A Short History of Nearly Everything

By Bill Bryson

two flying around a nucleus, like planets orbiting a sun. This image was created in 1904, based on little more than clever guesswork, by a Japanese physicist named Hantaro Nagaoka. It is completely wrong, but durable just the same. As Isaac Asimov liked to note, it inspired generations of science fiction writers to create stories of worlds within worlds, in which atoms become tiny inhabited solar systems or our solar system turns out to be merely a mote in some much larger scheme. Even now CERN, the European Organization for Nuclear Research, uses Nagaoka's image as a logo on its website. In fact, as physicists were soon to realize, electrons are not like orbiting planets at all, but more like the blades of a spinning fan, managing to fill every bit of space in their orbits simultaneously (but with the crucial difference that the blades of a fan only seem to be everywhere at once; electrons are).

Needless to say, very little of this was understood in 1910 or for many years afterward. Rutherford's finding presented some large and immediate problems, not least that no electron should be able to orbit a nucleus without crashing. Conventional electrodynamic theory demanded that a flying electron should very quickly run out of energy— in only an instant or so— and spiral into the nucleus, with disastrous consequences for both. There was also the problem of how protons with their positive charges could bundle together inside the nucleus without blowing themselves and the rest of the atom apart. Clearly whatever was going on down there in the world of the very small was not governed by the laws that applied in the macro world where our expectations reside.

As physicists began to delve into this subatomic realm, they realized that it wasn't merely different from anything we knew, but different from anything ever imagined. "Because atomic behavior is so unlike ordinary experience," Richard Feynman once observed, "it is very difficult to get used to and

it appears peculiar and mysterious to everyone, both to the novice and to the experienced physicist."

When Feynman made that comment, physicists had had half a century to adjust to the strangeness of

atomic behavior. So think how it must have felt to Rutherford and his colleagues in the early 1910s

when it was all brand new.

One of the people working with Rutherford was a mild and affable young Dane named Niels Bohr.

In 1913, while puzzling over the structure of the atom, Bohr had an idea so exciting that he

postponed his honeymoon to write what became a landmark paper. Because physicists couldn't see

anything so small as an atom, they had to try to work out its structure from how it behaved when

they did things to it, as Rutherford had done by firing alpha particles at foil. Sometimes, not

surprisingly, the results of these experiments were puzzling. One puzzle that had been around for a long time had to do with spectrum readings of the wavelengths of hydrogen. These produced patterns showing that hydrogen atoms emitted energy at certain wavelengths but not others. It was rather as if someone under surveillance kept turning up at particular locations but was never observed traveling between them. No one could understand why this should be.

It was while puzzling over this problem that Bohr was struck by a solution and dashed off his famous paper. Called "On the Constitutions of Atoms and Molecules," the paper explained how electrons could keep from falling into the nucleus by suggesting that they could occupy only certain welldefined orbits. According to the new theory, an electron moving between orbits would disappear from one and reappear instantaneously in another without visiting the space between. This idea— the famous "quantum leap"— is of course utterly strange, but it was too good not to be true. It not only kept electrons from spiraling catastrophically into the nucleus; it also explained hydrogen’s bewildering wavelengths. The electrons only appeared in certain orbits because they only existed in certain orbits. It was a dazzling insight, and it won Bohr the 1922 Nobel Prize in physics, the year after Einstein received his.

Meanwhile the tireless Rutherford, now back at Cambridge as J. J. Thomson’s successor as head of the Cavendish Laboratory, came up with a model that explained why the nuclei didn’t blow up. He saw that they must be offset by some type of neutralizing particles, which he called neutrons. The idea was simple and appealing, but not easy to prove. Rutherford’s associate, James Chadwick, devoted eleven intensive years to hunting for neutrons before finally succeeding in 1932. He, too, was awarded with a Nobel Prize in physics, in 1935. As Boorse and his colleagues point out in their history of the subject, the delay in discovery was probably a very good thing as mastery of the neutron was essential to the development of the atomic bomb. (Because neutrons have no charge, they aren’t repelled by the electrical fields at the heart of an atom and thus could be fired like tiny torpedoes into an atomic nucleus, setting off the destructive process known as fission.) Had the neutron been isolated in the 1920s, they note, it is “very likely the atomic bomb would have been developed first in Europe, undoubtedly by the Germans.”

As it was, the Europeans had their hands full trying to understand the strange behavior of the electron. The principal problem they faced was that the electron sometimes behaved like a particle and sometimes like a wave. This impossible duality drove physicists nearly mad. For the next decade all across Europe they furiously thought and scribbled and offered competing hypotheses. In France, Prince Louis-Victor de Broglie, the scion of a ducal family, found that certain anomalies in the behavior of electrons disappeared when one regarded them as waves. The observation excited the

attention of the Austrian Erwin Schrödinger, who made some deft

refinements and devised a handy

system called wave mechanics. At almost the same time the German

physicist Werner Heisenberg

came up with a competing theory called matrix mechanics. This was so

mathematically complex that

hardly anyone really understood it, including Heisenberg himself (“I do not

even know what a matrix

is,” Heisenberg despaired to a friend at one point), but it did seem to solve

certain problems that

Schrödinger’s waves failed to explain.

The upshot is that physics had two theories, based on conflicting premises,

that produced the same

results. It was an impossible situation.

Finally, in 1926, Heisenberg came up with a celebrated compromise,

producing a new discipline that

came to be known as quantum mechanics. At the heart of it was

Heisenberg’s Uncertainty Principle,

which states that the electron is a particle but a particle that can be described in terms of waves. The uncertainty around which the theory is built is that we can know the path an electron takes as it moves through a space or we can know where it is at a given instant, but we cannot know both.*22 Any attempt to measure one will unavoidably disturb the other. This isn't a matter of simply needing more precise instruments; it is an immutable property of the universe.

What this means in practice is that you can never predict where an electron will be at any given moment. You can only list its probability of being there. In a sense, as Dennis Overbye has put it, an electron doesn't exist until it is observed. Or, put slightly differently, until it is observed an electron must be regarded as being "at once everywhere and nowhere."

If this seems confusing, you may take some comfort in knowing that it was confusing to physicists, too. Overbye notes: "Bohr once commented that a person who wasn't outraged on first hearing about quantum theory didn't understand what had been said." Heisenberg, when asked how one could

envision an atom, replied: “Don’t try.”

So the atom turned out to be quite unlike the image that most people had created. The electron doesn’t fly around the nucleus like a planet around its sun, but instead takes on the more amorphous aspect of a cloud. The “shell” of an atom isn’t some hard shiny casing, as illustrations sometimes encourage us to suppose, but simply the outermost of these fuzzy electron clouds. The cloud itself is essentially just a zone of statistical probability marking the area beyond which the electron only very seldom strays. Thus an atom, if you could see it, would look more like a very fuzzy tennis ball than a hard-edged metallic sphere (but not much like either or, indeed, like anything you’ve ever seen; we are, after all, dealing here with a world very different from the one we see around us).

It seemed as if there was no end of strangeness. For the first time, as James Trefil has put it, scientists had encountered “an area of the universe that our brains just aren’t wired to understand.”

Or as Feynman expressed it, “things on a small scale behave nothing like things on a large scale.” As physicists delved deeper, they realized they had found a world where not only could electrons jump from one orbit to another without traveling across any intervening space, but matter could pop into existence from nothing at all— “provided,” in the words of Alan Lightman of MIT, “it disappears again with sufficient haste.”

Perhaps the most arresting of quantum improbabilities is the idea, arising from Wolfgang Pauli’s Exclusion Principle of 1925, that the subatomic particles in certain pairs, even when separated by the most considerable distances, can each instantly “know” what the other is doing. Particles have a quality known as spin and, according to quantum theory, the moment you determine the spin of one particle, its sister particle, no matter how distant away, will immediately

begin spinning in the
opposite direction and at the same rate.

It is as if, in the words of the science writer Lawrence Joseph, you had two identical pool balls, one in Ohio and the other in Fiji, and the instant you sent one spinning the other would immediately spin in a contrary direction at precisely the same speed. Remarkably, the phenomenon was proved in 1997 when physicists at the University of Geneva sent photons seven miles in opposite directions and demonstrated that interfering with one provoked an instantaneous response in the other.

Things reached such a pitch that at one conference Bohr remarked of a new theory that the question was not whether it was crazy, but whether it was crazy enough. To illustrate the nonintuitive nature of the quantum world, Schrödinger offered a famous thought experiment in which a hypothetical cat was placed in a box with one atom of a radioactive substance attached to a vial of hydrocyanic acid.

If the particle degraded within an hour, it would trigger a mechanism that would break the vial and

poison the cat. If not, the cat would live. But we could not know which was the case, so there was no

choice, scientifically, but to regard the cat as 100 percent alive and 100 percent dead at the same

time. This means, as Stephen Hawking has observed with a touch of understandable excitement, that

one cannot “predict future events exactly if one cannot even measure the present state of the universe

precisely!”

Because of its oddities, many physicists disliked quantum theory, or at least certain aspects of it, and

none more so than Einstein. This was more than a little ironic since it was he, in his annus mirabilis

of 1905, who had so persuasively explained how photons of light could sometimes behave like

particles and sometimes like waves— the notion at the very heart of the new physics. “Quantum

theory is very worthy of regard,” he observed politely, but he really didn’t like it. “God doesn’t play

dice,” he said.*23

Einstein couldn’t bear the notion that God could create a universe in which

some things were forever

unknowable. Moreover, the idea of action at a distance— that one particle

could instantaneously

influence another trillions of miles away— was a stark violation of the

special theory of relativity.

This expressly decreed that nothing could outrace the speed of light and yet

here were physicists

insisting that, somehow, at the subatomic level, information could. (No one,

incidentally, has ever

explained how the particles achieve this feat. Scientists have dealt with this

problem, according to

the physicist Yakir Aharanov, “by not thinking about it.”)

Above all, there was the problem that quantum physics introduced a level of

untidiness that hadn’t

previously existed. Suddenly you needed two sets of laws to explain the

behavior of the universe—

quantum theory for the world of the very small and relativity for the larger universe beyond. The gravity of relativity theory was brilliant at explaining why planets orbited suns or why galaxies tended to cluster, but turned out to have no influence at all at the particle level. To explain what kept atoms together, other forces were needed, and in the 1930s two were discovered: the strong nuclear force and weak nuclear force. The strong force binds atoms together; it's what allows protons to bed down together in the nucleus. The weak force engages in more miscellaneous tasks, mostly to do with controlling the rates of certain sorts of radioactive decay.

The weak nuclear force, despite its name, is ten billion billion billion times stronger than gravity, and the strong nuclear force is more powerful still— vastly so, in fact— but their influence extends to only the tiniest distances. The grip of the strong force reaches out only to about 1/100,000 of the diameter of an atom. That's why the nuclei of atoms are so compacted and dense and why elements with big, crowded nuclei tend to be so unstable: the strong force just can’t hold on to all the protons.

The upshot of all this is that physics ended up with two bodies of laws— one for the world of the very small, one for the universe at large— leading quite separate lives. Einstein disliked that, too. He devoted the rest of his life to searching for a way to tie up these loose ends by finding a grand unified theory, and always failed. From time to time he thought he had it, but it always unraveled on him in the end. As time passed he became increasingly marginalized and even a little pitied. Almost without exception, wrote Snow, “his colleagues thought, and still think, that he wasted the second half of his life.”

Elsewhere, however, real progress was being made. By the mid-1940s scientists had reached a point where they understood the atom at an extremely profound level— as they all too effectively demonstrated in August 1945 by exploding a pair of atomic bombs over

Japan.

By this point physicists could be excused for thinking that they had just about conquered the atom. In fact, everything in particle physics was about to get a whole lot more complicated. But before we take up that slightly exhausting story, we must bring another straw of our history up to date by considering an important and salutary tale of avarice, deceit, bad science, several needless deaths, and the final determination of the age of the Earth.

10 **GETTING THE LEAD OUT**

IN THE LATE 1940s, a graduate student at the University of Chicago named Clair Patterson (who was, first name notwithstanding, an Iowa farm boy by origin) was using a new method of lead isotope measurement to try to get a definitive age for the Earth at last. Unfortunately all his samples came up contaminated— usually wildly so. Most contained something like two hundred times the levels of lead that would normally be expected to occur. Many years would pass before Patterson

realized that the reason for this lay with a regrettable Ohio inventor named

Thomas Midgley, Jr.

Midgley was an engineer by training, and the world would no doubt have

been a safer place if he had

stayed so. Instead, he developed an interest in the industrial applications of

chemistry. In 1921, while

working for the General Motors Research Corporation in Dayton, Ohio, he

investigated a compound

called tetraethyl lead (also known, confusingly, as lead tetraethyl), and

discovered that it

significantly reduced the juddering condition known as engine knock.

Even though lead was widely known to be dangerous, by the early years of

the twentieth century it

could be found in all manner of consumer products. Food came in cans

sealed with lead solder.

Water was often stored in lead-lined tanks. It was sprayed onto fruit as a

pesticide in the form of lead

arsenate. It even came as part of the packaging of toothpaste tubes. Hardly a

product existed that

didn’t bring a little lead into consumers’ lives. However, nothing gave it a greater and more lasting intimacy than its addition to gasoline.

Lead is a neurotoxin. Get too much of it and you can irreparably damage the brain and central nervous system. Among the many symptoms associated with overexposure are blindness, insomnia, kidney failure, hearing loss, cancer, palsies, and convulsions. In its most acute form it produces abrupt and terrifying hallucinations, disturbing to victims and onlookers alike, which generally then give way to coma and death. You really don’t want to get too much lead into your system.

On the other hand, lead was easy to extract and work, and almost embarrassingly profitable to produce industrially— and tetraethyl lead did indubitably stop engines from knocking. So in 1923 three of America’s largest corporations, General Motors, Du Pont, and Standard Oil of New Jersey, formed a joint enterprise called the Ethyl Gasoline Corporation (later shortened to simply Ethyl

Corporation) with a view to making as much tetraethyl lead as the world was willing to buy, and that

proved to be a very great deal. They called their additive “ethyl” because it sounded friendlier and

less toxic than “lead” and introduced it for public consumption (in more ways than most people

realized) on February 1, 1923.

Almost at once production workers began to exhibit the staggered gait and confused faculties that

mark the recently poisoned. Also almost at once, the Ethyl Corporation embarked on a policy of

calm but unyielding denial that would serve it well for decades. As Sharon Bertsch McGrayne notes

in her absorbing history of industrial chemistry, Prometheans in the Lab, when employees at one

plant developed irreversible delusions, a spokesman blandly informed reporters: “These men

probably went insane because they worked too hard.” Altogether at least fifteen workers died in the

early days of production of leaded gasoline, and untold numbers of others became ill, often violently
so; the exact numbers are unknown because the company nearly always managed to hush up news of
embarrassing leakages, spills, and poisonings. At times, however, suppressing the news became
impossible, most notably in 1924 when in a matter of days five production workers died and thirtyfive
more were turned into permanent staggering wrecks at a single ill-ventilated facility.

As rumors circulated about the dangers of the new product, ethyl's ebullient inventor, Thomas
Midgley, decided to hold a demonstration for reporters to allay their concerns. As he chatted away
about the company's commitment to safety, he poured tetraethyl lead over his hands, then held a
beaker of it to his nose for sixty seconds, claiming all the while that he could repeat the procedure
daily without harm. In fact, Midgley knew only too well the perils of lead poisoning: he had himself

been made seriously ill from overexposure a few months earlier and now, except when reassuring
journalists, never went near the stuff if he could help it.
Buoyed by the success of leaded gasoline, Midgley now turned to another technological problem of
the age. Refrigerators in the 1920s were often appallingly risky because they used dangerous gases
that sometimes leaked. One leak from a refrigerator at a hospital in Cleveland, Ohio, in 1929 killed
more than a hundred people. Midgley set out to create a gas that was stable, nonflammable,
noncorrosive, and safe to breathe. With an instinct for the regrettable that was almost uncanny, he
invented chlorofluorocarbons, or CFCs.
Seldom has an industrial product been more swiftly or unfortunately embraced. CFCs went into
production in the early 1930s and found a thousand applications in everything from car air
conditioners to deodorant sprays before it was noticed, half a century later, that they were devouring

the ozone in the stratosphere. As you will be aware, this was not a good thing.

Ozone is a form of oxygen in which each molecule bears three atoms of oxygen instead of two. It is
a bit of a chemical oddity in that at ground level it is a pollutant, while way up in the stratosphere it
is beneficial, since it soaks up dangerous ultraviolet radiation. Beneficial ozone is not terribly
abundant, however. If it were distributed evenly throughout the stratosphere, it would form a layer
just one eighth of an inch or so thick. That is why it is so easily disturbed, and why such disturbances
don’t take long to become critical.

Chlorofluorocarbons are also not very abundant— they constitute only about one part per billion of
the atmosphere as a whole— but they are extravagantly destructive. One pound of CFCs can capture
and annihilate seventy thousand pounds of atmospheric ozone. CFCs also hang around for a long
time— about a century on average— wreaking havoc all the while. They are

also great heat sponges.

A single CFC molecule is about ten thousand times more efficient at exacerbating greenhouse effects

than a molecule of carbon dioxide— and carbon dioxide is of course no slouch itself as a greenhouse

gas. In short, chlorofluorocarbons may ultimately prove to be just about the worst invention of the

twentieth century.

Midgley never knew this because he died long before anyone realized how destructive CFCs were.

His death was itself memorably unusual. After becoming crippled with polio, Midgley invented a

contraption involving a series of motorized pulleys that automatically raised or turned him in bed. In

1944, he became entangled in the cords as the machine went into action and was strangled.

If you were interested in finding out the ages of things, the University of Chicago in the 1940s was

the place to be. Willard Libby was in the process of inventing radiocarbon dating, allowing scientists to get an accurate reading of the age of bones and other organic remains, something they had never been able to do before. Up to this time, the oldest reliable dates went back no further than the First Dynasty in Egypt from about 3000 B.C. No one could confidently say, for instance, when the last ice sheets had retreated or at what time in the past the Cro-Magnon people had decorated the caves of Lascaux in France.

Libby’s idea was so useful that he would be awarded a Nobel Prize for it in 1960. It was based on the realization that all living things have within them an isotope of carbon called carbon-14, which begins to decay at a measurable rate the instant they die. Carbon-14 has a half-life— that is, the time it takes for half of any sample to disappear*24— of about 5,600 years, so by working out how much a given sample of carbon had decayed, Libby could get a good fix on the age of an object— though only up to a point. After eight half-lives, only 1/256 of the original

radioactive carbon remains,
which is too little to make a reliable measurement, so radiocarbon dating works only for objects up
to forty thousand or so years old.

Curiously, just as the technique was becoming widespread, certain flaws within it became apparent.

To begin with, it was discovered that one of the basic components of Libby’s formula, known as the
decay constant, was off by about 3 percent. By this time, however, thousands of measurements had
been taken throughout the world. Rather than restate every one, scientists decided to keep the
inaccurate constant. “Thus,” Tim Flannery notes, “every raw radiocarbon date you read today is
given as too young by around 3 percent.” The problems didn’t quite stop there. It was also quickly
discovered that carbon-14 samples can be easily contaminated with carbon from other sources— a
tiny scrap of vegetable matter, for instance, that has been collected with the sample and not noticed.

For younger samples— those under twenty thousand years or so— slight contamination does not always matter so much, but for older samples it can be a serious problem because so few remaining atoms are being counted. In the first instance, to borrow from Flannery, it is like miscounting by a dollar when counting to a thousand; in the second it is more like miscounting by a dollar when you have only two dollars to count.

Libby's method was also based on the assumption that the amount of carbon-14 in the atmosphere, and the rate at which it has been absorbed by living things, has been consistent throughout history. In fact it hasn't been. We now know that the volume of atmospheric carbon-14 varies depending on how well or not Earth's magnetism is deflecting cosmic rays, and that that can vary significantly over time. This means that some carbon-14 dates are more dubious than others. This is particularly so with dates just around the time that people first came to the Americas,

which is one of the reasons
the matter is so perennially in dispute.
Finally, and perhaps a little unexpectedly, readings can be thrown out by seemingly unrelated
external factors— such as the diets of those whose bones are being tested. One recent case involved
the long-running debate over whether syphilis originated in the New World or the Old. Archeologists
in Hull, in the north of England, found that monks in a monastery graveyard had suffered from
syphilis, but the initial conclusion that the monks had done so before Columbus's voyage was cast
into doubt by the realization that they had eaten a lot of fish, which could make their bones appear to
be older than in fact they were. The monks may well have had syphilis, but how it got to them, and
when, remain tantalizingly unresolved.
Because of the accumulated shortcomings of carbon-14, scientists devised other methods of dating
ancient materials, among them thermoluminesence, which measures

electrons trapped in clays, and
electron spin resonance, which involves bombarding a sample with electromagnetic waves and measuring the vibrations of the electrons. But even the best of these could not date anything older than about 200,000 years, and they couldn't date inorganic materials like rocks at all, which is of course what you need if you wish to determine the age of your planet.

The problems of dating rocks were such that at one point almost everyone in the world had given up on them. Had it not been for a determined English professor named Arthur Holmes, the quest might well have fallen into abeyance altogether.

Holmes was heroic as much for the obstacles he overcame as for the results he achieved. By the 1920s, when Holmes was in the prime of his career, geology had slipped out of fashion— physics was the new excitement of the age— and had become severely underfunded, particularly in Britain, its spiritual birthplace. At Durham University, Holmes was for many years the entire geology

department. Often he had to borrow or patch together equipment in order to pursue his radiometric

dating of rocks. At one point, his calculations were effectively held up for a year while he waited for

the university to provide him with a simple adding machine. Occasionally, he had to drop out of

academic life altogether to earn enough to support his family— for a time he ran a curio shop in

Newcastle upon Tyne— and sometimes he could not even afford the £5 annual membership fee for

the Geological Society.

The technique Holmes used in his work was theoretically straightforward and arose directly from the

process, first observed by Ernest Rutherford in 1904, in which some atoms decay from one element

into another at a rate predictable enough that you can use them as clocks. If you know how long it

takes for potassium-40 to become argon-40, and you measure the amounts of each in a sample, you

can work out how old a material is. Holmes's contribution was to measure the decay rate of uranium
into lead to calculate the age of rocks, and thus— he hoped— of the Earth. But there were many technical difficulties to overcome. Holmes also needed— or at least would very
much have appreciated— sophisticated gadgetry of a sort that could make very fine measurements
from tiny samples, and as we have seen it was all he could do to get a simple adding machine. So it
was quite an achievement when in 1946 he was able to announce with some confidence that the
Earth was at least three billion years old and possibly rather more. Unfortunately, he now met yet
another formidable impediment to acceptance: the conservativeness of his fellow scientists.
Although happy to praise his methodology, many maintained that he had found not the age of the
Earth but merely the age of the materials from which the Earth had been formed.
It was just at this time that Harrison Brown of the University of Chicago

developed a new method for counting lead isotopes in igneous rocks (which is to say those that were created through heating, as opposed to the laying down of sediments). Realizing that the work would be exceedingly tedious, he assigned it to young Clair Patterson as his dissertation project. Famously he promised Patterson that determining the age of the Earth with his new method would be "duck soup." In fact, it would take years.

Patterson began work on the project in 1948. Compared with Thomas Midgley's colorful contributions to the march of progress, Patterson's discovery of the age of the Earth feels more than a touch anticlimactic. For seven years, first at the University of Chicago and then at the California Institute of Technology (where he moved in 1952), he worked in a sterile lab, making very precise measurements of the lead/uranium ratios in carefully selected samples of old rock.

The problem with measuring the age of the Earth was that you needed rocks that were extremely ancient, containing lead- and uranium-bearing crystals that were about as old as the planet itself— anything much younger would obviously give you misleadingly youthful dates— but really ancient rocks are only rarely found on Earth. In the late 1940s no one altogether understood why this should be. Indeed, and rather extraordinarily, we would be well into the space age before anyone could plausibly account for where all the Earth's old rocks went. (The answer was plate tectonics, which we shall of course get to.) Patterson, meantime, was left to try to make sense of things with very limited materials. Eventually, and ingeniously, it occurred to him that he could circumvent the rock shortage by using rocks from beyond Earth. He turned to meteorites.

The assumption he made— rather a large one, but correct as it turned out— was that many meteorites are essentially leftover building materials from the early days of the solar

system, and thus have
managed to preserve a more or less pristine interior chemistry. Measure the age of these wandering
rocks and you would have the age also (near enough) of the Earth.

As always, however, nothing was quite as straightforward as such a breezy description makes it
sound. Meteorites are not abundant and meteoritic samples not especially easy to get hold of.

Moreover, Brown's measurement technique proved finicky in the extreme and needed much
refinement. Above all, there was the problem that Patterson's samples were continuously and
unaccountably contaminated with large doses of atmospheric lead whenever they were exposed to
air. It was this that eventually led him to create a sterile laboratory— the world's first, according to at
least one account.

It took Patterson seven years of patient work just to assemble suitable samples for final testing. In the
spring of 1953 he traveled to the Argonne National Laboratory in Illinois,

where he was granted time
on a late-model mass spectrograph, a machine capable of detecting and measuring the minute
quantities of uranium and lead locked up in ancient crystals. When at last he had his results,
Patterson was so excited that he drove straight to his boyhood home in Iowa and had his mother
check him into a hospital because he thought he was having a heart attack.
Soon afterward, at a meeting in Wisconsin, Patterson announced a definitive age for the Earth of
4,550 million years (plus or minus 70 million years)— “a figure that stands unchanged 50 years
later,” as McGrayne admiringly notes. After two hundred years of trying, the Earth finally had an
age.

His main work done, Patterson now turned his attention to the nagging question of all that lead in the
atmosphere. He was astounded to find that what little was known about the effects of lead on humans
was almost invariably wrong or misleading— and not surprisingly, he

discovered, since for forty years every study of lead's effects had been funded exclusively by manufacturers of lead additives.

In one such study, a doctor who had no specialized training in chemical pathology undertook a fiveyear program in which volunteers were asked to breathe in or swallow lead in elevated quantities.

Then their urine and feces were tested. Unfortunately, as the doctor appears not to have known, lead is not excreted as a waste product. Rather, it accumulates in the bones and blood— that's what makes it so dangerous— and neither bone nor blood was tested. In consequence, lead was given a clean bill of health.

Patterson quickly established that we had a lot of lead in the atmosphere— still do, in fact, since lead never goes away— and that about 90 percent of it appeared to come from automobile exhaust pipes, but he couldn't prove it. What he needed was a way to compare lead levels in the atmosphere now with the levels that existed before 1923, when tetraethyl lead was introduced. It occurred to him that ice cores could provide the answer.

It was known that snowfall in places like Greenland accumulates into discrete annual layers (because seasonal temperature differences produce slight changes in coloration from winter to summer). By counting back through these layers and measuring the amount of lead in each, he could work out global lead concentrations at any time for hundreds, or even thousands, of years. The notion became the foundation of ice core studies, on which much modern climatological work is based.

What Patterson found was that before 1923 there was almost no lead in the atmosphere, and that since that time its level had climbed steadily and dangerously. He now made it his life’s quest to get lead taken out of gasoline. To that end, he became a constant and often vocal critic of the lead industry and its interests.

It would prove to be a hellish campaign. Ethyl was a powerful global corporation with many friends in high places. (Among its directors have been Supreme Court Justice Lewis Powell and Gilbert Grosvenor of the National Geographic Society.) Patterson suddenly found research funding withdrawn or difficult to acquire. The American Petroleum Institute canceled a research contract with him, as did the United States Public Health Service, a supposedly neutral government institution.

As Patterson increasingly became a liability to his institution, the school trustees were repeatedly pressed by lead industry officials to shut him up or let him go. According to Jamie Lincoln Kitman, writing in The Nation in 2000, Ethyl executives allegedly offered to endow a chair at Caltech “if Patterson was sent packing.” Absurdly, he was excluded from a 1971 National Research Council panel appointed to investigate the dangers of atmospheric lead poisoning even though he was by now unquestionably the leading expert on atmospheric lead.

To his great credit, Patterson never wavered or buckled. Eventually his efforts led to the introduction of the Clean Air Act of 1970 and finally to the removal from sale of all leaded gasoline in the United States in 1986. Almost immediately lead levels in the blood of Americans fell by 80 percent. But because lead is forever, those of us alive today have about 625 times more lead in our blood than people did a century ago. The amount of lead in the atmosphere also continues to grow, quite legally, by about a hundred thousand metric tons a year, mostly from mining, smelting, and industrial activities. The United States also banned lead in indoor paint, “forty-four years after most of Europe,” as McGrayne notes. Remarkably, considering its startling toxicity, lead solder was not removed from American food containers until 1993.

As for the Ethyl Corporation, it’s still going strong, though GM, Standard

Oil, and Du Pont no

longer have stakes in the company. (They sold out to a company called Albemarle Paper in 1962.)

According to McGrayne, as late as February 2001 Ethyl continued to contend "that research has failed to show that leaded gasoline poses a threat to human health or the environment." On its website, a history of the company makes no mention of lead— or indeed of Thomas Midgley— but simply refers to the original product as containing "a certain combination of chemicals."

