Precession discussion begins on this page, concludes on next.

layer of land). The water temperature therefore remains fairly steady both day and night, while the ground can heat up and cool down dramatically. The Southern Hemisphere's larger amount of ocean moderates its climate. The Northern Hemisphere, with more land and less ocean, heats up and cools down more easily, which is why it has the more extreme seasons.

Although distance from the Sun plays no role in Earth's seasons, the same is not always true for other planets, especially if they have significantly greater distance variations. For example, Mars is more than 20% closer to the Sun during its Southern Hemisphere summer than its Northern Hemisphere summer. This gives its Southern Hemisphere much more extreme seasons than its Northern Hemisphere, even though Mars has nearly the same axis tilt as Earth.

How does the orientation of Earth's axis change with time?

We have now discussed both daily and seasonal changes in the sky, but there are other changes that occur over longer periods of time. One of the most important of these slow changes is called **precession**, a gradual wobble that alters the orientation of Earth's axis in space.

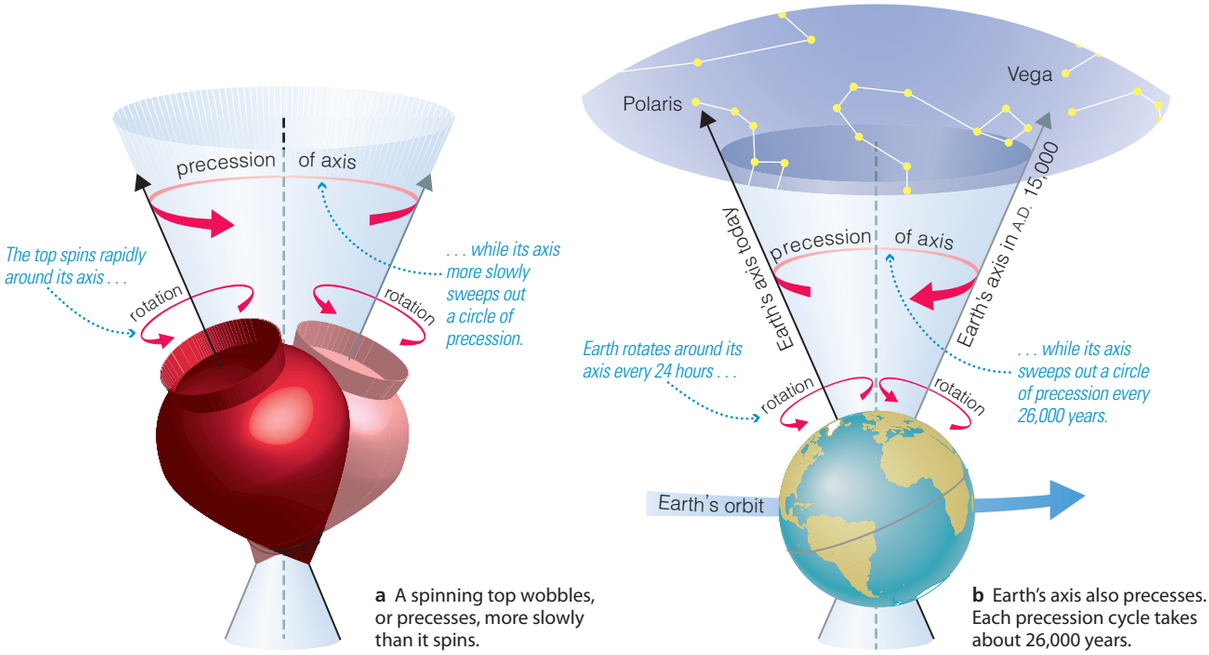
Precession occurs with many rotating objects. You can see it easily by spinning a top (Figure 2.20a). As the top spins rapidly, you'll notice that its axis sweeps out a circle at a somewhat slower rate. We say that the top's axis *precesses.* Earth's axis precesses in much the same way, but far more slowly (Figure 2.20b). Each cycle of Earth's precession takes about 26,000 years, gradually changing where the axis points in space. Today, the axis points toward Polaris, making it our North Star. Some 13,000 years from now, Vega will be the star closest to true north. At most other times, the axis does not point near any bright star.

