The study of physics is an *adventure*, all the *good* and all the *bad* I might say. It is challenging and frustrating, sometimes painful, but often it is rewarding and satisfying at the end of the day, which is why most physicists wake up in the morning, (aside from the few with untreated mental health problems like Ludwig Boltzmann, *that Boltzmann*, who did commit suicide and tombstone is engraved with the **entropy formula** $S = k \cdot \log W$ which in itself is a bit more morbid of a reminder of an eventual **heat death** for us all).

But we look to the achievements to remember the legacy of physicists like Boltzmann, Newton, Maxwell, Curie, Galileo, Einstein, etc. Much as the propaganda that lead many great minds, like Alan Turing (but I think he was in it for more of fun), to join up the brigade of big science during times of war. We now use science (*still a little bit for war*) for peace and driving *human ambitions* and *intellectual goals*. Sharing the excitement of discovery is what drives physics, one shares the excitement and the value of physics by solving practical problems to gain insight into everyday phenomena. I tend to think of this again in a *metaphysical* type of way where it is significant as an *achievement of the human conscious* to understand the world in which we live.

Taking apart the history side of physics, I like to entertain myself with how ancient people thought about the natural world in order to explain what we believe today. However, it is important to note (*as to deter conspiracy theories and skeptics, yes we did go to the Moon there's proof!*) that what separates the man of the past to the man of today is that science has an overwhelming amount of evidence to hold up it's fundamental beliefs, that can be <u>easily accessible</u> (given you know how to Google things correctly). Still it is important to tie this into our workings, because this is where the arts and literature side of human tradition come into part. The following passages will be taken from Carl Sagan's *Cosmos* (*because everyone loves the lulling sound of Carl Sagan entertaining their mind*).

"

Introduction

The time will come when diligent research over long periods will bring to light things which now lie hidden. A single lifetime, even though entirely devoted to the sky, would not be enough for the investigation of so vast a subject . . . And so this knowledge will be unfolded only through long successive ages. There will come a time when our descendants will be amazed that we did not know things that are so plain to them . . . Many discoveries are reserved for ages still to come, when memory of us will have been effaced. Our universe is a sorry little affair unless it has in it something for every age to investigate . Nature does not reveal her mysteries once and for all. -- *Seneca*, Natural Questions, Book 7, first century

In ancient times, in everyday speech and custom, the most mundane happenings were connected with the grandest cosmic events. A charming example is an incantation against the worm which the Assyrians of 1000 B.C. imagined to cause toothaches. It begins with the origin of the universe and ends with a cure for toothache:

After Anu had created the heaven,
And the heaven had created the earth,
And the earth had created the rivers,
And the rivers had created the canals,
And the canals had created the morass,
And the morass had created the worm,
The worm went before Shamash, weeping,
His tears flowing before
Ea: 'What wilt thou give me for my food,
What wilt thou give me for my drink?'
'I will give thee the dried fig And the apricot.'
'What are these to me? The dried fig
And the apricot! Lift me up, and among the teeth
And the gums let me dwell!
Because thou hast said this, O worm,
May Ea smite thee with the might of His hand!
(Incantation against toothache.)

Its treatment: Second-grade beer . . . and oil thou shalt mix together; The incantation thou shalt recite three times thereon and shalt put the medicine upon the tooth.

Our ancestors were eager to understand the world but had not quite stumbled upon the method. They imagined a small, quaint, tidy universe in which the dominant forces were gods like Anu, Ea, and Shamash. In that universe humans played an important if not a central role. We were intimately bound up with the rest of nature. The treatment of toothache with second-rate beer was tied to the deepest cosmological mysteries.

Today we have discovered a powerful and elegant way to understand the universe, a method called science; it has revealed to us a universe so ancient and so vast that human affairs seem at first sight to be of little consequence. We have grown distant from the Cosmos. It has seemed remote and irrelevant to everyday concerns. But science has found not only that the universe has a reeling and ecstatic grandeur, not only that it is accessible to human understanding, but also that we are, in a very real and profound sense, a part of that Cosmos, born from it, our fate deeply connected with it. The most basic human events and the most trivial trace back to the universe and its origins.

The Shores of the Cosmic Ocean

The Cosmos is all that is or ever was or ever will be. Our feeblest contemplations of the Cosmos stir us - there is a tingling in the spine, a catch in the voice, a faint sensation, as if a distant memory, of falling from a height. We know we are approaching the greatest of mysteries.

The size and age of the Cosmos are beyond ordinary human understanding. Lost somewhere between immensity and eternity is our tiny planetary home. In a cosmic perspective, most human concerns seem insignificant, even petty. And yet our species is young and curious and brave and shows much promise. In the last few millennia we have made the most astonishing and unexpected discoveries about the Cosmos and our place within it, explorations that are exhilarating to consider. They remind us that humans have evolved to wonder, that understanding is a joy, that knowledge is prerequisite to survival. I believe our future depends on how well we know this Cosmos in which we float like a mote of dust in the morning sky.

Those explorations required skepticism and imagination both. Imagination will often carry us to worlds that never were. But without it, we go nowhere. Skepticism enables us to distinguish fancy from fact, to test our speculations. The Cosmos is rich beyond measure - in elegant facts, in exquisite interrelationships, in the subtle machinery of awe.

The surface of the Earth is the shore of the cosmic ocean. From it we have learned most of what we know. Recently, we have waded a little out to sea, enough to dampen our toes or, at most, wet our ankles. The water seems inviting. The ocean calls. Some part of our being knows this is from where we came. We long to return. These aspirations are not, I think, irreverent, although they may trouble whatever gods may be.

The dimensions of the Cosmos are so large that using familiar units of distance, such as meters or miles, chosen for their utility on Earth, would make little sense. Instead, we measure distance with the speed of light. In one second a beam of light travels 186,000 miles, nearly 300,000 kilometers or seven times around the Earth. In eight minutes it will travel from the Sun to the Earth. We can say the Sun is eight light-minutes away. In a year, it crosses nearly ten trillion kilometers, about six trillion miles, of intervening space. That unit of length, the distance light goes in a year, is called a light-year. It measures not time but distances - enormous distances.

The Earth is a place. It is by no means the only place. It is not even a typical place. No planet or star or galaxy can be typical, because the Cosmos is mostly empty. The only typical place is within the vast, cold, universal vacuum, the everlasting night of intergalactic space, a place so strange and desolate that, by comparison, planets and stars and galaxies seem achingly rare and lovely. If we were randomly inserted into the Cosmos, the chance that we would find ourselves on or near a planet would be less than one in a billion trillion trillion* (1033, a one followed by 33 zeroes). In everyday life such odds are called compelling. Worlds are precious.

From an intergalactic vantage point we would see, strewn like sea froth on the waves of space, innumerable faint, wispy tendrils of light. These are the galaxies. Some are solitary wanderers; most inhabit communal clusters, huddling together, drifting endlessly in the great cosmic dark. Before us is the Cosmos on the grandest scale we know. We are in the realm of the nebulae, eight billion light-years from Earth, halfway to the edge of the known universe.

A galaxy is composed of gas and dust and stars billions upon billions of stars. Every star may be a sun to someone. Within a galaxy are stars and worlds and, it may be, a proliferation of living things and intelligent beings and spacefaring civilizations. But from afar, a galaxy reminds me more of a collection of lovely found objects - seashells, perhaps, or corals, the productions of Nature laboring for aeons in the cosmic ocean.

There are some hundred billion (10^11) galaxies, each with, on the average, a hundred billion stars. In all the galaxies, there are perhaps as many planets as stars, 10^11 x 10^11 = 10^22, ten billion trillion. In the face of such overpowering numbers, what is the likelihood that only one ordinary star, the Sun, is accompanied by an inhabited planet? Why should we, tucked away in some forgotten corner of the Cosmos, be so fortunate? To me, it seems far more likely that the universe is brimming over with life. But we humans do not yet know. We are just beginning our explorations. From eight billion light-years away we are hard pressed to find even the cluster in which our Milky Way Galaxy is embedded, much less the Sun or the Earth. The only planet we are sure is inhabited is a tiny speck of rock and metal, shining feebly by reflected sunlight, and at this distance utterly lost.

