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Introducing Life in the Universe

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▲ **About the photo:** Earth is home to an abundance of life, making us wonder if other worlds might also be home to life.

1 A Universe of Life?

OVERVIEW

Sometimes I think we're alone in the universe, and sometimes I think we're not. In either case the idea is quite staggering.

Arthur C. Clarke (1917–2008)

LEARNING OBJECTIVE

Chapter 1 Overview

The night sky glitters with stars, each a sun, much like our own Sun. Many stars have planets, some of which may be much like Earth and other planets of our own solar system. Among these countless worlds, it may seem hard to imagine that ours could be the only home for life. But while the possibility of life beyond Earth might seem quite reasonable, we do not yet know if such life actually exists.

Learning whether the universe is full of life holds great significance for the way we view ourselves and our planet. If life is rare or nonexistent elsewhere, we will view our planet with added wonder. If life is common, we'll know that Earth is not quite as special as it may seem. If civilizations are common, we'll be forced to accept that humanity is just one of many intelligent species inhabiting the universe. The profound implications of finding—or not finding—extraterrestrial life make the question of life beyond Earth an exciting topic of study.

The primary purpose of this book is to give you the background needed to understand new and exciting developments in the human quest to find life beyond Earth. We'll begin in this chapter with a brief introduction to the subject and to why it has become such a hot topic of scientific research.

LEARNING OBJECTIVE

Goals of Astrobiology

1.1 The Possibility of Life Beyond Earth

Aliens are everywhere, at least if you follow the popular media (Figure 1.1). Starships on television and in movies are on constant prowl throughout the galaxy, seeking out new life and hoping it speaks English (or something close enough to English to be understood by a "universal translator"). In *Star Wars,* aliens from many planets gather at bars to share drinks and stories, and presumably to marvel at the fact that they have greater similarity in their level of technology than do different nations on Earth. Closer to home, movies like *Independence Day, Men in Black,* and *War of the Worlds* feature brave Earthlings battling evil aliens—or, as in the case of *Avatar,* brave aliens battling evil humans—while numerous websites carry headlines about the latest alien landings. Even serious newspapers and magazines run occasional articles about UFO (or UAP*) sightings or about claims

FIGURE 1.1
Aliens have become a part of modern culture, as illustrated by this movie poster.

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*UAP stands for "unidentified aerial phenomena," which is sometimes used (particularly within the U.S. military) as an alternative to UFO, which stands for "unidentified flying object."

that the U.S. government is hiding hardware or alien corpses at "Area 51."

Scientists are interested in aliens too, although most scientists remain deeply skeptical about reports of aliens on Earth (for reasons we'll discuss later in the book). Scientists are therefore searching for life elsewhere, looking for evidence of life on other worlds in our solar system, trying to learn whether we should expect to find life on planets orbiting other stars, and scanning for signals broadcast by other civilizations. Indeed, the study of life in the universe is one of the most exciting fields of active scientific research, largely because of its clear significance: The discovery of life of any kind beyond Earth would forever change our perspective on how we fit into the universe as a whole, and would undoubtedly teach us much more about life here on Earth as well.

1.1.1 What are we searching for?

When we say we are searching for *life* in the universe, just what is it that we are looking for? Is it the kind of intelligent life we see portrayed in science fiction TV shows and films? Is it something more akin to the plants and animals we see in parks and zoos? Is it tiny, bacteria-like microbes? Or could it be something else entirely?

The simple answer is "all of the above." When we search for **extraterrestrial life**, or life beyond Earth, we are looking for any sign of life, be it simple, complex, or intelligent. We don't care if it looks exactly like life we are familiar with on Earth or if it is dramatically different. However, we can't really answer the question of what we are looking for unless we know what life *is*.

Unfortunately, defining life is no simple matter, not even here on Earth where we have bountiful examples of it. Ask yourself: What common attributes make us think that a bacterium, a beetle, a mushroom, a tumbleweed, a maple tree, and a human are all alive, while we think that a crystal, a cloud, an ocean, or a fire is not? If you spend just a little time considering this question, you'll begin to appreciate its difficulty. For example, you might say that life can move, but the same is true of clouds and oceans. You might say that life can grow, but so can crystals. Or you might say that life can reproduce and spread, but so can fire. We will explore in Chapter 5 how scientists try to answer this question and come up with a general definition of life, but for now it should be clear that this is a complicated question that affects how we search for life in the universe.

Because of this definitional difficulty, the scientific search for extraterrestrial life in the universe generally presumes a search for life that is at least somewhat Earth-like and that we could therefore recognize based on what we know from studying life on our own planet. Science fiction fans will object that this search is far too limited, and they may be right—but we have to start somewhere, so we begin with what we understand.

Think About It Name a few recent TV shows and movies that involve aliens of some sort. Do you think any of these shows portray aliens in a scientifically realistic fashion? Explain.

1.1.2 Is it reasonable to imagine life beyond Earth?

The scientific search for life in the universe is a relatively recent development in human history, but the idea of extraterrestrial life is not. Many ancient cultures told stories about beings living among the stars and, as we'll discuss in Chapter 2, the ancient Greeks engaged in serious philosophical debate about the possibility of life beyond Earth.

Until quite recently, however, all these ideas remained purely speculative, because there was no way to study the question of extraterrestrial life scientifically. It was always possible to *imagine* extraterrestrial life, but there was no scientific reason to think that it could (or could not) really exist. Indeed, the relatively small amounts of data that might have shed some light on the question of life beyond Earth were often misinterpreted. Prior to the twentieth century, for example, some scientists guessed that Venus might harbor a tropical paradise—a guess that was based on little more than the fact that Venus is covered by clouds and closer than Earth to the Sun. Mars was the subject of even more intense speculation, largely because a handful of scientists thought they saw long, straight canals on the surface [Section 8.1]. The canals, which don't really exist, were cited as evidence of a sophisticated martian society.

Today, we have enough telescopic and spacecraft photos of the planets and large moons in our solar system to be quite confident that no civilization has ever existed on any of them. The prospect of large animals or plants seems almost equally improbable. Nevertheless, scientific interest in life beyond Earth has exploded in the past few decades. Why?

We'll spend most of the rest of the book answering this question, but we can summarize the key points briefly. First, although large, multicellular life in our solar system seems unlikely anywhere but on Earth, recent discoveries in both planetary science and biology make it seem plausible that simpler life—perhaps tiny microbes—might exist on other planets or moons of our solar system. Second, while we've long known that the universe is full of *stars*, we've only recently gained concrete evidence that it is also full of *planets*, which means there are far more places where we could potentially search for life. Third, advances in both scientific understanding and technology now make it possible to study the question of life in the universe through established techniques of science, something that was not possible just a few decades ago. For example, we now understand enough about biology to explore the conditions that might make it possible for life to exist on other worlds, and we know enough about planets, and many of their moons, to consider which ones might be capable of harboring life. We are also rapidly developing the spacecraft technology needed to search for microbes on other worlds of our solar system and the telescope technology needed to look for signs of life among the stars.

The bottom line is that while it remains possible that life exists only on Earth, we now have plenty of scientific reasons to think that life might be widespread and that we might detect it if it is.

LEARNING OBJECTIVE

Three Contexts

1.2 The Scientific Context of the Search

Almost every field of scientific research has at least some bearing on the search for life in the universe. Even seemingly unrelated fields such as mathematics and computer science play important roles. For example, we use mathematics to do the many computations that help us understand all other areas of science, and we use computers to simulate everything from the formation of stars and planets to the ways in which the molecules of life interact. However, three disciplines play an especially important role in framing the context of the scientific search for life: astronomy, planetary science (which includes geology and atmospheric science), and biology.

1.2.1 How does astronomy help us understand the possibilities for extraterrestrial life?

For most of human history, our conception of the cosmos was quite different from what it is today. Earth was widely assumed to be the center of the universe. Other planets of our solar system were mere lights in the sky, often named for mythical gods, and no one had reason to think they could be *worlds* on which we might search for life. Stars were simply other lights in the sky, distinguished from the planets only by the fact that they remained fixed in the patterns of the constellations, and few people even considered the possibility that stars might be other suns. Moreover, with the Sun and planets presumed to be orbiting around Earth, there was no reason to think that stars could have planets of their own, let alone planets on which there might be life.

When you consider that this Earth-centered, or **geocentric,** view of the universe dominated human thinking for thousands of years, it becomes obvious that astronomy plays a key role in framing the context of the modern search for life. We will discuss in Chapter 2 how and why the human view of the cosmos changed dramatically about 400 years ago, and we'll consider the modern astronomical context in some detail in Chapter 3. But the point should already be clear: We now know that Earth is but one tiny world orbiting one rather ordinary star in a vast cosmos, and this fact opens up countless possibilities for life on other worlds.

Astronomy provides context to the search for life in many other ways as well, but one more is important enough to mention right now: By studying distant objects, we have learned that the physical laws that operate in the rest of the universe are the same as those that operate right here on Earth (Figure 1.2). This tells us that if something happened here, it is possible that the same thing could have happened somewhere else, at least in principle. We are not the center of the universe in location, and we have no reason

FIGURE 1.2
The astronomical context tells us that our Sun is an ordinary star in a vast universe, implying that there could be an enormous number of stars with planets that might potentially host life. This Hubble Space Telescope photo shows a cluster of young, massive stars (NGC 3603) surrounded by a gas cloud in which Sun-like stars may still be forming. Careful study of distant stars and gas clouds shows that they are made of the same basic chemical elements and obey the same physical laws that we are familiar with on Earth.

to think we are "central" in any other way, either. To summarize, the astronomical context makes it clear that the universe holds an enormous number of stars that could potentially be orbited by planets with life.

1.2.2 How does planetary science help us understand the possibilities for extraterrestrial life?

Planetary science is the name we give to the study of almost everything having to do with planets. It includes the study of planets themselves, as well as the study of moons orbiting planets, the study of how planets form, and the study of other objects that may form in association with planets (such as asteroids and comets). Planetary science helps set the context for the search for life in the universe in several different ways, but two are especially important.

First, by learning how planets form, we develop an understanding of how common we might expect planets to be. Until just about the middle of the last century, we really had no basis for assuming that many other stars would have their own planets. Some scientists thought this likely, while others did not, and we lacked the data needed to distinguish between the two possibilities [Section 3.5]. But during the latter half of the twentieth century, a growing understanding of the processes by which our own solar system formed—much of it based on evidence obtained through human visits to the Moon and spacecraft visits to other planets—gradually made it seem more likely that other stars might similarly be born with planetary systems.

Nonetheless, as recently as 1995, no one was sure whether planets encircled other stars.* That was the year in which scientists obtained the first strong evidence for the existence of **exoplanets**, or planets outside our solar system (*exo* means "outside" or "external to"). Since that time, additional exoplanets have been discovered at an astonishing rate, so that the number of known exoplanets now far exceeds the number of planets of our solar system (Figure 1.3). Based on the statistics of these discoveries, it seems highly likely that most stars have planets and, as we'll discuss in Chapter 11, it seems reasonable to imagine that life—and possibly even civilizations—could exist on at least some of these planets or their moons.

A second way in which planetary science shapes the context for the search for extraterrestrial life is by helping us understand why planets differ. For example, by studying planets and comparing them to one another, we have learned why some planets are rocky like Earth while others, like Jupiter, lack a well-defined surface and contain vast amounts of hydrogen and helium gas. We've also learned why Venus is *so* much hotter than Earth despite the fact that, in the scheme of our solar system, it is only slightly closer to the Sun. Similarly, we can now explain why the Moon is desolate and barren even though it orbits the Sun at essentially the same distance as Earth, and we have a fairly good idea of why Mars is cold and dry today, when evidence shows that it was warmer and wetter in the distant past.

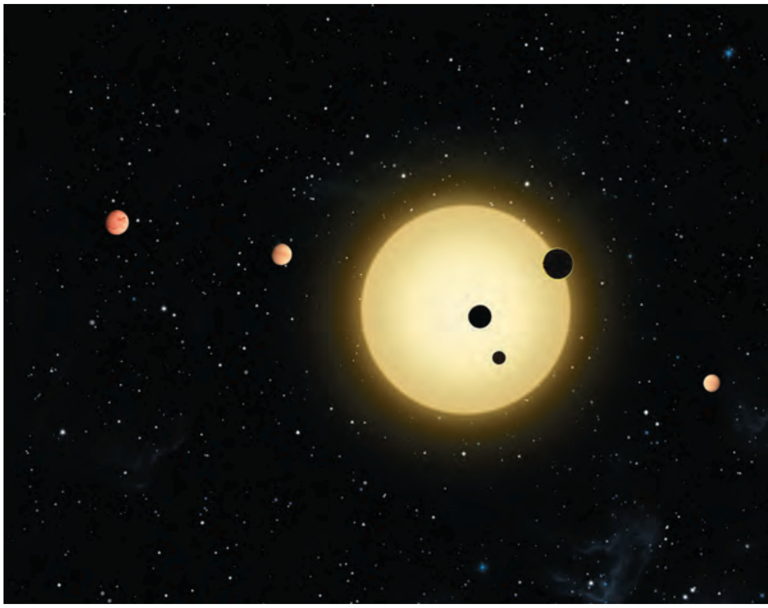

FIGURE 1.3

Artist's conception of the "Kepler 11" system, which contains at least six planets orbiting a Sun-like star. These planets are among thousands discovered by the *Kepler* spacecraft.

This understanding of how planets work gives us deeper insight into the nature of planetary systems in general. More important to our purposes, it also helps us understand what to look for as we search for **habitable worlds**—worlds that have the ingredients and conditions necessary for life. After all, given that there are far more worlds in the universe than we can ever hope to study in detail, we can improve our odds of success in finding life by constraining the search to those worlds that are the most promising. Be sure to note that when we ask whether a world is *habitable*, we are asking whether it offers environmental conditions under which life *could* arise or survive, not whether it actually harbors life.

Also keep in mind that when we say a world is habitable, we do not necessarily mean that familiar plants, animals, or people could survive there. For

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*There was an earlier discovery (1992) of exoplanets orbiting an object called a *pulsar,* which is an object (a spinning neutron star) that forms only after a star dies in a supernova explosion. We ignore such "pulsar planets" in this book, since we generally presume that planets with life would have to be orbiting a "living" star that shines as a result of nuclear fusion.

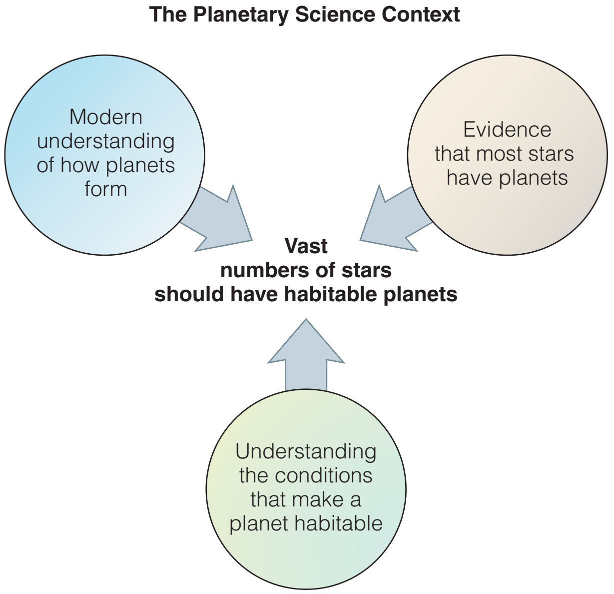

FIGURE 1.4
The astronomical context showed us that vast numbers of stars could be hosts to planets. This diagram summarizes the planetary science context, which suggests that these stars are indeed orbited by planets, many of which should be habitable.

much of Earth's history, nearly all life was microscopic, and even today, the total mass of microbes on Earth is greater than that of all plants and animals combined. The search for habitable worlds is primarily a search for places where microbes of some kind might survive, though we might find larger organisms as well. To summarize, the planetary science context suggests that most of the stars in the universe should indeed have planets and that we should expect many of them to be at least potential homes for life (Figure 1.4).

1.2.3 How does biology help us understand the possibilities for extraterrestrial life?

Astronomy, planetary science, and other science disciplines play important roles in shaping the context for the search for life in the universe, but since we are searching for *life*, the context of biology is especially important. Just as you wouldn't look for a house to buy without knowing something about real estate, it would make no sense to search for life if we didn't know something about how life functions. The key question about the biological context of the search revolves around whether we should expect biology to be rare or common in the cosmos.

Wherever we have looked in the universe, we have found clear evidence that the same laws of nature are operating. We see galaxies sprinkled throughout space, and we see that the same stellar processes that occur in one place also occur in others. In situations in which we can observe orbital motions, we find that they agree with what we expect from the law of gravity. These and other measurements make us confident that the basic laws of physics that we've discovered here on Earth also hold throughout the universe.

We can be similarly confident that the laws of chemistry are universal. Observations of distant stars show that they are made of the same chemical elements that we find here in our own solar system, and that interstellar gas clouds contain many of the same molecules we find on Earth. This provides conclusive evidence that atoms come in the same types and combine in the same ways throughout the universe.

Could biology also be universal? That is, could the biological processes we find on Earth be common throughout the cosmos? If the answer is yes, then the search for life elsewhere should be exciting and fruitful. If the answer is no, then life may be a rarity.

Because we haven't yet observed biology anywhere beyond Earth, we can't yet know whether biology is universal. However, evidence from our own planet gives us at least some reason to think that it might be. Laboratory experiments suggest that chemical constituents found on the early Earth would have combined readily into complex organic (carbon-based) molecules, including many of the building blocks of life [Section 6.2]. Indeed, scientists have found organic molecules in meteorites (chunks of rock that fall to Earth from space) and, through spectroscopy [Section 3.4], in clouds of gas between the stars. The fact that such molecules form even under the extreme conditions of space suggests that they form quite readily and may be common on many worlds.

Of course, the mere presence of organic molecules does not necessarily mean that life will arise, but the history of life on Earth gives us some reason to think that the step from chemistry to biology is not especially difficult. As we'll discuss in Chapter 6, geological evidence tells us that life on Earth arose quite early in Earth's history, at least on a geological time scale. If the transition from chemistry to biology were exceedingly improbable, we might expect that it would have required much more time. The early origin of life on Earth therefore suggests—but certainly does not prove—that life might also emerge quickly on other worlds with similar conditions.

Think About It Microbial life on Earth predates intelligent life like us by at least 3 to 4 billion years. Do you think this fact tells us anything about the likelihood of finding *intelligent* life, as opposed to finding any life, on exoplanets? Explain.

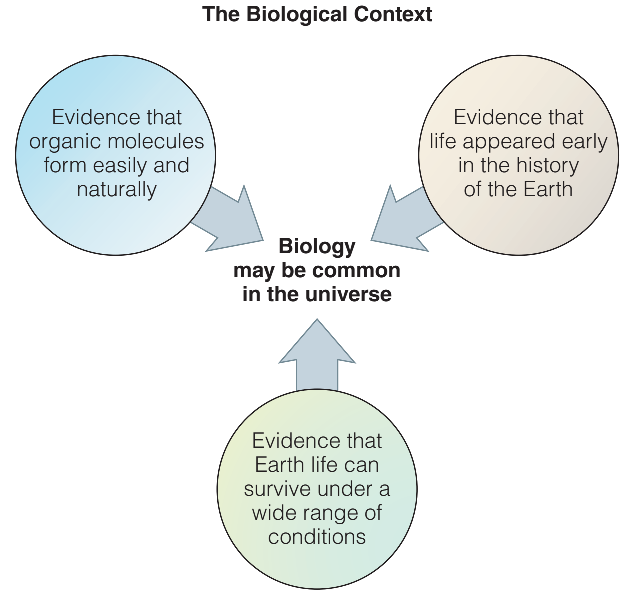

FIGURE 1.5

This diagram summarizes the biological context based on the study of life on Earth, which adds to the astronomical and planetary contexts and gives us at least some reason to think that biology may be common among the many potentially habitable worlds in the universe.

If life really can be expected to emerge under the right conditions, the only remaining question is the prevalence of those "right" conditions. Here, too, recent discoveries give us reason to think that biology could be common. In particular, biologists have found that microscopic life can survive and prosper under a much wider range of circumstances than was believed only a few decades ago [Section 5.5]. For example, we now know that life exists in extremely hot water near deep-sea volcanic vents, in the frigid environments of Antarctica, and inside rocks buried a kilometer or more beneath the Earth's surface. Indeed, if we were to export these strange organisms from Earth to other worlds in our solar system—perhaps to Mars or Jupiter's moon Europa—it seems possible that at least some of them would survive. This suggests that the range of "right" conditions for life may be quite broad, in which case it might be possible to find life even on planets or moons that are significantly different in character from Earth.

In summary, we have no reason to think that life ought to be rare and several reasons to expect that it may be quite common (Figure 1.5). If life is indeed common, studying it will give us new insights into life on Earth, even if we don't find other intelligent civilizations. These enticing prospects have captured the interest of scientists from many disciplines and from around the world, giving birth to a relatively new science devoted to the study of, and search for, life in the universe.

LEARNING OBJECTIVE
Places to Search

1.3 Places to Search

The study of life in the universe involves fundamental research in all the scientific areas we have already mentioned, and others as well. Indeed, as you'll see throughout this book, the study of extraterrestrial life goes far beyond simply searching for living organisms. Still, all of this study is driven by the possibility that life exists elsewhere, so before we dive into any details, it's worth a quick overview of the places and methods we use in the search.

