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To Every Season There is a Reason

by George Musser, Astronomical Society of the Pacific

There are two kinds of people: Those who enjoy the ebb and flow of the seasons, the dapples of autumnal color, the hoary headed frosts of winter, the flowers anew of spring, the live murmur of a summer's day. And those who don't find anything romantic in blinding snowstorms, ice-covered roads, or gangrenous frostbite; who would just as soon go south in the winter, and stay there.

Whatever you think of seasons, the annual cycle is imprinted on nearly everything we do. The seasons tell us the time to plant and the time to reap, the time to go skiing and the time to go scuba-diving. From the earliest days of humanity, kings, farmers, and vacation-goers in nearly every culture have set astronomers to work explaining the seasons.

Every society experiences seasons, but the four seasons of the temperate climates don't mean much to people who live in the tropics, where two seasons are more common: the rainy season and the dry season (see *Superseasons*). In Ethiopia, for example, the rainy season runs from mid-June to mid-September. Why do temperate and tropical climates have different seasonal cycles? This is one of the many questions that any explanation of the seasons has to answer.

The Measure of the Year

It might be easier if I just told you why seasons occur. But then we'd lose out on a chance to learn how scientists came up with the answer. Many people have gotten used to the idea that scientists always have the answer, but they have to work things out just like everybody else. So let's figure out the seasons, starting from what we see:

Fact #1. It's cold in winter and hot in summer. Only the hardiest Alaskan or Lapp would deny that. In the Northern Hemisphere, the coldest temperatures generally occur in January and February, and the hottest in July and August.

Fact #2. The seasons happen on a regular schedule. Northern winter, for example, starts around December and ends around March.

Fact #3. As every duck knows, winters are milder toward the equator. The strength of the seasons varies as you go north or south, but not as you go east or west. As you cross the equator, the seasons reverse. During winter in the Northern Hemisphere, it's summer in the Southern Hemisphere, and vice-versa (see figure 1). By flying from Canada to Brazil, some clever birds avoid winter altogether.

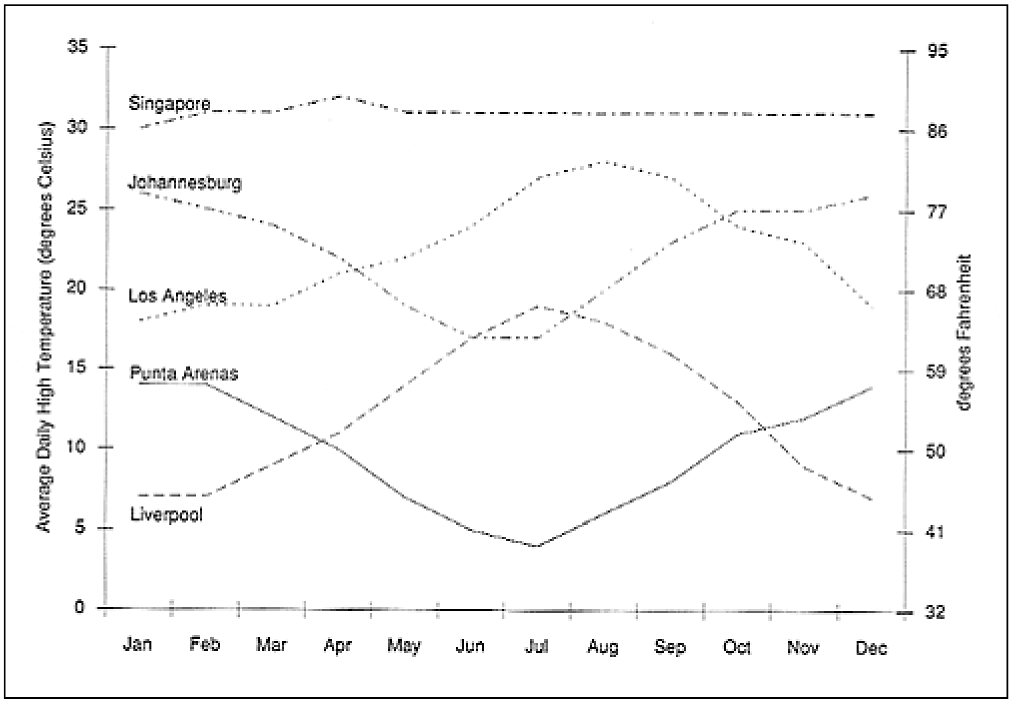

Figure 1
Average daily high temperature in five cities: Liverpool, England (53 degrees north latitude); Los Angeles, Calif. (34 degrees north latitude); Singapore (1 degree north latitude); Johannesburg, South Africa (26 degrees south latitude); and Punta Arenas (53 degrees south latitude), Chile. When it's winter in the Northern Hemisphere, it's summer in the Southern Hemisphere, and vice-versa. Near the equator, the seasonal fluctuations are small.

Fact #4. The days are shorter, and nights longer, in winter than in summer (see figure 2). The longest day of the year is the summer *solstice*, which occurs in the Northern Hemisphere around June 21. The shortest day is the winter solstice, around Dec. 21 in the Northern Hemisphere. In between the two solstices are the *equinoxes*, when days and nights are equally long. The northern vernal (spring) equinox occurs on March 21 and the autumnal equinox on Sept. 21. The length of the day also depends on your latitude. In the arctic and antarctic, at latitudes above 66.5 degrees, there are days when the Sun never sets or rises -- the midnight Sun.