But presently our journey takes us to what astronomers on Earth like to call the Local Group of galaxies. Several million light-years across, it is composed of some twenty constituent galaxies. It is a sparse and obscure and unpretentious cluster. One of these galaxies is M31, seen from the Earth in the constellation Andromeda. Like other spiral galaxies, it is a huge pinwheel of stars, gas and dust. M31 has two small satellites, dwarf elliptical galaxies bound to it by gravity, by the identical law of physics that tends to keep me in my chair. The laws of nature are the same throughout the Cosmos. We are now two million light-years from home.

Beyond M31 is another, very similar galaxy, our own, its spiral arms turning slowly, once every quarter billion years. Now, forty thousand light-years from home, we find ourselves falling toward the massive center of the Milky Way. But if we wish to find the Earth, we must redirect our course to the remote outskirts of the Galaxy, to an obscure locale near the edge of a distant spiral arm.

Our overwhelming impression, even between the spiral arms, is of stars streaming by us - a vast array of exquisitely self-luminous stars, some as flimsy as a soap bubble and so large that they could contain ten thousand Suns or a trillion Earths; others the size of a small town and a hundred trillion times denser than lead. Some stars are solitary, like the Sun. Most have companions. Systems are commonly double, two stars orbiting one another. But there is a continuous gradation from triple systems through loose clusters of a few dozen stars to the great globular clusters, resplendent with a million suns. Some double stars are so close that they touch, and starstuff flows beneath them. Most are as separated as Jupiter is from the Sun. Some stars, the supernovae, are as bright as the entire galaxy that contains them; others, the black holes, are invisible from a few kilometers away. Some shine with a constant brightness; others flicker uncertainly or blink with an unfaltering rhythm. Some rotate in stately elegance; others spin so feverishly that they distort themselves to oblateness. Most shine mainly in visible and infrared light; others are also brilliant sources of X-rays or radio waves. Blue stars are hot and young; yellow stars, conventional and middle-aged; red stars, often elderly and dying; and small white or black stars are in the final throes of death. The Milky Way contains some 400 billion stars of all sorts moving with a complex and orderly grace. Of all the stars, the inhabitants of Earth know close-up, so far, but one.

Each star system is an island in space, quarantined from its neighbors by the lightyears. I can imagine creatures evolving into glimmerings of knowledge on innumerable worlds, every one of them assuming at first their puny planet and paltry few suns to be all that is. We grow up in isolation. Only slowly do we teach ourselves the Cosmos.

Some stars may be surrounded by millions of lifeless and rocky worldlets, planetary systems frozen at some early stage in their evolution. Perhaps many stars have planetary systems rather like our own: at the periphery, great gaseous ringed planets and icy moons, and nearer to the center, small, warm, blue-white, cloud-covered worlds. On some, intelligent life may have evolved, reworking the planetary surface in some massive engineering enterprise. These are our brothers and sisters in the Cosmos. Are they very different from us? What is their form, biochemistry, neurobiology, history, politics, science, technology, art, music, religion, philosophy? Perhaps some day we will know them.

We have now reached our own backyard, a light-year from Earth. Surrounding our Sun is a spherical swarm of giant snow-balls composed of ice and rock and organic molecules: the cometary nuclei. Every now and then a passing star gives a tiny gravitational tug, and one of them obligingly careens into the inner solar system. There the Sun heats it, the ice is vaporized, and a lovely cometary tail develops.

We approach the planets of our system, largish worlds, captives of the Sun, gravitationally constrained to follow nearly circular orbits, heated mainly by sunlight. Pluto, covered with methane ice and accompanied by its solitary giant moon Charon, is illuminated by a distant Sun, which appears as no more than a bright point of light in a pitchblack sky. The giant gas worlds, Neptune, Uranus, Saturn - the jewel of the solar system - and Jupiter all have an entourage of icy moons. Interior to the region of gassy planets and orbiting icebergs are the warm, rocky provinces of the inner solar system. There is, for example, the red planet Mars, with soaring volcanoes, great rift valleys, enormous planet-wide sandstorms, and, just possibly, some simple forms of life. All the planets orbit the Sun, the nearest star, an inferno of hydrogen and helium gas engaged in thermonuclear reactions, flooding the solar system with light.

Finally, at the end of all our wanderings, we return to our tiny, fragile, blue-white world, lost in a cosmic ocean vast beyond our most courageous imaginings. It is a world among an immensity of others. It may be significant only for us. The Earth is our home, our parent. Our kind of life arose and evolved here. The human species is coming of age here. It is on this world that we developed our passion for exploring the Cosmos, and it is here that we are, in some pain and with no guarantees, working out our destiny.

Welcome to the planet Earth - a place of blue nitrogen skies, oceans of liquid water, cool forests and soft meadows, a world positively rippling with life. In the cosmic perspective it is, as I have said, poignantly beautiful and rare; but it is also, for the moment, unique. In all our journeying through space and time, it is, so far, the only world on which we know with certainty that the matter of the Cosmos has become alive and aware. There must be many such worlds scattered through space, but our search for them begins here, with the accumulated wisdom of the men and women of our species, garnered at great cost over a million years. We are privileged to live among brilliant and passionately inquisitive people, and in a time when the search for knowledge is generally prized. Human beings, born ultimately of the stars and now for a while inhabiting a world called Earth, have begun their long voyage home.

The discovery that the Earth is a little world was made, as so many important human discoveries were, in the ancient Near East, in a time some humans call the third century B.C., in the greatest metropolis of the age, the Egyptian city of Alexandria. Here there lived a man named Eratosthenes. One of his envious contemporaries called him 'Beta,' the second letter of the Greek alphabet, because, he said, Eratosthenes was second best in the world in everything. But it seems clear that in almost everything Eratosthenes was 'Alpha.' He was an astronomer, historian, geographer, philosopher, poet, theater critic and mathematician. The titles of the books he wrote range from Astronomy to On Freedom from Pain. He was also the director of the great library of Alexandria, where one day he read in a papyrus book that in the southern frontier outpost of Syene, near the first cataract of the Nile, at noon on June 21 vertical sticks cast no shadows. On the summer solstice, the longest day of the year, as the hours crept toward midday, the shadows of temple columns grew shorter. At noon, they were gone. A reflection of the Sun could then be seen in the water at the bottom of a deep well. The Sun was directly overhead.

It was an observation that someone else might easily have ignored. Sticks, shadows, reflections in wells, the position of the Sun - of what possible importance could such simple everyday matters be? But Eratosthenes was a scientist, and his musings on these commonplaces changed the world; in a way, they made the world. Eratosthenes had the presence of mind to do an experiment, actually to observe whether in Alexandria vertical sticks cast shadows near noon on June 21. And, he discovered, sticks do.

Eratosthenes asked himself how, at the same moment, a stick in Syene could cast no shadow and a stick in Alexandria, far to the north, could cast a pronounced shadow. Consider a map of ancient Egypt with two vertical sticks of equal length, one stuck in Alexandria, the other in Syene. Suppose that, at a certain moment, each stick casts no shadow at all. This is perfectly easy to understand - provided the Earth is flat. The Sun would then be directly overhead. If the two sticks cast shadows of equal length, that also would make sense on a flat Earth: the Sun's rays would then be inclined at the same angle to the two sticks. But how could it be that at the same instant there was no shadow at Syene and a substantial shadow at Alexandria?

The only possible answer, he saw, was that the surface of the Earth is curved. Not only that: the greater the curvature, the greater the difference in the shadow lengths. The Sun is so far away that its rays are parallel when they reach the Earth. Sticks placed at different angles to the Sun's rays cast shadows of different lengths. For the observed difference in the shadow lengths, the distance between Alexandria and Syene had to be about seven degrees along the surface of the Earth; that is, if you imagine the sticks extending down to the center of the Earth, they would there intersect at an angle of seven degrees. Seven degrees is something like one-fiftieth of three hundred and sixty degrees, the full circumference of the Earth. Eratosthenes knew that the distance between Alexandria and Syene was approximately 800 kilometers, because he hired a man to pace it out. Eight hundred kilometers times 50 is 40,000 kilometers: so that must be the circumference of the Earth.

This is the right answer. Eratosthenes' only tools were sticks, eyes, feet and brains, plus a taste for experiment. With them he deduced the circumference of the Earth with an error of only a few percent, a remarkable achievement for 2,200 years ago. He was the first person accurately to measure the size of a planet.

...

If we lived on a planet where nothing ever changed, there would be little to do. There would be nothing to figure out. There would be no impetus for science. And if we lived in an unpredictable world, where things changed in random or very complex ways, we would not be able to figure things out. Again, there would be no such thing as science. But we live in an in-between universe, where things change, but according to patterns, rules, or, as we call them, laws of nature. If I throw a stick up in the air, it always falls down. If the sun sets in the west, it always rises again the next morning in the east. And so it becomes possible to figure things out. We can do science, and with it we can improve our lives.

