1.2

The Seasons

Many people mistakenly believe that we have seasons because the Earth’s orbit is elliptical. They suppose that summer occurs when we are closest to the Sun and winter when we are farthest away. It turns out, however, that the Earth is nearest the Sun in early January, when the Northern Hemisphere is coldest. Clearly, then, seasons must have some other cause.

To see what *does* cause seasons, we need to look at how our planet is oriented in space. As the Earth orbits the Sun, our planet also spins. That spin is around an imaginary line—the **rotation axis**—that runs through the Earth from its North Pole to its South Pole. The Earth’s rotation axis is *not* perpendicular to its orbit around the Sun. Rather, it is tipped by 23.5° from the vertical, as shown in figure 1.7A. As our planet moves along its orbit, its rotation axis maintains nearly exactly the same tilt and direction, as figure 1.7B shows. That is, the Earth behaves much like a giant gyroscope. The tendency of the Earth to preserve its tilt is shared by all spinning objects. For example, it is what keeps a rolling coin upright, a Frisbee horizontal, and a thrown football pointed properly (fig. 1.8). You can easily feel this tendency of a spinning object to resist changes in its orientation by lifting a bicycle by the handlebars with the wheel spinning, then trying to twist it from side to side.

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ANIMATION

The Earth's rotation axis

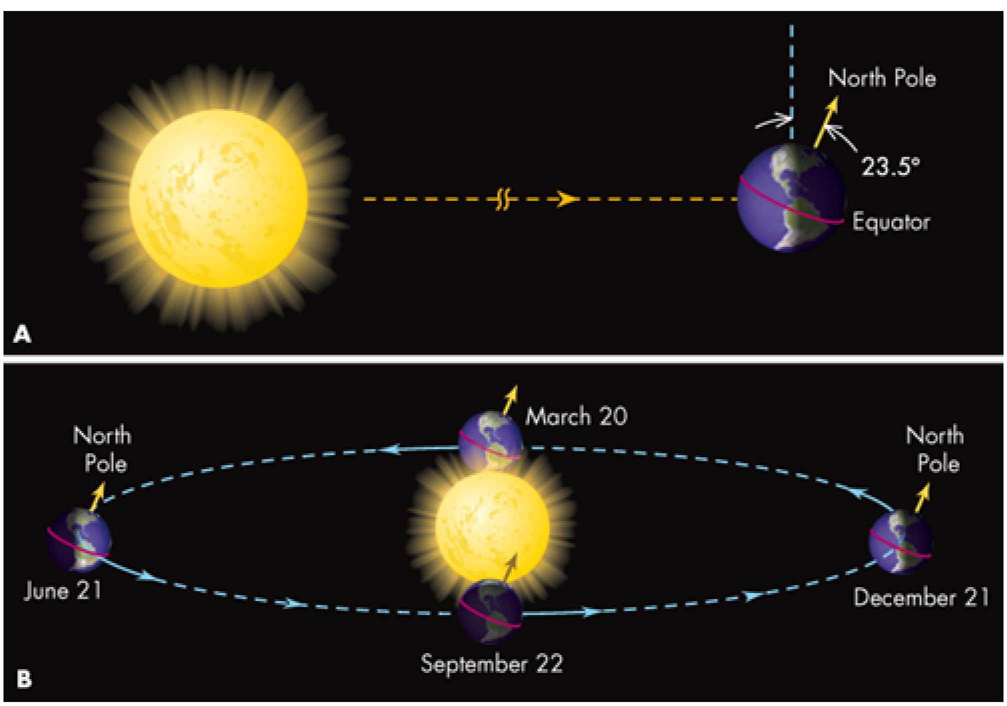

FIGURE 1.7

(A) The Earth's rotation axis is tilted 23.5° to the Earth's orbit around the Sun. (B) The Earth's rotation axis keeps the same tilt and direction as it moves around the Sun. (Sizes and distances are not to scale.)

