an exceedingly
delicate instrument.

The nineteenth century was already a chilly time. For two hundred years Europe and North America
in particular had experienced a Little Ice Age, as it has become known, which permitted all kinds of
wintry events— frost fairs on the Thames, ice-skating races along Dutch canals— that are mostly
impossible now. It was a period, in other words, when frigidity was much on people's minds. So we
may perhaps excuse nineteenth-century geologists for being slow to realize that the world they lived
in was in fact balmy compared with former epochs, and that much of the land around them had been
shaped by crushing glaciers and cold that would wreck even a frost fair.

They knew there was something odd about the past. The European landscape

was littered with
inexplicable anomalies— the bones of arctic reindeer in the warm south of France, huge rocks
stranded in improbable places— and they often came up with inventive but not terribly plausible
explanations. One French naturalist named de Luc, trying to explain how granite boulders had come
to rest high up on the limestone flanks of the Jura Mountains, suggested that perhaps they had been
shot there by compressed air in caverns, like corks out of a popgun. The term for a displaced boulder
is an erratic, but in the nineteenth century the expression seemed to apply more often to the theories
than to the rocks.

The great British geologist Arthur Hallam has suggested that if James Hutton, the father of geology,
had visited Switzerland, he would have seen at once the significance of the carved valleys, the
polished striations, the telltale strand lines where rocks had been dumped, and the other abundant

clues that point to passing ice sheets. Unfortunately, Hutton was not a traveler. But even with nothing better at his disposal than secondhand accounts, Hutton rejected out of hand the idea that huge boulders had been carried three thousand feet up mountainsides by floods— all the water in the world won't make a boulder float, he pointed out— and became one of the first to argue for widespread glaciation. Unfortunately his ideas escaped notice, and for another half century most naturalists continued to insist that the gouges on rocks could be attributed to passing carts or even the scrape of hobnailed boots.

Local peasants, uncontaminated by scientific orthodoxy, knew better, however. The naturalist Jean de Charpentier told the story of how in 1834 he was walking along a country lane with a Swiss woodcutter when they got to talking about the rocks along the roadside. The woodcutter matter-offactly told him that the boulders had come from the Grimsel, a zone of granite some distance away.

“When I asked him how he thought that these stones had reached their location, he answered without hesitation: ‘The Grimsel glacier transported them on both sides of the valley, because that glacier extended in the past as far as the town of Bern.’ ”

Charpentier was delighted. He had come to such a view himself, but when he raised the notion at scientific gatherings, it was dismissed. One of Charpentier’s closest friends was another Swiss naturalist, Louis Agassiz, who after some initial skepticism came to embrace, and eventually all but appropriate, the theory.

Agassiz had studied under Cuvier in Paris and now held the post of Professor of Natural History at the College of Neuchâtel in Switzerland. Another friend of Agassiz’s, a botanist named Karl Schimper, was actually the first to coin the term ice age (in German Eiszeit), in 1837, and to propose that there was good evidence to show that ice had once lain heavily across

not just the Swiss Alps,
but over much of Europe, Asia, and North America. It was a radical notion. He lent Agassiz his
notes— then came very much to regret it as Agassiz increasingly got the credit for what Schimper
felt, with some legitimacy, was his theory. Charpentier likewise ended up a bitter enemy of his old
friend. Alexander von Humboldt, yet another friend, may have had Agassiz at least partly in mind
when he observed that there are three stages in scientific discovery: first, people deny that it is true;
then they deny that it is important; finally they credit the wrong person.
At all events, Agassiz made the field his own. In his quest to understand the dynamics of glaciation,
he went everywhere— deep into dangerous crevasses and up to the summits of the craggiest Alpine
peaks, often apparently unaware that he and his team were the first to climb them. Nearly
everywhere Agassiz encountered an unyielding reluctance to accept his theories. Humboldt urged

him to return to his area of real expertise, fossil fish, and give up this mad obsession with ice, but

Agassiz was a man possessed by an idea.

Agassiz's theory found even less support in Britain, where most naturalists had never seen a glacier

and often couldn't grasp the crushing forces that ice in bulk exerts. "Could scratches and polish just

be due to ice?" asked Roderick Murchison in a mocking tone at one meeting, evidently imagining

the rocks as covered in a kind of light and glassy rime. To his dying day, he expressed the frankest

incredulity at those "ice-mad" geologists who believed that glaciers could account for so much.

William Hopkins, a Cambridge professor and leading member of the Geological Society, endorsed

this view, arguing that the notion that ice could transport boulders presented "such obvious

mechanical absurdities" as to make it unworthy of the society's attention.

Undaunted, Agassiz traveled tirelessly to promote his theory. In 1840 he read a paper to a meeting of the British Association for the Advancement of Science in Glasgow at which he was openly criticized by the great Charles Lyell. The following year the Geological Society of Edinburgh passed a resolution conceding that there might be some general merit in the theory but that certainly none of it applied to Scotland.

Lyell did eventually come round. His moment of epiphany came when he realized that a moraine, or line of rocks, near his family estate in Scotland, which he had passed hundreds of times, could only be understood if one accepted that a glacier had dropped them there. But having become converted, Lyell then lost his nerve and backed off from public support of the Ice Age idea. It was a frustrating time for Agassiz. His marriage was breaking up, Schimper was hotly accusing him of the theft of his ideas, Charpentier wouldn’t speak to him, and the greatest living geologist offered support of only the most tepid and vacillating kind.

In 1846, Agassiz traveled to America to give a series of lectures and there at last found the esteem he craved. Harvard gave him a professorship and built him a first-rate museum, the Museum of Comparative Zoology. Doubtless it helped that he had settled in New England, where the long winters encouraged a certain sympathy for the idea of interminable periods of cold. It also helped that six years after his arrival the first scientific expedition to Greenland reported that nearly the whole of that semicontinent was covered in an ice sheet just like the ancient one imagined in Agassiz's theory. At long last, his ideas began to find a real following. The one central defect of Agassiz's theory was that his ice ages had no cause. But assistance was about to come from an unlikely quarter.

In the 1860s, journals and other learned publications in Britain began to receive papers on hydrostatics, electricity, and other scientific subjects from a James Croll of