PART I

How We Came to Believe the Big Bang Theory

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The First Cosmologies

In the beginning, there was nothing. Well, not quite nothing—more of a Nothing with Potential. A nothingness in which packets of energy fleeted in and out of existence, popping into oblivion as quickly as they appeared. One of these fluctuations had just enough energy to take off. It inflated wildly out of control—one moment infinitesimally small, moments later light-years across. All of space and time was created in that instant, and as that energy slowed, it cooled and froze into matter—protons and neutrons and photons. This baby universe kept expanding, over billions of years, and those particles coalesced into stars and planets and eventually humans.

And that's how the universe came to be.

Or at least that's the modern version. Descriptions of how the cosmos was born, from the dramatic to the lyrical, have proliferated throughout human history. Take the Enuma Elish, the creation myth recited in about 4000 B.C.E. on the fourth day of each new year by the Babylonians as they lay prostrate before a statue of their great god Marduk.

The epic begins:

When heaven was not named,
and the earth beneath did not bear a name
nor the primeval Apsu,
who begat them,
nor Tiamet, the mother of them.

Their waters, sweet and bitter,
mingled together.
And no field was formed,
no marsh was to be seen.
When none of the gods
had been called into being,
And none bore a name,
and no destinies were ordained.
Then in the midst of the waters,
gods were created.

Lahmu and Lahamu,
were called into being.

The non-Babylonians among us may need help understanding who these divine beings are. Apsu is the sweet river water; Tiamat, the salty ocean. They come together—just the way the Babylonians would have watched a river delta hit the sea—and they create the first gods: Lahmu and Lahamu represent silt and muddy slime, the earth itself.

A child hearing these two stories for the first time would have no way of choosing which one was correct. As stories, one simply chooses the prettier version—and most would probably want to go with the poetry. But there is a dramatic difference between the two: the big bang description is more than just a fable. Science prides itself on providing physically accurate descriptions of the observable universe; it seeks literal truths about what *really* happened. The methods of religion and science are vastly different.

So how does science decide on just one theory, the accurate one, the *true* one?

The way many people like to imagine the process is that everyone keeps an admirably open mind and changes his or her beliefs when enough contradictory proof collapses an old theory. Science is cumulative, they think, refining theories over time, always getting closer and closer to the "truth."

Thomas Kuhn explained the process a very different way. A historian of science who taught at Harvard, Kuhn advanced the notion of the "paradigm shift." He said that scientists worked within the confines of their theories long after there was enough factual proof to disprove them. A new theory was embraced only when someone finally overturned the whole shebang completely, as thoroughly as upsetting a dinner table of dishes and silverware to the floor. A new theory would arise in place of the old one, with a whole new language and set of assumptions to go with it. We believed new theories not because of the preponderance of evidence, but because they "made sense" to us, much the way a creation myth might.

And then there is a third view, bluntly expressed by Max Planck, who simply said that scientific theories don't change because scientists change their minds; they change because old scientists die.

Like most philosophical truths, the answer is probably some combination of all of the above. The story of how the big bang theory became accepted certainly contains a bit of each. There are geniuses who scoffed at all previous theories and devised brand-new, innovative solutions; and there are those who refused to reject their preconceived notions no matter how overwhelming the evidence. There are people who accepted cosmology theories based on the experiments only; and there are those who simply believed them with the same faith they might bring to a religion. There are those today who say they believe the big bang model because all the experiments support it; and there are those who say there are enough holes that we shouldn't believe it just yet.

The story of how the big bang theory was accepted incorporates all these scientific styles, and it begins in ancient Greece.

EARLY BELIEFS

Imagine looking at the sky for the first time—as if you knew nothing about its workings. Every day you'd see the sun rise and then set as the moon rose up to replace it. By and large you'd think they were similar bodies, both traveling around the globe in exactly the same way.

At first, all those other bright stars in the night sky would seem to be entirely different. They could be as small as fireflies hovering just a mile or so up in the air for all you knew. The fact that the moon passes in front of them in her nightly journey will tell you they're at least farther away than the moon, but that's about all. In time you'd see the night sky move around the earth, too, all the stars moving in unison, and assume it was some two-dimensional backdrop twirling around a fixed earth at the center.

Eventually you'd notice that six of those stars didn't move in sync with the others. Each has its own erratic path. Each moves across the sky in one direction until suddenly it slows down, stops completely, and begins moving in the opposite direction for a while before finally resuming its course. Sometimes these six would even get larger, as if they were coming closer. You'd know these were different somehow, and your first guess might be that they were like the sun, just much, much farther away, circling the earth as the sun does.

