THE COPERNICUS COMPLEX

OUR COSMIC SIGNIFICANCE IN A UNIVERSE OF PLANETS AND PROBABILITIES

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PROLOGUE: FROM MICROCOSM TO COSMOS

It all begins with a single drop of water.

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With one eye scrunched shut, the drapery tradesman and budding scientist Antony van Leeuwenhoe stares intently through the tiny lens he has fashioned from a piece of soda-lime glass. On the oth side of this shiny bead is a quivering sample of lake water, scooped up during an outing the previou day around the city of Delft in the Netherlands. As he adjusts the instrument and lets his eye relax ar focus, van Leeuwenhoek suddenly finds himself falling headlong into a new world, a swarmi metropolis of alien design.

Within the previously invisible universe of this single speck of water are arrays of beautiful coiled spirals, animated blobs, and bell-shaped creatures with skinny tails, wiggling, gyrating, ar swimming busily with absolutely no regard for his right to be peering in at them. It's a shockir vision: van Leeuwenhoek is not just a human, he is a cosmically huge giant observing another wor contained within his own. And if this one drop can be home to its own universe, then what abo another, and another, and all the drops of water on Earth?

* * *

The year is 1674, a time sandwiched between some of the most profound changes in Western scienc and thought. A little more than a century earlier the Polish scientist and polymath Nicolau Copernicus had published *De revolutionibus orbium coelestium*—"On the revolutions of the celesti spheres." In this book Copernicus had put forth his completed heliocentric model of the univers shifting the Earth from the center of the cosmos to a secondary place, spinning and orbiting around th Sun—a demotion that would reshape our species' scientific history.

In the intervening decades the Italian Galileo Galilei had built his telescopes and seen the moor of Jupiter and phases of Venus, convincing him that Copernicus was right—a heretical view at th time, one that cost him dearly when it attracted the scrutiny of the Roman Inquisition. H contemporary, the German Johannes Kepler, went even further by stating that the orbits of the planet including the Earth, traced not perfect circles but rather eccentric ellipses, unsettling any conceptic of a rational universe. And in a little over ten years' time from when we find van Leeuwenhoek gazir through his lens, the great English scientist Isaac Newton will publish his monumental *Principi*

laying out the laws of gravitation and mechanics that will, unwittingly, make the arrangement of ou
~~solar system and of the universe at large a thing of austere beauty, untended by any guiding ha~~nd b
physics and mathematics. It is by any standards an extraordinary time in human history.

* * *

Antony van Leeuwenhoek was born into this rapidly transforming world in 1632 in Delft. His ear life was relatively ordinary. He never received much education beyond the basics. As a young man h quickly established himself as a tradesman dealing successfully in linens and woolens. He was also relentlessly interested and curious person, once describing himself as “craving after knowledge,” characteristic that would result in a voluminous legacy of observations and writings about his greate passion, the microcosm.

Sometime in the year 1665 van Leeuwenhoek came across the great work *Micrographia*, by th English scientist Robert Hooke. *Micrographia* was a phenomenon: the first major publication of th fledgling Royal Society in England, the first best-selling science book, and a cornucopia of the mo fabulously detailed illustrations of the magnified textures of everything from insects to minerals, bi feathers, and plant life. It was an atlas of the world seen through a new set of eyes, those of th microscope.

This novel technical art of magnifying objects using a series of lenses had begun not long befor in the late 1500s. The compound microscope enabled the sharp-eyed and sharp-minded Hooke to mak his beautiful drawings of all these incredible things that were sitting right under everyone’s nose. B even Hooke’s best microscopes achieved magnification factors of only ten times to perhaps fif times. What might be lying even deeper beneath? For van Leeuwenhoek the mystery was impossib to resist, and so he took it upon himself to learn to build the optics necessary to catch his own glimp of this unexplored realm.

Exactly how van Leeuwenhoek made his microscopes remains a little unclear to this day. He wa incredibly secretive and a bit dramatic about it all, beavering away behind closed doors at his hom But from instruments he bequeathed to the Royal Society, and from the accounts of people wh visited, we do know that his principal trick was to fashion tiny, perfect beads of glass—probably b pulling molten glass fibers and fusing their ends together. Then he mounted these spherical lense with focal lengths of barely a couple of millimeters, in small brass plates with screwlike arms th would position a sample right by the lens. By holding the plate across his eye, van Leeuwenhoek cou gain some astonishing magnifications, possibly as high as *five hundred* times in the very best cases.

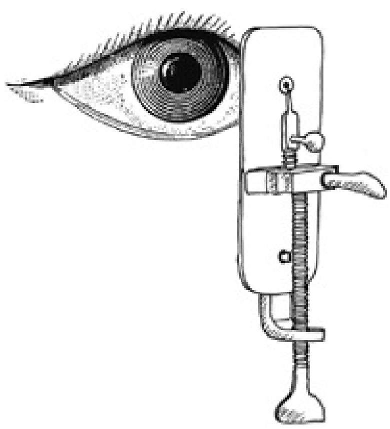

Figure 1: An illustration of the van Leeuwenhoek microscope. Samples could be placed on the tip of an adjustable metal pro just in front of the opening in a plate that holds the glass lens. Bringing it up to the eye completes the optical system.

He also didn’t just make a single microscope, or even a few. In a remarkably modern burst o ~~innovation, he made well over two hundred. In fact, it appears he made a microscope for pretty muc~~ every subject he wanted to study—a customized job each time. And thus it was a few years later, on September day in 1674, that the tradesman could be found putting a fateful drop of water in front of lens in its purpose-built viewing platform.

* * *

Van Leeuwenhoek’s innate gift for fashioning optics took him not to outer space but to a microscopi cosmos, on what was perhaps an equally shocking journey. Within these drops of water he discovere unknown types of living organisms, hidden away from prying humans by simply being too small see with the naked eye. He also quickly realized that if these minute life-forms could be in a drop lake water, they could be anywhere, and he extended his investigations to other realms.

These included the fascinating, but rarely appreciated, nooks and crannies of the human mouth an the sticky mix of saliva and plaque gumming up our teeth. Putting these samples under his lens, va Leeuwenhoek found even more diversity: dozens, hundreds, thousands of even smaller “animalcule swimming about in their rather repulsive oceans. These varied and active organisms offered the fir human glimpses of bacteria, the single-celled living things that we today know represent the majori of life on the planet, outdoing everything else by sheer number and diversity, just as they have don for the past 3 to 4 billion years.

* * *

I’ve often thought about how van Leeuwenhoek might have felt when he came across these swarmin populations of “animalcules.” There is little doubt he was amazed—his notes and writings convey gleeful pleasure in being able to unveil what was previously invisible to us all—and he spe subsequent years examining and recording more and more specimens and samples. But did he ev wonder if one of those swimming, spinning little creatures was looking back at him? Did he wonder the occupants of a drop of water were busy asking whether they were the center of the universe, tryin to deduce the mechanics of their own heavens, which might have included his great eye hoverin above them?

There is no good evidence to suggest that van Leeuwenhoek thought about these questions. Peop were certainly excited about discoveries like these. But there’s not much to indicate that va Leeuwenhoek, or anyone else at the time, stepped back to reflect on any cosmic meaning. It practically inconceivable to me that no one ran through the streets shouting the news: “We’re no alone! We’re full of tiny creatures!” But it doesn’t seem that people felt their place in the univers undergo a seismic shift with the discovery of these microscopic underpinnings—even though the revealed a layer of reality that didn’t include us.