Human beings are good at understanding the world. We always have been. We were able to hunt game or build fires only because we had figured something out. There was a time before television, before motion pictures, before radio, before books. The greatest part of human existence was spent in such a time. Over the dying embers of the campfire, on a moonless night, we watched the stars.

...

For thousands of years humans were oppressed - as some of us still are - by the notion that the universe is a marionette whose strings are pulled by a god or gods, unseen and inscrutable. Then, 2,500 years ago, there was a glorious awakening in Ionia: on Samos and the other nearby Greek colonies that grew up among the islands and inlets of the busy eastern Aegean Sea.* Suddenly there were people who believed that everything was made of atoms; that human beings and other animals had sprung from simpler forms; that diseases were not caused by demons or the gods; that the Earth was only a planet going around the Sun. And that the stars were very far away.

This revolution made Cosmos and Chaos. The early Greeks had believed that the first being was Chaos, corresponding to the phrase in Genesis in the same context, 'without form'. Chaos created and then mated with a goddess called Night, and their offspring eventually produced all the gods and men. A universe created from Chaos was in perfect keeping with the Greek belief in an unpredictable Nature run by capricious gods. But in the sixth century B.C., in Ionia, a new concept developed, one of the great ideas of the human species. The universe is knowable, the ancient Ionians argued, because it exhibits an internal order: there are regularities in Nature that permit its secrets to be uncovered. Nature is not entirely unpredictable; there are rules even she must obey. This ordered and admirable character of the universe was called Cosmos.

But why Ionia, why in these unassuming and pastoral landscapes, these remote islands and inlets of the Eastern Mediterranean? Why not in the great cities of India or Egypt, Babylonia, China or Mesoamerica? China had an astronomical tradition millennia old; it invented paper and printing, rockets, clocks, silk, porcelain, and ocean-going navies. Some historians argue it was nevertheless too traditionalist a society, too unwilling to adopt innovations. Why not India, an extremely rich, mathematically gifted culture? Because, some historians maintain, of a rigid fascination with the idea of an infinitely old universe condemned to an endless cycle of deaths and rebirths, of souls and universes, in which nothing fundamentally new could ever happen. Why not Mayan and Aztec societies, which were accomplished in astronomy and captivated, as the Indians were, by large numbers? Because, some historians declare, they lacked the aptitude or impetus for mechanical invention. The Mayans and the Aztecs did not even - except for children's toys - invent the wheel.

The Ionians had several advantages. Ionia is an island realm. Isolation, even if incomplete, breeds diversity. With many different islands, there was a variety of political systems. No single concentration of power could enforce social and intellectual conformity in all the islands. Free inquiry became possible. The promotion of superstition was not considered a political necessity. Unlike many other cultures, the Ionians were at the crossroads of civilizations, not at one of the centers. In Ionia, the Phoenician alphabet was first adapted to Greek usage and widespread literacy became possible. Writing was no longer a monopoly of the priests and scribes. The thoughts of many were available for consideration and debate. Political power was in the hands of the merchants, who actively promoted the technology on which their prosperity depended. It was in the Eastern Mediterranean that African, Asian, and European civilizations, including the great cultures of Egypt and Mesopotamia, met and cross-fertilized in a vigorous and heady confrontation of prejudices, languages, ideas and gods. What do you do when you are faced with several different gods each claiming the same territory? The Babylonian Marduk and the Greek Zeus was each considered master of the sky and king of the gods. You might decide that Marduk and Zeus were really the same. You might also decide, since they had quite different attributes, that one of them was merely invented by the priests. But if one, why not both?

And so it was that the great idea arose, the realization that there might be a way to know the world without the god hypothesis; that there might be principles, forces, laws of nature, through which the world could be understood without attributing the fall of every sparrow to the direct intervention of Zeus.

China and India and Mesoamerica would, I think, have tumbled to science too, if only they had been given a little more time. Cultures do not develop with identical rhythms or evolve in lockstep. They arise at different times and progress at different rates. The scientific world view works so well, explains so much and resonates so harmoniously with the most advanced parts of our brains that in time, I think, virtually every culture on the Earth, left to its own devices, would have discovered science. Some culture had to be first. As it turned out, Ionia was the place where science was born.

Between 600 and 400 B.C., this great revolution in human thought began. The key to the revolution was the hand. Some of the brilliant Ionian thinkers were the sons of sailors and farmers and weavers. They were accustomed to poking and fixing, unlike the priests and scribes of other nations, who, raised in luxury, were reluctant to dirty their hands. They rejected superstition, and they worked wonders. In many cases we have only fragmentary or secondhand accounts of what happened. The metaphors used then may be obscure to us now. There was almost certainly a conscious effort a few centuries later to suppress the new insights. The leading figures in this revolution were men with Greek names, largely unfamiliar to us today, but the truest pioneers in the development of our civilization and our humanity.

The first Ionian scientist was Thales of Miletus, a city in Asia across a narrow channel of water from the island of Samos. He had traveled in Egypt and was conversant with the knowledge of Babylon. It is said that he predicted a solar eclipse. He learned how to measure the height of a pyramid from the length of its shadow and the angle of the Sun above the horizon, a method employed today to determine the heights of the mountains of the Moon. He was the first to prove geometric theorems of the sort codified by Euclid three centuries later - for example, the proposition that the angles at the base of an isosceles triangle are equal. There is a clear continuity of intellectual effort from Thales to Euclid to Isaac Newton’s purchase of the Elements of Geometry at Stourbridge Fair in 1663 (Chapter 3), the event that precipitated modern science and technology.

Thales attempted to understand the world without invoking the intervention of the gods. Like the Babylonians, he believed the world to have once been water. To explain the dry land, the Babylonians added that Marduk had placed a mat on the face of the waters and piled dirt upon it.Thales held a similar view, but, as Benjamin Farrington said, ‘left Marduk out.’ Yes, everything was once water, but the Earth formed out of the oceans by a natural process - similar, he thought, to the silting he had observed at the delta of the Nile. Indeed, he thought that water was a common principle underlying all of matter, just as today we might say the same of electrons, protons and neutrons, or of quarks. Whether Thales’ conclusion was correct is not as important as his approach: The world was not made by the gods, but instead was the work of material forces interacting in Nature. Thales brought back from Babylon and Egypt the seeds of the new sciences of astronomy and geometry, sciences that would sprout and grow in the fertile soil of Ionia.

Anaximander of Miletus was a friend and colleague of Thales, one of the first people we know of to do an experiment. By examining the moving shadow cast by a vertical stick he determined accurately the length of the year and the seasons. For ages men had used sticks to club and spear one another. Anaximander used one to measure time. He was the first person in Greece to make a sundial, a map of the known world and a celestial globe that showed the patterns of the constellations. He believed the Sun, the Moon and the stars to be made of fire seen through moving holes in the dome of the sky, probably a much older idea. He held the remarkable view that the Earth is not suspended or supported from the heavens, but that it remains by itself at the center of the universe; since it was equidistant from all places on the ‘celestial sphere,’ there was no force that could move it.

This was the time of Theodorus, the master engineer of the age, credited among the Greeks with the invention of the key, the ruler, the carpenter’s square, the level, the lathe, bronze casting and central heating. Why are there no monuments to this man? Those who dreamed and speculated about the laws of Nature talked with the technologists and the engineers. They were often the same people. The theoretical and the practical were one.

About the same time, on the nearby island of Cos, Hippocrates was establishing his famous medical tradition, now barely remembered because of the Hippocratic oath. It was a practical and effective school of medicine, which Hippocrates insisted had to be based on the contemporary equivalent of physics and chemistry.But it also had its theoretical side. In his book On Ancient Medicine, Hippocrates wrote: ‘Men think epilepsy divine, merely because they do not understand it. But if they called everything divine which they do not understand, why, there would be no end of divine things.’