And that would be about as far as you'd get. You could record daily movements of these wandering planets (the very word "planet" means "wanderer" in Greek), but your predictions about why they moved and how they were created would be based only on what you saw with the naked eye—and would be highly inaccurate.

Sure, you might realize that the sun moving around the earth would make the sky look just the same as if the earth twirled on its own axis, but relying on nothing more than your unaided vision, you really couldn't prove anything one way or the other. And the idea of the world twirling wouldn't make too much sense, because wouldn't you expect to feel the wind rushing past?

It's into this world, with just this much knowledge and this much observation, that the Greek philosophers arrived. They could map the night sky, they could predict eclipses, they could geometer their way into beautiful drawings of planetary motions, and they used all of this to devise theories about the universe, but they didn't have the tools to prove any of it.

The Greek philosophers didn't rely on experiments the way modern scientists do, but they took a giant step in that direction by rejecting religious explanations and denying that gods caused daily phenomena. Lightning bolts weren't hurled to the ground by the angry arm of Zeus, but born of natural processes, processes that could be rationally explained. Lucretius, for example, writing in the first century B.C.E., said: "Nature is free and uncontrolled by proud masters and runs the universe by herself without the aid of gods. For who—by the sacred hearts of the gods who pass their unruffled lives, their placid aeon, in calm and peace!—who can rule the sum total of the measureless?"[1]

Notice how just as Lucretius denies divine intervention he invokes the existence of gods. He's our very first example of someone who embraced a new theory yet couldn't quite let go of what he'd been taught all his life. His whole philosophy was based on the idea that nature—made of little atoms—ran independently of the divine. But jettisoning the gods altogether? That would be going too far.

The Greek philosophers came up with numerous versions of how the universe worked. (A personal favorite: Anaximander's proposal that we live inside a huge sphere with fire along the outside rim—the sun is nothing but a hole in the sphere through which we can see the fire.) But one model truly captured the imagination of the Western world well into the 1600s. This was the version described by Aristotle; his would be the unquestioned assumptions that philosophers and scientists embraced for centuries. And Aristotle got the assumptions from his teacher Plato.

ARISTOTLE AND PLATO

Plato lived in tumultuous times. Born in 427 B.C.E., he grew up during the Peloponnesian War and learned his philosophy in the marketplace where Socrates preached to the young men, telling them to question the morals they'd been taught. The community elders—who'd done all that moral teaching—weren't pleased, and Socrates was soon tried and sentenced to death.

Perhaps it was his friend's death and the chaos of a war-torn nation that led Plato to seek solid truths to put order and calm into his world. Plato lived in the world of ideals. The physical world, he claimed, was merely a facsimile of the perfection created in some divine mind. Plato referred to this divinity as the *Demiurge*. We, too, could experience true reality only in our own minds: a circle can only be perfect in our thoughts, after all—draw one and it's invariably slightly off-kilter.

Plato's universe depended on these "perfections." He picked five ideal shapes and claimed that the "elements" matched them: fire was a tetrahedron (a three-sided pyramid), the sharp sides of which could cut the connection between other elements; earth was a solid cube; air, an octahedron (a solid with eight sides that look like pentagons); and water was a slippery twenty-sided icosahedron (each side is an equilateral triangle). The planets, he believed, must travel in circles with uniform motion.

No matter that there was no proof of any of this, or even that the planets zigzagged across the sky in a way that looked distinctly noncircular. Because it was a beautiful theory, Plato believed it must be true. Those who thought they could understand the stars by, gasp, *observation* were as empty-headed as birds, as he wrote in his *Timaeus:* "But the race of birds was created out of innocent light-minded men, who, although their minds were directed toward heaven, imagined, in their simplicity, that the clearest demonstration of the things above was to be obtained by sight."