1.3.1 Where should we search for life in the universe?

The search for life in the universe takes place on several different levels. First, and foremost in many ways, it is a study of life right here on Earth. As we discussed earlier, we are still learning about the places and conditions in which terrestrial life exists, and many scientists are busy searching for undiscovered species of life on our own world. After all, the more we know about life here, the better we'll be able to search for it elsewhere.

SEARCHING OUR OWN SOLAR SYSTEM Turning our attention to places besides Earth, the first place to search for life is on other worlds in our own solar system. Our solar system has many objects worthy of our attention: It has the planets and dwarf planets orbiting the Sun, moons orbiting planets, and huge numbers of smaller objects such as asteroids and comets.

Figure 1.6 shows some of our best current views of the planets (and two of the five currently identified dwarf planets) in our solar system. Note that it is *not* to scale, since its purpose is to show each planet as we know it today from spacecraft or through telescopes; you can turn to Figure 3.3 to see the sizes correctly scaled.

The photos alone make clear how different Earth is from every other planet in our solar system. Ours is the only planet with oceans of liquid water on its surface, a fact that provides an instant clue about why Earth is home to so much life: Water is crucial to all terrestrial life. Indeed, as we'll discuss in Chapters 5 and 7, we have some reason to think that liquid water may *always* be a requirement for life, though it's possible that a few other liquids might work in place of water.

Given that we are primarily looking for life that is at least somewhat Earth-like, the need for water or some other liquid places constraints on where we might find life. Among the planets, Mars is the

FIGURE 1.6
A "family portrait" of the eight official planets that orbit our Sun, along with two dwarf planets: Ceres (located in the asteroid belt between Mars and Jupiter) and Pluto (located in the Kuiper belt beyond Neptune). Going across the top row and then the bottom row, the planets and dwarf planets are shown in order of increasing average distance from the Sun; the photos are not shown to scale.

FIGURE 1.7
The surface of Mars, photographed by NASA's *Curiosity* rover. The martian surface is dry and barren today, but strong evidence points to liquid water on it in the distant past.

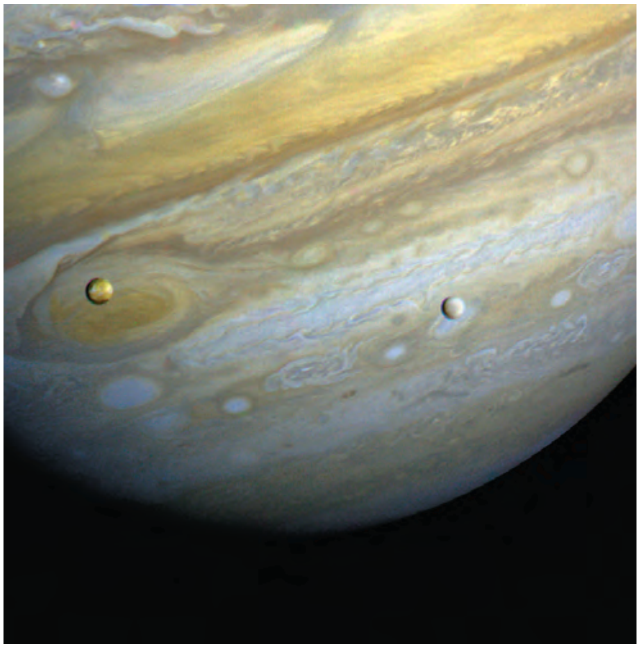

FIGURE 1.8
This photograph shows Jupiter and two of its moons: Io is the moon in front of Jupiter's Great Red Spot, and Europa is to the right. Scientists suspect that Europa has a deep ocean beneath its surface of ice, making it a prime target in the search for life in our solar system.

most promising candidate. As we'll discuss in detail in Chapter 8, strong evidence tells us that the now-barren surface of Mars (Figure 1.7) once had flowing water, making it seem reasonable to imagine life having arisen on Mars at that time. Mars still has significant amounts of water ice, so it is even possible that life exists on Mars today, perhaps hidden away in places where volcanic heat keeps underground water liquid. Past or present life seems much less likely on any of the other planets, though we can't rule it out completely. We'll discuss general prospects for life within our solar system in Chapter 7.

Aside from the planets, the most promising abodes for life in the solar system are a few of the large moons. At least five moons are potential candidates for life, including Jupiter's moon Europa (Figure 1.8). Current evidence strongly suggests that Europa hides a deep ocean of liquid water under its icy crust. Indeed, if we are interpreting the evidence correctly, the Europan ocean may have twice as much water as all of Earth's oceans combined [Section 9.2]. Because we suspect that life on Earth got started in the deep oceans [Section 6.1], Europa may well have all the conditions needed both for life to have arisen and for its ongoing survival. Two other moons of Jupiter—Ganymede and Callisto—also show some evidence for subsurface oceans, though the evidence is less strong and other considerations (primarily availability of energy) make them poorer prospects for harboring life. Other candidates for life include Saturn's moons Titan, which has a thick atmosphere and lakes of liquid methane, and Enceladus, which appears to have a subsurface ocean from which we observe fountains of ice spraying out into space [Section 9.3].

SEARCHING AMONG THE STARS In terms of numbers, there are many more places to look for life on planets and moons around other stars than in our own solar system. However, the incredible distances to the stars [Section 3.2] make searches of these worlds much more difficult. All stars are so far away that we will need great leaps in technology to have any hope at all of sending spacecraft to study their planets up close. For example, with current spacecraft technology, journeys to even the nearest stars would take close to 100,000 years.

With visits out of reach, telescopic searches represent our only near-term hope of finding life beyond our solar system. As we'll discuss in Chapter 11, current telescopes can in most cases detect exoplanets only indirectly, which means we don't yet have images or spectra through which we might identify signs of life. But the technology is advancing rapidly. The recently launched James Webb Space Telescope (JWST)* may be able to obtain spectra of at least some exoplanet atmospheres, and within a couple of decades, even more advanced telescopes may be able to obtain moderate-resolution images of planets and moons around other stars. As a result, one important area of research is trying to figure out the photographic or spectral "signatures" that would tell us we are looking at a world with life.

1.3.2 Could aliens be searching for us?

So far we have talked about searching for life that we could identify only by seeing it with our spacecraft or telescopes. But if life really is common in the universe, there could be other places like Earth where life has evolved to become intelligent enough to be interested in searching for life beyond its home world. In that case, it is possible that other civilizations might actually be broadcasting signals that we could detect. The **search for extraterrestrial intelligence,** or **SETI,** which we'll discuss in Chapter 12, focuses on the search for such signals from alien civilizations

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*There has been considerable controversy about naming this telescope after former NASA Administrator James Webb. As this book goes to press, NASA considers the matter closed, but some scientists are pushing for it to be reopened.

Movie Madness CINEMA ALIENS

Aliens should probably join the Screen Actors Guild. Every year, Hollywood reliably cranks out a handful of films in which visitors from distant star systems mess with our minds, our bodies, or our entire planet.

Cinema aliens are typecast, usually available in only two flavors: good and bad. A few, like loveable, wrinkly-faced little E.T., are willing to make a field trip of a few million light-years simply to pick some plants and hang with the kids. But most of these uninvited guests are cranky: They spend their time either dithering with our personal lives or blowing up famous landmarks just because they can.

Extraterrestrials didn't snag many movie roles until after the Second World War, when the rapid development of rocketry seemed to suggest that we'd soon be taking rides to the Moon, to Mars, and beyond. For the popcorn-eating public, it seemed inevitable that our descendants would visit other worlds as casually as you might head for the coffee shop. And if we could do this, then it seemed only reasonable that advanced aliens were already roaming space, like motorcycle gangs on a Sunday afternoon.

The movie moguls studiously ignored the fact (which you'll encounter later in this book) that traveling between the stars is enormously more difficult than checking out the planets of your own solar system. The aliens won't do it just to share play time with the neighborhood children, or to abduct you for unauthorized breeding experiments.

But the really big problem with Hollywood aliens, other than the fact that they seldom wear clothes, is that these frequently nasty visitors are inevitably portrayed as being close to our own level of technical development. We can engage the bad ones in aerial dogfights, or challenge them to a light-saber duel. But the reality is somewhat different. As we'll discuss in Chapter 13, if we ever make contact with actual aliens, their culture will almost certainly be thousands, millions, or billions of years beyond ours.

Of course, an invasion by hostile aliens with a million-year head start on *Homo sapiens* wouldn't make for an interesting movie. It would be Godzilla versus the chipmunks. But you don't mistake the movies for reality, do you?

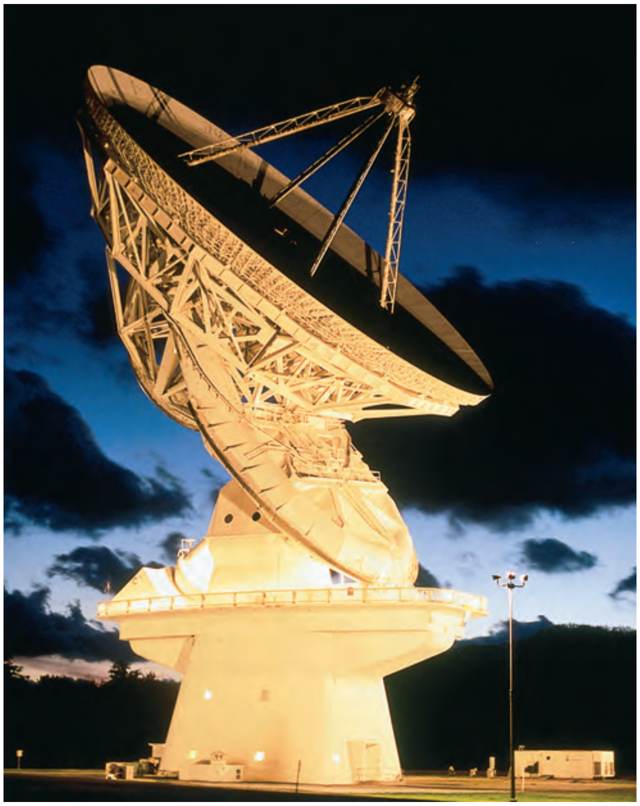


FIGURE 1.9
This 140-foot radio telescope in West Virginia was used in 1996 to search for signals from extraterrestrial civilizations.

(Figure 1.9). Although we don't know whether the search will meet with success, we can be sure that the unambiguous receipt of an alien message would be one of the most significant events in human history—not to mention the fact that it would also probably answer many of our other questions about life in the universe.

LEARNING OBJECTIVE
Goals of Astrobiology

1.4 The Science of Astrobiology

We have seen that the study of life in the universe is a multidisciplinary field of scientific research, involving scientists with training in many different specialties. Nevertheless, because it has become a prominent and important area of study, it's useful to give the science of life in the universe its own name. A number of different names are in use, including "exobiology" and "bioastronomy," but in this book we follow the lead of NASA and call it **astrobiology**. This term is meant to invoke the combination of astronomy (the study of the universe) and biology (the study of life), so *astrobiology* literally means "the study of life in the universe."

1.4.1 How do we study the possibility of life beyond Earth?

Because astrobiology is a young science, scientists are still working to decide where to focus their research efforts. One major player in this effort has been the NASA Astrobiology Program, which encourages collaborations between scientists both within the United States and around the world. Similar efforts exist in many other countries, including the United Kingdom, Sweden, France, Spain, Russia, and Australia. These collaborations are among the most interdisciplinary in any area of science, bringing together astronomers, biologists, geologists, chemists, and many others seeking to understand the prospects of finding life beyond Earth.

Although different groups concentrate on different problems, most astrobiology research is concentrated in the following three areas:

1. Studying the conditions conducive to the origin and ongoing existence of life
2. Looking for such conditions on other planets in our solar system and around other stars
3. Looking for the actual occurrence of life elsewhere

Astrobiology therefore includes much more than simply searching for extraterrestrial life or civilizations. At a fundamental level, astrobiology research seeks to reveal the connections between living organisms and the places where they reside. In this sense, finding *no life* (on Mars, for example) is just as significant a result as finding life, because either way we learn about the conditions that can lead to the presence of life, about how life evolves in conjunction with planets, and about whether life is likely to be rare or common throughout the universe.

In the rest of this book, we will focus on the three areas listed above. After discussing the scientific context of the search in greater detail in Chapters 2 and 3, we'll turn our attention in Chapters 4 through 6 to the nature, origin, and evolution of life on Earth. This study of the history of life on our planet will help us understand the conditions under which we might expect to find life elsewhere. We'll then discuss prospects for life elsewhere in our solar system in Chapters 7 through 10, and the prospects for finding life—including intelligent life—beyond our solar system in Chapters 11 through 13. Along the way, we'll also learn what science can currently say about the future of life on Earth, we'll consider possible futures for our own species, and we'll discuss the philosophical implications of the search for—and potential discovery of—life beyond Earth.

The Big Picture

This chapter has offered a brief overview of the ideas we will cover in more depth in the rest of the book, primarily so that you will have a sense of what to expect in the rest of your study of life in the universe. As we will do in every chapter, we conclude with a brief "big picture" recap of how these ideas fit into the overall goals of the scientific study of life in the universe:

- Despite the abundance of aliens in popular media, we don't yet have any convincing evidence for life, even microscopic life, beyond Earth. Nevertheless, current understanding of astronomy, planetary science, and biology gives us good reason to think that it is at least reasonable to imagine that life may be widespread, and the discovery of extraterrestrial life of any kind would have profound significance to our understanding of life in the universe.
- It's conceivable that life may exist on any of several worlds in our own solar system, but it's extremely unlikely that any of this life is intelligent. However, we find many more possibilities when we consider life on planets or moons around other stars. And, through the search for extraterrestrial intelligence (SETI), it is even possible that we could receive a signal from an advanced civilization.
- The prospect that life may be common in the universe has given rise to the science of *astrobiology*, an exciting and interdisciplinary topic of research that focuses both on understanding the possibility of finding life elsewhere and on the actual search for life beyond Earth.

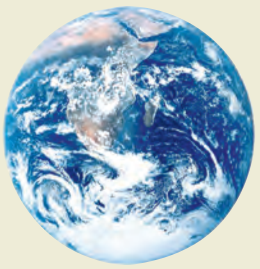
Summary of Key Concepts

1.1 The Possibility of Life Beyond Earth

1.1.1 What are we searching for?

The search for **extraterrestrial life** is in principle a search for *any* kind of life. However, the difficulty of clearly defining life means that it's easier to focus the search on life that is at least somewhat similar to life here on Earth. This still opens a wide range of possibilities, from bacteria-like microbes to complex plants and animals.

1.1.2 Is it reasonable to imagine life beyond Earth?



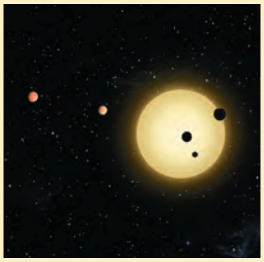
People have long considered the possibility of life beyond Earth, but only recently have we been able to examine this possibility through the lens of science. While we have no evidence at this time of actual life beyond Earth, our scientific understanding of the possibilities makes it reasonable to think that life could exist elsewhere.

1.2 The Scientific Context of the Search

1.2.1 How does astronomy help us understand the possibilities for extraterrestrial life?

Astronomy tells us that we live on a tiny planet orbiting one rather ordinary star in a vast cosmos, and that the same physical laws that operate here also operate throughout the universe. Together these ideas suggest that there could be many other worlds with life.

1.2.2 How does planetary science help us understand the possibilities for extraterrestrial life?



Based on current understanding of how planets form, we expect planets to be common around other stars—an idea that has been confirmed by discoveries of **exoplanets**. By learning how planets work, we learn the conditions that might make a **habitable world**, meaning a world that has the basic necessities for life, even if it does not actually have life.

1.2.3 How does biology help us understand the possibilities for extraterrestrial life?

Modern biology provides three lines of evidence suggesting that life *might* be common on other habitable worlds: (1) The fact that life arose quickly on Earth suggests that it might occur on any world that has the "right" conditions. (2) We know from observations of meteorites and interstellar clouds that organic molecules are common throughout the galaxy, suggesting that we'll find them on many other worlds. (3) The fact that some life on Earth survives even under extremely harsh conditions suggests that life is hardy enough to survive in many other places as well.

1.3 Places to Search

1.3.1 Where should we search for life in the universe?

The search begins right here on Earth, as we seek to learn more about the life on our own planet. Elsewhere in our solar system we can search many planets and moons, but current understanding suggests that the most promising candidates for life are Mars and a few moons, including Jupiter's moon Europa or Saturn's moon Enceladus. In the future, we should be able to conduct telescopic searches for life around other stars.

1.3.2 Could aliens be searching for us?

If life is common in the universe, civilizations might also be common, in which case other civilizations might be conducting their own searches and broadcasting signals that would indicate their existence. We look for such signals from alien civilizations through the **search for extraterrestrial intelligence**, or **SETI**.

1.4 The Science of Astrobiology

1.4.1 How do we study the possibility of life beyond Earth?

The science of life in the universe, or **astrobiology,** focuses on three major areas: (1) studying the conditions conducive to the origin and ongoing existence of life; (2) looking for such conditions on other planets in our solar system and around other stars; and (3) looking for the actual occurrence of life elsewhere. Together, these studies should help us understand the connections between living organisms and the places where they reside.

Exercises and Problems

You will find many of these questions and more, including guidance and study aids, in the Life in the Universe *courseware.*

QUICK QUIZ

Start with these questions as a quick test of your general understanding. Choose the best answer in each case, and explain your reasoning. Answers are provided in the back of the book.

1. An *exoplanet* is (a) a planet that orbits the Sun far beyond Pluto; (b) a planet that orbits a star other than our Sun; (c) a planet that orbits the center of another galaxy.
2. A *habitable planet* is (a) a planet that has oceans like Earth; (b) a planet that has life of some kind; (c) a planet that may or may not have life, but that has environmental conditions under which it seems that life could arise or survive.
3. By a *geocentric* view of the universe, we mean (a) the ancient idea that Earth resided at the center of the universe; (b) the idea that Earth is the only planet with life in the universe; (c) a view of the universe shaped by current understanding of geological science.
4. According to current scientific understanding, life on Earth (a) was exceedingly improbable; (b) arose quite soon after conditions allowed it; (c) may have been inevitable, but took billions of years to develop.
5. The correct order for the eight official planets in our solar system, from closest to farthest from the Sun, is (a) Mercury, Venus, Earth, Mars, Saturn, Jupiter, Neptune, Uranus; (b) Mercury, Venus, Earth, Mars, Jupiter, Uranus, Neptune, Saturn; (c) Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune.
6. Today, the research known as the *search for extraterrestrial intelligence*, or *SETI,* is conducted primarily by (a) scanning the skies for signals from alien civilizations; (b) sending spacecraft to the planets; (c) using telescopes to observe exoplanets.
7. If we sent a spacecraft to a nearby star (besides the Sun) using currently available rockets, the trip would take about (a) a decade; (b) a century; (c) 100,000 years.
8. Scientists today are interested in searching for life on Mars because (a) we see clear evidence of a past civilization on Mars; (b) Mars contains frozen water ice at its polar caps; (c) evidence suggests that Mars had liquid water on its surface in the distant past.

9. Based on current evidence, which of these objects in our solar system is most likely to have a deep, subsurface ocean of liquid water? (a) Mars; (b) Europa; (c) Neptune
10. Based on the way scientists view the study of astrobiology, failure to find life on any other world would mean (a) the whole subject has been a waste of time; (b) we must have done something wrong, since life has to exist beyond Earth; (c) we have learned important lessons about the conditions that made life on Earth possible.

READING REVIEW QUESTIONS

You should be able to answer these questions by re-reading portions of the chapter as needed.

11. Why are scientists interested in the possibility of life beyond Earth?
12. People have long speculated about life beyond Earth. What changed in recent times that now allows us to *scientifically* investigate the possibility of extraterrestrial life?
13. What do we mean by a *geocentric universe*? In general terms, contrast a geocentric view of the universe with our modern view of the universe.
14. What are *exoplanets*? In what way does their discovery make it seem more reasonable to imagine finding life elsewhere?
15. What do we mean by a *habitable* world? Does a habitable world necessarily have life?
16. What do we mean by the "universality" of physics and chemistry? Although we don't know yet whether biology is similarly universal, what evidence makes it seem that it might be?
17. Besides Earth, what worlds in our solar system seem most likely to have life? Why?
18. Could we actually detect life on exoplanets or their moons with current technology? Explain.
19. What is the *search for extraterrestrial intelligence* (*SETI*)?
20. What do we mean by *astrobiology*? What are the major areas of research in astrobiology?