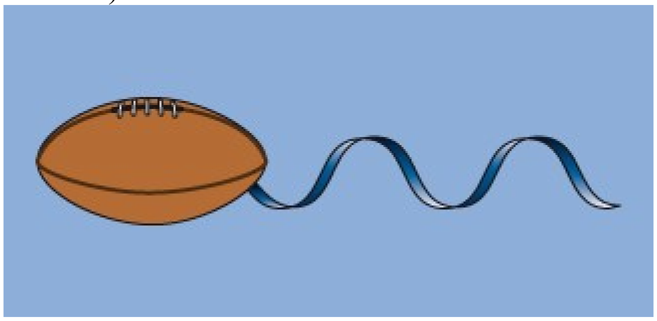

FIGURE 1.8
The tendency of a spinning object to keep its orientation is called "conservation of angular momentum," and it is the principle on which gyroscopes operate and the reason a quarterback puts "spin" on a football.

Because the Earth's tilt remains nearly constant as we move around the Sun, sunlight falls more directly on the Northern Hemisphere in June and surrounding months and more directly on the Southern Hemisphere around the month of December, as illustrated in figure 1.9. This causes a variation in the amount of heat each hemisphere receives from the Sun over the course of a year.

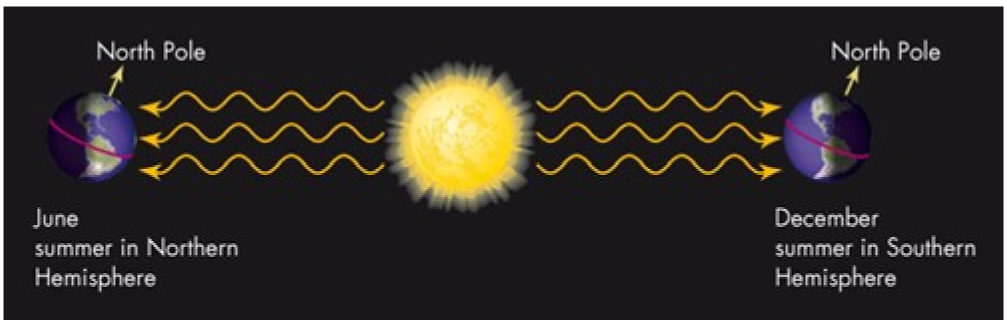

FIGURE 1.9
Because the Earth's rotation axis keeps the same tilt as we orbit the Sun, sunlight falls more directly on the Northern Hemisphere during part of the year and on the Southern Hemisphere during the other part of the year. (Sizes and distances are not to scale.)

A surface facing directly toward a source of radiation is heated more than when the same surface is tilted. You take advantage of this effect instinctively when you warm your hands at a fire by holding your palms flat toward the fire, not edgewise. Figure 1.10 illustrates how this affects regions north and south of the equator. Equal areas of land do not receive the same amount of sunlight. When the North Pole is tilted toward the Sun in June, an area south of the equator receives an amount of radiation that is only a portion of the radiation intercepted by an equal area north of the equator. Therefore, over the course of a June day, the Northern Hemisphere is heated more than the Southern Hemisphere.