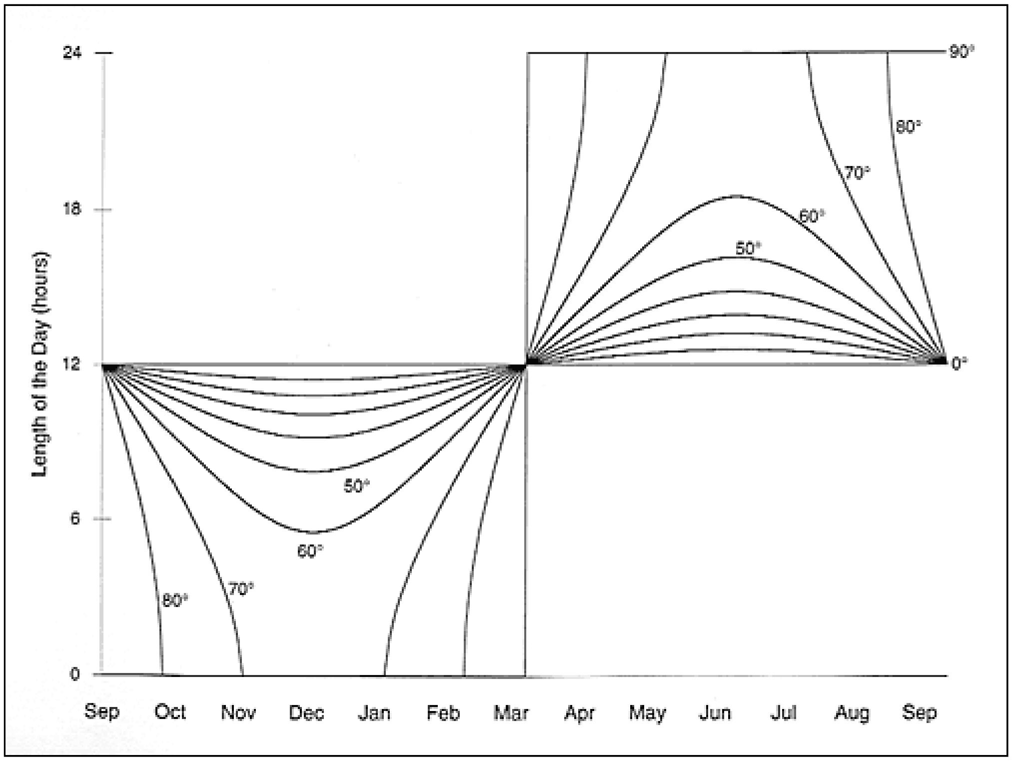

Figure 2
The length of the day at various northern latitudes. This chart does not take into account bending of sunlight by the atmosphere, which lengthens the day by about 10 minutes, or the slight noncircularity of the Earth's orbit, which causes Northern summer to be four days longer than Northern winter.

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Fact #5. The Sun rises higher in summer than in winter. If you drive south on a sunny day in northern winter, the Sun is in your eyes more than it would be in summer. The change in the height of the Sun is pretty substantial. Over the course of the year, the angle between the Sun and the zenith (straight up) varies by 47 degrees -- a fourth of the way across the sky. You can simulate this behavior with the Solar Motion Demonstrator (see *Using Your Solar Motion Demonstrator*).

To keep track of the Sun's position, you can watch the shadow of a street sign, telephone pole, or tree. When the Sun is lower, shadows extend a longer distance (see figure 3). The shadow will be shortest around noon (the exact time varies because our clocks are not exactly synchronized to the Sun). If you measure the shadow every day at noon, you'll notice that its length changes from day to day. The daily change is greatest at the equinoxes.

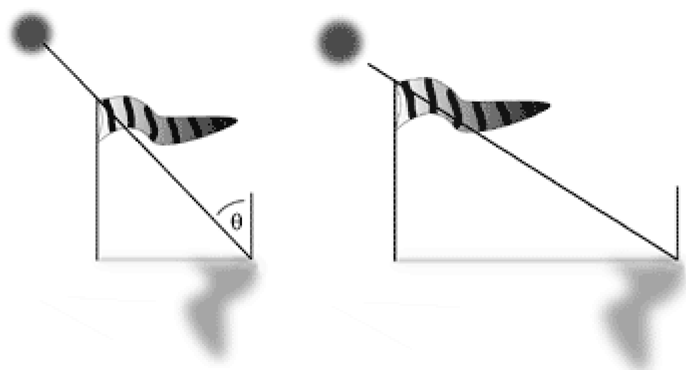

Figure 3
The seasonal cycle of shadows. On the left is the Sun as it appears in summer, high in the sky. Shadows are short. On the right is the Sun as it appears in winter, lower in the sky. Shadows are long. When the height of the Sun changes, so does the angle its rays strike the ground, the incidence angle. The incidence angle is smaller in summer than in winter. You can calculate the incidence angle if you know the height of the flagpole and the length of the shadow, using the trigonometric formula angle = arctan(shadow/height).

Like the length of the day, the shadow length varies with latitude as well as season (see figure 4). In the temperate zones, the shadow is shortest at the summer solstice, indicating that the Sun is at its highest point in the sky. In the tropics, at latitudes below 23.5 degrees, the Sun is overhead twice a year; on those days, telephone poles don't cast a shadow.

