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Introduction: mysterious skies

1.1 Three mysteries

Throughout recorded history humans have watched the sky. They have marveled not only at the beauty of the Sun, the Moon, and the stars, but also at the motions of these objects across the sky. In tracking the motions of these heavenly objects they encountered three fundamental mysteries. This book is about how those mysteries were solved … and then solved again (and again).

The first mystery is revealed by even casual observation of the heavens. The Sun moves westward across the sky throughout the day. The Moon displays a similar westward motion that may be visible during the day or the night. Likewise, the stars move westward throughout the night but they do not seem to move *relative to each other*. They maintain fixed patterns that we have come to associate with pictures known as constellations. Why do these lights in the sky move in this way? That's the first mystery.

Uncovering the second mystery requires much more than an occasional glance at the sky, but careful observations made over weeks or months show that the Sun moves relative to the fixed pattern of the stars. Even easier to spot is the motion of the Moon relative to the stars. Much harder to see, but still discernable to the careful observer, is the fact that five of the stars don't maintain their positions in the fixed pattern held by the thousands of other stars visible to the naked eye. Like the Sun and Moon, these five "wandering stars" move around relative to the "fixed stars." Why do these seven objects move around relative to the thousands of fixed stars that seem to form a static pattern? That is the second mystery.

Once these seven wanderers were identified, people began to track their motions against the background of the fixed stars. They found that the Sun and Moon move steadily eastward against this background. In fact, the Sun and Moon both move through the same set of constellations so they not only move in the same direction against the starry background but they also follow nearly the same path. The five wandering stars are usually seen to trudge along that same path, moving eastward against the starry background like the Sun and Moon. Occasionally, though, one of these wanderers will halt its eastward motion through the fixed stars, move westward for a while, stop again, and then resume its eastward motion. What could possibly make these wandering stars move in this bizarre way? That is the third, and perhaps the deepest, mystery. It was the key that unlocked the secret of the heavens.

The story begins with careful observations of the sky, like those made by ancient Babylonian astronomers. From the 2nd century BC to the 2nd century AD, ancient Greek astronomers built on this observational foundation and created sophisticated geometrical models to explain the mysterious motions. Their models assumed what seemed to be obvious: that the Earth sat stationary while the heavens moved around it. The mysteries, it seemed, were solved.

The solutions proposed by the ancient Greeks were so successful that they went largely unchallenged for 1400 years. Then, in 1543, Nicolaus Copernicus published a book that offered a new solution to these mysteries. The model proposed by Copernicus made sense of the strange forward-and-back motions of the wandering stars in a way that the ancient Greek models did not, but Copernicus' theory was not easy to accept. He proposed something that went against common sense: he suggested that the Earth moves. He claimed that the Earth spins around and also that the Earth and all of the wandering planets, but not the Moon, orbit around a stationary Sun that rests near the center of the "solar system."

At first astronomers and natural philosophers could not make sense of Copernicus' idea and his theory was not widely adopted. But a few astronomers found Copernicus' model compelling and they worked to refine and further explain his ideas until they became acceptable. By the end of the 17th century astronomers had reached a deep understanding not only of how the Earth and the wandering stars (or planets) move, but why they move that way. The ancient Greek theory was dead and the motions of the Earth became common knowledge.

The transition from the Earth-centered (or "geocentric") universe of the ancient Greeks to the Sun-centered (or "heliocentric") solar system that we accept today is known as the "Copernican Revolution." This book tells the story of the Copernican Revolution from ancient observations of the skies to the explanation of planetary motions in terms of a universal gravitational force in the 17th century and beyond.

The full story of the Copernican Revolution involves politics, religion, social and economic change, literary traditions, translation, intercultural exchange, patronage, personal rivalries, war, plague, and death. No single book could hope to address all aspects of this story. While this book will touch on these issues, it aims primarily to tell the *scientific* story of the Copernican Revolution, focusing on observations and experiments, mathematical models and scientific theories, instruments and measurement techniques, and the principal works of the scientists who sought to understand the operations of the heavens.

1.2 Why should you read this book?

Why, though, would you want to know the scientific story of the Copernican Revolution? After all, you already know the punch line: the Earth really does spin on its axis and orbit the Sun. Copernicus was right about that. You learned that in grade school. Case closed. But do you know *why* we believe that the Earth moves? If you think about it, the motions of the Earth are certainly not obvious.