CONCEPTUAL QUESTIONS

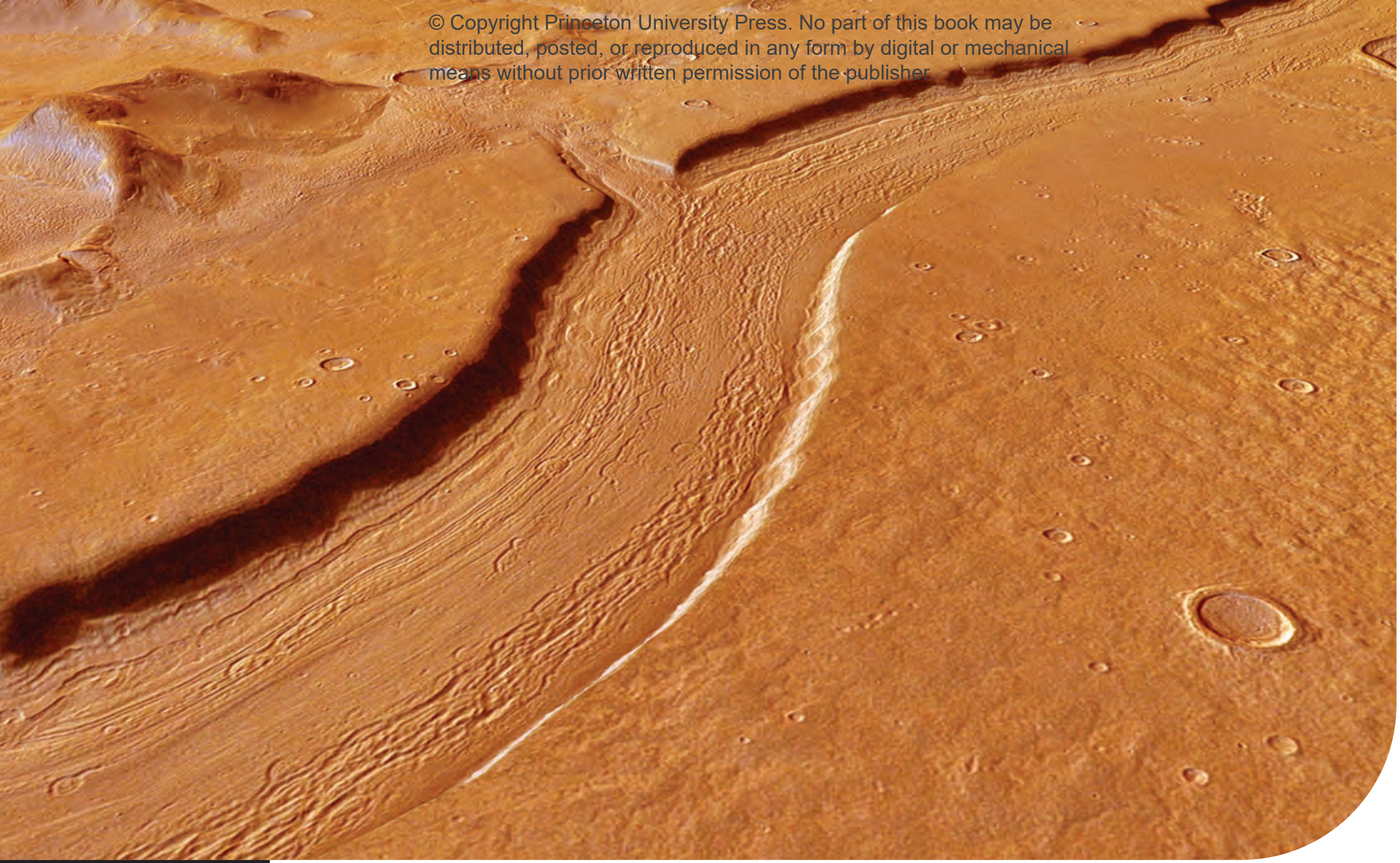
Answer each question in short answer or essay form.

21. *Astrobiology Course Goals*. Assuming you are reading this book for a course in astrobiology, write a short statement about what you hope to learn in your course, and why.
22. *Aliens Among Us*. Conduct an informal survey of friends or family, asking each person to tell you whether they believe we have been visited by aliens and why they think so (or why not). Write a brief summary of your survey results, and add a paragraph or two discussing whether the people you spoke with are likely or unlikely to reflect general public opinion on the topic of alien visits.
23. *Three Contexts*. This chapter introduced the idea that astrobiology is informed by three major scientific "contexts": astronomy, planetary science, and biology. Briefly explain how each of these contexts enables us to study astrobiology as a scientific endeavor.
24. *Universal Laws*. Briefly discuss how the idea that the laws of nature are universal is important to the study of astrobiology. Based on what you know about the universality of the laws of physics and chemistry, do you think it is likely that there are also universal laws of biology? Defend your opinion.
25. *Conducting the Search*. Given the large number of possible places to look for life, how would you prioritize the search? In other words, where would you look first for life on other worlds in our own solar system, and how would you come up with a search strategy for other star systems? Make a list of priorities and write a few sentences to explain your search strategy.
26. *Funding for Astrobiology*. Imagine that you are a member of Congress, so it is your job to decide how much government funding goes to research in astrobiology. What factors would influence your decision? Make a brief list of at least five important factors, then write a paragraph summarizing whether you would increase or decrease such funding from the current level and why.

ACTIVITY AND DISCUSSION

These questions are intended to prompt additional research and/or discussion.

27. *Astrobiology News*. Go to NASA's Astrobiology home page and read some of the recent news from astrobiology research. Choose one recent news article, and write a one- to two-page summary of the research and how it fits into astrobiology research in general.
28. *International Astrobiology*. Search the Web for information on astrobiology research outside the United States. Learn about the effort in one particular country or group of countries. What areas of research are emphasized? How do the researchers involved in the effort collaborate with other international astrobiology efforts? Write a one- to two-page report on your findings.
29. *The Search for Extraterrestrial Intelligence*. Go to the home page for the SETI Institute. Learn more about how SETI is funded and how the institute does its work. Summarize your findings in about one page.
30. *Group Activity: Aliens in the Movies*. Work in small groups to make a list of movies that involve aliens, listing as many as you can. Then come to a group consensus on ranking the top five such movies of all time, giving a brief reason for why you like each movie in your top five. Compare your top five list with the lists made by other groups.



2

The Science of Life in the Universe

OVERVIEW

- **2.1 THE ANCIENT DEBATE ABOUT LIFE BEYOND EARTH**
  - 2.1.1 How did attempts to understand the sky start us on the road to science?
  - 2.1.2 Why did the Greeks argue about the possibility of life beyond Earth?
- **2.2 THE COPERNICAN REVOLUTION**
  - 2.2.1 How did the Copernican revolution further the development of science?
  - 2.2.2 How did the Copernican revolution alter the ancient debate on extraterrestrial life?
- **2.3 THE NATURE OF MODERN SCIENCE**
  - 2.3.1 How can we distinguish science from nonscience?
  - 2.3.2 What is a scientific theory?
- **THE PROCESS OF SCIENCE IN ACTION**
- **2.4 THE FACT AND THEORY OF GRAVITY**
  - 2.4.1 How does the fact of gravity differ from the theory of gravity?

▲ **About the photo:** This perspective view of an ancient riverbed on Mars (named Reull Vallis) was created using data from the *Mars Express* orbiter. Evidence like this lies at the heart of the modern scientific search for life beyond Earth.

We especially need imagination in science. It is not all mathematics, nor all logic, but it is somewhat beauty and poetry.

Maria Mitchell (1818–1889), astronomer and first woman elected to the American Academy of Arts and Sciences

LEARNING OBJECTIVE

Chapter 2 Overview

Extraterrestrial life may sound like a modern idea, but stories of life beyond Earth reach far back into ancient times. Many of these stories concerned mythical or supernatural beings living among the constellations, but some were not so different from the ideas we consider today. Nevertheless, the present-day search for life in the universe differs from ancient speculations in an important way: While ancient people could do little more than guess about the possibility of finding life elsewhere, we can now study this possibility with the powerful methods of modern science.

Given that we don't yet know of any life beyond Earth, you might wonder how we can make a science of life in the universe. The answer is that we use science to help us understand the conditions under which we might expect to find life, the likely characteristics of life elsewhere, and the methods we can use to search for it. Because the methods of science are so integral to the search for life beyond Earth, we devote this chapter to understanding those methods and how they developed.

LEARNING OBJECTIVE

The Ancient Debate

2.1 The Ancient Debate About Life Beyond Earth

More than 2300 years ago, scholars of ancient Greece were already engaged in a lively debate about the possibility of life beyond Earth. Some scholars argued that there *must* be life elsewhere, while others argued the opposite. This impassioned debate may in some ways seem a historical curiosity, but the mere fact that it occurred tells us that a major change in human thinking was already underway.

Deeper in the past, our ancestors looked at the sky and attributed what they saw to the arbitrary actions of mythological beings, an idea still reflected in the fact that the planets carry the names of mythological gods. In contrast, the Greek scholars sought rational explanations for what they could observe in the universe around them. As far as we know, these Greek efforts marked the first attempts to understand the universe through methods closely resembling the ones we use in science today. Therefore, if we want to understand how modern science works—and how we can use it to study the possibility of life beyond Earth—we must begin by peering into the past, to see how observations of the sky started humanity on the road to modern science and kindled interest in the question of whether the universe is ours alone.

2.1.1 How did attempts to understand the sky start us on the road to science?

Imagine living in ancient times, looking up at the sky without the benefit of our modern knowledge. What would you see?

Every day, the Sun rises in the east and sets in the west, its precise path varying with the seasons. At night, the stars circle the sky (Figure 2.1), with different constellations prominent at different times of year. The Moon goes through monthly phases, from new to full and back again, while the planets gradually meander among the stars in seemingly mysterious ways. All the while, the ground beneath you feels steady and solid. It would be quite natural to assume—as did people of many early cultures—that Earth is a flat, motionless surface under a domelike sky across which the heavenly bodies move.

The story of how we progressed from this primitive view of Earth and the heavens to our modern understanding of Earth as a tiny planet in a vast cosmos is in many ways the story of science itself. Our ancestors were curious about many aspects of the world around them, but astronomy held special interest. The Sun clearly plays a central role in our lives, governing daylight and darkness while its path across the sky changes with the seasons. The Moon's connection to the tides would have been obvious to people living near the sea. The evident power of these

FIGURE 2.1

This image shows "star trails" over Joshua Tree National Park in California, captured by leaving a camera's shutter open for several hours. Each trail represents the path of an individual star through the sky during those hours. Notice that stars near the North Star (Polaris) make complete daily circles, while those farther from the North Star rise in the east and set in the west. Ancient people were quite familiar with patterns of motion like these.

celestial bodies probably explains why they attained prominent roles in many early religions and may be one reason why it seemed so important to know the sky. Careful observations of the sky also served practical needs by enabling ancient peoples to keep track of the time and the seasons—crucial requirements for agricultural societies.

As civilizations rose, astronomical observations became more careful and elaborate. In some cases, the results were recorded in writing. The ancient Chinese kept detailed records of astronomical observations beginning some 5000 years ago. By about 2500 years ago, written records allowed the Babylonians (in the region of modern-day Iraq) to predict eclipses with great success. Halfway around the world (and a few centuries later), the Maya of Central America independently developed the same ability.

These ancient, recorded observations of astronomy represent databases of facts—the raw material of science. But modern science goes further, using these facts to help us understand the architecture of the cosmos. It is likely that many cultures took at least a few steps along a path toward modern science, but history inevitably takes only one of countless possible paths. The path that led to modern science began to take shape in ancient Greece.

EARLY GREEK SCIENCE Greece gradually rose as a power in the Middle East beginning around 800 B.C.E., and was well established by about 500 B.C.E. Its geographical location placed it at a crossroads for travelers, merchants, and armies of northern Africa, Asia, and Europe. Building on the diverse ideas brought forth by the meeting of these many cultures, ancient Greek philosophers began to move human understanding of nature from the mythological to the rational.

We generally trace the origin of Greek science to the philosopher Thales (c. 624–546 B.C.E.; pronounced "THAY-lees"). Among his many accomplishments, Thales was the first person known to have addressed the question "What is the universe made of?" without resorting to supernatural explanations. His own guess—that the universe fundamentally consisted of water and that Earth was a flat disk on an infinite ocean—was not widely accepted even in his own time, but his mere asking of the question helped set the stage for all later science. For the first time, someone had suggested that the world was inherently understandable and not just the result of arbitrary or incomprehensible events.

The scholarly tradition begun by Thales was carried on by others, perhaps most famously by Plato (428–348 B.C.E.) and his student Aristotle (384–322 B.C.E.). Each Greek philosopher introduced new ideas, sometimes in contradiction to the ideas of others. None of these ideas rose quite to the level of modern science, primarily because the Greeks tended to rely more on pure thought and intuition than on observations or experimental tests. Nevertheless, with hindsight we can see at least three major innovations in Greek thought that helped pave the way for modern science.

First, the Greek philosophers developed a tradition of trying to understand nature without resorting to supernatural explanations. For example, although earlier Greeks might simply have accepted that the Sun moves across the sky because it is pulled by the god Apollo in his chariot—an idea whose roots were already lost in antiquity—the philosophers sought a natural explanation that caused them to speculate anew about the construction of the heavens. They were free to think creatively because they were not simply trying to prove preconceived ideas, and they recognized that new ideas should be open to challenge. As a result, they often worked communally, debating and testing each other's proposals. This tradition of challenging virtually every new idea remains one of the distinguishing features of science today.

Second, the Greeks developed mathematics in the form of geometry. They valued this discipline for its own sake, and they understood its power, using geometry to solve both engineering and scientific problems. Without their mathematical sophistication, they would not have gone far in their attempts to make sense of the cosmos. Like the Greek tradition of challenging ideas, the use of mathematics to help explore the implications of new ideas remains an important part of modern science.

Third, while much of their philosophical activity consisted of subtle debates with little connection to observations or experiments, the Greeks also understood that an explanation about the world could not be right if it disagreed with observed facts. This willingness to discard explanations that simply don't work is also a crucial part of modern science.

THE GEOCENTRIC MODEL Perhaps the greatest Greek contribution to science came from the way they synthesized all three innovations into the idea of creating **models** of nature, another idea that is central to modern science. Scientific models differ somewhat from the models you may be familiar with in everyday life. In our daily lives, we tend to think of models as miniature physical representations, such as model cars or airplanes. In contrast, a scientific model is a conceptual representation whose purpose is to explain and predict observed phenomena. For example, a model of Earth's climate uses logic, mathematics, and known physical laws in an attempt to represent the way in which the climate works. Its purpose is to explain and predict climate changes, such as the changes that are likely to occur with global warming. Just as a model airplane does not faithfully represent every aspect of a real airplane, a scientific model may not fully explain all our observations of nature. Nevertheless, even the failings of a scientific model can be useful, because they often point the way toward building a better model.

Think About It Conceptual models aren't just important in science; they often affect day-to-day policy decisions. For example, economists use models to predict how new policies will affect the federal budget. Describe at least two other cases in which models affect our daily lives.

In astronomy, the Greeks constructed conceptual models of the universe in an attempt to explain what they observed in the sky, an effort that quickly led them past simplistic ideas of a flat Earth under a dome-shaped sky to a far more sophisticated view of the cosmos. One of the first crucial steps was taken by a student of Thales, Anaximander (c. 610–547 B.C.E.). In an attempt to explain the way the northern sky appears to turn around the North Star each day (see Figure 2.1), Anaximander suggested that the heavens must form a complete sphere—the **celestial sphere**—around Earth. Moreover, based on how the appearance of the sky varies with latitude, he realized that Earth's surface must be curved, though he incorrectly guessed Earth to be a cylinder rather than a sphere.

The idea of a round Earth probably followed soon, and by about 500 B.C.E. it was part of the teachings of Pythagoras (c. 560–480 B.C.E.). He and his followers most likely adopted a spherical Earth for philosophical reasons: The Pythagoreans had a mystical interest in mathematical perfection, and they considered a sphere to be geometrically perfect. More than a century later, Aristotle cited observations of Earth's curved shadow on the Moon during lunar eclipses as evidence for a spherical Earth. Greek philosophers therefore adopted a **geocentric model** (*geocentric* means "Earth-centered") of the universe, with a spherical Earth at the center of a great celestial sphere (Figure 2.2).

Incidentally, this shows the error of the widespread myth that Columbus proved Earth to be round when he sailed to America in 1492. Not only were scholars of the time well aware of Earth's round shape; they even knew Earth's approximate size: Earth's circumference was first measured (fairly accurately) in about 240 B.C.E. by the Greek scientist Eratosthenes. In fact, a likely reason why Columbus had so much difficulty finding a sponsor for his voyages was that he tried to argue a point on which he was wrong: He claimed the distance by sea from western Europe to eastern Asia to be much less than many scholars had estimated it to be. His erroneous belief would almost certainly have led his voyage to disaster if the Americas hadn't stood in his way.

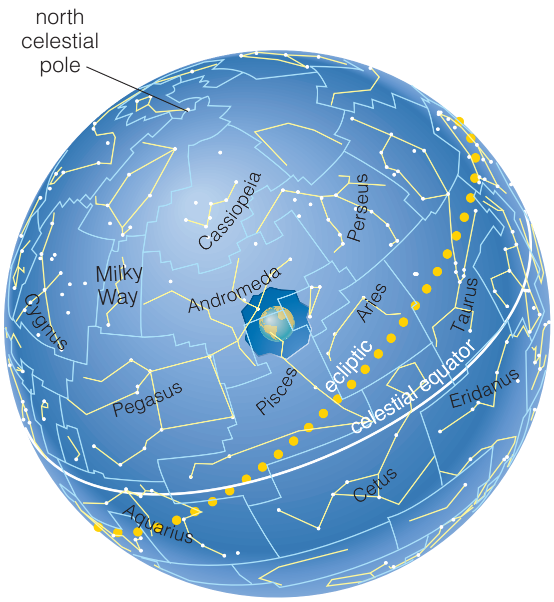


FIGURE 2.2
The early Greek geocentric model consisted of a central Earth surrounded by the celestial sphere, which is shown here marked with modern constellation borders and a few reference points and circles. We still use the idea of the celestial sphere when making astronomical observations, but we no longer imagine that it reflects reality.

THE MYSTERY OF PLANETARY MOTION If you watch the sky closely, you'll notice that while the patterns of the constellations seem not to change, the Sun, the Moon, and the five planets visible to the naked eye (Mercury, Venus, Mars, Jupiter, and Saturn) gradually move among the constellations from one day to the next. Indeed, the word *planet* comes from the Greek for "wanderer," and it originally referred to the Sun and Moon as well as to the five visible planets. Our seven-day week is directly traceable to the fact that seven "planets" are visible in the heavens (Table 2.1).

The wanderings of these objects convinced the Greek philosophers that there had to be more to the heavens than just a single sphere surrounding Earth. The Sun and Moon each move steadily through the constellations, with the Sun completing a circuit around the celestial sphere each year and the Moon completing each of its circuits in about a month (think "moonth"). The Greeks could account for this motion by adding separate spheres for the Sun and Moon, each nested within the sphere of the stars, and allowing these spheres to turn at different rates from the sphere of the stars. But the five visible planets posed a much greater mystery.

If you observe the position of a planet (such as Mars or Jupiter) relative to the stars over a period of many months, you'll find not only that its speed and brightness vary considerably but also that its direction of motion sometimes changes. While the planets usually move eastward relative to the constellations, sometimes they reverse course and go backward (Figure 2.3). These periods of **apparent retrograde motion** (*retrograde* means "backward") last from a few weeks to a few months, depending on the planet.

This seemingly erratic planetary motion was not so easy to explain with rotating spheres, especially because the Greeks generally accepted a notion of "heavenly perfection," enunciated most clearly by Plato, which demanded that all heavenly objects move in perfect circles. How could a planet sometimes go backward when moving in a perfect circle? The Greeks came up with a number of ingenious ideas that preserved Earth's central position, culminating in a complex model of planetary motion described by the astronomer Ptolemy (c. 100–170 C.E.; pronounced "TOL-e-mee"); we refer to Ptolemy's model as the **Ptolemaic model** to distinguish it from earlier geocentric models. This model reproduced retrograde motion by having planets move around Earth on small circles that turned around larger circles. A planet following this circle-on-circle motion traces a loop as seen from Earth, with the backward portion of the loop mimicking apparent retrograde motion (Figure 2.4).

The circle-on-circle motion may itself seem somewhat complex, but Ptolemy found that he also had to use many other mathematical tricks, including putting some of the circles off-center, to get his model to

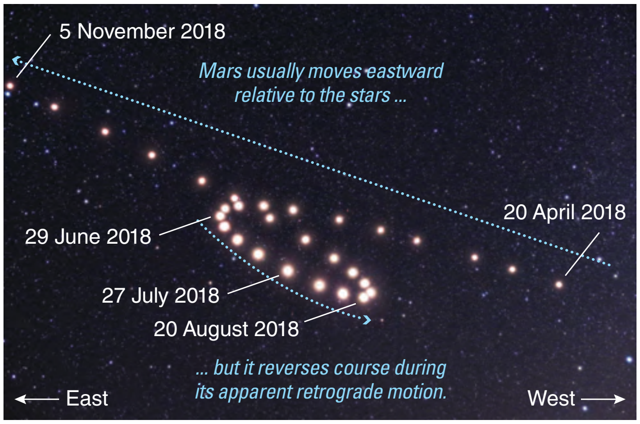


FIGURE 2.3
This composite of individual photos (taken at 5- to 9-day intervals in 2018) shows a retrograde loop of Mars. Note that Mars is biggest and brightest in the middle of the retrograde loop, because that is where it is closest to Earth in its orbit.