Ethyl no longer makes leaded gasoline, although, according to its 2001 company accounts, tetraethyl lead (or TEL as it calls it) still accounted for $25.1 million in sales in 2000 (out of overall sales of $795 million), up from $24.1 million in 1999, but down from $117 million in 1998. In its report the company stated its determination to "maximize the cash generated by TEL as its usage continues to phase down around the world." Ethyl markets TEL through an agreement with Associated Octel of England.

As for the other scourge left to us by Thomas Midgley, chlorofluorocarbons, they were banned in 1974 in the United States, but they are tenacious little devils and any that you loosed into the atmosphere before then (in your deodorants or hair sprays, for instance) will almost certainly be around and devouring ozone long after you have shuffled off. Worse, we are still introducing huge amounts of CFCs into the atmosphere every year. According to Wayne Biddle, 60 million pounds of the stuff, worth $1.5 billion, still finds its way onto the market every year. So who is making it? We are— that is to say, many of our large corporations are still making it at their plants overseas. It will not be banned in Third World countries until 2010.

Clair Patterson died in 1995. He didn’t win a Nobel Prize for his work. Geologists never do. Nor, more puzzlingly, did he gain any fame or even much attention from half a

century of consistent and
increasingly selfless achievement. A good case could be made that he was the most influential
geologist of the twentieth century. Yet who has ever heard of Clair Patterson? Most geology
textbooks don't mention him. Two recent popular books on the history of the dating of Earth actually
manage to misspell his name. In early 2001, a reviewer of one of these books in the journal Nature
made the additional, rather astounding error of thinking Patterson was a woman.

At all events, thanks to the work of Clair Patterson by 1953 the Earth at last had an age everyone
could agree on. The only problem now was it was older than the universe that contained it.

11 **MUSTER MARK'S QUARKS**

IN 1911, A British scientist named C. T. R. Wilson was studying cloud formations by tramping
regularly to the summit of Ben Nevis, a famously damp Scottish mountain, when it occurred to him

that there must be an easier way to study clouds. Back in the Cavendish Lab in Cambridge he built
an artificial cloud chamber— a simple device in which he could cool and moisten the air, creating a
reasonable model of a cloud in laboratory conditions.
The device worked very well, but had an additional, unexpected benefit. When he accelerated an
alpha particle through the chamber to seed his make-believe clouds, it left a visible trail— like the
contrails of a passing airliner. He had just invented the particle detector. It provided convincing
evidence that subatomic particles did indeed exist.
Eventually two other Cavendish scientists invented a more powerful proton-beam device, while in
California Ernest Lawrence at Berkeley produced his famous and impressive cyclotron, or atom
smasher, as such devices were long excitingly known. All of these contraptions worked— and indeed
still work— on more or less the same principle, the idea being to accelerate a proton or other charged

particle to an extremely high speed along a track (sometimes circular, sometimes linear), then bang it into another particle and see what flies off. That's why they were called atom smashers. It wasn't science at its subtlest, but it was generally effective.

As physicists built bigger and more ambitious machines, they began to find or postulate particles or particle families seemingly without number: muons, pions, hyperons, mesons, K-mesons, Higgs bosons, intermediate vector bosons, baryons, tachyons. Even physicists began to grow a little uncomfortable. "Young man," Enrico Fermi replied when a student asked him the name of a particular particle, "if I could remember the names of these particles, I would have been a botanist."

Today accelerators have names that sound like something Flash Gordon would use in battle: the Super Proton Synchrotron, the Large Electron-Positron Collider, the Large Hadron Collider, the Relativistic Heavy Ion Collider. Using huge amounts of energy (some operate only at night so that

people in neighboring towns don’t have to witness their lights fading when

the apparatus is fired up),

they can whip particles into such a state of liveliness that a single electron

can do forty-seven

thousand laps around a four-mile tunnel in a second. Fears have been raised

that in their enthusiasm

scientists might inadvertently create a black hole or even something called

“strange quarks,” which

could, theoretically, interact with other subatomic particles and propagate

uncontrollably. If you are

reading this, that hasn’t happened.

Finding particles takes a certain amount of concentration. They are not just

tiny and swift but also

often tantalizingly evanescent. Particles can come into being and be gone

again in as little as

0.000000000000000000000001 second (10-24). Even the most sluggish of

unstable particles hang

around for no more than 0.0000001 second (10-7).

Some particles are almost ludicrously slippery. Every second the Earth is

visited by 10,000 trillion
trillion tiny, all but massless neutrinos (mostly shot out by the nuclear broilings of the Sun), and
virtually all of them pass right through the planet and everything that is on it, including you and me,
as if it weren't there. To trap just a few of them, scientists need tanks holding up to 12.5 million
gallons of heavy water (that is, water with a relative abundance of deuterium in it) in underground
chambers (old mines usually) where they can't be interfered with by other types of radiation.
Very occasionally, a passing neutrino will bang into one of the atomic nuclei in the water and
produce a little puff of energy. Scientists count the puffs and by such means take us very slightly
closer to understanding the fundamental properties of the universe. In 1998, Japanese observers
reported that neutrinos do have mass, but not a great deal— about one ten-millionth that of an
electron.

What it really takes to find particles these days is money and lots of it. There is a curious inverse relationship in modern physics between the tininess of the thing being sought and the scale of facilities required to do the searching. CERN, the European Organization for Nuclear Research, is like a little city. Straddling the border of France and Switzerland, it employs three thousand people and occupies a site that is measured in square miles. CERN boasts a string of magnets that weigh more than the Eiffel Tower and an underground tunnel over sixteen miles around.

Breaking up atoms, as James Trefil has noted, is easy; you do it each time you switch on a fluorescent light. Breaking up atomic nuclei, however, requires quite a lot of money and a generous supply of electricity. Getting down to the level of quarks— the particles that make up particles— requires still more: trillions of volts of electricity and the budget of a small Central American nation.

CERN's new Large Hadron Collider, scheduled to begin operations in 2005, will achieve fourteen trillion volts of energy and cost something over $1.5 billion to construct.*25 But these numbers are as nothing compared with what could have been achieved by, and spent upon, the vast and now unfortunately never-to-be Superconducting Supercollider, which began being constructed near Waxahachie, Texas, in the 1980s, before experiencing a supercollision of its own with the United States Congress. The intention of the collider was to let scientists probe "the ultimate nature of matter," as it is always put, by re-creating as nearly as possible the conditions in the universe during its first ten thousand billionths of a second. The plan was to fling particles through a tunnel fifty-two miles long, achieving a truly staggering ninety-nine trillion volts of energy. It was a grand scheme, but would also have cost $8 billion to build (a figure that eventually rose to $10 billion) and hundreds of millions of dollars a year to run.

In perhaps the finest example in history of pouring money into a hole in the ground, Congress spent $2 billion on the project, then canceled it in 1993 after fourteen miles of tunnel had been dug. So Texas now boasts the most expensive hole in the universe. The site is, I am told by my friend Jeff Guinn of the Fort Worth Star-Telegram, “essentially a vast, cleared field dotted along the circumference by a series of disappointed small towns.”

Since the supercollider debacle particle physicists have set their sights a little lower, but even comparatively modest projects can be quite breathtakingly costly when compared with, well, almost anything. A proposed neutrino observatory at the old Homestake Mine in Lead, South Dakota, would cost $500 million to build— this in a mine that is already dug— before you even look at the annual running costs. There would also be $281 million of “general conversion costs.” A particle accelerator at Fermilab in Illinois, meanwhile, cost $260 million merely to refit.

Particle physics, in short, is a hugely expensive enterprise— but it is a productive one. Today the particle count is well over 150, with a further 100 or so suspected, but unfortunately, in the words of Richard Feynman, “it is very difficult to understand the relationships of all these particles, and what nature wants them for, or what the connections are from one to another.” Inevitably each time we manage to unlock a box, we find that there is another locked box inside. Some people think there are particles called tachyons, which can travel faster than the speed of light. Others long to find gravitons— the seat of gravity. At what point we reach the irreducible bottom is not easy to say. Carl Sagan in Cosmos raised the possibility that if you traveled downward into an electron, you might find that it contained a universe of its own, recalling all those science fiction stories of the fifties.

“Within it, organized into the local equivalent of galaxies and smaller structures, are an immense number of other, much tinier elementary particles, which are themselves universes at the next level and so on forever— an infinite downward regression, universes within universes, endlessly. And upward as well.”

For most of us it is a world that surpasses understanding. To read even an elementary guide to particle physics nowadays you must now find your way through lexical thickets such as this: “The charged pion and antipion decay respectively into a muon plus antineutrino and an antimuon plus neutrino with an average lifetime of 2.603 x 10-8 seconds, the neutral pion decays into two photons with an average lifetime of about 0.8 x 10-16 seconds, and the muon and antimuon decay respectively into . . .” And so it runs on— and this from a book for the general reader by one of the (normally) most lucid of interpreters, Steven Weinberg.

In the 1960s, in an attempt to bring just a little simplicity to matters, the Caltech physicist Murray

Gell-Mann invented a new class of particles, essentially, in the words of Steven Weinberg, “to restore some economy to the multitude of hadrons”— a collective term used by physicists for protons, neutrons, and other particles governed by the strong nuclear force. Gell-Mann’s theory was that all hadrons were made up of still smaller, even more fundamental particles. His colleague Richard Feynman wanted to call these new basic particles partons, as in Dolly, but was overruled. Instead they became known as quarks. Gell-Mann took the name from a line in Finnegans Wake: “Three quarks for Muster Mark!” (Discriminating physicists rhyme the word with storks, not larks, even though the latter is almost certainly the pronunciation Joyce had in mind.) The fundamental simplicity of quarks was not long lived. As they became better understood it was necessary to introduce subdivisions. Although quarks are much too small to have color or taste or any other physical characteristics we would recognize, they became clumped into six categories— up, down, strange, charm, top, and bottom— which physicists oddly refer to as their “flavors,” and these are further divided into the colors red, green, and blue. (One suspects that it was not altogether coincidental that these terms were first applied in California during the age of psychedelia.)

Eventually out of all this emerged what is called the Standard Model, which is essentially a sort of parts kit for the subatomic world. The Standard Model consists of six quarks, six leptons, five known bosons and a postulated sixth, the Higgs boson (named for a Scottish scientist, Peter Higgs), plus three of the four physical forces: the strong and weak nuclear forces and electromagnetism.

The arrangement essentially is that among the basic building blocks of matter are quarks; these are held together by particles called gluons; and together quarks and gluons form protons and neutrons, the stuff of the atom’s nucleus. Leptons are the source of electrons and neutrinos. Quarks and leptons together are called fermions. Bosons (named for the Indian physicist S. N. Bose) are particles that produce and carry forces, and include photons and gluons. The Higgs boson may or may not actually exist; it was invented simply as a way of endowing particles with mass.

It is all, as you can see, just a little unwieldy, but it is the simplest model that can explain all that happens in the world of particles. Most particle physicists feel, as Leon Lederman remarked in a 1985 PBS documentary, that the Standard Model lacks elegance and simplicity. “It is too complicated. It has too many arbitrary parameters,” Lederman said. “We don’t really see the creator twiddling twenty knobs to set twenty parameters to create the universe as we know it.” Physics is really nothing more than a search for ultimate simplicity, but so far all we have is a kind of elegant messiness— or as Lederman put it: “There is a deep feeling that the picture is not beautiful."

The Standard Model is not only ungainly but incomplete. For one thing, it has nothing at all to say about gravity. Search through the Standard Model as you will, and you won't find anything to explain why when you place a hat on a table it doesn't float up to the ceiling. Nor, as we've just noted, can it explain mass. In order to give particles any mass at all we have to introduce the notional Higgs boson; whether it actually exists is a matter for twenty-first-century physics. As Feynman cheerfully observed: "So we are stuck with a theory, and we do not know whether it is right or wrong, but we do know that it is a little wrong, or at least incomplete."

In an attempt to draw everything together, physicists have come up with something called superstring theory. This postulates that all those little things like quarks and leptons that we had previously thought of as particles are actually "strings"— vibrating strands of energy that oscillate in

eleven dimensions, consisting of the three we know already plus time and seven other dimensions
that are, well, unknowable to us. The strings are very tiny— tiny enough to pass for point particles.
By introducing extra dimensions, superstring theory enables physicists to pull together quantum laws
and gravitational ones into one comparatively tidy package, but it also means that anything scientists
say about the theory begins to sound worryingly like the sort of thoughts that would make you edge
away if conveyed to you by a stranger on a park bench. Here, for example, is the physicist Michio
Kaku explaining the structure of the universe from a superstring perspective: “The heterotic string
consists of a closed string that has two types of vibrations, clockwise and counterclockwise, which
are treated differently. The clockwise vibrations live in a ten-dimensional space. The
counterclockwise live in a twenty-six-dimensional space, of which sixteen dimensions have been

compactified. (We recall that in Kaluza's original five-dimensional, the fifth dimension was compactified by being wrapped up into a circle.)" And so it goes, for some 350 pages.

String theory has further spawned something called "M theory," which incorporates surfaces known as membranes— or simply "branes" to the hipper souls of the world of physics. I'm afraid this is the stop on the knowledge highway where most of us must get off. Here is a sentence from the New York Times, explaining this as simply as possible to a general audience: "The ekpyrotic process begins far in the indefinite past with a pair of flat empty branes sitting parallel to each other in a warped fivedimensional space. . . . The two branes, which form the walls of the fifth dimension, could have popped out of nothingness as a quantum fluctuation in the even more distant past and then drifted apart." No arguing with that. No understanding it either. Ekpyrotic, incidentally, comes from the

Greek word for “conflagration.”

Matters in physics have now reached such a pitch that, as Paul Davies noted in Nature, it is “almost impossible for the non-scientist to discriminate between the legitimately weird and the outright crackpot.” The question came interestingly to a head in the fall of 2002 when two French physicists, twin brothers Igor and Grickha Bogdanov, produced a theory of ambitious density involving such concepts as “imaginary time” and the “Kubo-Schwinger-Martin condition,” and purporting to describe the nothingness that was the universe before the Big Bang— a period that was always assumed to be unknowable (since it predated the birth of physics and its properties).

Almost at once the Bogdanov paper excited debate among physicists as to whether it was twaddle, a work of genius, or a hoax. “Scientifically, it’s clearly more or less complete nonsense,” Columbia University physicist Peter Woit told the New York Times, “but these days

that doesn’t much
distinguish it from a lot of the rest of the literature.”

Karl Popper, whom Steven Weinberg has called “the dean of modern philosophers of science,” once suggested that there may not be an ultimate theory for physics— that, rather, every explanation may require a further explanation, producing “an infinite chain of more and more fundamental principles.” A rival possibility is that such knowledge may simply be beyond us. “So far, fortunately,” writes Weinberg in Dreams of a Final Theory, “we do not seem to be coming to the end of our intellectual resources.”

Almost certainly this is an area that will see further developments of thought, and almost certainly these thoughts will again be beyond most of us.

While physicists in the middle decades of the twentieth-century were looking perplexedly into the world of the very small, astronomers were finding no less arresting an incompleteness of understanding in the universe at large.

When we last met Edwin Hubble, he had determined that nearly all the galaxies in our field of view
are flying away from us, and that the speed and distance of this retreat are neatly proportional: the
farther away the galaxy, the faster it is moving. Hubble realized that this could be expressed with a
simple equation, Ho = v/d (where Ho is the constant, v is the recessional velocity of a flying galaxy,
and d its distance away from us). Ho has been known ever since as the Hubble constant and the
whole as Hubble's Law. Using his formula, Hubble calculated that the universe was about two
billion years old, which was a little awkward because even by the late 1920s it was fairly obvious
that many things within the universe— not least Earth itself— were probably older than that. Refining
this figure has been an ongoing preoccupation of cosmology.

Almost the only thing constant about the Hubble constant has been the amount of disagreement over what value to give it. In 1956, astronomers discovered that Cepheid variables were more variable than they had thought; they came in two varieties, not one. This allowed them to rework their calculations and come up with a new age for the universe of from 7 to 20 billion years— not terribly precise, but at least old enough, at last, to embrace the formation of the Earth.

In the years that followed there erupted a long-running dispute between Allan Sandage, heir to Hubble at Mount Wilson, and Gérard de Vaucouleurs, a French-born astronomer based at the University of Texas. Sandage, after years of careful calculations, arrived at a value for the Hubble constant of 50, giving the universe an age of 20 billion years. De Vaucouleurs was equally certain that the Hubble constant was 100.*26 This would mean that the universe was only half the size and age that Sandage believed— ten billion years. Matters took a further lurch into uncertainty when in

1994 a team from the Carnegie Observatories in California, using measures from the Hubble space
telescope, suggested that the universe could be as little as eight billion years old— an age even they
conceded was younger than some of the stars within the universe. In February 2003, a team from
NASA and the Goddard Space Flight Center in Maryland, using a new, far-reaching type of satellite
called the Wilkinson Microwave Anistropy Probe, announced with some confidence that the age of
the universe is 13.7 billion years, give or take a hundred million years or so. There matters rest, at
least for the moment.

The difficulty in making final determinations is that there are often acres of room for interpretation.

Imagine standing in a field at night and trying to decide how far away two distant electric lights are.

Using fairly straightforward tools of astronomy you can easily enough determine that the bulbs are
of equal brightness and that one is, say, 50 percent more distant than the

other. But what you can’t be certain of is whether the nearer light is, let us say, a 58-watt bulb that is 122 feet away or a 61-watt light that is 119 feet, 8 inches away. On top of that you must make allowances for distortions caused by variations in the Earth’s atmosphere, by intergalactic dust, contaminating light from foreground stars, and many other factors. The upshot is that your computations are necessarily based on a series of nested assumptions, any of which could be a source of contention. There is also the problem that access to telescopes is always at a premium and historically measuring red shifts has been notably costly in telescope time. It could take all night to get a single exposure. In consequence, astronomers have sometimes been compelled (or willing) to base conclusions on notably scanty evidence. In cosmology, as the journalist Geoffrey Carr has suggested, we have “a mountain of theory built on a molehill of evidence.” Or as Martin Rees has put it: “Our present satisfaction [with our state of understanding] may reflect the paucity of the data rather than the excellence of the theory.”

This uncertainty applies, incidentally, to relatively nearby things as much as to the distant edges of the universe. As Donald Goldsmith notes, when astronomers say that the galaxy M87 is 60 million light-years away, what they really mean (“but do not often stress to the general public”) is that it is somewhere between 40 million and 90 million light-years away— not quite the same thing. For the universe at large, matters are naturally magnified. Bearing all that in mind, the best bets these days for the age of the universe seem to be fixed on a range of about 12 billion to 13.5 billion years, but we remain a long way from unanimity.

One interesting recently suggested theory is that the universe is not nearly as big as we thought, that when we peer into the distance some of the galaxies we see may simply be reflections, ghost images created by rebounded light.

The fact is, there is a great deal, even at quite a fundamental level, that we don't know— not least what the universe is made of. When scientists calculate the amount of matter needed to hold things together, they always come up desperately short. It appears that at least 90 percent of the universe, and perhaps as much as 99 percent, is composed of Fritz Zwicky's "dark matter"— stuff that is by its nature invisible to us. It is slightly galling to think that we live in a universe that, for the most part, we can't even see, but there you are. At least the names for the two main possible culprits are entertaining: they are said to be either WIMPs (for Weakly Interacting Massive Particles, which is to say specks of invisible matter left over from the Big Bang) or MACHOs (for MAssive Compact Halo Objects— really just another name for black holes, brown dwarfs, and other very dim stars).

Particle physicists have tended to favor the particle explanation of WIMPs, astrophysicists the stellar explanation of MACHOs. For a time MACHOs had the upper hand, but not nearly enough of them were found, so sentiment swung back toward WIMPs but with the problem that no WIMP has ever been found. Because they are weakly interacting, they are (assuming they even exist) very hard to detect. Cosmic rays would cause too much interference. So scientists must go deep underground.

One kilometer underground cosmic bombardments would be one millionth what they would be on the surface. But even when all these are added in, “two-thirds of the universe is still missing from the balance sheet,” as one commentator has put it. For the moment we might very well call them DUNNOS (for Dark Unknown Nonreflective Nondetectable Objects Somewhere).

Recent evidence suggests that not only are the galaxies of the universe racing away from us, but that they are doing so at a rate that is accelerating. This is counter to all expectations. It appears that the universe may not only be filled with dark matter, but with dark energy. Scientists sometimes also call it vacuum energy or, more exotically, quintessence. Whatever it is, it seems to be driving an expansion that no one can altogether account for. The theory is that empty space isn't so empty at all— that there are particles of matter and antimatter popping into existence and popping out again— and that these are pushing the universe outward at an accelerating rate. Improbably enough, the one thing that resolves all this is Einstein's cosmological constant— the little piece of math he dropped into the general theory of relativity to stop the universe's presumed expansion, and called "the biggest blunder of my life." It now appears that he may have gotten things right after all.

The upshot of all this is that we live in a universe whose age we can't quite compute, surrounded by stars whose distances we don't altogether know, filled with matter we can't

identify, operating in
conformance with physical laws whose properties we don’t truly understand.
And on that rather unsettling note, let’s return to Planet Earth and consider something that we do
understand— though by now you perhaps won’t be surprised to hear that we don’t understand it
completely and what we do understand we haven’t understood for long.

12 **THE EARTH MOVES**

IN ONE OF his last professional acts before his death in 1955, Albert Einstein wrote a short but
glowing foreword to a book by a geologist named Charles Hapgood entitled Earth’s Shifting Crust:
A Key to Some Basic Problems of Earth Science. Hapgood’s book was a steady demolition of the
idea that continents were in motion. In a tone that all but invited the reader to join him in a tolerant
chuckle, Hapgood observed that a few gullible souls had noticed “an apparent correspondence in
shape between certain continents.” It would appear, he went on, “that South America might be fitted

together with Africa, and so on. . . . It is even claimed that rock formations on opposite sides of the Atlantic match.”

Mr. Hapgood briskly dismissed any such notions, noting that the geologists K. E. Caster and J. C. Mendes had done extensive fieldwork on both sides of the Atlantic and had established beyond question that no such similarities existed. Goodness knows what outcrops Messrs. Caster and Mendes had looked at, beacuse in fact many of the rock formations on both sides of the Atlantic are the same— not just very similar but the same.

This was not an idea that flew with Mr. Hapgood, or many other geologists of his day. The theory Hapgood alluded to was one first propounded in 1908 by an amateur American geologist named Frank Bursley Taylor. Taylor came from a wealthy family and had both the means and freedom from academic constraints to pursue unconventional lines of inquiry. He was one of those struck by the similarity in shape between the facing coastlines of Africa and South America, and from this observation he developed the idea that the continents had once slid around. He suggested—presciently as it turned out— that the crunching together of continents could have thrust up the world's mountain chains. He failed, however, to produce much in the way of evidence, and the theory was considered too crackpot to merit serious attention.

In Germany, however, Taylor's idea was picked up, and effectively appropriated, by a theorist named Alfred Wegener, a meteorologist at the University of Marburg. Wegener investigated the many plant and fossil anomalies that did not fit comfortably into the standard model of Earth history and realized that very little of it made sense if conventionally interpreted. Animal fossils repeatedly turned up on opposite sides of oceans that were clearly too wide to swim. How, he wondered, did marsupials travel from South America to Australia? How did identical snails turn up in Scandinavia

and New England? And how, come to that, did one account for coal seams

and other semi-tropical

remnants in frigid spots like Spitsbergen, four hundred miles north of

Norway, if they had not

somehow migrated there from warmer climes?

Wegener developed the theory that the world's continents had once come

together in a single

landmass he called Pangaea, where flora and fauna had been able to mingle,

before the continents

had split apart and floated off to their present positions. All this he put

together in a book called Die

Entstehung der Kontinente und Ozeane, or The Origin of Continents and

Oceans, which was

published in German in 1912 and— despite the outbreak of the First World

War in the meantime— in

English three years later.

Because of the war, Wegener's theory didn't attract much notice at first, but

by 1920, when he

produced a revised and expanded edition, it quickly became a subject of discussion. Everyone agreed that continents moved— but up and down, not sideways. The process of vertical movement, known as isostasy, was a foundation of geological beliefs for generations, though no one had any good theories as to how or why it happened. One idea, which remained in textbooks well into my own school days, was the baked apple theory propounded by the Austrian Eduard Suess just before the turn of the century. This suggested that as the molten Earth had cooled, it had become wrinkled in the manner of a baked apple, creating ocean basins and mountain ranges. Never mind that James Hutton had shown long before that any such static arrangement would eventually result in a featureless spheroid as erosion leveled the bumps and filled in the divots. There was also the problem, demonstrated by Rutherford and Soddy early in the century, that Earthly elements hold huge reserves of heat— much too much to allow for the sort of cooling and shrinking Suess suggested. And anyway, if Suess's theory was correct then mountains should be evenly distributed across the face of the Earth, which patently they were not, and of more or less the same ages; yet by the early 1900s it was already evident that some ranges, like the Urals and Appalachians, were hundreds of millions of years older than others, like the Alps and Rockies. Clearly the time was ripe for a new theory. Unfortunately, Alfred Wegener was not the man that geologists wished to provide it.

For a start, his radical notions questioned the foundations of their discipline, seldom an effective way to generate warmth in an audience. Such a challenge would have been painful enough coming from a geologist, but Wegener had no background in geology. He was a meteorologist, for goodness sake. A weatherman— a German weatherman. These were not remediable deficiencies.

And so geologists took every pain they could think of to dismiss his evidence and belittle his suggestions. To get around the problems of fossil distributions, they posited ancient "land bridges" wherever they were needed. When an ancient horse named Hipparion was found to have lived in France and Florida at the same time, a land bridge was drawn across the Atlantic. When it was realized that ancient tapirs had existed simultaneously in South America and Southeast Asia a land bridge was drawn there, too. Soon maps of prehistoric seas were almost solid with hypothesized land bridges— from North America to Europe, from Brazil to Africa, from Southeast Asia to Australia, from Australia to Antarctica. These connective tendrils had not only conveniently appeared whenever it was necessary to move a living organism from one landmass to another, but then obligingly vanished without leaving a trace of their former existence. None of this, of course, was supported by so much as a grain of actual evidence— nothing so wrong could be— yet it was geological orthodoxy for the next half century.

Even land bridges couldn’t explain some things. One species of trilobite that was well known in Europe was also found to have lived on Newfoundland— but only on one side. No one could persuasively explain how it had managed to cross two thousand miles of hostile ocean but then failed to find its way around the corner of a 200-mile-wide island. Even more awkwardly anomalous was another species of trilobite found in Europe and the Pacific Northwest but nowhere in between, which would have required not so much a land bridge as a flyover. Yet as late as 1964 when the Encyclopaedia Britannica discussed the rival theories, it was Wegener’s that was held to be full of “numerous grave theoretical difficulties.”

To be sure, Wegener made mistakes. He asserted that Greenland is drifting west by about a mile a year, which is clearly nonsense. (It's more like half an inch.) Above all, he could offer no convincing explanation for how the landmasses moved about. To believe in his theory you had to accept that massive continents somehow pushed through solid crust, like a plow through soil, without leaving any furrow in their wake. Nothing then known could plausibly explain what motored these massive movements.

It was Arthur Holmes, the English geologist who did so much to determine the age of the Earth, who suggested a possible way. Holmes was the first scientist to understand that radioactive warming could produce convection currents within the Earth. In theory these could be powerful enough to slide continents around on the surface. In his popular and influential textbook Principles of Physical Geology, first published in 1944, Holmes laid out a continental drift theory that was in its fundamentals the theory that prevails today. It was still a radical proposition for the time and widely criticized, particularly in the United States, where resistance to drift lasted longer than elsewhere.

One reviewer there fretted, without any evident sense of irony, that Holmes presented his arguments so clearly and compellingly that students might actually come to believe them.

Elsewhere, however, the new theory drew steady if cautious support. In 1950, a vote at the annual meeting of the British Association for the Advancement of Science showed that about half of those present now embraced the idea of continental drift. (Hapgood soon after cited this figure as proof of how tragically misled British geologists had become.) Curiously, Holmes himself sometimes wavered in his conviction. In 1953 he confessed: “I have never succeeded in freeing myself from a nagging prejudice against continental drift; in my geological bones, so to speak, I feel the hypothesis is a fantastic one.”

Continental drift was not entirely without support in the United States. Reginald Daly of Harvard spoke for it, but he, you may recall, was the man who suggested that the Moon had been formed by a cosmic impact, and his ideas tended to be considered interesting, even worthy, but a touch too exuberant for serious consideration. And so most American academics stuck to the belief that the continents had occupied their present positions forever and that their surface features could be attributed to something other than lateral motions.

Interestingly, oil company geologists had known for years that if you wanted to find oil you had to allow for precisely the sort of surface movements that were implied by plate tectonics. But oil geologists didn't write academic papers; they just found oil.