In a way, this book is like a mystery novel in which you already know the answer to the puzzle. Even though you know the answer, the story of how that answer was discovered is fascinating. One thing that makes it particularly fascinating is that the answer we accept today was not the first answer to this puzzle. How did the ancient Greeks reach conclusions that differ so dramatically from our modern understanding? Once they had found their solution, how (and why) did we come to abandon that solution and accept a completely different one?

That story is a fascinating tale full of twists and turns, heroic effort, and brilliant insight. It is one of the great human stories. The geocentric theory of the universe developed by the ancient Greeks was one of humanity's great intellectual achievements. The heliocentric theory proposed by Copernicus and finalized by Isaac Newton is an even greater achievement. The change from a geocentric to a heliocentric perspective radically altered the way people thought about the universe and our place in it. That change affected far more than just astronomy: it had a tremendous impact on religion, philosophy, and other facets of society and it paved the way for modern science as we know it.

Let's briefly consider just one impact of the Copernican Revolution: the possibility of extra-terrestrial life. In the ancient Greek cosmos Earth was a unique place. The heavens were fundamentally different and could not serve as a home to "life as we know it." But in the heliocentric system proposed by Copernicus the Earth was just one planet among many. If there was life on Earth, then why not on other planets? Furthermore, if the Sun was just one star among many then why couldn't those other stars have planets, and life, of their own? The idea that there might be other life "out there," perhaps even creatures more intelligent than us, gave us a completely new perspective on ourselves. The Copernican Revolution didn't just change astronomy, it changed our views on what it means to be human. The story of such a profound change is one worth knowing.

It is also worth knowing the story of the Copernican Revolution because it is good to occasionally question the things you have been told. Most people learn about the motions of Earth from trusted authorities such as their parents or teachers. There is nothing wrong with believing what you are told by people you trust. In practice, we all must accept many things that we are told or we couldn't get on with life. But every now and then it is good to examine the evidence for yourself and see if you are convinced, and evaluate the arguments to see if they are valid. This exercise will improve your critical thinking skills and help you spot flawed arguments and invalid claims in other parts of your life. Inevitably, you will encounter such arguments and claims and it helps to be prepared for them.

You may have even heard invalid claims about the Copernican Revolution. In one version of the story the ancient Greek theories of the universe are silly and obviously wrong, and the only reason people did not immediately accept the Copernican theory was because of opposition by religious authorities. You may have heard that Copernicus was persecuted for proposing his heliocentric theory, or that people objected to the heliocentric theory because it "demoted" the Earth from its prime location at the center of the universe. None of these things is true. The real story is much more complicated, but also much more interesting.[1]

Perhaps the best reason to learn the *scientific* story of the Copernican Revolution, though, is that it will help you understand the nature of science. Science is a complex activity that cannot be reduced to a short list of rules and procedures, in spite of what your grade school teachers may have told you (see, sometimes you have to question authority!). That simplified version of the "scientific method" might be appropriate for young students first learning about science, but real science is much more complicated, messy, creative, and exciting. Learning the scientific story of the Copernican Revolution will help you better understand how science is really done, how scientific theories are proposed and evaluated, and how our scientific knowledge grows.

In fact, you can gain a better understanding of the nature of science by reading about the history of science than you can from reading a standard science textbook. Most science textbooks focus on the end products of science, the knowledge that is provided by our best current theories. An understanding of the end products of science is important if you want to *use* scientific knowledge, so science textbooks have good reason for focusing on current knowledge, but knowing how to use something is different from knowing how it was created. You may be able to drive a car, but do you know how that car was built? If you want to know how scientific knowledge is obtained, the best approach may be to do some scientific research yourself, but that option is not available to most people. The next best way to learn about the nature of science is to learn about the history of science.

The historical approach to science emphasizes *how* we learned what we know rather than just *what* we have learned. It shows that science is the creation of human beings, not something that fell from the sky. Science requires a lot of hard work and creativity. Science is difficult and the methods of science are far from infallible. Sometimes scientists get things wrong. By learning about the history of science you can glimpse this human side of scientific inquiry. The history of science shows how difficult it is to gain new scientific knowledge and how easy it is to go astray. It also shows how great effort and persistence can pay off as we gain not just new scientific knowledge, but also insight into how to determine when that knowledge is reliable and when it is not.