Plato's blindness did not, therefore, come from an inability to see but from his disdain for what he saw. He chose to ignore what he observed. He created a theory of the universe with everything moving in these perfect circles—even though it certainly doesn't look like this from earth as the planets wander backward and forward through the night sky—and then asked others to produce a mathematical model that would fit it.*

Yes, those planets obviously traveled back and forth through the sky, so how do you create a universe run only by perfect solids and circles? Eudoxus, born in Sparta in 408 B.C.E., and one of Plato's pupils, rose to the challenge. To "save the appearances," Eudoxus described a set of planets sitting on a series of moving spheres with the earth at their center. The sun, for example, had three spheres: one to move around the earth daily; another, slower sphere, which on an annual basis moved to account for the way the sun appears to move higher in the sky throughout the seasons; and a third sphere to explain some incorrect observations of the

*At least this is so according to Simplicius, who commented on Plato in the sixth century C.E. And in fact he is commenting on a commentary on a commentary of Eudoxus's report about Plato's teachings, so as with much of what we know about the ancient Greek philosophers, we get our information at the tail end of one big game of "telephone."

time that had the sun changing position on the horizon from equinox to equinox. Eudoxus described each planet this way, adding on spheres moving at different speeds and in different directions, until there were twenty-seven spheres in total.

The model was totally wrong, of course, but the concept itself was mind-boggling. For the first time, someone hammered out a mathematical model correlated to what he saw. Eudoxus didn't think it was a description of what was actually happening in the heavens, and his model didn't perfectly fit the data, but you could use it to predict where a planet should be with reasonable accuracy. Math corresponded to reality.

Math corresponding to reality is seductive. It makes you believe the model is correct. In fact, using a theory to successfully predict an outcome in the physical world is exactly the kind of thing that gives modern-day scientists confidence in their models. If a theory doesn't fit reality, that's easy—you discount it immediately. The theory is wrong, and it's time to move on. When a theory fits the data, however, one doesn't quite know what to think. Sure, there's a chance it's right, but what about Eudoxus's rings, a theory we now know to be hogwash? Scientists must always remember how false theories have been emphatically believed in the past. This one, with the help of Aristotle, would be believed for centuries as insistently as we believe today that the earth goes around the sun—all because it by and large fit the data.

Aristotle added a twist to Eudoxus's model: he turned those ephemeral spheres into something solid. If the math worked, why couldn't it be a valid physical description? Aristotle studied under Plato for some twenty years before founding his own academy, but he wasn't as afraid of observation as his mentor was. Perhaps Aristotle's world simply seemed more stable. Aristotle was born in northern Greece in Macedon in 384 B.C.E. His father served as personal physician to the ruler, Amyntas II. Aristotle's life in Athens was largely good, as he was originally tapped to be Plato's successor.

Aristotle eventually stepped far enough away from the master that he wasn't chosen to lead the academy, but Plato's influence over his philosophy would be the rut that kept Aristotle's theories from being accurate. Aristotle inherited Plato's incorrect assumptions: Aristotle trusts so implicitly in the obvious perfection of a sphere that he never bothers to offer detailed proofs, as he does for other ideas, that the planets move in circles. In "On the Heavens" he writes: "The shape of the heaven must be spherical. That is most suitable to its substance, and is the primary shape in nature." So there.

The spheres in Aristotle's cosmology stemmed from Eudoxus's, but they needed some jury-rigging to become a physical reality. Aristotle devised a system whereby each sphere forced the spheres inside to rotate with it. Consequently he had to add spheres not only to account for the oddities of each planet's rotation but also to negate movement from the sphere above it. In the end his version had fifty-six spheres and roughly accounted for most celestial movements. It failed to explain a couple of crucial points, however, including why the planets periodically shone brighter and larger, as if they had swung closer.

But these shortcomings didn't derail it. Aristotle's description of the universe caught the imagination of mankind in a way that no previous system did. Christians in the Middle Ages would take it as a perfect model of a God-governed cosmos, since Aristotle's universe included an outermost sphere, which they thought was "heaven."

The way it works is this: Everything on earth is made of the four elements, earth, air, fire, and water. All these elements seek to be at rest in their "natural" state. Earth and water seek rest by moving in straight lines "down" (toward the center of the earth), while fire and air naturally move in straight lines "up." A rock that moves horizontally—say, by being thrown through the air—does this only because an outer body has forced "unnatural motion" upon it.

At the beginning of time all the earth and water naturally fell down toward the center of the universe, clumped together, and formed the spherical globe on which we live. This automatically proved there were no other universes out there, because that would imply two conflicting "downs"—an absurdity to Aristotle. (Today we know there are billions of "downs" in the universe. "Down" is always in the direction of the greatest gravity nearby. For us it's earth, but it could be the moon or the sun or a black hole.)