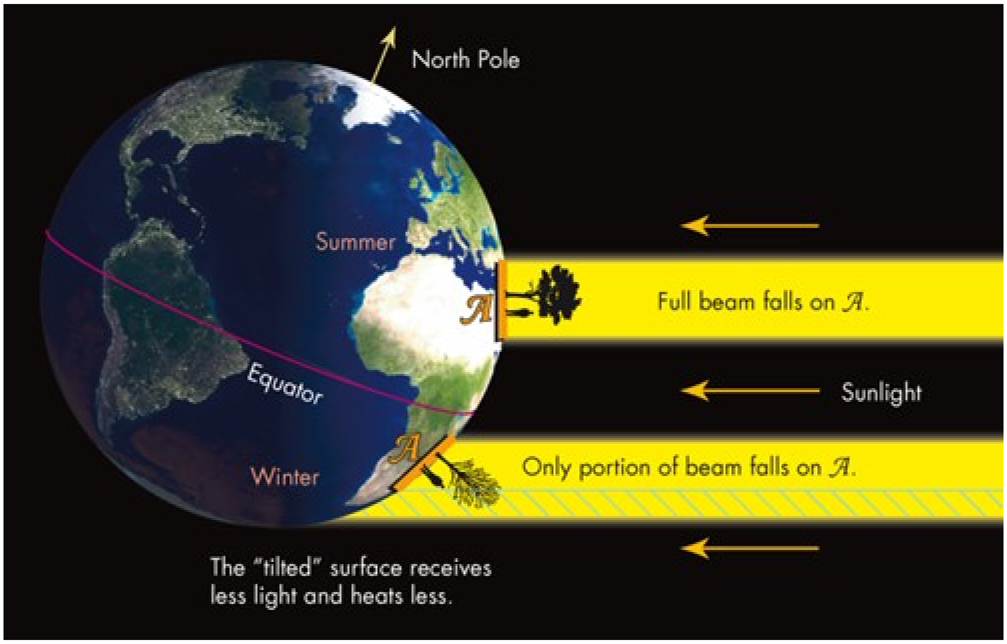

FIGURE 1.10
A portion of the Earth's surface directly facing the Sun receives more concentrated light (and thus more heat) than other parts of the Earth's surface of equal area. The same size "beam" of sunlight (carrying the same amount of energy) spreads out over a larger area where the surface is "tilted."

INTERACTIVE

Seasons

For the same reason, the Northern Hemisphere receives its greatest heating at the time of year when the Sun shines most directly on it, making it summer. Six months later, the Northern Hemisphere receives its sunlight least directly, and so it is colder and therefore winter (fig. 1.11). This heating difference is enhanced because the Earth's tilt leads to many more hours of daylight in the summer than in the winter. As a result, not only do we receive the Sun's light more directly, we receive it for a longer time. Thus,

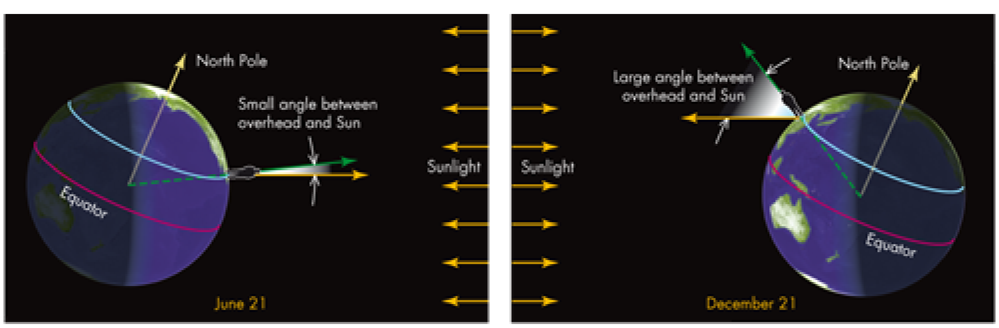

FIGURE 1.11
Between the extremes of the year six months apart, the angle at which sunshine strikes the ground at the same latitude can vary greatly.

Seasonal changes in daylight

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the seasons are caused by the tilt of the Earth's rotation axis.

From figure 1.11 it can be seen why the seasons are reversed between the Northern and Southern Hemispheres; when it is summer in one, it is winter in the other.

Solstices, Equinoxes, and the Ecliptic's Tilt

The Sun's motion north and south in the sky as the seasons change

The tilt of the Earth's rotation axis not only causes seasons, it also is why the Sun's path across the celestial sphere—the ecliptic—is tilted with respect to the celestial equator. Because the Earth's axis remains oriented in a fixed direction, there is a point in its orbit when the North Pole is tipped most closely toward the Sun. This occurs on about June 21, as illustrated in figure 1.12. On this date the North Pole is tilted 23.5° toward the Sun, so the Sun lies 23.5° north of the celestial equator. (The date can vary from year to year, mostly because a year is about a quarter of a day longer than 365 days—which is also what causes us to insert leap years.) Half a year later, on about December 21, the Earth is on the other side of the Sun, and the Sun lies 23.5° south of the celestial equator.

