Lesson 20: The Earth in its Orbit

Recall that the Earth's orbit around the Sun is an ellipse which is almost a perfect circle. The average distance from the Sun to the Earth is 152,100,000 km (to the nearest 10,000 km) or about 92,900,000 miles. Because the distance from the Sun to the Earth is much greater that the diameter of either the Sun (1,392,000 km) or the Earth (12,735 km), rays of light from the Sun striking two different points on Earth appear to be traveling along parallel lines.

The Earth completes its orbit about the Sun in 365.25 days. Since the calendar year is 365.00 days, we add one day to the calendar year every fourth year (leap year). This has the effect of putting the Earth at roughly the same position in its orbit at the beginning of each calendar year. This has the important advantage of making the seasons occur during the same period of the calendar year every year. (Winter is December to March, spring is March to June, summer is June to September, and fall is September to December.) As a consequence, the calendar becomes a tool on which farmers, for example, can rely to know when to plant and when to harvest. If we didn't add a day to the calendar every fourth year but instead made every calendar year exactly 365 days, then:

- after 4 years, winter would start one day later,
- after 365 years, winter would last from March to June, and
- after 730 years, winter would last from June to September.

The Earth's elliptical orbit together with the Sun lie in a plane in space which is called the *ecliptic plane.* In fact, the orbits of all of the planets around the Sun are ellipses. Remarkably, all of these orbits lie in or fairly close to the ecliptic plane! (The orbit of Pluto deviates most from the ecliptic plane. The plane of Pluto's orbit is tilted at an angle of 17º from the ecliptic plane.)

Recall that the Earth's axis is the line that passes through the north and south poles, and the Earth rotates about its axis once every 24 hours which creates day and night. As the Earth travels along its orbit around the Sun in the ecliptic plane, its axis is *not* perpendicular to the ecliptic plane. In fact, the Earth's axis is tilted away from the perpendicular to the ecliptic plane at an angle of 23.5º. This 23.5º tilt has a *huge impact* upon life on Earth which derives simply from the *geometry* of the situation. For example, this geometry provides the answers to the following three questions.

- Why is summer hotter than winter?
- Why does daylight last longer in summer than in winter?
- Why do all globes have axes that are tilted at about the same angle rather than straight up and down?

We will now explore this geometry.

There are four important points on the Earth's orbit around the Sun:

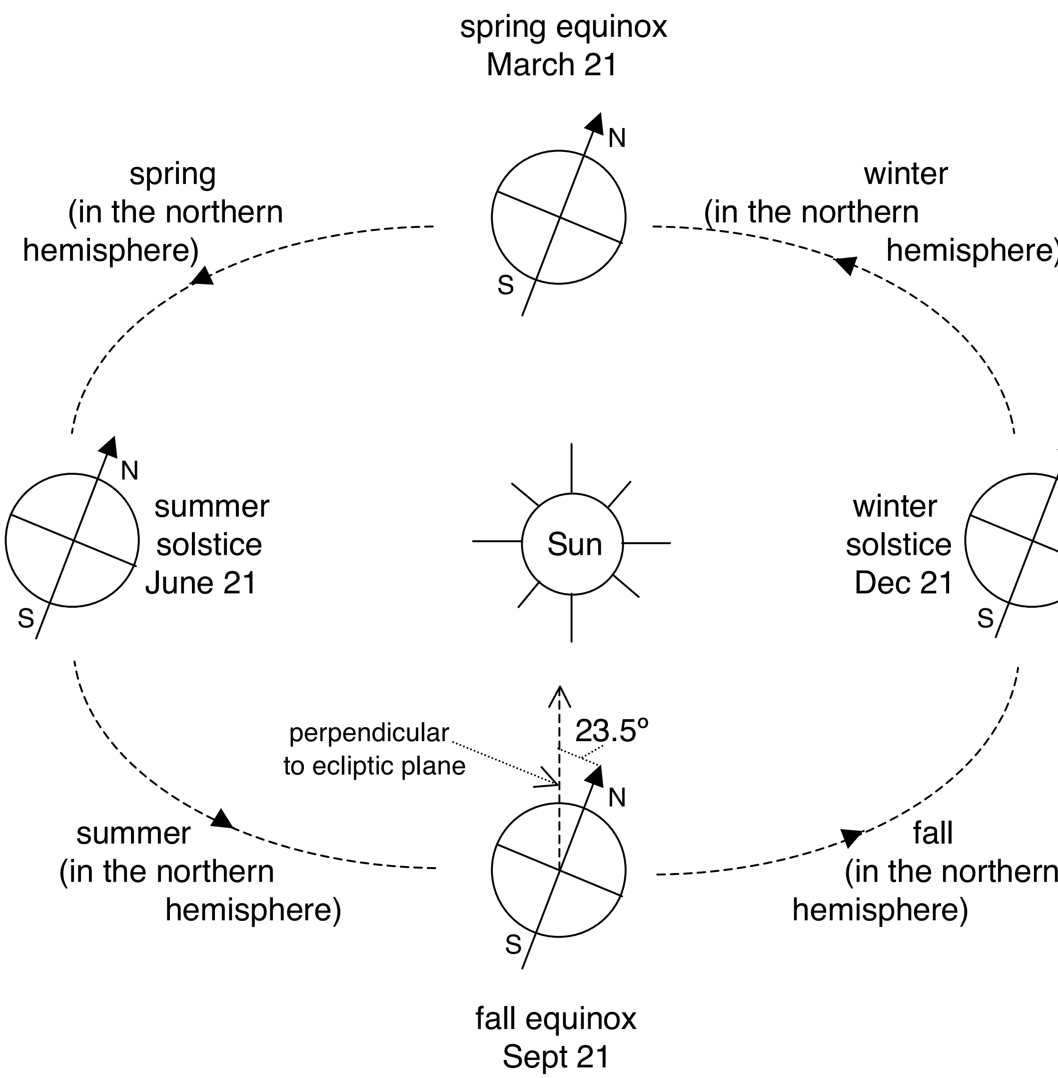
- the winter solstice which occurs each year on or within one day of December 21,
- the spring equinox which occurs each year on or within one day of March 21,
- the summer solstice which occurs each year on or within one day of June 21. and
- the fall equinox which occurs each year on or within one day of September 21.

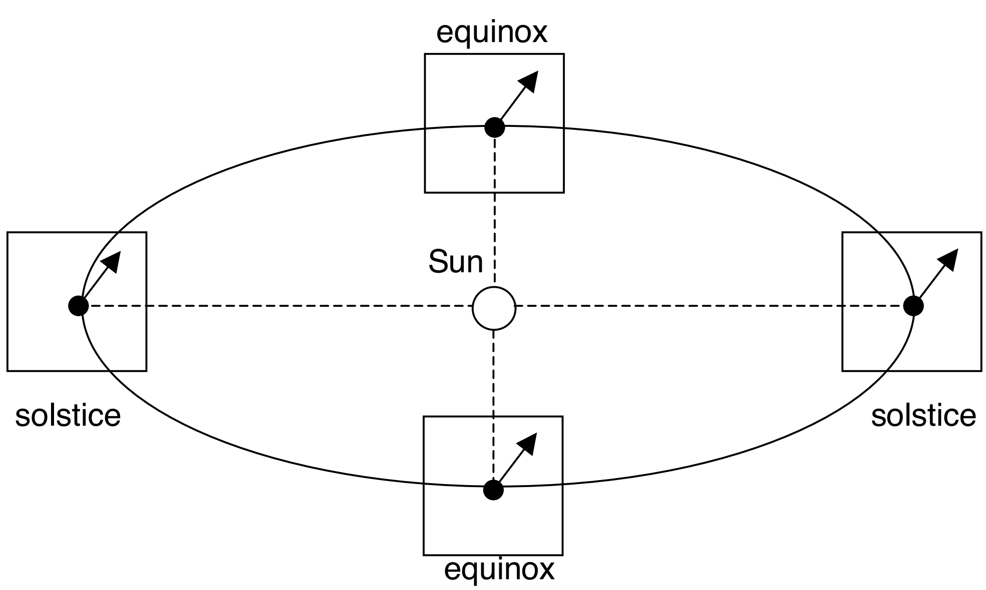
These points are illustrated in the upper figure on the next page. Notice that each of these points occurs at the beginning of the season (in the northern hemisphere) that bears its name: the winter solstice occurs at the beginning of winter, the spring equinox occurs at the beginning of spring, etc. We will now give geometric definitions of these four points on the Earth's orbit. Then we will explore the connection that relates the geometry of these points to the four seasons.