Once you made it out of our atmosphere, however, everything changed. Starting with the moon, the universe was made of a heavenly material known as "ether." While everything on earth moves in straight lines, ether naturally moves in circles—divine things simply must move in the "perfect" shape, after all. There were spheres for the moon, the sun, the planets on out to the stars, and then beyond that was an Unmoved Mover—the divine force that moved the outer sphere that set each of the next fifty-five moving. Interestingly, Aristotle created this complicated mathematical model of moving spheres, and yet at times he writes that each planet is moved by an individual divinity (medieval Christians would later update these creatures to angels). While Aristotle created a cosmology that doesn't *require* divine intervention, he nevertheless insists upon it. He couldn't escape an ingrained belief that even a rational universe was a place filled with gods and hallowed beings far more powerful than mankind. This was a lovely model for the early Christian world to hold on to, and religion and cosmology would remain intricately entwined for the next thirteen centuries.

While Aristotle's cosmology became dogma, one other ancient gets credit for giving the theory the grounding needed to make it so stable. Aristotle's spheres still didn't correspond well to everything observed; hammering out a mechanical model took a true mathematician: Ptolemy.

Klaudios Ptolemaios lived in the second century C.E. and created the most comprehensive model of the planets to date. Ptolemy knew that as the planets moved around the earth they appeared to stop and go backward for a while. (We now refer to this apparent jog in a planet's travels as a "retrograde"—the planet does not, in fact, ever move backward, it simply looks that way since we watch the planets moving around the sun as we ourselves move around the sun.) To account for this, Ptolemy added a twist to the orbits. He claimed that each planet moved in tight little circles, and it was the very center of *this* circle that moved in a gigantic circular orbit around the earth. This little extra orbit was named an *epicycle.*

Ptolemy's model corresponded quite well with what we see. After all, if you're trying to figure out where the sun is going to be at any given moment, you can do that fairly well whether you assume the sun stays still and the earth spins or that the sun moves around the earth. But an inaccurate model is bound to have some anomalies. The biggest weakness in Ptolemy's model was his complicated description of Mars. Mars, orbiting the sun so close to us, has the hardest path to pin down if you're afflicted with an incorrect theory. Mars just refuses to move in perfect circles. Mars was destined to be the first nail in the coffin for Ptolemy and Aristotle.

INTRODUCING OBSERVATION

Tycho Brahe had a love-hate relationship with his brash young assistant Johannes Kepler. Over the year and a half they worked together, Kepler and Brahe fought, Kepler left in angry fits or Brahe would order him to leave, then one or the other would beg to work together again. For some reason they needed each other. Brahe's observations of the universe were unsurpassed throughout the world. Kepler wanted access to them to devise better descriptions of how the heavens worked. Brahe, in turn, needed Kepler's brilliant math skills to help prove his own theories.

But they rubbed each other the wrong way, and Brahe wanted to keep him occupied and out of his hair. "Describe for me the orbit of Mars," he told Kepler in 1600, knowing full well that all the greats of history had wrestled with the prickly warrior planet and come up short.

"Give me a week," replied Kepler.

Kepler was overconfident. It would take him eight years to hammer out the orbit, but when he did, he turned Ptolemy's model on its head. He described the way the planets move with three laws that are still taught in introductory physics classes around the world.

Brahe and Kepler's names aren't well known outside the world of astronomy, but their contributions to science were as crucial as those of the more famous Copernicus and Galileo. In fact, some historians argue that the vision of a sun-centered cosmos that Copernicus devised in the 1500s wasn't so revolutionary—although Copernicus championed a moving earth, he clung unquestioningly to Aristotelian ideals such as circular motion. He wrote: "It is altogether absurd that a heavenly body should not always move with a uniform velocity in a perfect circle." In fact, Copernicus tried to connect to the ancients by writing his most important treatise, *De Revolutionibus Orbium* (The Revolutions of the Celestial Orbs), which echoed Ptolemy's *Amalgaest,* with each chapter of his book correlating to a chapter in Ptolemy. Moreover, Copernicus cited pre-Aristotelian philosophers such as the Pythagoreans to support his ideas for a sun-centered universe. To overturn Aristotle, he reached back even farther in time—not what one would call really taking a leap into the unknown.

Not to belittle Copernicus—he certainly provided a jump from the status quo. He also used a new concept to choose his theory: simplicity. Or even, one could say, beauty. The austerity of the simple Copernican system gave it an aesthetically appealing quality missing from Ptolemy's rings within rings. In modern times, scientists have almost deified this simplicity concept, known as Occam's Razor. If two theories fit the data, choose the simpler of the two. If you can explain the cosmos with just a few orbits instead of all those epicycles, then stick to the former.