There was one other major problem with Earth theories that no one had resolved, or even come close to resolving. That was the question of where all the sediments went. Every year Earth's rivers carried massive volumes of eroded material— 500 million tons of calcium, for instance— to the seas. If you multiplied the rate of deposition by the number of years it had been going on, it produced a disturbing figure: there should be about twelve miles of sediments on the ocean bottoms— or, put another way, the ocean bottoms should by now be well above the ocean tops. Scientists dealt with this paradox in the handiest possible way. They ignored it. But eventually there came a point when they could ignore it no longer.

In the Second World War, a Princeton University mineralogist named Harry Hess was put in charge of an attack transport ship, the USS Cape Johnson. Aboard this vessel was a fancy new depth sounder called a fathometer, which was designed to facilitate inshore maneuvers during beach landings, but Hess realized that it could equally well be used for scientific purposes and never switched it off, even when far out at sea, even in the heat of battle. What he found was entirely unexpected. If the ocean floors were ancient, as everyone assumed, they should be thickly blanketed with sediments, like the mud on the bottom of a river or lake. But Hess's readings showed that the ocean floor offered anything but the gooey smoothness of ancient silts. It was scored everywhere with canyons, trenches, and crevasses and dotted with volcanic seamounts that he called guyots after an earlier Princeton geologist named Arnold Guyot. All this was a puzzle, but Hess had a war to take part in, and put such thoughts to the back of his mind.

After the war, Hess returned to Princeton and the preoccupations of teaching, but the mysteries of the seafloor continued to occupy a space in his thoughts. Meanwhile, throughout the 1950s oceanographers were undertaking more and more sophisticated surveys of the ocean floors. In so doing, they found an even bigger surprise: the mightiest and most extensive mountain range on Earth was— mostly— underwater. It traced a continuous path along the world’s seabeds, rather like the stitching on a baseball. If you began at Iceland, you could follow it down the center of the Atlantic Ocean, around the bottom of Africa, and across the Indian and Southern Oceans, below Australia; there it angled across the Pacific as if making for Baja California before shooting up the west coast of the United States to Alaska. Occasionally its higher peaks poked above the water as an island or archipelago— the Azores and Canaries in the Atlantic, Hawaii in the Pacific, for instance— but mostly it was buried under thousands of fathoms of salty sea, unknown and unsuspected. When all its branches were added together, the network extended to 46,600 miles.

A very little of this had been known for some time. People laying ocean-floor cables in the nineteenth century had realized that there was some kind of mountainous intrusion in the mid-Atlantic from the way the cables ran, but the continuous nature and overall scale of the chain was a stunning surprise. Moreover, it contained physical anomalies that couldn’t be explained. Down the middle of the mid-Atlantic ridge was a canyon— a rift— up to a dozen miles wide for its entire 12,000-mile length. This seemed to suggest that the Earth was splitting apart at the seams, like a nut bursting out of its shell. It was an absurd and unnerving notion, but the evidence couldn’t be denied.

Then in 1960 core samples showed that the ocean floor was quite young at the mid-Atlantic ridge but grew progressively older as you moved away from it to the east or west. Harry Hess considered the matter and realized that this could mean only one thing: new ocean crust was being formed on either side of the central rift, then being pushed away from it as new crust came along behind. The Atlantic floor was effectively two large conveyor belts, one carrying crust toward North America, the other carrying crust toward Europe. The process became known as seafloor spreading.

When the crust reached the end of its journey at the boundary with continents, it plunged back into the Earth in a process known as subduction. That explained where all the sediment went. It was being returned to the bowels of the Earth. It also explained why ocean floors everywhere were so comparatively youthful. None had ever been found to be older than about 175 million years, which was a puzzle because continental rocks were often billions of years old. Now Hess could see why.

Ocean rocks lasted only as long as it took them to travel to shore. It was a beautiful theory that explained a great deal. Hess elaborated his ideas in an important paper, which was almost universally ignored. Sometimes the world just isn’t ready for a good idea.

Meanwhile, two researchers, working independently, were making some startling findings by drawing on a curious fact of Earth history that had been discovered several decades earlier. In 1906, a French physicist named Bernard Brunhes had found that the planet’s magnetic field reverses itself from time to time, and that the record of these reversals is permanently fixed in certain rocks at the time of their birth. Specifically, tiny grains of iron ore within the rocks point to wherever the magnetic poles happen to be at the time of their formation, then stay pointing in that direction as the rocks cool and harden. In effect they “remember” where the magnetic poles were at the time of their creation. For years this was little more than a curiosity, but in the 1950s Patrick Blackett of the University of London and S. K. Runcorn of the University of Newcastle studied the ancient magnetic patterns frozen in British rocks and were startled, to say the very least, to find them indicating that at some time in the distant past Britain had spun on its axis and traveled some distance to the north, as if it had somehow come loose from its moorings. Moreover, they also discovered that if you placed a map of Europe’s magnetic patterns alongside an American one from the same period, they fit together as neatly as two halves of a torn letter. It was uncanny.

Their findings were ignored too.

It finally fell to two men from Cambridge University, a geophysicist named Drummond Matthews and a graduate student of his named Fred Vine, to draw all the strands together. In 1963, using magnetic studies of the Atlantic Ocean floor, they demonstrated conclusively that the seafloors were spreading in precisely the manner Hess had suggested and that the continents were in motion too. An unlucky Canadian geologist named Lawrence Morley came up with the same conclusion at the same time, but couldn’t find anyone to publish his paper. In what has become a famous snub, the editor of the Journal of Geophysical Research told him: “Such speculations make interesting talk at cocktail parties, but it is not the sort of thing that ought to be published under serious scientific aegis.” One geologist later described it as "probably the most significant paper in the earth sciences ever to be denied publication."

At all events, mobile crust was an idea whose time had finally come. A symposium of many of the most important figures in the field was convened in London under the auspices of the Royal Society in 1964, and suddenly, it seemed, everyone was a convert. The Earth, the meeting agreed, was a mosaic of interconnected segments whose various stately jostlings accounted for much of the planet's surface behavior.

The name "continental drift" was fairly swiftly discarded when it was realized that the whole crust was in motion and not just the continents, but it took a while to settle on a name for the individual segments. At first people called them "crustal blocks" or sometimes "paving stones." Not until late 1968, with the publication of an article by three American seismologists in the Journal of

Geophysical Research, did the segments receive the name by which they have since been known:

plates. The same article called the new science plate tectonics.

Old ideas die hard, and not everyone rushed to embrace the exciting new theory. Well into the 1970s,

one of the most popular and influential geological textbooks, The Earth by the venerable Harold

Jeffreys, strenuously insisted that plate tectonics was a physical impossibility, just as it had in the

first edition way back in 1924. It was equally dismissive of convection and seafloor spreading. And

in Basin and Range, published in 1980, John McPhee noted that even then one American geologist

in eight still didn't believe in plate tectonics.

Today we know that Earth's surface is made up of eight to twelve big plates (depending on how you

define big) and twenty or so smaller ones, and they all move in different directions and at different

speeds. Some plates are large and comparatively inactive, others small but energetic. They bear only an incidental relationship to the landmasses that sit upon them. The North American plate, for instance, is much larger than the continent with which it is associated. It roughly traces the outline of the continent’s western coast (which is why that area is so seismically active, because of the bump and crush of the plate boundary), but ignores the eastern seaboard altogether and instead extends halfway across the Atlantic to the mid-ocean ridge. Iceland is split down the middle, which makes it tectonically half American and half European. New Zealand, meanwhile, is part of the immense Indian Ocean plate even though it is nowhere near the Indian Ocean. And so it goes for most plates.

The connections between modern landmasses and those of the past were found to be infinitely more complex than anyone had imagined. Kazakhstan, it turns out, was once attached to Norway and New England. One corner of Staten Island, but only a corner, is European. So is part of Newfoundland.

Pick up a pebble from a Massachusetts beach, and its nearest kin will now be in Africa. The Scottish Highlands and much of Scandinavia are substantially American. Some of the Shackleton Range of Antarctica, it is thought, may once have belonged to the Appalachians of the eastern U.S. Rocks, in short, get around.

The constant turmoil keeps the plates from fusing into a single immobile plate. Assuming things continue much as at present, the Atlantic Ocean will expand until eventually it is much bigger than the Pacific. Much of California will float off and become a kind of Madagascar of the Pacific. Africa will push northward into Europe, squeezing the Mediterranean out of existence and thrusting up a chain of mountains of Himalayan majesty running from Paris to Calcutta. Australia will colonize the islands to its north and connect by some isthmian umbilicus to Asia. These are future outcomes, but not future events. The events are happening now. As we sit here, continents are adrift, like leaves on a pond. Thanks to Global Positioning Systems we can see that Europe and North America are parting at about the speed a fingernail grows— roughly two yards in a human lifetime. If you were prepared to wait long enough, you could ride from Los Angeles all the way up to San Francisco. It is only the brevity of lifetimes that keeps us from appreciating the changes. Look at a globe and what you are seeing really is a snapshot of the continents as they have been for just one-tenth of 1 percent of the Earth's history.

Earth is alone among the rocky planets in having tectonics, and why this should be is a bit of a mystery. It is not simply a matter of size or density— Venus is nearly a twin of Earth in these respects and yet has no tectonic activity. It is thought— though it is really nothing more than a thought— that tectonics is an important part of the planet's organic well-being. As the physicist and writer James Trefil has put it, “It would be hard to believe that the continuous movement of tectonic plates has no effect on the development of life on earth.” He suggests that the challenges induced by tectonics— changes in climate, for instance— were an important spur to the development of intelligence. Others believe the driftings of the continents may have produced at least some of the Earth’s various extinction events. In November of 2002, Tony Dickson of Cambridge University in England produced a report, published in the journal Science, strongly suggesting that there may well be a relationship between the history of rocks and the history of life. What Dickson established was that the chemical composition of the world’s oceans has altered abruptly and vigorously throughout the past half billion years and that these changes often correlate with important events in biological history— the huge outburst of tiny organisms that created the chalk cliffs of England’s south coast, the sudden fashion for shells among marine organisms during the Cambrian period, and so on. No one can say what causes the oceans' chemistry to change so dramatically from time to time, but the opening and shutting of ocean ridges would be an obvious possible culprit.

At all events, plate tectonics not only explained the surface dynamics of the Earth— how an ancient Hipparion got from France to Florida, for example— but also many of its internal actions. Earthquakes, the formation of island chains, the carbon cycle, the locations of mountains, the coming of ice ages, the origins of life itself— there was hardly a matter that wasn't directly influenced by this remarkable new theory. Geologists, as McPhee has noted, found themselves in the giddying position that "the whole earth suddenly made sense."

But only up to a point. The distribution of continents in former times is much less neatly resolved than most people outside geophysics think. Although textbooks give confident-looking representations of ancient landmasses with names like Laurasia, Gondwana, Rodinia, and Pangaea, these are sometimes based on conclusions that don't altogether hold up. As George Gaylord Simpson observes in Fossils and the History of Life, species of plants and animals from the ancient world have a habit of appearing inconveniently where they shouldn't and failing to be where they ought.

The outline of Gondwana, a once-mighty continent connecting Australia, Africa, Antarctica, and South America, was based in large part on the distribution of a genus of ancient tongue fern called Glossopteris, which was found in all the right places. However, much later Glossopteris was also discovered in parts of the world that had no known connection to Gondwana. This troubling discrepancy was— and continues to be— mostly ignored. Similarly a Triassic reptile called Lystrosaurus has been found from Antarctica all the way to Asia, supporting the idea of a former connection between those continents, but it has never turned up in South America or Australia, which are believed to have been part of the same continent at the same time. There are also many surface features that tectonics can’t explain. Take Denver. It is, as everyone knows, a mile high, but that rise is comparatively recent. When dinosaurs roamed the Earth, Denver was part of an ocean bottom, many thousands of feet lower. Yet the rocks on which Denver sits are not fractured or deformed in the way they would be if Denver had been pushed up by colliding plates, and anyway Denver was too far from the plate edges to be susceptible to their actions. It would be as if you pushed against the edge of a rug hoping to raise a ruck at the opposite end. Mysteriously and over millions of years, it appears that Denver has been rising, like baking bread. So, too, has much of southern Africa; a portion of it a thousand miles across has risen nearly a mile in 100 million years without any known associated tectonic activity.

Australia, meanwhile, has been
tilting and sinking. Over the past 100 million years as it has drifted north toward Asia, its leading
edge has sunk by some six hundred feet. It appears that Indonesia is very slowly drowning, and
dragging Australia down with it. Nothing in the theories of tectonics can explain any of this.

Alfred Wegener never lived to see his ideas vindicated. On an expedition to Greenland in 1930, he
set out alone, on his fiftieth birthday, to check out a supply drop. He never returned. He was found a
few days later, frozen to death on the ice. He was buried on the spot and lies there yet, but about a
yard closer to North America than on the day he died.

Einstein also failed to live long enough to see that he had backed the wrong horse. In fact, he died at
Princeton, New Jersey, in 1955 before Charles Hapgood's rubbishing of continental drift theories
was even published.

The other principal player in the emergence of tectonics theory, Harry Hess, was also at Princeton at

the time, and would spend the rest of his career there. One of his students

was a bright young fellow

named Walter Alvarez, who would eventually change the world of science

in a quite different way.

As for geology itself, its cataclysms had only just begun, and it was young

Alvarez who helped to

start the process.

PART IV **DANGEROUS PLANET**

13 **BANG!**

PEOPLE KNEW FOR a long time that there was something odd about the

earth beneath Manson,

Iowa. In 1912, a man drilling a well for the town water supply reported

bringing up a lot of strangely

deformed rock— “crystalline clast breccia with a melt matrix” and

“overturned ejecta flap,” as it was

later described in an official report. The water was odd too. It was almost as

soft as rainwater.

Naturally occurring soft water had never been found in Iowa before.

Though Manson’s strange rocks and silken waters were matters of curiosity, forty-one years would

pass before a team from the University of Iowa got around to making a trip to the community, then

as now a town of about two thousand people in the northwest part of the state. In 1953, after sinking

a series of experimental bores, university geologists agreed that the site was indeed anomalous and

attributed the deformed rocks to some ancient, unspecified volcanic action. This was in keeping with

the wisdom of the day, but it was also about as wrong as a geological conclusion can get.

The trauma to Manson's geology had come not from within the Earth, but from at least 100 million

miles beyond. Sometime in the very ancient past, when Manson stood on the edge of a shallow sea, a

rock about a mile and a half across, weighing ten billion tons and traveling at perhaps two hundred

times the speed of sound ripped through the atmosphere and punched into the Earth with a violence

and suddenness that we can scarcely imagine. Where Manson now stands

became in an instant a hole
three miles deep and more than twenty miles across. The limestone that elsewhere gives Iowa its
hard mineralized water was obliterated and replaced by the shocked basement rocks that so puzzled
the water driller in 1912.

The Manson impact was the biggest thing that has ever occurred on the mainland United States. Of
any type. Ever. The crater it left behind was so colossal that if you stood on one edge you would only
just be able to see the other side on a good day. It would make the Grand Canyon look quaint and
trifling. Unfortunately for lovers of spectacle, 2.5 million years of passing ice sheets filled the
Manson crater right to the top with rich glacial till, then graded it smooth, so that today the landscape
at Manson, and for miles around, is as flat as a tabletop. Which is of course why no one has ever
heard of the Manson crater.

At the library in Manson they are delighted to show you a collection of newspaper articles and a box of core samples from a 1991–92 drilling program— indeed, they positively bustle to produce them— but you have to ask to see them. Nothing permanent is on display, and nowhere in the town is there any historical marker.

To most people in Manson the biggest thing ever to happen was a tornado that rolled up Main Street in 1979, tearing apart the business district. One of the advantages of all that surrounding flatness is that you can see danger from a long way off. Virtually the whole town turned out at one end of Main Street and watched for half an hour as the tornado came toward them, hoping it would veer off, then prudently scampered when it did not. Four of them, alas, didn't move quite fast enough and were killed. Every June now Manson has a weeklong event called Crater Days, which was dreamed up as a way of helping people forget that unhappy anniversary. It doesn't really have anything to do with the crater. Nobody’s figured out a way to capitalize on an impact site that isn’t visible.

“Very occasionally we get people coming in and asking where they should go to see the crater and we have to tell them that there is nothing to see,” says Anna Schlapkohl, the town’s friendly librarian. “Then they go away kind of disappointed.” However, most people, including most Iowans, have never heard of the Manson crater. Even for geologists it barely rates a footnote. But for one brief period in the 1980s, Manson was the most geologically exciting place on Earth.

The story begins in the early 1950s when a bright young geologist named Eugene Shoemaker paid a visit to Meteor Crater in Arizona. Today Meteor Crater is the most famous impact site on Earth and a popular tourist attraction. In those days, however, it didn’t receive many visitors and was still often referred to as Barringer Crater, after a wealthy mining engineer named Daniel M. Barringer who had staked a claim on it in 1903. Barringer believed that the crater had been formed by a ten-million-ton meteor, heavily freighted with iron and nickel, and it was his confident expectation that he would make a fortune digging it out. Unaware that the meteor and everything in it would have been vaporized on impact, he wasted a fortune, and the next twenty-six years, cutting tunnels that yielded nothing.

By the standards of today, crater research in the early 1900s was a trifle unsophisticated, to say the least. The leading early investigator, G. K. Gilbert of Columbia University, modeled the effects of impacts by flinging marbles into pans of oatmeal. (For reasons I cannot supply, Gilbert conducted these experiments not in a laboratory at Columbia but in a hotel room.) Somehow from this Gilbert concluded that the Moon's craters were indeed formed by impacts— in itself quite a radical notion for the time— but that the Earth's were not. Most scientists refused to go even that far. To them, the Moon's craters were evidence of ancient volcanoes and nothing more. The few craters that remained evident on Earth (most had been eroded away) were generally attributed to other causes or treated as fluky rarities.

By the time Shoemaker came along, a common view was that Meteor Crater had been formed by an underground steam explosion. Shoemaker knew nothing about underground steam explosions— he couldn't: they don't exist— but he did know all about blast zones. One of his first jobs out of college was to study explosion rings at the Yucca Flats nuclear test site in Nevada. He concluded, as Barringer had before him, that there was nothing at Meteor Crater to suggest volcanic activity, but that there were huge distributions of other stuff— anomalous fine silicas and magnetites principally— that suggested an impact from space. Intrigued, he began to study the subject in his spare time.

Working first with his colleague Eleanor Helin and later with his wife, Carolyn, and associate David Levy, Shoemaker began a systematic survey of the inner solar system. They spent one week each month at the Palomar Observatory in California looking for objects, asteroids primarily, whose trajectories carried them across Earth's orbit.

"At the time we started, only slightly more than a dozen of these things had ever been discovered in the entire course of astronomical observation," Shoemaker recalled some years later in a television interview. "Astronomers in the twentieth century essentially abandoned the solar system," he added.

"Their attention was turned to the stars, the galaxies."

What Shoemaker and his colleagues found was that there was more risk out there— a great deal more— than anyone had ever imagined.

Asteroids, as most people know, are rocky objects orbiting in loose formation in a belt between Mars and Jupiter. In illustrations they are always shown as existing in a jumble, but in fact the solar system is quite a roomy place and the average asteroid actually will be about a million miles from its nearest neighbor. Nobody knows even approximately how many asteroids there are tumbling through space, but the number is thought to be probably not less than a billion. They are presumed to be planets that never quite made it, owing to the unsettling gravitational pull of Jupiter, which kept— and keeps— them from coalescing.

When asteroids were first detected in the 1800s— the very first was discovered on the first day of the century by a Sicilian named Giuseppi Piazzi— they were thought to be planets, and the first two were named Ceres and Pallas. It took some inspired deductions by the astronomer William Herschel to work out that they were nowhere near planet sized but much smaller. He called them asteroids— Latin for “starlike”— which was slightly unfortunate as they are not like stars at all. Sometimes now

they are more accurately called planetoids.

Finding asteroids became a popular activity in the 1800s, and by the end of the century about a

thousand were known. The problem was that no one was systematically recording them. By the early

1900s, it had often become impossible to know whether an asteroid that popped into view was new

or simply one that had been noted earlier and then lost track of. By this time, too, astrophysics had

moved on so much that few astronomers wanted to devote their lives to anything as mundane as

rocky planetoids. Only a few astronomers, notably Gerard Kuiper, the Dutch-born astronomer for

whom the Kuiper belt of comets is named, took any interest in the solar system at all. Thanks to his

work at the McDonald Observatory in Texas, followed later by work done by others at the Minor

Planet Center in Cincinnati and the Spacewatch project in Arizona, a long list of lost asteroids was gradually whittled down until by the close of the twentieth century only one known asteroid was unaccounted for— an object called 719 Albert. Last seen in October 1911, it was finally tracked down in 2000 after being missing for eighty-nine years.

So from the point of view of asteroid research the twentieth century was essentially just a long exercise in bookkeeping. It is really only in the last few years that astronomers have begun to count and keep an eye on the rest of the asteroid community. As of July 2001, twenty-six thousand asteroids had been named and identified— half in just the previous two years. With up to a billion to identify, the count obviously has barely begun.

In a sense it hardly matters. Identifying an asteroid doesn't make it safe. Even if every asteroid in the solar system had a name and known orbit, no one could say what perturbations might send any of them hurtling toward us. We can't forecast rock disturbances on our own surface. Put them adrift in space and what they might do is beyond guessing. Any asteroid out there that has our name on it is very likely to have no other.

Think of the Earth's orbit as a kind of freeway on which we are the only vehicle, but which is crossed regularly by pedestrians who don't know enough to look before stepping off the curb. At least 90 percent of these pedestrians are quite unknown to us. We don't know where they live, what sort of hours they keep, how often they come our way. All we know is that at some point, at uncertain intervals, they trundle across the road down which we are cruising at sixty-six thousand miles an hour. As Steven Ostro of the Jet Propulsion Laboratory has put it, "Suppose that there was a button you could push and you could light up all the Earth-crossing asteroids larger than about ten meters, there would be over 100 million of these objects in the sky." In short, you would see not a couple of thousand distant twinkling stars, but millions upon millions upon millions of nearer, randomly moving objects— "all of which are capable of colliding with the Earth and all of which are moving on slightly different courses through the sky at different rates. It would be deeply unnerving." Well, be unnerved because it is there. We just can't see it.

Altogether it is thought— though it is really only a guess, based on extrapolating from cratering rates on the Moon— that some two thousand asteroids big enough to imperil civilized existence regularly cross our orbit. But even a small asteroid— the size of a house, say— could destroy a city. The number of these relative tiddlers in Earth-crossing orbits is almost certainly in the hundreds of thousands and possibly in the millions, and they are nearly impossible to track.

The first one wasn't spotted until 1991, and that was after it had already gone by. Named 1991 BA, it was noticed as it sailed past us at a distance of 106,000 miles— in cosmic terms the equivalent of a bullet passing through one’s sleeve without touching the arm. Two years later, another, somewhat larger asteroid missed us by just 90,000 miles— the closest pass yet recorded. It, too, was not seen until it had passed and would have arrived without warning. According to Timothy Ferris, writing in the New Yorker, such near misses probably happen two or three times a week and go unnoticed.

An object a hundred yards across couldn’t be picked up by any Earth-based telescope until it was within just a few days of us, and that is only if a telescope happened to be trained on it, which is unlikely because even now the number of people searching for such objects is modest. The arresting analogy that is always made is that the number of people in the world who are actively searching for asteroids is fewer than the staff of a typical McDonald’s restaurant. (It is actually somewhat higher now. But not much.)

While Gene Shoemaker was trying to get people galvanized about the potential dangers of the inner solar system, another development— wholly unrelated on the face of it— was quietly unfolding in Italy with the work of a young geologist from the Lamont Doherty Laboratory at Columbia University. In the early 1970s, Walter Alvarez was doing fieldwork in a comely defile known as the Bottaccione Gorge, near the Umbrian hill town of Gubbio, when he grew curious about a thin band of reddish clay that divided two ancient layers of limestone— one from the Cretaceous period, the other from the Tertiary. This is a point known to geology as the KT boundary,*27 and it marks the time, sixty-five million years ago, when the dinosaurs and roughly half the world's other species of animals abruptly vanish from the fossil record. Alvarez wondered what it was about a thin lamina of clay, barely a quarter of an inch thick, that could account for such a dramatic moment in Earth's history.

At the time the conventional wisdom about the dinosaur extinction was the same as it had been in
Charles Lyell’s day a century earlier— namely that the dinosaurs had died out over millions of years.
But the thinness of the clay layer clearly suggested that in Umbria, if nowhere else, something rather
more abrupt had happened. Unfortunately in the 1970s no tests existed for determining how long
such a deposit might have taken to accumulate.
In the normal course of things, Alvarez almost certainly would have had to leave the problem at that,
but luckily he had an impeccable connection to someone outside his discipline who could help— his
father, Luis. Luis Alvarez was an eminent nuclear physicist; he had won the Nobel Prize for physics
the previous decade. He had always been mildly scornful of his son’s attachment to rocks, but this
problem intrigued him. It occurred to him that the answer might lie in dust from space.
Every year the Earth accumulates some thirty thousand metric tons of

"cosmic spherules"— space
dust in plainer language— which would be quite a lot if you swept it into one pile, but is infinitesimal
when spread across the globe. Scattered through this thin dusting are exotic elements not normally
much found on Earth. Among these is the element iridium, which is a thousand times more abundant
in space than in the Earth's crust (because, it is thought, most of the iridium on Earth sank to the core
when the planet was young).

Alvarez knew that a colleague of his at the Lawrence Berkeley Laboratory in California, Frank
Asaro, had developed a technique for measuring very precisely the chemical composition of clays
using a process called neutron activation analysis. This involved bombarding samples with neutrons
in a small nuclear reactor and carefully counting the gamma rays that were emitted; it was extremely
finicky work. Previously Asaro had used the technique to analyze pieces of pottery, but Alvarez

reasoned that if they measured the amount of one of the exotic elements in his son's soil samples and compared that with its annual rate of deposition, they would know how long it had taken the samples to form. On an October afternoon in 1977, Luis and Walter Alvarez dropped in on Asaro and asked him if he would run the necessary tests for them.

It was really quite a presumptuous request. They were asking Asaro to devote months to making the most painstaking measurements of geological samples merely to confirm what seemed entirely selfevident to begin with— that the thin layer of clay had been formed as quickly as its thinness suggested. Certainly no one expected his survey to yield any dramatic breakthroughs.

"Well, they were very charming, very persuasive," Asaro recalled in an interview in 2002. "And it seemed an interesting challenge, so I agreed to try. Unfortunately, I had a lot of other work on, so it was eight months before I could get to it." He consulted his notes from the period. “On June 21, 1978, at 1:45 p.m., we put a sample in the detector. It ran for 224 minutes and we could see we were getting interesting results, so we stopped it and had a look.”

The results were so unexpected, in fact, that the three scientists at first thought they had to be wrong.

The amount of iridium in the Alvarez sample was more than three hundred times normal levels— far beyond anything they might have predicted. Over the following months Asaro and his colleague Helen Michel worked up to thirty hours at a stretch (“Once you started you couldn’t stop,” Asaro explained) analyzing samples, always with the same results. Tests on other samples— from Denmark, Spain, France, New Zealand, Antarctica— showed that the iridium deposit was worldwide and greatly elevated everywhere, sometimes by as much as five hundred times normal levels. Clearly something big and abrupt, and probably cataclysmic, had produced this arresting spike.

After much thought, the Alvarezes concluded that the most plausible explanation— plausible to them,
at any rate— was that the Earth had been struck by an asteroid or comet.
The idea that the Earth might be subjected to devastating impacts from time to time was not quite as
new as it is now sometimes presented. As far back as 1942, a Northwestern University astrophysicist
named Ralph B. Baldwin had suggested such a possibility in an article in Popular Astronomy
magazine. (He published the article there because no academic publisher was prepared to run it.)
And at least two well-known scientists, the astronomer Ernst Öpik and the chemist and Nobel
laureate Harold Urey, had also voiced support for the notion at various times. Even among
paleontologists it was not unknown. In 1956 a professor at Oregon State University, M. W. de
Laubenfels, writing in the Journal of Paleontology, had actually anticipated the Alvarez theory by
suggesting that the dinosaurs may have been dealt a death blow by an impact

from space, and in

1970 the president of the American Paleontological Society, Dewey J.

McLaren, proposed at the

group's annual conference the possibility that an extraterrestrial impact may

have been the cause of

an earlier event known as the Frasnian extinction.

As if to underline just how un-novel the idea had become by this time, in

1979 a Hollywood studio

actually produced a movie called Meteor ("It's five miles wide . . . It's

coming at 30,000 m.p.h.—

and there's no place to hide!") starring Henry Fonda, Natalie Wood, Karl

Malden, and a very large

rock.

So when, in the first week of 1980, at a meeting of the American

Association for the Advancement

of Science, the Alvarezes announced their belief that the dinosaur extinction

had not taken place over

millions of years as part of some slow inexorable process, but suddenly in a

single explosive event, it

shouldn't have come as a shock.

But it did. It was received everywhere, but particularly in the paleontological community, as an outrageous heresy.