To give a geometric definition of these four points (two solstices and two equinoxes), we must first imagine at every point P on the Earth's orbit a *moving plane* that is determined by the following three properties:

- The moving plane associated to the point P passes through P.
- Every moving plane is perpendicular to the ecliptic plane (the plane that contains the Earth's orbit).
- The moving plane at the point P contains axis of the Earth when the center of the Earth is at the point P.

We are now ready to define the solstices and equinoxes. Let P be a point on the Earth's orbit. A *solstice* occurs at P if the moving plane at P *contains* the line from P to the center of the Sun. On the other hand, an *equinox* occurs at P if the moving plane at P is *perpendicular to* the line from P to the center of the. This definition is illustrated in the lower figure on the next page.

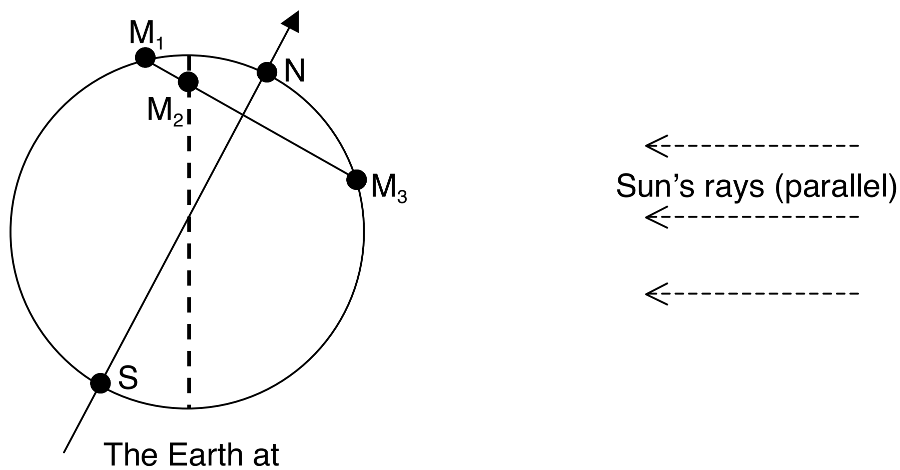

spring equinox
March 21
N
S
spring
(in the northern
hemisphere)
winter
(in the northern
hemisphere)
N
S
summer
solstice
June 21
Sun
winter
solstice
Dec 21
N
S
perpendicular
to ecliptic plane
23.5°
N
S
summer
(in the northern
hemisphere)
fall
(in the northern
hemisphere)
fall equinox
Sept 21


equinox
Sun
solstice
solstice
equinox

Activity 1. The class should *act out* the Earth's one-year trip around the Sun. One member of the class should stand and represent the Sun. Another member of the class should simulate the Earth's one-year trip around the Sun by holding a globe and walking around the person representing the Sun, keeping the axis of the globe pointing in the right direction. The members of the class should identify the points at which the globe representing the Earth is at the points of its orbit at which the summer solstice, the winter solstice and equinoxes occur.

Activity 2. Each group should carry out the activity described here, answer the questions below, and report its conclusions to the class.

The two-dimension figure below represents the summer solstice. The Earth is shown as a circle rather than a sphere. The dots labeled "N" and "S" represent the north and south poles. The dashed vertical line segment through the center of the Earth represents a certain great circle on the surface of the Earth. The dots labeled M_1, M_2 and M_3 represent the city of Milwaukee at three different times during the day of the summer solstice, and the line segment passing through these three dots represents the parallel of latitude on which Milwaukee lies.



The Earth at
the summer solstice

Loosely crumple a piece of paper into a ball and place it on your table to represent the Sun. Position a globe on the table so that its axis is oriented with respect to the paper ball in the same way that the Earth's axis is oriented with respect to the Sun on the day of the summer solstice. On the globe, locate the great circle that represents the vertical line segment in the above figure, and locate the parallel of latitude that passes through Milwaukee.

