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1.

THE UNFINISHED REVOLUTION

There are infinite worlds both like and unlike this world of ours. . . . [W]e must believe that in all other worlds there are living creatures and plants and other things we see in this world.

—**Epicurus** (341–270 B.C.E.), letter to Herodotus

The young scholar clutches the book to his chest as he works his way through the crowd. Campo dei Fiori is packed; it's a jubilee year, and Rome teems with pilgrims, beggars, and pickpockets. He edges forward, brushing aside the vendors who tug at his sleeve. Days earlier, a small item in a local broadsheet caught his eye. A Dominican monk from Nola was to be put to death, having exhausted the patience and goodwill of the authorities. The scholar sighs. His heart is heavy at the prospect. It is not yet a century since the death of Leonardo, but enlightenment has dimmed so much that it seems like eons.

With difficulty, the scholar climbs scaffolding behind a merchant stall so he can see over the heads of the mob. Yelling at the far side of the square tells him that Bruno has arrived, having been paraded naked through the streets of Rome. He is bound to the stake with thick rope while a local functionary reads the charges. The scholar can only catch fragments: "impenitent heretic . . . failure to recant . . . persistent follies."

A soldier drives a nail through Bruno's tongue and into his jaw to stop him from speaking. As a token of mercy, the soldier hangs a bag of gunpowder around his neck to speed the end of his suffering. Bruno shakes his head as the crucifix is offered to him. Shouts fill the air; lit torches are raised and then lowered. The scholar cannot bear to watch; he pushes his way out of the square.

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THE BOOK IN THE HAND of the young scholar was *On the Infinite Universe and Worlds*, written by Giordano Bruno in 1584. Bruno was a mystic and a philosopher. He had no formal training in science, and he never made astronomical observations. Yet his vision of the universe was strikingly modern and, for its time, dangerously bold.

Bruno was condemned for heresy—violation of the teachings of the Catholic Church. He wasn't put to death specifically for his astronomical ideas, but they were audacious. Decades before Galileo turned his simple telescope to the stars, Bruno was dreaming of other worlds. He thought it ludicrous that the Earth should be the center of the universe. The stars, he imagined, were huge balls of glowing gas just like the Sun, appearing faint only because they were so far away. He speculated that those stars would also have planets orbiting them. With a multitude of planets flung through space, surely there were some that hosted living creatures.

Bruno could only imagine, but we're on the verge of being able to know. You're about to read a survey of the frontiers of astrobiology: the study of the origin, nature, and evolution of life on Earth and beyond. In the past twenty years, we've pieced together important aspects of the origins of life on Earth and discovered a dizzying array of microbes. We've sent spacecraft to all of the major planets and moons in the Solar System. We've discovered more than a thousand planets orbiting other stars. So far, we know of life on only one planet: Earth. But we live in a time of tumultuous scientific and technological change. If we find that terrestrial biology is not unique—that this is a living cosmos—it will be a discovery as profound as any in human history.

This book is framed by three questions. Each begins by looking inward but then turns outward to ask about our place in the universe. *Is the Earth special?* Astrobiology turns this into the question, How many habitable worlds are there? *Is life special?* In astrobiology, this becomes, Is biology unique to the Earth? *Are we alone?* That last question may be the most profound, and astrobiology frames it this way: Are there any intelligent, communicable civilizations out there? In this chapter, we'll see that these questions were considered by the first scientists over two millennia ago, and we'll see how the science of astrobiology emerged.

THE AUDACITY OF THE GREEKS

The journey that brings us to this point began 2,500 years ago on the coast of Asia Minor. For thousands of years, large and complex civilizations had existed in Egypt and Mesopotamia without developing the means to investigate what lay beyond the edge of the sky. When later scholars decoded the artifacts from these civilizations, they found mostly long lists of land and property: the bureaucratic baggage of everyday living. They left us no theories of the universe. The Greeks were different. As members of a small maritime culture, they lived by trade and their wits. They were open to ideas and to new ways of looking at the natural world.

THINKING DEEPLY ABOUT NATURE

In the age before science, people had no mental constructs for interpreting nature, so they generally accepted the world as they found it. A rock was a rock, a flower was a flower, and a star was a star. Each had its own immutable nature. Humans were clearly special, the preeminent inhabitants of the world. The dawn of science meant that simple acceptance could give way to inquiry. Science accepts the challenge of looking below the surface for deeper meanings. Its goal is to answer the question of why things are the way they are.