“Well, you have to remember,” Asaro recalls, “that we were amateurs in this field. Walter was a geologist specializing in paleomagnetism, Luis was a physicist and I was a nuclear chemist. And now here we were telling paleontologists that we had solved a problem that had eluded them for over a century. It’s not terribly surprising that they didn’t embrace it immediately.” As Luis Alvarez joked: “We were caught practicing geology without a license.”

But there was also something much deeper and more fundamentally abhorrent in the impact theory.

The belief that terrestrial processes were gradual had been elemental in natural history since the time of Lyell. By the 1980s, catastrophism had been out of fashion for so long that it had become literally unthinkable. For most geologists the idea of a devastating impact was, as Eugene Shoemaker noted, "against their scientific religion."

Nor did it help that Luis Alvarez was openly contemptuous of paleontologists and their contributions to scientific knowledge. "They're really not very good scientists. They're more like stamp collectors," he wrote in the New York Times in an article that stings yet.

Opponents of the Alvarez theory produced any number of alternative explanations for the iridium deposits— for instance, that they were generated by prolonged volcanic eruptions in India called the Deccan Traps— and above all insisted that there was no proof that the dinosaurs disappeared abruptly from the fossil record at the iridium boundary. One of the most vigorous opponents was Charles Officer of Dartmouth College. He insisted that the iridium had been deposited by volcanic action even while conceding in a newspaper interview that he had no actual evidence of it. As late as 1988 more than half of all American paleontologists contacted in a survey continued to believe that the extinction of the dinosaurs was in no way related to an asteroid or cometary impact.

The one thing that would most obviously support the Alvarezes' theory was the one thing they didn't have— an impact site. Enter Eugene Shoemaker. Shoemaker had an Iowa connection— his daughterin-law taught at the University of Iowa— and he was familiar with the Manson crater from his own studies. Thanks to him, all eyes now turned to Iowa.

Geology is a profession that varies from place to place. In Iowa, a state that is flat and stratigraphically uneventful, it tends to be comparatively serene. There are no Alpine peaks or grinding glaciers, no great deposits of oil or precious metals, not a hint of a pyroclastic flow. If you are a geologist employed by the state of Iowa, a big part of the work you do is to evaluate Manure Management Plans, which all the state's "animal confinement operators"— hog farmers to the rest of us— are required to file periodically. There are fifteen million hogs in Iowa, so a lot of manure to manage. I’m not mocking this at all— it’s vital and enlightened work; it keeps Iowa’s water clean— but with the best will in the world it’s not exactly dodging lava bombs on Mount Pinatubo or scrabbling over crevasses on the Greenland ice sheet in search of ancient life-bearing quartzes. So we may well imagine the flutter of excitement that swept through the Iowa Department of Natural Resources when in the mid-1980s the world’s geological attention focused on Manson and its crater.

Trowbridge Hall in Iowa City is a turn-of-the-century pile of red brick that houses the University of Iowa’s Earth Sciences department and— way up in a kind of garret— the geologists of the Iowa Department of Natural Resources. No one now can remember quite when, still less why, the state geologists were placed in an academic facility, but you get the impression that the space was conceded grudgingly, for the offices are cramped and low-ceilinged and not

very accessible. When
being shown the way, you half expect to be taken out onto a roof ledge and helped in through a
window.

Ray Anderson and Brian Witzke spend their working lives up here amid disordered heaps of papers,
journals, furled charts, and hefty specimen stones. (Geologists are never at a loss for paperweights.)

It's the kind of space where if you want to find anything— an extra chair, a coffee cup, a ringing
telephone— you have to move stacks of documents around.

"Suddenly we were at the center of things," Anderson told me, gleaming at the memory of it, when I
met him and Witzke in their offices on a dismal, rainy morning in June. "It was a wonderful time."

I asked them about Gene Shoemaker, a man who seems to have been universally revered. "He was
just a great guy," Witzke replied without hesitation. "If it hadn't been for him, the whole thing would
never have gotten off the ground. Even with his support, it took two years to

get it up and running.

Drilling's an expensive business— about thirty-five dollars a foot back then, more now, and we needed to go down three thousand feet."

"Sometimes more than that," Anderson added.

"Sometimes more than that," Witzke agreed. "And at several locations. So you're talking a lot of money. Certainly more than our budget would allow."

So a collaboration was formed between the Iowa Geological Survey and the U.S. Geological Survey.

"At least we thought it was a collaboration," said Anderson, producing a small pained smile.

"It was a real learning curve for us," Witzke went on. "There was actually quite a lot of bad science going on throughout the period— people rushing in with results that didn't always stand up to scrutiny." One of those moments came at the annual meeting of the American Geophysical Union in 1985, when Glenn Izett and C. L. Pillmore of the U.S. Geological Survey announced that the

Manson crater was of the right age to have been involved with the dinosaurs' extinction. The
declaration attracted a good deal of press attention but was unfortunately premature. A more careful
examination of the data revealed that Manson was not only too small, but also nine million years too
early.

The first Anderson or Witzke learned of this setback to their careers was when they arrived at a
conference in South Dakota and found people coming up to them with sympathetic looks and saying:
"We hear you lost your crater." It was the first they knew that Izett and the other USGS scientists
had just announced refined figures revealing that Manson couldn't after all have been the extinction
crater.

"It was pretty stunning," recalls Anderson. "I mean, we had this thing that was really important and
then suddenly we didn't have it anymore. But even worse was the realization that the people we

thought we'd been collaborating with hadn't bothered to share with us their new findings."

"Why not?"

He shrugged. "Who knows? Anyway, it was a pretty good insight into how unattractive science can get when you're playing at a certain level."

The search moved elsewhere. By chance in 1990 one of the searchers, Alan Hildebrand of the University of Arizona, met a reporter from the Houston Chronicle who happened to know about a large, unexplained ring formation, 120 miles wide and 30 miles deep, under Mexico's Yucatán Peninsula at Chicxulub, near the city of Progreso, about 600 miles due south of New Orleans. The formation had been found by Pemex, the Mexican oil company, in 1952—the year, coincidentally, that Gene Shoemaker first visited Meteor Crater in Arizona— but the company's geologists had concluded that it was volcanic, in line with the thinking of the day. Hildebrand traveled to the site and decided fairly swiftly that they had their crater. By early 1991 it had been established to nearly everyone's satisfaction that Chicxulub was the impact site.

Still, many people didn't quite grasp what an impact could do. As Stephen Jay Gould recalled in one of his essays: "I remember harboring some strong initial doubts about the efficacy of such an event . . . [W]hy should an object only six miles across wreak such havoc upon a planet with a diameter of eight thousand miles?"

Conveniently a natural test of the theory arose when the Shoemakers and Levy discovered Comet Shoemaker-Levy 9, which they soon realized was headed for Jupiter. For the first time, humans would be able to witness a cosmic collision— and witness it very well thanks to the new Hubble space telescope. Most astronomers, according to Curtis Peebles, expected little, particularly as the comet was not a coherent sphere but a string of twenty-one fragments. "My sense," wrote one, "is

that Jupiter will swallow these comets up without so much as a burp.” One week before the impact,
Nature ran an article, “The Big Fizzle Is Coming,” predicting that the impact would constitute
nothing more than a meteor shower.
The impacts began on July 16, 1994, went on for a week and were bigger by far than anyone— with
the possible exception of Gene Shoemaker— expected. One fragment, known as Nucleus G, struck
with the force of about six million megatons— seventy-five times more than all the nuclear weaponry
in existence. Nucleus G was only about the size of a small mountain, but it created wounds in the
Jovian surface the size of Earth. It was the final blow for critics of the Alvarez theory.
Luis Alvarez never knew of the discovery of the Chicxulub crater or of the Shoemaker-Levy comet,
as he died in 1988. Shoemaker also died early. On the third anniversary of the Shoemaker-Levy
impact, he and his wife were in the Australian outback, where they went

every year to search for impact sites. On a dirt track in the Tanami Desert— normally one of the emptiest places on Earth— they came over a slight rise just as another vehicle was approaching. Shoemaker was killed instantly, his wife injured. Part of his ashes were sent to the Moon aboard the Lunar Prospector spacecraft. The rest were scattered around Meteor Crater.

Anderson and Witzke no longer had the crater that killed the dinosaurs, "but we still had the largest and most perfectly preserved impact crater in the mainland United States," Anderson said. (A little verbal dexterity is required to keep Manson's superlative status. Other craters are larger— notably, Chesapeake Bay, which was recognized as an impact site in 1994— but they are either offshore or deformed.) "Chicxulub is buried under two to three kilometers of limestone and mostly offshore, which makes it difficult to study," Anderson went on, "while Manson is really quite accessible. It's because it is buried that it is actually comparatively pristine.”

I asked them how much warning we would receive if a similar hunk of rock was coming toward us today.

“Oh, probably none,” said Anderson breezily. “It wouldn’t be visible to the naked eye until it warmed up, and that wouldn’t happen until it hit the atmosphere, which would be about one second before it hit the Earth. You’re talking about something moving many tens of times faster than the fastest bullet. Unless it had been seen by someone with a telescope, and that’s by no means a certainty, it would take us completely by surprise.”

How hard an impactor hits depends on a lot of variables— angle of entry, velocity and trajectory, whether the collision is head-on or from the side, and the mass and density of the impacting object, among much else— none of which we can know so many millions of years after the fact. But what scientists can do— and Anderson and Witzke have done— is measure the impact site and calculate the amount of energy released. From that they can work out plausible scenarios of what it must have been like— or, more chillingly, would be like if it happened now.

An asteroid or comet traveling at cosmic velocities would enter the Earth's atmosphere at such a speed that the air beneath it couldn't get out of the way and would be compressed, as in a bicycle pump. As anyone who has used such a pump knows, compressed air grows swiftly hot, and the temperature below it would rise to some 60,000 Kelvin, or ten times the surface temperature of the Sun. In this instant of its arrival in our atmosphere, everything in the meteor's path— people, houses, factories, cars— would crinkle and vanish like cellophane in a flame.

One second after entering the atmosphere, the meteorite would slam into the Earth's surface, where the people of Manson had a moment before been going about their business. The meteorite itself would vaporize instantly, but the blast would blow out a thousand cubic kilometers of rock, earth, and superheated gases. Every living thing within 150 miles that hadn’t been killed by the heat of entry would now be killed by the blast. Radiating outward at almost the speed of light would be the initial shock wave, sweeping everything before it.

For those outside the zone of immediate devastation, the first inkling of catastrophe would be a flash of blinding light— the brightest ever seen by human eyes— followed an instant to a minute or two later by an apocalyptic sight of unimaginable grandeur: a roiling wall of darkness reaching high into the heavens, filling an entire field of view and traveling at thousands of miles an hour. Its approach would be eerily silent since it would be moving far beyond the speed of sound. Anyone in a tall building in Omaha or Des Moines, say, who chanced to look in the right direction would see a bewildering veil of turmoil followed by instantaneous oblivion.

Within minutes, over an area stretching from Denver to Detroit and encompassing what had once been Chicago, St. Louis, Kansas City, the Twin Cities— the whole of the Midwest, in short— nearly every standing thing would be flattened or on fire, and nearly every living thing would be dead.

People up to a thousand miles away would be knocked off their feet and sliced or clobbered by a blizzard of flying projectiles. Beyond a thousand miles the devastation from the blast would gradually diminish.

But that’s just the initial shockwave. No one can do more than guess what the associated damage would be, other than that it would be brisk and global. The impact would almost certainly set off a chain of devastating earthquakes. Volcanoes across the globe would begin to rumble and spew.

Tsunamis would rise up and head devastatingly for distant shores. Within an hour, a cloud of blackness would cover the planet, and burning rock and other debris would be pelting down everywhere, setting much of the planet ablaze. It has been estimated that at least a billion and a half

people would be dead by the end of the first day. The massive disturbances to the ionosphere would

knock out communications systems everywhere, so survivors would have no idea what was

happening elsewhere or where to turn. It would hardly matter. As one commentator has put it,

fleeing would mean “selecting a slow death over a quick one. The death toll would be very little

affected by any plausible relocation effort, since Earth’s ability to support life would be universally

diminished.”

The amount of soot and floating ash from the impact and following fires would blot out the sun,

certainly for months, possibly for years, disrupting growing cycles. In 2001 researchers at the

California Institute of Technology analyzed helium isotopes from sediments left from the later KT

impact and concluded that it affected Earth’s climate for about ten thousand years. This was actually

used as evidence to support the notion that the extinction of dinosaurs was

swift and emphatic— and

so it was in geological terms. We can only guess how well, or whether,

humanity would cope with

such an event.

And in all likelihood, remember, this would come without warning, out of a

clear sky.

But let's assume we did see the object coming. What would we do?

Everyone assumes we would

send up a nuclear warhead and blast it to smithereens. The idea has some

problems, however. First,

as John S. Lewis notes, our missiles are not designed for space work. They

haven't the oomph to

escape Earth's gravity and, even if they did, there are no mechanisms to

guide them across tens of

millions of miles of space. Still less could we send up a shipload of space

cowboys to do the job for

us, as in the movie Armageddon; we no longer possess a rocket powerful

enough to send humans

even as far as the Moon. The last rocket that could, Saturn 5, was retired years ago and has never been replaced. Nor could we quickly build a new one because, amazingly, the plans for Saturn launchers were destroyed as part of a NASA housecleaning exercise.

Even if we did manage somehow to get a warhead to the asteroid and blasted it to pieces, the chances are that we would simply turn it into a string of rocks that would slam into us one after the other in the manner of Comet Shoemaker-Levy on Jupiter— but with the difference that now the rocks would be intensely radioactive. Tom Gehrels, an asteroid hunter at the University of Arizona, thinks that even a year's warning would probably be insufficient to take appropriate action. The greater likelihood, however, is that we wouldn't see any object— even a comet— until it was about six months away, which would be much too late. Shoemaker-Levy 9 had been orbiting Jupiter in a fairly conspicuous manner since 1929, but it took over half a century before anyone noticed.

Interestingly, because these things are so difficult to compute and must incorporate such a significant margin of error, even if we knew an object was heading our way we wouldn’t know until nearly the end— the last couple of weeks anyway— whether collision was certain. For most of the time of the object’s approach we would exist in a kind of cone of uncertainty. It would certainly be the most interesting few months in the history of the world. And imagine the party if it passed safely.

“So how often does something like the Manson impact happen?” I asked Anderson and Witzke before leaving.

“Oh, about once every million years on average,” said Witzke.

“And remember,” added Anderson, “this was a relatively minor event. Do you know how many extinctions were associated with the Manson impact?”

“No idea,” I replied.

“None,” he said, with a strange air of satisfaction. “Not one.”

Of course, Witzke and Anderson added hastily and more or less in unison, there would have been terrible devastation across much of the Earth, as just described, and complete annihilation for hundreds of miles around ground zero. But life is hardy, and when the smoke cleared there were enough lucky survivors from every species that none permanently perished.

The good news, it appears, is that it takes an awful lot to extinguish a species. The bad news is that the good news can never be counted on. Worse still, it isn't actually necessary to look to space for petrifying danger. As we are about to see, Earth can provide plenty of danger of its own.

14 **THE FIRE BELOW**

IN THE SUMMER of 1971, a young geologist named Mike Voorhies was scouting around on some grassy farmland in eastern Nebraska, not far from the little town of Orchard, where he had grown up.

Passing through a steep-sided gully, he spotted a curious glint in the brush above and clambered up to have a look. What he had seen was the perfectly preserved skull of a young rhinoceros, which had been washed out by recent heavy rains.

A few yards beyond, it turned out, was one of the most extraordinary fossil beds ever discovered in North America, a dried-up water hole that had served as a mass grave for scores of animals—rhinoceroses, zebra-like horses, saber-toothed deer, camels, turtles. All had died from some mysterious cataclysm just under twelve million years ago in the time known to geology as the Miocene. In those days Nebraska stood on a vast, hot plain very like the Serengeti of Africa today.

The animals had been found buried under volcanic ash up to ten feet deep. The puzzle of it was that there were not, and never had been, any volcanoes in Nebraska.

Today, the site of Voorhies's discovery is called Ashfall Fossil Beds State Park, and it has a stylish new visitors' center and museum, with thoughtful displays on the geology of Nebraska and the history of the fossil beds. The center incorporates a lab with a glass wall through which visitors can watch paleontologists cleaning bones. Working alone in the lab on the morning I passed through was a cheerfully grizzled-looking fellow in a blue work shirt whom I recognized as Mike Voorhies from a BBC television documentary in which he featured. They don't get a huge number of visitors to Ashfall Fossil Beds State Park— it's slightly in the middle of nowhere— and Voorhies seemed pleased to show me around. He took me to the spot atop a twenty-foot ravine where he had made his find.

"It was a dumb place to look for bones," he said happily. "But I wasn't looking for bones. I was thinking of making a geological map of eastern Nebraska at the time, and really just kind of poking around. If I hadn't gone up this ravine or the rains hadn't just washed out that skull, I'd have walked on by and this would never have been found." He indicated a roofed enclosure nearby, which had become the main excavation site. Some two hundred animals had been found lying together in a jumble.

I asked him in what way it was a dumb place to hunt for bones. “Well, if you’re looking for bones, you really need exposed rock. That’s why most paleontology is done in hot, dry places. It’s not that there are more bones there. It’s just that you have some chance of spotting them. In a setting like this”— he made a sweeping gesture across the vast and unvarying prairie—“you wouldn’t know where to begin. There could be really magnificent stuff out there, but there’s no surface clues to show you where to start looking.”

At first they thought the animals were buried alive, and Voorhies stated as much in a National Geographic article in 1981. “The article called the site a ‘Pompeii of prehistoric animals,’ ” he told me, “which was unfortunate because just afterward we realized that the

animals hadn’t died suddenly
at all. They were all suffering from something called hypertrophic
pulmonary osteodystrophy, which
is what you would get if you were breathing a lot of abrasive ash— and they
must have been
breathing a lot of it because the ash was feet thick for hundreds of miles.”
He picked up a chunk of
grayish, claylike dirt and crumbled it into my hand. It was powdery but
slightly gritty. “Nasty stuff to
have to breathe,” he went on, “because it’s very fine but also quite sharp. So
anyway they came here
to this watering hole, presumably seeking relief, and died in some misery.
The ash would have
ruined everything. It would have buried all the grass and coated every leaf
and turned the water into
an undrinkable gray sludge. It couldn’t have been very agreeable at all.”
The BBC documentary had suggested that the existence of so much ash in
Nebraska was a surprise.
In fact, Nebraska’s huge ash deposits had been known about for a long time.
For almost a century

they had been mined to make household cleaning powders like Comet and Ajax. But curiously no one had ever thought to wonder where all the ash came from.

“I’m a little embarrassed to tell you,” Voorhies said, smiling briefly, “that the first I thought about it was when an editor at the National Geographic asked me the source of all the ash and I had to confess that I didn’t know. Nobody knew.”

Voorhies sent samples to colleagues all over the western United States asking if there was anything about it that they recognized. Several months later a geologist named Bill Bonnichsen from the Idaho Geological Survey got in touch and told him that the ash matched a volcanic deposit from a place called Bruneau-Jarbidge in southwest Idaho. The event that killed the plains animals of Nebraska was a volcanic explosion on a scale previously unimagined— but big enough to leave an ash layer ten feet deep almost a thousand miles away in eastern Nebraska. It turned out that under the western

United States there was a huge cauldron of magma, a colossal volcanic hot spot, which erupted cataclysmically every 600,000 years or so. The last such eruption was just over 600,000 years ago.

The hot spot is still there. These days we call it Yellowstone National Park.

We know amazingly little about what happens beneath our feet. It is fairly remarkable to think that Ford has been building cars and baseball has been playing World Series for longer than we have known that the Earth has a core. And of course the idea that the continents move about on the surface like lily pads has been common wisdom for much less than a generation. "Strange as it may seem," wrote Richard Feynman, "we understand the distribution of matter in the interior of the Sun far better than we understand the interior of the Earth."

The distance from the surface of Earth to the center is 3,959 miles, which isn't so very far. It has been calculated that if you sunk a well to the center and dropped a brick into it, it would take only forty-five minutes for it to hit the bottom (though at that point it would be weightless since all the Earth's gravity would be above and around it rather than beneath it). Our own attempts to penetrate toward the middle have been modest indeed. One or two South African gold mines reach to a depth of two miles, but most mines on Earth go no more than about a quarter of a mile beneath the surface.

If the planet were an apple, we wouldn't yet have broken through the skin. Indeed, we haven't even come close.

Until slightly under a century ago, what the best-informed scientific minds knew about Earth's interior was not much more than what a coal miner knew— namely, that you could dig down through soil for a distance and then you'd hit rock and that was about it. Then in 1906, an Irish geologist named R. D. Oldham, while examining some seismograph readings from an earthquake in Guatemala, noticed that certain shock waves had penetrated to a point deep within the Earth and then

bounced off at an angle, as if they had encountered some kind of barrier. From this he deduced that

the Earth has a core. Three years later a Croatian seismologist named Andrija Mohorovii´c was

studying graphs from an earthquake in Zagreb when he noticed a similar odd deflection, but at a

shallower level. He had discovered the boundary between the crust and the layer immediately below,

the mantle; this zone has been known ever since as the Mohorovii;c discontinuity, or Moho for short.

We were beginning to get a vague idea of the Earth's layered interior—though it really was only

vague. Not until 1936 did a Danish scientist named Inge Lehmann, studying seismographs of

earthquakes in New Zealand, discover that there were two cores— an inner one that we now believe

to be solid and an outer one (the one that Oldham had detected) that is thought to be liquid and the

seat of magnetism.

At just about the time that Lehmann was refining our basic understanding of the Earth's interior by studying the seismic waves of earthquakes, two geologists at Caltech in California were devising a way to make comparisons between one earthquake and the next. They were Charles Richter and Beno Gutenberg, though for reasons that have nothing to do with fairness the scale became known almost at once as Richter's alone. (It has nothing to do with Richter either. A modest fellow, he never referred to the scale by his own name, but always called it "the Magnitude Scale.")

The Richter scale has always been widely misunderstood by nonscientists, though perhaps a little less so now than in its early days when visitors to Richter's office often asked to see his celebrated scale, thinking it was some kind of machine. The scale is of course more an idea than an object, an arbitrary measure of the Earth's tremblings based on surface measurements. It rises exponentially, so

that a 7.3 quake is fifty times more powerful than a 6.3 earthquake and 2,500 times more powerful
than a 5.3 earthquake.

At least theoretically, there is no upper limit for an earthquake— nor, come to that, a lower limit. The
scale is a simple measure of force, but says nothing about damage. A magnitude 7 quake happening
deep in the mantle— say, four hundred miles down— might cause no surface damage at all, while a
significantly smaller one happening just four miles under the surface could wreak widespread
devastation. Much, too, depends on the nature of the subsoil, the quake's duration, the frequency and
severity of aftershocks, and the physical setting of the affected area. All this means that the most
fearsome quakes are not necessarily the most forceful, though force obviously counts for a lot.

The largest earthquake since the scale's invention was (depending on which source you credit) either
one centered on Prince William Sound in Alaska in March 1964, which

measured 9.2 on the Richter
scale, or one in the Pacific Ocean off the coast of Chile in 1960, which was initially logged at 8.6
magnitude but later revised upward by some authorities (including the United States Geological
Survey) to a truly grand-scale 9.5. As you will gather from this, measuring earthquakes is not always
an exact science, particularly when interpreting readings from remote locations. At all events, both
quakes were whopping. The 1960 quake not only caused widespread damage across coastal South
America, but also set off a giant tsunami that rolled six thousand miles across the Pacific and slapped
away much of downtown Hilo, Hawaii, destroying five hundred buildings and killing sixty people.

Similar wave surges claimed yet more victims as far away as Japan and the Philippines.

For pure, focused, devastation, however, probably the most intense earthquake in recorded history
was one that struck— and essentially shook to pieces— Lisbon, Portugal, on

All Saints Day

(November 1), 1755. Just before ten in the morning, the city was hit by a sudden sideways lurch now estimated at magnitude 9.0 and shaken ferociously for seven full minutes. The convulsive force was so great that the water rushed out of the city's harbor and returned in a wave fifty feet high, adding to the destruction. When at last the motion ceased, survivors enjoyed just three minutes of calm before a second shock came, only slightly less severe than the first. A third and final shock followed two hours later. At the end of it all, sixty thousand people were dead and virtually every building for miles reduced to rubble. The San Francisco earthquake of 1906, for comparison, measured an estimated 7.8 on the Richter scale and lasted less than thirty seconds.

Earthquakes are fairly common. Every day on average somewhere in the world there are two of magnitude 2.0 or greater— that's enough to give anyone nearby a pretty good jolt. Although they tend to cluster in certain places— notably around the rim of the Pacific— they can occur almost anywhere. In the United States, only Florida, eastern Texas, and the upper Midwest seem— so far— to be almost entirely immune. New England has had two quakes of magnitude 6.0 or greater in the last two hundred years. In April 2002, the region experienced a 5.1 magnitude shaking in a quake near Lake Champlain on the New York–Vermont border, causing extensive local damage and (I can attest) knocking pictures from walls and children from beds as far away as New Hampshire.

The most common types of earthquakes are those where two plates meet, as in California along the San Andreas Fault. As the plates push against each other, pressures build up until one or the other gives way. In general, the longer the interval between quakes, the greater the pent-up pressure and thus the greater the scope for a really big jolt. This is a particular worry for Tokyo, which Bill

McGuire, a hazards specialist at University College London, describes as "the city waiting to die" (not a motto you will find on many tourism leaflets). Tokyo stands on the boundary of three tectonic plates in a country already well known for its seismic instability. In 1995, as you will remember, the city of Kobe, three hundred miles to the west, was struck by a magnitude 7.2 quake, which killed 6,394 people. The damage was estimated at $99 billion. But that was as nothing— well, as comparatively little— compared with what may await Tokyo.

Tokyo has already suffered one of the most devastating earthquakes in modern times. On September 1, 1923, just before noon, the city was hit by what is known as the Great Kanto quake— an event more than ten times more powerful than Kobe's earthquake. Two hundred thousand people were killed. Since that time, Tokyo has been eerily quiet, so the strain beneath the surface has been building for eighty years. Eventually it is bound to snap. In 1923, Tokyo had a population of about three million. Today it is approaching thirty million. Nobody cares to guess how many people might die, but the potential economic cost has been put as high as $7 trillion.

Even more unnerving, because they are less well understood and capable of occurring anywhere at any time, are the rarer type of shakings known as intraplate quakes. These happen away from plate boundaries, which makes them wholly unpredictable. And because they come from a much greater depth, they tend to propagate over much wider areas. The most notorious such quakes ever to hit the United States were a series of three in New Madrid, Missouri, in the winter of 1811–12. The adventure started just after midnight on December 16 when people were awakened first by the noise of panicking farm animals (the restiveness of animals before quakes is not an old wives' tale, but is in fact well established, though not at all understood) and then by an almighty rupturing noise from deep within the Earth. Emerging from their houses, locals found the land rolling in waves up to three feet high and opening up in fissures several feet deep. A strong smell of sulfur filled the air. The shaking lasted for four minutes with the usual devastating effects to property. Among the witnesses was the artist John James Audubon, who happened to be in the area. The quake radiated outward with such force that it knocked down chimneys in Cincinnati four hundred miles away and, according to at least one account, "wrecked boats in East Coast harbors and . . . even collapsed scaffolding erected around the Capitol Building in Washington, D.C." On January 23 and February 4 further quakes of similar magnitude followed. New Madrid has been silent ever since— but not surprisingly, since such episodes have never been known to happen in the same place twice. As far as we know, they are as random as lightning. The next one could be under Chicago or Paris or

Kinshasa. No one can even begin to guess. And what causes these massive intraplate rupturings?

Something deep within the Earth. More than that we don't know.

By the 1960s scientists had grown sufficiently frustrated by how little they understood of the Earth's interior that they decided to try to do something about it. Specifically, they got the idea to drill through the ocean floor (the continental crust was too thick) to the Moho discontinuity and to extract a piece of the Earth's mantle for examination at leisure. The thinking was that if they could understand the nature of the rocks inside the Earth, they might begin to understand how they interacted, and thus possibly be able to predict earthquakes and other unwelcome events.

The project became known, all but inevitably, as the Mohole and it was pretty well disastrous. The hope was to lower a drill through 14,000 feet of Pacific Ocean water off the coast of Mexico and drill some 17,000 feet through relatively thin crustal rock. Drilling from a

ship in open waters is, in
the words of one oceanographer, “like trying to drill a hole in the sidewalks of New York from atop
the Empire State Building using a strand of spaghetti.” Every attempt ended in failure. The deepest
they penetrated was only about 600 feet. The Mohole became known as the No Hole. In 1966,
exasperated with ever-rising costs and no results, Congress killed the project.