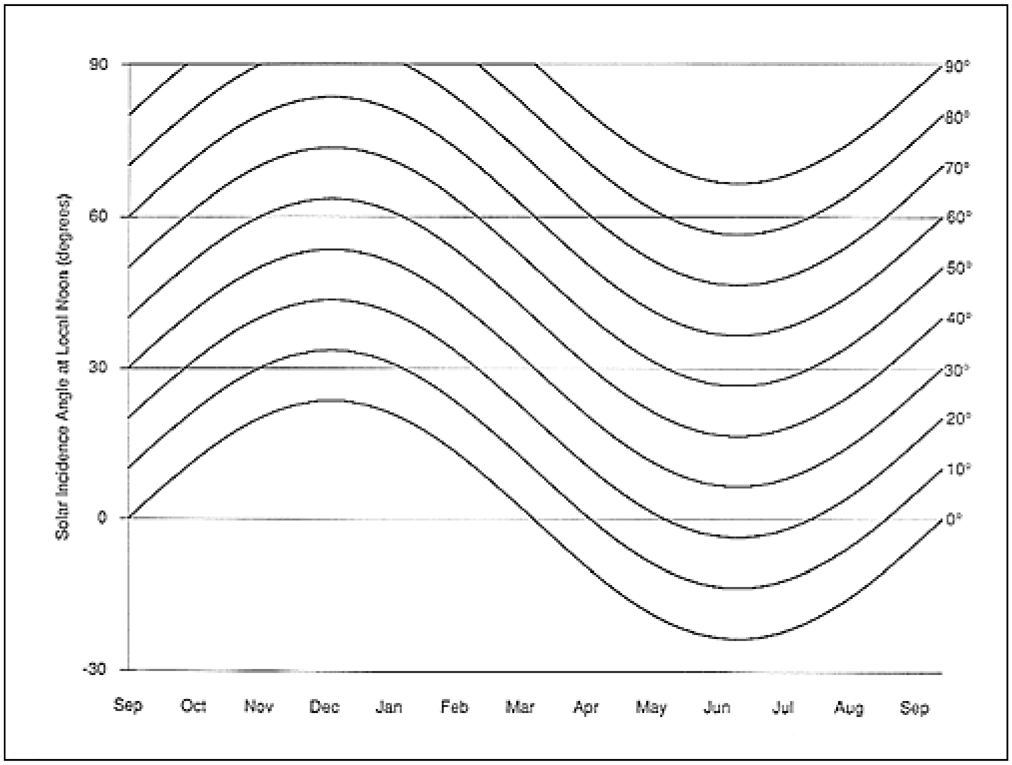

Figure 4
The angle of the Sun at various northern latitudes. The angle varies as the Sun rises and sets, but reaches the maximum shown here around noontime. A solar incidence angle of 90 degrees means the Sun is on the horizon; an angle of 0 degrees means the Sun is directly overhead; negative angles, which occur only in the tropics, mean that shadows point toward the equator. In the tropics, the Sun is overhead twice during the year; at other latitudes, the Sun is never overhead. In the arctic and antarctic, the Sun is on or below the horizon for part of the year. If you want to know your latitude, measure the solar angle on the vernal or autumnal equinox. To do so without looking directly at the Sun, measure the shadow of a stick placed in the ground and use trigonometry to calculate the angle (see figure 3).

Many cultures kept track of the Sun's position by observing its position on the horizon at sunrise or sunset. Stonehenge, the Big Horn Medicine Wheel in Wyoming, and the Sun Dagger of the Anasazi were clocks that told their builders when it was the summer solstice. You can make the same observations. Look out your window and draw the position of the sunrise or sunset with respect to landmarks, such as buildings, mountains, or trees. If you do this even for a few days, you'll notice that the sunrise moves. Around the solstice, the Sun seems to stop moving for several days, and then reverses direction. In fact, the word *solstice* is Latin for "Sun stands still."

Fact #6. The Sun seems to be the same size in winter as in summer.

Fact #7. Different stars and constellations appear in the sky in winter than in summer, a fact used by many cultures to keep track of the seasons. The Sotho-Tswana peoples of southern Africa ran a contest: The first person to see the star Canopus in the predawn sky won a cow. The appearance of Canopus, in late May, means the dry season is about to start in southern Africa.

The appearance of the sky changes gradually. At northern temperate latitudes, the constellation Orion rises about 11 p.m. in September, 9 p.m. in October, and 7 p.m. in November. Every night, stars rise 1/365 day (four minutes) earlier than they did the previous night. This occurs because the Sun and stars don't move at the same rate.

Fact #8. Not only do the Sun and stars move at slightly different rates, they move in slightly different directions. Every day, the stars rise and set along arcs parallel to the *celestial equator*. If you hold your arms in an 'L' shape and point one arm at the North Star, the other arm points at the celestial equator. The belt of Orion lies almost exactly on the celestial equator; other bright stars near the celestial equator are Altair and Procyon.

The celestial equator is directly above the Earth's equator. In Kenya and Ecuador, the stars rise straight up, cross the sky in straight lines, and set straight down. At the north or south pole, the celestial equator is on the horizon; stars never rise or set, but move in circles parallel to the horizon.

The Sun almost moves along a path parallel to the celestial equator -- but not quite. In Kenya and Ecuador, the Sun rises straight up only on the equinoxes; on other days, it rises at an angle. Over time, the difference causes the Sun to move slowly with respect to the stars. The Sun is north of the celestial equator in northern summer and south of the celestial equator in northern winter.

If you look at the constellations just after sunset or just before sunrise, you can tell the location of the Sun relative to the stars. In January, for example, the Sun appears in front of Sagittarius; in February, it's in front of Capricorn. (This whole idea of the Sun being in *front* of a constellation might seem strange. After all, there are no stars during the day, right? Actually, the stars are still there during the day. You can't see them because the sky is so bright. On the Moon, the astronauts could see stars even in broad daylight because the Moon has no blue sky to get in the way.)

If, like the astronomers of antiquity, you plotted the Sun's path on a star map, you could tell that the Sun slowly moves along a path called the *ecliptic*, marked by the constellations of the zodiac.

The Sun is like a freeway driver who uses the right lane on Monday, the middle lane on Tuesday, and the left lane on Wednesday. The driver takes the same basic path every day, just as the Sun rises and sets every day. But the driver is also slowly moving across the road to the left, just as the Sun is slowly moving across the sky on the ecliptic. You can see this behavior with the Solar Motion Demonstrator (see *Using Your Solar Motion Demonstrator*).

The ecliptic and celestial equator intersect in the constellations of Pisces and Virgo. The intersection isn't just some astronomical abstraction. It defines the seasons, because the Sun reaches the intersection points at the time of the equinoxes. Ancient Roman art often had an 'X' to represent the intersection. The intersection occurs at an angle of 23.5 degrees. Chinese astronomers may have known this angle as early as 1100 B.C.

To Every Season There is a Reason

Watching the Detective

Although a lot is happening during the seasons, the facts seem to fit together. The angle of 23.5 degrees pops up in different places: the latitudes, the ecliptic, the height of the Sun. And special things tend to happen on either a solstice or an equinox. In science as in murder mysteries, coincidences suggest there's an underlying cause. From these facts, we should be able to figure out the cause of the seasons. The usual approach scientists take is to come up with various ideas and try them out. Does the idea contradict a fact? If so, toss it out and try another one.

Let's begin with Fact 1. The change in temperature indicates that one of the Earth's heat sources is changing on a regular cycle. Which source might be involved?

1. Volcanoes. Volcanoes are a heat source that changes. They are hot during eruptions and cooler in the meantime. But volcanoes erupt on their own erratic schedule, which contradicts fact 2.
2. Human activity. People and their machines generate a lot of heat; cities are several degrees warmer than the countryside. But fact 2 seems to eliminate this as the cause of the seasons. People drive their cars and play their stereos all year round, and it has little effect on the seasons. Indeed, the seasons took place long before people affected the climate. Tree rings, for example, show a steady seasonal cycle for thousands of years.
3. The Sun. Facts 4, 5, and 8 indicate that the seasons have something to do with the Sun. This would make sense, because the Sun is our main source of heat. If this heating changes, the whole world is affected.