In time, the Ionian influence and the experimental method spread to the mainland of Greece, to Italy, to Sicily. There was once a time when hardly anyone believed in air. They knew about breathing, of course, and they thought the wind was the breath of the gods. But the idea of air as a static, material but invisible substance was unimagined. The first recorded experiment on air was performed by a physician named Empedocles, who flourished around 450 B.C. Some accounts claim he identified himself as a god. But perhaps it was only that he was so clever that others thought him a god. He believed that light travels very fast, but not infinitely fast. He taught that there was once a much greater variety of living things on the Earth, but that many races of beings ‘must have been unable to beget and continue their kind. For in the case of every species that exists, either craft or courage or speed has from the beginning of its existence protected and preserved it.’ In this attempt to explain the lovely adaptation of organisms to their environments, Empedocles, like Anaximander and Democritus (see below), clearly anticipated some aspects of Darwin’s great idea of evolution by natural selection.

Empedocles performed his experiment with a household implement people had used for centuries, the so-called clepsydra or ‘water thief’, which was used as a kitchen ladle. A brazen sphere with an open neck and small holes in the bottom, it is filled by immersing it in water. If you pull it out with the neck uncovered, the water pours out of the holes, making a little shower. But if you pull it out properly, with your thumb covering the neck, the water is retained within the sphere until you lift your thumb. If you try to fill it with the neck covered, nothing happens. Some material substance must be in the way of the water. We cannot see such a substance. What could it be? Empedocles argued that it could only be air. A thing we cannot see can exert pressure, can frustrate my wish to fill a vessel with water if I were dumb enough to leave my finger on the neck. Empedocles had discovered the invisible. Air, he thought, must be matter in a form so finely divided that it could not be seen.

Empedocles is said to have died in an apotheotic fit by leaping into the hot lava at the summit caldera of the great volcano of Aetna. But I sometimes imagine that he merely slipped during a courageous and pioneering venture in observational geophysics.

This hint, this whiff, of the existence of atoms was carried much further by a man named Democritus, who came from the Ionian colony of Abdera in northern Greece. Abdera was a kind of joke town. If in 430 B.C. you told a story about someone from Abdera, you were guaranteed a laugh. It was in a way the Brooklyn of its time. For Democritus all of life was to be enjoyed and understood; understanding and enjoyment were the same thing. He said that ‘a life without festivity is a long road without an inn.’ Democritus may have come from Abdera, but he was no dummy. He believed that a large number of worlds had formed spontaneously out of diffuse matter in space, evolved and then decayed. At a time when no one knew about impact craters, Democritus thought that worlds on occasion collide; he believed that some worlds wandered alone through the darkness of space, while others were accompanied by several suns and moons; that some worlds were inhabited, while others had no plants or animals or even water; that the simplest forms of life arose from a kind of primeval ooze. He taught that perception - the reason, say, I think there is a pen in my hand - was a purely physical and mechanistic process; that thinking and feeling were attributes of matter put together in a sufficiently fine and complex way and not due to some spirit infused into matter by the gods.

Democritus invented the word atom, Greek for ‘unable to be cut.’ Atoms were the ultimate particles, forever frustrating our attempts to break them into smaller pieces. Everything, he said, is a collection of atoms, intricately assembled. Even we. ‘Nothing exists,’ he said, ‘but atoms and the void.’

When we cut an apple, the knife must pass through empty spaces between the atoms, Democritus argued. If there were no such empty spaces, no void, the knife would encounter the impenetrable atoms, and the apple could not be cut. Having cut a slice from a cone, say, let us compare the cross sections of the two pieces. Are the exposed areas equal? No, said Democritus. The slope of the cone forces one side of the slice to have a slightly smaller cross section than the other. If the two areas were exactly equal, we would have a cylinder, not a cone. No matter how sharp the knife, the two pieces have unequal cross sections. Why? Because, on the scale of the very small, matter exhibits some irreducible roughness. This fine scale of roughness Democritus identified with the world of the atoms. His arguments were not those we use today, but they were subtle and elegant, derived from everyday life. And his conclusions were fundamentally correct.

In related exercise. Democritus imagined calculating the volume of a cone or a pyramid by a very large number of extremely small stacked plates tapering in size from the base to the apex. He had stated the problem that, in mathematics, is called the theory of limits. He was knocking at the door of the differential and integral calculus, that fundamental tool for understanding the world that was not, so far as we know from written records, in fact discovered until the time of Isaac Newton. Perhaps if Democritus’ work had not been almost completely destroyed, there would have been calculus by the time of Christ.

As a person, Democritus seems to have been somewhat unusual. Women, children and sex discomfited him, in part because they took time away from thinking. But he valued friendship, held cheerfulness to be the goal of life and devoted a major philosophical inquiry to the origin and nature of enthusiasm. He journeyed to Athens to visit Socrates and then found himself too shy to introduce himself. He was a close friend of Hippocrates. He was awed by the beauty and elegance of the physical world. He felt that poverty in a democracy was preferable to wealth in a tyranny. He believed that the prevailing religions of his time were evil and that neither immortal souls nor immortal gods exist: ‘Nothing exists, but atoms and the void.’

...

However, in his time the brief tradition of tolerance for unconventional views began to erode and then to shatter. People came to be punished for having unusual ideas. A portrait of

Democritus is now on the Greek hundred-drachma bill. But his insights were suppressed, his influence on history made minor. The mystics were beginning to win.

Anaxagoras was an Ionian experimentalist who flourished around 450 B.C. and lived in Athens. He was a rich man, indifferent to his wealth but passionate about science. Asked what was the purpose of life, he replied, 'the investigation of the Sun, the Moon, and the heavens,' the reply of a true astronomer. He performed a clever experiment in which a single drop of white liquid, like cream, was shown not to lighten perceptibly the contents of a great pitcher of dark liquid, like wine. There must, he concluded, be changes deducible by experiment that are too subtle to be perceived directly by the senses.

Anaxagoras was not nearly so radical as Democritus. Both were thoroughgoing materialists, not in prizing possessions but in holding that matter alone provided the underpinnings of the world. Anaxagoras believed in a special mind substance and disbelieved in the existence of atoms. He thought humans were more intelligent than other animals because of our hands, a very Ionian idea.

He was the first person to state clearly that the Moon shines by reflected light, and he accordingly devised a theory of the phases of the Moon. This doctrine was so dangerous that the manuscript describing it had to be circulated in secret, an Athenian samizdat. It was not in keeping with the prejudices of the time to explain the phases or eclipses of the Moon by the relative geometry of the Earth, the Moon and the self-luminous Sun. Aristotle, two generations later, was content to argue that those things happened because it was the nature of the Moon to have phases and eclipses - mere verbal juggling, an explanation that explains nothing.

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The great scientists from Thales to Democritus and Anaxagoras have usually been described in history or philosophy books as 'Presocratics', as if their main function was to hold the philosophical fort until the advent of Socrates, Plato, and Aristotle and perhaps influence them a little. Instead, the old Ionians represent a different and largely contradictory tradition, one in much better accord with modern science. That their influence was felt powerfully for only two or three centuries is an irreparable loss for all those human beings who lived between the Ionian Awakening and the Italian Renaissance.

Perhaps the most influential person ever associated with Samos was Pythagoras,* a contemporary of Polycrates in the sixth century B.C. According to local tradition, he lived for a time in a cave on the Samian Mount Kerkis, and was the first person in the history of the world to deduce that the Earth is a sphere. Perhaps he argued by analogy with the Moon and the Sun, or noticed the curved shadow of the Earth on the Moon during a lunar eclipse, or recognized that when ships leave Samos and recede over the horizon, their masts disappear last.

He or his disciples discovered the Pythagorean theorem: the sum of the squares of the shorter sides of a right triangle equals the square of the longer side. Pythagoras did not simply enumerate examples of this theorem; he developed a method of mathematical deduction to prove the thing generally. The modern tradition of mathematical argument, essential to all of science, owes much to Pythagoras. It was he who first used the word Cosmos to denote a well-ordered and harmonious universe, a world amenable to human understanding.

Many Ionians believed the underlying harmony of the universe to be accessible through observation and experiment, the method that dominates science today. However, Pythagoras employed a very different method. He taught that the laws of Nature could be deduced by pure thoughts. He and his followers were not fundamentally experimentalists.* They were mathematicians. And they were thoroughgoing mystics. According to Bertrand Russell, in a perhaps uncharitable passage, Pythagoras 'founded a religion, of which the main tenets were the transmigration of souls and the sinfulness of eating beans. His religion was embodied in a religious order, which, here and there, acquired control of the State and established a rule of the saints. But the unregenerate hankered after beans, and sooner or later rebelled.'