Four years later, Soviet scientists decided to try their luck on dry land. They chose a spot on Russia’s
Kola Peninsula, near the Finnish border, and set to work with the hope of drilling to a depth of
fifteen kilometers. The work proved harder than expected, but the Soviets were commendably
persistent. When at last they gave up, nineteen years later, they had drilled to a depth of 12,262
meters, or about 7.6 miles. Bearing in mind that the crust of the Earth represents only about 0.3
percent of the planet’s volume and that the Kola hole had not cut even

one-third of the way through
the crust, we can hardly claim to have conquered the interior.
Interestingly, even though the hole was modest, nearly everything about it was surprising. Seismic
wave studies had led the scientists to predict, and pretty confidently, that they would encounter
sedimentary rock to a depth of 4,700 meters, followed by granite for the next 2,300 meters and basalt
from there on down. In the event, the sedimentary layer was 50 percent deeper than expected and the
basaltic layer was never found at all. Moreover, the world down there was far warmer than anyone
had expected, with a temperature at 10,000 meters of 180 degrees centigrade, nearly twice the
forecasted level. Most surprising of all was that the rock at that depth was saturated with water—
something that had not been thought possible.
Because we can't see into the Earth, we have to use other techniques, which mostly involve reading
waves as they travel through the interior. We also know a little bit about the

mantle from what are known as kimberlite pipes, where diamonds are formed. What happens is that deep in the Earth there is an explosion that fires, in effect, a cannonball of magma to the surface at supersonic speeds. It is a totally random event. A kimberlite pipe could explode in your backyard as you read this. Because they come up from such depths— up to 120 miles down— kimberlite pipes bring up all kinds of things not normally found on or near the surface: a rock called peridotite, crystals of olivine, and— just occasionally, in about one pipe in a hundred— diamonds. Lots of carbon comes up with kimberlite ejecta, but most is vaporized or turns to graphite. Only occasionally does a hunk of it shoot up at just the right speed and cool down with the necessary swiftness to become a diamond. It was such a pipe that made Johannesburg the most productive diamond mining city in the world, but there may be others even bigger that we don’t know about. Geologists know that somewhere in the vicinity of northeastern Indiana there is evidence of a pipe or group of pipes that may be truly colossal. Diamonds up to twenty carats or more have been found at scattered sites throughout the region. But no one has ever found the source. As John McPhee notes, it may be buried under glacially deposited soil, like the Manson crater in Iowa, or under the Great Lakes.

So how much do we know about what's inside the Earth? Very little. Scientists are generally agreed that the world beneath us is composed of four layers— rocky outer crust, a mantle of hot, viscous rock, a liquid outer core, and a solid inner core.*28 We know that the surface is dominated by silicates, which are relatively light and not heavy enough to account for the planet's overall density.

Therefore there must be heavier stuff inside. We know that to generate our magnetic field somewhere in the interior there must be a concentrated belt of metallic elements in a liquid state.

That much is universally agreed upon. Almost everything beyond that—how the layers interact, what causes them to behave in the way they do, what they will do at any time in the future— is a matter of at least some uncertainty, and generally quite a lot of uncertainty.

Even the one part of it we can see, the crust, is a matter of some fairly strident debate. Nearly all geology texts tell you that continental crust is three to six miles thick under the oceans, about twentyfive miles thick under the continents, and forty to sixty miles thick under big mountain chains, but there are many puzzling variabilities within these generalizations. The crust beneath the Sierra Nevada Mountains, for instance, is only about nineteen to twenty-five miles thick, and no one knows why. By all the laws of geophysics the Sierra Nevadas should be sinking, as if into quicksand. (Some people think they may be.)

How and when the Earth got its crust are questions that divide geologists

into two broad camps—
those who think it happened abruptly early in the Earth's history and those who think it happened
gradually and rather later. Strength of feeling runs deep on such matters. Richard Armstrong of Yale
proposed an early-burst theory in the 1960s, then spent the rest of his career fighting those who did
not agree with him. He died of cancer in 1991, but shortly before his death he "lashed out at his
critics in a polemic in an Australian earth science journal that charged them with perpetuating
myths," according to a report in Earth magazine in 1998. "He died a bitter man," reported a
colleague.

The crust and part of the outer mantle together are called the lithosphere (from the Greek lithos,
meaning "stone"), which in turn floats on top of a layer of softer rock called the asthenosphere (from
Greek words meaning "without strength"), but such terms are never entirely satisfactory. To say that

the lithosphere floats on top of the asthenosphere suggests a degree of easy buoyancy that isn't quite right. Similarly it is misleading to think of the rocks as flowing in anything like the way we think of materials flowing on the surface. The rocks are viscous, but only in the same way that glass is. It may not look it, but all the glass on Earth is flowing downward under the relentless drag of gravity.

Remove a pane of really old glass from the window of a European cathedral and it will be noticeably thicker at the bottom than at the top. That is the sort of "flow" we are talking about. The hour hand on a clock moves about ten thousand times faster than the "flowing" rocks of the mantle.

The movements occur not just laterally as the Earth's plates move across the surface, but up and down as well, as rocks rise and fall under the churning process known as convection. Convection as a process was first deduced by the eccentric Count von Rumford at the end of the eighteenth century.

Sixty years later an English vicar named Osmond Fisher presciently suggested that the Earth's interior might well be fluid enough for the contents to move about, but that idea took a very long time to gain support.

In about 1970, when geophysicists realized just how much turmoil was going on down there, it came as a considerable shock. As Shawna Vogel put it in the book Naked Earth: The New Geophysics: "It was as if scientists had spent decades figuring out the layers of the Earth's atmosphere— troposphere, stratosphere, and so forth— and then had suddenly found out about wind."

How deep the convection process goes has been a matter of controversy ever since. Some say it begins four hundred miles down, others two thousand miles below us. The problem, as Donald Trefil has observed, is that "there are two sets of data, from two different disciplines, that cannot be reconciled." Geochemists say that certain elements on Earth's surface cannot have come from the upper mantle, but must have come from deeper within the Earth. Therefore the materials in the upper and lower mantle must at least occasionally mix. Seismologists insist that there is no evidence to support such a thesis.

So all that can be said is that at some slightly indeterminate point as we head toward the center of Earth we leave the asthenosphere and plunge into pure mantle. Considering that it accounts for 82 percent of the Earth's volume and 65 percent of its mass, the mantle doesn't attract a great deal of attention, largely because the things that interest Earth scientists and general readers alike happen either deeper down (as with magnetism) or nearer the surface (as with earthquakes). We know that to a depth of about a hundred miles the mantle consists predominantly of a type of rock known as peridotite, but what fills the space beyond is uncertain. According to a Nature report, it seems not to be peridotite. More than this we do not know.

Beneath the mantle are the two cores— a solid inner core and a liquid outer one. Needless to say, our understanding of the nature of these cores is indirect, but scientists can make some reasonable assumptions. They know that the pressures at the center of the Earth are sufficiently high— something over three million times those found at the surface— to turn any rock there solid. They also know from Earth's history (among other clues) that the inner core is very good at retaining its heat. Although it is little more than a guess, it is thought that in over four billion years the temperature at the core has fallen by no more than 200°F. No one knows exactly how hot the Earth's core is, but estimates range from something over 7,000°F to 13,000°F— about as hot as the surface of the Sun.

The outer core is in many ways even less well understood, though everyone is in agreement that it is fluid and that it is the seat of magnetism. The theory was put forward by E.

C. Bullard of Cambridge

University in 1949 that this fluid part of the Earth's core revolves in a way that makes it, in effect, an electrical motor, creating the Earth's magnetic field. The assumption is that the convecting fluids in the Earth act somehow like the currents in wires. Exactly what happens isn't known, but it is felt pretty certain that it is connected with the core spinning and with its being liquid. Bodies that don't have a liquid core— the Moon and Mars, for instance— don't have magnetism.

We know that Earth's magnetic field changes in power from time to time: during the age of the dinosaurs, it was up to three times as strong as now. We also know that it reverses itself every 500,000 years or so on average, though that average hides a huge degree of unpredictability. The last reversal was about 750,000 years ago. Sometimes it stays put for millions of years— 37 million years appears to be the longest stretch— and at other times it has reversed after as little as 20,000 years.

Altogether in the last 100 million years it has reversed itself about two hundred times, and we don't have any real idea why. It has been called "the greatest unanswered question in the geological sciences."

We may be going through a reversal now. The Earth's magnetic field has diminished by perhaps as much as 6 percent in the last century alone. Any diminution in magnetism is likely to be bad news, because magnetism, apart from holding notes to refrigerators and keeping our compasses pointing the right way, plays a vital role in keeping us alive. Space is full of dangerous cosmic rays that in the absence of magnetic protection would tear through our bodies, leaving much of our DNA in useless tatters. When the magnetic field is working, these rays are safely herded away from the Earth's surface and into two zones in near space called the Van Allen belts. They also interact with particles in the upper atmosphere to create the bewitching veils of light known as the auroras.

A big part of the reason for our ignorance, interestingly enough, is that traditionally there has been little effort to coordinate what's happening on top of the Earth with what's going on inside.

According to Shawna Vogel: "Geologists and geophysicists rarely go to the same meetings or collaborate on the same problems."

Perhaps nothing better demonstrates our inadequate grasp of the dynamics of the Earth's interior than how badly we are caught out when it acts up, and it would be hard to come up with a more salutary reminder of the limitations of our understanding than the eruption of Mount St. Helens in Washington in 1980.

At that time, the lower forty-eight United States had not seen a volcanic eruption for over sixty-five years. Therefore the government volcanologists called in to monitor and forecast St. Helens's behavior primarily had seen only Hawaiian volcanoes in action, and they, it turned out, were not the same thing at all.

St. Helens started its ominous rumblings on March 20. Within a week it was erupting magma, albeit in modest amounts, up to a hundred times a day, and being constantly shaken with earthquakes.

People were evacuated to what was assumed to be a safe distance of eight miles. As the mountain’s rumblings grew St. Helens became a tourist attraction for the world. Newspapers gave daily reports on the best places to get a view. Television crews repeatedly flew in helicopters to the summit, and people were even seen climbing over the mountain. On one day, more than seventy copters and light aircraft circled the summit. But as the days passed and the rumblings failed to develop into anything dramatic, people grew restless, and the view became general that the volcano wasn’t going to blow after all.

On April 19 the northern flank of the mountain began to bulge conspicuously. Remarkably, no one in a position of responsibility saw that this strongly signaled a lateral blast. The seismologists resolutely based their conclusions on the behavior of Hawaiian volcanoes, which don't blow out sideways.

Almost the only person who believed that something really bad might happen was Jack Hyde, a geology professor at a community college in Tacoma. He pointed out that St. Helens didn't have an open vent, as Hawaiian volcanoes have, so any pressure building up inside was bound to be released dramatically and probably catastrophically. However, Hyde was not part of the official team and his observations attracted little notice.

We all know what happened next. At 8:32 A.M. on a Sunday morning, May 18, the north side of the volcano collapsed, sending an enormous avalanche of dirt and rock rushing down the mountain slope at 150 miles an hour. It was the biggest landslide in human history and

carried enough material to
bury the whole of Manhattan to a depth of four hundred feet. A minute later, its flank severely
weakened, St. Helens exploded with the force of five hundred Hiroshima-sized atomic bombs,
shooting out a murderous hot cloud at up to 650 miles an hour— much too fast, clearly, for anyone
nearby to outrace. Many people who were thought to be in safe areas, often far out of sight of the
volcano, were overtaken. Fifty-seven people were killed. Twenty-three of the bodies were never
found. The toll would have been much higher except that it was a Sunday. Had it been a weekday
many lumber workers would have been working within the death zone. As it was, people were killed
eighteen miles away.

The luckiest person on that day was a graduate student named Harry Glicken. He had been manning
an observation post 5.7 miles from the mountain, but he had a college placement interview on May

18 in California, and so had left the site the day before the eruption. His place was taken by David Johnston. Johnston was the first to report the volcano exploding; moments later he was dead. His body was never found. Glicken's luck, alas, was temporary. Eleven years later he was one of fortythree scientists and journalists fatally caught up in a lethal outpouring of superheated ash, gases, and molten rock— what is known as a pyroclastic flow— at Mount Unzen in Japan when yet another volcano was catastrophically misread.

Volcanologists may or may not be the worst scientists in the world at making predictions, but they are without question the worst in the world at realizing how bad their predictions are. Less than two years after the Unzen catastrophe another group of volcano watchers, led by Stanley Williams of the University of Arizona, descended into the rim of an active volcano called Galeras in Colombia.

Despite the deaths of recent years, only two of the sixteen members of

Williams’s party wore safety helmets or other protective gear. The volcano erupted, killing six of the scientists, along with three tourists who had followed them, and seriously injuring several others, including Williams himself.

In an extraordinarily unself-critical book called Surviving Galeras, Williams said he could “only shake my head in wonder” when he learned afterward that his colleagues in the world of volcanology had suggested that he had overlooked or disregarded important seismic signals and behaved recklessly. “How easy it is to snipe after the fact, to apply the knowledge we have now to the events of 1993,” he wrote. He was guilty of nothing worse, he believed, than unlucky timing when Galeras “behaved capriciously, as natural forces are wont to do. I was fooled, and for that I will take responsibility. But I do not feel guilty about the deaths of my colleagues. There is no guilt. There was only an eruption.”

But to return to Washington. Mount St. Helens lost thirteen hundred feet of peak, and 230 square miles of forest were devastated. Enough trees to build 150,000 homes (or 300,000 in some reports) were blown away. The damage was placed at $2.7 billion. A giant column of smoke and ash rose to a height of sixty thousand feet in less than ten minutes. An airliner some thirty miles away reported being pelted with rocks.

Ninety minutes after the blast, ash began to rain down on Yakima, Washington, a community of fifty thousand people about eighty miles away. As you would expect, the ash turned day to night and got into everything, clogging motors, generators, and electrical switching equipment, choking pedestrians, blocking filtration systems, and generally bringing things to a halt. The airport shut down and highways in and out of the city were closed.

All this was happening, you will note, just downwind of a volcano that had been rumbling menacingly for two months. Yet Yakima had no volcano emergency procedures. The city's emergency broadcast system, which was supposed to swing into action during a crisis, did not go on the air because "the Sunday-morning staff did not know how to operate the equipment." For three days, Yakima was paralyzed and cut off from the world, its airport closed, its approach roads impassable. Altogether the city received just five-eighths of an inch of ash after the eruption of Mount St. Helens. Now bear that in mind, please, as we consider what a Yellowstone blast would do.

15 **DANGEROUS BEAUTY**

IN THE 1960s, while studying the volcanic history of Yellowstone National Park, Bob Christiansen of the United States Geological Survey became puzzled about something that, oddly, had not troubled anyone before: he couldn't find the park's volcano. It had been known for a long time that Yellowstone was volcanic in nature— that's what accounted for all its geysers and other steamy

features— and the one thing about volcanoes is that they are generally pretty conspicuous. But

Christiansen couldn't find the Yellowstone volcano anywhere. In particular what he couldn't find

was a structure known as a caldera.

Most of us, when we think of volcanoes, think of the classic cone shapes of a Fuji or Kilimanjaro,

which are created when erupting magma accumulates in a symmetrical mound. These can form

remarkably quickly. In 1943, at Parícutin in Mexico, a farmer was startled to see smoke rising from a

patch on his land. In one week he was the bemused owner of a cone five hundred feet high. Within

two years it had topped out at almost fourteen hundred feet and was more than half a mile across.

Altogether there are some ten thousand of these intrusively visible volcanoes on Earth, all but a few

hundred of them extinct. But there is a second, less celebrated type of volcano that doesn't involve

mountain building. These are volcanoes so explosive that they burst open in a single mighty rupture,
leaving behind a vast subsided pit, the caldera (from a Latin word for cauldron). Yellowstone
obviously was of this second type, but Christiansen couldn't find the caldera anywhere.

By coincidence just at this time NASA decided to test some new high-altitude cameras by taking
photographs of Yellowstone, copies of which some thoughtful official passed on to the park
authorities on the assumption that they might make a nice blow-up for one of the visitors' centers. As
soon as Christiansen saw the photos he realized why he had failed to spot the caldera: virtually the
whole park— 2.2 million acres— was caldera. The explosion had left a crater more than forty miles
across— much too huge to be perceived from anywhere at ground level. At some time in the past
Yellowstone must have blown up with a violence far beyond the scale of anything known to humans.

Yellowstone, it turns out, is a supervolcano. It sits on top of an enormous hot spot, a reservoir of
molten rock that rises from at least 125 miles down in the Earth. The heat from the hot spot is what
powers all of Yellowstone’s vents, geysers, hot springs, and popping mud pots. Beneath the surface
is a magma chamber that is about forty-five miles across— roughly the same dimensions as the
park— and about eight miles thick at its thickest point. Imagine a pile of TNT about the size of
Rhode Island and reaching eight miles into the sky, to about the height of the highest cirrus clouds,
and you have some idea of what visitors to Yellowstone are shuffling around on top of. The pressure
that such a pool of magma exerts on the crust above has lifted Yellowstone and about three hundred
miles of surrounding territory about 1,700 feet higher than they would otherwise be. If it blew, the
cataclysm is pretty well beyond imagining. According to Professor Bill McGuire of University

College London, “you wouldn’t be able to get within a thousand kilometers of it” while it was erupting. The consequences that followed would be even worse. Superplumes of the type on which Yellowstone sits are rather like martini glasses— thin on the way up, but spreading out as they near the surface to create vast bowls of unstable magma. Some of these bowls can be up to 1,200 miles across. According to theories, they don’t always erupt explosively but sometimes burst forth in a vast, continuous outpouring— a flood— of molten rock, such as with the Deccan Traps in India sixty-five million years ago. (Trap in this context comes from a Swedish word for a type of lava; Deccan is simply an area.) These covered an area of 200,000 square miles and probably contributed to the demise of the dinosaurs— they certainly didn’t help— with their noxious outgassings. Superplumes may also be responsible for the rifts that cause continents to break up.

Such plumes are not all that rare. There are about thirty active ones on the Earth at the moment, and they are responsible for many of the world's best-known islands and island chains— Iceland, Hawaii, the Azores, Canaries, and Galápagos archipelagos, little Pitcairn in the middle of the South Pacific, and many others— but apart from Yellowstone they are all oceanic. No one has the faintest idea how or why Yellowstone's ended up beneath a continental plate. Only two things are certain: that the crust at Yellowstone is thin and that the world beneath it is hot. But whether the crust is thin because of the hot spot or whether the hot spot is there because the crust is thin is a matter of heated (as it were) debate. The continental nature of the crust makes a huge difference to its eruptions. Where the other supervolcanoes tend to bubble away steadily and in a comparatively benign fashion, Yellowstone blows explosively. It doesn't happen often, but when it does you want to stand well back.

Since its first known eruption 16.5 million years ago, it has blown up about a hundred times, but the most recent three eruptions are the ones that get written about. The last eruption was a thousand times greater than that of Mount St. Helens; the one before that was 280 times bigger, and the one before was so big that nobody knows exactly how big it was. It was at least twenty-five hundred times greater than St. Helens, but perhaps eight thousand times more monstrous.

We have absolutely nothing to compare it to. The biggest blast in recent times was that of Krakatau in Indonesia in August 1883, which made a bang that reverberated around the world for nine days, and made water slosh as far away as the English Channel. But if you imagine the volume of ejected material from Krakatau as being about the size of a golf ball, then the biggest of the Yellowstone blasts would be the size of a sphere you could just about hide behind. On this scale, Mount St.

Helens's would be no more than a pea.

The Yellowstone eruption of two million years ago put out enough ash to

bury New York State to a

depth of sixty-seven feet or California to a depth of twenty. This was the ash

that made Mike

Voorhies's fossil beds in eastern Nebraska. That blast occurred in what is

now Idaho, but over

millions of years, at a rate of about one inch a year, the Earth's crust has

traveled over it, so that

today it is directly under northwest Wyoming. (The hot spot itself stays in

one place, like an

acetylene torch aimed at a ceiling.) In its wake it leaves the sort of rich

volcanic plains that are ideal

for growing potatoes, as Idaho's farmers long ago discovered. In another two

million years,

geologists like to joke, Yellowstone will be producing French fries for

McDonald's, and the people

of Billings, Montana, will be stepping around geysers.

The ash fall from the last Yellowstone eruption covered all or parts of

nineteen western states (plus
parts of Canada and Mexico)— nearly the whole of the United States west of the Mississippi. This,
bear in mind, is the breadbasket of America, an area that produces roughly half the world's cereals.

And ash, it is worth remembering, is not like a big snowfall that will melt in the spring. If you
wanted to grow crops again, you would have to find some place to put all the ash. It took thousands
of workers eight months to clear 1.8 billion tons of debris from the sixteen acres of the World Trade
Center site in New York. Imagine what it would take to clear Kansas.

And that's not even to consider the climatic consequences. The last supervolcano eruption on Earth
was at Toba, in northern Sumatra, seventy-four thousand years ago. No one knows quite how big it
was other than that it was a whopper. Greenland ice cores show that the Toba blast was followed by
at least six years of "volcanic winter" and goodness knows how many poor growing seasons after

that. The event, it is thought, may have carried humans right to the brink of extinction, reducing the global population to no more than a few thousand individuals. That means that all modern humans arose from a very small population base, which would explain our lack of genetic diversity. At all events, there is some evidence to suggest that for the next twenty thousand years the total number of people on Earth was never more than a few thousand at any time. That is, needless to say, a long time to recover from a single volcanic blast.

All this was hypothetically interesting until 1973, when an odd occurrence made it suddenly momentous: water in Yellowstone Lake, in the heart of the park, began to run over the banks at the lake's southern end, flooding a meadow, while at the opposite end of the lake the water mysteriously flowed away. Geologists did a hasty survey and discovered that a large area of the park had developed an ominous bulge. This was lifting up one end of the lake and

causing the water to run out
at the other, as would happen if you lifted one side of a child’s wading pool. By 1984, the whole
central region of the park— several dozen square miles— was more than three feet higher than it had
been in 1924, when the park was last formally surveyed. Then in 1985, the whole of the central part
of the park subsided by eight inches. It now seems to be swelling again.

The geologists realized that only one thing could cause this— a restless magma chamber.

Yellowstone wasn’t the site of an ancient supervolcano; it was the site of an active one. It was also at
about this time that they were able to work out that the cycle of Yellowstone’s eruptions averaged
one massive blow every 600,000 years. The last one, interestingly enough, was 630,000 years ago.

Yellowstone, it appears, is due.

“It may not feel like it, but you’re standing on the largest active volcano in the world,” Paul Doss,
Yellowstone National Park geologist, told me soon after climbing off an

enormous Harley-Davidson motorcycle and shaking hands when we met at the park headquarters at Mammoth Hot Springs early on a lovely morning in June. A native of Indiana, Doss is an amiable, soft-spoken, extremely thoughtful man who looks nothing like a National Park Service employee. He has a graying beard and hair tied back in a long ponytail. A small sapphire stud graces one ear. A slight paunch strains against his crisp Park Service uniform. He looks more like a blues musician than a government employee. In fact, he is a blues musician (harmonica). But he sure knows and loves geology. "And I've got the best place in the world to do it," he says as we set off in a bouncy, battered four-wheeldrive vehicle in the general direction of Old Faithful. He has agreed to let me accompany him for a day as he goes about doing whatever it is a park geologist does. The first assignment today is to give an introductory talk to a new crop of tour guides.

Yellowstone, I hardly need point out, is sensationally beautiful, with plump, stately mountains, bison-specked meadows, tumbling streams, a sky-blue lake, wildlife beyond counting. “It really doesn’t get any better than this if you’re a geologist,” Doss says. “You’ve got rocks up at Beartooth Gap that are nearly three billion years old— three-quarters of the way back to Earth’s beginning— and then you’ve got mineral springs here”— he points at the sulfurous hot springs from which Mammoth takes its title— “where you can see rocks as they are being born. And in between there’s everything you could possibly imagine. I’ve never been any place where geology is more evident— or prettier.”

“So you like it?” I say.

“Oh, no, I love it,” he answers with profound sincerity. “I mean I really love it here. The winters are tough and the pay’s not too hot, but when it’s good, it’s just— ”

He interrupted himself to point out a distant gap in a range of mountains to

the west, which had just
come into view over a rise. The mountains, he told me, were known as the Gallatins. “That gap is
sixty or maybe seventy miles across. For a long time nobody could understand why that gap was
there, and then Bob Christiansen realized that it had to be because the mountains were just blown
away. When you’ve got sixty miles of mountains just obliterated, you know you’re dealing with
something pretty potent. It took Christiansen six years to figure it all out.”

I asked him what caused Yellowstone to blow when it did.

“Don’t know. Nobody knows. Volcanoes are strange things. We really don’t understand them at all.
Vesuvius, in Italy, was active for three hundred years until an eruption in 1944 and then it just
stopped. It’s been silent ever since. Some volcanologists think that it is recharging in a big way,
which is a little worrying because two million people live on or around it. But nobody knows.”

“And how much warning would you get if Yellowstone was going to go?”

He shrugged. “Nobody was around the last time it blew, so nobody knows what the warning signs are. Probably you would have swarms of earthquakes and some surface uplift and possibly some changes in the patterns of behavior of the geysers and steam vents, but nobody really knows.”

“So it could just blow without warning?”

He nodded thoughtfully. The trouble, he explained, is that nearly all the things that would constitute warning signs already exist in some measure at Yellowstone. “Earthquakes are generally a precursor of volcanic eruptions, but the park already has lots of earthquakes— 1,260 of them last year. Most of them are too small to be felt, but they are earthquakes nonetheless.”

A change in the pattern of geyser eruptions might also be taken as a clue, he said, but these too vary unpredictably. Once the most famous geyser in the park was Excelsior Geyser. It used to erupt regularly and spectacularly to heights of three hundred feet, but in 1888 it just stopped. Then in 1985 it erupted again, though only to a height of eighty feet. Steamboat Geyser is the biggest geyser in the world when it blows, shooting water four hundred feet into the air, but the intervals between its eruptions have ranged from as little as four days to almost fifty years. “If it blew today and again next week, that wouldn’t tell us anything at all about what it might do the following week or the week after or twenty years from now,” Doss says. “The whole park is so volatile that it’s essentially impossible to draw conclusions from almost anything that happens.”

Evacuating Yellowstone would never be easy. The park gets some three million visitors a year, mostly in the three peak months of summer. The park’s roads are comparatively few and they are kept intentionally narrow, partly to slow traffic, partly to preserve an air of picturesqueness, and partly because of topographical constraints. At the height of summer, it can easily take half a day to cross the park and hours to get anywhere within it. “Whenever people see animals, they just stop,

wherever they are," Doss says. "We get bear jams. We get bison jams. We get wolf jams."

In the autumn of 2000, representatives from the U.S. Geological Survey and National Park Service, along with some academics, met and formed something called the Yellowstone Volcanic Observatory. Four such bodies were in existence already— in Hawaii, California, Alaska, and Washington— but oddly none in the largest volcanic zone in the world. The YVO is not actually a thing, but more an idea— an agreement to coordinate efforts at studying and analyzing the park's diverse geology. One of their first tasks, Doss told me, was to draw up an "earthquake and volcano hazards plan"— a plan of action in the event of a crisis.

"There isn't one already?" I said.

"No. Afraid not. But there will be soon."

"Isn't that just a little tardy?"

He smiled. "Well, let's just say that it's not any too soon."

Once it is in place, the idea is that three people— Christiansen in Menlo Park, California, Professor Robert B. Smith at the University of Utah, and Doss in the park— would assess the degree of danger of any potential cataclysm and advise the park superintendent. The superintendent would take the decision whether to evacuate the park. As for surrounding areas, there are no plans. If Yellowstone were going to blow in a really big way, you would be on your own once you left the park gates.

Of course it may be tens of thousands of years before that day comes. Doss thinks such a day may not come at all. "Just because there was a pattern in the past doesn't mean that it still holds true," he says. "There is some evidence to suggest that the pattern may be a series of catastrophic explosions, then a long period of quiet. We may be in that now. The evidence now is that most of the magma chamber is cooling and crystallizing. It is releasing its volatiles; you need to trap volatiles for an explosive eruption.”

In the meantime there are plenty of other dangers in and around Yellowstone, as was made devastatingly evident on the night of August 17, 1959, at a place called Hebgen Lake just outside the park. At twenty minutes to midnight on that date, Hebgen Lake suffered a catastrophic quake. It was magnitude 7.5, not vast as earthquakes go, but so abrupt and wrenching that it collapsed an entire mountainside. It was the height of the summer season, though fortunately not so many people went to Yellowstone in those days as now. Eighty million tons of rock, moving at more than one hundred miles an hour, just fell off the mountain, traveling with such force and momentum that the leading edge of the landslide ran four hundred feet up a mountain on the other side of the valley. Along its path lay part of the Rock Creek Campground. Twenty-eight campers were killed, nineteen of them buried too deep ever to be found again. The devastation was swift but heartbreakingly fickle. Three brothers, sleeping in one tent, were spared. Their parents, sleeping in another tent beside them, were swept away and never seen again.

“A big earthquake— and I mean big— will happen sometime,” Doss told me. “You can count on that. This is a big fault zone for earthquakes.”

Despite the Hebgen Lake quake and the other known risks, Yellowstone didn’t get permanent seismometers until the 1970s.