Try coming up with other ideas and ask yourself, do they explain the facts? Scientists have thought about this for thousands of years, and concluded that the seasons are caused by changes in the way the Sun heats the Earth.

What is changing? Perhaps the Sun is getting bigger and smaller or, equivalently, closer and farther away. Summer is hotter because the Earth is closer to the Sun. This is the explanation that most Americans have adopted, according to surveys of scientific knowledge. The Quechua people of the Andes also favored this explanation. In their skylore, the Sun shrank when it became thirsty (during the dry season) and bloated when it gulped river water (during the rainy season).

But this idea contradicts facts 3, 6, and 7. If Earth moved toward the Sun enough to affect the weather, the Sun would look bigger. In Canada and northern Europe, for example, solar heating is *four times* stronger in June than in December. If size explained this increased strength, the Sun would have to appear *four times* bigger in area.

In fact, astronomers have found that the distance to the Sun varies by only 3 percent during the year. We are closest to the Sun in early January. This makes northern winter a few days shorter than northern summer -- the Earth moves fastest when it is closest to the Sun -- but affects temperature by 7 degrees Celsius (13 degrees Fahrenheit) at most. Besides, if fluctuating distance caused the seasons, both hemispheres would have summer at the same time. And how would a change in the distance to the Sun affect the constellations we see?

The difference between the hemispheres also eliminates the possibility that the Sun is getting brighter and dimmer. The total amount of heat coming from the Sun doesn't change. What's changing is how the heat is *distributed*. The seasons are a zero-sum game. When the Northern Hemisphere loses heat, the Southern Hemisphere gains heat. All's fair in love and seasons.

The Shadow Knows

The same sort of redistribution happens every day. The warmest time of day is early afternoon. But not every city can be the warmest at the same time. Each time zone has to take its turn. When New York is at its hottest, Chicago is still warming up; when Chicago is at its hottest, New York is cooling down. It depends on where the Sun is. When the Sun is overhead, it beats down on your forehead; at sunset, it doesn't feel nearly as hot.

If the changing angle of the Sun explains the daily redistribution of heat, maybe it also explains the seasonal redistribution of heat. After all, according to fact 4, the angle seems to have something to do with the seasons. It sounds plausible, but does it account for the other facts? For a start, fact 1 is satisfied. When the Sun climbs higher in the sky, its rays hit the ground more directly and heat the ground with greater intensity. When the Sun is lower in the sky, its rays hit the surface at an oblique angle, heating the ground with diminished intensity.

Think of shining a flashlight at the wall. When you shine the flashlight straight at the wall, the light is concentrated in a small, intense spot. When you tilt the flashlight, the light is diffused over a larger, dimmer area. In both cases, the amount of light remains the same; what changes is the area over which you're distributing the light.

Because the angle of the Sun changes, so does the length of the day (fact 5). If the Sun has to climb higher in the sky, it needs more time to move from east to west, so the day is longer. The length of the day, in turn, reinforces the redistribution of sunlight. The shorter days of winter reduce the total amount of heating, so it's colder.

The solar angle depends not only on the season, but also on your latitude. Although the angle varies by the same amount at every latitude (see figure 4), the effect of this variation on solar heating increases with latitude, a fact you can confirm with a little trigonometry (see *Geometry of the Seasons*). This explains why the seasonal swings in temperature are greater the further away you get from equator (see figure 1). Near the equator the swing is so small that you lose the transitions of spring and fall, and are left with a summer and winter that don't differ much in temperature.

What could cause the angle of the Sun to vary over the whole world? One possibility is that the Sun is sliding back and forth above a flat Earth (see figure 5). The Sun would be directly above the Tropic of Cancer on the vernal equinox, and above the Tropic of Capricorn on the autumnal equinox. Scientists are always brainstorming such scenarios, or *models*, and testing them out. This model would have seemed perfectly reasonable to the Babylonians, who thought the Earth was flat. But the flat-Earth model conflicts with figure 4, which shows that the solar angle oscillates by the same amount at every latitude. If the Earth were flat, the angle would oscillate less at high latitudes than at low latitudes.

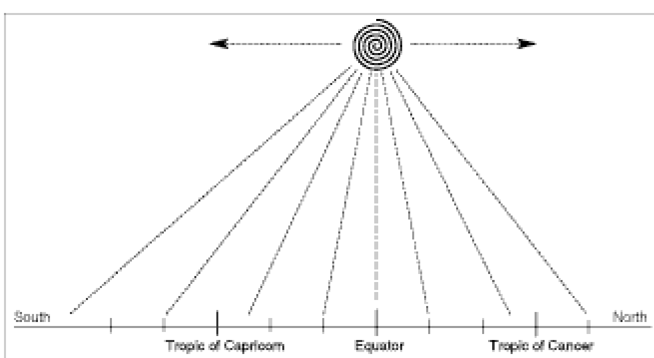

Figure 5
The Sun above the Earth, if the Earth were flat. In this scenario -- or model, as scientists would call it -- the seasons occur because the Sun slides back and forth above the tropics; the variation of solar angle with latitude occurs because Sun is so close to the Earth that its rays splay out. The flat-Earth model accounts for many aspects of the seasons, but fails to predict the exact variation of the solar angle with latitude (see figure

4). On a flat Earth, the solar angle would not vary in direct proportion to latitude.

The variation in the angle of the Sun and stars with latitude allowed the ancient Greek astronomers to deduce that the Earth is round. Nowadays, everybody knows the Earth is round, but this wasn't so obvious 2,500 years ago. Scientists always insist on proof -- and figure 4 is pretty good proof that the Earth is round.

To Every Season There is a Reason

The Tilt Tells the Tale

If the Earth is round, the Sun must be north of the equator in northern summer, and south of the equator in northern winter. You can check this by plotting the solar angle at different latitudes onto a semicircle using a protractor (see figure 6). The solar rays are parallel, indicating that the Sun is immensely far away. From the Earth's perspective, the Sun is spiraling from north to south and back again along the ecliptic (see figure 7). From the Sun's perspective, however, the equator is moving (see figure 8). Both perspectives are valid.