But, alas for Copernicus, his simple ring system of planets orbiting a slightly off-center sun didn't correspond to reality substantially better than Ptolemy's model. Sticky Mars was still out of whack. Copernicus's *De Revolutionibus Orbium* was edited by a man named Rheticus, who, legend has it, became so frustrated with mapping the path of the red planet that he called upon the spirit world to help. A demon appeared, threw him against a couple of walls, and shouted, "*Thus* are the motions of Mars!"

Until someone decided to map the orbit of Mars first and *then* determine the math that described it instead of the other way around, no one was going to produce a complete model of the sky. That was not something Copernicus, firmly enmeshed in the philosophies of his day, was capable of doing. It was Brahe and Kepler, with their willingness to really observe what they were studying, to insist that the observations match their theories, who nudged cosmology a little closer to modern-day "science."

That these two characters—for they were definitely both characters—had the chance to come together and collaborate is almost beyond belief. Brahe was of Danish nobility, Kepler of the German lower class, but together they provided the most accurate depictions of the stars until that time.

Brahe was a nobleman born in 1546, who by family connections was in favor with the Danish king, Frederick, who gave him an entire island in the Danish Sound on which to set up his astronomy lab. Brahe's microcosm, which he named Uraniborg, consisted of a chemical lab, a printing press, a paper mill, a prison, a game preserve, a library, a castle, and, of course, the largest observatory ever seen. Brahe built it all with money from the Danish coffers (30 percent of that year's Danish budget, to be exact—who says NASA isn't a bargain?), and he then lived off the income generated by his tenants and the various factories. Living in high style, Brahe even had a jester dwarf who sat under his chair at dinner and begged for scraps.

But Brahe's love for the stars was genuine. He knew them like the back of his hand—they were as familiar to him as the landscape around our homes is to most of us. So the sudden appearance one day of a bright star where none had been before threw him off the way the sudden appearance of a fifty-foot oak tree in our backyards would affect the rest of us. Ever since Aristotle, everyone had agreed that the heavens did not change. They were immutable, perfect, the way divine things should be. So convinced was everyone of this that when Western astronomers had noticed various comets throughout the centuries, they just assumed the comets were below the moon, the only possible place such change was allowed.

And yet, one night—it was November 11, 1572—Brahe looked up into the sky after dinner and there was a new star, smack in the middle of the constellation Cassiopeia, brighter than all the rest. For the next few weeks it was even visible during the day, slowly fading over the course of the next year and a half until it disappeared.

Brahe had witnessed a supernova—the gigantic explosion that occurs during a star's last death throes. Of course, Brahe didn't know that at the time. All he knew was that he had witnessed the impossible: the perfect, ever-constant, starry sky had just changed. He may not have realized the implications immediately, but by the time he spotted a comet in 1577, Brahe knew what to look for. Making the most precise measurements anyone had ever seen, and presenting them—in an unprecedented move—with all his data and all the possible errors, Brahe showed that the comet was far above the moon. Not just change in the heavens, then, but a body slicing right through Aristotle's crystalline celestial spheres.

With the level of detail presented, Brahe's destruction of the Aristotelian universe was hard to dispute. The celestial spheres had been smashed, never to return. That was one of Brahe's major contributions to cosmology, but his largest may well have been simply his incredible attention to detail. His data were orders of magnitude better than anyone else's. (Remarkably, Brahe never once looked through a telescope—an instrument that arrived in Europe several years after he died.)

The minutiae matter in science. It is the minutiae that disprove a false theory and support a true one. And that is a lesson learned from Tycho Brahe.

But Brahe, like so many before him, was also a slave to his preconceptions. Unable to convince himself that the earth moved, and unable to make his observations match a geocentric universe, Brahe drew a solar system in which the sun and the moon orbited the earth, while all the other planets revolved around the sun.

The glory of Uraniborg didn't last long. In 1597, after a new king had claimed the Danish throne, Brahe ceased to be a royal favorite. He picked up his instruments and left. By 1599 he had taken on a new job: imperial mathemetician to Holy Roman Emperor Rudolph II in modern-day Czechoslovakia. It was here that he met Johannes Kepler.