Starting in the sixth century B.C.E., a series of philosophers made bold speculations about the natural world. Thales supposed that the source of the universe was water, the substance from which all materials emerged. His student Anaximander extended this idea, but in his version the primal element was an infinite substance called *apeiron.* Since everything formed from one material and would return to it, constant recycling allowed for the possibility that other worlds might have existed at other times.

Meanwhile, Pythagoras and his followers were experimenting with numbers and inventing the foundations of geometry. Pythagoras saw mathematics as a powerful tool to understand music—harmony resulted from the ratio of lengths of a plucked string or of air columns in an open flute. He extended this idea of mathematical perfection to the heavens. The Sun, Moon, planets, and stars were carried overhead on crystalline spheres, and an enlightened person might even be able to hear their "harmony." Pythagoras knew that the Moon shone by reflected light, and its phases could be explained only if it was a sphere. The arcing motions of the stars overhead, and the fact that new stars appeared as one traveled south, meant that the Earth, too, was a sphere. We can understand why Plato inscribed "Let Only Geometers Enter Here" above the entrance when he founded the world's first university in an olive grove outside Athens.[1]

FROM ATOMS TO WORLDS

Another Greek idea with profound implications was atomism. Initially proposed by Leucippus, the idea was developed more fully by his student Democritus. Suppose you cut a stone in half with a sharp knife, then in half and in half again. Eventually, it'll be reduced to a grain of sand and then become too small to see or too small to cut. Democritus found it implausible that this process could continue infinitely, so he proposed tiny, indivisible units of matter called atoms. It's a moniker that survives today: everything is made of atoms, and the atoms are in constant motion. All the familiar aspects of matter—color, smell, taste, texture—are secondary properties of collections of atoms; the atoms themselves have none of these attributes.[2]

Atomism gave new impetus to speculations about life beyond Earth. In the theory, everything on Earth and in the heavens was made of indivisible atoms, and there were an enormous number of them. The Greek idea of elements was rudimentary; there were only four: earth, air, fire, and water. Anaxagoras thought celestial bodies were made of the same elements as the Earth and suggested that the Sun was a flaming rock as large as Greece. This was brave indeed, to suggest that the world was not unique.

Democritus went even further, speculating that the Moon had mountains and valleys and that the Milky Way was an aggregation of stars. He postulated space as infinite and occupied by atoms with pure void in between. This is strikingly close to modern cosmological views. He had no trouble imagining the variety of worlds that an infinite number of atoms might provide: "On some worlds there is no Sun and Moon, others are larger than our world, in some places they are more numerous. . . . There are some worlds devoid of living creatures or plants or even moisture." Democritus was known as the laughing philosopher, content to think about puzzles of matter and space. He said, "I would rather discover a single cause than become king of the Persians."[3]

This is the birth of the "many worlds" concept, which holds that the Earth isn't special. It sits in opposition to the geocentric view. The Earth is just one world among many—perhaps an infinite number—scattered through space. And if the Earth is littered with diverse forms of life, why should other worlds be barren?

Radical ideas are risky—or, rather, the act of questioning everything is radical because it threatens the social order, as Socrates had found out. Pythagoras and his followers were hounded from the Greek mainland for operating a cult with mathematics as its secret language, and Anaxagoras was banished for impiety in daring to suggest that the Sun was as large as a country. Hypatia the geometer engaged in political intrigue and was torn apart by a mob in Alexandria. It would be recasting history to present Giordano Bruno as an archetype of science in conflict with religion; his writings had no coherent explanatory framework. But he collided with authority over ideas that are uncontroversial today and paid the ultimate price.

THE MAN WHO DISPLACED THE EARTH

Viewed through the mists of time, the Greek philosophers are enigmatic. We know very little about the man who anticipated Copernicus by nearly two millennia. Aristarchus lived on the rugged island of Samos, a wealthy city-state that had been run by the tyrant Polykrates during the time of Pythagoras. Aristarchus wrote many commentaries on mathematics and natural philosophy, but only one survives. He was one of the strange breed of men who thought deeply about the heavens—like the earlier philosopher who fell into a ditch and was mocked by a servant girl because he cared more about the things above his head than he did about the things under his feet.