Another advantage of the historical approach to learning about science is that it automatically starts from relatively simple ideas and works up to more complicated and difficult theories. Building from the ground up makes it easier to understand the science at a deep level, and therefore it puts you in a better position to understand what the scientists were doing at each stage of the story. Importantly, a historical account of science *is* a story. We often learn best through stories, and the story of the Copernican Revolution provides an excellent opportunity to learn about the nature of science.

1.3 The nature of science

The scientific story of the Copernican Revolution describes the change from one scientific theory, the geocentric theory of the universe, to another, the heliocentric theory of the solar system. But what are scientific theories? What are they used for and how do we judge them? Scientific theories are complex things and this book cannot hope to provide a thorough discussion of every aspect of scientific theories. For the most part, we will simply examine particular theories in their historical context and see how they were used and evaluated by actual scientists. However, it may help to start by briefly considering in general what scientific theories are supposed to do.

First and foremost, scientific theories are supposed to fit with observed phenomena. That might mean that we expect our theories to reproduce previously observed phenomena in a qualitative way (e.g. the Sun has risen in the east every morning of your life). It might also mean that we expect them to provide qualitative predictions for as yet unobserved phenomena (e.g. the Sun will rise in the east tomorrow morning).

For some types of theories, particularly mathematical theories, we expect the theory to provide a quantitative fit to the data. That means our theories should be able to produce numerical values that agree with prior quantitative measurements, as well as successfully predict the numerical values of future measurements (e.g. the Sun will rise tomorrow at 6:43 AM and will be first visible at a point on the horizon that is 12° south of due east). Of course, any quantitative theory is likely to have uncertainties and errors due to flaws or approximations in the theory or because of inaccuracy of the numerical parameters that go into the theory. Note that, whether a theory is qualitative or quantitative, it is only meaningful if it is possible for observations to contradict the theory. A theory that can be made to fit with any conceivable observational result is not much of a theory at all.

We may also expect our theories to do more than just fit with our observations. We may expect them to *explain* what we observe. Ideally we would like for the observed phenomena to follow necessarily if the world is the way our theory says it is. In that case the theory doesn't just reproduce our observations, it purports to tell us what is really going on that results in the phenomena we observe. Of course, it is possible that more than one theory can successfully explain the same set of observations, so even if a theory seems to explain what we see that doesn't mean the world really works that way.

If we do expect our theories to tell us how the world really works, then we must demand that our successful theories don't contradict each other. If two theories give different predictions for some observable phenomenon, then they can't both be correct descriptions of how the world works. We would like for our best scientific theories to fit together to provide a coherent picture of the physical world. If our theories do contradict, then at least one of them must not be a correct description of the world, but the contradiction alone does not tell us which one is wrong and which one (if any) is right.

Finally, we may expect our theories to be beautiful. Beauty, of course, is subjective. However, we often expect our theories to be simple, to not involve too many "adjustable parameters," to not have many exceptions or caveats, to be, in a word, elegant. Many of our best theories, once we fully understand them, make us say "of course it must be that way!"

It can be helpful to think about scientific theories in terms of an analogy. Scientific theories are, in some ways, like maps. Like maps, scientific theories are created for a specific purpose (or set of purposes). Different purposes require different types of maps. If you are driving through a city you might want a street map, but if you are planning a hike in the wilderness a topographic map might be more useful. Maps are supposed to mimic some aspects of the physical world, but they also ignore many other aspects that aren't important for the map's intended purpose. For that reason maps, like scientific theories, are always approximate. They are never exact in every possible detail, and that's a good thing. Think about how useless would be a map of London that was exact in every detail. For one thing, it would have to be constantly updated in order to be accurate. Even worse, it would be so complicated that using the map would be no easier than simply walking around London itself!

This map analogy leads to some interesting questions. How might we expect different maps of the same area to relate to each other? What happens if we try to use a map for some purpose other than that for which it was intended? Could we create a map that, although it would not be exact in every detail, might provide concise and accurate information suitable for a wide variety of purposes? Even if we could, would we be able to claim that such a map was true? What does it even mean for a map to be true? We can ask similar questions about scientific theories.