Whereas Brahe was near-royalty, Kepler grew up in the poor neighborhoods of Weil der Stadt, a town in Germany. Born in 1575, Kepler was cranky, sickly, and dirty (he took exactly one bath in his entire life and claimed it made him ill). He nearly died of smallpox when he was four, and the litany of illnesses continues from there. He was nearsighted, and had multiple vision his whole life. He didn't make many friends and got into fights with his classmates. His father was a mercenary soldier, fighting for the best pay; his mother had nearly been burned as a witch in their hometown, so now she stayed with her husband in the battle camps. Kepler was raised by his grandmother, whom he described in his diary as "restless, clever, and lying, of a fiery nature, an inveterate troublemaker, violent." Kepler always kept meticulous diaries. They are a combination of harsh portraits of the people around him and detailed descriptions of his life and contributions to science. (This makes Kepler one of the few scientists in history for whom we have a description of how he lost his virginity. He was twenty-one and—surprise—it made him sick.)

And from these inauspicious beginnings sprang genius. Young Johannes Kepler was lucky enough to be born at a time when the new Lutheran religion sweeping Europe gave rise to numerous public schools. Kepler received a free education, and he eventually attended a Lutheran university in Tübingen. It was there that he first discovered Copernicus, learning of a sun-centered world from his mentor Michael Mastlin. So it was that Kepler was one of the first astronomers thoroughly indoctrinated in a heliocentric universe—he never doubted that the sun stood still while the earth rotated around it.

After college, Kepler took a job as a math teacher, in which position his ability to win friends and influence people continued at the same abysmal rate. (First day of classes, his second year: Kepler walked into an empty classroom. Not a soul had registered for his class.) While he didn't do much for his students, that classroom did a great deal for Kepler. In the middle of a lecture on geometry, Kepler had what he would later describe as one of the most profound thoughts of his life. It's a thought we now know to have no scientific merit, but to Kepler it was his greatest achievement. And while it isn't valued today, it was the first step that led him to three beautiful equations that describe the whole solar system.

Kepler had long wrestled with the question of *why* there were six planets—not seven, not five.* In a flash—as he stood in front of that class—Kepler thought that the planets themselves might be organized according to the five Platonic "ideal" shapes. First came Mercury's circular orbit. Next, imagine an octahedron (with eight sides) positioned around that circle the way any regular shape can be snugly fit around a sphere. Put another sphere directly around that, and you get the orbit for Venus. Next an icosahedron (twenty sides), the sphere of earth's orbit; then a dodecahedron (twelve sides), Mars; then a pyramid, Jupiter; then a cube; and finally Saturn. This pretty arrangement of geometry now showed *why* each planet's orbit was just so far out and no farther.

*Today, of course, we know there are nine planets (if you include Pluto, which isn't exactly a planet like the others), but in those days six it was.

As it happened, the ratios among the planets didn't perfectly match up to the ratios of the solids, and these days we know that there are more than six planets. We also know that invoking the Platonic solids as a logical "reason" for why there were six doesn't make much sense to begin with. But by and large Kepler's vision of the solar system linked up to what he observed—and that alone was pretty novel for a medieval astronomer.

Perhaps sensing a kindred spirit who understood the value of matching observation to theory, Tycho Brahe invited Kepler to work with him in 1600. Upon studying Brahe's details of the Martian orbit, Kepler realized that the planet did not move at a constant speed. (Aristotle's spheres and unchanging heavens were already discredited; now his theories of uniform motion were under attack.) But that revelation alone wasn't enough to account for Brahe's precise data. It was a struggle that took years, but finally Kepler had to face the facts: Aristotle's perfect circles must go. Kepler showed that the planets moved in egg-shaped ovals, in ellipses.

Not that anyone listened. One who dismissed it outright was Galileo Galilei. He was the only other contemporary scientist who believed that the earth revolved around the sun, but he basically ignored all of Kepler's ideas.

THE FIRST SCIENTIST

Galileo is often credited with being the first scientist, the first experimenter. And it's a valid title—his work with pendulums and gravity and momentum all revolved around experiments. But when it came to the sky, he had his failings. He refused to admit that the close correlation between Kepler's ellipses and observation discounted the theory of circles. Possibly this was mere pride, a way to discredit the only other champion of a sun-centered universe so he could hoard all the glory. After all, if there's one thing we know for sure about Galileo it's that he was extremely sure of himself, even when he was spectacularly wrong. He once wrote, "It was granted to me alone to discover all the new phenomena in the sky and nothing to anybody else. This is the truth which neither malice nor envy can suppress."