To be fair, this was in part because we just didn’t yet appreciate the true relationship betwee microbial life and our own. It would be another two hundred years, till the mid-1800s, before the ide that bacteria could cause disease was formally recognized. In turn, it would be another century aft that before we would appreciate how these denizens of the microcosm are part of our ov fundamental composition, swarming within our guts in their hundreds of trillions, intimate connected to our physiological well-being. And even now, in the twenty-first century, we are only ju beginning to understand this remarkable symbiosis.

In the 1600s the vast underworld of van Leeuwenhoek’s animalcules was accepted as an interestin fact, but one that was largely irrelevant to our own cosmic importance. This narrow viewpoint was n just a product of the times. It was a reflection of a tendency so deeply rooted in the strange ar powerful human psyche that it must relate to our most fundamental evolutionary history and o instincts for survival. It’s a type of behavior that we all carry with us today—a tendency automatically assume our significance above all other things, regardless of what evidence is place right in front of us.

Cultures vary, for sure, with differing degrees of respect for our natural surroundings and ou worldly cohabitants, but most of us assume our overall importance more than our insignificance. Th solipsistic behavior crops up again and again, despite our endless desire to know how and why w exist. Perhaps we sense that these questions open the door to scenarios that leave us among the filth and irrelevant chaff of the passage of cosmic time. The most critical example is that of the Copernica Principle, which states that the Sun, not the Earth, occupies the center of the heavens, and that spinning Earth, as well as the other planets, circles around this fiery orb. It is a worldview that asser that we are not the center of all existence; we are not “special.” In fact, we are as dull as they come.

Indeed, the last five hundred years of science have seen the chalice of our significance shake more than at any other period in recorded human history. The overlapping revolutions of moder optics, astronomy, biology, chemistry, and physics reveal that we inhabit merely one sliver of nature that our normal awareness of the world resides in neither the microscopic nor the cosmic, but in wh might be considered the narrow borderlands in between. And now, in the twenty-first century, w stand on the cusp of the ultimate in disruptive events: the real possibility of discovering whether li exists elsewhere, beyond the confines of planet Earth. We could find out that we are, after all, just lik the animalcules in a drop of Delft lake water—one occupied world among billions. Or that we are good as alone in the cosmos, a tiny swarm in one crevice of an incomprehensibly enormous mouth expanding space and time.

Most surprising, we now have some reason to believe that these possible outcomes may also b linked to an even deeper question: whether or not this universe is itself just one instance of a nea infinite array of universe-like entities emerging from the most fundamental characteristics of th vacuum. Some of these ideas are positively head-spinning—inducing precisely the same kind vertiginous feeling that van Leeuwenhoek must have had when he gazed at the microscopic cosmo for the first time.

* * *

Much of this book is about *how* we may get to answer these questions; how our quest to understan our cosmic significance is making practical and tangible progress and, in the process, challenging s many preconceptions and conceits. I will argue that we can already draw some conclusions, and I wi present a proposal for how to take our knowledge about life in the cosmos far beyond its present stat to a new level of insight.

* * *

To get to the crux of the problem requires a careful dissection of one of the greatest principles to ev serve science and philosophy. The roots of this idea are modest; they are in nothing more than ou daily and nightly experience of the sky above.

We’ll see how the decentralized reality that Copernicus proposed was logically compellin because it helped explain the detailed motions of the Sun, Moon, and planets across the heavens. An it accomplished this explanation in a more direct and elegant way than preceding theories. But f ~~many people in his time, it was a horrible concept. As well as being theologically unappealing becaus~~ it suggested we were unimportant, parts of the idea were also scientifically distasteful: the represented a challenge to the very core of prevailing analytical thought about the mechanics of th cosmos.

Over time, we have taken this decentralization even further, and we now consider any scientif theory that depends on a special origin or a unique viewpoint to be inherently flawed. This eminently sensible. If such generalization weren't true, the laws of physics that apply to you might n apply to your friend who happens to live on the bad side of town, a possibility that runs counter everything we know. However, as I'll argue, the Copernican Principle may have reached the end of i usefulness as an all-encompassing guide to certain scientific questions.

Indeed, while we cannot be at the center of what we now know to be a centerless universe, v appear to occupy a very interesting place within it—in time, space, and scale. Various arguments hav certainly been made along these lines before, sometimes culminating in the hypothesis that Earth exceptionally "rare," especially in regard to the development of technologically intelligent life. Th conclusion is extreme, however—and I don't believe it's been convincingly substantiated. I'll sho you why.

Nonetheless, the specifics of our circumstances—our place between the microscopic and th cosmic, on a rocky planet around a star of a certain age—do most certainly affect the way we mal inferences about nature, and the way we search for other life in the universe. The specifics of our ov cosmic "address" also provide vital clues. Taking it further, I'm going to argue that for us to mal genuine scientific progress in determining our cosmic status, we must find a way to see past our ov mediocrity. I'm going to present a way to do this.

The quest to find our cosmic significance, to resolve the conflict between our Copernica mediocrity and our specialness, will take us from the deepest history of the Earth to its farthest futur to planetary systems across our galaxy, and from the great universe of astronomy to the microscop universe of biology. It's also going to take us to the cutting edge of scientific inquiry into our cosm origins—an exploration being carried out through mathematical wizardry and cunning observations nature. And it will lead us to an unwavering examination of the specific circumstances we fin ourselves in, our place in the cosmos.

1

THE COPERNICUS COMPLEX

At a rather pleasant spot in the Aegean Sea in the third century B.C., on the vine-rich island of Samo
off the western coast of what is now Turkey, the Greek philosopher Aristarchus had just had a brillian
idea. He proposed that the Earth spun and moved around the Sun, placing this scorching solar orb
the center of the heavens. It was, to say the least, a bold notion—Aristarchus's idea of "heliocentrism
was as outrageous in his time as Copernicus's revival would be in the distant future.

Records of Aristarchus's works are fragmentary, and most concern the clever geometrical analyse
that he used to argue that the Sun is significantly larger than the Earth. But it's clear that from th
insight he arrived at the idea that the Sun was central to the known cosmos, and that the stars we
extraordinarily distant. This was a huge conceptual leap to ask of people. It also require
understanding a phenomenon called *parallax*.

Parallax is earthbound as well as celestial, and is an easy concept to grasp. Close an eye and ho
one hand up, fingers spread and viewed on edge. If you move your head side to side you will s
different fingers appear and disappear from behind each other as your vantage point, or your angle
view, changes. This is all that parallax is: the apparent change in where distant objects appear relativ
to each other, depending on a line of sight. The farther away those objects are, the smaller th
apparent change—the smaller the perceived angular displacement between them.

Part of Aristarchus's bold argument involved the fact that the stars in the night sky *didn't* appe
to have any parallax; they never moved among themselves. So if the Earth were *not* stationary at th
center of all existence, he reasoned, the stars must be so distant, so enormously far away from us, th
we couldn't measure their parallax as the Earth moved its position.

Not long before Aristarchus made his ideas known, the great philosopher Aristotle had alread
dismissed the possibility that the stars were any more distant than planets by appealing to this sam
lack of parallax, among other things. Aristotle's argument was founded in reason and common sens
It built on even earlier ideas that the Earth was central to existence. The way he put it was simple:
no parallax could be seen in the stars—they did not shift around relative to one another at all—the
must be all affixed to some layer of the sky that surrounded us at the unmoving origin.