Notice that precession does not change the *amount* of the axis tilt (which stays close to $23\frac{1}{2}°$) and therefore does not affect the pattern of the seasons. However, because the solstices and equinoxes correspond to points in Earth's orbit that depend on the direction the axis points in space, their positions in the orbit gradually shift with the cycle of precession. As a result, the constellations associated with the solstices and equinoxes gradually change. For example, a couple thousand years ago the Sun appeared in the constellation Cancer on the day of the summer solstice, but it now appears in Gemini on that day. This explains something you can see on any world map: The latitude at which the Sun is directly overhead on the summer solstice ($23\frac{1}{2}°$N) is called the *Tropic of Cancer,* telling us that it got its name back when the Sun used to appear in Cancer on the summer solstice.

THINK ABOUT IT

What constellation will the Sun be in on the summer solstice about 2000 years from now? (*Hint:* Figure 2.14 shows the names and order of the zodiac constellations.)

Why does precession occur? It is caused by gravity's effect on a tilted, rotating object that is *not* a perfect sphere. You have probably seen how gravity affects a top. If you try to balance a nonspinning top on its point, it will fall over almost immediately. This happens because a top that is not spherical will inevitably lean a little to one side. No matter how slight this lean, gravity will quickly tip the nonspinning top over. However, if you spin the top rapidly, it does not fall over so



a A spinning top wobbles, or precesses, more slowly than it spins.

b Earth's axis also precesses. Each precession cycle takes about 26,000 years.

FIGURE 2.20 Interactive Figure Precession affects the orientation of a spinning object's axis but not the amount of its tilt.

COMMON MISCONCEPTIONS

Sun Signs

You probably know your astrological "Sun sign." When astrology began a few thousand years ago, your Sun sign was supposed to represent the constellation in which the Sun appeared on your birth date. However, because of precession, this is no longer the case for most people. For example, if your birthday is March 21, your Sun sign is Aries even though the Sun now appears in Pisces on that date. The problem is that astrological Sun signs are based on the positions of the Sun among the stars as they were almost 2000 years ago. Because Earth's axis has moved about 1/13 of the way through its 26,000-year precession cycle since that time, the Sun signs are off by nearly a month from the actual positions of the Sun among the constellations today.

easily. The spinning top stays upright because rotating objects tend to keep spinning around the same rotation axis (a consequence of the *law of conservation of angular momentum* [Section 4.3]). This tendency prevents gravity from immediately pulling the spinning top over, since falling over would mean a change in the spin axis from near-vertical to horizontal. Instead, gravity succeeds only in making the axis trace circles of precession. As friction slows the top's spin, the circles of precession get wider and wider, and ultimately the top falls over. If there were no friction to slow its spin, the top would spin and precess forever.

The spinning (rotating) Earth precesses because of gravitational tugs from the Sun and Moon. Earth is not quite a perfect sphere, instead bulging slightly at its equator. Because the equator is tilted $23\frac{1}{2}°$ to the ecliptic plane, the gravitational attractions of the Sun and Moon try to pull the equatorial bulge into the ecliptic plane, effectively trying to "straighten out" Earth's axis tilt. However, like the spinning top, Earth tends to keep rotating around the same axis. Gravity therefore does not succeed in changing Earth's axis tilt and instead only makes the axis precess. If you want to gain a better understanding of precession and how it works, you might wish to experiment with a simple toy *gyroscope*. Gyroscopes are essentially rotating wheels mounted in a way that allows them to move freely, which makes it easy to see how their spin rate affects their motion. (The fact that gyroscopes tend to keep the same rotation axis makes them very useful in aircraft and spacecraft navigation.)

MA™ **Phases of the Moon Tutorial, Lessons 1–3**

2.3 THE MOON, OUR CONSTANT COMPANION

Aside from the Sun, the Moon is the brightest and most noticeable object in our sky. The Moon is our constant companion in space, orbiting Earth about once every $27\frac{1}{3}$ days.