TABLE 2.1 The Seven Days of the Week and the Astronomical Objects They Honor

The names of the seven days were originally based on the seven visible "wanderers" of the sky. The correspondence is no longer perfect, but the pattern is clear in many languages: Some English names come from the corresponding names of Germanic gods; other connections are clearer in languages such as French and Spanish.

Object	*Germanic God*	*English*	*French*	*Spanish*
Sun	—	Sunday	dimanche	domingo
Moon	—	Monday	lundi	lunes
Mars	Tiw	Tuesday	mardi	martes
Mercury	Woden	Wednesday	mercredi	miércoles
Jupiter	Thor	Thursday	jeudi	jueves
Venus	Fria	Friday	vendredi	viernes
Saturn	—	Saturday	samedi	sábado

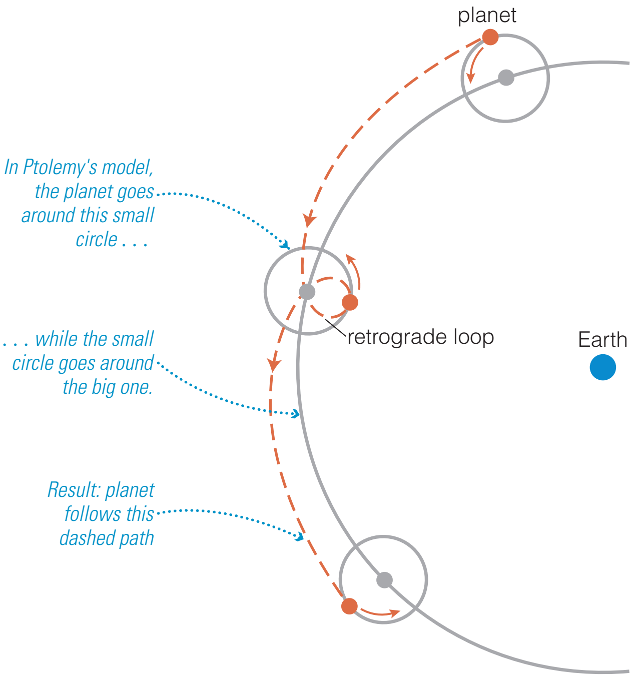


FIGURE 2.4
This diagram shows how the Ptolemaic model accounted for apparent retrograde motion. Each planet is assumed to move around a small circle that turns on a larger circle. The resulting path (dashed) includes a loop in which the planet goes backward as seen from Earth.

agree with observations. Despite all this complexity, he achieved remarkable success: His model could correctly forecast future planetary positions to within a few degrees of arc—roughly equivalent to the width of your hand held at arm's length against the sky. Indeed, the Ptolemaic model generally worked so well that it remained in use for the next 1500 years. When Arabic scholars translated Ptolemy's book describing the model in around 800 C.E., they gave it the title *Almagest,* derived from words meaning "the greatest work."

AN ALTERNATIVE MODEL In about 260 B.C.E., the Greek scientist Aristarchus (c. 310–230 B.C.E.) offered a radical departure from the conventional wisdom: He suggested that Earth goes around the Sun, rather than vice versa. Little of Aristarchus's work survives to the present day, so we do not know exactly how he came up with his Sun-centered (or *heliocentric**) idea. We do know that he made measurements that convinced him that the Sun is much larger than Earth, so perhaps he simply concluded that it was more natural for the smaller Earth to orbit the larger Sun. In addition, he almost certainly recognized that a Sun-centered system offers a much more natural explanation for apparent retrograde motion.

You can see how the Sun-centered system explains retrograde motion with a simple demonstration (**Figure 2.5a**). Find an empty area (such as a sports field or a big lawn), and place a ball in the middle to represent the Sun. You can represent Earth, walking counterclockwise around the Sun, while a friend represents a more distant planet (such as Mars, Jupiter, or Saturn) by walking counterclockwise around the Sun at a greater distance. Your friend should walk more slowly than you, because more distant planets orbit the Sun more slowly. As you walk, watch how your friend appears to move relative to buildings or trees in the distance. Although both of you always walk in the same direction around the Sun, your friend will appear to move backward against the background during the part of your "orbit" at which you catch up to and pass him or her. To understand the apparent retrograde motions of Mercury and Venus, which are closer to the Sun (than Earth), simply switch places with your friend and repeat the demonstration. The demonstration applies to all the planets. For example, because Mars takes about 2 years to orbit the Sun (actually, 1.88 years), it covers about half its orbit during the 1 year in which Earth makes a complete orbit. If you trace lines of sight from Earth to Mars from different points in their orbits, you will see that the line of sight usually moves eastward relative to the stars but moves westward during the time when Earth is passing Mars in its orbit (**Figure 2.5b**). Like your friend in the demonstration, Mars never actually changes direction. It only appears to change direction from our perspective on Earth.

Despite the elegance of this Sun-centered model for the universe, Aristarchus had little success in convincing his contemporaries to accept it. Some of the reasons for this rejection were purely philosophical and not based on any hard evidence. However, at least one major objection was firmly rooted in observations: Aristarchus's idea seemed inconsistent with observations of stellar positions in the sky.

To understand the inconsistency, imagine what would happen if you placed the Sun rather than Earth at the center of the celestial sphere, with Earth orbiting the Sun some distance away. In that case, Earth would be closer to different portions of the celestial sphere at different times of year. When we were closer to a particular part of the sphere, the stars on that part of the sphere would appear more widely separated than they would when we were farther from that part of the sphere, just as the spacing between the two headlights on a car looks greater when you are closer to the car. This would create annual shifts in the separations of stars—but the Greeks observed no

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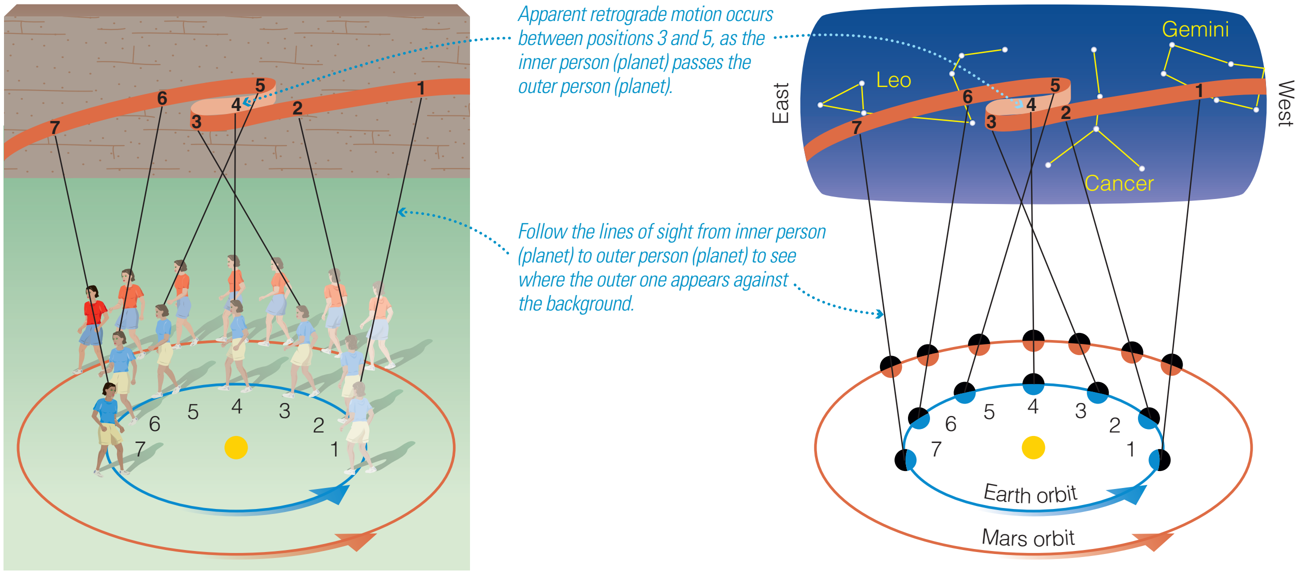
*The term *heliocentric* is equivalent to "Sun-centered," because *helios* is Greek for the Sun. The element helium also shares this root, because helium was first identified in solar spectra before it was discovered on Earth.



a The retrograde motion demonstration: Watch how your friend (in red) usually appears to you (in blue) to move forward against the background of the building in the distance but appears to move backward as you catch up to and pass him or her in your "orbit."

b This diagram shows how the idea from the demonstration applies to planets. Follow the lines of sight from Earth to Mars in numerical order. Notice that Mars appears to move westward relative to the distant stars as Earth passes by it in Earth's own orbit (roughly from points 3 to 5 in the diagram).

FIGURE 2.5
Apparent retrograde motion—the occasional "backward" motion of the planets relative to the stars—has a simple explanation in a Sun-centered system.

such shifts. They knew that there were only two possible ways to account for the lack of an observed shift: Either Earth was at the center of the universe or the stars were so far away as to make the shift undetectable by eye. To most Greeks, it seemed unreasonable to imagine that the stars could be *that* far away, which led them to conclude that Earth must hold a central place.

This argument about stellar shifts still holds when we allow for the reality that stars lie at different distances rather than all on the same sphere: As Earth orbits the Sun, we look at particular stars from slightly different positions at different times of year, causing the positions of nearby stars to shift slightly relative to the positions of more distant stars (Figure 2.6). Although such shifts are much too small to measure with the naked eye—because stars really are very far away [Section 3.2]—they are easily detectable with modern telescopes. These annual shifts in stellar position, called **stellar parallax,** now provide concrete proof that Earth really does go around the Sun.

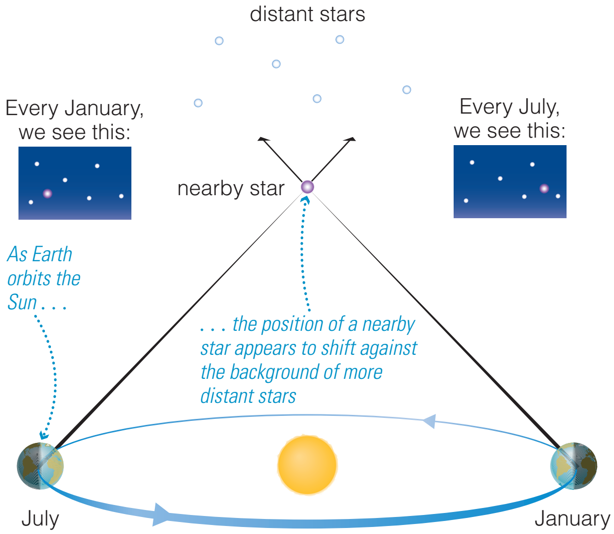


FIGURE 2.6
If Earth orbits the Sun, then over the course of each year we should see nearby stars shift slightly back and forth relative to more distant stars (*stellar parallax*). The Greeks could not detect any such shift, and they used this fact to argue that Earth must be at the center of the universe. Today, we *can* detect stellar parallax with telescopic observations, proving that Earth does orbit the Sun. (This figure is greatly exaggerated; the actual shift is far too small to detect with the naked eye.)

THE ROOTS OF MODERN SCIENCE Although the Greeks ultimately rejected the correct idea—that Earth orbits the Sun—we have seen that they did so for reasons that made good sense at the time. Not all of their reasons would pass the test of modern science; for example, their preference for motion in perfect circles came only from their cultural ideas of aesthetics and not from any actual data. But they also went to a lot of effort to ensure that their models were consistent with observations, and in that way they laid the foundation of modern science. And while Aristarchus may not have won the day in his own time, his idea remained alive in books. Some 1800 years after he first proposed it, Aristarchus's Sun-centered model apparently came to the attention of a Polish astronomer named Nicolaus Copernicus (1473–1543), who took the idea and ran with it in a way that led directly to the development of modern science. We'll return to this story shortly.

2.1.2 Why did the Greeks argue about the possibility of life beyond Earth?

Almost from the moment that Thales wondered what the universe was made of, the Greeks realized that the answer would have bearing on the possibility of life elsewhere. This might seem surprising in light of their geocentric beliefs, because they didn't think of the planets or stars as worlds in the way we think of them today. Instead, the Greeks generally considered the "world" to include both Earth and the heavenly spheres that they imagined to surround it, and they were at least open to the possibility that other such "worlds" might exist.

As we noted earlier, Thales guessed that the world consisted fundamentally of water, with Earth floating on an infinite ocean, but his student Anaximander imagined a more mystical element that he called *apeiron,* meaning "infinite." Anaximander suggested that all material things arose from and returned to the apeiron, which allowed him to imagine that worlds might be born and die repeatedly through eternal time. So even though he made no known claim of life existing elsewhere in the present, Anaximander essentially suggested that other Earths and other beings might exist at other times.

Other Greeks took the debate in a slightly different direction, and eventually a consensus emerged in favor of the idea that our "world" was built from four elements: fire, water, earth, and air. However, two distinct schools of thought emerged concerning the nature and extent of these elements:

- The *atomists* held that both Earth and the heavens were made from an infinite number of indivisible atoms of each of the four elements.
- The *Aristotelians* (after Aristotle) held that the four elements—not necessarily made from atoms—were confined to the realm of Earth, while the heavens were made of a fifth element, often called the *aether* (or *ether*) or the *quintessence* (literally, "the fifth essence").

The differences in the two schools of thought led to two fundamentally different conclusions about the possibility of extraterrestrial life.

Think About It Look up the words *ethereal* and *quintessence* in the dictionary. How do their definitions relate to the Aristotelian idea that the heavens were composed of an element distinct from the elements of Earth? Explain.

The atomist doctrine was developed largely by Democritus (c. 470–380 B.C.E.), and his views show how the idea led almost inevitably to belief in extraterrestrial life. Democritus argued that the world—both Earth and the heavens—had been created by the random motions of infinite atoms. Because this idea held that the number of atoms was infinite, it was natural to assume that the same processes that created our world could also have created others. This philosophy on life beyond Earth is clearly described in the following quotation from a later atomist, Epicurus (341–270 B.C.E.):

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

Aristotle had a different view. He believed that each of the four elements had its own natural motion and place. For example, he believed that the element earth moved naturally toward the center of the universe, an idea that offered an explanation for the Greek assumption that Earth resided in a central place. The element fire, he claimed, naturally rose away from the center, which explained why flames jut upward into the sky. These incorrect ideas about physics, which were not disproved until the time of Galileo and Newton almost 2000 years later, caused Aristotle to reject the atomist idea of many worlds. If there was more than one world, there would be more than one natural place for the elements to go, which would be a logical contradiction. Aristotle concluded:

> *The world must be unique. ... There cannot be several worlds.*

Interestingly, Aristotle's philosophies were not particularly influential until many centuries after his death. His books were preserved and valued—in particular, by Islamic scholars of the late first millennium—but they were unknown in Europe until they were translated into Latin in the twelfth and thirteenth centuries. St. Thomas Aquinas (1225–1274) integrated Aristotle's philosophy into Christian theology. At this point, the contradiction between the

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*From Epicurus's "Letter to Herodotus"; the authors thank David Darling for finding this quotation and the one from Aristotle, both of which appear in Darling's book *The Extraterrestrial Encyclopedia,* Three Rivers Press, 2000.

Aristotelian notion of a single world and the atomist notion of many worlds became a subject of great concern to Christian theologians. Moreover, because the atomist view held that our world came into existence through random motions of atoms, and hence without the need for any intelligent Creator, atomism became associated with atheism. The debate about extraterrestrial life thereby became intertwined with debates about religion. Even today, the theological issues are not fully settled, and echoes of the ancient Greek debate between the atomists and the Aristotelians still reverberate in our time.

LEARNING OBJECTIVE

The Copernican Revolution

2.2 The Copernican Revolution

Greek ideas gained great influence in the ancient world, in large part because the Greeks proved to be as adept at politics and war as they were at philosophy. In about 330 B.C.E., Alexander the Great began a series of conquests that expanded the Greek Empire throughout the Middle East. Alexander had a keen interest in science and education, perhaps because he grew up with Aristotle as his personal tutor. Alexander established the city of Alexandria in Egypt, and his successors founded the renowned Library of Alexandria (Figure 2.7). Though it is sometimes difficult to distinguish fact from legend in stories about this great Library, there is little doubt that it was once the world's preeminent center of research, housing up to a half million books written on papyrus scrolls. While the details of the Library's ultimate destruction are hazy and subject to disagreement among historians, most of its books were lost forever.

FIGURE 2.7

This photo shows the new Library of Alexandria in Egypt (opened in 2003), which was built in commemoration of the ancient Library of Alexandria. That library housed up to a half million books, most of which were single copies that were lost forever when it was destroyed.

The relatively few books from the Library that survive today were preserved primarily thanks to the rise of a new center of intellectual inquiry in Baghdad (in present-day Iraq). As European civilization fell into the Dark Ages, scholars of the new religion of Islam sought knowledge of mathematics and astronomy in hopes of better understanding the wisdom of Allah. The Islamic scholars translated and thereby saved many of the remaining ancient Greek works. Building on what they learned from the Greek manuscripts, they went on to develop the mathematics of algebra as well as many new instruments and techniques for astronomical observation.

The Islamic world of the Middle Ages was in frequent contact with Hindu scholars from India, who in turn brought ideas and discoveries from China. Hence, the intellectual center in Baghdad achieved a synthesis of the surviving work of the ancient Greeks, the Indians, the Chinese, and the contributions of its own scholars. This accumulated knowledge spread throughout the Byzantine Empire (the eastern part of the former Roman Empire). When the Byzantine capital of Constantinople (modern-day Istanbul) was conquered by the Ottomans in 1453, many Eastern scholars headed west to Europe, carrying with them the knowledge that helped ignite the European Renaissance. The stage was set for a dramatic rethinking of humanity and our place in the universe.

2.2.1 How did the Copernican revolution further the development of science?

In 1543, Nicolaus Copernicus published *De Revolutionibus Orbium Coelestium* ("Concerning the Revolutions of the Heavenly Spheres"), launching what we now call the **Copernican revolution.** In his book, Copernicus revived Aristarchus's radical suggestion of a Sun-centered system and described the idea with enough mathematical detail to make it a valid competitor to the Earth-centered Ptolemaic model. Over the next century and a half, philosophers and scientists (who were often one and the same) debated and tested the Copernican idea. Many of the ideas that now form the foundation of modern science first arose as this debate played out. Indeed, the Copernican revolution had such a profound impact on philosophy that we cannot understand modern science without first understanding the key features of this revolution.

COPERNICUS—THE REVOLUTION BEGINS By the time of Copernicus's birth in 1473, tables of planetary motion based on the Ptolemaic model had become noticeably inaccurate. However, few people were willing to undertake the difficult calculations required to revise the tables. Indeed, the best tables available were already two centuries old, having been compiled under the guidance of the Spanish monarch Alphonso X (1221–1284). Commenting on the tedious nature of the work involved, the monarch is said to have complained, “If I had been present at the creation, I would have recommended a simpler design for the universe.”

Copernicus began studying astronomy in his late teens. He soon became aware of the inaccuracies of the Ptolemaic predictions and began a quest for a better way to predict planetary positions. He adopted Aristarchus’s Sun-centered idea, probably because he was drawn to its simple explanation for the apparent retrograde motion of the planets (see Figure 2.5). As he worked out the mathematical details of his model, Copernicus discovered simple geometric relationships that allowed him to calculate each planet’s orbital period around the Sun and its relative distance from the Sun in terms of Earth–Sun distance. The success of his model in providing a geometric layout for the solar system further convinced him that the Sun-centered idea must be correct. Despite his own confidence in the model, Copernicus was hesitant to publish his work, fearing that the idea of a moving Earth would be considered absurd.* However, he discussed his system with other scholars, including high-ranking officials of the Church, who urged him to publish a book. Copernicus saw the first printed copy of his book on the day he died—May 24, 1543.

Publication of the book spread the Sun-centered idea widely, and many scholars were drawn to its aesthetic advantages. However, the Copernican model gained relatively few converts over the next 50 years, for a good reason: It didn’t work all that well. The primary problem was that while Copernicus had been willing to overturn Earth’s central place in the cosmos, he held fast to the ancient belief that heavenly motion must occur in perfect circles. This incorrect assumption forced him to add numerous complexities to his system (including circles on circles much like those used by Ptolemy) to get it to make decent predictions. In the end, his complete model was no more accurate and no less complex than the Ptolemaic model, and few people were willing to throw out thousands of years of tradition for a new model that worked just as poorly as the old one.

TYCHO—A NEW STANDARD IN OBSERVATIONAL DATA

Part of the difficulty faced by astronomers who sought to improve either the Ptolemaic or the Copernican model was a lack of quality data. The telescope had not yet been invented, and existing naked-eye observations were not particularly accurate. In the late sixteenth century, Danish nobleman Tycho Brahe (1546–1601), usually known simply as Tycho (commonly pronounced “TIE-koe”), set about correcting this problem.

Tycho was an eccentric genius who, at age 20, lost part of his nose in a sword fight with another student over who was the better mathematician. Taking advantage of his royal connections, he built large naked-eye observatories (Figure 2.8) that worked much like giant protractors, and over a period of three decades he used them to measure planetary positions to within 1 minute of arc ($\frac{1}{60}$ of 1°)—which is less than the thickness of a fingernail held at arm’s length.