The Pythagoreans delighted in the certainty of mathematical demonstration, the sense of a pure and unsullied world accessible to the human intellect, a Cosmos in which the sides of right triangles perfectly obey simple mathematical relationships. It was in striking contrast to the messy reality of the workaday world. They believed that in their mathematics they had glimpsed a perfect reality, a realm of the gods, of which our familiar world is but an imperfect reflection. In Plato's famous parable of the cave, prisoners were imagined tied in such a way that they saw only the shadows of passersby and believed the shadows to be real - never guessing the complex reality that was accessible if they would but turn their heads. The Pythagoreans would powerfully influence Plato and, later, Christianity.

The Pythagoreans were fascinated by the regular solids, symmetrical three-dimensional objects all of whose sides are the same regular polygon. The cube is the simplest example, having six squares as sides. There are an infinite number of regular polygons, but only five regular solids. (The proof of this statement, a famous example of mathematical reasoning, is given in Appendix 2.) For some reason, knowledge of a solid called the dodecahedron having twelve pentagons as sides seemed to them dangerous. It was mystically associated with the Cosmos. The other four regular solids were identified, somehow, with the four 'elements' then imagined to constitute the world: earth, fire, air and water. The fifth regular solid must then, they thought, correspond to some fifth element that could only be the substance of the heavenly bodies. (This notion of a fifth essence is the origin of our word quintessence.) Ordinary people were to be kept ignorant of the dodecahedron.

In love with whole numbers, the Pythagoreans believed all things could be derived from them, certainly all other numbers. A crisis in doctrine arose when they discovered that the square root of two (the ratio of the diagonal to the side of a square) was irrational, that it cannot be expressed accurately as the ratio of any two whole numbers, no matter how big these numbers are. Ironically this discovery (reproduced in Appendix 1) was made with the Pythagorean theorem as a tool. 'Irrational' originally meant only that a number could not be expressed as a ratio. But for the Pythagoreans it came to mean something threatening, a hint that their world view might not make sense, which is today the other meaning of 'irrational.' Instead of sharing these important mathematical discoveries, the Pythagoreans suppressed knowledge of the square root of two and the dodecahedron. The outside world was not to know.* Even today there are scientists opposed to the popularization of science: the sacred knowledge is to be kept within the cult, unsullied by public understanding.

The Pythagoreans believed the sphere to be 'perfect', all points on its surface being at the same distance from its center. Circles were also perfect. And the Pythagoreans insisted that planets moved in circular paths at constant speeds. They seemed to believe that moving slower or faster at different places in the orbit would be unseemly; noncircular motion was somehow flawed, unsuitable for the planets, which, being free of the Earth, were also deemed 'perfect.'

The pros and cons of the Pythagorean tradition can be seen clearly in the life's work of Johannes Kepler (Chapter 3). The Pythagorean idea of a perfect and mystical world, unseen by the senses, was readily accepted by the early Christians and was an integral component of Kepler's early training. On the one hand, Kepler was convinced that mathematical harmonies exist in nature (he wrote that 'the universe was stamped with the adornment of harmonic proportions'); that simple numerical relationships must determine the motion of the planets. On the other hand, again following the Pythagoreans, he long believed that only uniform circular motion was admissible. He repeatedly found the observed planetary motions could not be explained in this way, and repeatedly tried again. But unlike many Pythagoreans, he believed in observations and experiment in the real world. Eventually the detailed observations of the apparent motion of the planets forced him to abandon the idea of circular paths and to realize that planets travel in ellipses. Kepler was both inspired in his search for the harmony of planetary motion and delayed for more than a decade by the attractions of Pythagorean doctrine.

A disdain for the practical swept the ancient world. Plato urged astronomers to think about the heavens, but not to waste their time observing them. Aristotle believed that: ‘The lower sort are by nature slaves, and it is better for them as for all inferiors that they should be under the rule of a master .... The slave shares in his master’s life; the artisan is less closely connected with him, and only attains excellence in proportion as he becomes a slave. The meaner sort of mechanic has a special and separate slavery.’ Plutarch wrote: ‘It does not of necessity follow that, if the work delight you with its grace, the one who wrought it is worthy of esteem.’ Xenophon’s opinion was: ‘What are called the mechanical arts carry a social stigma and are rightly dishonoured in our cities.’ As a result of such attitudes, the brilliant and promising Ionian experimental method was largely abandoned for two thousand years. Without experiment, there is no way to choose among contending hypotheses, no way for science to advance. The antiempirical taint of the Pythagoreans survives to this day. But why? Where did this distaste for experiment come from?

An explanation for the decline of ancient science has been put forward by the historian of science, Benjamin Farrington: The mercantile tradition, which led to Ionian science, also led to a slave economy. The owning of slaves was the road to wealth and power. Polycrates’ fortifications were built by slaves. Athens in the time of Pericles, Plato and Aristotle had a vast slave population. All the brave Athenian talk about democracy applied only to a privileged few. What slaves characteristically perform is manual labor. But scientific experimentation is manual labor, from which the slaveholders are preferentially distanced; while it is only the slaveholders - politely called ‘gentle-men’ in some societies - who have the leisure to do science. Accordingly, almost no one did science. The Ionians were perfectly able to make machines of some elegance. But the availability of slaves undermined the economic motive for the development of technology. Thus the mercantile tradition contributed to the great Ionian awakening around 600 B.C., and, through slavery, may have been the cause of its decline some two centuries later. There are great ironies here.

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Similar trends are apparent throughout the world. A major problem in the contemporary (political) Third World is that the educated classes tend to be the children of the wealthy, with a vested interest in the status quo, and are unaccustomed either to working with their hands or to challenging conventional wisdom. Science has been very slow to take root. In the recognition by Pythagoras and Plato that the Cosmos is knowable, that there is a mathematical underpinning to nature, they greatly advanced the cause of science. But in the suppression of disquieting facts, the sense that science should be kept for a small elite, the distaste for experiment, the embrace of mysticism and the easy acceptance of slave societies, they set back the human enterprise. After a long mystical sleep in which the tools of scientific inquiry lay moldering, the Ionian approach, in some cases transmitted through scholars at the Alexandrian Library, was finally rediscovered. The Western world reawakened. Experiment and open inquiry became once more respectable. Forgotten books and fragments were again read. Leonardo and Columbus and Copernicus were inspired by or independently retraced parts of this ancient Greek tradition. There is in our time much Ionian science, although not in politics and religion, and a fair amount of courageous free inquiry. But there are also appalling superstitions and deadly ethical ambiguities. We are flawed by ancient contradictions.

Between the times of Aristarchus and Huygens, humans answered the question that had so excited me as a boy growing up in Brooklyn: What are the stars? The answer is that the stars are mighty suns, light-years away in the vastness of interstellar space. The great legacy of Aristarchus is this: neither we nor our planet enjoys a privileged position in Nature. This insight has since been applied upward to the stars, and sideways to many subsets of the human family, with great success and invariable opposition. It has been responsible for major advances in astronomy, physics, biology, anthropology, economics and politics. I wonder if its social extrapolation is a major reason for attempts at its suppression.

The legacy of Aristarchus has been extended far beyond the realm of the stars. At the end of the eighteenth century, William Herschel, musician and astronomer to George III of England, completed a project to map the starry skies and found apparently equal numbers of stars in all directions in the plane or band of the Milky Way; from this, reasonably enough, he deduced that we were at the center of the Galaxy.* Just before World War I, Harlow Shapley of Missouri devised a technique for measuring the distances to the globular clusters, those lovely spherical arrays of stars which resemble a swarm of bees. Shapley had found a stellar standard candle, a star noticeable because of its variability, but which had always the same average intrinsic brightness. By comparing the faintness of such stars when found in globular clusters with their real brightness, as determined from nearby representatives, Shapley could calculate how far away they are - just as, in a field, we can estimate the distance of a lantern of known intrinsic brightness from the feeble light that reaches us - essentially, the method of Huygens. Shapley discovered that the globular clusters were not centered around the solar neighborhood but rather about a distant region of the Milky Way, in the direction of the constellation Sagittarius, the Archer. It seemed to him very likely that the globular clusters used in this investigation, nearly a hundred of them, would be orbiting about, paying homage to, the massive center of the Milky Way.