Aristarchus was the first philosopher we know of to make actual observations. Presuming only that the Moon shone with reflected light from the Sun, he used the curved shadow of the Earth during a lunar eclipse to measure the relative sizes of the Moon and Earth. He then used timing of lunar phases to argue that the Sun was much farther away from us than the Moon. Combining the observations, he showed that the Sun was much larger than Earth (Fig. 1).

To Aristarchus, the idea that the larger Sun could orbit the smaller Earth was as nonsensical as a hammer thrower spinning a hammer that exceeded his weight. He proposed a Sun-centered, or heliocentric, cosmology, which was a radical idea at a time when to most people the Earth *was* the universe. But Aristarchus still had to explain why the stars did not change their relative positions or apparent brightness as the Earth moved in its orbit. He guessed correctly that the stars were so far away that these effects were too small to detect. His universe was one billion miles across, a phenomenal number in an age when most people never ventured far from where they were born.

This glimpse into the true nature of the Solar System was a cul-de-sac; the tradition established by Plato and Aristotle was to define astronomical thought for two more millennia. Aristotle dismissed the notion that the stars moved

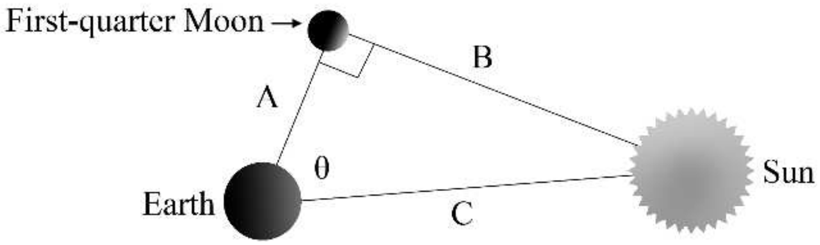

Figure 1. Aristarchus knew that the Moon was illuminated by the Sun's reflected light. By imagining the geometry of a quarter Moon, he realized he could use the triangle to calculate the relative size of the Sun and the Moon. He also used the fact that the Sun and Moon appear to be the same size during an eclipse. Note: object sizes and distances are not to scale.

overhead because the Earth was spinning. If that was true, he argued, we should be moving at nearly one thousand miles per hour—a speed we would certainly feel. He dismissed the heliocentric model. If the Earth was moving around the Sun, Aristotle reasoned, the stars should alter their alignment and apparent brightness over the course of a year, just as we know that nearby objects appear to move against a distant backdrop when we look out of a car window. This phenomenon is called parallax. Aristotle's universe was a cozy million miles across, and its outermost crystalline sphere shut out any thought of distant worlds.

Aristotle also argued against atomism because he believed that each element had its own natural tendencies of motion. Earth and water moved naturally to the center of the universe—the center of the Earth. In our world (in Aristotle's mind it was The World), everything was composed of earth, air, fire, and water. The celestial realm was made of utterly different material, an ethereal substance called quintessence.

Greek thinking ran far ahead of Greek technology. They simply didn't have the tools to test their hypotheses. However, their early instinct that the universe had an underlying unity described by mathematics has proved to be uncannily accurate.[4]

The brilliant mathematician Archimedes even used the Aristarchan Sun-centered model to estimate the amount of matter in the universe. His work *The Sand Reckoner* is a remarkable work designed to impress his sponsor, King Gelon II, with his mathematical prowess. In it, he estimates that the universe is several trillion miles across and calculates that it would take a staggering 10^{64} grains of sand to fill it. If we imagine that these grains are clumped into planets and spread over the much larger volume of the modern universe, we can calculate the number of Earths it would contain: 10^{33}, a billion trillion trillion.

WITNESSING THE BIRTH OF SCIENCE

The scene is Asia Minor. The year is 584 B.C.E. We can imagine the scene as two Greek tribes are hacking away at each other with clubs and swords on a rocky plain near the shore. It's near noon, but the air chills, and the sky darkens. Dazed and confused, the warriors drop their weapons and wander from the battlefield. History veers slightly in its course. A hundred miles away, according to Herodotus, Thales has used knowledge of astronomy to predict this event.[5] He knows that solar eclipses are part of the rhythm of the heavens and not omens from vengeful gods. It's a pivotal moment in history—the first recorded time that humans use sheer intellect to make sense of the cosmos.