Figure 2.21 shows the Moon's orbit on the same scale we used for the model solar system in Section 1.2. Remember that on this scale, the Sun is about the size of a large grapefruit and is located about 15 meters from Earth. The entire

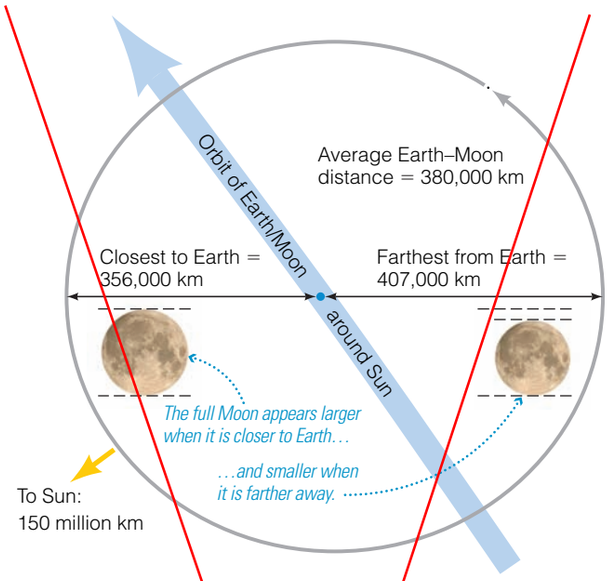


FIGURE 2.21 The Moon's orbit around Earth, shown on the 1-to-10-billion scale used in Section 1.2 (see Figure 1.6). The segment shown of our orbit around the Sun looks nearly straight because the distance to the Sun is so great compared to the size of the Moon's orbit. The inset photos contrast the relative angular sizes of the full moon in our sky when the Moon is at the near and far points of its orbit; of course, full moon occurs only when the Moon is opposite the Sun as seen from Earth.

orbit of the Moon would fit easily inside the Sun, and for practical purposes we can consider Earth and the Moon to share the same orbit around the Sun.

Like all objects in space, the Moon appears to reside on the celestial sphere. Earth's daily rotation makes the Moon appear to rise in the east and set in the west each day. In addition, because of its orbit around Earth, the Moon appears to move eastward from night to night through the constellations of the zodiac. Each circuit through the constellations takes the same $27\frac{1}{3}$ days that the Moon takes to orbit Earth. If you do the math, you'll see that this means the Moon moves relative to the stars by about $\frac{1}{2}°$—its own angular size—each hour. You can notice this gradual motion in just a few hours by checking the Moon's position compared to bright stars near it in the sky.

Why do we see phases of the Moon?

As the Moon moves through the sky, both its appearance and the times at which it rises and sets change with the cycle of **lunar phases**. The phase of the Moon on any given day depends on its position relative to the Sun as it orbits Earth.

The easiest way to understand the lunar phases is with the simple demonstration illustrated in Figure 2.22. Take a ball outside on a sunny day. (If it's dark or cloudy, you can use a flashlight instead of the Sun; put the flashlight on a table a few meters away and shine it toward you.) Hold the ball at arm's length to represent the Moon while your head represents Earth. Slowly spin around (counterclockwise), so that the ball goes around you just as the Moon orbits Earth. As you turn, you'll see the ball go through phases just like

Astrology discussion begins on this page, concludes on next.

SPECIAL TOPIC

Logic and Science

In science, we attempt to acquire knowledge through logical reasoning. A logical argument begins with a set of premises and leads to one or more conclusions. Note that logical argument therefore differs somewhat from the definition of argument in everyday life, since logical arguments need not imply any animosity. There are two basic types of logical argument: *deductive* and *inductive.* Both are important in science.

In a deductive argument, the conclusion follows automatically from the premises, as in this example:

PREMISE: All planets orbit the Sun in ellipses with the Sun at one focus.

PREMISE: Earth is a planet.

CONCLUSION: Earth orbits the Sun in an ellipse with the Sun at one focus.