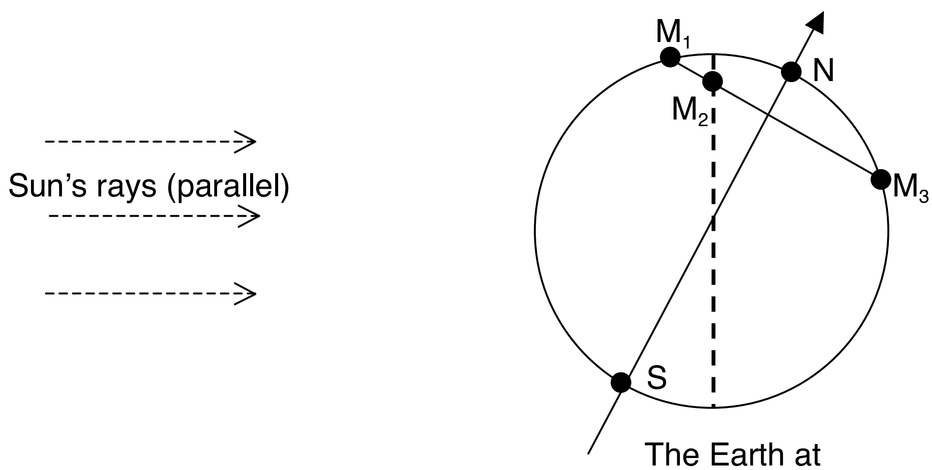
a) What is the significance of the great circle represented by the dashed vertical line segment in the above figure?

b) What is happening when Milwaukee is at the points represented by M_1, M_2 and M_3 in the above figure?

c) On the day of the summer solstice, which lasts longer in Milwaukee – daytime or nighttime? Justify your answer in terms of the geometry of the situation.

Activity 3. The class as a whole should carry out the activity described here and answer the questions below.

The two-dimension figure below represents the winter solstice. The dots labeled "N" and "S", the dashed vertical line segment, and the dots labeled M_1, M_2 and M_3 have the same significance in this figure as they do in the figure in Activity 2.



The Earth at
the winter solstice

Again crumple a piece of paper into a ball and place it on your table to represent the Sun. Position a globe on the table so that its axis is oriented with respect to the paper ball in the same way that the Earth's axis is oriented with respect to the Sun on the day of the winter solstice. On the globe, locate the great circle that represents the vertical line segment in the above figure, and locate the parallel of latitude that passes through Milwaukee.

a) What is the significance of the great circle represented by the dashed vertical line segment in the above figure?

b) What is happening when Milwaukee is at the points represented by M_1, M_2 and M_3 in the above figure?

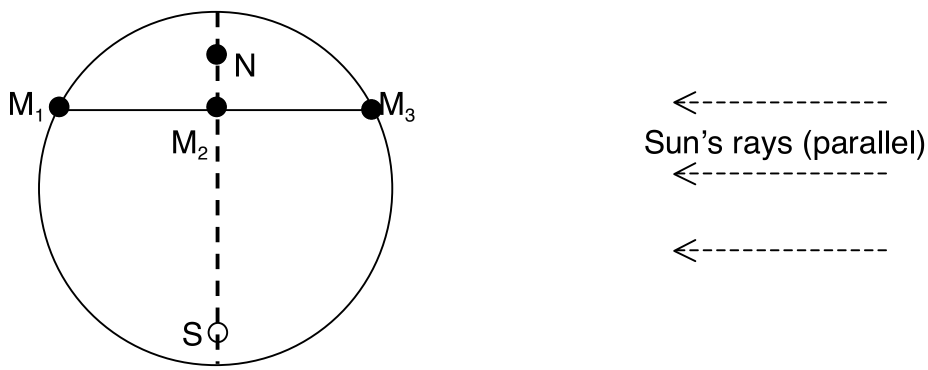
c) On the day of the winter solstice, which lasts longer in Milwaukee – daytime or nighttime? Justify your answer in terms of the geometry of the situation.

Activity 4. Based on the answers to the questions raised in Activities 2 and 3, the members of the class should discuss and propose answers the following question.

- What are some reasons that it is usually warmer in Milwaukee on the summer solstice (June 21) than on the winter solstice (December 21)?

Activity 5. Each group should carry out the activity described here, answer the questions below, and report its conclusions to the class.