KEPLER—A SUCCESSFUL MODEL OF PLANETARY MOTION

Tycho never came up with a fully satisfactory explanation for his observations (though he made a valiant attempt), but he found someone else who did. In 1600, he hired a young German astronomer named Johannes Kepler (1571–1630). Kepler and Tycho had

FIGURE 2.8

Tycho Brahe in his naked-eye observatory, which worked much like a giant protractor. He could sit and observe a planet through the rectangular hole in the wall as an assistant used a sliding marker to measure the angle on the protractor.

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*Indeed, in the Preface of *De Revolutionibus,* Copernicus offered a theological defense of the Sun-centered idea: “Behold, in the middle of the universe resides the Sun. For who, in this most beautiful Temple, would set this lamp in another or a better place, whence to illumine all things at once?”

a strained relationship,* but in 1601, as he lay on his deathbed, Tycho begged Kepler to find a system that would make sense of his observations so "that it may not appear I have lived in vain."

Kepler was deeply religious and believed that understanding the geometry of the heavens would bring him closer to God. Like Copernicus, he believed that planetary orbits should be perfect circles, so he worked diligently to match circular motions to Tycho's data. After years of effort, he found a set of circular orbits that matched most of Tycho's observations quite well. Even in the worst cases, which were for the planet Mars, Kepler's predicted positions differed from Tycho's observations by only about 8 arcminutes.

Kepler surely was tempted to ignore these discrepancies and attribute them to errors by Tycho. After all, 8 arcminutes is barely one-fourth the angular diameter of the full moon. But Kepler trusted Tycho's careful work. The small discrepancies finally led Kepler to abandon the idea of circular orbits—and to find the correct solution to the ancient riddle of planetary motion. About this event, Kepler wrote,

> *If I had believed that we could ignore these eight minutes [of arc], I would have patched up my hypothesis accordingly. But, since it was not permissible to ignore, those eight minutes pointed the road to a complete reformation in astronomy.*

Kepler's decision to trust the data over his preconceived beliefs marked an important transition point in the history of science. Once he abandoned perfect circles, he was free to try other ideas and he soon hit on the correct one: Planetary orbits take the shapes of the special types of ovals known as *ellipses.* He then used his knowledge of mathematics to put his new model of planetary motion on a firm footing, expressing the key features of the model with what we now call **Kepler's laws of planetary motion:**

- **Kepler's first law:** *The orbit of each planet about the Sun is an ellipse with the Sun at one focus* (Figure 2.9). This law tells us that a planet's distance from the Sun varies during its orbit. Its closest point is called **perihelion** (from the Greek for "near the Sun") and its farthest point is called **aphelion** ("away from the Sun"). The *average* of a planet's perihelion and aphelion distances is the length of its **semimajor axis** (which we will refer to simply as the planet's average distance from the Sun), which is defined to be *half* the distance across the long axis of an ellipse.
- **Kepler's second law:** *A planet moves faster in the part of its orbit nearer the Sun and slower when farther from the Sun, sweeping out equal areas in equal times.* As shown in Figure 2.10, the "sweeping" refers to an imaginary line connecting the planet to the Sun, and keeping the areas equal means that the planet moves a greater distance (and hence is moving faster) when it is near perihelion than it does in the same amount of time near aphelion.
- **Kepler's third law:** *More distant planets orbit the Sun at slower average speeds, obeying the precise mathematical relationship* $p^2 = a^3$, where p is the planet's orbital period in years and a is its average distance (semimajor axis) from the Sun in astronomical units. (One **astronomical unit,** abbreviated AU, is defined as Earth's average distance from the Sun, or about 149.6 million kilometers.) The mathematical statement of Kepler's third law allows us to calculate the average orbital speed of each planet (Figure 2.11).

Kepler published his first two laws in 1609 and his third in 1619. Together, they made a model that could predict planetary positions with far greater accuracy than Ptolemy's Earth-centered model. Indeed, Kepler's model has worked so well that we now see it

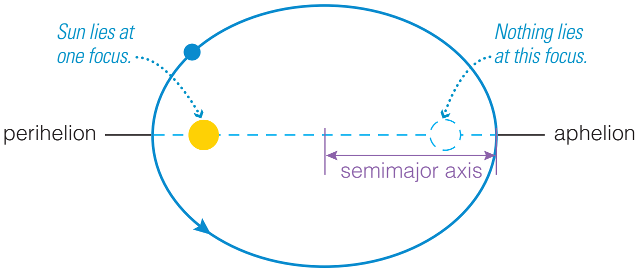

FIGURE 2.9
Kepler's first law: The orbit of each planet about the Sun is an ellipse with the Sun at one focus. (The ellipse shown here is more eccentric, or "stretched out," than any of the actual planetary orbits in our solar system.)

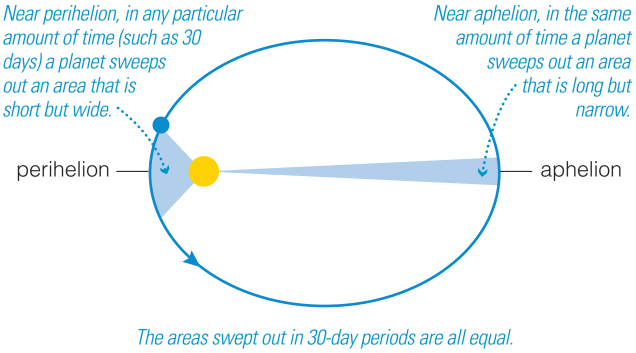

FIGURE 2.10
Kepler's second law: As a planet moves around its orbit, it moves faster when closer to the Sun than when farther away, so that an imaginary line connecting it to the Sun sweeps out equal areas (the shaded regions) in equal times.

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*For a particularly moving version of the story of Tycho and Kepler, see episode 3 of the TV series *Cosmos,* with Carl Sagan.

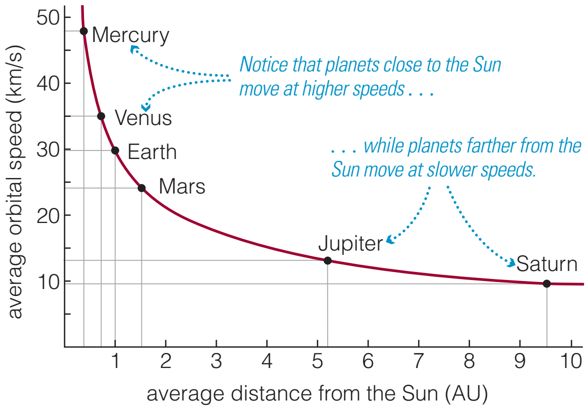


FIGURE 2.11

This graph, based on Kepler's third law ($p^2 = a^3$) and modern values of planetary distances, shows that more distant planets orbit the Sun more slowly.

not just as an abstract model, but instead as revealing a deep, underlying truth about planetary motion.

LEARNING OBJECTIVE

NOT the Center of the Universe

GALILEO—ANSWERING THE REMAINING OBJECTIONS

The success of Kepler's laws in matching Tycho's data provided strong evidence in favor of Copernicus's placement of the Sun, rather than Earth, at the center of the solar system. Nevertheless, many scientists still voiced reasonable objections to the Copernican view. There were three basic objections, all rooted in the 2000-year-old beliefs of Aristotle:

1. Aristotle had held that Earth could not be moving because, if it were, objects such as birds, falling stones, and clouds would be left behind as Earth moved along its way.
2. The idea of noncircular orbits contradicted the view that the heavens—the realm of the Sun, Moon, planets, and stars—must be perfect and unchanging.
3. No one had detected the stellar parallax that should occur if Earth orbits the Sun.

Galileo Galilei (1564–1642), usually known by only his first name, answered all three objections.

Galileo defused the first objection with experiments that almost single-handedly overturned the Aristotelian view of physics. In particular, he used experiments with rolling balls to demonstrate that a moving object remains in motion *unless* a force acts to stop it (an idea now codified in Newton's first law of motion). This insight explained why objects that share Earth's motion through space—such as birds, falling stones, and clouds—should *stay* with Earth rather than falling behind as Aristotle had argued. This same idea explains why passengers stay with a moving airplane even when they leave their seats.

The second objection, the notion of heavenly perfection, was already under challenge by Galileo's time, because Tycho had observed a supernova and proved that comets lie beyond the Moon; these observations showed that the heavens *do* sometimes undergo change. But Galileo drove the new idea home after he built a telescope in late 1609. (Galileo did not invent the telescope, but his innovations made it much more powerful.) Through his telescope, Galileo saw sunspots on the Sun, which were considered "imperfections" at the time. He also used his telescope to prove that the Moon has mountains and valleys like the "imperfect" Earth by noticing the shadows cast near the dividing line between the light and dark portions of the lunar face (Figure 2.12). If the heavens were not perfect, then the idea of elliptical orbits (as opposed to "perfect" circles) was not so objectionable.

The third objection—the absence of observable stellar parallax—had been a particular concern of Tycho's. Based on his estimates of the distances of stars, Tycho believed that his naked-eye observations were sufficiently precise to detect stellar parallax if Earth did in fact orbit the Sun. Refuting Tycho's argument required showing that the stars were more distant than Tycho had thought and therefore too distant for him to have observed stellar parallax. Although Galileo didn't actually prove this fact, he provided strong evidence in its favor. For example, he saw with his telescope that the Milky Way resolved into countless individual stars. This discovery helped him argue that the stars were far more numerous and more distant than Tycho had believed.

In hindsight, the final nails in the coffin of the Earth-centered universe came with two of Galileo's

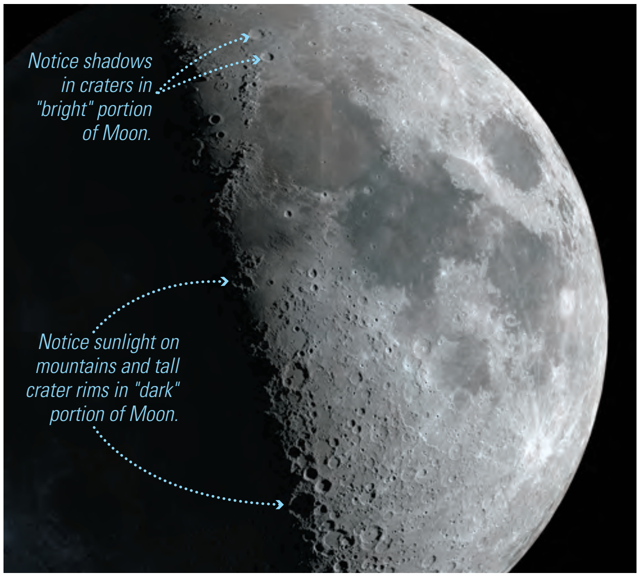
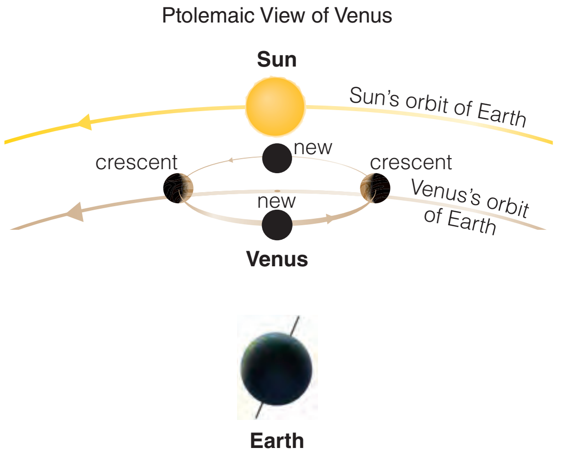
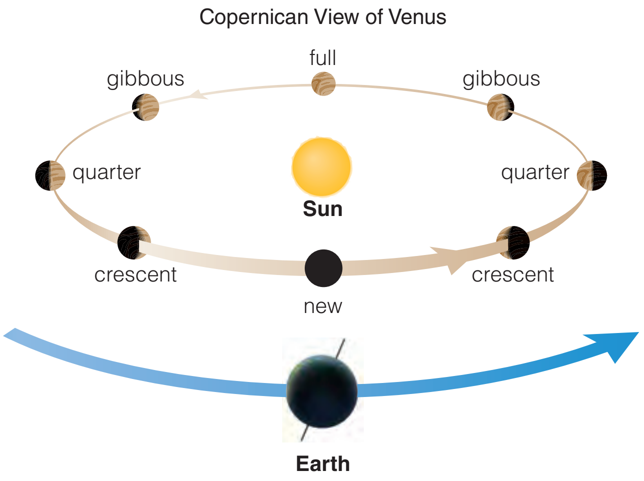


FIGURE 2.12

Shadows visible near the dividing line between the light and dark portions of the lunar face prove that the Moon's surface is not perfectly smooth.



a In the Ptolemaic model, Venus orbits Earth, moving around a small circle on its larger orbital circle; the center of the small circle lies on the Earth–Sun line. If this view were correct, Venus's phases would range only from new to crescent.



b In reality, Venus orbits the Sun, so from Earth we can see it in many different phases. This is just what Galileo observed, allowing him to prove that Venus orbits the Sun.

FIGURE 2.13

Galileo's telescopic observations of Venus proved that it orbits the Sun rather than Earth.

Do the Math 2.1

KEPLER'S THIRD LAW

When Kepler discovered his third law, he knew only that it applied to the orbits of planets about the Sun. In fact, it applies to any orbiting object as long as the following two conditions are met:

1. The object orbits the Sun *or* another object of precisely the same mass.
2. We use units of *years* for the orbital period and *AU* for the orbital distance.

(Newton later extended the law to *all* orbiting objects; see **DO THE MATH 7.1**.)

Example 1: The largest asteroid, Ceres, orbits the Sun at an average distance (semimajor axis) of 2.77 AU. What is its orbital period?

Solution: Both conditions are met, so we solve Kepler's third law for the orbital period p and substitute the given orbital distance, $a = 2.77$ AU:

$$p^2 = a^3 \Rightarrow p = \sqrt{a^3} = \sqrt{2.77^3} \approx 4.6$$

Ceres has an orbital period of 4.6 years.

Example 2: A planet is discovered orbiting every three months around a star of the same mass as our Sun. What is the planet's average orbital distance?

Solution: The first condition is met, and we can satisfy the second by converting the orbital period from months to years: $p = 3$ months $= 0.25$ year. We now solve Kepler's third law for the average distance a:

$$p^2 = a^3 \Rightarrow a = \sqrt[3]{p^2} = \sqrt[3]{0.25^2} \approx 0.40$$

The planet orbits its star at an average distance of 0.40 AU, which is nearly the same as Mercury's average distance from the Sun.

earliest discoveries using his telescope. First, he observed four moons clearly orbiting Jupiter, not Earth. Soon thereafter, he observed that Venus goes through phases in a way that proved that it must orbit the Sun and not Earth (Figure 2.13). Together, these observations offered clear proof that Earth is *not* the center of everything.*

Although we now recognize that Galileo won the day, the story was more complex in his own time, when Catholic Church doctrine still held Earth to be the center of the universe. On June 22, 1633, Galileo was brought before a Church inquisition in Rome and ordered to recant his claim that Earth orbits the Sun. Nearly 70 years old and likely fearing for his life, Galileo did as ordered. However, legend has it that as he rose from his knees, he whispered under his breath, "*Eppur si muove*"—Italian for "And yet it moves." (Given the likely consequences if Church officials had heard him say this, most historians doubt the legend.)

The Church did not formally vindicate Galileo until 1992, but it had given up the argument long before that. Today, Catholic scientists are at the forefront of much astronomical research, and official Church teachings are compatible not only with Earth's planetary status but also with the theories of the Big Bang and the subsequent evolution of the cosmos and of life.

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*While these observations proved that Earth is not the center of everything, they did not by themselves prove that Earth orbits the Sun; direct proof of that fact did not come until later, with measurements of stellar parallax and of an effect known as the *aberration of starlight* that also occurs only because of Earth's motion. Nevertheless, the existence of Jupiter's moons showed that moons can orbit a moving planet like Jupiter, which overcame some critics' complaints that the Moon could not stay with a moving Earth, and the proof that Venus orbits the Sun provided clear validation of Kepler's model of Sun-centered planetary motion.

Think About It Although the Catholic Church today teaches that science and the Bible are compatible, not all religious denominations hold the same belief. Do *you* think that science and the Bible are compatible? Defend your opinion.

NEWTON—THE REVOLUTION CONCLUDES Kepler's model worked so well and Galileo so successfully defused the remaining objections that by about the 1630s, scientists were nearly unanimous in accepting the validity of Kepler's laws of planetary motion. However, no one yet knew *why* the planets should move in elliptical orbits with varying speeds. The question became a topic of great debate, and a few scientists even guessed the correct answer—but they could not prove it, largely because the necessary understanding of physics and mathematics didn't exist yet. This understanding finally came through the remarkable work of Sir Isaac Newton (1642–1727), who invented the mathematics of calculus and used it to explain and discover many fundamental principles of physics.

In 1687, Newton published a famous book usually called *Principia,* short for *Philosophiae Naturalis Principia Mathematica* ("Mathematical Principles of Natural Philosophy"). In it, he laid out precise mathematical descriptions of how motion works in general, ideas that we now describe as **Newton's laws of motion.** For reference, Figure 2.14 illustrates the three laws of motion, although we will not make much use of them in this book. (Be careful not to confuse *Newton's* three laws, which apply to all motion, with *Kepler's* three laws, which describe only the motion of planets moving about the Sun.)

Newton continued on in *Principia* to describe his universal law of gravitation (see Section 2.4), and then used mathematics to prove that Kepler's laws are natural consequences of the laws of motion and gravity. In essence, Newton had created a new model of the universe in which motion is governed by clear laws and the force of gravity. The model explained so much about the nature of motion in the everyday world, as well as about the movements of the planets, that the geocentric idea could no longer be taken seriously.

LOOKING BACK AT REVOLUTIONARY SCIENCE Fewer than 150 years passed between Copernicus's publication of *De Revolutionibus* in 1543 and Newton's publication of *Principia* in 1687, such a short time in the scope of human history that we call it a revolution. A quick look back shows that the revolution not only caused a radical change in the human perspective on our place in the universe—shifting Earth from a central role to being just one of many worlds—but also altered our ideas about how knowledge should be acquired. For example, while previous generations had tolerated inaccuracies in the predictions of the Ptolemaic model, Copernicus and his followers felt compelled to find models of nature that could actually reproduce what they observed.

The eventual success of Kepler's model also led to a new emphasis on understanding *why* nature works as it does. Past generations had relied almost solely on their cultural senses of aesthetics in guessing that the world was built with perfect circles and spheres and indivisible atoms, and they seemed content to accept these guesses even without any evidence of their reality. By Newton's time, guessing was no longer good enough. Instead, you had to present hard evidence, backed by rigorous mathematics, to convince your colleagues that you'd hit on something that truly brought us closer to understanding the nature of the universe.

Newton's first law of motion: An object moves at constant velocity unless a net force acts to change its speed or direction.

Newton's second law of motion: Force = mass × acceleration

Newton's third law of motion: For any force, there is always an equal and opposite reaction force.

Example: *A spaceship needs no fuel to keep moving in space.*

Example: *A baseball accelerates as the pitcher applies a force by moving his arm. (Once the ball is released, the force from the pitcher's arm ceases, and the ball's path changes only because of the forces of gravity and air resistance.)*

Example: *A rocket is propelled upward by a force equal and opposite to the force with which gas is expelled out its back.*

FIGURE 2.14
Newton's three laws of motion.

2.2.2 How did the Copernican revolution alter the ancient debate on extraterrestrial life?

The Copernican revolution did not deal directly with the question of life in the universe, but it had a major effect on the way people thought about the issue. You can see why by thinking back to the ancient Greek debate.

Recall that while the atomists believed that there were many worlds, Aristotle held that this world *must* be unique and located in the center of everything, largely because his ideas of physics convinced him that all the "earth" in the universe would have naturally fallen to the center. The Copernican revolution therefore proved that Aristotle was wrong: Earth is not the center of the universe, after all.

Of course, the fact that Aristotle was wrong did *not* mean that the atomists had been right, but many of the Copernican-era scientists assumed that they had been. Galileo suggested that lunar features he saw through his telescope might be land and water much like that on Earth. Kepler agreed and went further, suggesting that the Moon had an atmosphere and was inhabited by intelligent beings. Kepler even wrote a science fiction story, *Somnium* ("The Dream"), in which he imagined a trip to the Moon and described the lunar inhabitants. The Dominican friar and philosopher Giordano Bruno was convinced of the existence of extraterrestrial life, a belief that contributed to battles with authorities that ultimately got him burned at the stake (see Special Topic 2.1).

Later scientists took the atomist belief even further. William Herschel (1738–1822), most famous as

Special Topic 2.1 GEOCENTRISM AND THE CHURCH

The case of Galileo is often portrayed as having exposed a deep conflict between science and religion. However, the history of the debate over geocentrism shows that the reality was much more complex, with deep divisions even within the Church hierarchy.

Perhaps the clearest evidence for a more open-minded Church comes from the case of Copernicus, whose revolutionary work was supported by many Church officials. A less well-known and even earlier example concerns Nicholas of Cusa (1401–1464), who published a book arguing for a Sun-centered system in 1440, more than a century before Copernicus's book. Nicholas even weighed in on the subject of extraterrestrial life in that work:

> *Rather than think that so many stars and parts of the heavens are uninhabited and that this earth of ours alone is peopled … we will suppose that in every region there are inhabitants, differing in nature by rank and allowing their origin to God …*

Church officials were apparently so untroubled by these radical ideas that they ordained Nicholas as a priest in the same year his book was published, and he later became a Cardinal. (Copernicus probably was not aware of this earlier work by Nicholas of Cusa.)