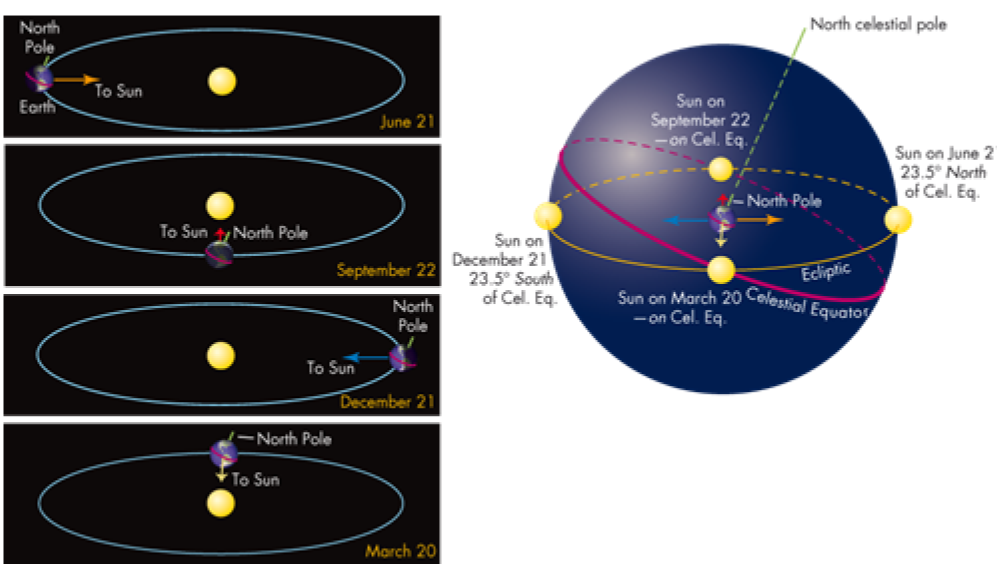

FIGURE 1.12
As the Earth orbits the Sun, the Sun's position with respect to the celestial equator changes. The Sun reaches 23.5° north of the celestial equator on June 21 but 23.5° south of the celestial equator on December 21. The Sun crosses the celestial equator on about March 20 and September 22 each year.

The times when the Sun reaches its extremes are known as the solstices; the times when it crosses the celestial equator are the equinoxes. (The dates can vary because of the extra day inserted in leap years.)

As a result of this north–south motion, the Sun's path crosses the celestial equator twice during the year as illustrated in figure 1.12. The dates when the Sun reaches its extreme north and south positions are used to mark the beginning of summer and of winter, while the dates when the Sun crosses the celestial equator mark the beginning of spring and of autumn.

Astronomers give these dates special names. When the Sun is on the celestial equator, the days and nights are of equal length (approximately), so these dates are called the **equinoxes**, for "equal nights." The spring (or vernal) equinox occurs near March 20; the fall or autumnal equinox occurs near September 22. The beginning of summer and of winter mark the times of year when the Sun pauses in its north–south motion and changes direction. Accordingly, these times are called the **solstices**, meaning the Sun (sol) has stopped its motion north or south and is *static* and about to reverse direction. The dates of the solstices (summer and winter) also change slightly from one year to the next, but they are always close to June 21 and December 21.

Although the seasons begin on the solstices and equinoxes, the hottest and coldest times of year occur roughly 6 weeks after the solstices. The delay, known as the lag of the seasons, results from the oceans and land being slow to warm up in summer and slow to cool down in winter.

Tracking the Sun's Changing Position

The motion of the Sun north and south in the sky over the course of the year causes the Sun to follow different paths through the sky each day as the Earth rotates. For a northern observer the Sun is high in the sky at noon on a summer day but low in the sky at noon on a winter day (fig. 1.13A). For example, on June 21 at a midnorthern latitude of 40°, the noon Sun is about 73.5° above the horizon, or about 16.5° away from the **zenith**—the point in the sky straight overhead. On December 21 at this latitude, on the other hand, the highest point the Sun reaches is only about 26.5° above the horizon. See Astronomy by the Numbers: "The Angle of the Sun at Noon."