Shapley had in 1915 the courage to propose that the solar system was in the outskirts and not near the core of our galaxy. Herschel had been misled because of the copious amount of obscuring dust in the direction of Sagittarius; he had no way to know of the enormous numbers of stars beyond. It is now very clear that we live some 30,000 lightyears from the galactic core, on the fringes of a spiral arm, where the local density of stars is relatively sparse. There may be those who live on a planet that orbits a central star in one of Shapley's globular clusters, or one located in the core. Such beings may pity us for our handful of naked-eye stars, because their skies will be ablaze with them. Near the center of the Milky Way, millions of brilliant stars would be visible to the naked eye, compared to our paltry few thousand. Our Sun or suns might set, but the night would never come.

Well into the twentieth century, astronomers believed that there was only one galaxy in the Cosmos, the Milky Way - although in the eighteenth century Thomas Wright of Durban and Immanuel Kant of Königsberg each had a premonition that the exquisite luminous spiral forms, viewed through the telescope, were other galaxies. Kant suggested explicitly that M31 in the constellation Andromeda was another Milky Way, composed of enormous numbers of stars, and proposed calling such objects by the evocative and haunting phrase 'island universes.' Some scientists toyed with the idea that the spiral nebulae were not distant island universes but rather nearby condensing clouds of interstellar gas, perhaps on their way to make solar systems. To test the distance of the spiral nebula a class of intrinsically much brighter variable stars was needed to furnish a new standard candle. Such stars, identified in M31 by Edwin Hubble in 1924, were discovered to be alarmingly dim, and it became apparent that M31 was a prodigious distance away, a number now estimated at a little more than two million light-years. But if M31 were at such a distance, it could not be a cloud of mere interstellar dimensions; it had to be much larger - an immense galaxy in its own right. And the other, fainter galaxies must be more distant still, a hundred billion of them, sprinkled through the dark to the frontiers of the known Cosmos.

As long as there have been humans, we have searched for our place in the Cosmos. In the childhood of our species (when our ancestors gazed a little idly at the stars), among the Ionian scientists of ancient Greece, and in our own age, we have been transfixed by this question: Where are we? Who are we? We find that we live on an insignificant planet of a humdrum star lost between two spiral arms in the outskirts of a galaxy which is a member of a sparse cluster of galaxies, tucked away in some forgotten corner of a universe in which there are far more galaxies than people. This perspective is a courageous continuation of our penchant for constructing and testing mental models of the skies; the Sun as a red-hot stone, the stars as celestial flame, the Galaxy as the backbone of night.

Since Aristarchus, every step in our quest has moved us farther from center stage in the cosmic drama. There has not been much time to assimilate these new findings. The discoveries of Shapley and Hubble were made within the lifetimes of many people still alive today. There are those who secretly deplore these great discoveries, who consider every step a demotion, who in their heart of hearts still pine for a universe whose center, focus and fulcrum is the Earth. But if we are to deal with the Cosmos we must first understand it, even if our hopes for some unearned preferential status are, in the process, contravened. Understanding where we live is an essential precondition for improving the neighborhood. Knowing what other neighborhoods are like also helps. If we long for our planet to be important, there is something we can do about it. We make our world significant by the courage of our questions and by the depth of our answers.

We embarked on our cosmic voyage with a question first framed in the childhood of our species and in each generation asked anew with undiminished wonder: What are the stars? Exploration is in our nature. We began as wanderers, and we are wanderers still. We have lingered long enough on the shores of the cosmic ocean. We are ready at last to set sail for the stars.

If the Ionian spirit had won, I think we - a different 'we,' of course - might by now be venturing to the stars. Our first survey ships to Alpha Centauri and Barnard's Star, Sirius and Tau Ceti would have returned long ago. Great fleets of interstellar transports would be under construction in Earth orbit - unmanned survey ships, liners for immigrants, immense trading ships to plow the seas of space. On all these ships there would be symbols and writing. If we looked closely, we might see that the language was Greek. And perhaps the symbol on the bow of one of the first starships would be a dodecahedron, with the inscription 'Starship Theodorus of the Planet Earth.'

In the time line of our world, things have gone somewhat more slowly. We are not yet ready for the stars. But perhaps in another century or two, when the solar system is all explored, we will also have put our planet in order. We will have the will and the resources and the technical knowledge to go to the stars. We will have examined from great distances the diversity of other planetary systems, some very much like our own and some extremely different. We will know which stars to visit. Our machines and our descendants will then skim the light years, the children of Thales and Aristarchus, Leonardo and Einstein.

We are not yet certain how many planetary systems there are, but there seem to be a great abundance. In our immediate vicinity, there is not just one, but in a sense four: Jupiter, Saturn and Uranus each has a satellite system that, in the relative sizes and spacings of the moons, resembles closely the planets about the Sun. Extrapolation of the statistics of double stars which are greatly disparate in mass suggests that almost all single stars like the Sun should have planetary companions.

The Lives of the Stars

To make an apple pie, you need wheat, apples, a pinch of this and that, and the heat of the oven. The ingredients are made of molecules - sugar, say, or water. The molecules, in turn, are made of atoms - carbon, oxygen, hydrogen and a few others. Where do these atoms come from? Except for hydrogen, they are all made in stars. A star is a kind of cosmic kitchen inside which atoms of hydrogen are cooked into heavier atoms. Stars condense from interstellar gas and dust, which are composed mostly of hydrogen. But the hydrogen was made in the Big Bang, the explosion that began the Cosmos. If you wish to make an apple pie from scratch, you must first invent the universe.

Suppose you take an apple pie and cut it in half; take one of the two pieces, cut it in half; and, in the spirit of Democritus, continue. How many cuts before you are down to a single atom? The answer is about ninety successive cuts. Of course, no knife could be sharp enough, the pie is too crumbly, and the atom would in any case be too small to see unaided. But there is a way to do it.

At Cambridge University in England, in the forty-five years centered on 1910, the nature of the atom was first understood - partly by shooting pieces of atoms at atoms and watching how they bounce off. A typical atom has a kind of cloud of electrons on the outside. Electrons are electrically charged, as their name suggests. The charge is arbitrarily called negative. Electrons determine the chemical properties of the atom - the glitter of gold, the cold feel of iron, the crystal structure of the carbon diamond. Deep inside the atom, hidden far beneath the electron cloud, is the nucleus, generally composed of positively charged protons and electrically neutral neutrons. Atoms are very small - one hundred million of them end to end would be as large as the tip of your little finger. But the nucleus is a hundred thousand times smaller still, which is part of the reason it took so long to be discovered.* Nevertheless, most of the mass of an atom is in its nucleus; the electrons are by comparison just clouds of moving fluff. Atoms are mainly empty space. Matter is composed chiefly of nothing.

I am made of atoms. My elbow, which is resting on the table before me, is made of atoms. The table is made of atoms. But if atoms are so small and empty and the nuclei smaller still, why does the table hold me up? Why, as Arthur Eddington liked to ask, do the nuclei that comprise my elbow not slide effortlessly through the nuclei that comprise the table? Why don’t I wind up on the floor? Or fall straight through the Earth?

The answer is the electron cloud. The outside of an atom in my elbow has a negative electrical charge. So does every atom in the table. But negative charges repel each other. My elbow does not slither through the table because atoms have electrons around their nuclei and because electrical forces are strong. Everyday life depends on the structure of the atom.

Turn off the electrical charges and everything crumbles to an invisible fine dust. Without electrical forces, there would no longer be things in the universe - merely diffuse clouds of electrons, protons and neutrons, and gravitating spheres of elementary particles, the featureless remnants of worlds.

When we consider cutting an apple pie, continuing down beyond a single atom, we confront an infinity of the very small. And when we look up at the night sky, we confront an infinity of the very large. These infinities represent an unending regress that goes on not just very far, but forever. If you stand between two mirrors - in a barber shop, say - you see a large number of images of yourself, each the reflection of another. You cannot see an infinity of images because the mirrors are not perfectly flat and aligned, because light does not travel infinitely fast, and because you are in the way. When we talk about infinity we are talking about a quantity greater than any number, no matter how large. The American mathematician Edward Kasner once asked his nine-year-old nephew to invent a name for an extremely large number - ten to the power one hundred (10^100), a one followed by a hundred zeroes. The boy called it a googol. If a googol seems large, consider a googolplex. It is ten to the power of a googol - that is, a one followed by a googol zeros. By comparison, the total number of atoms in your body is about 1028, and the total number of elementary particles - protons and neutrons and electrons - in the observable universe is about 1080. If the universe were packed solid* with neutrons, say, so there was no empty space anywhere, there would still be only about 10128 particles in it, quite a bit more than a googol but trivially small compared to a googolplex. And yet these numbers, the googol and the googolplex, do not approach, they come nowhere near, the idea of infinity. A googolplex is precisely as far from infinity as is the number one. We could try to write out a googolplex, but it is a forlorn ambition. A piece of paper large enough to have all the zeroes in a googolplex written out explicitly could not be stuffed into the known universe. Happily, there is a simpler and very concise way of writing a googolplex: 101010; and even infinity: (pronounced ‘infinity’).