If you needed a way to appreciate the grandeur and inexorable nature of geologic processes, you could do worse than to consider the Tetons, the sumptuously jagged range that stands just to the south of Yellowstone National Park. Nine million years ago, the Tetons didn’t exist. The land around Jackson Hole was just a high grassy plain. But then a forty-mile-long fault opened within the Earth, and since then, about once every nine hundred years, the Tetons experience a really big earthquake,

enough to jerk them another six feet higher. It is these repeated jerks over eons that have raised them
to their present majestic heights of seven thousand feet.

That nine hundred years is an average— and a somewhat misleading one. According to Robert B.
Smith and Lee J. Siegel in Windows into the Earth, a geological history of the region, the last major
Teton quake was somewhere between about five and seven thousand years ago. The Tetons, in short,
are about the most overdue earthquake zone on the planet.

Hydrothermal explosions are also a significant risk. They can happen anytime, pretty much
anywhere, and without any predictability. “You know, by design we funnel visitors into thermal
basins,” Doss told me after we had watched Old Faithful blow. “It’s what they come to see. Did you
know there are more geysers and hot springs at Yellowstone than in all the rest of the world
combined?”

“I didn’t know that.”

He nodded. “Ten thousand of them, and nobody knows when a new vent might open.” We drove to a place called Duck Lake, a body of water a couple of hundred yards across. “It looks completely innocuous,” he said. “It’s just a big pond. But this big hole didn’t used to be here. At some time in the last fifteen thousand years this blew in a really big way. You’d have had several tens of millions of tons of earth and rock and superheated water blowing out at hypersonic speeds. You can imagine what it would be like if this happened under, say, the parking lot at Old Faithful or one of the visitors’ centers.” He made an unhappy face.

“Would there be any warning?”

“Probably not. The last significant explosion in the park was at a place called Pork Chop Geyser in 1989. That left a crater about five meters across— not huge by any means, but big enough if you happened to be standing there at the time. Fortunately, nobody was around so nobody was hurt, but that happened without warning. In the very ancient past there have been explosions that have made holes a mile across. And nobody can tell you where or when that might happen again. You just have to hope that you're not standing there when it does."

Big rockfalls are also a danger. There was a big one at Gardiner Canyon in 1999, but again fortunately no one was hurt. Late in the afternoon, Doss and I stopped at a place where there was a rock overhang poised above a busy park road. Cracks were clearly visible.

"It could go at any time," Doss said thoughtfully.

"You're kidding," I said. There wasn't a moment when there weren't two cars passing beneath it, all filled with, in the most literal sense, happy campers.

"Oh, it's not likely," he added. "I'm just saying it could. Equally it could stay like that for decades. There's just no telling. People have to accept that there is risk in coming here. That's all there is to it."

As we walked back to his vehicle to head back to Mammoth Hot Springs, Doss added: “But the thing is, most of the time bad things don’t happen. Rocks don’t fall. Earthquakes don’t occur. New vents don’t suddenly open up. For all the instability, it’s mostly remarkably and amazingly tranquil.”

“Like Earth itself,” I remarked.

“Precisely,” he agreed.

The risks at Yellowstone apply to park employees as much as to visitors. Doss got a horrific sense of that in his first week on the job five years earlier. Late one night, three young summer employees engaged in an illicit activity known as “hot-potting”— swimming or basking in warm pools. Though the park, for obvious reasons, doesn’t publicize it, not all the pools in Yellowstone are dangerously hot. Some are extremely agreeable to lie in, and it was the habit of some of the summer employees to have a dip late at night even though it was against the rules to do so. Foolishly the threesome had failed to take a flashlight, which was extremely dangerous because much of the soil around the warm pools is crusty and thin and one can easily fall through into a scalding vent below. In any case, as they made their way back to their dorm, they came across a stream that they had had to leap over earlier. They backed up a few paces, linked arms and, on the count of three, took a running jump. In fact, it wasn’t the stream at all. It was a boiling pool. In the dark they had lost their bearings. None of the three survived.

I thought about this the next morning as I made a brief call, on my way out of the park, at a place called Emerald Pool, in the Upper Geyser Basin. Doss hadn’t had time to take me there the day before, but I thought I ought at least to have a look at it, for Emerald Pool is a historic site.

In 1965, a husband-and-wife team of biologists named Thomas and Louise Brock, while on a summer study trip, had done a crazy thing. They had scooped up some of the

yellowy-brown scum
that rimmed the pool and examined it for life. To their, and eventually the wider world's, deep
surprise, it was full of living microbes. They had found the world's first extremophiles— organisms
that could live in water that had previously been assumed to be much too hot or acid or choked with
sulfur to bear life. Emerald Pool, remarkably, was all these things, yet at least two types of living
things, Sulpholobus acidocaldarius and Thermophilus aquaticus as they became known, found it
congenial. It had always been supposed that nothing could survive above temperatures of 50°C (122°
F), but here were organisms basking in rank, acidic waters nearly twice that hot.

For almost twenty years, one of the Brocks' two new bacteria, Thermophilus aquaticus, remained a
laboratory curiosity until a scientist in California named Kary B. Mullis realized that heat-resistant
enzymes within it could be used to create a bit of chemical wizardry known

as a polymerase chain
reaction, which allows scientists to generate lots of DNA from very small amounts— as little as a
single molecule in ideal conditions. It’s a kind of genetic photocopying, and it became the basis for
all subsequent genetic science, from academic studies to police forensic work. It won Mullis the
Nobel Prize in chemistry in 1993.

Meanwhile, scientists were finding even hardier microbes, now known as hyperthermophiles, which
demand temperatures of 80°C (176°F) or more. The warmest organism found so far, according to
Frances Ashcroft in Life at the Extremes, is Pyrolobus fumarii, which dwells in the walls of ocean
vents where the temperature can reach 113°C (235.4°F). The upper limit for life is thought to be
about 120°C (248°F), though no one actually knows. At all events, the Brocks’ findings completely
changed our perception of the living world. As NASA scientist Jay Bergstralh has put it: “Wherever

we go on Earth— even into what's seemed like the most hostile possible environments for life— as long as there is liquid water and some source of chemical energy we find life."

Life, it turns out, is infinitely more clever and adaptable than anyone had ever supposed. This is a very good thing, for as we are about to see, we live in a world that doesn't altogether seem to want us here.

PART V **LIFE ITSELF**

16 **LONELY PLANET**

IT ISN'T EASY being an organism. In the whole universe, as far as we yet know, there is only one place, an inconspicuous outpost of the Milky Way called Earth, that will sustain you, and even it can be pretty grudging.

From the bottom of the deepest ocean trench to the top of the highest mountain, the zone that covers nearly the whole of known life, is only something over a dozen miles— not much when set against the roominess of the cosmos at large.

For humans it is even worse because we happen to belong to the portion of living things that took the rash but venturesome decision 400 million years ago to crawl out of the seas and become land based and oxygen breathing. In consequence, no less than 99.5 percent of the world's habitable space by volume, according to one estimate, is fundamentally— in practical terms completely— off-limits to us.

It isn't simply that we can't breathe in water, but that we couldn't bear the pressures. Because water is about 1,300 times heavier than air, pressures rise swiftly as you descend— by the equivalent of one atmosphere for every ten meters (thirty-three feet) of depth. On land, if you rose to the top of a fivehundred-foot eminence— Cologne Cathedral or the Washington Monument, say— the change in pressure would be so slight as to be indiscernible. At the same depth underwater, however, your veins would collapse and your lungs would compress to the approximate dimensions of a Coke can.

Amazingly, people do voluntarily dive to such depths, without breathing apparatus, for the fun of it
in a sport known as free diving. Apparently the experience of having your internal organs rudely
deformed is thought exhilarating (though not presumably as exhilarating as having them return to
their former dimensions upon resurfacing). To reach such depths, however, divers must be dragged
down, and quite briskly, by weights. Without assistance, the deepest anyone has gone and lived to
talk about it afterward was an Italian named Umberto Pelizzari, who in 1992 dove to a depth of 236
feet, lingered for a nanosecond, and then shot back to the surface. In terrestrial terms, 236 feet is just
slightly over the length of one New York City block. So even in our most exuberant stunts we can
hardly claim to be masters of the abyss.

Other organisms do of course manage to deal with the pressures at depth, though quite how some of them do so is a mystery. The deepest point in the ocean is the Mariana Trench in the Pacific. There, some seven miles down, the pressures rise to over sixteen thousand pounds per square inch. We have managed once, briefly, to send humans to that depth in a sturdy diving vessel, yet it is home to colonies of amphipods, a type of crustacean similar to shrimp but transparent, which survive without any protection at all. Most oceans are of course much shallower, but even at the average ocean depth of two and a half miles the pressure is equivalent to being squashed beneath a stack of fourteen loaded cement trucks.

Nearly everyone, including the authors of some popular books on oceanography, assumes that the human body would crumple under the immense pressures of the deep ocean. In fact, this appears not to be the case. Because we are made largely of water ourselves, and water is "virtually incompressible," in the words of Frances Ashcroft of Oxford University, "the body remains at the same pressure as the surrounding water, and is not crushed at depth." It is the gases inside your body, particularly in the lungs, that cause the trouble. These do compress, though at what point the compression becomes fatal is not known. Until quite recently it was thought that anyone diving to one hundred meters or so would die painfully as his or her lungs imploded or chest wall collapsed, but the free divers have repeatedly proved otherwise. It appears, according to Ashcroft, that "humans may be more like whales and dolphins than had been expected."

Plenty else can go wrong, however. In the days of diving suits— the sort that were connected to the surface by long hoses— divers sometimes experienced a dreaded phenomenon known as "the squeeze." This occurred when the surface pumps failed, leading to a catastrophic loss of pressure in the suit. The air would leave the suit with such violence that the hapless diver would be, all too literally, sucked up into the helmet and hosepipe. When hauled to the surface, "all that is left in the suit are his bones and some rags of flesh," the biologist J. B. S. Haldane wrote in 1947, adding for the benefit of doubters, "This has happened."

(Incidentally, the original diving helmet, designed in 1823 by an Englishman named Charles Deane, was intended not for diving but for fire-fighting. It was called a "smoke helmet," but being made of metal it was hot and cumbersome and, as Deane soon discovered, firefighters had no particular eagerness to enter burning structures in any form of attire, but most especially not in something that heated up like a kettle and made them clumsy into the bargain. In an attempt to save his investment, Deane tried it underwater and found it was ideal for salvage work.)

The real terror of the deep, however, is the bends— not so much because they are unpleasant, though of course they are, as because they are so much more likely. The air we breathe is 80 percent nitrogen. Put the human body under pressure, and that nitrogen is transformed into tiny bubbles that migrate into the blood and tissues. If the pressure is changed too rapidly—as with a too-quick ascent by a diver— the bubbles trapped within the body will begin to fizz in exactly the manner of a freshly opened bottle of champagne, clogging tiny blood vessels, depriving cells of oxygen, and causing pain so excruciating that sufferers are prone to bend double in agony—hence “the bends.”

The bends have been an occupational hazard for sponge and pearl divers since time immemorial but didn’t attract much attention in the Western world until the nineteenth century, and then it was among people who didn’t get wet at all (or at least not very wet and not generally much above the ankles). They were caisson workers. Caissons were enclosed dry chambers built on riverbeds to facilitate the construction of bridge piers. They were filled with compressed

air, and often when the
workers emerged after an extended period of working under this artificial pressure they experienced
mild symptoms like tingling or itchy skin. But an unpredictable few felt more insistent pain in the
joints and occasionally collapsed in agony, sometimes never to get up again.

It was all most puzzling. Sometimes workers would go to bed feeling fine, but wake up paralyzed.

Sometimes they wouldn't wake up at all. Ashcroft relates a story concerning the directors of a new
tunnel under the Thames who held a celebratory banquet as the tunnel neared completion. To their
consternation their champagne failed to fizz when uncorked in the compressed air of the tunnel.

However, when at length they emerged into the fresh air of a London evening, the bubbles sprang
instantly to fizziness, memorably enlivening the digestive process.

Apart from avoiding high-pressure environments altogether, only two strategies are reliably
successful against the bends. The first is to suffer only a very short exposure

to the changes in
pressure. That is why the free divers I mentioned earlier can descend to depths of five hundred feet
without ill effect. They don't stay under long enough for the nitrogen in their system to dissolve into
their tissues. The other solution is to ascend by careful stages. This allows the little bubbles of
nitrogen to dissipate harmlessly.

A great deal of what we know about surviving at extremes is owed to the extraordinary father-andson
team of John Scott and J. B. S. Haldane. Even by the demanding standards of British
intellectuals, the Haldanes were outstandingly eccentric. The senior Haldane was born in 1860 to an
aristocratic Scottish family (his brother was Viscount Haldane) but spent most of his career in
comparative modesty as a professor of physiology at Oxford. He was famously absent-minded. Once
after his wife had sent him upstairs to change for a dinner party he failed to return and was

discovered asleep in bed in his pajamas. When roused, Haldane explained that he had found himself disrobing and assumed it was bedtime. His idea of a vacation was to travel to Cornwall to study hookworm in miners. Aldous Huxley, the novelist grandson of T. H. Huxley, who lived with the Haldanes for a time, parodied him, a touch mercilessly, as the scientist Edward Tantamount in the novel Point Counter Point.

Haldane’s gift to diving was to work out the rest intervals necessary to manage an ascent from the depths without getting the bends, but his interests ranged across the whole of physiology, from studying altitude sickness in climbers to the problems of heatstroke in desert regions. He had a particular interest in the effects of toxic gases on the human body. To understand more exactly how carbon monoxide leaks killed miners, he methodically poisoned himself, carefully taking and measuring his own blood samples the while. He quit only when he was on the verge of losing all

muscle control and his blood saturation level had reached 56 percent— a level, as Trevor Norton

notes in his entertaining history of diving, Stars Beneath the Sea, only fractionally removed from

nearly certain lethality.

Haldane's son Jack, known to posterity as J.B.S., was a remarkable prodigy who took an interest in

his father's work almost from infancy. At the age of three he was overheard demanding peevishly of

his father, "But is it oxyhaemoglobin or carboxyhaemoglobin?" Throughout his youth, the young

Haldane helped his father with experiments. By the time he was a teenager, the two often tested

gases and gas masks together, taking turns to see how long it took them to pass out.

Though J. B. S. Haldane never took a degree in science (he studied classics at Oxford), he became a

brilliant scientist in his own right, mostly in Cambridge. The biologist Peter Medawar, who spent his life around mental Olympians, called him “the cleverest man I ever knew.” Huxley likewise parodied the younger Haldane in his novel Antic Hay, but also used his ideas on genetic manipulation of humans as the basis for the plot of Brave New World. Among many other achievements, Haldane played a central role in marrying Darwinian principles of evolution to the genetic work of Gregor Mendel to produce what is known to geneticists as the Modern Synthesis.

Perhaps uniquely among human beings, the younger Haldane found World War I “a very enjoyable experience” and freely admitted that he “enjoyed the opportunity of killing people.” He was himself wounded twice. After the war he became a successful popularizer of science and wrote twenty-three books (as well as over four hundred scientific papers). His books are still thoroughly readable and instructive, though not always easy to find. He also became an enthusiastic Marxist. It has been suggested, not altogether cynically, that this was out of a purely contrarian instinct, and that if he had been born in the Soviet Union he would have been a passionate monarchist. At all events, most of his articles first appeared in the Communist Daily Worker.

Whereas his father’s principal interests concerned miners and poisoning, the younger Haldane became obsessed with saving submariners and divers from the unpleasant consequences of their work. With Admiralty funding he acquired a decompression chamber that he called the “pressure pot.” This was a metal cylinder into which three people at a time could be sealed and subjected to tests of various types, all painful and nearly all dangerous. Volunteers might be required to sit in ice water while breathing “aberrant atmosphere” or subjected to rapid changes of pressurization. In one experiment, Haldane simulated a dangerously hasty ascent to see what would happen. What happened was that the dental fillings in his teeth exploded. “Almost every experiment,” Norton writes, “ended with someone having a seizure, bleeding, or vomiting.” The chamber was virtually soundproof, so the only way for occupants to signal unhappiness or distress was to tap insistently on the chamber wall or to hold up notes to a small window.

On another occasion, while poisoning himself with elevated levels of oxygen, Haldane had a fit so severe that he crushed several vertebrae. Collapsed lungs were a routine hazard. Perforated eardrums were quite common, but, as Haldane reassuringly noted in one of his essays, “the drum generally heals up; and if a hole remains in it, although one is somewhat deaf, one can blow tobacco smoke out of the ear in question, which is a social accomplishment.”

What was extraordinary about this was not that Haldane was willing to subject himself to such risk and discomfort in the pursuit of science, but that he had no trouble talking colleagues and loved ones into climbing into the chamber, too. Sent on a simulated descent, his wife once had a fit that lasted thirteen minutes. When at last she stopped bouncing across the floor, she was helped to her feet and sent home to cook dinner. Haldane happily employed whoever happened to be around, including on one memorable occasion a former prime minister of Spain, Juan Negrín. Dr. Negrín complained afterward of minor tingling and "a curious velvety sensation on the lips" but otherwise seems to have escaped unharmed. He may have considered himself very lucky. A similar experiment with oxygen deprivation left Haldane without feeling in his buttocks and lower spine for six years.

Among Haldane's many specific preoccupations was nitrogen intoxication. For reasons that are still poorly understood, beneath depths of about a hundred feet nitrogen becomes a powerful intoxicant.

Under its influence divers had been known to offer their air hoses to passing fish or decide to try to have a smoke break. It also produced wild mood swings. In one test, Haldane noted, the subject "alternated between depression and elation, at one moment begging to be decompressed because he felt 'bloody awful' and the next minute laughing and attempting to interfere with his colleague's dexterity test." In order to measure the rate of deterioration in the subject, a scientist had to go into the chamber with the volunteer to conduct simple mathematical tests. But after a few minutes, as Haldane later recalled, "the tester was usually as intoxicated as the testee, and often forgot to press the spindle of his stopwatch, or to take proper notes." The cause of the inebriation is even now a mystery. It is thought that it may be the same thing that causes alcohol intoxication, but as no one knows for certain what causes that we are none the wiser. At all events, without the greatest care, it is easy to get in trouble once you leave the surface world.

Which brings us back (well, nearly) to our earlier observation that Earth is not the easiest place to be an organism, even if it is the only place. Of the small portion of the planet's surface that is dry enough to stand on, a surprisingly large amount is too hot or cold or dry or steep or lofty to be of much use to us. Partly, it must be conceded, this is our fault. In terms of adaptability, humans are pretty amazingly useless. Like most animals, we don’t much like really hot places, but because we sweat so freely and easily stroke, we are especially vulnerable. In the worst circumstances— on foot without water in a hot desert— most people will grow delirious and keel over, possibly never to rise again, in no more than six or seven hours. We are no less helpless in the face of cold. Like all mammals, humans are good at generating heat but— because we are so nearly hairless— not good at keeping it. Even in quite mild weather half the calories you burn go to keep your body warm. Of course, we can counter these frailties to a large extent by employing clothing and shelter, but even so the portions of Earth on which we are prepared or able to live are modest indeed: just 12 percent of

the total land area, and only 4 percent of the whole surface if you include the

seas.

Yet when you consider conditions elsewhere in the known universe, the

wonder is not that we use so

little of our planet but that we have managed to find a planet that we can use

even a bit of. You have

only to look at our own solar system— or, come to that, Earth at certain

periods in its own history—

to appreciate that most places are much harsher and much less amenable to

life than our mild, blue

watery globe.

So far space scientists have discovered about seventy planets outside the

solar system, out of the ten

billion trillion or so that are thought to be out there, so humans can hardly

claim to speak with

authority on the matter, but it appears that if you wish to have a planet

suitable for life, you have to

be just awfully lucky, and the more advanced the life, the luckier you have

to be. Various observers

have identified about two dozen particularly helpful breaks we have had on Earth, but this is a flying survey so we'll distill them down to the principal four. They are:

Excellent location. We are, to an almost uncanny degree, the right distance from the right sort of star, one that is big enough to radiate lots of energy, but not so big as to burn itself out swiftly. It is a curiosity of physics that the larger a star the more rapidly it burns. Had our sun been ten times as massive, it would have exhausted itself after ten million years instead of ten billion and we wouldn't be here now. We are also fortunate to orbit where we do. Too much nearer and everything on Earth would have boiled away. Much farther away and everything would have frozen.

In 1978, an astrophysicist named Michael Hart made some calculations and concluded that Earth would have been uninhabitable had it been just 1 percent farther from or 5 percent closer to the Sun.

That's not much, and in fact it wasn't enough. The figures have since been refined and made a little more generous— 5 percent nearer and 15 percent farther are thought to be more accurate assessments for our zone of habitability— but that is still a narrow belt.*29

To appreciate just how narrow, you have only to look at Venus. Venus is only twenty-five million miles closer to the Sun than we are. The Sun's warmth reaches it just two minutes before it touches us. In size and composition, Venus is very like Earth, but the small difference in orbital distance made all the difference to how it turned out. It appears that during the early years of the solar system Venus was only slightly warmer than Earth and probably had oceans. But those few degrees of extra warmth meant that Venus could not hold on to its surface water, with disastrous consequences for its climate. As its water evaporated, the hydrogen atoms escaped into space, and the oxygen atoms combined with carbon to form a dense atmosphere of the greenhouse gas CO_2. Venus became stifling. Although people of my age will recall a time when astronomers hoped that Venus might harbor life beneath its padded clouds, possibly even a kind of tropical verdure, we now know that it is much too fierce an environment for any kind of life that we can reasonably conceive of. Its surface temperature is a roasting 470 degrees centigrade (roughly 900 degrees Fahrenheit), which is hot enough to melt lead, and the atmospheric pressure at the surface is ninety times that of Earth, or more than any human body could withstand. We lack the technology to make suits or even spaceships that would allow us to visit. Our knowledge of Venus's surface is based on distant radar imagery and some startled squawks from an unmanned Soviet probe that was dropped hopefully into the clouds in 1972 and functioned for barely an hour before permanently shutting down.

So that's what happens when you move two light minutes closer to the Sun. Travel farther out and the problem becomes not heat but cold, as Mars frigidly attests. It, too, was once a much more congenial place, but couldn't retain a usable atmosphere and turned into a frozen waste.

But just being the right distance from the Sun cannot be the whole story, for otherwise the Moon would be forested and fair, which patently it is not. For that you need to have:

The right kind of planet. I don't imagine even many geophysicists, when asked to count their blessings, would include living on a planet with a molten interior, but it's a pretty near certainty that without all that magma swirling around beneath us we wouldn't be here now. Apart from much else, our lively interior created the outgassing that helped to build an atmosphere and provided us with the magnetic field that shields us from cosmic radiation. It also gave us plate tectonics, which continually renews and rumples the surface. If Earth were perfectly smooth, it would be covered everywhere with water to a depth of four kilometers. There might be life in that lonesome ocean, but there certainly wouldn't be baseball.

In addition to having a beneficial interior, we also have the right elements in the correct proportions.

In the most literal way, we are made of the right stuff. This is so crucial to our well-being that we are going to discuss it more fully in a minute, but first we need to consider the two remaining factors, beginning with another one that is often overlooked:

We're a twin planet. Not many of us normally think of the Moon as a companion planet, but that is in effect what it is. Most moons are tiny in relation to their master planet. The Martian satellites of Phobos and Deimos, for instance, are only about ten kilometers in diameter. Our Moon, however, is more than a quarter the diameter of the Earth, which makes ours the only planet in the solar system with a sizeable moon in comparison to itself (except Pluto, which doesn't really count because Pluto is itself so small), and what a difference that makes to us.

Without the Moon's steadying influence, the Earth would wobble like a dying top, with goodness knows what consequences for climate and weather. The Moon's steady gravitational influence keeps the Earth spinning at the right speed and angle to provide the sort of stability necessary for the long and successful development of life. This won't go on forever. The Moon is slipping from our grasp at a rate of about 1.5 inches a year. In another two billion years it will have receded so far that it won't keep us steady and we will have to come up with some other solution, but in the meantime you should think of it as much more than just a pleasant feature in the night sky.

For a long time, astronomers assumed that the Moon and Earth either formed together or that the Earth captured the Moon as it drifted by. We now believe, as you will recall from an earlier chapter, that about 4.5 billion years ago a Mars-sized object slammed into Earth, blowing out enough

material to create the Moon from the debris. This was obviously a very good thing for us— but
especially so as it happened such a long time ago. If it had happened in 1896 or last Wednesday
clearly we wouldn't be nearly so pleased about it. Which brings us to our fourth and in many ways
most crucial consideration:

Timing. The universe is an amazingly fickle and eventful place, and our existence within it is a
wonder. If a long and unimaginably complex sequence of events stretching back 4.6 billion years or
so hadn't played out in a particular manner at particular times— if, to take just one obvious instance,
the dinosaurs hadn't been wiped out by a meteor when they were— you might well be six inches
long, with whiskers and a tail, and reading this in a burrow.

We don't really know for sure because we have nothing else to compare our own existence to, but it
seems evident that if you wish to end up as a moderately advanced, thinking society, you need to be

at the right end of a very long chain of outcomes involving reasonable periods of stability interspersed with just the right amount of stress and challenge (ice ages appear to be especially helpful in this regard) and marked by a total absence of real cataclysm. As we shall see in the pages that remain to us, we are very lucky to find ourselves in that position.

And on that note, let us now turn briefly to the elements that made us.

There are ninety-two naturally occurring elements on Earth, plus a further twenty or so that have been created in labs, but some of these we can immediately put to one side—as, in fact, chemists themselves tend to do. Not a few of our earthly chemicals are surprisingly little known. Astatine, for instance, is practically unstudied. It has a name and a place on the periodic table (next door to Marie Curie's polonium), but almost nothing else. The problem isn't scientific indifference, but rarity.

There just isn't much astatine out there. The most elusive element of all, however, appears to be francium, which is so rare that it is thought that our entire planet may contain, at any given moment, fewer than twenty francium atoms. Altogether only about thirty of the naturally occurring elements are widespread on Earth, and barely half a dozen are of central importance to life.

As you might expect, oxygen is our most abundant element, accounting for just under 50 percent of the Earth’s crust, but after that the relative abundances are often surprising. Who would guess, for instance, that silicon is the second most common element on Earth or that titanium is tenth?

Abundance has little to do with their familiarity or utility to us. Many of the more obscure elements are actually more common than the better-known ones. There is more cerium on Earth than copper, more neodymium and lanthanum than cobalt or nitrogen. Tin barely makes it into the top fifty, eclipsed by such relative obscurities as praseodymium, samarium, gadolinium, and dysprosium.

Abundance also has little to do with ease of detection. Aluminum is the fourth most common element on Earth, accounting for nearly a tenth of everything that’s underneath your feet, but its existence wasn’t even suspected until it was discovered in the nineteenth century by Humphry Davy, and for a long time after that it was treated as rare and precious. Congress nearly put a shiny lining of aluminum foil atop the Washington Monument to show what a classy and prosperous nation we had become, and the French imperial family in the same period discarded the state silver dinner service and replaced it with an aluminum one. The fashion was cutting edge even if the knives weren’t.

Nor does abundance necessarily relate to importance. Carbon is only the fifteenth most common element, accounting for a very modest 0.048 percent of Earth’s crust, but we would be lost without it. What sets the carbon atom apart is that it is shamelessly promiscuous. It is the party animal of the atomic world, latching on to many other atoms (including itself) and holding tight, forming molecular conga lines of hearty robustness— the very trick of nature necessary to build proteins and DNA. As Paul Davies has written: “If it wasn’t for carbon, life as we know it would be impossible. Probably any sort of life would be impossible.” Yet carbon is not all that plentiful even in humans, who so vitally depend on it. Of every 200 atoms in your body, 126 are hydrogen, 51 are oxygen, and just 19 are carbon.*30

Other elements are critical not for creating life but for sustaining it. We need iron to manufacture hemoglobin, and without it we would die. Cobalt is necessary for the creation of vitamin B12. Potassium and a very little sodium are literally good for your nerves. Molybdenum, manganese, and vanadium help to keep your enzymes purring. Zinc— bless it— oxidizes alcohol.

We have evolved to utilize or tolerate these things— we could hardly be here otherwise— but even

then we live within narrow ranges of acceptance. Selenium is vital to all of us, but take in just a little

too much and it will be the last thing you ever do. The degree to which organisms require or tolerate

certain elements is a relic of their evolution. Sheep and cattle now graze side by side, but actually

have very different mineral requirements. Modern cattle need quite a lot of copper because they

evolved in parts of Europe and Africa where copper was abundant. Sheep, on the other hand,

evolved in copper-poor areas of Asia Minor. As a rule, and not surprisingly, our tolerance for

elements is directly proportionate to their abundance in the Earth's crust. We have evolved to expect,

and in some cases actually need, the tiny amounts of rare elements that accumulate in the flesh or

fiber that we eat. But step up the doses, in some cases by only a tiny amount, and we can soon cross

a threshold. Much of this is only imperfectly understood. No one knows, for example, whether a tiny amount of arsenic is necessary for our well-being or not. Some authorities say it is; some not. All that is certain is that too much of it will kill you.