All of which sounds logical, except that Aristotle's own preferred cosmology (elaborating on idea
from his mentor, Plato) consisted of approximately fifty-five thick, crystalline, transparent sphere
concentrically nested about the stationary Earth and carrying the planets and stars about the
business. In this geocentric universe we were at the focus of all natural motions, with the stars an
planets simply following perpetual circular paths around us as the crystalline spheres slid and rotated

You might well ask why it took fifty-five spherical crystalline layers for Aristotle to build h
cosmology. Part of the reason is that he had to justify a system of cosmic mechanics, a transfer

forces whereby one shell would rub on another, pushing it around—a great scheme of motions ar ~~machinery to keep everything tracking through the sky. This structure was intended to deal~~ with th other most critical issue facing would-be cosmologists of the time; unlike the stars, the planets move around the skies in a complicated fashion.

These tricky motions were a major piece of the puzzle that Aristarchus, and later Copernicus, trie solving by displacing the Earth. The word “planet” is derived from the Greek phrase for “wanderin star,” and our brightly reflective planets most certainly do wander. Not only do they appear to mov relative to the stars, noticeably shifting in position as the nights go by; sometimes they reverse cours performing a celestial loop-the-loop over a few months before carrying on. Planets like Venus ar Mercury are even more subversive; often they’re nowhere to be seen. And even the speed of planeta paths across the heavens seems to be slower and faster at different times, with the brightness of the miscreants changing as well.

So you might think that when Aristarchus proposed his heliocentric system there would have bee a huge sigh of relief, because placing the Earth on its own circular path around the Sun quick provided a solution for much of the curious backward motion of the planets—what would later b known as “retrograde” movements. In this configuration the simple reason for such odd behavior w that our own vantage point was shifting as the Earth itself moved in a circle. There would naturally b times when our motion relative to a planet was either forward or backward, and our distance from planet would change—lowering or raising its apparent brightness.

It was a lovely, elegant, and fact-based idea—and many people hated it. If the Earth moved, the should be a noticeable parallax among the stars, which surely couldn’t be *that* far away. And apa from this lack of observable parallax, displacing the Earth from its vaunted central position w anathema; it was ludicrous to consider that the very hub of our existence was not at the core everything, and so poor Aristarchus got it in the neck.

The other part of this antipathy toward heliocentricity likely came from distaste for ideas th hinted of pluralism. In opposition to the likes of Plato and Aristotle, who argued for a divine ar unique creation of the Earth, Greek thinkers such as Democritus and Epicurus instead advocated picture of reality rooted in the notion of indivisible pieces and empty void—atoms and space. The atoms weren’t atoms as we now know them, but a philosophical concept of units of matter—too sma to be seen, solid and uniform within, varied in size, shape, and weight—that could be used to describ an infinite number of structures. The idea of atoms led these thinkers to consider that the Earth w unlikely to be unique. Far from it—there should be an infinite number of inhabited worlds locate within an abstract form of space and time and what, in retrospect, amounted to parallel universes. N surprisingly, the plurality of worlds did not sit well with anyone following the Platonic or Aristotelia schools of thought.

What happened instead was that a number of natural philosophers in the decades followin Aristarchus came up with a geocentric “fix” to account for the annoyingly unconventional motion the planets across the skies, and to keep Earth rooted as the unique center of existence. Their solutio to the dilemma of celestial movements probably first originated almost a century after Aristarchu and Aristotle butted heads, with the astronomer and geometer Apollonius of Perga around the turn the second century B.C.

Later on, this explanation was subsumed into the works of Claudius Ptolemy. Living some thre hundred years after Aristarchus, the Greek-Roman citizen Ptolemy resided in Egypt under the rule the Roman Empire. He was a prolific thinker, producing significant works on many topics, includin astronomy, geography, astrology, and optics. And most important, he produced an astronomica treatise known as the *Almagest* that laid out a cosmological vision that would stick for the next 1,40 years.

In Ptolemy's system, the Earth is firmly stationed at the center of the universe. Moving outwa are the Moon, Mercury, Venus, then the Sun, and then Mars, Jupiter, Saturn, and the fixed tapestry o stars—all following circular paths. To translate this arrangement into the messy movements seen i our skies, he added a clever set of extra motions along special circular paths called deferents an epicycles. And these were, rather ironically, centered on a location *offset* from the Earth (a peculiari that seems to have escaped the scrutiny of zealous geocentrists across the centuries).

In this ingenious arrangement, the planets and the Sun move around the smaller perfect circles the epicycles, which in turn move along the larger circles of the deferents, which rotate around a poi separated from the Earth. The end result matches up with the major features of the looping, back-an forth pathways of the planets. To do this, Ptolemy's system had to be very fine-tuned to actu observations of the planets. Each and every deferent and epicycle was meticulously sized and locate in order to give the best fit possible to the real meanderings of the known worlds.

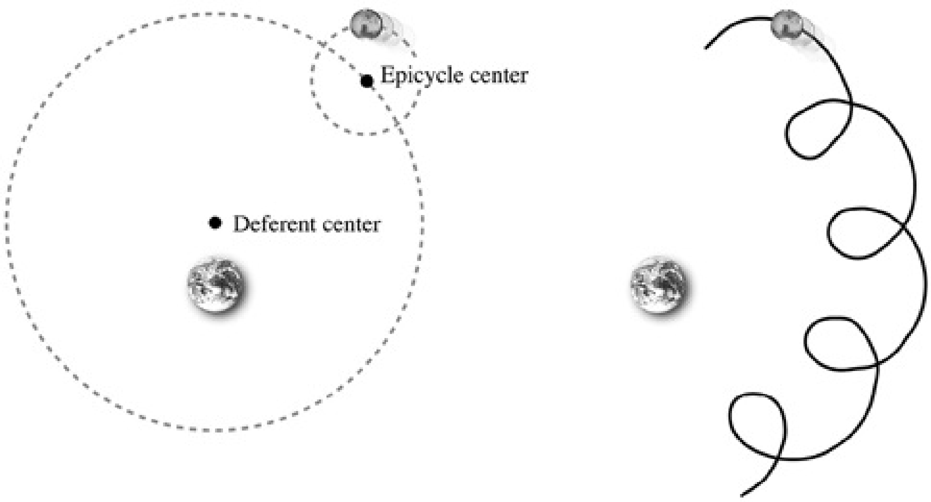

Figure 2: A sketch of one of the simpler versions of Ptolemy's geometric explanation for planetary motions in a geocentr cosmology. Here Mars follows a circular path around a small epicycle that in turn moves around a larger circular deferent. T result? Mars appears to loop back and forth across the sky, getting nearer and farther as it goes.

Even with such fine engineering, the system couldn't quite get everything right—there were litt deviations here and there from astronomers' measurements over the years. Planets would arrive a b early or late to certain positions on the sky—not enough, though, to discourage everyone. Here was plausible model for the nature and motion of the Sun, Moon, and planets that was geocentri grounded in the precision and truth of geometry, and in agreement with the thinking of the Gre Philosophers. The model comforted mathematicians and theologians alike.