Note the construction of the deductive argument: The first premise is a general statement that applies to all planets, and the conclusion is a specific statement that applies only to Earth. As this example suggests, we often use deduction to *deduce* a specific prediction from a more general theory. If the specific prediction proves to be false, then something must be wrong with the premises from which it was deduced. If it proves true, then we've acquired a piece of evidence in support of the premises.

Now, contrast the deductive argument above with the following example of an *inductive argument:*

PREMISE: Birds fly up into the air but eventually come back down.

PREMISE: People who jump into the air fall back down.

PREMISE: Rocks thrown into the air come back down.

PREMISE: Balls thrown into the air come back down.

CONCLUSION: What goes up must come down.

Because each premise supports the conclusion, you might at first think that this is a strong inductive argument and that its conclusion probably is true. However, no matter how many more examples you consider of objects that go up and come down, you could never *prove* that the conclusion is true—only that it seems likely to be true. Moreover, a single counterexample can prove the conclusion of an inductive argument to be false. For example, in this case we know that the conclusion is false because the spacecraft *Voyager 2* was launched from Earth and never fell back down.

Inductive arguments *generalize* from specific facts to a broader model or theory. Thus, inductive arguments are the arguments used to build scientific theories, because we use them to *infer* general principles from observations and experiments. That is why theories can never be proved true beyond all doubt—they can only be shown to be consistent with ever larger bodies of evidence. Theories *can* be proved false, however, if they fail to account for observed or experimental facts.

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.

3.5 ASTROLOGY

We have discussed the development of astronomy and the nature of science in some depth. Now let's talk a little about a subject often confused with the science of astronomy: *astrology.* Although the terms *astrology* and *astronomy* sound very similar, today they describe very different practices. In ancient times, however, astrology and astronomy often went hand in hand, and astrology played an important role in the historical development of astronomy.

How is astrology different from astronomy?

The basic tenet of astrology is that the apparent positions of the Sun, Moon, and planets among the stars in our sky influence human events. The origins of this idea are easy to understand. After all, the position of the Sun in the sky certainly influences our lives, since it determines the seasons and the times of daylight and darkness, and the Moon's position determines the tides. It probably therefore seemed natural to imagine that planets—which are the only other objects to move among the stars besides the Sun and Moon—should also influence our lives, even if these influences were more subtle.

Ancient astrologers hoped to learn how the positions of the Sun, Moon, and planets influence our lives by charting the skies and seeking correlations with events on Earth. For example, if an earthquake occurred when Saturn was entering the constellation Leo, might Saturn's position have been the cause of the earthquake? If the king became ill when Mars appeared in the constellation Gemini and the first-quarter moon appeared in Scorpio, might it mean another tragedy for the king when this particular alignment of the Moon and Mars next recurred? Surely, the ancient astrologers thought, the patterns of influence would eventually become clear, and they would then be able to forecast human events with the same reliability with which astronomical observations of the Sun could forecast the coming of spring.

Because forecasts of the seasons and forecasts of human events were imagined to be closely related, astrologers and astronomers usually were one and the same in the ancient world. For example, in addition to his books on astronomy, Ptolemy published a treatise on astrology called *Tetrabiblios* that remains the foundation for much of astrology today. But Ptolemy himself recognized that astrology stood upon a far

shakier foundation than astronomy. In the introduction to *Tetrabiblios,* Ptolemy compared astronomical and astrological predictions:

> *[Astronomy], which is first both in order and effectiveness, is that whereby we apprehend the aspects of the movements of sun, moon, and stars in relation to each other and to the earth.... I shall now give an account of the second and less sufficient method [of prediction (astrology)] in a proper philosophical way, so that one whose aim is the truth might never compare its perceptions with the sureness of the first, unvarying science....*

Other ancient scientists surely also recognized that their astrological predictions were far less reliable than their astronomical ones. Nevertheless, if there were even a slight possibility that astrologers could forecast the future, no king or political leader would dare to be without one. Astrologers held esteemed positions as political advisers in the ancient world and were provided with the resources they needed to continue charting the heavens and human history. Indeed, wealthy political leaders' support of astrology made possible much of the development of ancient astronomy.