Many other scientists received similar support within the Church. Indeed, for most of his life, Galileo counted cardinals—and even the pope who later excommunicated him—among his friends. Some historians suspect that Galileo got into trouble less for his views than for the way he portrayed them. For example, in 1632—just a year before his famous trial—he published a book in which two fictional characters debated the geocentric and Sun-centered views. He named the character taking the geocentric position Simplicio—essentially "simple-minded"—and someone apparently convinced the pope that the character was a caricature of him. Moreover, as described by the noted modern author Isaac Asimov,

> *The book was all the more damaging to those who felt themselves insulted, because it was written in vigorous Italian for the general public (and not merely for the Latin-learned scholars) and was quickly translated into other languages—even Chinese!*

If it was personality rather than belief that got Galileo into trouble, he was not the only one. The Italian philosopher Giordano Bruno (1548–1600), who had once been a Dominican monk, became an early and extreme supporter not only of the Copernican system but also of the idea of extraterrestrial life. In his book *On the Infinite Universe and Worlds,* published in 1584, Bruno wrote:

> *[It] is impossible that a rational being … can imagine that these innumerable worlds, manifest as like to our own or yet more magnificent, should be destitute of similar or even superior inhabitants.*

Note that Bruno was so adamant in his beliefs that he claimed that no "rational being" could disagree with him, so it's unsurprising that he drew the wrath of conservative Church officials (on numerous issues, not just extraterrestrial life). Bruno was branded a heretic and burned at the stake on February 17, 1600.

Perhaps the main lesson to be drawn from these stories is that while science has advanced dramatically in the past several centuries, people remain much the same. The Church was never a monolithic entity, and just as different people today debate the meaning of words in the Bible or other religious texts, Church scholars also held many different opinions at the time of the Copernican revolution. The political pendulum swung back and forth—or perhaps even chaotically—between the geocentric and Copernican views. Even when the evidence became overwhelming, a few diehards never gave in, and only the passing of generations finally ended the antagonism that had accompanied the great debate.

co-discoverer (with his sister Caroline) of the planet Uranus, assumed that all the planets were inhabited. In the late nineteenth century, when Percival Lowell (1855–1916) believed he saw canals on Mars (despite the fact that other astronomers wielding even bigger telescopes could not [Section 8.1]), it's quite likely that he was still being influenced by the philosophical ruminations of people who had lived more than 2000 years earlier.

If this debate about extraterrestrial life shows anything, it's probably this: *It's possible to argue almost endlessly, as long as there are no actual facts to get in the way.* With hindsight, it's easy for us to see that everything from the musings of the ancient Greeks to Lowell's martian canals was based more on hopes and beliefs than on any type of real evidence.

Nevertheless, the Copernican revolution really did mark a turning point in the debate about extraterrestrial life. For the first time, it was possible to test one of the ancient ideas—Aristotle's—and its failure caused it to be discarded. And while the Copernican revolution did not tell us whether the atomists had been right about life, it did make clear that the Moon and the planets really are other *worlds,* not mere lights in the sky. That fact alone makes it plausible to imagine life elsewhere, even if we still do not have the data necessary to conclude whether such life actually exists.

2.3 The Nature of Modern Science

The story of how our ancestors gradually figured out the basic architecture of the cosmos exhibits many features of what we now consider "good science." For example, we have seen how models were formulated and tested against observations, and then modified or replaced if they failed those tests. The story also illustrates some classic mistakes, such as the apparent failure of anyone before Kepler to question the belief that orbits must be circles. The ultimate success of the Copernican revolution led scientists, philosophers, and theologians to reassess the various modes of thinking that played a role in the 2000-year process of discovering Earth's place in the universe. Now, let's examine how the principles of modern science emerged from the lessons learned in the Copernican revolution.

LEARNING OBJECTIVE

Hallmarks of Science

2.3.1 How can we distinguish science from nonscience?

It's surprisingly difficult to define the term *science* precisely. The word comes from the Latin *scientia,* meaning "knowledge," but not all knowledge is science. For example, you may know what music you like best, but your musical taste is not a result of scientific study.

APPROACHES TO SCIENCE One reason science is difficult to define is that not all science works in the same way. For example, you've probably heard that science is supposed to proceed according to something called the "scientific method." As an idealized illustration of this method, consider what you would do if your flashlight suddenly stopped working. You might *hypothesize* that the flashlight's batteries have died. This type of tentative explanation, or **hypothesis,** is sometimes called an *educated guess*—in this case, it is "educated" because you already know that flashlights need batteries. Your hypothesis allows you to make a simple prediction: If you replace or recharge the batteries, the flashlight should work. You can test this prediction by doing that. If the flashlight now works, you've confirmed your hypothesis. If it doesn't, you must revise or discard your hypothesis, usually in favor of some other one that you can also test (such as that the bulb is burned out). Figure 2.15 illustrates the basic flow of this process.

The scientific method can be a useful idealization, but real science rarely progresses in such an orderly way. Scientific progress often begins with someone going out and looking at nature in a general way, rather than conducting a careful set of experiments. For example, Galileo wasn't looking for anything in particular when he pointed his telescope at the sky and made his first startling discoveries. We still often approach science in this way today, such as when we build new telescopes or send missions to other worlds.

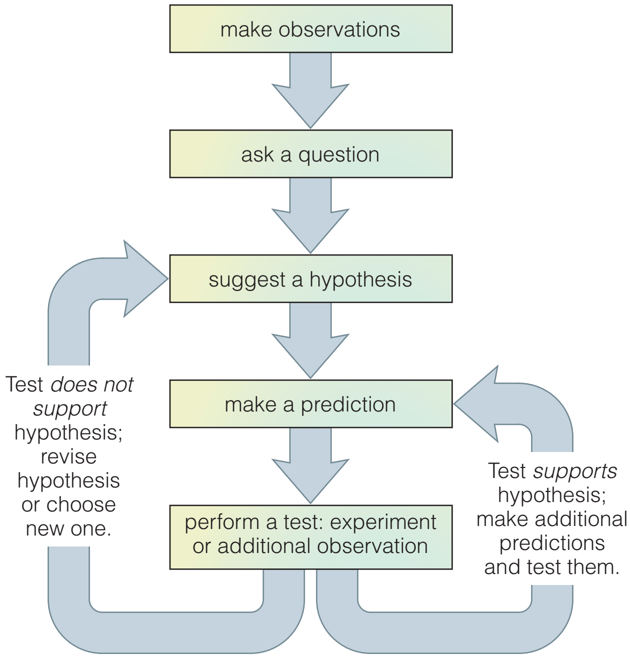


FIGURE 2.15

This diagram illustrates what we often call the *scientific method.*

We must also use alternative approaches when we attempt to understand past events, such as the history of Earth or the origin and evolution of life on Earth. We cannot repeat or vary the past, so we must instead rely on careful study of evidence left behind by past events. For example, we learn about early life on Earth not by observing it directly but by piecing together its story from an examination of fossils and other evidence that we can find today. Nevertheless, we can still apply at least some elements of the scientific method. For example, when scientists first proposed the idea that a massive impact may have been responsible for the death of the dinosaurs [Section 6.4], they were able to predict some of the other types of evidence that should exist if their hypothesis was correct. These predictions allowed other scientists to plan observations that might uncover this evidence, and when they succeeded—for example, by discovering an impact crater of the right age—support for the impact hypothesis grew much stronger.

A further complication in describing how science works comes from the fact that scientists are human beings, so their intuitions and personal beliefs inevitably influence their work. Copernicus, for example, adopted the idea that Earth orbits the Sun not because he had carefully tested this idea but because he believed it made more sense than the prevailing view of an Earth-centered universe. While his intuition guided him to the right general idea, he erred in the specifics because he still held Plato's ancient belief that heavenly motion must be in perfect circles.

Given the variety of ways in which it is possible to approach science, how can we identify what is science and what is not? To answer this question, we must look a little deeper at the distinguishing characteristics of scientific thinking.

HALLMARKS OF SCIENCE One way to define scientific thinking is to list the criteria that scientists use when they judge competing models of nature. Historians and philosophers of science have examined (and continue to examine) this issue in great depth, and different experts express somewhat different viewpoints on the details. Nevertheless, everything we now consider to be science shares the following three basic characteristics, which we will refer to as the *hallmarks of science* (Figure 2.16):

- Modern science seeks explanations for observed phenomena that rely solely on natural causes.
- Science progresses through the creation and testing of models of nature that explain the observations as simply as possible.
- A scientific model must make testable predictions about natural phenomena that would force us to revise or abandon the model if the predictions did not agree with observations.

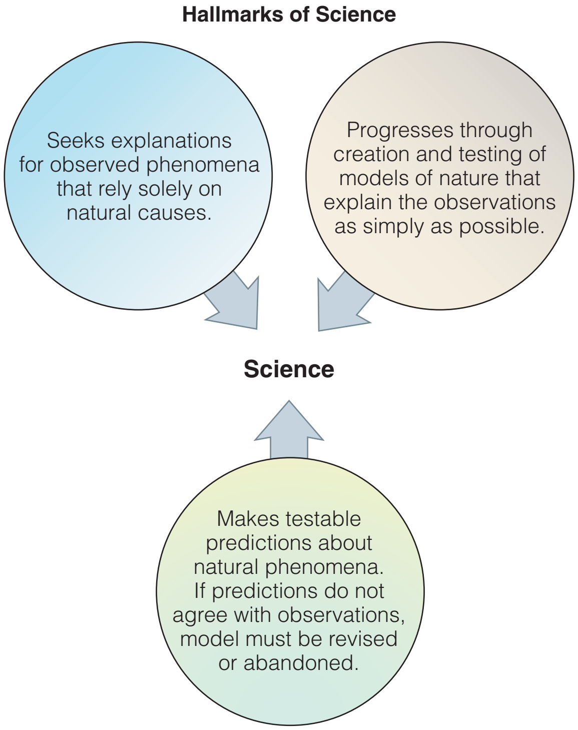


FIGURE 2.16
Hallmarks of science.

Each of these hallmarks is evident in the story of the Copernican revolution. The first shows up in the way Tycho's careful measurements of planetary motion motivated Kepler to come up with a better explanation for those motions. The second is evident in the way several competing models were compared and tested, most notably those of Ptolemy, Copernicus, and Kepler. We see the third in the fact that each model could make precise predictions about the future motions of the Sun, Moon, planets, and stars in our sky. Kepler's model gained acceptance because it worked, while the competing models lost favor because their predictions failed to match the observations. Figure 2.17 (pp. 32–33) summarizes the Copernican revolution and how it illustrates the hallmarks of science.

OCCAM'S RAZOR The criterion of simplicity in the second hallmark deserves additional explanation. Remember that Copernicus's original model did *not* match the data noticeably better than Ptolemy's model. If scientists had judged this model solely on the accuracy of its predictions, they might have rejected it immediately. However, many scientists found elements of the Copernican model appealing, such as its simple explanation for apparent retrograde motion. They therefore kept the model alive until Kepler found a way to make it work.

If agreement with data were the sole criterion for judgment, we could imagine a modern-day Ptolemy adding millions or billions of additional circles to the geocentric model in an effort to improve its agreement with observations. A sufficiently complex geocentric model could in principle reproduce the observations with almost perfect accuracy—but it still would not convince us that Earth is the center of the universe. We would still choose the Copernican view over the geocentric view because its predictions would be just as accurate but follow a much simpler model of nature. The idea that scientists should prefer the simpler of two models that agree equally well with observations is called *Occam's razor,* after the medieval scholar William of Occam (1285–1349).

VERIFIABLE OBSERVATIONS The third hallmark of science forces us to face the question of what counts as an "observation" against which a prediction can be tested. Consider the claim that aliens are visiting Earth in UFOs. Proponents of this claim say that thousands of eyewitness reports of UFO encounters provide evidence that it is true. But do these personal testimonials count as *scientific* evidence? On the surface, the answer isn't obvious, because all scientific studies involve eyewitness accounts on some level. For example, only a handful of scientists have personally made detailed tests of Einstein's theory of relativity, and it is their personal reports of the results that have convinced other scientists of the theory's validity. However, there's an important difference between personal testimony about a scientific test and personal reports of a UFO sighting: The first can be verified by anyone, at least in principle, while the second cannot.

Understanding this difference is crucial to understanding what counts as science and what does not. Even though you may never have conducted a test of Einstein's theory of relativity yourself, there's nothing stopping you from doing so. It might require several years of study before you have the necessary background to conduct the test, but you could then confirm the results reported by other scientists. In other words, while you may currently be trusting the eyewitness testimony of scientists, you always have the option of verifying their testimony for yourself.

In contrast, there is no way for you to verify someone's eyewitness account of a UFO. Without hard evidence such as clear photographs or pieces of the UFO, there is nothing that you could evaluate for yourself, even in principle. (And in those cases where "hard evidence" for UFO sightings has been presented, scientific study has never yet found the evidence to be strong enough to support the claim of alien spacecraft [Section 12.4].) Moreover, scientific studies of eyewitness testimony show it to be notoriously unreliable. For example, different eyewitnesses often disagree on what they saw even immediately after an event has occurred. As time passes, memories of the event may change further. In some cases in which memory has been checked against reality, people have reported vivid memories of events that never happened at all. This explains something that virtually all of us have experienced: disagreements with a friend about who did what and when. Since both people cannot be right in such cases, at least one person must have a memory that differs from reality.

The demonstrated unreliability of eyewitness testimony explains why it is generally considered insufficient for a conviction in criminal court; at least some other evidence is required. For the same reason, we cannot accept eyewitness testimony by itself as evidence in science, no matter who reports it or how many people offer similar testimony.

SCIENCE AND PSEUDOSCIENCE It's important to realize that science is not the only valid way of seeking knowledge. For example, suppose you are shopping for a car, learning to play drums, or pondering the meaning of life. In each case, you might make observations, exercise logic, and test hypotheses. Yet these pursuits clearly are not science, because they are not directed at developing testable explanations for observed natural phenomena. As long as nonscientific searches for knowledge make no claims about how the natural world works, they do not conflict with science.

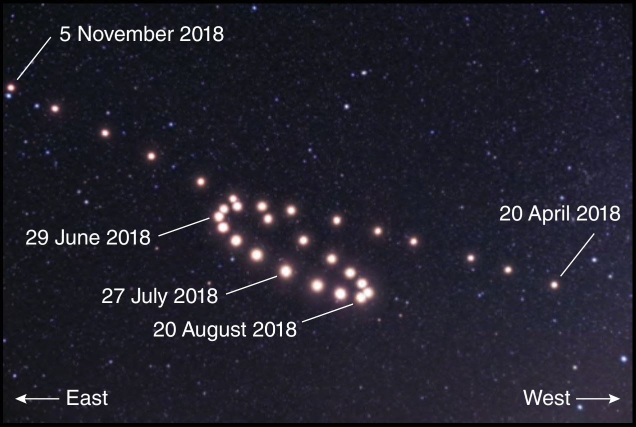
However, you will often hear claims about the natural world that seem to be based on observational evidence but do not treat evidence in a truly scientific way. Such claims are often called **pseudoscience,** which means "false science." To distinguish real science from pseudoscience, a good first step is to check whether a particular claim exhibits all three hallmarks of science. Consider the example of people who claim a psychic ability to "see" the future and use it to make specific, testable predictions. In this sense, "seeing" the future sounds scientific, since we can test it. However, numerous studies have examined the predictions of "seers" and have found that their predictions come true no more often than would be expected by pure chance. If the seers were scientific, they would admit that this evidence undercuts their claim of psychic abilities. Instead, they generally make excuses, such as saying that the predictions didn't come true because of some type of "psychic interference." Making testable claims but then ignoring the results of the tests marks the claimed ability to see the future as pseudoscience.

OBJECTIVITY IN SCIENCE The idea that science is objective, meaning that all people should be able to find the same results, is important to the validity of

FIGURE 2.17 The Copernican revolution

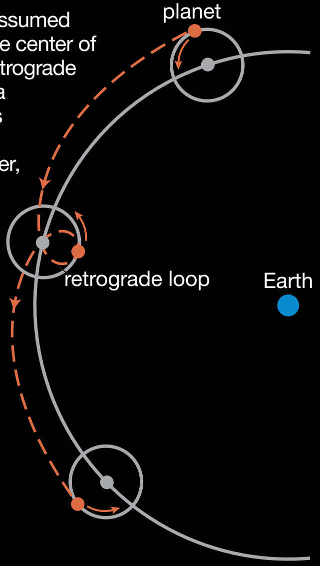
Ancient Earth-centered models of the universe easily explained the simple motions of the Sun and Moon through our sky, but had difficulty explaining the more complicated motions of the planets. The quest to understand planetary motions ultimately led to a revolution in our thinking about Earth's place in the universe that illustrates the process of science. This figure summarizes the major steps in that process.

① Night by night, planets usually move from west to east relative to the stars. However, during periods of *apparent retrograde motion,* they reverse direction for a few weeks to months [Section 2.1]. The ancient Greeks knew that any credible model of the solar system had to explain these observations.



This composite photo shows the apparent retrograde motion of Mars.

② Most ancient Greek thinkers assumed that Earth remained fixed at the center of the solar system. To explain retrograde motion, they therefore added a complicated scheme of circles moving upon circles to their Earth-centered model. However, at least some Greeks, such as Aristarchus, preferred a Sun-centered model, which offered a simpler explanation for retrograde motion.



The Greek geocentric model explained apparent retrograde motion by having planets move around Earth on small circles that turned on larger circles.

HALLMARK OF SCIENCE **A scientific model must seek explanations for observed phenomena that rely solely on natural causes.** The ancient Greeks used geometry to explain their observations of planetary motion.

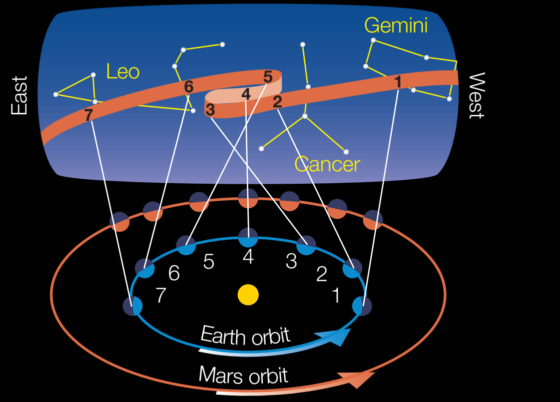
(Left page)
A schematic map of the universe from 1539 with Earth at the center and the Sun (Solis) orbiting it between Venus (Veneris) and Mars (Martis).

(Right page)
A page from Copernicus's De Revolutionibus, published in 1543, showing the Sun (Sol) at the center and Earth (Terra) orbiting between


LIBRI COSMO. Fo.V.
Schema huius præmiſſæ diuiſionis
Sphærarum.


net,in q
diximus
deniq l
currens.

③ By the time of Copernicus (1473–1543), predictions based on the Earth-centered model had become noticeably inaccurate. Hoping for improvement, Copernicus revived the Sun-centered idea. He did not succeed in making substantially better predictions because he retained the ancient belief that planets must move in perfect circles, but he inspired a revolution continued over the next century by Tycho, Kepler, and Galileo.



Apparent retrograde motion is simply explained in a Sun-centered system. Notice how Mars appears to change direction as Earth moves past it.

HALLMARK OF SCIENCE **Science progresses through creation and testing of models of nature that explain the observations as simply as possible.** Copernicus developed a Sun-centered model in hopes of explaining observations better than the more complicated Earth-centered model.

NICOLAI COPERNICI

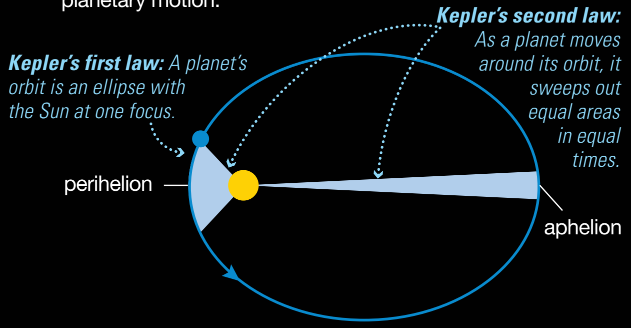
uo terram cum orbe lunari tanquam epicyclo contineri

s.Quinto loco Venus nono menſe reducitur. Sextum

ocum Mercurius tenet, octuaginta dierum ſpacio circū

.In medio uero omnium reſidet Sol. Quis enim in hoc

④ Tycho exposed flaws in both the ancient Greek and Copernican models by observing planetary motions with unprecedented accuracy. His observations led to Kepler's breakthrough insight that planetary orbits are elliptical, not circular, and enabled Kepler to develop his three laws of planetary motion.