While he denied Kepler, Galileo wasn't normally so dismissive of observation. It was observation that made him a legend. At the beginning of the seventeenth century, someone invented the telescope in Holland. No one can quite agree on who it was, but it was Galileo who made the telescope great. Fitting two lenses together on either end of a long tube, Galileo pointed that telescope to the sky and saw farther than anyone had seen before. (He also sold the patent rights to the Venetian government—patent rights to an instrument he didn't invent, but no matter . . . he got himself a nice raise in the bargain.)

While others used the telescope to track the movements of ships or approaching armies, Galileo focused his tubes upward. He saw more stars than had ever been seen. He saw planets—full circles instead of mere sparks of light. He saw rings around Saturn. And, most of all, he saw phases of the planet Venus. Just as the moon appears to cycle from new moon to full because it circles the earth, so Venus appears thinner and wider in the sky as it circles the sun. It was in deciphering this pattern that Galileo saw proof that Copernicus had been right all along.

Unfortunately, the church wasn't so quick to agree. When Copernicus lived, thought, and wrote, the church was actively involved with philosophy and science, allowing and even encouraging new ideas and detailed analyses. But nearly a century later, the pope had suffered an unprecedented attack: heeding the cry of Martin Luther, many Christians had rejected the papacy. Having seen what dissent could do, the Catholic Church became infinitely less tolerant. This sun-centered stuff—directly contradictory to what was said in the Bible—must stop. (It didn't help that in Galileo's book defending heliocentrism, a quasi-fictional account of three men discussing the universe, for which he did in fact receive permission ahead of time from the Catholic Church, he attributed the church's point of view to the stupidest, dullest man in the book, thus appearing to mock papal views.)

In a trial still famous today, Galileo was summoned before the pope's inquisitors and made to denounce his work. Opting to keep his life, Galileo signed papers stating that the earth most definitely, unequivocally did not now move, and never had. He was sentenced to house arrest for the rest of his life.

Legend has it that as he stood up and walked out of the church he muttered, *"Eppur si muove"* (Yet it moves). Whether or not Galileo said the actual words, the earth's movement was something no one could deny for much longer. The cracks in Aristotle's theory were too large. It would soon fall apart.

NEWTON

What we have so far are brilliant men—for they were all men at this point—each able to see a piece of the puzzle. As in the fable of the blind men exploring an elephant—in which one man touches the trunk and thinks that's what an elephant looks like, while the others make different decisions based on touching the leg or tail—each of these greats had an awesome understanding of his one piece of the animal. Their fault lay in denying the other's bit. Copernicus envisioned a sun-centered universe but refused to let go of Greek philosophy. Brahe was willing to ditch the crystalline spheres but wouldn't let go of a geocentric universe. Kepler abandoned Plato's circles but couldn't abandon the Platonic solids. Galileo accepted Copernicus but refused to embrace Kepler's ellipses. Each took a giant step forward but couldn't pull everything together into a whole. It was Newton who, a generation later, took a step back and saw the whole elephant.

Like the geniuses before him, Newton was an arrogant man. Perhaps the courage to capsize centuries-old theories must stem from a certain amount of hubris. Perhaps confidence in the face of criticism is the most important ingredient for toppling dogma. After all, no matter how much we try to make our choices based on logic, no matter how much mathematical proof there is for a theory, humans tend to "believe" a scientific theory the same way they believe in a creation myth—somewhere in their gut. So overthrowing a universally accepted theory takes more than data; it takes superhuman conviction.

Newton didn't have as much of an uphill battle to convince his peers as those who came before him. In his day, many already accepted the theories of Kepler and Galileo. Newton lived to see his ideas embraced, and so he spent the last thirty years of his life basking in England's admiration of their real-life hero.

Newton was born on Christmas Day in 1642. His mother saw to it that he got a first-rate education—Newton was the first person in his family who could write his own name—but other than that, she by and large neglected him. Newton was raised by his grandmother, while his mother and stepfather lived in another village down the road. Newton's estrangement from his mother seems to have affected the rest of his life—he never made close connections with the people around him, never married, never felt comfortable in society. He turned whatever energies might have gone into personal relations inward. Once caught up in a puzzle, he would work around the clock, ignoring everything around him, including the most basic of problems such as hunger and exhaustion.