Throughout the Middle Ages and into the Renaissance, many astronomers continued to practice astrology. For example, Kepler cast numerous *horoscopes*—the predictive charts of astrology (Figure 3.28)—even as he was discovering the laws of planetary motion. However, given Kepler's later description of astrology as "the foolish stepdaughter of astronomy" and "a dreadful superstition," he may have cast the horoscopes solely as a source of much-needed income. Modern-day astrologers also claim Galileo as one of their own, in part for his having cast a horoscope for the Grand Duke of Tuscany. However, while Galileo's astronomical discoveries changed human history, the horoscope was just plain wrong: The Duke died just a few weeks after Galileo predicted that he would have a long and fruitful life.

The scientific triumph of Kepler and Galileo in showing Earth to be a planet orbiting the Sun heralded the end of the linkage between astronomy and astrology. Astronomy has since gained status as a successful science that helps us understand our universe, while astrology no longer has any connection to the modern science of astronomy.

Does astrology have any scientific validity?

Although astronomers gave up on it centuries ago, astrology remains popular with the general public. Many people read their daily horoscopes in newspapers, and some pay significant fees to have personal horoscopes cast by "professional" astrologers. Worldwide, more people earn incomes by casting horoscopes than through astronomical research, and books and articles on astrology often outsell all but the most popular books on astronomy. With so many people giving credence to astrology, is it possible that it has some scientific validity after all?

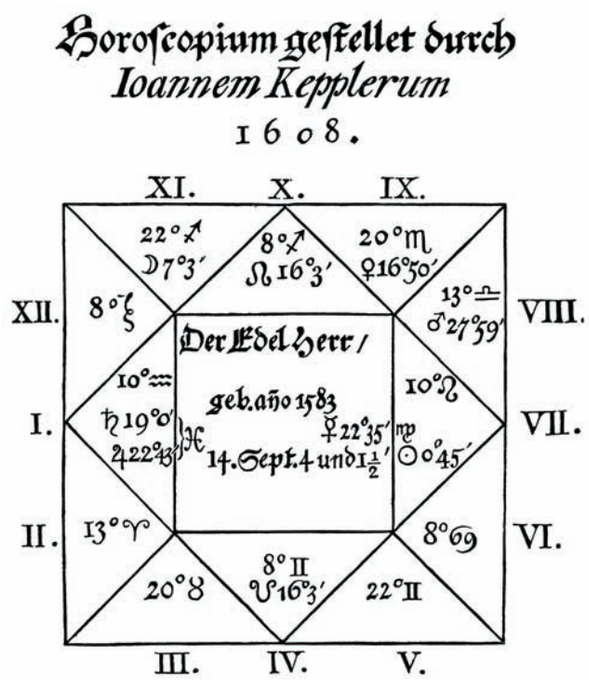


FIGURE 3.28 This chart, cast by Kepler, is an example of a horoscope.

Testing Astrology The validity of astrology can be difficult to assess, because there's no general agreement among astrologers even on such basic things as what astrology is or what it can predict. For example, "Western astrology" is quite different in nature from the astrology practiced in India and China. Some astrologers do not make testable predictions at all; rather, they give vague guidance about how to live one's life. Most newspaper horoscopes fall into this category. Although your horoscope may seem to ring true at first, a careful read will usually show it to be so vague as to be untestable. For example, a horoscope that says "It is a good day to spend time with your friends" may be good advice but doesn't offer much to test. If you read the horoscopes for all 12 astrological signs, you'll probably find that several of them apply equally well to you. When astrology offers only vague advice rather than testable predictions, the question of scientific validity does not apply.

SEE IT FOR YOURSELF

Look in a local newspaper for today's weather forecast and for your horoscope. Contrast the nature of their predictions. At the end of the day, you will know if the weather forecast was accurate. Can you also say whether the horoscope was accurate? Explain.