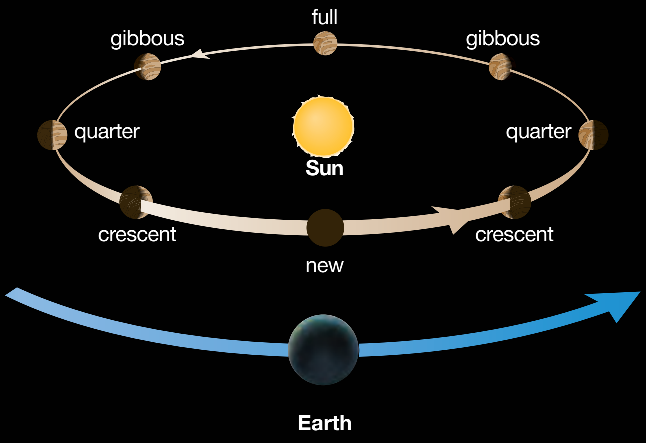
Kepler's first law: *A planet's orbit is an ellipse with the Sun at one focus.*

Kepler's second law: *As a planet moves around its orbit, it sweeps out equal areas in equal times.*

Kepler's third law: *More distant planets orbit at slower average speeds, obeying* $p^2 = a^3$.

HALLMARK OF SCIENCE **A scientific model makes testable predictions about natural phenomena. If predictions do not agree with observations, the model must be revised or abandoned.** Kepler could not make his model agree with observations until he abandoned the belief that planets move in perfect circles.

⑤ Galileo's experiments and telescopic observations overcame remaining scientific objections to the Sun-centered model. Together, Galileo's discoveries and the success of Kepler's laws in predicting planetary motion overthrew the Earth-centered model once and for all.



With his telescope, Galileo saw phases of Venus that are consistent only with the idea that Venus orbits the Sun rather than Earth.

science as a means of seeking knowledge. However, there is a difference between the overall objectivity of science and the objectivity of individual scientists.

Science is practiced by human beings, and individual scientists may bring their personal biases and beliefs to their scientific work. For example, most scientists choose their research projects based on personal interests rather than on some objective formula. In extreme cases, scientists have even been known to cheat—either deliberately or subconsciously—to obtain a result they desire. For example, in the late nineteenth century, astronomer Percival Lowell claimed to see a network of artificial canals when he observed Mars through the telescopes available at the time, leading him to conclude that there was a great Martian civilization. But no such canals actually exist, so Lowell must have allowed his beliefs about extraterrestrial life to influence the way he interpreted what he saw. A more deliberate—and much more damaging—case of cheating occurred in 1998, when British physician Andrew Wakefield published results claiming a link between childhood vaccines and autism, but follow-up research revealed the claim to be fraudulent. Much of today's unscientific "anti-vax" movement can be traced back to this fraudulent claim.

Bias can sometimes show up even in the thinking of the scientific community as a whole. Some valid ideas may not be considered by any scientist because they fall too far outside the general patterns of thought, or **paradigm,** of the time. Einstein's theory of relativity provides an example. Many scientists in the decades before Einstein had gleaned hints of the theory but did not investigate them, at least in part because the ideas seemed too outlandish.

The beauty of science is that it encourages continued testing by many people. Even if personal biases affect some results, tests by others should eventually uncover the mistakes. Similarly, if a new idea is correct but falls outside the accepted paradigm, sufficient testing and verification of the idea should eventually force a paradigm shift. In that sense, *science ultimately provides a means of bringing people to agreement*, at least on topics that can be studied scientifically.

LEARNING OBJECTIVE

Scientific Theories

2.3.2 What is a scientific theory?

The most successful scientific models explain a wide variety of observations in terms of just a few general principles. When a powerful yet simple model makes predictions that survive repeated and varied testing, scientists elevate its status and call it a **theory.** Some famous examples are Isaac Newton's theory of gravity, Charles Darwin's theory of evolution, and Albert Einstein's theory of relativity.

THE MEANING OF *THEORY* AND OTHER SCIENTIFIC TERMS

The scientific meaning of the word *theory* is quite different from its everyday meaning, in which we equate a theory more closely with speculation or a hypothesis. In everyday life, someone might say, "I have a new theory about why people enjoy the beach." Without the support of a broad range of evidence that others have tested and confirmed, this "theory" is really only a guess. In contrast, Newton's theory of gravity qualifies as a scientific theory because it uses simple physical principles to explain many observations and experiments. *Theory* is just one of many terms that are used with different meaning in science than in everyday life. Table 2.2 summarizes some of these terms, emphasizing those that you'll encounter in this book.

Despite its success in explaining observed phenomena, a scientific theory can never be proved true beyond all doubt, because future observations may disagree with its predictions. However, anything that qualifies as a scientific theory must be supported by a large, compelling body of evidence.

In this sense, a scientific theory is not at all like a hypothesis or any other type of guess. We are free to change a hypothesis at any time, because it has not yet been carefully tested. In contrast, we can discard or replace a scientific theory only if we have a better way of explaining the evidence that supports it.

Again, the theories of Newton and Einstein offer great examples. A vast body of evidence supports Newton's theory of gravity, but by the late nineteenth century scientists had begun to discover cases where its predictions did not perfectly match observations. These discrepancies were explained only when Einstein developed his general theory of relativity, which was able to match the observations. Still, the many successes of Newton's theory could not be ignored, and Einstein's theory would not have gained acceptance if it had not been able to explain these successes equally well. It did, and that is why we now view Einstein's theory as a broader theory of gravity than Newton's theory. As we will discuss in the next section, some scientists today are seeking a theory of gravity that will go beyond Einstein's. If any new theory ever gains acceptance, it will have to match all the successes of Einstein's theory as well as work in new realms where Einstein's theory does not.

Think About It When people claim that something is "only a theory," what do you think they mean? Does this meaning of *theory* agree with the definition of a theory in science? Do scientists always use the word *theory* in its "scientific" sense? Explain.

TABLE 2.2 Scientific Usage Often Differs from Everyday Usage

This table lists some words you will encounter in this book that have a different meaning in science than in everyday life. (Adapted from a table published by Richard Somerville and Susan Joy Hassol in Physics Today, *Oct. 2011.)*

Term	*Everyday Meaning*	*Scientific Meaning*	*Example*
model	something you build, like a model airplane	a representation of nature, sometimes using mathematics or computer simulations, that is intended to explain or predict observed phenomena	A model of planetary motion can be used to calculate exactly where planets should appear in our sky.
hypothesis	a guess or assumption of almost any type	a model that has been proposed to explain some observations, but which has not yet been rigorously confirmed	Scientists hypothesize that the Moon was formed by a giant impact, but there is not enough evidence to be fully confident in this model.
theory	speculation	a particularly powerful model that has been so extensively tested and verified that we have extremely high confidence in its validity	Einstein's theory of relativity successfully explains a broad range of natural phenomena and has passed a great many tests of its validity.
bias	distortion, political motive	tendency toward a particular result	Current techniques for detecting extrasolar planets are biased toward detecting large planets.
critical	really important; involving criticism, often negative	right on the edge	A boiling point is a "critical value" because above that temperature, a liquid will boil away.
deviation	strangeness or unacceptable behavior	change or difference	The recent deviation in global temperatures compared to their long-term average implies that something is heating the planet.
enhance/enrich	improve	increase or add more, but not necessarily making something "better"	"Enhanced color" means colors that have been brightened. "Enriched with iron" means containing more iron.
error	mistake	range of uncertainty	The "margin of error" tells us how closely measured values are likely to reflect true values.
feedback	a response	a self-regulating (negative feedback) or self-reinforcing (positive feedback) cycle	Gravity can provide positive feedback to a forming planet: Adding mass leads to stronger gravity, which attracts more mass, and so on.
state (as a noun)	a place or location	a description of a current condition	The Sun is in a state of balance, so it shines steadily.
trick	deception or prank	clever approach	She used a great mathematical trick to solve the problem.
uncertainty	ignorance	a range of possible values around some central value	The measured age of our solar system is 4.55 billion years with an uncertainty of 0.02 billion years.
values	ethics, monetary value	numbers or quantities	The speed of light has a measured value of 300,000 km/s.

THE QUEST FOR A THEORY OF LIFE IN THE UNIVERSE We do not yet have a theory of life in the universe, because we do not yet have the data to distinguish between many different hypotheses, which range from the hypothesis of no life anyplace else to the hypothesis that civilizations are abundant in our own galaxy. But thanks to the historical process that gave us the principles of modern science, we have a good idea of what we need to do if we ever hope to verify one of those hypotheses and turn it into a broad-based theory of life in the universe. That is why we can now make a modern science of astrobiology: not because we actually understand it yet but because we now know how to choose appropriate research projects to help us learn about the possibility of finding life elsewhere, and how to go out and search for life that might exist within our solar system or beyond.

THE PROCESS OF SCIENCE IN ACTION

2.4 The Fact and Theory of Gravity

We've completed our overview of the nature of modern science and its historical development. We've discussed the general process by which science advances, a process that is crucial to all sciences but is particularly important in astrobiology, where, for example, widespread belief in aliens sometimes makes it difficult to separate fact from fiction. Because of its importance, we will continue to focus on the process of science throughout the book. In addition, in the final numbered section of this and all remaining chapters, we will take one topic and explore it in more depth, using it to illustrate some aspect of the process of science in action.

In this chapter, we focus on gravity. Gravity is obviously important to life in the universe. On a simple level, life would float off its planet without gravity. On a deeper level, stars and planets could never have been born in the first place without gravity, so we presume that life could not start in a universe in which gravity were absent or in which it worked significantly differently than it does in our universe. Gravity also provides a great example of the distinction in science between a "fact" and a "theory," which is the idea we will focus on here.

LEARNING OBJECTIVE
The Example of Gravity

2.4.1 How does the fact of gravity differ from the theory of gravity?

Gravity is clearly a fact: Things really do fall when you drop them, and planets really do orbit the Sun. However, despite our daily experience with gravity, an adequate *theory* of gravity took a long time to develop. In ancient Greece, Aristotle imagined gravity to be an inherent property of heavy objects and claimed that heavier objects would fall to the ground faster than lighter-weight objects. Galileo put this idea to the test in a series of experiments that supposedly included dropping weights from the Leaning Tower of Pisa (Figure 2.18). His results showed that all objects fall to the ground at the same rate, as long as air resistance is unimportant. Aristotle was therefore wrong about gravity, but Galileo's ideas about gravity still fell short of being a useful theory.

Think About It Find a piece of paper and a small rock. Hold both at the same height, one in each hand, and let them go at the same instant. The rock, of course, hits the ground first. Next, crumple the paper into a small ball and repeat the experiment. What happens? Explain how this experiment suggests that, without air resistance, gravity causes all falling objects to fall at the same rate.

Movie Madness GRAVITY

Want to go into space? All you have to do is write a big check to a private rocket company and wait in a long line for a short ride. Alternatively, you can put on your 3D glasses and watch the movie *Gravity*, which took home seven Oscars.

It's an "incident" story. A small handful of astronauts are on a servicing mission for the Hubble Space Telescope (apparently they didn't get the memo that repair efforts ended in 2009), and as the film opens they're busy torquing up bolts on a solar panel while engaging in the witty banter that characterizes all movie astronauts. This could get boring, but fortunately the situation quickly turns uglier than monkfish.

The Russians, doing something they did in real life in 2021, have blown up a satellite somewhere, creating lots of hi-tech shrapnel in space. Now, that's bad manners, and self-destructive too, as there's a chance that the resulting junk will hit one of their own space assets. And this sudden trove of trash is threatening the repair crew with catastrophe 350 miles above the Earth.

Mind you, in reality, there wouldn't be much chance that the debris would actually hit them (or anything else). Space is big—really big—and space stations and orbiting telescopes don't follow one another around like horses on a carousel. They're bound by Kepler's laws, and they careen about the planet at different heights and in different directions. (The exceptions are satellites in geosynchronous orbit, but that's not where the Hubble Telescope, the Space Station, or anything else in this film is located.) The chance that you'd be hit even once by a freshly formed cloud of satellite debris is not much different from the odds of being beaned by a meteor in your backyard.

But in *Gravity*, getting hit once is just the initial round, and the astronauts are compelled to save themselves by repeatedly jet-packing their way to new orbiting oases, a tactic about as plausible as rescuing yourself at sea by backstroking from one island to another. In truth, you'd need real rockets to get to that next astronaut safe house.

Of course, it's easy to nitpick about the goofy orbital mechanics in *Gravity*. But what's really exceptional about this film is that it conveys the sensation of being in space a whole lot better than most of those NASA videos you watched as a kid. Shot in large format and 3D, this movie is as stunning as a taser and will boldly take you where you've never been before: into orbit.

And you and your friends or family will be back home, safe and sound, by bedtime.

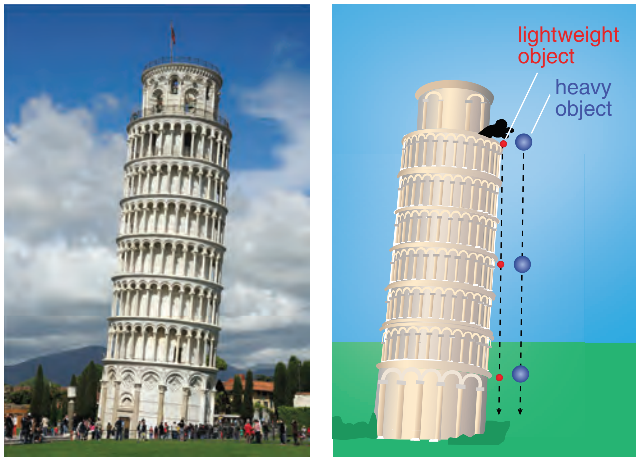


FIGURE 2.18
Galileo may never have actually dropped weights from the Leaning Tower of Pisa, but he did other experiments proving that, in the absence of air resistance, gravity makes all objects fall to the ground at the same rate.

NEWTON'S THEORY OF GRAVITY The breakthrough in our understanding of gravity came from Isaac Newton. By his own account, he experienced a moment of inspiration in 1666 when he saw an apple fall to the ground. He suddenly realized that the gravity making the apple fall was the same force that held the Moon in orbit around Earth. With this insight, Newton eliminated the long-held distinction between the realm of the heavens and the realm of Earth. For the first time, the two realms were brought together as one *universe* governed by a single set of principles.

Newton worked hard to turn his insight into a theory of gravity, which he published in 1687 in his book *Principia* (Figure 2.19). Newton expressed the force of gravity mathematically with his **universal law of gravitation.** Three simple statements summarize this law:

- Every mass attracts every other mass through the force called *gravity.*
- The strength of the gravitational force attracting any two objects is *directly proportional* to the product of their masses. For example, doubling the mass of *one* object doubles the force of gravity between the two objects.
- The strength of gravity between two objects decreases with the *square* of the distance between their centers. That is, the gravitational force follows an **inverse square law** with distance. For example, doubling the distance between two objects weakens the force of gravity by a factor of 2^2, or 4.

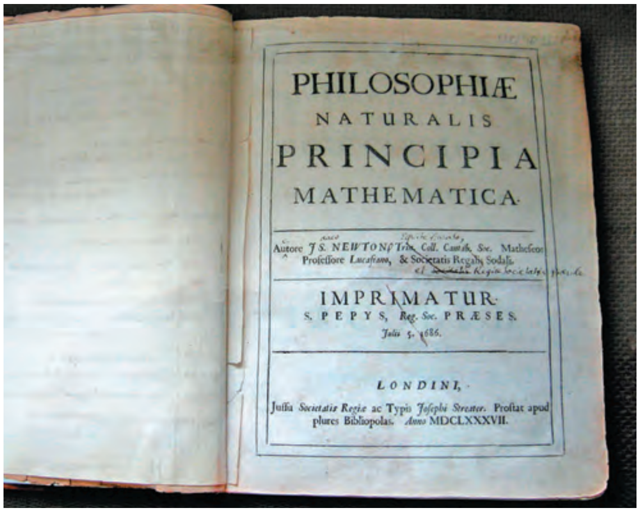
These three statements tell us everything we need to know about Newton's universal law of gravitation. Mathematically, all three statements can be combined into a single equation, usually written like this:

$$F_g = G\frac{M_1 M_2}{d^2}$$

where F_g is the force of gravitational attraction, M_1 and M_2 are the masses of the two objects, and d is the distance between their centers (Figure 2.20). The symbol G is a constant called the **gravitational constant,** and its numerical value has been measured to be $G = 6.67 \times 10^{-11}\,\text{m}^3/(\text{kg} \times \text{s}^2)$.

Think About It How does the gravitational force between two objects change if the distance between them triples? If the distance between them drops by half?

Newton's theory of gravity gained rapid acceptance because it explained a great many facts that other scientists had already discovered. For example, it explained Galileo's observations about falling objects and Kepler's laws of planetary motion. Even more impressively, it led to new predictive successes. Shortly after


PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore J S. NEWTON, Trin. Coll. Cantab. Soc. Matheſeos
Profeſſore Lucaſiano, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, Reg. Soc. PRÆSES.
Julii 5. 1686.

LONDINI,
Juſſu Societatis Regiæ ac Typis Joſephi Streater. Proſtat apud
plures Bibliopolas. Anno MDCLXXXVII.

FIGURE 2.19
Newton laid out his theory of gravity in mathematical detail in his book *Principia.* This photo shows Newton's own first-edition copy, which includes his handwritten notes.

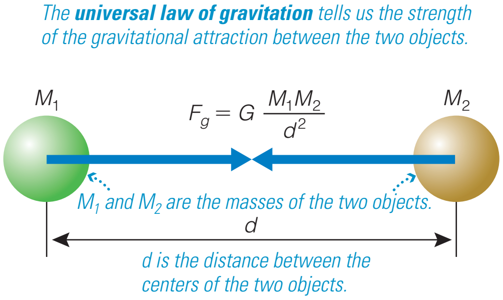


FIGURE 2.20
The universal law of gravitation is an inverse square law, which means the force of gravity declines with the square of the distance d between two objects.

FIGURE 2.21
Halley's Comet during its 1986 passage. Halley never actually saw this comet himself, but it bears his name because he used Newton's theory of gravity to correctly predict its passage near Earth in 1758. Halley's Comet returns near Earth about every 75 years, and it will next be visible in our skies in 2061.

Newton published his theory, Sir Edmund Halley used it to calculate the orbit of a comet that had been seen in 1682, from which he predicted the comet's return in 1758. Halley's Comet returned on schedule, which is why it now bears his name (Figure 2.21). In 1846, after carefully examining the orbit of Uranus, the French astronomer Urbain Leverrier used Newton's theory to predict that Uranus's orbit was being affected by a previously undiscovered eighth planet.* He predicted the location of the planet and sent a letter suggesting a search to Johann Galle of the Berlin Observatory. On the night of September 23, 1846, Galle discovered Neptune within 1° of the position predicted by Leverrier. It was a stunning triumph for Newton's theory.

A PROBLEM APPEARS Today, we can apply Newton's theory of gravity to the motions of objects throughout the universe, including the orbits of exoplanets around their stars, of stars around the center of the Milky Way Galaxy, and of galaxies in orbit around each other. There seems no reason to doubt the universality of the law. However, we also now know that Newton's law does not tell the entire story of gravity.

The first hint of a problem with Newton's theory arose not long after Leverrier's success in predicting the existence of Neptune. Astronomers discovered a slight discrepancy between the observed characteristics of the orbit of Mercury and the characteristics predicted by Newton's theory. The discrepancy was very small, and Mercury was the only planet that showed any problem, but there seemed no way to make it go away: Unless the data were wrong, which seemed highly unlikely, Newton's theory was giving a slightly incorrect prediction for the orbit of Mercury.

Leverrier set to work on this new problem, suggesting it might be solved if there were yet another unseen planet, this one orbiting the Sun closer than Mercury. He even gave it a name—Vulcan. But searches turned up no sign of this planet, and we now know that it does not exist. So why was there a discrepancy in Mercury's orbit? Albert Einstein (1879–1955) provided the answer when he published his general theory of relativity in 1915.

EINSTEIN'S SOLUTION To understand what Einstein did, we need to look a little more deeply at Newton's conception of gravity. According to Newton's theory, every mass exerts a gravitational attraction on every other mass, no matter how far away it is. If you think about it, this idea of "action at a distance" is rather mysterious. For example, how does Earth "feel" the Sun's attraction and know to orbit it? Newton himself was troubled by this idea. A few years after publishing his law of gravity in 1687, Newton wrote:

> *That one body may act upon another at a distance through a vacuum, … and force may be conveyed from one to another, is to me so great an absurdity, that I believe no man, who has … a competent faculty in thinking, can ever fall into it.*†

This type of "absurdity" was troubling to Einstein, whose scientific career can in many ways be viewed as a quest to find simple principles underlying mysterious laws. Although we will not go into the details, Einstein discovered that he could explain the mysterious action at a distance by assuming that all objects reside in something known as four-dimensional *spacetime*. Massive objects curve this spacetime, and other objects simply follow the curvature much like marbles following the contours of a bowl. Figure 2.22 uses a two-dimensional analogy to illustrate the idea, showing how planetary orbits are the straightest paths allowed by the structure of spacetime near the Sun. Einstein removed the mystery of "action at a distance" by telling us that gravity arises from the way in which masses affect the basic structure of the universe; in other words, he told us that gravity *is* "curvature of spacetime."

When Einstein worked out the mathematical details of his theory, he found that it predicted an orbit

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*The same idea had been put forward a few years earlier in England by a student named John Adams, but he did not succeed soon enough in convincing anyone to search for the planet; Leverrier was apparently unaware of Adams's work.