We can also consider some helpful analogies for the process of doing science. In some ways science is like putting together a jigsaw puzzle. We want to fit all of the pieces together to form a coherent and sensible picture. Sometimes you can't tell if the pieces form a sensible picture until several more pieces are added to the puzzle.

If science is like solving a jigsaw puzzle, then that puzzle is an extremely challenging one. For one thing, the puzzle doesn't have well-defined boundaries. You certainly can't look at the box cover to see if you are "getting it right." There are lots of missing pieces … and there always will be. In fact, in real science the pieces don't come pre-cut. Scientists have to cut their own pieces by performing experiments and making observations. Each piece serves as a tiny window into the nature of the physical world, but the shape of those pieces and the picture they show depends very much on choices made by the scientist: what they choose to observe and how they make their observations. It is possible that these "slices of reality" could be cut along natural "seams," but we have no way to know in advance what those seams are.

When we find that some pieces don't fit together it may be because they really don't connect to each other in the puzzle, but it may also be that we have just cut the pieces the wrong way. We might even end up with false pieces that aren't part of the puzzle at all. How can we ever know if our puzzle is correct or complete? In practice, we probably can't know. However, we can still feel that we are making progress if we are able to fit more and more pieces into the puzzle in a way that seems to form a coherent and sensible picture.

Doing science is also a bit like cooking. Great chefs follow recipes, to be sure, but they also modify recipes and even invent entirely new ones. They use some standard cooking techniques (baking, grilling, frying, etc.) but the results they get will depend on how they blend different techniques and different ingredients to create something new. In a similar way, scientists use some standard methods to make observations, perform experiments, and build models and theories. But how it all comes out will depend on the creative ways in which they combine these methods and the ingredients (data, theories, assumptions) they use in their work. Just as the greatest chefs may invent new techniques for cooking, so too the greatest scientists sometimes invent new methods for scientific inquiry. Success in science, as in cooking, can be subjective, but often we can achieve widespread agreement about failure. Skilled scientists, like skilled chefs, obtain their skill by practicing constantly and overcoming repeated failures.

Finally, science is like art or literature. Artists create art because it pleases them to do so. Likewise, scientists do science because it brings them joy to make a novel observation or develop a successful new theory. Scientific work can be tedious and difficult, but at times it is thrilling.

Like a great work of art, great science can (and should) be appreciated by others. Just as knowledge of artistic and literary techniques can help someone appreciate a work of art or literature, so knowledge of the nature of science can help someone appreciate a great scientific accomplishment like the Copernican Revolution. It is our hope that this book will help you appreciate this great human achievement, just as you should appreciate the great works of art and literature.

1.4 Changing knowledge

This book describes theories that were developed to explain the observed motions of the heavens, as well as the process by which those theories were developed and tested. However, this book is primarily about the change from the geocentric picture of the world to the heliocentric picture of the solar system. To understand the process of theory change it may help to consider what happens when we abandon one theory in favor of another.

As mentioned earlier, we often expect our theories to *explain* observed phenomena. We want the theory to tell us what is really going on that led to our observations. A theory gives meaning to our observations. When we make observations we *see* a phenomenon, but a theory allows us to see that phenomenon *as* something meaningful. Theories let us see our observational data as the outcome of processes that are not directly visible to us.

Because more than one theory can explain the same set of data, it is possible to see a certain set of observations as being two (or more) different things. When

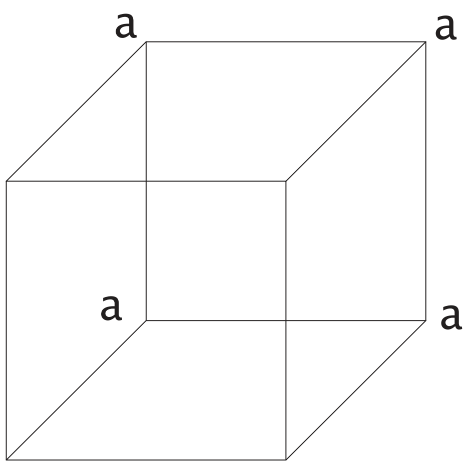

Figure 1.1 A Necker cube. The face whose corners are labeled with the letter a could be at the front or at the back of the cube.

we abandon one theory and adopt another we go from seeing our data as one thing to seeing them as something else.