The properties of the elements can become more curious still when they are combined. Oxygen and hydrogen, for instance, are two of the most combustion-friendly elements around, but put them together and they make incombustible water.*31 Odder still in combination are sodium, one of the most unstable of all elements, and chlorine, one of the most toxic. Drop a small lump of pure sodium into ordinary water and it will explode with enough force to kill. Chlorine is even more notoriously hazardous. Though useful in small concentrations for killing microorganisms (it's chlorine you smell in bleach), in larger volumes it is lethal. Chlorine was the element of choice for many of the poison gases of the First World War. And, as many a sore-eyed swimmer will attest, even in exceedingly dilute form the human body doesn’t appreciate it. Yet put these two nasty elements together and what do you get? Sodium chloride— common table salt.

By and large, if an element doesn’t naturally find its way into our systems— if it isn’t soluble in water, say— we tend to be intolerant of it. Lead poisons us because we were never exposed to it until we began to fashion it into food vessels and pipes for plumbing. (Not incidentally, lead’s symbol is Pb, for the Latin plumbum, the source word for our modern plumbing.) The Romans also flavored their wine with lead, which may be part of the reason they are not the force they used to be. As we have seen elsewhere, our own performance with lead (not to mention mercury, cadmium, and all the other industrial pollutants with which we routinely dose ourselves) does not leave us a great deal of room for smirking. When elements don’t occur naturally on Earth, we have evolved no tolerance for them, and so they tend to be extremely toxic to us, as with plutonium. Our

tolerance for plutonium is
zero: there is no level at which it is not going to make you want to lie down.
I have brought you a long way to make a small point: a big part of the reason that Earth seems so
miraculously accommodating is that we evolved to suit its conditions. What we marvel at is not that
it is suitable to life but that it is suitable to our life— and hardly surprising, really. It may be that
many of the things that make it so splendid to us— well-proportioned Sun, doting Moon, sociable
carbon, more magma than you can shake a stick at, and all the rest— seem splendid simply because
they are what we were born to count on. No one can altogether say.

Other worlds may harbor beings thankful for their silvery lakes of mercury and drifting clouds of
ammonia. They may be delighted that their planet doesn't shake them silly with its grinding plates or
spew messy gobs of lava over the landscape, but rather exists in a permanent nontectonic tranquility.

Any visitors to Earth from afar would almost certainly, at the very least, be

bemused to find us living
in an atmosphere composed of nitrogen, a gas sulkily disinclined to react with anything, and oxygen,
which is so partial to combustion that we must place fire stations throughout our cities to protect
ourselves from its livelier effects. But even if our visitors were oxygen-breathing bipeds with
shopping malls and a fondness for action movies, it is unlikely that they would find Earth ideal. We
couldn't even give them lunch because all our foods contain traces of manganese, selenium, zinc,
and other elemental particles at least some of which would be poisonous to them. To them Earth
might not seem a wondrously congenial place at all.
The physicist Richard Feynman used to make a joke about a posteriori conclusions, as they are
called. "You know, the most amazing thing happened to me tonight," he would say. "I saw a car with
the license plate ARW 357. Can you imagine? Of all the millions of license plates in the state, what

was the chance that I would see that particular one tonight? Amazing!" His point, of course, was that
it is easy to make any banal situation seem extraordinary if you treat it as fateful.

So it is possible that the events and conditions that led to the rise of life on Earth are not quite as
extraordinary as we like to think. Still, they were extraordinary enough, and one thing is certain: they
will have to do until we find some better.

17 **INTO THE TROPOSPHERE**

THANK GOODNESS FOR the atmosphere. It keeps us warm. Without it, Earth would be a lifeless
ball of ice with an average temperature of minus 60 degrees Fahrenheit. In addition, the atmosphere
absorbs or deflects incoming swarms of cosmic rays, charged particles, ultraviolet rays, and the like.

Altogether, the gaseous padding of the atmosphere is equivalent to a fifteen-foot thickness of
protective concrete, and without it these invisible visitors from space would slice through us like tiny

daggers. Even raindrops would pound us senseless if it weren't for the atmosphere's slowing drag.

The most striking thing about our atmosphere is that there isn't very much of it. It extends upward for about 120 miles, which might seem reasonably bounteous when viewed from ground level, but if you shrank the Earth to the size of a standard desktop globe it would only be about the thickness of a couple of coats of varnish.

For scientific convenience, the atmosphere is divided into four unequal layers: troposphere, stratosphere, mesosphere, and ionosphere (now often called the thermosphere). The troposphere is the part that's dear to us. It alone contains enough warmth and oxygen to allow us to function, though even it swiftly becomes uncongenial to life as you climb up through it. From ground level to its highest point, the troposphere (or "turning sphere") is about ten miles thick at the equator and no more than six or seven miles high in the temperate latitudes where most of us live. Eighty percent of the atmosphere's mass, virtually all the water, and thus virtually all the weather are contained within this thin and wispy layer. There really isn't much between you and oblivion. Beyond the troposphere is the stratosphere. When you see the top of a storm cloud flattening out into the classic anvil shape, you are looking at the boundary between the troposphere and stratosphere.

This invisible ceiling is known as the tropopause and was discovered in 1902 by a Frenchman in a balloon, Léon-Philippe Teisserenc de Bort. Pause in this sense doesn't mean to stop momentarily but to cease altogether; it's from the same Greek root as menopause. Even at its greatest extent, the tropopause is not very distant. A fast elevator of the sort used in modern skyscrapers could get you there in about twenty minutes, though you would be well advised not to make the trip. Such a rapid ascent without pressurization would, at the very least, result in severe cerebral and pulmonary edemas, a dangerous excess of fluids in the body's tissues. When the doors opened at the viewing platform, anyone inside would almost certainly be dead or dying. Even a more measured ascent would be accompanied by a great deal of discomfort. The temperature six miles up can be -70 degrees Fahrenheit, and you would need, or at least very much appreciate, supplementary oxygen.

After you have left the troposphere the temperature soon warms up again, to about 40 degrees Fahrenheit, thanks to the absorptive effects of ozone (something else de Bort discovered on his daring 1902 ascent). It then plunges to as low as -130 degrees Fahrenheit in the mesosphere before skyrocketing to 2,700 degrees Fahrenheit or more in the aptly named but very erratic thermosphere, where temperatures can vary by a thousand degrees from day to night—though it must be said that "temperature" at such a height becomes a somewhat notional concept. Temperature is really just a

measure of the activity of molecules. At sea level, air molecules are so thick that one molecule can
move only the tiniest distance— about three-millionths of an inch, to be precise— before banging into
another. Because trillions of molecules are constantly colliding, a lot of heat gets exchanged. But at
the height of the thermosphere, at fifty miles or more, the air is so thin that any two molecules will
be miles apart and hardly ever come in contact. So although each molecule is very warm, there are
few interactions between them and thus little heat transference. This is good news for satellites and
spaceships because if the exchange of heat were more efficient any man-made object orbiting at that
level would burst into flame.

Even so, spaceships have to take care in the outer atmosphere, particularly on return trips to Earth, as
the space shuttle Columbia demonstrated all too tragically in February 2003. Although the
atmosphere is very thin, if a craft comes in at too steep an angle— more than

about 6 degrees— or too

swiftly it can strike enough molecules to generate drag of an exceedingly

combustible nature.

Conversely, if an incoming vehicle hit the thermosphere at too shallow an

angle, it could well

bounce back into space, like a pebble skipped across water.

But you needn't venture to the edge of the atmosphere to be reminded of

what hopelessly groundhugging

beings we are. As anyone who has spent time in a lofty city will know, you

don't have to

rise too many thousands of feet from sea level before your body begins to

protest. Even experienced

mountaineers, with the benefits of fitness, training, and bottled oxygen,

quickly become vulnerable

at height to confusion, nausea, exhaustion, frostbite, hypothermia, migraine,

loss of appetite, and a

great many other stumbling dysfunctions. In a hundred emphatic ways the

human body reminds its

owner that it wasn't designed to operate so far above sea level.

"Even under the most favorable circumstances," the climber Peter Habeler

has written of conditions
atop Everest, “every step at that altitude demands a colossal effort of will. You must force yourself
to make every movement, reach for every handhold. You are perpetually threatened by a leaden,
deadly fatigue.” In The Other Side of Everest, the British mountaineer and filmmaker Matt
Dickinson records how Howard Somervell, on a 1924 British expedition up Everest, “found himself
choking to death after a piece of infected flesh came loose and blocked his windpipe.” With a
supreme effort Somervell managed to cough up the obstruction. It turned out to be “the entire mucus
lining of his larynx.”

Bodily distress is notorious above 25,000 feet— the area known to climbers as the Death Zone— but
many people become severely debilitated, even dangerously ill, at heights of no more than 15,000
feet or so. Susceptibility has little to do with fitness. Grannies sometimes caper about in lofty

situations while their fitter offspring are reduced to helpless, groaning heaps until conveyed to lower altitudes.

The absolute limit of human tolerance for continuous living appears to be about 5,500 meters, or 18,000 feet, but even people conditioned to living at altitude could not tolerate such heights for long.

Frances Ashcroft, in Life at the Extremes, notes that there are Andean sulfur mines at 5,800 meters, but that the miners prefer to descend 460 meters each evening and climb back up the following day, rather than live continuously at that elevation. People who habitually live at altitude have often spent thousands of years developing disproportionately large chests and lungs, increasing their density of oxygen-bearing red blood cells by almost a third, though there are limits to how much thickening with red cells the blood supply can stand. Moreover, above 5,500 meters even the most well-adapted women cannot provide a growing fetus with enough oxygen to bring it to its full term.

In the 1780s when people began to make experimental balloon ascents in Europe, something that surprised them was how chilly it got as they rose. The temperature drops about 3 degrees Fahrenheit with every thousand feet you climb. Logic would seem to indicate that the closer you get to a source of heat, the warmer you would feel. Part of the explanation is that you are not really getting nearer the Sun in any meaningful sense. The Sun is ninety-three million miles away. To move a couple of thousand feet closer to it is like taking one step closer to a bushfire in Australia when you are standing in Ohio, and expecting to smell smoke. The answer again takes us back to the question of the density of molecules in the atmosphere. Sunlight energizes atoms. It increases the rate at which they jiggle and jounce, and in their enlivened state they crash into one another, releasing heat. When you feel the sun warm on your back on a summer's day, it's really excited atoms you feel. The higher you climb, the fewer molecules there are, and so the fewer collisions between them.

Air is deceptive stuff. Even at sea level, we tend to think of the air as being ethereal and all but weightless. In fact, it has plenty of bulk, and that bulk often exerts itself. As a marine scientist named Wyville Thomson wrote more than a century ago: “We sometimes find when we get up in the morning, by a rise of an inch in the barometer, that nearly half a ton has been quietly piled upon us during the night, but we experience no inconvenience, rather a feeling of exhilaration and buoyancy, since it requires a little less exertion to move our bodies in the denser medium.” The reason you don’t feel crushed under that extra half ton of pressure is the same reason your body would not be crushed deep beneath the sea: it is made mostly of incompressible fluids, which push back, equalizing the pressures within and without.

But get air in motion, as with a hurricane or even a stiff breeze, and you will quickly be reminded that it has very considerable mass. Altogether there are about 5,200 million million tons of air around us— 25 million tons for every square mile of the planet— a not inconsequential volume. When you get millions of tons of atmosphere rushing past at thirty or forty miles an hour, it's hardly a surprise that limbs snap and roof tiles go flying. As Anthony Smith notes, a typical weather front may consist of 750 million tons of cold air pinned beneath a billion tons of warmer air. Hardly a wonder that the result is at times meteorologically exciting.

Certainly there is no shortage of energy in the world above our heads. One thunderstorm, it has been calculated, can contain an amount of energy equivalent to four days' use of electricity for the whole United States. In the right conditions, storm clouds can rise to heights of six to ten miles and contain updrafts and downdrafts of one hundred miles an hour. These are often side by side, which is why

pilots don’t want to fly through them. In all, the internal turmoil particles

within the cloud pick up

electrical charges. For reasons not entirely understood the lighter particles

tend to become positively

charged and to be wafted by air currents to the top of the cloud. The heavier

particles linger at the

base, accumulating negative charges. These negatively charged particles

have a powerful urge to

rush to the positively charged Earth, and good luck to anything that gets in

their way. A bolt of

lightning travels at 270,000 miles an hour and can heat the air around it to a

decidedly crisp 50,000

degrees Fahrenheit, several times hotter than the surface of the sun. At any

one moment 1,800

thunderstorms are in progress around the globe— some 40,000 a day. Day

and night across the planet

every second about a hundred lightning bolts hit the ground. The sky is a

lively place.

Much of our knowledge of what goes on up there is surprisingly recent. Jet streams, usually located about 30,000 to 35,000 feet up, can bowl along at up to 180 miles an hour and vastly influence weather systems over whole continents, yet their existence wasn't suspected until pilots began to fly into them during the Second World War. Even now a great deal of atmospheric phenomena is barely understood. A form of wave motion popularly known as clear-air turbulence occasionally enlivens airplane flights. About twenty such incidents a year are serious enough to need reporting. They are not associated with cloud structures or anything else that can be detected visually or by radar. They are just pockets of startling turbulence in the middle of tranquil skies. In a typical incident, a plane en route from Singapore to Sydney was flying over central Australia in calm conditions when it suddenly fell three hundred feet— enough to fling unsecured people against the ceiling. Twelve people were injured, one seriously. No one knows what causes such disruptive cells of air.

The process that moves air around in the atmosphere is the same process that drives the internal engine of the planet, namely convection. Moist, warm air from the equatorial regions rises until it hits the barrier of the tropopause and spreads out. As it travels away from the equator and cools, it sinks. When it hits bottom, some of the sinking air looks for an area of low pressure to fill and heads back for the equator, completing the circuit.

At the equator the convection process is generally stable and the weather predictably fair, but in temperate zones the patterns are far more seasonal, localized, and random, which results in an endless battle between systems of high-pressure air and low. Low-pressure systems are created by rising air, which conveys water molecules into the sky, forming clouds and eventually rain. Warm air can hold more moisture than cool air, which is why tropical and summer storms tend to be the heaviest. Thus low areas tend to be associated with clouds and rain, and highs generally spell sunshine and fair weather. When two such systems meet, it often becomes manifest in the clouds.

For instance, stratus clouds— those unlovable, featureless sprawls that give us our overcast skies— happen when moisture-bearing updrafts lack the oomph to break through a level of more stable air above, and instead spread out, like smoke hitting a ceiling. Indeed, if you watch a smoker sometime, you can get a very good idea of how things work by watching how smoke rises from a cigarette in a still room. At first, it goes straight up (this is called a laminar flow, if you need to impress anyone), and then it spreads out in a diffused, wavy layer. The greatest supercomputer in the world, taking measurements in the most carefully controlled environment, cannot tell you what forms these ripplings will take, so you can imagine the difficulties that confront meteorologists when they try to predict such motions in a spinning, windy, large-scale world.

What we do know is that because heat from the Sun is unevenly distributed, differences in air pressure arise on the planet. Air can't abide this, so it rushes around trying to equalize things everywhere. Wind is simply the air's way of trying to keep things in balance. Air always flows from areas of high pressure to areas of low pressure (as you would expect; think of anything with air under pressure— a balloon or an air tank— and think how insistently that pressured air wants to get someplace else), and the greater the discrepancy in pressures the faster the wind blows.

Incidentally, wind speeds, like most things that accumulate, grow exponentially, so a wind blowing at two hundred miles an hour is not simply ten times stronger than a wind blowing at twenty miles an hour, but a hundred times stronger— and hence that much more destructive. Introduce several million tons of air to this accelerator effect and the result can be exceedingly

energetic. A tropical hurricane
can release in twenty-four hours as much energy as a rich, medium-sized nation like Britain or
France uses in a year.

The impulse of the atmosphere to seek equilibrium was first suspected by Edmond Halley— the man
who was everywhere— and elaborated upon in the eighteenth century by his fellow Briton George
Hadley, who saw that rising and falling columns of air tended to produce "cells" (known ever since
as "Hadley cells"). Though a lawyer by profession, Hadley had a keen interest in the weather (he
was, after all, English) and also suggested a link between his cells, the Earth's spin, and the apparent
deflections of air that give us our trade winds. However, it was an engineering professor at the École
Polytechnique in Paris, Gustave-Gaspard de Coriolis, who worked out the details of these
interactions in 1835, and thus we call it the Coriolis effect. (Coriolis's other distinction at the school

was to introduce watercoolers, which are still known there as Corios, apparently.) The Earth revolves at a brisk 1,041 miles an hour at the equator, though as you move toward the poles the rate slopes off considerably, to about 600 miles an hour in London or Paris, for instance. The reason for this is selfevident when you think about it. If you are on the equator the spinning Earth has to carry you quite a distance— about 40,000 kilometers— to get you back to the same spot. If you stand beside the North Pole, however, you may need travel only a few feet to complete a revolution, yet in both cases it takes twenty-four hours to get you back to where you began. Therefore, it follows that the closer you get to the equator the faster you must be spinning.

The Coriolis effect explains why anything moving through the air in a straight line laterally to the Earth's spin will, given enough distance, seem to curve to the right in the northern hemisphere and to the left in the southern as the Earth revolves beneath it. The standard way to

envision this is to
imagine yourself at the center of a large carousel and tossing a ball to someone positioned on the
edge. By the time the ball gets to the perimeter, the target person has moved on and the ball passes
behind him. From his perspective, it looks as if it has curved away from him. That is the Coriolis
effect, and it is what gives weather systems their curl and sends hurricanes spinning off like tops.

The Coriolis effect is also why naval guns firing artillery shells have to adjust to left or right; a shell
fired fifteen miles would otherwise deviate by about a hundred yards and plop harmlessly into the
sea.

Considering the practical and psychological importance of the weather to nearly everyone, it's
surprising that meteorology didn't really get going as a science until shortly before the turn of the
nineteenth century (though the term meteorology itself had been around since 1626, when it was

coined by a T. Granger in a book of logic).

Part of the problem was that successful meteorology requires the precise measurement of temperatures, and thermometers for a long time proved more difficult to make than you might expect. An accurate reading was dependent on getting a very even bore in a glass tube, and that wasn’t easy to do. The first person to crack the problem was Daniel Gabriel Fahrenheit, a Dutch maker of instruments, who produced an accurate thermometer in 1717. However, for reasons unknown he calibrated the instrument in a way that put freezing at 32 degrees and boiling at 212 degrees. From the outset this numeric eccentricity bothered some people, and in 1742 Anders Celsius, a Swedish astronomer, came up with a competing scale. In proof of the proposition that inventors seldom get matters entirely right, Celsius made boiling point zero and freezing point 100 on his scale, but that was soon reversed.

The person most frequently identified as the father of modern meteorology was an English pharmacist named Luke Howard, who came to prominence at the beginning of the nineteenth century. Howard is chiefly remembered now for giving cloud types their names in 1803. Although he was an active and respected member of the Linnaean Society and employed Linnaean principles in his new scheme, Howard chose the rather more obscure Askesian Society as the forum to announce his new system of classification. (The Askesian Society, you may just recall from an earlier chapter, was the body whose members were unusually devoted to the pleasures of nitrous oxide, so we can only hope they treated Howard's presentation with the sober attention it deserved. It is a point on which Howard scholars are curiously silent.)

Howard divided clouds into three groups: stratus for the layered clouds, cumulus for the fluffy ones (the word means "heaped" in Latin), and cirrus (meaning "curled") for the high, thin feathery formations that generally presage colder weather. To these he subsequently added a fourth term, nimbus (from the Latin for “cloud”), for a rain cloud. The beauty of Howard’s system was that the basic components could be freely recombined to describe every shape and size of passing cloud—stratocumulus, cirrostratus, cumulocongestus, and so on. It was an immediate hit, and not just in England. The poet Johann von Goethe in Germany was so taken with the system that he dedicated four poems to Howard.

Howard’s system has been much added to over the years, so much so that the encyclopedic if little read International Cloud Atlas runs to two volumes, but interestingly virtually all the post-Howard cloud types— mammatus, pileus, nebulosis, spissatus, floccus, and mediocris are a sampling— have never caught on with anyone outside meteorology and not terribly much there, I’m told. Incidentally, the first, much thinner edition of that atlas, produced in 1896, divided clouds into ten basic types, of which the plumpest and most cushiony-looking was number nine, cumulonimbus.*32 That seems to have been the source of the expression “to be on cloud nine.”

For all the heft and fury of the occasional anvil-headed storm cloud, the average cloud is actually a benign and surprisingly insubstantial thing. A fluffy summer cumulus several hundred yards to a side may contain no more than twenty-five or thirty gallons of water— “about enough to fill a bathtub,” as James Trefil has noted. You can get some sense of the immaterial quality of clouds by strolling through fog— which is, after all, nothing more than a cloud that lacks the will to fly. To quote Trefil again: “If you walk 100 yards through a typical fog, you will come into contact with only about half a cubic inch of water— not enough to give you a decent drink.” In consequence, clouds are not great reservoirs of water. Only about 0.035 percent of the Earth’s fresh water is

floating around above us
at any moment.

Depending on where it falls, the prognosis for a water molecule varies widely. If it lands in fertile soil it will be soaked up by plants or reevaporated directly within hours or days. If it finds its way down to the groundwater, however, it may not see sunlight again for many years— thousands if it gets really deep. When you look at a lake, you are looking at a collection of molecules that have been there on average for about a decade. In the ocean the residence time is thought to be more like a hundred years. Altogether about 60 percent of water molecules in a rainfall are returned to the atmosphere within a day or two. Once evaporated, they spend no more than a week or so— Drury says twelve days— in the sky before falling again as rain.

Evaporation is a swift process, as you can easily gauge by the fate of a puddle on a summer’s day.

Even something as large as the Mediterranean would dry out in a thousand years if it were not continually replenished. Such an event occurred a little under six million years ago and provoked what is known to science as the Messinian Salinity Crisis. What happened was that continental movement closed the Strait of Gibraltar. As the Mediterranean dried, its evaporated contents fell as freshwater rain into other seas, mildly diluting their saltiness— indeed, making them just dilute enough to freeze over larger areas than normal. The enlarged area of ice bounced back more of the Sun's heat and pushed Earth into an ice age. So at least the theory goes.

What is certainly true, as far as we can tell, is that a little change in the Earth's dynamics can have repercussions beyond our imagining. Such an event, as we shall see a little further on, may even have created us.

Oceans are the real powerhouse of the planet's surface behavior. Indeed, meteorologists increasingly treat oceans and atmosphere as a single system, which is why we must give

them a little of our
attention here. Water is marvelous at holding and transporting heat. Every day, the Gulf Stream
carries an amount of heat to Europe equivalent to the world's output of coal for ten years, which is
why Britain and Ireland have such mild winters compared with Canada and Russia.

But water also warms slowly, which is why lakes and swimming pools are cold even on the hottest
days. For that reason there tends to be a lag in the official, astronomical start of a season and the
actual feeling that that season has started. So spring may officially start in the northern hemisphere in
March, but it doesn't feel like it in most places until April at the very earliest.

The oceans are not one uniform mass of water. Their differences in temperature, salinity, depth,
density, and so on have huge effects on how they move heat around, which in turn affects climate.

The Atlantic, for instance, is saltier than the Pacific, and a good thing too.

The saltier water is the

denser it is, and dense water sinks. Without its extra burden of salt, the

Atlantic currents would

proceed up to the Arctic, warming the North Pole but depriving Europe of

all that kindly warmth.

The main agent of heat transfer on Earth is what is known as thermohaline

circulation, which

originates in slow, deep currents far below the surface— a process first

detected by the scientistadventurer

Count von Rumford in 1797.*33 What happens is that surface waters, as

they get to the

vicinity of Europe, grow dense and sink to great depths and begin a slow trip

back to the southern

hemisphere. When they reach Antarctica, they are caught up in the Antarctic

Circumpolar Current,

where they are driven onward into the Pacific. The process is very slow— it

can take 1,500 years for

water to travel from the North Atlantic to the mid-Pacific— but the volumes

of heat and water they

move are very considerable, and the influence on the climate is enormous.

(As for the question of how anyone could possibly figure out how long it takes a drop of water to get from one ocean to another, the answer is that scientists can measure compounds in the water like chlorofluorocarbons and work out how long it has been since they were last in the air. By comparing a lot of measurements from different depths and locations they can reasonably chart the water's movement.)

Thermohaline circulation not only moves heat around, but also helps to stir up nutrients as the currents rise and fall, making greater volumes of the ocean habitable for fish and other marine creatures. Unfortunately, it appears the circulation may also be very sensitive to change. According to computer simulations, even a modest dilution of the ocean's salt content— from increased melting of the Greenland ice sheet, for instance— could disrupt the cycle disastrously.

The seas do one other great favor for us. They soak up tremendous volumes of carbon and provide a means for it to be safely locked away. One of the oddities of our solar system is that the Sun burns about 25 percent more brightly now than when the solar system was young. This should have resulted in a much warmer Earth. Indeed, as the English geologist Aubrey Manning has put it, “This colossal change should have had an absolutely catastrophic effect on the Earth and yet it appears that our world has hardly been affected.”

So what keeps the world stable and cool?

Life does. Trillions upon trillions of tiny marine organisms that most of us have never heard of—foraminiferans and coccoliths and calcareous algae— capture atmospheric carbon, in the form of carbon dioxide, when it falls as rain and use it (in combination with other things) to make their tiny shells. By locking the carbon up in their shells, they keep it from being reevaporated into the atmosphere, where it would build up dangerously as a greenhouse gas.

Eventually all the tiny foraminiferans and coccoliths and so on die and fall to the bottom of the sea, where they are compressed into limestone. It is remarkable, when you behold an extraordinary natural feature like the White Cliffs of Dover in England, to reflect that it is made up of nothing but tiny deceased marine organisms, but even more remarkable when you realize how much carbon they cumulatively sequester. A six-inch cube of Dover chalk will contain well over a thousand liters of compressed carbon dioxide that would otherwise be doing us no good at all. Altogether there is about twenty thousand times as much carbon locked away in the Earth's rocks as in the atmosphere. Eventually much of that limestone will end up feeding volcanoes, and the carbon will return to the atmosphere and fall to the Earth in rain, which is why the whole is called the long-term carbon cycle. The process takes a very long time— about half a million years for a typical carbon atom— but in the

absence of any other disturbance it works remarkably well at keeping the

climate stable.

Unfortunately, human beings have a careless predilection for disrupting this

cycle by putting lots of

extra carbon into the atmosphere whether the foraminiferans are ready for it

or not. Since 1850, it

has been estimated, we have lofted about a hundred billion tons of extra

carbon into the air, a total

that increases by about seven billion tons each year. Overall, that’s not

actually all that much.

Nature— mostly through the belchings of volcanoes and the decay of

plants— sends about 200 billion

tons of carbon dioxide into the atmosphere each year, nearly thirty times as

much as we do with our

cars and factories. But you have only to look at the haze that hangs over our

cities to see what a

difference our contribution makes.

We know from samples of very old ice that the “natural” level of carbon

dioxide in the

atmosphere— that is, before we started inflating it with industrial activity— is about 280 parts per million. By 1958, when people in lab coats started to pay attention to it, it had risen to 315 parts per million. Today it is over 360 parts per million and rising by roughly one-quarter of 1 percent a year.

By the end of the twenty-first century it is forecast to rise to about 560 parts per million.

So far, the Earth's oceans and forests (which also pack away a lot of carbon) have managed to save us from ourselves, but as Peter Cox of the British Meteorological Office puts it: "There is a critical threshold where the natural biosphere stops buffering us from the effects of our emissions and actually starts to amplify them." The fear is that there would be a runaway increase in the Earth's warming. Unable to adapt, many trees and other plants would die, releasing their stores of carbon and adding to the problem. Such cycles have occasionally happened in the distant past even without a human contribution. The good news is that even here nature is quite wonderful. It is almost certain that eventually the carbon cycle would reassert itself and return the Earth to a situation of stability and happiness. The last time this happened, it took a mere sixty thousand years.

18 **THE BOUNDING MAIN**

IMAGINE TRYING TO live in a world dominated by dihydrogen oxide, a compound that has no taste or smell and is so variable in its properties that it is generally benign but at other times swiftly lethal. Depending on its state, it can scald you or freeze you. In the presence of certain organic molecules it can form carbonic acids so nasty that they can strip the leaves from trees and eat the faces off statuary. In bulk, when agitated, it can strike with a fury that no human edifice could withstand. Even for those who have learned to live with it, it is an often murderous substance. We call it water.

Water is everywhere. A potato is 80 percent water, a cow 74 percent, a bacterium 75 percent. A tomato, at 95 percent, is little but water. Even humans are 65 percent water, making us more liquid than solid by a margin of almost two to one. Water is strange stuff. It is formless and transparent, and yet we long to be beside it. It has no taste and yet we love the taste of it. We will travel great distances and pay small fortunes to see it in sunshine. And even though we know it is dangerous and drowns tens of thousands of people every year, we can't wait to frolic in it.