Nevertheless, most professional astrologers still earn their livings by casting horoscopes that either predict future events in an individual's life or describe characteristics of the person's personality and life. If the horoscope predicts future events, we can check to see whether the predictions come

true. If it describes a person's personality and life, the description can be checked for accuracy. A scientific test of astrology requires evaluating many horoscopes and comparing their accuracies to what would be expected by pure chance. For example, suppose a horoscope states that a person's best friend is female. Because roughly half the population of the United States is female, an astrologer who casts 100 such horoscopes would be expected by pure chance to be right about 50 times. We would be impressed with the predictive ability of the astrologer only if he or she were right much more often than 50 times out of 100.

In hundreds of scientific tests, astrological predictions have never proved to be accurate by a substantially greater margin than expected from pure chance. Similarly, in tests in which astrologers are asked to cast horoscopes for people they have never met, the horoscopes fail to match actual personality profiles more often than expected by chance. The verdict is clear: The methods of astrology are useless for predicting the past, the present, or the future.

Examining the Underpinnings of Astrology In science, observations and experiments are the ultimate judge of any idea. No matter how outlandish an idea might appear, it cannot be dismissed if it successfully meets observational or experimental tests. The idea that Earth rotates and orbits the Sun at one time seemed outlandish, yet today it is so strongly supported by the evidence that we consider it a fact. The idea that the positions of the Sun, Moon, and planets among the stars influence our lives might sound outlandish today, but if astrology were to make predictions that came true, adherence to the principles of science would force us to take astrology seriously. However, given that scientific tests of astrology have never found any evidence that its predictive methods work, it is worth looking at its premises to see whether they make sense. Might there be a few kernels of wisdom buried within the lore of astrology?

Let's begin with one of the key premises of astrology: that there is special meaning in the patterns of the stars in the constellations. This idea may have seemed quite reasonable in ancient times, when the stars were assumed to be fixed on an unchanging celestial sphere, but today we know that the patterns of the stars in the constellations are accidents of the moment. Long ago the constellations did not look the same, and they will look still different far in the future [Section 1.3]. Moreover, the stars in a constellation don't necessarily have any *physical* association (see Figure 2.3). Because stars vary in distance, two stars that appear on opposite sides of our sky might be closer together than two stars in the same constellation. Constellations are only *apparent* associations of stars, with no more physical reality than the water in a desert mirage.

Astrology also places great importance on the positions of the planets among the constellations. Again, this idea might have seemed quite reasonable in ancient times, when it was thought that the planets truly wandered among the stars. Today we know that the planets only *appear* to wander among the stars. In reality, the planets are in our own solar system, while the stars are vastly farther away. It is difficult to see how mere appearances could have profound effects on our lives.

Many other ideas at the heart of astrology are equally suspect. For example, most astrologers claim that a proper horoscope must account for the positions of *all* the planets. Does that mean that all horoscopes cast before the discovery of Neptune in 1846 were invalid? If so, why didn't astrologers notice that something was wrong with their horoscopes and predict the existence of Neptune? (In contrast, astronomers *did* predict its existence; see the Special Topic box on p. 322.) Most astrologers have also included Pluto since its discovery in 1930; does that mean they should now stop including it since it has been demoted to "dwarf planet," or that they need to include Eris and other dwarf planets that may not yet have been discovered? And why stop with our own solar system; shouldn't horoscopes also depend on the positions of all planets orbiting all other stars? Given seemingly unanswerable questions like these, there seems little hope that astrology will ever meet its ancient goal of forecasting human events.

THE BIG PICTURE

Putting Chapter 3 into Context

In this chapter, we focused on the scientific principles through which we have learned so much about the universe. Key "big picture" concepts from this chapter include the following:

- The basic ingredients of scientific thinking—careful observation and trial-and-error testing—are a part of everyone's experience. Modern science simply provides a way of organizing this thinking to facilitate the learning and sharing of new knowledge.
- Although our understanding of the universe is growing rapidly today, each new piece of knowledge builds on ideas that came before.
- The Copernican revolution, which overthrew the ancient Greek belief in an Earth-centered universe, did not occur instantaneously. It unfolded over a period of more than a century, during which many of the characteristics of modern science first appeared.
- Science exhibits several key features that distinguish it from nonscience and that in principle allow anyone to come to the same conclusions when studying a scientific question.
- Astronomy and astrology once developed hand in hand, but today they represent very different things.