The ferocity with which Newton attacked problems in science and math is mind-boggling. In a scant two years, beginning when he was twenty-two, Newton created calculus, learned that white light was a superposition of all the colors in the rainbow, and—most interestingly for us—devised the theory of gravity.

Newton began to think about gravity because he couldn't figure out why the moon merrily continued to orbit the earth instead of flinging off into space. (Think about whirling something like a yo-yo around and around your head—the only thing keeping it moving in circles is the fact that you're holding the string. The moment you let go, it will shoot off in a straight line. Contrary to Aristotle's assumptions, Newton knew that nothing *naturally* traveled in a circle.) Sitting under an apple tree one day—you know the story—Newton saw an apple plop to the ground. He realized that the same force that pulled on fruits and humans and animals might extend all the way up to the moon. This force of gravity could bind the moon to the earth as firmly as a yo-yo string keeps that yo-yo whirling around your head.

It would be some time before Newton realized that the implications went farther than the moon's path. Incorporating gravity into Kepler's equations, Newton realized he could produce mathematical descriptions of gravity that matched up perfectly with elliptical orbits. Gravity governed not only the moon but all the planets.

Perhaps it went even farther than that. In the end Newton proposed a theory of universal gravitation: Every single object in the universe, he claimed, attracts all others through the force of gravity. Small bodies, such as this book, create such weak gravity that you don't feel it. But take something as massive as a planet, and you're going to be pulled to its surface like a magnet to a refrigerator. It would be more than twenty years after that falling apple before Newton published, in 1687, a complete description of his insight, in *Philosophiae naturalis principia mathematica* (Mathematical Principles of Natural Philosophy).

Today we refer to the work as the *Principia,* and it is still considered one of the most revolutionary books of all time.

Starting from a few basic principles, incorporating some math, and throwing in completely new insights about the nature of matter, Newton explained everything that was known about movement. From how a rock moves through the air, to why friction slows down a rolling ball, to why the planets orbit the sun, Newton's laws explained it all.

Of course, universal gravitation had implications for cosmology as well. If everything is attracted to everything else, then planets and stars and the earth should be constantly in erratic motion, constantly pulled one way or another. Our universe shouldn't be stable, and yet by all appearances it was. (It never occurred to anyone that the universe *wasn't* stable, completely static. Figuring out that the universe expands would be crucial in developing the big bang theory, but the idea was considered so bizarre that even Einstein refused to believe it at first.) To solve the problem, Newton claimed that the universe must be infinite. If it was infinitely large, it was just possible that the force from every body in space perfectly balanced the force from every other body. Pulled an equal amount in all directions, each planet would stay put. Newton granted that this was the equivalent of balancing an infinite number of needles on their points, but nothing was beyond the ability of God.

Yes, God was still a large part of Newton's vision. He believed that such universal order could be explained only by the hand of a divine being. Moreover, such perfect stability would require God's hand constantly intervening, constantly tweaking, moving this star slightly to the left, this planet slightly to the right to maintain the perfect balance. Newton knew the difference between "science" and "religion." Science had to be backed up by proof and observation—you couldn't just make up random hypotheses; they had to correspond to physical reality. But it never occurred to him that religion wasn't as important a force in the universe as his neat gravity. God and science didn't clash at all, but worked in harmony.

BEYOND THE SUN

As all these scientists described the solar system, it never occurred to them to track much farther. For most, the stars were no more than a backdrop—a fixed, two-dimensional tapestry against which everything else moved. On his drawings, Copernicus merely labeled an outer sphere of stars; he never commented on what might be beyond it. A less well-known British astronomer, Thomas Digges, was the first to expand the heavens. In 1576, he translated passages from Copernicus into English and drew a famous picture showing stars beyond Saturn, extending out in all directions. It was the first suggestion in medieval times that the universe might spread in three dimensions past the planets.

With bigger and better telescopes, scientists began to map the galactic neighborhood. Having understood our home and our street, it was now time to move on to the whole block, perhaps the whole city. Of course, that's a lot like having to map a town while being forced to sit on your front porch with a pair of nice binoculars.

It's a wonder, when you think of it that way, that we have the hubris to think we really know our way around the universe at all. After all, if you see something green at the farthest edge of your visibility, that doesn't mean it's a plant. It could be a billboard, for all you know. Scientists must maintain a constant awareness of the limitations of their tools. On the other hand, you can do a fair amount of observation while sitting on your porch.