Something analogous can happen in our visual perception. We can view a certain visual image and see it as a certain object, but then we may find that it is possible to view the same visual image as a different object. Changing from seeing the image as one thing to seeing it as a different thing is known as a "gestalt shift." One of the classic gestalt shifts can be generated by looking at the "Necker cube" shown in Figure 1.1. The image itself consists of several straight line segments, but our visual system tends to assign meaning to these line segments by seeing them as a projection of a three-dimensional cube. But there is some ambiguity in our interpretation of the image. One of the "faces" of the cube in Figure 1.1 has labeled corners. It is possible to see that labeled face as being at the front of the cube, but it is also possible to see the labeled face as being at the back of the cube.

In both cases the viewer is seeing the same visual image, but the visual image is interpreted differently. It is possible for a viewer to switch back and forth between the two different interpretations, first seeing the labeled face as the back of the cube, then seeing it as the front of the cube, and so on. Although this is a particularly simple example of a gestalt shift, it is analogous in some ways to the shift between the geocentric and heliocentric viewpoints in astronomy. Both geocentric and heliocentric astronomers saw the same lights in the sky moving in the same way, but they interpreted those motions very differently.

In an isolated image like the one in Figure 1.1 it may be impossible to decide which interpretation is "correct." However, if that image is put into a

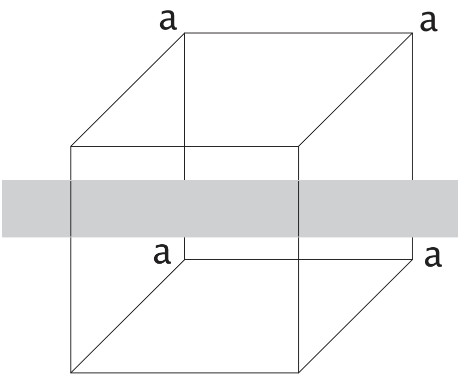

Figure 1.2 A gray bar passing through the Necker cube in Figure 1.1 provides clues to the cube's orientation. In this case the labeled face must be at the back of the cube.

relationship with other images then that relationship can provide clues about how best to interpret the original image. For example, Figure 1.2 shows the original Necker cube but this time with a gray bar passing through the image. Careful inspection of which lines are blocked by the gray bar, and which are not, suggests that in this Necker cube the labeled face is at the back of the cube so that we can consistently interpret the gray bar as passing through the middle of the cube.

In a similar way, astronomers had no good way to decide between the geocentric and heliocentric viewpoints when all they considered was the motions of lights in the heavens. However, astronomers did not judge their astronomical theories in isolation from everything else. They judged them in the context of other knowledge, particularly theories about how things move. Originally these theories of motion seemed to indicate that the geocentric viewpoint was correct. The heliocentric theory was inconsistent with ancient physics in the same way that the appearance of the gray bar in Figure 1.2 is inconsistent with the labeled face being at the font of the cube.

When we change from one theory to another, that change can lead to conflict with other knowledge, just as viewing the Necker cube as having the labeled face in front is inconsistent with the appearance of the gray bar in Figure 1.2, or it may help to resolve conflicts that already existed. When theory changes occur, scientists are left to sort out all of the conflicts with existing knowledge that may arise from the new theory. As we will see, an important part of the story of the Copernican Revolution deals with the way scientists resolved the conflict between the heliocentric model and ancient theories about motion. Viewing the heavenly motions from a new perspective ultimately led us to think differently about *all* motions.

The Necker cube is a simple example in that it presents two obvious interpretations and we just have to choose between those two. Real science deals with much more complicated situations, and it can be hard to formulate even one theory that can adequately explain the available data while remaining consistent with our other knowledge. Because of that difficulty, once we have found an interpretation that seems to work we may be very reluctant to let go of it. The gestalt shift from a geocentric universe to a heliocentric solar system was not an easy change to make, and Copernicus' proposal was not widely accepted until about two hundred years after he published it.

To understand why the Copernican Revolution took so long, and why it happened at all, we need first to understand the geocentric theory that was overthrown in that revolution. We need to know why the ancient Greeks believed in a geocentric universe. To understand their reasons for adopting a geocentric theory we must first carefully examine what they saw in the skies.