(*The spirit of this calculation is very old. The opening sentences of Archimedes’ The Sand Reckoner are: ‘There are some, King Gelon, who think that the number of the sand is infinite in multitude: and I mean by the sand not only that which exists about Syracuse and the rest of Sicily, but also that which is found in every region, whether inhabited or uninhabited. And again, there are some who, without regarding it as infinite, yet think that no number has been named which is great enough to exceed its multitude.’ Archimedes then went on not only to name the number but to calculate it. Later he asked how many grains of sand would fit, side by side, into the universe that he knew. His estimate; 10^63, which corresponds, by a curious coincidence, to 10^83 or so atoms.)*

In a burnt apple pie, the char is mostly carbon. Ninety cuts and you come to a carbon atom, with six protons and six neutrons in its nucleus and six electrons in the exterior cloud. If we were to pull a chunk out of the nucleus - say, one with two protons and two neutrons - it would be not the nucleus of a carbon atom, but the nucleus of a helium atom. Such a cutting or fission of atomic nuclei occurs in nuclear weapons and conventional nuclear power plants, although it is not carbon that is split. If you make the ninety-first cut of the apple pie, if you slice a carbon nucleus, you make not a smaller piece of carbon, but something else - an atom with completely different chemical properties. If you cut an atom, you transmute the elements.

But suppose we go farther. Atoms are made of protons, neutrons and electrons. Can we cut a proton? If we bombard protons at high energies with other elementary particles - other protons, say - we begin to glimpse more fundamental units hiding inside the proton. Physicists now propose that so-called elementary particles such as protons and neutrons are in fact made of still more elementary particles called quarks, which come in a variety of ‘colors’ and ‘flavors’, as their properties have been termed in a poignant attempt to make the subnuclear world a little more like home. Are quarks the ultimate constituents of matter, or are they too composed of still smaller and more elementary particles? Will we ever come to an end in our understanding of the nature of matter, or is there an infinite regression into more and more fundamental particles? This is one of the great unsolved problems in science.

The transmutation of the elements was pursued in medieval laboratories in a quest called alchemy. Many alchemists believed that all matter was a mixture of four elementary substances: water, air, earth and fire, an ancient Ionian speculation. By altering the relative proportions of earth and fire, say, you would be able, they thought, to change copper into gold. The field swarmed with charming frauds and con men, such as Cagliostro and the Count of Saint-Germain, who pretended not only to transmute the elements but also to hold the secret of immortality. Sometimes gold was hidden in a wand with a false bottom, to appear miraculously in a crucible at the end of some arduous experimental demonstration. With wealth and immortality the bait, the European nobility found itself transferring large sums to the practitioners of this dubious art. But there were more serious alchemists such as Paracelsus and even Isaac Newton. The money was not altogether wasted - new chemical elements, such as phosphorous, antimony and mercury, were discovered. In fact, the origin of modern chemistry can be traced directly to these experiments.

There are ninety-two chemically distinct kinds of naturally occurring atoms. They are called the chemical elements and until recently constituted everything on our planet, although they are mainly found combined into molecules. Water is a molecule made of hydrogen and oxygen atoms. Air is made mostly of the atoms nitrogen (N), oxygen (O), carbon (C), hydrogen (H) and argon (Ar), in the molecular forms N2, O2, CO2, H2O and Ar. The Earth itself is a very rich mixture of atoms, mostly silicon,* oxygen, aluminum, magnesium and iron. Fire is not made of chemical elements at all. It is a radiating plasma in which the high temperature has stripped some of the electrons from their nuclei. Not one of the four ancient Ionian and alchemical 'elements' is in the modern sense an element at all: one is a molecule, two are mixtures of molecules, and the last is a plasma.

Since the time of the alchemists, more and more elements have been discovered, the latest to be found tending to be the rarest. Many are familiar - those that primarily make up the Earth; or those fundamental to life. Some are solids, some gases, and two (bromine and mercury) are liquids at room temperature. Scientists conventionally arrange them in order of complexity. The simplest, hydrogen, is element 1; the most complex, uranium is element 92. Other elements are less familiar - hafnium, erbium, dysprosium and praseodymium, say, which we do not much bump into in everyday life. By and large, the more familiar an element is, the more abundant it is. The Earth contains a great deal of iron and rather little yttrium. There are, of course, exceptions to this rule, such as gold or uranium, elements prized because of arbitrary economic conventions or aesthetic judgments, or because they have remarkable practical applications.

The fact that atoms are composed of three kinds of elementary particles - protons, neutrons and electrons is a comparatively recent finding. The neutron was not discovered until 1932. Modern physics and chemistry have reduced the complexity of the sensible world to an astonishing simplicity: three units put together in various patterns make, essentially, everything.

The neutrons, as we have said and as their name suggests, carry no electrical charge. The protons have a positive charge and the electrons an equal negative charge. The attraction between the unlike charges of electrons and protons is what holds the atom together. Since each atom is electrically neutral, the number of protons in the nucleus must exactly equal the number of electrons in the electron cloud. The chemistry of an atom depends only on the number of electrons, which equals the number of protons, and which is called the atomic number. Chemistry is simply numbers, an idea Pythagoras would have liked. If you are an atom with one proton, you are hydrogen; two, helium; three, lithium; four, beryllium; five, boron; six, carbon; seven, nitrogen; eight, oxygen; and so on, up to 92 protons, in which case your name is uranium.

Like charges, charges of the same sign, strongly repel one another. We can think of it as a dedicated mutual aversion to their own kind, a little as if the world were densely populated by anchorites and misanthropes. Electrons repel electrons. Protons repel protons. So how can a nucleus stick together? Why does it not instantly fly apart? Because there is another force of nature: not gravity, not electricity, but the short-range nuclear force, which, like a set of hooks that engage only when protons and neutrons come very close together, thereby overcomes the electrical repulsion among the protons. The neutrons, which contribute nuclear forces of attraction and no electrical forces of repulsion, provide a kind of glue that helps to hold the nucleus together. Longing for solitude, the hermits have been chained to their grumpy fellows and set among others given to indiscriminate and voluble amiability.

Two protons and two neutrons are the nucleus of a helium atom, which turns out to be very stable. Three helium nuclei make a carbon nucleus; four, oxygen; five, neon; six, magnesium; seven, silicon; eight, sulfur; and so on. Every time we add one or more protons and enough neutrons to keep the nucleus together, we make a new chemical element. If we subtract one proton and three neutrons from mercury, we make gold, the dream of the ancient alchemists. Beyond uranium there are other elements that do not naturally occur on Earth. They are synthesized by human beings and in most cases promptly fall to pieces. One of them, Element 94, is called plutonium and is one of the most toxic substances known. Unfortunately, it falls to pieces rather slowly.

Where do the naturally occurring elements come from? We might contemplate a separate creation of each atomic species. But the universe, all of it, almost everywhere, is 99 percent hydrogen and helium,* the two simplest elements. Helium, in fact, was detected on the Sun before it was found on the Earth - hence its name (from Helios, one of the Greek sun gods). Might the other chemical elements have somehow evolved from hydrogen and helium? To balance the electrical repulsion, pieces of nuclear matter would have to be brought very close together so that the short-range nuclear forces are engaged. This can happen only at very high temperatures where the particles are moving so fast that the repulsive force does not have time to act - temperatures of tens of millions of degrees. In nature, such high temperatures and attendant high pressures are common only in the insides of the stars.

We have examined our Sun, the nearest star, in various wavelengths from radio waves to ordinary visible light to X-rays, all of which arise only from its outermost layers. It is not exactly a red-hot stone, as Anaxagoras thought, but rather a great ball of hydrogen and helium gas, glowing because of its high temperatures, in the same way that a poker glows when it is brought to red heat. Anaxagoras was at least partly right. Violent solar storms produce brilliant flares that disrupt radio communications on Earth; and immense arching plumes of hot gas, guided by the Sun's magnetic field, the solar prominences, which dwarf the Earth. The sunspots, sometimes visible to the naked eye at sunset, are cooler regions of enhanced magnetic field strength. All this incessant, roiling, turbulent activity is in the comparatively cool visible surface. We see only to temperatures of about 6,000 degrees. But the hidden interior of the Sun, where sunlight is being generated, is at 40 million degrees.