Consider this for a moment. At the end of the classical Greek era, most people traveled no more than a total of fifty miles in the course of their lifetimes, yet the average educated person knew that the Earth was round and twenty-five thousand miles in circumference. They had no atom smashers or telescopes, yet they suspected that matter was made of invisibly small atoms and that the universe was millions of times larger than the Earth. While most people saw the objects of the night sky as mysterious and supernatural, the Greeks knew they were subject to rational inquiry. Armed only with logic and rudimentary math, they gave birth to science.

A brave few even ventured the questions that form the heart of astrobiology. They imagined there were many other worlds in space and that life wouldn't be confined to our realm. At the end of the Greek era, Lucian of Samosta even asked the third question: are we alone? His work *True Histories* is a precursor of modern science fiction, extremely speculative but written in the style of a travelogue or a historical narrative. He wrote of trips to the Moon and interstellar warfare. Everything about his work was designed to make the reader think "what if . . . ?"

HOW WE KNOW WHAT WE KNOW

The study of astrobiology takes us to the edge of knowledge. Understanding the range of diverse conditions under which life can exist on Earth takes us to the limit of exploration of our own planet. Exploring the Solar System for life takes us to the limit of space technology. Looking for life on planets around other stars takes us to the limit of the telescope. Conjecture can fill the sails, but observations are the ballast that keeps the ship of science on course. To critically examine astrobiology, we first must answer the question, How do we know what we know?

Scientists aren't prone to introspection about what they do; they just get on with it. But scientists in all fields use the same method to create knowledge. This method is the source of all technological innovation—just try to imagine the world without air travel or medicine or electronics.

The scientific method centers on evidence. Evidence separates the factual from the fanciful. It's the reason scientists think there may have been life on Mars but don't think UFOs are alien visitors. It's the reason they think the dinosaurs died sixty-five million years ago even though nobody was there to witness the event. It's the reason they believe that stars in distant galaxies are made of the same stuff as the Sun. Painstakingly gathered evidence is fashioned into nuggets of knowledge, which form the bedrock on which scientists build castles of theory and speculation. Science is exciting because we don't know where it will end or how far it can take us.

WE ARE ALL SCIENTISTS

Everyone is naturally born a scientist. Babies are endlessly curious; their freshly minted senses eagerly absorb every aspect of the surrounding world. The plasticity of their brains enables them to forge new connections every day. At some point in the first six months, a baby learns the power of abstraction. Before that, when an object is held in front of its gaze and then removed, it's lost from the world: out of sight, out of mind. But at some stage, the baby can hold the idea of a toy or a doll even when it's removed from plain view. The ability to use an idea as a placeholder for something concrete is the basis of mathematics.

Science begins with the recognition of patterns in nature. We can use playing cards as an analogy of this process. Looking at Figure 2, you'll see four sequences of numbered cards. The first pattern is trivial: a simple pattern of increasing numbers. The second shows no obvious numerical pattern, but

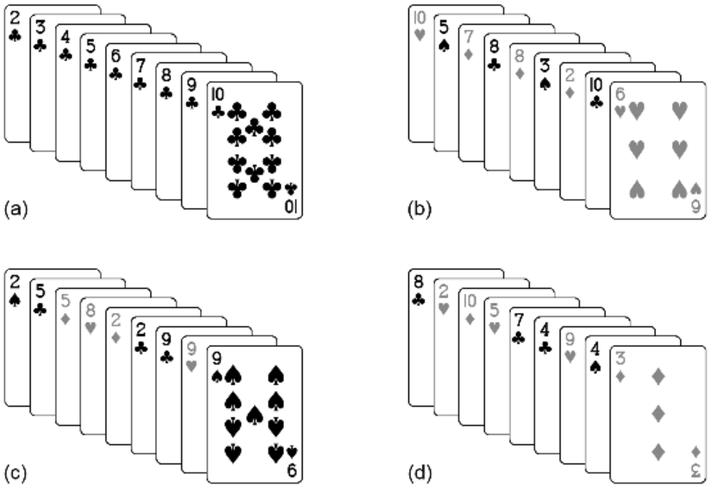

Figure 2. Card sequences as an analogy for the discovery of patterns in nature. Sequence (a) is trivial, while sequence (b) is simple only when you realize what color is associated with each suit and that card value is irrelevant. In (c), each successive card matches either the color or the value of the card before it. In (d), even-numbered cards are followed by any red card, while odd-numbered cards are followed by any black card. This black-and-white image removes an important visual cue to the suit and shows how important the hidden or "coded" information of color is in the analysis.

once you recall that hearts and diamonds are red while spades and clubs are black, it can easily be identified as alternating red and black cards. What about the third and fourth examples? Without reading the caption, can you think of a simple rule that describes how the cards have been laid down?