The two-dimension figure below represents the fall equinox. The dots labeled "N" and "S", the dashed vertical line segment, and the dots labeled M_1, M_2 and M_3 have the same significance in this figure as they do in the figure in Activity 2. In this figure, the north pole is visible from the side of the Earth facing us, but the south pole is not. For this reason, the north pole is represented by a "filled in" dot while the south pole is represented by an "open" dot.



The Earth
on the fall equinox

Again crumple a piece of paper into a ball and place it on your table to represent the Sun. Position a globe on the table so that its axis is oriented with respect to the paper ball in the same way that the Earth's axis is oriented with respect to the Sun on the day of the fall equinox. On the globe, locate the great circle that represents the vertical line segment in the above figure, and locate the parallel of latitude that passes through Milwaukee.

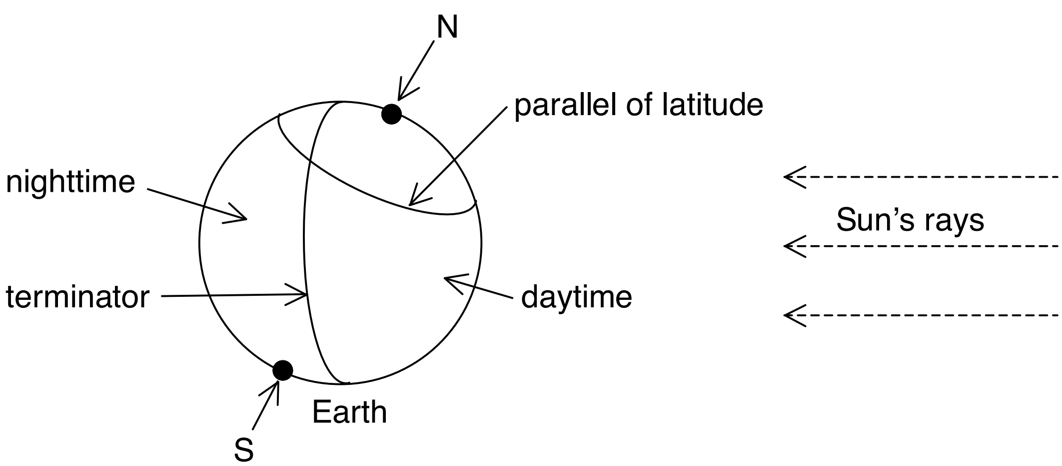
a) What is the significance of the great circle represented by the dashed vertical line segment in the above figure?

b) What is happening when Milwaukee is at the points represented by M_1, M_2 and M_3 in the above figure?

c) On the day of the fall equinox, which lasts longer in Milwaukee – daylight or nighttime? Justify your answer in terms of the geometry of the situation.

d) On the day of the fall equinox, which lasts longer in Rio de Janeiro – daytime or nighttime? Justify your answer in terms of the geometry of the situation.

The curve on the Earth's surface that divides daytime from nighttime is called the *terminator* (not to be confused with the governor of California). The terminator moves as the Earth rotates. It passes through a particular location twice a day: once when the sun rises at that location, and once when the sun sets. As the Earth rotates each point on the Earth's surface follows its parallel of latitude. Typically (though not always), the terminator intersects a parallel of latitude at two points and divides the parallel of latitude into two arcs. One of these arcs experiences nighttime while the other experiences daytime.



Activity 6. Members of the class should discuss and propose answers to the following questions.

a) What kind of curve is the terminator?

b) What can be said about the intersection points of two great circles on a sphere?

c) Based on your answers to parts a) and b) of this question, what can be asserted about the intersection points of the equator and the terminator? What can then be concluded about the relative lengths of daytime and nighttime for a location on the equator at various times of the year?