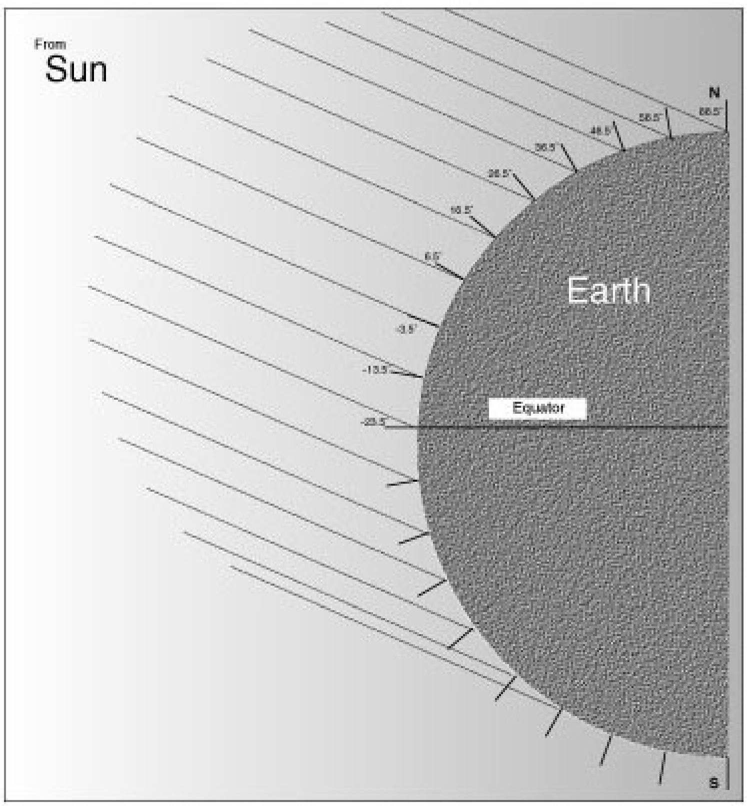

Figure 6
The round Earth, at the summer solstice. At the solstice, the Sun's rays hit the Tropic of Cancer (23.5 degrees north latitude) straight-on, indicating that the Sun must be north of the equator. On that day, the roundness of the Earth blocks sunlight from hitting the south pole and every latitude greater than 66.5 degrees south. To recreate this diagram, draw a semicircle and mark off every 10 degrees with a protractor. Draw the tangent to the circle at every 10 degree mark. Read off the solar angle for each latitude at summer solstice from figure 4 (it doesn't have to be exact) and draw a ray at that angle.

Science is a process of adding more *becauses* to every explanation. With every *because* we come to understand the universe more fully. Winter is cold because the solar heating is less, because the angle of sunlight changes, because the Sun seems to move north and south. Each *because* requires more ideas and more facts, and we are beginning to exhaust our supply. Ideally, to know why the Sun seems to move, we'd have to fly into space and look at the situation from an wholly different perspective. In lieu of more facts or a new perspective, people have had to guess.

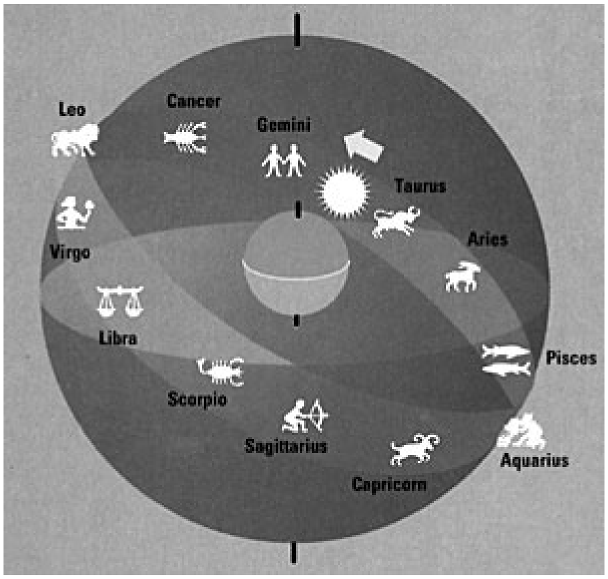

Figure 7
The Sun on the celestial sphere. The top frame shows the daily motion of the Sun around the Earth. The bottom shows the seasonal motion of the Sun through the zodiac. Diagram from Biblical Archaeology Review, September/October 1994. (c) 1994 Biblical Archaeology Society. Reproduced with permission. For information on subscriptions to BAR, write to P.O. Box 7026, Red Oak, Iowa 51591, or call 800-678-5555.

The ancient Greek philosopher Aristotle guessed that the Earth was the center of the universe. The Sun moved north and south because it was mounted on a gigantic transparent sphere that rotated around the Earth. The stars were mounted on a larger sphere. To account for facts 7 and 8, the two spheres rotated differently; their axes of rotation were *tilted*.

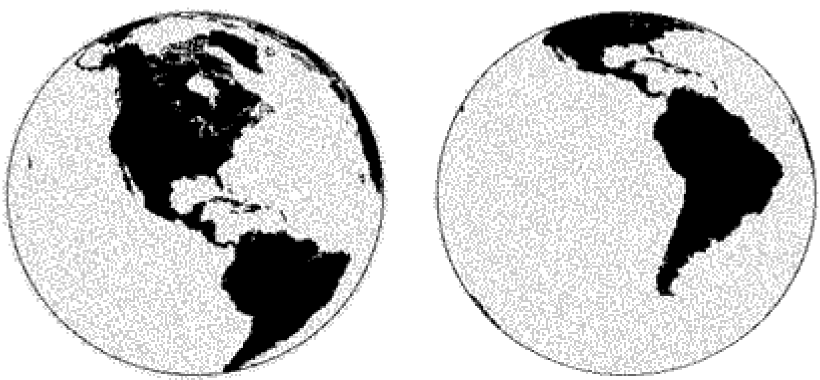

Figure 8
The Earth as seen from the Sun, at northern summer solstice (left) and northern winter solstice (right). This perspective shows how the seasons involve a redistribution of sunlight. From this perspective, the Earth looks like a disc. The Sun shines uniformly on this disc: If a region covers half the disc, it captures half the sunlight. Because of the tilt of the Earth, regions appear to change in size. The Northern Hemisphere appears bigger during the summer than during the winter; therefore, it captures more sunlight during the summer during the winter. Figure generated using the Earthplot computer program by The Black Swamp Software Company.