Later, as Ptolemy's ideas were subsumed and integrated into the religious and philosophic doctrines of the Western world in the Middle Ages, they became intricately attached to a unifie conceptual framework. Like arterial conduits helping to keep the blood flowing, the geocentr spheres and their epicycles were a key part of the machinery of the perceived universe. If yo challenged geocentric cosmology you effectively challenged the whole body of scientifi philosophical, and religious thought—including its powerful institutions of rule and administration.

* * *

Despite geocentrism's importance, in the fourteen centuries between Ptolemy and Copernicus the was ~~in fact no single generally accepted picture of the detailed specifics of the arrangement~~ of th universe. This disconnect is one of the most interesting aspects of the development of "cosmology"– or at the very least the development of a model of our solar system. During this entire time span, bi and pieces of ideas and worldviews were typically cobbled together for convenience, as and whe needed—a cosmic mix-and-match. It depended on whether you wanted a mathematically drive universe, or a more abstract philosophical one. And all of these ideas in turn reached back to th varied hypotheses and proposals of a multitude of long-departed Greek thinkers.

Equally important for this cosmological history was that so much of its character hinged on th available precision of measurement. Aristotle and Aristarchus were no slouches when it came t making careful astronomical observations, but they were severely limited with only human eyes an basic tools for assessing angles and distances. This limitation meant that they actually had no ide what something like the true parallax motion of the stars really was; they just assumed it was zero.

The data on the motion of the planets themselves was also of limited precision, and it left gaps knowledge that would let Aristotle and Ptolemy squeeze geocentric models, with their increasingl elaborate geometric arrangements, into the picture. The models may not have been perfect, b humanity's observations of the heavens weren't good enough to disprove them.

So by the late 1400s there had been little real progress in formulating a better model for th motions of the Earth, the planets, and the stars—especially given the accepted need to be consiste with the religious and philosophical doctrines of the Western world. In fact, I think it's fair to say tha to our modern scientific eyes, medieval cosmological models were in a thoroughly messy an inconsistent state. The time was certainly ripe for some drastic improvements to be made. All that wa needed was the right person.

* * *

Nicolaus Copernicus was born on February 19, 1473. Growing up in a part of Prussia that had recent been ceded to Poland, Copernicus had the good fortune to be part of a sophisticated and well-o family. He got an excellent education that included a thorough grounding in philosophy (which b default was the intensive study of the works of the ancient Greeks), mathematics, and the natur sciences—including astronomy. He was also genuinely voracious in his appetite for knowledge, an doesn't seem to have shied away from hard work during his entire lifetime, even producin manuscripts on poetry and politics in addition to his scientific investigations.

His early schooling led him on to further studies in Italy, where he began to get more and mo interested in astronomical observations, especially those that related to the measurable deviations lunar and planetary behavior from the Ptolemaic system. Other investigators of the time were als well aware of these deviations, but the industrious Copernicus was particularly moved to step outsid the usual bounds in looking for answers, and was eager to find a more accurate solution than the on that Ptolemy had devised so long before.

In the early 1500s Copernicus drafted what would later become the basis for his full heliocentr model of the solar system—a forty-page work known as his *Commentariolus*, or "little commentary It was never officially published during his lifetime, but instead a few copies circulated in a limite fashion, garnering interest and respect from his contemporaries and no doubt some stern glares fro the prevailing establishment. While it may have been little, the commentary contains seven critic and visionary axioms.

Paraphrasing these in more modern terms, this is what Copernicus had to say about the cosmos:

- There is no single center to the universe.
- ~~The Earth's center is not the center of the universe.~~
- The center of the universe is near the Sun.[*]
- The distance from the Earth to the Sun is imperceptible compared with the distance to the stars, and so no parallax is seen in the stars.
- The rotation of the Earth accounts for the apparent daily rotation across the sky of the Sun and of the stars, which are immovable.
- The annual variations of the Sun's movements across the sky are actually caused by the Earth revolving around the Sun.
- The looping (retrograde) motion that we see for the planets is actually caused by the movement of the Earth.

After this last idea Copernicus was sufficiently excited to add in his brief commentary: "Th motion of the earth alone, therefore, suffices to explain so many irregularities in the heavens."

Here in these sentences was the genesis of a colossal revolution in human thought. Through th power of little more than deductive reasoning, Copernicus had set the cherished Earth spinning an traveling through the universe. But although the circulation of the *Commentariolus* helped him gain considerable reputation, it wasn't until decades later that he finally took these writings and mo thoroughly worked out the mathematical pieces of his theory in order to have them published effectively posthumously—in the great *De revolutionibus orbium coelestium*, "On the Revolutions the Celestial Spheres," in 1543.[†]

As much as this model shook the heavens into shape, it was also still very far from perfec Despite, as we now know, correctly arranging the Earth, the Sun, planets, and stars in their respectiv places, Copernicus still assumed certain properties that made fitting his model to astronomic observations awkward. In fact, rather than doing away with all of Ptolemy's complicated geometric devices, Copernicus merely did away with some parts. He continued to use epicycles to get a bett match to the real behavior of the planets and the Sun as they passed through their annual tracks.

The underlying physical arrangement was better, but the application of the model was still a bit a nightmare, and the reason was that Copernicus was clinging to a set of ideas that went all the wa back to Aristotle. He assumed that all motions, whether on great shells or in epicycles, followe perfect circles and took place at constant velocity. This was consistent with classical idea wonderfully geometric, and—unknown to him—completely wrong. But Copernicus had certain seeded the revolution of scientific thought, and what a revolution it would turn out to be.

* * *

The decades that came after Copernicus's *De revolutionibus* brought a host of new dissenters from th Ptolemaic universe, as well as many equally vociferous defenders. Some of the dissenters, such Giordano Bruno, paid dearly for their views. The Dominican friar was born in 1548, five years aft Copernicus's death. His scientific and philosophical studies led him to advocate not only th heliocentric worldview, but also the idea that the universe was truly infinite, that the Sun was mere another star, and that there must be an endless number of other inhabited worlds across the immensi of existence. By building on the works of the ancient Greek atomists, Bruno advocated a prescie vision of nature. But together with his extremely provocative stance on other religious matters, caught the full attention of the establishment, and in 1600 the Roman Inquisition burned poor Bruno the stake for heresy.

~~During this same period the wealthy Danish nobleman and astronomer Tycho Brahe was makin~~ enormous strides in the observation and record keeping of the heavens. Without telescopes he used h keen eyes and clever measuring devices to track the cosmos—inventing new versions of quadrant sextants, and armillary spheres to measure angles, positions, and coordinate systems with impressiv accuracy. One night in 1572 the twenty-six-year old Brahe witnessed a new star in the November skie of Western Europe. It showed no discernible parallax but had clearly not been there in previous night and Brahe came to the conclusion that the universe was therefore not immutable—it could change an it could change dramatically.

We realize now that he had observed a supernova, in this case the powerful implosion of critically overweight white dwarf stellar remnant, some 8,000 light-years from the solar system. Th experience of seeing this primal event helped encourage Western astronomers to devise even bette ways of measuring the positions and brightness of objects and to explain their arrangements. Brah himself worked hard to try to combine, or at least reconcile, the Ptolemaic cosmology with that Copernicus. He produced his own “Tychonic” geo-heliocentric system, in which the Sun and Moo orbited the Earth, but all the other planets orbited the Sun.