Because water is so ubiquitous we tend to overlook what an extraordinary substance it is. Almost nothing about it can be used to make reliable predictions about the properties of other liquids and vice versa. If you knew nothing of water and based your assumptions on the behavior of compounds most chemically akin to it— hydrogen selenide or hydrogen sulphide notably— you would expect it to boil at minus 135 degrees Fahrenheit and to be a gas at room temperature.

Most liquids when chilled contract by about 10 percent. Water does too, but only down to a point.

Once it is within whispering distance of freezing, it begins— perversely, beguilingly, extremely improbably— to expand. By the time it is solid, it is almost a tenth more voluminous than it was before. Because it expands, ice floats on water— "an utterly bizarre property," according to John Gribbin. If it lacked this splendid waywardness, ice would sink, and lakes and oceans would freeze from the bottom up. Without surface ice to hold heat in, the water's warmth would radiate away, leaving it even chillier and creating yet more ice. Soon even the oceans would freeze and almost certainly stay that way for a very long time, probably forever— hardly the conditions to nurture life.

Thankfully for us, water seems unaware of the rules of chemistry or laws of physics.

Everyone knows that water's chemical formula is H2O, which means that it consists of one largish oxygen atom with two smaller hydrogen atoms attached to it. The hydrogen atoms cling fiercely to

their oxygen host, but also make casual bonds with other water molecules. The nature of a water

molecule means that it engages in a kind of dance with other water molecules, briefly pairing and

then moving on, like the ever-changing partners in a quadrille, to use Robert Kunzig's nice phrase. A

glass of water may not appear terribly lively, but every molecule in it is changing partners billions of

times a second. That's why water molecules stick together to form bodies like puddles and lakes, but

not so tightly that they can't be easily separated as when, for instance, you dive into a pool of them.

At any given moment only 15 percent of them are actually touching.

In one sense the bond is very strong— it is why water molecules can flow uphill when siphoned and

why water droplets on a car hood show such a singular determination to bead with their partners. It is

also why water has surface tension. The molecules at the surface are attracted more powerfully to the like molecules beneath and beside them than to the air molecules above. This creates a sort of membrane strong enough to support insects and skipping stones. It is what gives the sting to a belly flop.

I hardly need point out that we would be lost without it. Deprived of water, the human body rapidly falls apart. Within days, the lips vanish “as if amputated, the gums blacken, the nose withers to half its length, and the skin so contracts around the eyes as to prevent blinking.” Water is so vital to us that it is easy to overlook that all but the smallest fraction of the water on Earth is poisonous to us— deadly poisonous— because of the salts within it.

We need salt to live, but only in very small amounts, and seawater contains way more— about seventy times more— salt than we can safely metabolize. A typical liter of seawater will contain only about 2.5 teaspoons of common salt— the kind we sprinkle on food— but much larger amounts of other elements, compounds, and other dissolved solids, which are collectively known as salts. The proportions of these salts and minerals in our tissues is uncannily similar to seawater— we sweat and cry seawater, as Margulis and Sagan have put it— but curiously we cannot tolerate them as an input.

Take a lot of salt into your body and your metabolism very quickly goes into crisis. From every cell, water molecules rush off like so many volunteer firemen to try to dilute and carry off the sudden intake of salt. This leaves the cells dangerously short of the water they need to carry out their normal functions. They become, in a word, dehydrated. In extreme situations, dehydration will lead to seizures, unconsciousness, and brain damage. Meanwhile, the overworked blood cells carry the salt to the kidneys, which eventually become overwhelmed and shut down. Without functioning kidneys you die. That is why we don't drink seawater.

There are 320 million cubic miles of water on Earth and that is all we're ever going to get. The system is closed: practically speaking, nothing can be added or subtracted. The water you drink has been around doing its job since the Earth was young. By 3.8 billion years ago, the oceans had (at least more or less) achieved their present volumes.

The water realm is known as the hydrosphere and it is overwhelmingly oceanic. Ninety-seven percent of all the water on Earth is in the seas, the greater part of it in the Pacific, which covers half the planet and is bigger than all the landmasses put together. Altogether the Pacific holds just over half of all the ocean water (51.6 percent to be precise); the Atlantic has 23.6 percent and the Indian Ocean 21.2 percent, leaving just 3.6 percent to be accounted for by all the other seas. The average depth of the ocean is 2.4 miles, with the Pacific on average about a thousand feet deeper than the Atlantic and Indian Oceans. Altogether 60 percent of the planet's surface is ocean more than a mile

deep. As Philip Ball notes, we would better call our planet not Earth but

Water.

Of the 3 percent of Earth's water that is fresh, most exists as ice sheets. Only

the tiniest amount—

0.036 percent— is found in lakes, rivers, and reservoirs, and an even smaller

part— just 0.001

percent— exists in clouds or as vapor. Nearly 90 percent of the planet's ice

is in Antarctica, and most

of the rest is in Greenland. Go to the South Pole and you will be standing on

nearly two miles of ice,

at the North Pole just fifteen feet of it. Antarctica alone has six million cubic

miles of ice— enough to

raise the oceans by a height of two hundred feet if it all melted. But if all the

water in the atmosphere

fell as rain, evenly everywhere, the oceans would deepen by only an inch.

Sea level, incidentally, is an almost entirely notional concept. Seas are not

level at all. Tides, winds,

the Coriolis force, and other effects alter water levels considerably from one

ocean to another and

within oceans as well. The Pacific is about a foot and a half higher along its western edge— a consequence of the centrifugal force created by the Earth's spin. Just as when you pull on a tub of water the water tends to flow toward the other end, as if reluctant to come with you, so the eastward spin of Earth piles water up against the ocean's western margins.

Considering the age-old importance of the seas to us, it is striking how long it took the world to take a scientific interest in them. Until well into the nineteenth century most of what was known about the oceans was based on what washed ashore or came up in fishing nets, and nearly all that was written was based more on anecdote and supposition than on physical evidence. In the 1830s, the British naturalist Edward Forbes surveyed ocean beds throughout the Atlantic and Mediterranean and declared that there was no life at all in the seas below 2,000 feet. It seemed a reasonable assumption.

There was no light at that depth, so no plant life, and the pressures of water

at such depths were
known to be extreme. So it came as something of a surprise when, in 1860, one of the first
transatlantic telegraph cables was hauled up for repairs from more than two miles down, and it was
found to be thickly encrusted with corals, clams, and other living detritus.

The first really organized investigation of the seas didn't come until 1872, when a joint expedition
between the British Museum, the Royal Society, and the British government set forth from
Portsmouth on a former warship called HMS Challenger. For three and a half years they sailed the
world, sampling waters, netting fish, and hauling a dredge through sediments. It was evidently dreary
work. Out of a complement of 240 scientists and crew, one in four jumped ship and eight more died
or went mad— "driven to distraction by the mind-numbing routine of years of dredging" in the words
of the historian Samantha Weinberg. But they sailed across almost 70,000 nautical miles of sea,

collected over 4,700 new species of marine organisms, gathered enough information to create a fiftyvolume
report (which took nineteen years to put together), and gave the world the name of a new
scientific discipline: oceanography. They also discovered, by means of depth measurements, that
there appeared to be submerged mountains in the mid-Atlantic, prompting some excited observers to
speculate that they had found the lost continent of Atlantis.

Because the institutional world mostly ignored the seas, it fell to devoted—and very occasional—
amateurs to tell us what was down there. Modern deep-water exploration begins with Charles
William Beebe and Otis Barton in 1930. Although they were equal partners, the more colorful Beebe
has always received far more written attention. Born in 1877 into a well-to-do family in New York
City, Beebe studied zoology at Columbia University, then took a job as a birdkeeper at the New
York Zoological Society. Tiring of that, he decided to adopt the life of an

adventurer and for the next
quarter century traveled extensively through Asia and South America with a
succession of attractive
female assistants whose jobs were inventively described as “historian and
technicist” or “assistant in
fish problems.” He supported these endeavors with a succession of popular
books with titles like
Edge of the Jungle and Jungle Days, though he also produced some
respectable books on wildlife
and ornithology.

In the mid-1920s, on a trip to the Galápagos Islands, he discovered “the
delights of dangling,” as he
described deep-sea diving. Soon afterward he teamed up with Barton, who
came from an even
wealthier family, had also attended Columbia, and also longed for adventure.
Although Beebe nearly
always gets the credit, it was in fact Barton who designed the first
bathysphere (from the Greek word
for “deep”) and funded the $12,000 cost of its construction. It was a tiny and
necessarily robust

chamber, made of cast iron 1.5 inches thick and with two small portholes containing quartz blocks three inches thick. It held two men, but only if they were prepared to become extremely well acquainted. Even by the standards of the age, the technology was unsophisticated. The sphere had no maneuverability— it simply hung on the end of a long cable— and only the most primitive breathing system: to neutralize their own carbon dioxide they set out open cans of soda lime, and to absorb moisture they opened a small tub of calcium chloride, over which they sometimes waved palm fronds to encourage chemical reactions.

But the nameless little bathysphere did the job it was intended to do. On the first dive, in June 1930 in the Bahamas, Barton and Beebe set a world record by descending to 600 feet. By 1934, they had pushed the record to 3,028 feet, where it would stay until after the war. Barton was confident the device was safe to a depth of 4,500 feet, though the strain on every bolt and

rivet was audibly
evident with each fathom they descended. At any depth, it was brave and risky work. At 3,000 feet,
their little porthole was subjected to nineteen tons of pressure per square inch. Death at such a depth
would have been instantaneous, as Beebe never failed to observe in his many books, articles, and
radio broadcasts. Their main concern, however, was that the shipboard winch, straining to hold on to
a metal ball and two tons of steel cable, would snap and send the two men plunging to the seafloor.
In such an event, nothing could have saved them.

The one thing their descents didn't produce was a great deal of worthwhile science. Although they
encountered many creatures that had not been seen before, the limits of visibility and the fact that
neither of the intrepid aquanauts was a trained oceanographer meant they often weren't able to
describe their findings in the kind of detail that real scientists craved. The sphere didn't carry an

external light, merely a 250-watt bulb they could hold up to the window, but the water below five hundred feet was practically impenetrable anyway, and they were peering into it through three inches of quartz, so anything they hoped to view would have to be nearly as interested in them as they were in it. About all they could report, in consequence, was that there were a lot of strange things down there. On one dive in 1934, Beebe was startled to spy a giant serpent "more than twenty feet long and very wide." It passed too swiftly to be more than a shadow. Whatever it was, nothing like it has been seen by anyone since. Because of such vagueness their reports were generally ignored by academics.

After their record-breaking descent of 1934, Beebe lost interest in diving and moved on to other adventures, but Barton persevered. To his credit, Beebe always told anyone who asked that Barton was the real brains behind the enterprise, but Barton seemed unable to step from the shadows. He, too, wrote thrilling accounts of their underwater adventures and even starred in a Hollywood movie called Titans of the Deep, featuring a bathysphere and many exciting and largely fictionalized encounters with aggressive giant squid and the like. He even advertised Camel cigarettes ("They don't give me jittery nerves"). In 1948 he increased the depth record by 50 percent, with a dive to 4,500 feet in the Pacific Ocean near California, but the world seemed determined to overlook him.

One newspaper reviewer of Titans of the Deep actually thought the star of the film was Beebe.

Nowadays, Barton is lucky to get a mention.

At all events, he was about to be comprehensively eclipsed by a father-and-son team from Switzerland, Auguste and Jacques Piccard, who were designing a new type of probe called a bathyscaphe (meaning "deep boat"). Christened Trieste, after the Italian city in which it was built, the new device maneuvered independently, though it did little more than just go up and down. On

one of its first dives, in early 1954, it descended to below 13,287 feet, nearly three times Barton's

record-breaking dive of six years earlier. But deep-sea dives required a great deal of costly support,

and the Piccards were gradually going broke.

In 1958, they did a deal with the U.S. Navy, which gave the Navy ownership but left them in control.

Now flush with funds, the Piccards rebuilt the vessel, giving it walls five inches thick and shrinking

the windows to just two inches in diameter— little more than peepholes. But it was now strong

enough to withstand truly enormous pressures, and in January 1960 Jacques Piccard and Lieutenant

Don Walsh of the U.S. Navy sank slowly to the bottom of the ocean's deepest canyon, the Mariana

Trench, some 250 miles off Guam in the western Pacific (and discovered, not incidentally, by Harry

Hess with his fathometer). It took just under four hours to fall 35,820 feet, or almost seven miles.

Although the pressure at that depth was nearly 17,000 pounds per square inch, they noticed with surprise that they disturbed a bottom-dwelling flatfish just as they touched down. They had no facilities for taking photographs, so there is no visual record of the event.

After just twenty minutes at the world's deepest point, they returned to the surface. It was the only occasion on which human beings have gone so deep.

Forty years later, the question that naturally occurs is: Why has no one gone back since? To begin with, further dives were vigorously opposed by Vice Admiral Hyman G. Rickover, a man who had a lively temperament, forceful views, and, most pertinently, control of the departmental checkbook.

He thought underwater exploration a waste of resources and pointed out that the Navy was not a research institute. The nation, moreover, was about to become fully preoccupied with space travel and the quest to send a man to the Moon, which made deep sea investigations seem unimportant and rather old-fashioned. But the decisive consideration was that the Trieste descent didn’t actually achieve much. As a Navy official explained years later: “We didn’t learn a hell of a lot from it, other than that we could do it. Why do it again?” It was, in short, a long way to go to find a flatfish, and expensive too. Repeating the exercise today, it has been estimated, would cost at least $100 million.

When underwater researchers realized that the Navy had no intention of pursuing a promised exploration program, there was a pained outcry. Partly to placate its critics, the Navy provided funding for a more advanced submersible, to be operated by the Woods Hole Oceanographic Institution of Massachusetts. Called Alvin, in somewhat contracted honor of the oceanographer Allyn C. Vine, it would be a fully maneuverable minisubmarine, though it wouldn’t go anywhere near as deep as the Trieste. There was just one problem: the designers couldn’t find

anyone willing to build
it. According to William J. Broad in The Universe Below: “No big company like General Dynamics,
which made submarines for the Navy, wanted to take on a project disparaged by both the Bureau of
Ships and Admiral Rickover, the gods of naval patronage.” Eventually, not to say improbably, Alvin
was constructed by General Mills, the food company, at a factory where it made the machines to
produce breakfast cereals.

As for what else was down there, people really had very little idea. Well into the 1950s, the best
maps available to oceanographers were overwhelmingly based on a little detail from scattered
surveys going back to 1929 grafted onto, essentially an ocean of guesswork. The Navy had excellent
charts with which to guide submarines through canyons and around guyots, but it didn't wish such
information to fall into Soviet hands, so it kept its knowledge classified. Academics therefore had to

make do with sketchy and antiquated surveys or rely on hopeful surmise. Even today our knowledge of the ocean floors remains remarkably low resolution. If you look at the Moon with a standard backyard telescope you will see substantial craters— Fracastorious, Blancanus, Zach, Planck, and many others familiar to any lunar scientist— that would be unknown if they were on our own ocean floors. We have better maps of Mars than we do of our own seabeds.

At the surface level, investigative techniques have also been a trifle ad hoc. In 1994, thirty-four thousand ice hockey gloves were swept overboard from a Korean cargo ship during a storm in the Pacific. The gloves washed up all over, from Vancouver to Vietnam, helping oceanographers to trace currents more accurately than they ever had before.

Today Alvin is nearly forty years old, but it still remains America’s premier research vessel. There are still no submersibles that can go anywhere near the depth of the Mariana Trench and only five, including Alvin, that can reach the depths of the “abyssal plain”— the deep ocean floor— that covers more than half the planet’s surface. A typical submersible costs about $25,000 a day to operate, so they are hardly dropped into the water on a whim, still less put to sea in the hope that they will randomly stumble on something of interest. It’s rather as if our firsthand experience of the surface world were based on the work of five guys exploring on garden tractors after dark. According to Robert Kunzig, humans may have scrutinized “perhaps a millionth or a billionth of the sea’s darkness. Maybe less. Maybe much less.”

But oceanographers are nothing if not industrious, and they have made several important discoveries with their limited resources— including, in 1977, one of the most important and startling biological discoveries of the twentieth century. In that year Alvin found teeming colonies of large organisms living on and around deep-sea vents off the Galápagos Islands— tube worms over ten feet long,

clams a foot wide, shrimps and mussels in profusion, wriggling spaghetti worms. They all owed their existence to vast colonies of bacteria that were deriving their energy and sustenance from hydrogen sulfides— compounds profoundly toxic to surface creatures— that were pouring steadily from the vents. It was a world independent of sunlight, oxygen, or anything else normally associated with life.

This was a living system based not on photosynthesis but on chemosynthesis, an arrangement that biologists would have dismissed as preposterous had anyone been imaginative enough to suggest it.

Huge amounts of heat and energy flow from these vents. Two dozen of them together will produce as much energy as a large power station, and the range of temperatures around them is enormous.

The temperature at the point of outflow can be as much as 760 degrees Fahrenheit, while a few feet away the water may be only two or three degrees above freezing. A type of worm called an alvinellid was found living right on the margins, with the water temperature 140 degrees warmer at its head than at its tail. Before this it had been thought that no complex organisms could survive in water warmer than about 130 degrees, and here was one that was surviving warmer temperatures than that and extreme cold to boot. The discovery transformed our understanding of the requirements for life.

It also answered one of the great puzzles of oceanography— something that many of us didn't realize was a puzzle— namely, why the oceans don't grow saltier with time. At the risk of stating the obvious, there is a lot of salt in the sea— enough to bury every bit of land on the planet to a depth of about five hundred feet. Millions of gallons of fresh water evaporate from the ocean daily, leaving all their salts behind, so logically the seas ought to grow more salty with the passing years, but they don't. Something takes an amount of salt out of the water equivalent to the

amount being put in. For
the longest time, no one could figure out what could be responsible for this. Alvin's discovery of the deep-sea vents provided the answer. Geophysicists realized that the vents
were acting much like the filters in a fish tank. As water is taken down into the crust, salts are
stripped from it, and eventually clean water is blown out again through the chimney stacks. The
process is not swift— it can take up to ten million years to clean an ocean— but it is marvelously
efficient as long as you are not in a hurry.

Perhaps nothing speaks more clearly of our psychological remoteness from the ocean depths than
that the main expressed goal for oceanographers during International Geophysical Year of 1957–58
was to study "the use of ocean depths for the dumping of radioactive wastes." This wasn't a secret
assignment, you understand, but a proud public boast. In fact, though it wasn't much publicized, by
1957–58 the dumping of radioactive wastes had already been going on, with

a certain appalling vigor, for over a decade. Since 1946, the United States had been ferrying fifty-five-gallon drums of radioactive gunk out to the Farallon Islands, some thirty miles off the California coast near San Francisco, where it simply threw them overboard.

It was all quite extraordinarily sloppy. Most of the drums were exactly the sort you see rusting behind gas stations or standing outside factories, with no protective linings of any type. When they failed to sink, which was usually, Navy gunners riddled them with bullets to let water in (and, of course, plutonium, uranium, and strontium out). Before it was halted in the 1990s, the United States had dumped many hundreds of thousands of drums into about fifty ocean sites— almost fifty thousand of them in the Farallons alone. But the U.S. was by no means alone. Among the other enthusiastic dumpers were Russia, China, Japan, New Zealand, and nearly all the nations of Europe.

And what effect might all this have had on life beneath the seas? Well, little, we hope, but we actually have no idea. We are astoundingly, sumptuously, radiantly ignorant of life beneath the seas.

Even the most substantial ocean creatures are often remarkably little known to us— including the most mighty of them all, the great blue whale, a creature of such leviathan proportions that (to quote David Attenborough) its “tongue weighs as much as an elephant, its heart is the size of a car and some of its blood vessels are so wide that you could swim down them.” It is the most gargantuan beast that Earth has yet produced, bigger even than the most cumbrous dinosaurs. Yet the lives of blue whales are largely a mystery to us. Much of the time we have no idea where they are— where they go to breed, for instance, or what routes they follow to get there. What little we know of them comes almost entirely from eavesdropping on their songs, but even these are a mystery. Blue whales will sometimes break off a song, then pick it up again at the same spot six months later. Sometimes they strike up with a new song, which no member can have heard before but which each already knows. How they do this is not remotely understood. And these are animals that must routinely come to the surface to breathe.

For animals that need never surface, obscurity can be even more tantalizing. Consider the fabled giant squid. Though nothing on the scale of the blue whale, it is a decidedly substantial animal, with eyes the size of soccer balls and trailing tentacles that can reach lengths of sixty feet. It weighs nearly a ton and is Earth’s largest invertebrate. If you dumped one in a normal household swimming pool, there wouldn’t be much room for anything else. Yet no scientist— no person as far as we know— has ever seen a giant squid alive. Zoologists have devoted careers to trying to capture, or just glimpse, living giant squid and have always failed. They are known mostly from being washed up on beaches— particularly, for unknown reasons, the beaches of the South Island of New Zealand. They must exist in large numbers because they form a central part of the sperm whale's diet, and sperm whales take a lot of feeding.*34

According to one estimate, there could be as many as thirty million species of animals living in the sea, most still undiscovered. The first hint of how abundant life is in the deep seas didn't come until as recently as the 1960s with the invention of the epibenthic sled, a dredging device that captures organisms not just on and near the seafloor but also buried in the sediments beneath. In a single onehour trawl along the continental shelf, at a depth of just under a mile, Woods Hole oceanographers Howard Sandler and Robert Hessler netted over 25,000 creatures— worms, starfish, sea cucumbers, and the like— representing 365 species. Even at a depth of three miles, they found some 3,700

creatures representing almost 200 species of organism. But the dredge could only capture things that
were too slow or stupid to get out of the way. In the late 1960s a marine biologist named John Isaacs
got the idea to lower a camera with bait attached to it, and found still more, in particular dense
swarms of writhing hagfish, a primitive eel-like creature, as well as darting shoals of grenadier fish.
Where a good food source is suddenly available— for instance, when a whale dies and sinks to the
bottom— as many as 390 species of marine creature have been found dining off it. Interestingly,
many of these creatures were found to have come from vents up to a thousand miles distant. These
included such types as mussels and clams, which are hardly known as great travelers. It is now
thought that the larvae of certain organisms may drift through the water until, by some unknown
chemical means, they detect that they have arrived at a food opportunity and fall onto it.

So why, if the seas are so vast, do we so easily overtax them? Well, to begin with, the world's seas are not uniformly bounteous. Altogether less than a tenth of the ocean is considered naturally productive. Most aquatic species like to be in shallow waters where there is warmth and light and an abundance of organic matter to prime the food chain. Coral reefs, for instance, constitute well under 1 percent of the ocean's space but are home to about 25 percent of its fish. Elsewhere, the oceans aren't nearly so rich. Take Australia. With over 20,000 miles of coastline and almost nine million square miles of territorial waters, it has more sea lapping its shores than any other country, yet, as Tim Flannery notes, it doesn't even make it into the top fifty among fishing nations. Indeed, Australia is a large net importer of seafood. This is because much of Australia's waters are, like much of Australia itself, essentially desert. (A notable exception is the Great Barrier Reef off Queensland, which is sumptuously fecund.) Because the soil is poor, it produces little in the way of nutrient-rich runoff.

Even where life thrives, it is often extremely sensitive to disturbance. In the 1970s, fishermen from Australia and, to a lesser extent, New Zealand discovered shoals of a little-known fish living at a depth of about half a mile on their continental shelves. They were known as orange roughy, they were delicious, and they existed in huge numbers. In no time at all, fishing fleets were hauling in forty thousand metric tons of roughy a year. Then marine biologists made some alarming discoveries. Roughy are extremely long lived and slow maturing. Some may be 150 years old; any roughy you have eaten may well have been born when Victoria was Queen. Roughy have adopted this exceedingly unhurried lifestyle because the waters they live in are so resource-poor. In such waters, some fish spawn just once in a lifetime. Clearly these are populations that cannot stand a great deal of disturbance. Unfortunately, by the time this was realized the stocks had been severely depleted. Even with careful management it will be decades before the populations recover, if they ever do.

Elsewhere, however, the misuse of the oceans has been more wanton than inadvertent. Many fishermen “fin” sharks— that is, slice their fins off, then dump them back into the water to die. In 1998, shark fins sold in the Far East for over $250 a pound. A bowl of shark fin soup retailed in Tokyo for $100. The World Wildlife Fund estimated in 1994 that the number of sharks killed each year was between 40 million and 70 million.

As of 1995, some 37,000 industrial-sized fishing ships, plus about a million smaller boats, were between them taking twice as many fish from the sea as they had just twenty-five years earlier.

Trawlers are sometimes now as big as cruise ships and haul behind them nets big enough to hold a dozen jumbo jets. Some even use spotter planes to locate shoals of fish from the air.

It is estimated that about a quarter of every fishing net hauled up contains “by-catch”— fish that can’t be landed because they are too small or of the wrong type or caught in the wrong season. As one observer told the Economist: “We’re still in the Dark Ages. We just drop a net down and see what comes up.” Perhaps as much as twenty-two million metric tons of such unwanted fish are dumped back in the sea each year, mostly in the form of corpses. For every pound of shrimp harvested, about four pounds of fish and other marine creatures are destroyed.

Large areas of the North Sea floor are dragged clean by beam trawlers as many as seven times a year, a degree of disturbance that no ecosystem can withstand. At least two-thirds of species in the North Sea, by many estimates, are being overfished. Across the Atlantic things are no better. Halibut once abounded in such numbers off New England that individual boats could

land twenty thousand
pounds of it in a day. Now halibut is all but extinct off the northeast coast of North America.

Nothing, however, compares with the fate of cod. In the late fifteenth century, the explorer John
Cabot found cod in incredible numbers on the eastern banks of North America— shallow areas of
water popular with bottom-feeding fish like cod. Some of these banks were vast. Georges Banks off
Massachusetts is bigger than the state it abuts. The Grand Banks off Newfoundland is bigger still and
for centuries was always dense with cod. They were thought to be inexhaustible. Of course they were
anything but.

By 1960, the number of spawning cod in the north Atlantic had fallen to an estimated 1.6 million
metric tons. By 1990 this had sunk to 22,000 metric tons. In commercial terms, the cod were extinct.

“Fishermen,” wrote Mark Kurlansky in his fascinating history, Cod, “had caught them all.” The cod may have lost the western Atlantic forever. In 1992, cod fishing was stopped altogether on the Grand Banks, but as of last autumn, according to a report in Nature, stocks had not staged a comeback.

Kurlansky notes that the fish of fish fillets and fish sticks was originally cod, but then was replaced by haddock, then by redfish, and lately by Pacific pollock. These days, he notes drily, “fish” is “whatever is left.”

Much the same can be said of many other seafoods. In the New England fisheries off Rhode Island, it was once routine to haul in lobsters weighing twenty pounds. Sometimes they reached thirty pounds. Left unmolested, lobsters can live for decades— as much as seventy years, it is thought— and they never stop growing. Nowadays few lobsters weigh more than two pounds on capture.

“Biologists,” according to the New York Times, “estimate that 90 percent of lobsters are caught within a year after they reach the legal minimum size at about age six.”

Start by marking â€œA Short History of Nearly Everythingâ€ as Want to Read: Want to Read savingâ€¦ Want to Read.Â Taking as territory everything from the Big Bang to the rise of civilization, Bryson seeks to understand how we got from there being nothing at all to there being us. To that end, he has attached himself to a host of the worldâ€™s most advanced (and often obsessed) archaeologists, anthropologists, and mathematicians, travelling to their offices, laboratories, and field camps. He has read (or tried to read) their books, pestered them with questions, apprenticed himself to their powerful minds. Though A Short History clocks in at a daunting 500-plus pages and covers the same material as every science book before it, it reads something like a particularly detailed novel (albeit without a plot). Each longish chapter is devoted to a topic like the age of our planet or how cells work, and these chapters are grouped into larger sections such as "The Size of the Earth" and "Life Itself." Bryson chats with experts like Richard Fortey (author of Life and Trilobite) and these interviews are charming.Â I have just completed Bill Brysonâ€™s â€œA Short History of Nearly Everythingâ€ for the second time. I am quite certain it will not be my last reading. I cannot think of any other single-volume book I have ever read that was as informative, entertaining, and broad in scope as this classic. Copyright Â© 2003 by Bill Bryson David Bryson, Felicity Bryson, Dan McLean, a book on mathematical A Short H Forex : The Ultimate Guide To Price Action Trading âˆšPDF. 129 Pages Â· 2014 Â· 3.87 MB Â· 70,171 Downloads. forex fundamental news release: This is one experience I will never forget. I traded a perfect Forex : The Ultimate Gui A ShortHistory of NearlyEverything. 298 Pages Â· 2003 Â· 1.76 MB Â· 1,781 Downloads.Â U N E S C O General History of Africa. Volume I. Methodology and African Prehistory. (Editor J General histor A ShortHistory of NearlyEverything. 337 Pages Â· 2004 Â· 694 KB Â· 1,156 Downloads. explanation for what might have provoked an ice age, the whole theory fell By this time, write A ShortHistory of NearlyEverything.