This theory explains facts 1 to 8, and people adopted it for 2,000 years. It wasn't until the 19th century that astronomers detected fact 9: slight shifts in the positions of stars over the course of a year. These shifts mean that we must be looking at the universe from different vantage points. The Earth, therefore, cannot be fixed at the center of the universe; it must be moving, revolving around the Sun. The stars hardly move at all.

To account for facts 7 and 8, the revolution must occur at a slight tilt to the rotation. If the rotation axis of the Earth is tilted with respect to its orbit, the equator bobs back and forth, causing the Sun to be north for half the year, and south for the other half (see figure 9).

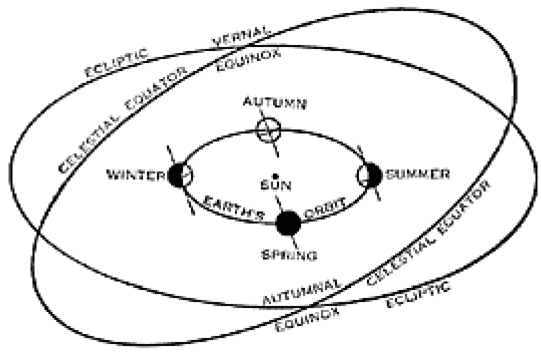

Figure 9
The tilt theory of seasons. The Earth is the little circle shown at four positions in its orbit, and its axis is the short diagonal line. The axis always points in the same direction, but because the Earth moves in its orbit, the axis leans toward the Sun in summer and away from the Sun in winter. Diagram courtesy of Yerkes Observatory.

This is easy to demonstrate. One person can hold a basketball representing the Sun in the middle of a room. Another person holds the Earth, a styrofoam ball with a knitting needle stuck through it to represent the axis, and a rubber band around it to represent the equator. The bearer of the Earth mimics the orbit of the Earth by carrying the styrofoam around the basketball. All the while, the needle should point in the same direction, just as the Earth's axis is always pointed toward the North Star. Northern summer occurs when the needle is tilted toward the Sun, because then the Sun is to the north. Northern winter occurs when the needle is tilted away from the Sun, because then the Sun is to the south. As the Earth travels, it sees the stars and Sun from different perspectives.

The idea of tilt is what scientists mean by a theory. The word *theory* confuses some people, who think that "it's only a theory." But a theory isn't just some random hunch; it is a set of principles that explains facts. No one has ever gathered any evidence that disproves the theory of the tilt of the Earth, and no other theory fits into the broader picture of physics and astronomy. Scientists use theories not only to explain facts, but to make predictions. In many cases, scientific predictions are the basis for technological innovation.

To Every Season There is a Reason

Springtime in the Solar System

In our case, we can use the tilt theory of the seasons to make a prediction: that any tilted planet will have seasons, and that the strength of these seasons will depend on the amount of the tilt. Astronomers have tested this prediction by looking at the other planets (see table below).

Inclination of equator to solar orbit	
Mercury	2 degrees
Venus	2.7 degrees
Earth	23.5 degrees
Moon	1.5 degrees
Mars	25.2 degrees
Jupiter	3.1 degrees
Saturn	26.7 degrees
Uranus	82.1 degrees
Neptune	29.6 degrees
Pluto	57.5 degrees

Venus and Jupiter are tilted by only 3 degrees, so the seasonal variation is quite mild. Every day is almost an equinox. Some might think it boring; personally, I wouldn't mind an eternal spring.

Uranus has extreme seasons, because its axis is tilted 82 degrees. It lies flat on its side as it orbits the Sun. At summer solstice, the north pole points straight at the Sun; the north polar regions have tropical weather, but the Southern Hemisphere is in total darkness. At winter solstice, the north pole points straight away from the Sun, plunging the Northern Hemisphere into total darkness.

Of all the planets, Mars has the seasons that most closely resemble Earth. Mars is tilted by 25 degrees. Its seasons were first seen by the English astronomer Frederick William Herschel in the late 18th century. He noticed changes in the polar caps: They enlarged in winter and shrank in summer. Other areas on Mars seem to get brighter and darker depending on the season, a phenomenon that many scientists used to attribute to vegetation growing on a seasonal basis. On closer observation, Marsologists realized that the seasonal changes were not plants, but dust storms.

Currently it's spring in the martian Northern Hemisphere. Northern summer begins in April. The next vernal equinox occurs on Aug. 26, 1996. On Mars, summers are hotter in the Southern Hemisphere than in the Northern Hemisphere, because the planet's orbit is so noncircular.

There's one missing link in the tilt theory of the seasons. The solstice occurs in December, but December isn't the coldest month in the Northern Hemisphere. A delay occurs for the same reason that water doesn't start boiling just as soon as you turn on the stove. The ground, air, and oceans need time to warm up and cool down. The Earth's atmosphere is so thick that it takes about a month to adjust to the new season. For the same reason, the daily maximum temperature occurs not at noon, when the Sun is highest, but at 2 p.m. On Mars, the atmosphere is so thin that it adjusts almost instantaneously to seasonal changes.

It's pretty incredible that the tilt of the Earth can cause so many effects. Scientists have found that the simplest explanation for a phenomena, as long as it explains all the facts, is probably the best one. It's equally incredible that by looking at the sky, we can understand processes and worlds so much mightier than we.

Geometry of the Seasons

You don't need math to understand why the seasons occur, but it helps. With a little trigonometry, you can calculate the angle of the Sun and the intensity of solar heating.

In Figure A, I've drawn a cross section of the Earth. Because the Earth is a sphere, its cross section is a circle. The equator is the line EOW, perpendicular to the rotation axis NOS. To find the latitude of any point P on the surface of the Earth, draw a line from P to the center of the circle, O. The acute angle between the line OP and the equator EOW is the latitude, *L*. To distinguish between north and south, we use positive angles for north latitudes and negative angles for south latitudes. At the equator, *L* = 0 degrees; at the north pole, *L* = 90 degrees; at the south pole, *L* = -90 degrees. Each degree of latitude corresponds to a fixed distance on the circumference, 110 kilometers (69 miles) for the Earth. That is, if you drive due north 110 kilometers, you will have gone 1 degree in latitude, or 1/360 around the Earth.