As contrived as it was, he found this arrangement satisfying because he had still not detected parallax for the stars, and keeping the “sluggish” Earth stationary meant he could easily account f that fact. Better yet, his system allowed a convenient compromise position for advocates of th Copernican vision who were still feeling very nervous about their scientific beliefs. But it was Brahe meticulous care with astronomical observations that really set the stage for one of the most critic next steps—steps that came from his onetime assistant, the German-born Johannes Kepler.

Four years before meeting Brahe in 1600, Kepler had published a rousing defense of th Copernican system of the heavens in his *Mysterium Cosmographicum*—“The Cosmographic Mystery Interestingly, Kepler was not only an obsessive mathematician, but also deeply religious, and he fe that everything that determined the positioning and motion of celestial bodies was of divine influenc (This might help explain why his first stab at modeling a heliocentric cosmos relied on a series three-dimensional polyhedra nestling inside each other—a geometric and appealingly designed, b deeply flawed, concept.)

The full story of Kepler’s life and studies is convoluted; he was an exhaustingly busy an productive person, particularly in matters of science. His investigations of optics led him to dedu the fundamental inverse-square law of brightness: the intensity of a light source is proportional to th inverse of the square of its distance. With the observation of another supernova in 1604, Kepler als reasoned, just as Brahe had, that in the absence of a measurable parallax, Aristotle’s unchanging an immutable universe was probably not a correct model. But most important, when it came to th problems of the Ptolemaic and Copernican explanations of planetary motions, Kepler found himself a unique position.

The high-living Tycho Brahe suffered an unfortunate and untimely death from an infection in la 1601, and Kepler wound up inheriting that master astronomer’s most complete and precise tabulatio of celestial positions and variations. Some sources suggest that Kepler was instrumental in makin very sure that he got his hands on these records before Brahe’s estate was disbursed. Having alread started working with Brahe, he knew exactly what he needed.

Brahe’s unprecedented measurements gave Kepler an opportunity to keep tackling the endless nagging issue of finding a perfect fit to the motions of planets, where solutions in the existin schemes were still full of holes, including so-called residuals, gaps between the predicted positions planets and their actual places at various times. Planets would simply not be quite where models sa they should be on particular nights, which was quite a glaring problem.

When Kepler settled down to study these extensive data, he chose to focus his attention on th observations of the planet Mars. That choice was, I think, one of the biggest strokes of educated luc in the entire history of Western science, even if it was likely encouraged by Brahe's earlie suggestions.

Of the six planets that Kepler knew of, Mars exhibited the worst residuals of all. In fact, Kepl demonstrated that Mars could not conceivably be following a fixed path if the Earth were at the cent of everything. He went on to consider what had heretofore been absent from all models of th universe: the possibility that objects might not move with constant velocity all the time. By allowin this behavior into the mix he wrenched open a new window onto nature, because if objects moved wi varying speed they might also move along paths that were not perfect circles. This wasn't an easy tas—it took Kepler eight years from the time he started his investigation to the time he had his answer.

Kepler tried out various shapes for his planetary motions; egg-like ovals didn't work, nor did oth forms. He then tackled the movements using only mathematics, obtaining a solution and rejecting before coming back to the exact same idea by guesswork. The answer, he finally realized, was that a planetary motions belonged to a class of curves known as conic sections. These could be circle parabolas, hyperbolas, and most critically—ellipses.

The reason why Mars has such awful residuals in the Copernican model is, as we now kno because it has the least circular, or the most elliptical, orbit compared with Venus, Earth, Jupiter, an Saturn. Of the planets familiar to Kepler, only Mercury had an orbit with greater ellipticity. But th observation of Mercury is complicated by its proximity to the Sun. Kepler deduced that in an elliptic orbit, a planet or any object slows down at its far point, and speeds up at its near point. This variatio was exactly what was needed to eliminate the residuals afflicting Mars.

Gathering his ideas together, in 1609 Kepler published *Astronomia Nova*, "A New Astronomy," t present the first two of his famous laws describing planetary motion: the path of every planet is a ellipse with one focus centered on the Sun; and a line joining a planet and the Sun sweeps out equ areas in equal time as the planet moves.

Kepler also realized that there might be some kind of unseen influence at play between the Sun an the planets (what we would today term a force). This concept was revolutionary, and although it wa all couched in somewhat mystical terms, he went as far as suggesting that such an influence might b reduced with distance from the Sun. Hence the farther planets would move more slowly, which o course they do.

* * *

Merely a year after *Astronomia Nova*, in 1610, Galileo Galilei made his telescopic observations of th periodic motion of the brightest moons around Jupiter and of the phases of Venus. Both of thes observations brought the clash between celestial worldviews to a boiling point by providing even mo convincing evidence for a Sun-centered system, putting Galileo into a head-on collision with th established doctrines of the time. But there is something else lurking in the picture of the universe th emerged out of Kepler's work that is just as vital to our quest to understand our cosmic significance.

If planets follow elliptical paths as a general rule, and those paths need not be all within a sing plane around a centrally massive star, the possibility exists for an extraordinary range of planetar motions and arrangements that nonetheless all obey Kepler's rules (and what would soon be Newton physics). I doubt anyone suspected it at the time, but the door had been opened to a universe of f greater abundance and diversity than anything yet imagined, even by the atomists and pluralists of th past. ~~Galileo's observations produced other surprises as well. With a telescope he could find stars~~ th were too faint to be noticed with normal human vision. When he looked at the seemingly smooth an cloudy expanse of the Milky Way, he was amazed to discover that it was in fact *made* of stars, s many and so tiny that the naked eye blurs them together. His observations of these other phenomen tend to get less attention than they deserve, but they were beginning to reveal the true enormity nature.

Just like the shock of Tycho Brahe's supernova, the notion that there were hidden objects in th sky ran counter to the cosmological perceptions of the time. These observations, together with Anton van Leeuwenhoek's discovery a few decades later of the teeming microscopic universe in every spec of water and in human sputum, began to lift a previously opaque veil from the enormous intricacy an depth of reality. Yet these pivotal revelations of the sheer depth of nature—inward and outward— didn't cause anything like the controversy sparked by the simple decentralization of our place in th universe.

The upset of that shift was mostly confined to the camps of the church and establishment. In fac it doesn't appear that either Galileo or Kepler saw heliocentrism as a *demotion* of the terrestrial statu Quite the contrary: it meant we were no longer at the "bottom" of the planetary pile; we were on noble orb within the pathways of others. Ironically, Kepler even wrote that he considered this to mea that the Earth was at the *center* of the planetary globes (the orbits), with Mercury, Venus, and the Su on the inside, and Mars, Jupiter, and Saturn outside. Yet again, such a robust certitude about ou significance in the grand scheme of things actually lessened the impact of the growing evidence f the true immensity of nature, from the world within to the world without.

* * *

Time passed, and the year 1642 saw the death of Galileo in January, and the birth of Isaac Newton i December. The full story of Newton's life, much like those of Copernicus, Bruno, Brahe, Kepler, an Galileo, is immensely rich. But the most important piece for our quest comes with the publication 1687 of his monumental *Philosophiæ Naturalis Principia Mathematica*—"Mathematical Principles Natural Philosophy," more often known simply as the *Principia*. In this text Newton lays out not on the mathematical laws of motion, including the concepts of inertia, momentum, force, an acceleration, but also a universal law of gravitation.