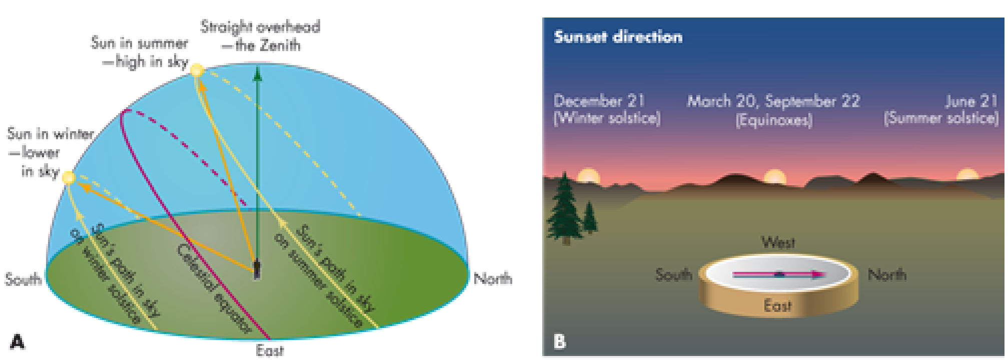

FIGURE 1.13
(A) The shifting location of the Sun north and south of the celestial equator causes it to reach different heights in the sky each day throughout the year. This diagram illustrates the Sun's path in the sky for an observer at about 40° northern latitude. (B) The motion of the Sun throughout the year results in the sunset (and sunrise) position shifting relative to features on the horizon each day.

Because the Sun moves north and south of the celestial equator during the year, the Sun does *not* rise due east or set due west on most days. Rather, over a year, the direction to the rising and setting position of the Sun constantly changes (fig. 1.13B). On the vernal equinox the Sun is on the celestial equator, so it rises due east and sets due west. From this date up to the summer solstice, the Sun's rising and setting points shift northward each day. From the summer solstice to the winter solstice, the position shifts southward each day, rising and setting due east and due west again on the autumnal equinox. After the winter solstice, the Sun begins to move north again. The shift of the Sun's position is particularly obvious near the equinoxes, when the Sun's position on the horizon shifts by almost its own diameter each day (fig. 1.14).

FIGURE 1.14
The sunset position shifted about 4° to the south between these two photos taken 8 days apart in September. The width of the outstretched thumb in thelower picture indicates a scale of about 2°.

ASTRONOMY *by the numbers*
THE ANGLE OF THE SUN AT NOON

The angle of the Sun above the horizon at noon is almost never straight overhead, contrary to common belief. The only place the Sun ever passes straight overhead is in the tropics (between latitudes 23.5° South and 23.5° North), and this happens on only one or two days each year.

Because the celestial sphere's equator and poles lie directly above the Earth's equator and poles, an observer's zenith is as far north or south of the celestial equator as the observer's latitude is north or south of the Earth's equator. This tells you where the noon Sun will be on the equinoxes, when the Sun is on the celestial equator.

For example, consider Phoenix, Arizona, at latitude 33.5° North. At noon on the equinoxes, the Sun is 33.5° south of the zenith. Because the zenith is by definition 90° above the horizon, this means the Sun is 56.5° above the horizon. And the Sun is never straight overhead.

On the summer solstice in Phoenix, the Sun is 23.5° north of the celestial equator, so it is only 10° from the zenith, or 80° (= 90° – 10°) above the horizon. On the other hand, at the winter solstice, the

Sun is 23.5° south of the celestial equator, so it is now 57° south of the zenith (33.5° + 23.5°), or only 33° above the horizon.

The path the Sun follows each day can be quite different at different latitudes, as illustrated in figure 1.15. At the North Pole the Sun remains above the horizon for half the year, circling the sky above the horizon in each 24-hour period while gradually changing its height above the horizon. At the equator the Sun is up for 12 hours every day of the year, but it reaches its highest point in the sky on the equinoxes rather than one of the solstices. The Sun's path in equatorial regions is almost perpendicular to the horizon, so the Sun seems to set quickly and the period of twilight is short. At the edge of the tropics, the Sun reaches the zenith just on the day of one of the solstices.