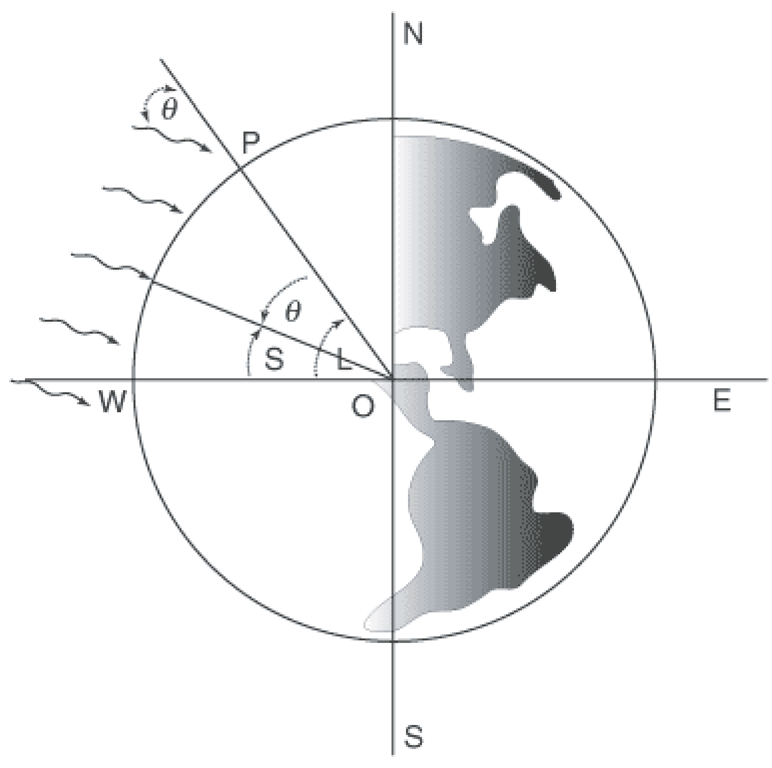

Figure A

The Sun is directly overhead at a latitude *S*. Overhead means that the Sun's rays are perpendicular to the tangent to the circle. The latitude *S* changes depending on the seasons. At the vernal and autumnal equinox, *S* = 0 degrees; at the summer solstice, *S* = 23.5 degrees; at the winter solstice, *S* = ä23.5 degrees. In fact, *S* is a simple trigonometric function of time. (Can you figure out what this function is?)

Once you know *S*, it's easy to calculate the angle of the Sun, *theta*, at any latitude *L*. Using the principle of similar triangles, the solar angle *theta* = *L* - *S*. Therefore, the solar angle increases in direct proportion to latitude: If you go north 10 degrees, the solar angle increases by 10 degrees. That's why the Sun is lower in the sky the farther north you go. You can also work backwards. For example, on an equinox or solstice, you can figure out your latitude. How would you go about doing this?

When the solar angle is bigger, sunlight spreads over a larger area of ground. In Figure B, I've shown a beam of sunlight. The beam has the same width, *b*, at all times. The beam illuminates a patch of ground of width *g*. When the Sun is directly overhead, *g* = *b*. When *g* > *b*, the beam shines on a wider area. This dilutes the energy in the beam, causing each spot on the ground to be cooler. Therefore, we can estimate the intensity of the beam as *i* = *b*/*g*. When *i* = 1, the intensity is greatest; when *i* = 0, the intensity is weakest.

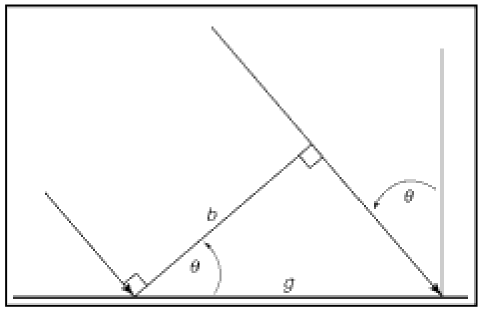

Figure B

As figure B shows, *b* is the adjacent side of the triangle and *g* is the hypotenuse. Therefore, *i* = cos *theta*. To check whether this equation is correct, test it in simple cases that we already know the answer for. When the Sun is directly overhead, *theta* = 0 degrees, so that *i* = 1. When the Sun is on the horizon, *theta* = 90 degrees, so that *i* = 0. Our little equation seems to work.

Now we can combine the two equations into one: *i* = cos(*L* - *S*). This is the key formula for the seasons. It tells us how strong the Sun is at different times of year and at different latitudes. Suppose it is the summer solstice. At what latitude is the solar intensity strongest? At what latitude is the intensity weakest? Compare the seasons at two different latitudes: Your own city and some other city in the same hemisphere. What is the solar intensity at the summer solstice? What is the solar intensity at the winter solstice? By what percentage does the intensity change? Is the percentage change greatest at the higher latitude or the lower latitude?

To Every Season There is a Reason

Superseasons

by Brett Gladman, Cornell University

The annual seasonal cycle is one example of how celestial events affect the Earth. Tides, caused largely by the gravity of the Moon, are another example. But the Moon has another influence on the Earth that cause changes noticeable only over longer periods of time.

This influence depends on the fact the Earth isn't exactly a sphere. Since the Earth rotates quickly (1,000 miles an hour at the equator), centrifugal force causes the equator to bulge out and the poles to flatten by a small amount; the same thing happens to a water balloon when you spin it rapidly. The Moon's gravity yanks on the bulging equator. This wouldn't matter if the Moon orbit was aligned with the Earth's equator. But the Moon does not orbit exactly in the Earth's equatorial plane -- it's inclined by about 5 degrees -- and consequently it tries to change the tilt of the Earth.

The Earth's spin resists this change. The tug-of-war between spin and Moon causes the Earth's axis to *precess*, or wobble. It's the same effect that makes a spinning top wobble: Gravity wants to make the top fall over, and it would if it weren't spinning, but rotation stabilizes the top -- and the result is that the spin axis precesses. In the case of the Earth, the spin axis completes precesses once every 26,000 years.

This precession has two consequences. First, because the axis is moving, the star that is closest to the celestial north pole (extending the Earth's pole out into space) changes. At present, the pole star is Polaris, but by A.D. 14,000 the celestial pole will be close to Vega. Around 3,000 B.C., the pole star was Thuban in the constellation Draco.