Newton saw that the attraction of bodies to each other could be described as a force that grew wi mass but diminished as the inverse of the square of distance. From this hypothesis he derived th mathematical proof of Kepler's empirical laws—showing for the first time that the rules governin the planets came from fundamental physics. He also presented analyses of the motion of the Moo the paths of comets, and the gravitational interactions of more than two bodies. He noted that despi the clear heliocentric nature of the solar system, the Sun does in fact orbit around a variable point– the center-of-mass or balance point of all objects in the system. He even determined that this poi was close to the observed surface of the Sun—well offset from its core, a result largely due to th gravitational bulk of Jupiter and Saturn. (This latter fact is familiar to modern astronomers, becau the same type of offset in other star systems provides one of the key techniques for finding exoplanet the planets beyond our solar system that we will encounter in a later chapter. We measure the orbita motion of a star around this pivot point, since it marks the presence of unseen but massive worlds.)

Newton was a strange and complicated character with deeply held religious beliefs, and for hi this beautiful physical explanation of planetary motion was evidence of a supreme divinit

maintaining the paths of objects in a perfect clockwork dance. For other thinkers in the followi
century, like the great French mathematician and scientist Pierre-Simon Laplace, it meant quite th
opposite. There need be no guiding hand, no preordained paths or configurations in the Copernica
universe, just the innate physical laws to determine where and when any object would find itself. B
Laplace also felt that, armed with these laws, and with a complete knowledge of the locations ar
movements of all objects at any time, we could always know the past and future. There might be r
guiding hand, but there was determinism in the universe.

* * *

Observations of the cosmos around us continued to improve as the next few hundred years went by, a
did the toolbox of mathematics and physics available to work with. Mystical and philosophic
reasons for the arrangements of nature gave way to the application of simpler, more general laws. A
the same time, what we knew of the composition of the universe became richer and richer, and th
notions of extreme scale and of the variety of phenomena that were hidden by time or by faintne
grew and grew. The idea that stars were not only vastly distant, but perhaps scattered throughout a
enormous volume, gained greater acceptance among philosophers and scientists. With this growin
sense of scale, even the musings of the ancient Greek atomists on an infinite cosmos returned
people's thoughts.

Our scientific sense of our own importance also evolved, in a variety of directions. Hot on th
heels of Newton, the Dutch scientist Christiaan Huygens wrote about his thoughts on the possibility
extraterrestrial life just prior to his death in 1695. Huygens was convinced of the "plurality of worlds
imagining a wealth of watery and hospitable locations in his telescopic observations of the planet
and even of the moons of Jupiter and Saturn. Life like ours seemed to him to be nearly inevitab
elsewhere. This was certainly not a view shared by everyone, and debate on our place among the sta
raged on.

Something else was also taking place during this period: a contentious and surprising
underappreciated scientific debate that began in the early 1700s and arguably didn't reach any kind
satisfactory closure until as recently as the 1970s. With the monumental advances in physics due
scientists like Kepler, Galileo, Newton, and Laplace, the solar system became a phenomenon whos
origins now begged for a proper scientific explanation.

Where did the Sun and planets come from if they were less of a divine construction and more of
consequence of the laws of nature? The answer, as I'll soon show you, is quite stunning, and neat
frames our more modern debate on origins and significance. Before that, though, we need to reach th
present day in our brief history of cosmic perspective.

* * *

By the end of the 1800s we were beginning to appreciate the true vastness of the universe. Stars we
now accepted to be extremely distant analogues of our Sun, a fact supported by astronomers final
having success in measuring their barely noticeable parallax movements from Earth's annual motio
through space. New planets had also been discovered in our solar system—from the darkly dista
Uranus and Neptune to minor but still massive objects like Ceres and Vesta, just beyond the orbit o
Mars. And the elemental composition of extraterrestrial objects was beginning to reveal itself throug
the spectra of light, including the discovery of an atomic species in the Sun—the stuff we now ca
helium.

But other big questions remained: Was the universe infinite in space or perhaps even time? Wa the ~~spread of stars we call the Milky Way the full extent of the universe, or could some of these~~ othe strange little smudges of nebulosity, like the one called Andromeda, actually be other “islan universes,” other galaxies?

In an unprecedented burst of discovery and invention, in the first three decades of the twentie century there was another series of scientific revolutions. Their stories have been told innumerab times: Albert Einstein’s theory of relativity, the measurement of the true scale of the cosmos and th nature of galaxies, and the development of quantum mechanics. These all produced radical views nature that dealt with the intertwined properties of the very large, the submicroscopic, the fast and th energetic, and the underpinnings of reality itself. These revolutions would also have to confront, an contend with, our perceived place in the cosmos.

The implication of a heliocentric Copernican model was that the universe would look more or le the same no matter which planet you stood on. The obvious extension was that the universe wou look more or less the same *wherever* you stood within it—from our solar system to another, or fro our galaxy to another that might be tens of millions of light-years away. For Einstein, working in th years following 1915, this was a philosophically comfortable proposition, and made the application his theory of general relativity to the universe as a whole that much more straightforward, giving bir to the so-called *Cosmological Principle*.

In slightly more technical terms, the idea stated that the universe was homogeneous. While might contain many small asymmetries, like patches of stars and galaxies, it would have the sam amount of these lumps and bumps no matter where you were. It’s a bit like the Earth’s terrain: som places are mountainous and some places consist of flat oceans, but on average you can always fin roughly the same mix of mountains and oceans wherever you are. This was very helpful if you we trying to apply a generalized theory of space and time, as Einstein was, to the workings of the cosmo

It also meant assuming that the universe was isotropic, meaning that it would look the same in a directions from any place. This is a bit harder to swallow. After all, we can hardly claim that this the way we experience the world or the solar system, and even the interstellar night sky is beset by b nonuniformities like the band of the Milky Way. But again, on scales that reach beyond our galax and out into the cosmos, the number and arrangement of objects seen in any direction should be mo or less constant.

The first time that anyone seems to have publicly connected this cosmological principle Copernican ideas was in the early 1950s, when the famous Austrian-born physicist Hermann Bon used the phrase “Copernican Cosmological Principle” in his discussion of a now-disprove cosmological model known as the steady-state theory.

Much as its name implies, the steady-state theory proposed that the universe was eternal, with n beginning or end. To help make this theory palatable, Bondi asserted an even stronger principle: th not only would the universe appear the same in all directions to any observer anywhere, but for an observer *at any time*. Although we now know that our universe is most definitely not in a steady stat the Copernican Cosmological Principle reinforced the general notion that there was absolutely nothin special or privileged about our place in the cosmos, throughout space or time.

This middle period of the twentieth century saw the explosive development of a multitude fields, from cosmology to microbiology and genetics, as well as the emergence of several generation of extremely influential scientists. But as it became clearer and clearer that the universe itself was a evolving and diverse place, several different people had begun to notice certain strange coincidenc in the value of fundamental physical constants. These are numbers that describe things like th

strength of gravity or the masses of subatomic particles, and in particular the estimated lifetime of th
~~cosmos. Certain combinations of these numbers could yield surprising relationships. For example~~, th
ratio of gravitational and electric forces, involving constant quantities describing the strength
gravity, and the masses and charges of electrons and protons is about 10^{39}. This number is remarkab
similar to the current age of the universe when described in atomic units of time (a unit being abo
2×10^{-17} seconds), a fact first pointed out by the physicist Paul Dirac.