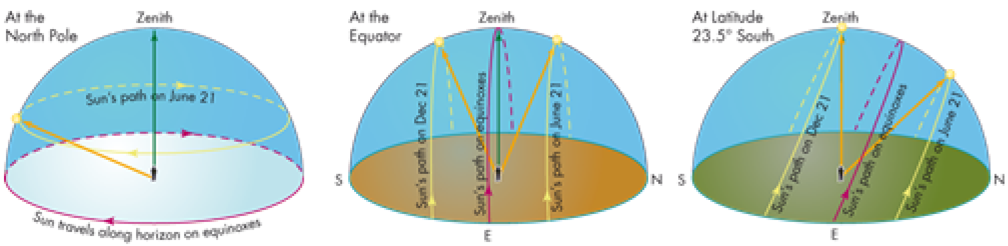

FIGURE 1.15
The path of the Sun in the sky differs depending on your latitude. At the North Pole, the Sun never sets for six months but gradually spirals up from the horizon from the vernal equinox to the summer solstice, then spirals back down to the horizon at the autumnal equinox before it disappears for six months. At the equator, the Sun rises straight upward from the horizon, but reaches the zenith only on the equinoxes. At 23.5° South, the Sun reaches the zenith at noon only on December 21, the start of summer in the Southern Hemisphere.

Outside of the polar regions, the Sun's rising and setting positions on the horizon shift each day as the Sun travels northward and southward. And just as the changing position of the Sun against the constellations can be used as an indicator of the seasons, so too can the position of the rising and setting Sun. One well-known example is Stonehenge, the ancient stone circle in England (a photograph of which opens this chapter on page 14). Although we do not know for certain how this ancient monument was used, it was laid out so that such seasonal changes in the Sun's position could be observed by noting through which of the stone arches the Sun was visible when it rose or set. For example, on the summer solstice at sunrise, an observer standing at the center of this circle of immense standing stones would see the rising Sun framed by an arch, as illustrated in figure 1.16A. Similarly, some ancient Egyptian temples and pyramids have astronomical alignments, such as the Temple of Amun-Ra at Karnak, whose main axis points toward the position of sunrise at the winter solstice (fig. 1.16B).

FIGURE 1.16

(A) Stonehenge, built more than 4000 years ago on the Salisbury plain in Britain. The enormous stones are arranged to frame various positions of the Sun on the horizon, helping to mark dates such as when the Sun reaches its point farthest north on the summer solstice. (B) The huge Karnak Temple complex in Luxor was built with its main axis aligned in the direction of the rising Sun on the winter solstice. It was begun almost 4000 years ago, and was expanded repeatedly.
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Structures designed with astronomical alignments were built in many other places as well. For example, in Chankillo, Peru, a series of towers was built on a ridge about 2300 years ago. As viewed from an ancient observatory at the base of the ridge, the towers span the shift on the horizon of the rising Sun (fig. 1.17A). The Maya, native peoples of Central America, and their neighbors built pyramids from the summits of which they could get a clear view of the sky over the surrounding rain forest. The pyramid at Chichén Itzá was specially designed so that on the equinoxes, sunlight would create the image of a snake slithering down the steps (fig. 1.17B).

FIGURE 1.17
(A) The oldest known astronomical observatory in the Americas is found in Chankillo, Peru. This ancient observatory marked the shifting position of sunrise with a series of 13 towers built along a ridge about 2300 years ago. (B) At sunrise on the equinoxes, sunlight raking across the edge of the Mayan pyramid at Chichén Itzá creates a shape that resembles a serpent slithering down the steps. The head of the serpent is depicted in a sculpture at the base of the stairs.

Many cultures also built monuments that appear to have been used to track another important celestial body: the Moon. Like the Sun, the Moon shifts relative to the stars, and its cyclic changes formed the basis for calendar systems around the world. Some archaeo-astronomers claim that sites such as Stonehenge were used to track the moonrises and moonsets and perhaps even used to predict eclipses.