In nature, a pattern is rarely as simple as a numbered sequence. It can be very complex, like the three billion base pairs in the human genome, or imperfect, like layers of rock that have been jumbled by geological activity. Our innate drive to recognize patterns is so strong that we sometimes see patterns that aren't there. If you shuffle a deck of cards and lay out sequences as shown in the image, you might find a few where you could come up with a rule that explains them. Is this evidence of a deeper meaning or pure delusion? On the plains of Africa hundreds of thousands of years ago, there was adaptive advantage to our skill at recognizing patterns. If you saw a leopard hiding in the dappled grass of the savannah when none was really there, you would be spooked; if you missed the leopard, you'd be lunch!

FROM PATTERNS TO UNDERSTANDING

The card analogy demonstrates other aspects of the scientific method. In the top right panel of Figure 2, the pattern is determined by color. If we had no sense of color or inferred by number instead, we'd see no pattern. The senses through which we absorb information are important, because they're intimately tied to cognition. And not all the information is equally relevant; in this case, color is more important than number. At a first glance, the two lower panels appear inscrutable. Yet the rule that describes each sequence can be simply stated. Are these the only rules? There's often more than one hypothesis that describes the data, which is one reason scientists can disagree.

We also see why science is such a data-hungry enterprise. The sequence on the top left can be recognized after only three or four cards. It takes more cards to identify and confirm the alternating color pattern on the top right, mostly to be sure card number is irrelevant. But decoding the lower two sequences requires even more data, because the patterns aren't as obvious. Scientists are always pressing for more experiments and better observations because the patterns in nature are so subtle and profound.

However, pattern recognition does not imply understanding. It's merely a first step. Our ancestors observed seasons and eclipses and planet motions for thousands of years and thought it was a complex shadow play orchestrated around us. They had no way to know that these phenomena acted in a space that dwarfed the Earth.

Imagine a deck of cards with one-third of the cards randomly removed. If you tried to lay the cards out in rows, from ace to king, one row per suit, the gaps would be scattered across the sequence. In 1869, Dmitri Mendeleev used this kind of arrangement of elements to discover the periodic table. He didn't know about the role of electrons in chemistry, but he could see patterns in chemical behavior, and he used the placement of the gaps to predict properties of elements that hadn't yet been discovered.[6]

In another example, the ancient Egyptians resurveyed their rich alluvial delta every year after the Nile flooded, using huge loops of rope knotted at intervals. This let them lay out the land with right-angled triangles. Although they knew sets of numbers that had this useful property, like 3, 4, and 5 ($3^2 + 4^2 = 5^2$) and 5, 12, and 13 ($5^2 + 12^2 = 13^2$), it took Pythagoras to figure out the general case that applies for any right-angled triangle. His equation gave him an algebraic "net" where the Egyptians had just caught a few fish. He was sufficiently impressed by his aha moment that he sacrificed one hundred oxen to the gods, and as we all know from the Scarecrow's rapturous recapitulation in *The Wizard of Oz*, the Pythagorean theorem is the definition of braininess.

THE TOOLKIT OF SCIENCE

The foundation of the scientific method was invented by Greek philosophers. Modern scientists inherited two ways of looking at the world. From Plato, we acquired rationalism: the idea that nature can be understood by the power of thought alone. Plato disdained observation, as he considered senses to be flawed. This thread continues today in the almost mystical power of mathematics to describe the natural world. Aristotle, Plato's student, was by contrast an empiricist who thought there could be no real understanding without observation. Science today is driven by observations. Assertions must be backed up by evidence that's shared and verified by other scientists. That's why scientists don't believe in ghosts and psychic powers and other ideas that have continuing traction in the popular culture.

On the other hand, data alone are mute to meaning. Scientists are known for being fanatical counters and classifiers—obsessive to the point of being slightly scary. Methods like these are essential to progress. But without theories, a rock is just a rock, a flower just a flower, and a star just a star.[7]

When a scientific field is healthy, there's close interplay and sometimes tension between theory and observation. Speculation unconstrained by evidence descends into intellectual exhibitionism, and a pile of data without a conceptual framework in which to interpret it doesn't advance knowledge. Astrobiologists must lean on speculation to an uncomfortable degree. Since we know of only one planet with life, our sample size is small—all biology is based on