But why should these immutable constants be related to the age of the universe *now*? Too far bac
or forward in cosmic time, this obviously wouldn't be the case. Furthermore, at some other cosm
time, conditions might not allow for any intelligent life to be around to observe these coincidences
the first place! This was a rather pesky issue for a Copernican Principle, since it suggested there w
something special about when and where we found ourselves, and about the present physic
properties of the cosmos.

The final, definitive proof that the universe was finite in age came in 1965, with the discovery
an all-pervasive flood of microwave photons originating from the young cosmos—effectively part
the remains of a hot big bang. This trace of a very different universe, one that was once upon a tin
ferociously dense and energetic, was more than one fly in the ointment. It was a whole bucket of flie
dumped into the vat of Copernican mediocrity. And things came to a head in a famous presentation b
an Australian-born physicist named Brandon Carter in 1973.

Carter, who has played a central role in the modern development of black hole physics, wa
encouraged by the interest of a number of colleagues, including the physicist John Wheeler and
young Stephen Hawking. So he chose to stir things up at no less than a special conference in Krakow
Poland, held to commemorate the five hundredth anniversary of Copernicus's birth. In his talk, Cart
articulated the ideas that had been brewing among a number of scientists puzzling over all the
apparent coincidences between cosmic properties and our circumstances. He plunged into the thick
it by discussing just how different the universe might be if just a few characteristics were changed-
like the relative strength of the fundamental forces that glue matter together.

Considering these changes raised an intriguing idea that Carter elaborated on for his audience.
tweaked version of nature might, for example, make no stars, but since we come from the elemen
produced by stars, and since we are here observing the cosmos, this very fact can be used to tell
something about the universe we live in. In other words, our existence itself tells us something abo
the nature of physics in the universe—we might be more important than we thought. Carter labele
this approach to examining the cosmos as the "anthropic principle," since "anthropic" means th
something pertains to human existence. This wasn't exactly what he was driving at, since it could
any observer of the universe, not just humans. But although he later proposed a more semantical
accurate term, the word "anthropic" stuck.

The underlying sense of this approach to understanding the world is well summarized in Carter
own words at the time: "Copernicus taught us the very sound lesson that we must not assun
gratuitously that we occupy a privileged *central* position in the Universe. Unfortunately there has bee
a strong (not always subconscious) tendency to extend this to a most questionable dogma to the effe
that our situation cannot be privileged in any sense." The point being that one cannot, and should no
ignore the multitude of phenomena that apparently need to line up just right for life, and us, to exist.

Now, a great deal has been written about the anthropic principle. It's been a veritable gold min
for some physicists and many philosophers, and an often confusing and confounding topic for snak
eats-own-tail conversations over cocktails. Extreme versions of the principle have even bee
constructed to argue that a viable universe *must* produce intelligent life capable of observing it—

notion that I’m going to steer very clear of.

~~However, the anthropic principle is an important idea, one that prompts us to face some~~ of ou preconceptions about the cosmos around us and to examine our innate biases of observation. An since it directly challenges the Copernican Principle (or rather, what has come to be the orthodoxy o our mediocrity), we ought to look at a couple of the details.

* * *

These days, anthropic ideas tend to crop up mostly in discussions of a phenomenon called “fin tuning,” which involves a more detailed examination of the cosmic coincidences that originally led scientists’ puzzlement over these questions. The notion of fine-tuning goes as follows: if we loo carefully at a variety of properties of the universe, embodied in constants of nature such as th strength of gravity relative to other forces, or the proportions of matter and energy in the universe, w can see that were these properties to be changed by a small amount, life might not have arisen.

Except this tweaking is a little more complicated, because what we really mean is that objects lik stars and galaxies wouldn’t exist, or that they’d never forge the heavy elements, like carbon, that a so critical for the chemistry of life. So, in other words, a variety of primary cosmic functions wou fail to set the stage for the secondary ones that we rely on. This, of course, also presumes that life h to be like us—but it does seem hard to imagine how a universe of just hydrogen and helium could giv rise to structures with the complexity seen in carbon-based life.

Exactly which characteristics are most important to life’s existence is not immediately obviou The best way of narrowing down the possibilities comes from making clever mathematic combinations of quantities that in turn relate to tangible phenomena. The scientists Bernard Carr an Martin Rees did just this in 1979, and later on, in 1999, Rees revisited the ideas and came up with s numbers that have to lie within a comparatively narrow range for our universe to be the way it is, an to be amenable to life as we know it. These numbers are:

- the ratio of the strength of gravity to electromagnetic forces
- the percentage of matter that’s converted to energy by the nuclear fusion of hydrogen into helium
- the total density of normal matter in the universe
- the energy density of quantum vacuum fluctuations (which may be the same dark energy that is accelerating the expansion of our universe)
- the sizes of the minute variations in the early universe that eventually grew into such structures as galaxies and their groupings
- the actual number of spatial dimensions in our universe

It’s quite an array, and the odds appear extraordinarily low for any universe popping into existenc to—by chance—have all the necessary properties for life to arise. Of course, as you read this you ma be thinking to yourself, “But if it weren’t like this we wouldn’t be around to think about it; we simp have to exist in this type of universe.” And that’s absolutely correct. However, if this is the one an only universe, with no universe before or after it, that raises the uncomfortable question of why turned out this way: suitable for life.

One of the most appealing answers is that ours is only one of a near-uncountable array of viab universes. It is a single example of a type of reality that is separated by time and space, or dimensio from gazillions of others. The word “appealing” may seem almost comical here—I’ve just invoke what you might think is an unsubstantiated hypothesis for the nature of reality. But this idea of ~~“multiverse” is a leading contender for the deeper truth of the physical world. Indeed, when Brando~~ Carter came up with the anthropic principle he was already thinking along these lines.

Although I don’t think anyone could yet claim that we have direct evidence for there being multiverse, there are several compelling theoretical ideas that readily accommodate it, and that als seem to provide solutions to other aspects of fundamental subatomic physics and cosmology. correct, it would mean that there is no fine-tuning problem per se. We simply exist in one of th universes that happen to be “right” for the formation of galaxies, stars, heavy elements, and comple carbon chemistry. It sounds as if this would neatly resolve the issue, and in many respects it would— we actually knew that we lived inside a multiverse.

Another tricky thing about the multiverse solution is that it is still partially motivated by th notion that our particular universe is genuinely fine-tuned for life. It’s still thinking in pure anthrop terms—and in those terms it is assumed that life is entirely represented by us. One doesn’t need invoke any other life, or type of life, anywhere else in the cosmos to make this argument, and th seems a bit parochial. It would be like arbitrarily basing your entire philosophy of science on th existence of a particular type of unusual parrot. The last thing we want is to be misled up a dead-en alley. So it’s worth pursuing this further, because we don’t yet know if we live in a part of multiverse, and because none of the above gets us much closer to evaluating our immediate cosm significance, or lack thereof.

With only some very simple changes to our perspective on the universe, one can appreciate ho some aspects of fine-tuning and anthropic reasoning begin to look like a bit of a distraction in o quest for significance. I’ll visit some other ideas along these lines, but let’s kick off with th following—a playful question to make a serious point.

Let’s suppose for a moment that Galileo Galilei’s interpretations of his observations of th universe had been immediately embraced as a crowning achievement of reason and technolog Instead of being raked over the proverbial coals, he becomes the darling of the seventeenth-centu church and state. And in this alternative timeline the enlightened establishment seizes this moment initiate a grand technological push, seeing the potential economic benefit of engineering and science.