†Letter from Newton, 1692–1693, as quoted in J. A. Wheeler, *A Journey into Gravity and Spacetime*, Scientific American Library, 1990, p. 2.

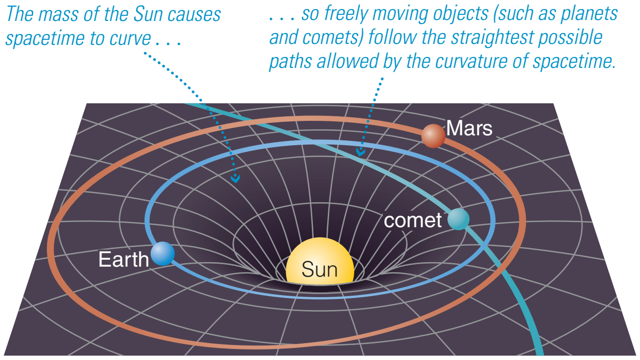


FIGURE 2.22
According to Einstein's general theory of relativity, the Sun curves spacetime much like the way a heavy weight curves a rubber sheet, and planets simply follow this curvature in their orbits.

FIGURE 2.23
This amazing image from the Event Horizon Telescope shows light (radio waves) from the region just outside a giant black hole at the center of the galaxy M87. The existence of black holes was first predicted using Einstein's general theory of relativity, and this photo provides strong evidence that black holes really exist and that Einstein's theory is valid. Nevertheless, the extreme conditions that must exist *inside* black holes suggest that Einstein's theory may not yet be the final word on gravity.

for Mercury that matched the observations. Not long after, astronomers put Einstein's new theory, which also predicted that massive objects would bend light, to the test during a solar eclipse. The eclipse meant it was possible to see stars that appeared close to the Sun in the sky, so if the theory was correct, the stars should have appeared slightly out of place from their normal positions due to the bending of their light paths by the Sun. The results confirmed Einstein's prediction, while Newton's theory gave a different prediction that did not match the observations. Scientists have continued to test both Newton's and Einstein's theories ever since. In every case in which the two theories give different answers, Einstein's theory has matched the observations while Newton's theory has not. That is why, today, we consider Einstein's general theory of relativity to have supplanted Newton's theory as our "best" theory of gravity.

Does this mean that Newton's theory of gravity was "wrong"? Remember that Newton's theory successfully explains nearly all observations of gravity in the universe, and it works so well that we can use it to plot the courses of spacecraft to the planets. Moreover, in all cases in which Newton's theory works well, Einstein's theory gives essentially the same answers. The differences in the predictions between the two theories are noticeable only with extremely precise measurements or in cases where gravity is unusually strong. We therefore do not say that Newton's theory was wrong, but rather that it was only an *approximation* to a more exact theory of gravity—Einstein's general theory of relativity. Under most circumstances, the approximation is so good that we can barely tell the difference between the two theories of gravity, but in cases of strong gravity, Einstein's theory works and Newton's fails.

While Einstein's theory of gravity has so far passed every test that it has been subjected to, most scientists suspect that we'll eventually find an even better theory of gravity. The reason is that for the most extreme possible case of gravity—which occurs at the infinitely small and high-density center of a *black hole* (Figure 2.23)—Einstein's theory of relativity gives a different answer than the equally well tested theory of the very small (known as the theory of quantum mechanics). Because these two theories contradict each other in this special case, scientists know that one or both will ultimately have to be modified.

THE BOTTOM LINE Gravity is both a fact and a theory. The *fact* of gravity is obvious in the observations we make of falling objects on Earth and orbiting objects in space. The *theory* of gravity is our best explanation of those observations, and we can use it to make precise predictions of how objects will behave due to gravity. In the future, our theory of gravity may be further improved, but gravity remains a fact regardless of how we revise the theory. Note that gravity is not unique in this way: Scientists make the same type of distinction in many other cases, such as when they talk about the fact of atoms being real and the atomic theory used to explain them, and when they talk about fact of evolution revealed in the fossil record and the theory used to explain how evolution occurs.

The Big Picture

In this chapter, we've explored the development and nature of science, and how thoughts about life in the universe changed with the development of science. As you continue your studies, keep in mind the following "big picture" ideas:

- The questions that drive research about life in the universe have been debated for thousands of years, but only recently have we begun to acquire data that allow us to address the questions scientifically. In particular, the fundamental change in human perspective that came with the Copernican revolution had a dramatic impact on the question of life in the universe, because it showed that planets really are other *worlds* and not mere lights in the sky.
- The ideas that underlie modern science—what we've called the "hallmarks of science"—developed gradually, and largely as a result of the attempt to understand Earth's place in the universe. Science always begins by assuming that the world is inherently understandable and that we can learn how it works by observing it and by examining the processes that affect it. All of science, therefore, is based on observations of the world around us.
- Science is not the only valid way in which we can seek knowledge, but it has proved enormously useful, having driven the great progress both in our understanding of nature and in the development of technology that has occurred in the past 400 years.

Summary of Key Concepts

2.1 The Ancient Debate About Life Beyond Earth

2.1.1 How did attempts to understand the sky start us on the road to science?

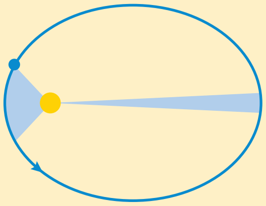
The development of science began with Greek attempts to create **models** to explain observations of the heavens. Although most Greek philosophers favored a **geocentric model,** which we now know to be incorrect, their reasons for this choice made sense at the time. One of the primary difficulties of that model was that it required a complicated explanation for the **apparent retrograde motion** of the planets, in which planets went around small circles on larger circles that went around Earth, rather than the much simpler explanation that we find with a Sun-centered model.

2.1.2 Why did the Greeks argue about the possibility of life beyond Earth?

Some Greek philosophers (the *atomists*) held that our world formed out of an infinite number of indivisible atoms, and this infinity implied the existence of other worlds. In contrast, Aristotle and his followers (the *Aristotelians*) argued that all earth must have fallen to the center of the universe, which rationalized the belief in a geocentric universe and the belief that the heavens were fundamentally different from Earth. These beliefs implied that Earth must be unique, in which case no other worlds or other life could exist.

2.2 The Copernican Revolution

2.2.1 How did the Copernican revolution further the development of science?



During the **Copernican revolution,** scientists began to place much greater emphasis on making sure that models successfully reproduced observations, and learned to trust data even when it contradicted deeply held beliefs. This willingness to let data drive the development of models led Kepler to propose what we now call **Kepler's laws of planetary motion,** and later led to the deeper understanding that came with **Newton's laws of motion** and the **universal law of gravitation.**

2.2.2 How did the Copernican revolution alter the ancient debate on extraterrestrial life?

The Copernican revolution showed that Aristotle's Earth-centered beliefs had been incorrect, effectively ruling out his argument for Earth's uniqueness. Many scientists of the time therefore assumed that the atomists had been correct, and that other worlds and life are widespread. However, the data didn't really support this view, which is why we still seek to learn whether life exists elsewhere.

2.3 The Nature of Modern Science

2.3.1 How can we distinguish science from nonscience?

Science generally exhibits these three hallmarks: (1) Modern science seeks explanations for observed phenomena that rely solely on natural causes. (2) Science progresses through the creation and testing of models of nature that explain the observations as simply as possible. (3) A scientific model must make testable predictions about natural phenomena that would force us to revise or abandon the model if the predictions did not agree with observations.

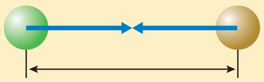
2.3.2 What is a scientific theory?

A scientific **theory** is a simple yet powerful model that explains a wide variety of observations in terms of just a few general principles, and has attained the status of a theory by surviving repeated and varied testing.

THE PROCESS OF SCIENCE IN ACTION

2.4 The Fact and Theory of Gravity

2.4.1 How does the fact of gravity differ from the theory of gravity?



Gravity is a *fact* in that objects really do fall to the ground and planets really do orbit the Sun. The *theory* of gravity is used to explain why gravity acts as it does. While the fact of gravity does not change, the theory can be improved with time: Einstein's general theory of relativity improved on Newton's theory of gravity.

Exercises and Problems

You will find many of these questions and more, including guidance and study aids, in the Life in the Universe *courseware.*

QUICK QUIZ

Start with these questions as a quick test of your general understanding. Choose the best answer in each case, and explain your reasoning. Answers are provided in the back of the book.

1. In Ptolemy's geocentric model, the retrograde motion of a planet occurs when (a) Earth is about to pass the planet in its orbit around the Sun; (b) the planet actually goes backward in its orbit around Earth; (c) the planet is aligned with the Moon in our sky.
2. Which of the following was *not* a major advantage of Copernicus's Sun-centered model over the Ptolemaic model? (a) It made significantly better predictions of planetary positions in our sky. (b) It offered a more natural explanation for the apparent retrograde motion of planets in our sky. (c) It allowed calculation of the orbital periods and distances of the planets.
3. Earth is closer to the Sun in January than in July. Therefore, in accord with Kepler's second law, (a) Earth travels faster in its orbit around the Sun in July than in January; (b) Earth travels faster in its orbit around the Sun in January than in July; (c) Earth has summer in January and winter in July.
4. According to Kepler's *third* law, (a) Mercury travels fastest in the part of its orbit in which it is closest to the Sun; (b) Jupiter orbits the Sun at a faster speed than Saturn; (c) all the planets have nearly circular orbits.
5. Tycho Brahe's contributions to astronomy included (a) inventing the telescope; (b) proving that Earth orbits the Sun; (c) collecting data that enabled Kepler to discover the laws of planetary motion.
6. Galileo's contributions to astronomy included (a) discovering the laws of planetary motion; (b) discovering the universal law of gravitation; (c) making observations and conducting experiments that dispelled scientific objections to the Sun-centered model.
7. Which of the following is *not* true about scientific progress? (a) Science progresses through the creation and testing of models of nature. (b) Science advances only through strict application of the scientific method. (c) Science avoids explanations that invoke the supernatural.
8. Which of the following is *not* true about a scientific theory? (a) A theory must explain a wide range of observations or experiments. (b) Even the strongest theories can never be proved true beyond all doubt. (c) A theory is essentially an educated guess.
9. How did the Copernican revolution alter perceptions of the ancient Greek debate over extraterrestrial life? (a) It showed that Aristotle's argument for why life must be unique to Earth was incorrect. (b) It showed that the atomists were correct in their belief in an infinite cosmos. (c) It proved that extraterrestrial life must really exist.
10. When Einstein's theory of gravity (general relativity) gained acceptance, it demonstrated that Newton's theory had been (a) wrong; (b) incomplete; (c) really only a guess.

READING REVIEW QUESTIONS

You should be able to answer these questions by re-reading portions of the chapter as needed.

11. Describe at least three characteristics of Greek thinking that helped pave the way for the development of modern science.
12. What do we mean by a *model* of nature? Summarize the development of the Greek *geocentric model,* from Thales through Ptolemy.
13. What is *apparent retrograde motion*, and why was it so difficult to explain with the geocentric model? What is its real explanation?
14. Who first proposed the idea that Earth is a planet orbiting the Sun, and when? Why didn't this model gain wide acceptance in ancient Greece?
15. Briefly describe and contrast the different views of the atomists and the Aristotelians on the subject of extraterrestrial life.
16. What was the *Copernican revolution,* and how did it change the human view of the universe? Briefly describe the major players and events in the Copernican revolution.
17. Why didn't Copernicus's model gain immediate acceptance? Why did some scientists favor it, despite this drawback?
18. State and explain each of *Kepler's laws of planetary motion*. Why did they gain acceptance?
19. Briefly describe three reasonable objections to the Sun-centered model that still remained even after Kepler's work, and explain how Galileo's work overcame each of these objections.
20. How did Newton's discoveries about the laws of motion and the universal law of gravitation put the Sun-centered model on an even stronger footing?
21. How did the Copernican revolution affect scholarly thought regarding the question of life beyond Earth?
22. What is the difference between a *hypothesis* and a *theory* in science?
23. Describe each of the three hallmarks of science, and give an example of how we can see each one in the unfolding of the Copernican revolution.
24. What is Occam's razor? Give an example of how it can be applied.
25. Why doesn't science accept personal testimony as evidence? Explain.
26. In what sense is gravity both a fact and a theory? Explain clearly.
27. What is *Newton's universal law of gravitation*? Write it in equation form, and clearly explain what the equation tells us. What do we mean when we say that the law is an *inverse square law*?
28. How did Einstein's general theory of relativity change our view of gravity?

THINK CRITICALLY

Science or Nonscience? Each of the following statements makes some type of claim. Decide in each case whether the claim could be evaluated scientifically or whether it falls into the realm of nonscience. Explain clearly; not all of these have definitive answers, so your explanation is more important than your chosen answer.

29. Lionel Messi is the best soccer player of his generation.
30. Europa has an ocean of liquid water several kilometers below its surface.
31. My house is haunted by ghosts, who make the creaking noises I hear each night.
32. There are no lakes or seas on Mars today.
33. All life in the universe must use DNA as its genetic material.
34. Children born when Jupiter is in the constellation Taurus are more likely to be musicians than other children.
35. Aliens can manipulate time so that they can abduct and perform experiments on people who never realize they were taken.
36. Newton's law of gravity explains the orbits of planets around other stars just as well as it explains the orbits of planets in our own solar system.
37. God created the laws of motion that were discovered by Newton.
38. A huge fleet of alien spacecraft will land on Earth and introduce an era of peace and prosperity on January 1, 2050.

CONCEPTUAL QUESTIONS

Answer each question in short answer or essay form.

39. *Copernican Players.* Using a bulleted list format, write a one-page summary of the major roles that Copernicus, Tycho, Kepler, Galileo, and Newton played in overturning the ancient belief in an Earth-centered universe, including a brief description of how each individual's work contributed to the development of modern science.
40. *Atomists and Aristotelians.* The ancient Greek arguments about the possible existence of extraterrestrial life continued for centuries. Write a short summary of the arguments, and then write a one- to two-page essay in which you describe how the Greek debate differs from the current scientific debate about extraterrestrial life.
41. *Science or Nonscience?* Find a recent news report from "mainstream" media (such as a major newspaper or magazine) that makes some type of claim about extraterrestrial life. Analyze the report and decide whether the claim is scientific or nonscientific. Write two or three paragraphs explaining your conclusion.
42. *Influence on History.* Based on what you have learned about the Copernican revolution, write a one- to two-page essay about how you believe it altered the course of human history.
43. *Discovery of Neptune.*
    a. In what sense was Neptune discovered with mathematics, rather than with a telescope? How did this discovery lend further support to Newton's theory of gravity? Explain.
    b. According to the idea known as *astrology,* the positions of the planets among the constellations,

as seen from Earth, determine the courses of our lives. Astrologers claim that they must carefully chart the motions of *all* the planets to cast accurate predictions (horoscopes). In that case, say skeptics, astrologers should have been able to predict the existence of Neptune long before it was predicted by astronomers, since they should have noticed inaccuracies in their predictions. But they did not. Do you think this fact tells us anything about the validity of astrology? Defend your opinion in a one- to two-page essay.

44. *Religion and Life Beyond Earth.* Choose one religion (your own or another) and investigate its beliefs with regard to the possibility of life on other worlds. If scholars of this religion have made any definitive statements about this possibility, what did they conclude? If there are no definitive statements, discuss whether the religious beliefs are compatible or incompatible with the idea of extraterrestrial life. Report your findings in a short essay.

45. *UFOlogy.* Choose one website that focuses on UFOs (or UAPs). Based on what you have learned about the nature of science, evaluate the site critically and determine whether you think it is presenting its claims scientifically or nonscientifically. Write a short essay summarizing your conclusions.

46. *Gravitational Lensing.* Go to the Hubble Space Telescope website to find out what astronomers mean by "gravitational lensing," and locate at least two pictures that show examples of this phenomenon. How does the existence of gravitational lensing support Einstein's general theory of relativity, and what does it tell us about the idea that gravity works the same way throughout the universe?

47. *The Galileo Affair.* The Vatican has devoted a lot of resources to learning more about the trial of Galileo and understanding past actions of the Church in the Galileo case. Learn more about such studies, and write a short report about the current Vatican view of the case.

48. *Biographical Research: Post-Copernican Viewpoints on Life in the Universe.* Many seventeenth- and eighteenth-century writers expressed interesting opinions on extraterrestrial life. Each individual listed below wrote a book that discussed this topic; book titles (and original publication dates) follow each name. Choose one or more individuals and research their arguments about extraterrestrial life. (You can find many of these books online in their entirety.) Write a one- to two-page summary of the person's arguments, and discuss which (if any) parts of these arguments are still valid in the current debate over life on other worlds.

    Bishop John Wilkins, *Discovery of a World in the Moone* (1638)
    René Descartes, *Philosophical Principles* (1644)
    Bernard Le Bovier De Fontenelle, *Conversations on the Plurality of Worlds* (1686)
    Richard Bentley, *A Confutation of Atheism from the Origin and Frame of the World* (1693)
    Christiaan Huygens, *Cosmotheros, or, Conjectures Concerning the Celestial Earths and Their Adornments* (1698)
    William Derham, *Astro-Theology: Or a Demonstration of the Being and Attributes of God from a Survey of the Heavens* (1715)
    Thomas Wright, *An Original Theory or New Hypothesis of the Universe* (1750)
    Thomas Paine, *The Age of Reason* (1793)

QUANTITATIVE PROBLEMS

Be sure to show all calculations clearly and state your final answers in complete sentences.

49. *Newton's Universal Law of Gravitation.*
    a. How does quadrupling the distance between two objects affect the gravitational force between them?
    b. Suppose the Sun were somehow replaced by a star with twice as much mass. What would happen to the gravitational force between Earth and the Sun?
    c. Suppose Earth were moved to one-third of its current distance from the Sun. What would happen to the gravitational force between Earth and the Sun?

50. *Sedna Orbit.* The object Sedna orbits our Sun at an average distance (semimajor axis) of 509 AU. What is its orbital period?

51. *Eris Orbit.* The dwarf planet Eris, which is slightly larger than Pluto, orbits the Sun every 557 years. What is its average distance (semimajor axis) from the Sun? How does its average distance compare to that of Pluto?

52. *New Planet Orbit.* A newly discovered planet orbits a distant star with the same mass as the Sun at an average distance of 112 million kilometers. Find the planet's orbital period.

53. *Halley's Orbit.* Halley's Comet orbits the Sun every 76.0 years. (a) Find its semimajor axis distance. (b) Halley's perihelion distance is about 90 million kilometers from the Sun. What is its aphelion distance? (c) Does Halley's Comet spend most of its time near its perihelion distance, near its aphelion distance, or halfway in between? Explain.

ACTIVITY AND DISCUSSION

These questions are intended to prompt additional research and/or discussion.

54. *Greek Models.* As we discussed in this chapter, the Greeks actually considered both Earth-centered and Sun-centered models of the cosmos.
    a. Briefly list the pros and cons of each model as they were seen in ancient times, and explain why most Greeks preferred the geocentric model.
    b. Suppose you could travel back in time and show the Greeks *one* observation from modern times. If your goal was to convince the Greeks to accept the Sun-centered model, what observation would you choose? Do you think it would convince them? Explain.

55. *What Makes It Science?* Choose one idea that is important to our modern view of the universe, such as "The universe is expanding," "The universe began with a Big Bang," "We are made from elements manufactured by stars," or "The Sun orbits the center of the Milky Way Galaxy" (you may wish to look ahead to Chapter 3 for other ideas).
    a. Briefly describe how the idea you have chosen is rooted in each of the three hallmarks of science discussed in this chapter. (That is, explain how it is based on observations, how our understanding of it depends on a model, and how the model is testable.)
    b. No matter how strongly the evidence may support a scientific idea, we can never be certain beyond all doubt that the idea is true. Describe an observation that might cause us to question the idea you have chosen. Then briefly discuss whether you think that, overall, the idea is likely or unlikely to hold up to future observations. Defend your opinion.
56. *Science and Religion.* Science and religion are often claimed to be in conflict. Do you believe this conflict is real and irreconcilable, or is it a result of misunderstanding the differing natures of science and religion? Defend your opinion.
57. *The Impact of Science.* The modern world is filled with ideas, knowledge, and technology that developed through science and application of the scientific method. Discuss some of these things and how they affect our lives. Which of these impacts do you think are positive? Which are negative? Overall, do you think science has benefited the human race? Defend your opinion.
58. *Absolute Truth.* An important issue in the philosophy of science is whether science deals with absolute truth. We can think about this issue by imagining the science of other civilizations. For example, would aliens necessarily discover the same laws of physics that we have discovered, or would the laws they observe depend on the type of culture they have? How does the answer to this question relate to the idea of absolute truth in science? Overall, do you believe that science is concerned with absolute truth? Defend your opinion.
59. *Group Activity: Testing UFOs*. As a group, search the Web and identify at least one popular claim of alien visitation (such as a claim based on videos made by the U.S. Navy, about an alien abduction, or about aliens among us). Imagine that you had access to all the relevant material on which the claim is based, and create a plan that would allow you to test the validity of the claim. Speculate on what you would expect your test to show. *Note*: This activity works particularly well in groups of four students, with each student taking on one of the following roles: the scribe takes notes on the group's activities; the proposer suggests tentative explanations to the group; the skeptic points out weaknesses in proposed explanations; the moderator leads group discussion and makes sure everyone contributes.

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