Stars and their accompanying planets are born in the gravitational collapse of a cloud of interstellar gas and dust. The collision of the gas molecules in the interior of the cloud heats it, eventually to the point where hydrogen begins to fuse into helium: four hydrogen nuclei combine to form a helium nucleus, with an attendant release of a gamma ray photon. Suffering alternate absorption and emission by the overlying matter, gradually working its way toward the surface of the star, losing energy at every step, the photon's epic journey takes a million years until, as visible light, it reaches the surface and is radiated to space. The star has turned on. The gravitational collapse of the prestellar cloud has been halted. The weight of the outer layers of the star is now supported by the high temperatures and pressures generated in the interior nuclear reactions. The Sun has been in such a stable situation for the past five billion years. Thermonuclear reactions like those in a hydrogen bomb are powering the Sun in a contained and continuous explosion, converting some four hundred million tons (4 x 10^14 grams) of hydrogen into helium every second. When we look up at night and view the stars, everything we see is shining because of distant nuclear fusion.

The conversion of hydrogen into helium in the center of the Sun not only accounts for the Sun's brightness in photons of visible light; it also produces a radiance of a more mysterious and ghostly kind: The Sun glows faintly in neutrinos, which, like photons, weigh nothing and travel at the speed of light. But neutrinos are not photons. They are not a kind of light. Neutrinos, like protons, electrons and neutrons, carry an intrinsic angular momentum, or spin, while photons have no spin at all. Matter is transparent to neutrinos, which pass almost effortlessly through the Earth and through the Sun. Only a tiny fraction of them is stopped by the intervening matter. As I look up at the Sun for a second, a billion neutrinos pass through my eyeball. Of course, they are not stopped at the retina as ordinary photons are but continue unmolested through the back of my head. The curious part is that if at night I look down at the ground, toward the place where the Sun would be (if the Earth were not in the way), almost exactly the same number of solar neutrinos pass through my eyeball, pouring through an interposed Earth which is as transparent to neutrinos as a pane of clear glass is to visible light.

If our knowledge of the solar interior is as complete as we think, and if we also understand the nuclear physics that makes neutrinos, then we should be able to calculate with fair accuracy how many solar neutrinos we should receive in a given area - such as my eyeball - in a given unit of time, such as a second. Experimental confirmation of the calculation is much more difficult. Since neutrinos pass directly through the Earth, we cannot catch a given one. But for a vast number of neutrinos, a small fraction will interact with matter and in the appropriate circumstances might be detected. Neutrinos can on rare occasion convert chlorine atoms into argon atoms, with the same total number of protons and neutrons. To detect the predicted solar neutrino flux, you need an immense amount of chlorine, so American physicists have poured a huge quantity of cleaning fluid into the Homestake Mine in Lead, South Dakota. The chlorine is microchemically swept for the newly produced argon. The more argon found, the more neutrinos inferred. These experiments imply that the Sun is dimmer in neutrinos than the calculations predict.

There is a real and unsolved mystery here. The low solar neutrino flux probably does not put our view of stellar nucleosynthesis in jeopardy, but it surely means something important. Proposed explanations range from the hypothesis that neutrinos fall to pieces during their passage between the Sun and the Earth to the idea that the nuclear fires in the solar interior are temporarily banked, sunlight being generated in our time partly by slow gravitational contraction. But neutrino astronomy is very new. For the moment we stand amazed at having created a tool that can peer directly into the blazing heart of the Sun. As the sensitivity of the neutrino telescope improves, it may become possible to probe nuclear fusion in the deep interiors of the nearby stars.

But hydrogen fusion cannot continue forever: in the Sun or any other star, there is only so much hydrogen fuel in its hot interior. The fate of a star, the end of its life cycle, depends very much on its initial mass. If, after whatever matter it has lost to space, a star retains two or three times the mass of the Sun, it ends its life cycle in a startlingly different mode than the Sun. But the Sun's fate is spectacular enough. When the central hydrogen has all reacted to form helium, five or six billion years from now, the zone of hydrogen fusion will slowly migrate outward, an expanding shell of thermonuclear reactions, until it reaches the place where the temperatures are less than about ten million degrees. Then hydrogen fusion will shut itself off. Meanwhile the self-gravity of the Sun will force a renewed contraction of its helium-rich core and a further increase in its interior temperatures and pressures. The helium nuclei will be jammed together still more tightly, so much so that they begin to stick together, the hooks of their short-range nuclear forces becoming engaged despite the mutual electrical repulsion. The ash will become fuel, and the Sun will be triggered into a second round of fusion reactions.

This process will generate the elements carbon and oxygen and provide additional energy for the Sun to continue shining for a limited time. A star is a phoenix, destined to rise for a time from its own ashes.* Under the combined influence of hydrogen fusion in a thin shell far from the solar interior and the high temperature helium fusion in the core, the Sun will undergo a major change: its exterior will expand and cool. The Sun will become a red giant star, its visible surface so far from its interior that the gravity at its surface grows feeble, its atmosphere expanding into space in a kind of stellar gale. When the Sun, ruddy and bloated, becomes a red giant, it will envelop and devour the planets Mercury and Venus - and probably the Earth as well. The inner solar system will then reside within the Sun.

Billions of years from now, there will be a last perfect day on Earth. Thereafter the Sun will slowly become red and distended, presiding over an Earth sweltering even at the poles. The Arctic and Antarctic icecaps will melt, flooding the coasts of the world. The high oceanic temperatures will release more water vapor into the air, increasing cloudiness, shielding the Earth from sunlight and delaying the end a little. But solar evolution is inexorable. Eventually the oceans will boil, the atmosphere will evaporate away to space and a catastrophe of the most immense proportions imaginable will overtake our planet.* In the meantime, human beings will almost certainly have evolved into something quite different. Perhaps our descendants will be able to control or moderate stellar evolution. Or perhaps they will merely pick up and leave for Mars or Europa or Titan or, at last, as Robert Goddard envisioned, seek out an uninhabited planet in some young and promising planetary system.

The Sun's stellar ash can be reused for fuel only up to a point. Eventually the time will come when the solar interior is all carbon and oxygen, when at the prevailing temperatures and pressures no further nuclear reactions can occur. After the central helium is almost all used up, the interior of the Sun will continue its postponed collapse, the temperatures will rise again, triggering a last round of nuclear reactions and expanding the solar atmosphere a little. In its death throes, the Sun will slowly pulsate, expanding and contracting once every few millennia, eventually spewing its atmosphere into space in one or more concentric shells of gas. The hot exposed solar interior will flood the shell with ultraviolet light, inducing a lovely red and blue fluorescence extending beyond the orbit of Pluto. Perhaps half the mass of the Sun will be lost in this way. The solar system will then be filled with an eerie radiance, the ghost of the Sun, outward bound.

Atoms synthesized in the interiors of stars are commonly returned to the interstellar gas. Red giants find their outer atmospheres blowing away into space; planetary nebulae are the final stages of Sunlike stars blowing their tops. Supernovae violently eject much of their stellar mass into space. The atoms returned are, naturally, those most readily made in the thermonuclear reactions in stellar interiors: Hydrogen fuses into helium, helium into carbon, carbon into oxygen and thereafter, in massive stars, by the successive addition of further helium nuclei, neon, magnesium, silicon, sulfur, and so on are built additions by stages, two protons and two neutrons per stage, all the way to iron. Direct fusion of silicon also generates iron, a pair of silicon atoms, each with twenty-eight protons and neutrons, joining, at a temperature of billions of degrees, to make an atom of iron with fifty-six protons and neutrons.

These are all familiar chemical elements. We recognize their names. Such stellar nuclear reactions do not readily generate erbium, hafnium, dysprosium, praseodymium or yttrium, but rather the elements we know in everyday life, elements returned to the interstellar gas, where they are swept up in a subsequent generation of cloud collapse and star and planet formation. All the elements of the Earth except hydrogen and some helium have been cooked by a kind of stellar alchemy billions of years ago in stars, some of which are today inconspicuous white dwarfs on the other side of the Milky Way Galaxy. The nitrogen in our DNA, the calcium in our teeth, the iron in our blood, the carbon in our apple pies were made in the interiors of collapsing stars. We are made of starstuff.