Flush with the warmth of acceptance and patronage, Galileo quickly sets to work buildin sophisticated telescopes that will let him become the first human to find planets around other star and to confirm the presence of biological systems across many of these worlds. It’s a lovely fantasy, horse- and water-powered science-fiction reworking of history, but most critically it also lets us as how things would be different *today* if this had really happened.

For the intervening centuries we would have known that life was not confined to Earth alone, an we might even have figured out if any of it was more than just microbes or uncommunicativ creatures. In either case, the point is that we would have at our fingertips a real answer to the questio of how likely, or how unusual, our type of life is in this universe.

Let’s suppose that in this parallel reality we find that life resembling Earth’s is moderatel common. It occurs often, but it’s neither spilling across every suitable world, nor so unusual that exists only in certain galaxies sparsely distributed across the universe. What then of the fine-tunin arguments embedded in the anthropic ideas about cosmology? It might not even occur to us to as these questions in the first place. It would be like suddenly deciding to question why the wor produces a certain number of snails. But even if we did ask, the notion of “tuning” doesn’t exact hold up so well in this hypothetical reality.

The universe would appear to be suitable for producing only *some* life, hardly the stuff of gre cosmic significance; a modestly fertile pond of occasionally making something functional. Now ~~course we could also discover that the answer lies at one of two possible extremes: from life~~ as a utterly freakish rarity across 14 billion years' worth of cosmic time, to life run amok, clogging ever planetary system with some new variant.

In the former case we'd hardly think the universe was well suited to life, and the coincidence physical parameters with the requirements of life would just be seen as a cruel joke. By contrast, the latter case we might deduce that life itself, not so much the cosmic underpinnings, is a remarkab robust phenomenon. We might even be asking whether there were any (almost unimaginable circumstances in which life could *not* spring from the underpinnings of the physical laws.

There are two points to make here. The first is trivial, and it is that the questions we end up askin are themselves a direct function of what we've already observed about our surroundings. The secon is much more important, because unlike the inhabitants of my fantasy Earth with its alterna astronomical history, we do not know at present which of the above scenarios applies in this universe

Furthermore, fine-tuning may not be a make-or-break situation. Instead it could be a "coars tuning" problem with the real fine-tuning hidden inside. As in my fictional example, the issue of th universe being suitable for life is not an all-or-nothing question. It could rest within a spectrum fertility and likelihood. In fact, I think that there is an implicit assumption in anthropic arguments th life is a bit wimpy, that it must have everything perfectly aligned or else it won't happen.

Yet we know from the abundant and remarkable wealth of paleontological evidence on Earth th brutal natural selection has allowed life to fine-tune *itself* to the environment around it. In the face varying chemical mixes and abundances of vital elements, as well as a multitude of different sourc of energy, life has found a way. Admittedly this is within a set of circumstances determined by th basic laws of the universe. But life on Earth has become diverse enough to exploit a variety secondary biochemical strategies—not just a single one.

It's not obvious that life needs anything more than a rough-and-ready environment to originate an survive in. So true cosmological fine-tuning should be more about the particular ease with which li can occur—and for now, at least, I make no distinction between intelligent life and "simple" lif since there's nothing simple about life in any form.

* * *

This way of looking at things is consistent with studies of the coincidences of physical constants an other quantities such as the proportions of mass and energy in the universe. In most of these cas there is a little bit of wiggle room—an issue well illustrated by the way in which elements a produced by nuclear fusion inside large stars.

During the first half of the twentieth century, scientists realized that conditions inside stars coul give rise to the fusion of atomic nuclei, powering their prodigious energy output and forging heavi and heavier elements. But the recipes were not straightforward, and in the early 1950s the Englis physicist Fred Hoyle realized that there was a problem with carbon. At the time, physicists' emergin theories of stellar fusion were suggesting that stars should make relatively little carbon. But Hoy observed that since we're made with carbon, the universe must actually have a way to generate plen of it. This puzzling discrepancy helped prompt him to find that carbon-producing process.

He discovered that carbon gets readily formed in the universe because of a specific phenomeno The energy of one of the stages involved in combining three helium nuclei in a star's interior almo exactly matches that of an agitated carbon nucleus—which is the natural product of combining tho three helium nuclei. This correspondence results in what's called a nuclear resonance, a harmonizin of energy states that boosts the efficiency of the nuclear reaction enormously, so that, instead of sta making almost no carbon, they can make lots of it.

For a long time, the carbon resonance was considered one of the strongest pieces of evidence f an anthropic principle to be in play—namely, the existence of carbon and carbon-based life itse suggested this special nuclear process in stars. This is true, but only up to a point, because there is devil in the details. We now know that these nuclear energies need not match so precisely for carbo to be produced: there's a certain amount of leeway, and so the fine-tuning is not quite so fine after al And the same is true of many of the fine-tuning parameters. Things could be a teeny bit different ar conditions would still be passably okay for life as we know it.

The concept of such wiggle room goes deeper still. If we are able to eventually *measure* th propensity of the universe for making life—the efficiency, or density, with which life occurs in ar given patch of the cosmos—we will have a new tool for probing the basic properties of nature and f *predicting* the occurrence of life according to those fundamental circumstances.

This is not to say that there is necessarily something "special" about life but rather that life is a excellent example of a highly complex phenomenon, and one that is conceivably the most complicate in the cosmos, with an intricate web of connections to many key features of the physical laws in th universe. As such, life represents a natural litmus test of cosmic properties, a canary in a cage fo examining the detailed interplay between characteristics where there are a vast array of potenti permutations and combinations.

This is more than rephrasing the anthropic argument. At its core that argument states that a so occurrence of life yields predictions about the universe. Instead I'm proposing a way to learn how take the properties of the universe and predict the abundance of life, and therefore predict o significance. It's a bit like taking an opinion poll and using that to predict the outcome of an election

* * *

The catch is that we have developed a bit of a complex thanks to Copernicus, whose ideas so clear and accurately describe our solar system, and who helped break us out of a deep and awful rut provinciality. The apparent confirmation of our unprivileged ordinariness is surprisingly compellin (flying as it does in the face of all our solipsistic and egotistic tendencies), and it has allowed us make extraordinary progress in understanding the universe around us, as well as the universe with us. But it creates some confusing situations.

On the face of it, the Copernican Principle suggests that we *cannot* be alone in the universe; we a neither central nor special, and our circumstances should be representative of the circumstances in ar number of physical locations at this point in the history of the universe.

So, by that logic, not only should there be plenty of other life out there, but a great deal of it shou be very similar to that on Earth. But is the assumption of our own averageness really a sound basis f making such an argument? It smacks of an overly literal reading of the scientific gospel. Copernicu was simply trying to understand the motions of planets in our solar system in the least contrived ar most mathematically logical way. Are we reading too much into what was primarily a mechanic solution to a mechanical problem?

Recognizing the limitations of the Copernican Principle is not a particularly controversi suggestion. Anthropic ideas are one good example of a counterpoint, and many astronomers ar physicists find similar clues in some straightforward aspects of our circumstances. The fact that v are so manifestly located in a specific place in the universe—around a star, in an outer region of galaxy, not isolated in the intergalactic void, and at just this time in cosmic history—is simpl