Second, precession moves the position of the equinoxes on the sky. The spring equinox occurs when the path of the Sun on the sky crosses the Earth's equatorial plane moving north. Civilizations with astronomical knowledge have used the vernal equinox to signal the beginning of spring. For the ancient Babylonians, the vernal equinox was in the constellation of Taurus; now it is in Pisces, and soon it will cross into Aquarius -- hence the "dawning of the age of Aquarius." This precession is so rapid that astronomers, who use a coordinate system on the sky based on the location of the Earth's pole, must constantly correct for the effect.

The Earth is affected not only by the Moon, but also by the other planets. Over hundreds of thousands of years, the gravitational pull of the other planets causes small oscillations both in the tilt of the Earth's orbit and in how elliptical the orbit is. As the orbit changes, the average amount of sunlight that the Earth receives over a year varies slightly.

This is the basis of the Milankovitch theory of climate change. In this theory, changes in the overall climate, such as the ice ages, are caused by changes in the amount of sunlight received due to variations in the Earth's orbit. Even though the changes are small, the climate is so finely balanced that they can develop into noticeable effects. During times of reduced sunlight, temperatures drop, and the Earth enters an ice age, a sort of superwinter. Right now, it's supersummer.

The Earth's climate is so complicated, however, that this theory is still controversial. Other hypotheses for climate cycles have been put forward, but many of them also involve changes in the Earth's orbit. It's one example of how interaction with the rest of the solar system has had profound consequences for life on Earth.

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The Traditional Seasons of Pohnpei

by Pamela Eastlick, University of Guam

Pohnpei is a beautiful green island of coconut palms, crystal ocean, cool breezes, and tropical sunsets, located near the equator 4,600 kilometers (2,900 miles) southwest of Hawaii. About 32,000 people live there, and despite the cultural changes of the 20th century, they have held onto their traditional lore, especially of the seasons.

The lore, collected and compiled by Stewo Gallen at the Pohnpeian Department of Education, designates two seasons: *rahk* and *isol*. *Rahk* runs from March to September, the rainy season on Pohnpei. It is the traditional season of plenty, when the breadfruit ripens. Five traditional feasts during *rahk* honor the breadfruit. *Isol* runs from September through March, the dry season. Historically this is the time of little food, or even famine. Six traditional feasts during *isol* honor various types of yam. There are 177 locally recognized varieties of yam on Pohnpei, probably more than you'll find at your local supermarket.

Pohnpeians are mostly farmers and fishermen, and their traditional calendar is suited to their needs. The calendar has 10 months. Each is 36 or 37 days long and shares its name with a bright star or group of stars prominent during that month. The months are closely tied to the tribute feasts for the yam and breadfruit, and also denote the appearance of strong trade winds and the traditional times to catch certain types of fish.

The Pohnpeian days are based on the phases of the Moon. There are 30 Moon days corresponding to the phase. If you told someone that it was the day *Rotenpahwel* of the month *Daliaram*, they would know it was a good day to catch coconut crabs. *Rotenpahwel* is two days after full Moon, when the tides are at their highest and lowest for any month, and *Daliaram* occurs in late December and January when the tides are at their highest and lowest for the year. Coconut crabs, one of the island's greatest culinary delicacies, must return to the water to lay their eggs and they do so at the time of highest high and lowest low tides. Like the seasons, the calendar reflects the closeness of the Pohnpeian people to the land and sea.

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Using Your Solar Motion Demonstrator

by Joseph L. Snider, Oberlin College

This device accurately models the motion of the Sun as seen from any place in the Northern Hemisphere at any time of year. Notice the way the months are spread out along the MONTH part of the frame. The region they occupy is determined by the 23.5 degree tilt of the Earth's axis with respect to the plane of its orbit about the Sun. If the tilt were greater, the months would be spread out more along the frame; if it were less, they would be crowded closer together.

The compass disk represents a part of the surface of the Earth. You can imagine a tiny observer (standing on the black dot at the center of the disk) looking out at the horizon in any direction. The round head of the paper fastener represents the Sun. Setting the paper fastener at the desired month adjusts for the time of year. Swinging the frame from east to west moves the Sun in its apparent daily path through the sky. The LATITUDE part of the frame is used to adjust the compass disk to put the imaginary observer at any latitude from the equator (0 degrees) to the north pole (90 degrees).

Hold the device in your left hand so that the green compass disk is horizontal. Imagine that you are standing in the middle of a large open field, at the location of the black dot, with a clear horizon all around you. The geographical directions are marked around the horizon. With your right hand, smoothly swing around the part of the frame which carries the paper-fastener Sun. When the head of the paper-fastener lies below the compass disk, the Sun lies below the horizon, and so it is night where you are. As the head of the paper-fastener passes the edge of the compass disk, the Sun rises, at a definite location around the horizon. As you continue to swing the frame, the Sun gets higher in the sky, reaches a maximum height, gets lower, and finally sets at some definite location on the horizon.

Here are a few ways to use the Solar Motion Demonstrator:

1. At what times of year are the lengths of day and night equal? On the vernal equinox in March and fall equinox in September, the Sun rises due east and sets due west at every latitude.
2. What are the relative lengths of day and night? Swing the piece carrying the Sun around at a constant rate, over its entire range. This corresponds to one rotation of the Earth, taking 24 hours. The Sun lies above the horizon for part of this motion (daytime) and below it for the remainder (nighttime). From this, you can estimate the relative lengths of day and night.
3. What are the reasons for the Earth's seasons? Move the paper fastener to its June position. Swing the Sun and observe the relative lengths of day and night and the maximum height of the Sun. Do the same with the Sun down in its December position. This demonstrates the two most important factors responsible for the seasons: the length of the day and the angle at which sunlight strikes the ground.
4. Where on Earth does the Sun remain above the horizon for 24 hours? Explore the range of latitudes and times of year for which the paper-fastener Sun remains above the compass disk as you swing it through its entire daily motion. This corresponds to a 24-hour day, with the Sun above the horizon at midnight! Places for which this is true are the "Land of the Midnight Sun". For an observer north of the so-called Arctic Circle at 66.5 degrees latitude, the Sun will never set on at least one day of the year.

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