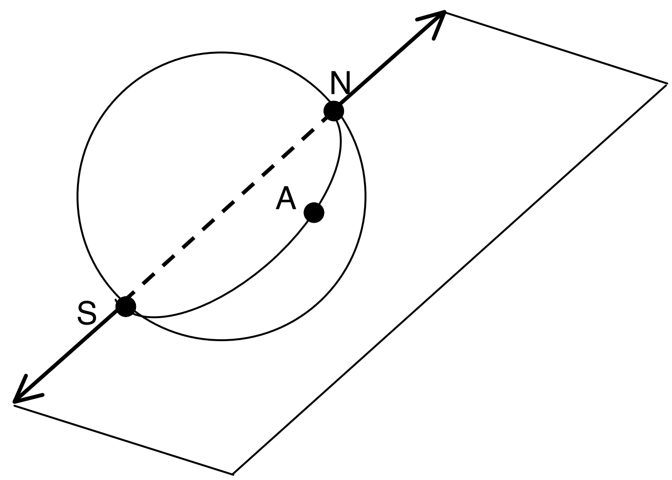
We return to our discussion of the terminator. (For this discussion, it may help to review the figures on pages 283 throught 286.) On the day of the summer solstice (when the north end of the Earth's axis points toward the Sun more than on any other day of the year), the terminator divides each parallel of latitude into two arcs: a daytime arc and a nighttime arc. The daytime arc is longer than the nighttime arc for parallels of latitude in the northern hemisphere. This is why days are longer than nights in the northern hemisphere on the day of the summer solstice. On the other hand, the daytime arc is shorter than the nighttime arc for parallels of latitude in the southern hemisphere. Consequently, days are shorter than nights in the southern hemisphere on the day of the summer solstice. The fact that the northern hemisphere receives more sunlight than the southern hemisphere on and near the day of the summer solstice partially explains why the northern hemisphere is warmer than the southern hemisphere at this time of year.

On the day of the winter solstice (when the north end of the Earth's axis points away the Sun more than on any other day of the year), the situation is reversed. The terminator again divides each parallel of latitude into daytime and nighttime arcs. However, the daytime arc is shorter than the nighttime arc for parallels of latitude in the northern hemisphere, while the daytime arc is longer than the nighttime arc for parallels of latitude in the southern hemisphere. Hence, on the day of the winter solstice, days are shorter than nights in the northern hemisphere while days are longer than nights in the southern hemisphere. Therefore, around the time of the winter solstice, the northern hemisphere receives less sunlight than the southern hemisphere. This partially explains why the northern hemisphere is colder than the southern hemisphere at this time of year.

On the days of the fall and spring equinoxes, the terminator is a great circle that passes through the north and south poles. Hence, on these days, the terminator cuts each parallel of latitude into two arcs of equal length. It follows that daytime and nighttime are of equal length at every point on the Earth's surface on the days of the fall and spring equinox.

Once a day every day, each point on Earth's surface experiences a moment called *solar noon*. At each point on the Earth's surface, solar noon occurs at the instant of the day when that point is closest to the Sun. Each day as the Earth rotates on its axis and a particular point follows its parallel of latitude, there is one spot on the parallel of latitude that is closest to the Sun and the point experiences solar noon when it passes through this spot.

Here is a way to picture solar noon at a point A on the Earth's surface. Imagine a half-plane whose edge is the axis of the Earth and which contains the point A. (This half-plane cuts the Earth's surface in the meridian of longitude that contains the point A.) As the Earth rotates about its axis and the point A rotates along its parallel of latitude, this half-plane rotates around its edge. The point A experiences solar noon at the instant that this rotating half-plane passes through the center of the Sun. It follows that every point on the meridian of longitude that contains the points A experiences solar noon at the same moment of time.



Here is another way to describe solar noon at a point A on the Earth's surface. Solar noon occurs at the point A at the moment of the day when the Sun as seen from the point A reaches its highest point in the sky. In other words, solar noon occurs at the point A at the instant of the day that the angle between the Sun and the horizon as seen from point A appears to be the greatest. It is not obvious why these two descriptions of solar noon – one in terms of a rotating half-plane and the other in terms of the angle above the horizon – should coincide. In fact, they do coincide, but the justification of this assertion would involve a digression from the goals of this course.

If you were to stand at a point A on the Earth's surface and set your watch to 12:00 noon at the instant of solar noon at point A, then your watch would read *solar time at A.* If someone else were to stand at a point B that is on the same meridian of longitude as A and were to set his watch to read solar time at B, then your watch would agree with his watch, because two points on the same meridian of longitude experience solar noon at the same instant. However, if a third person were to move a little to the east or west of you to a point C on a different meridian of longitude and were to set his watch to read solar time at C, then his watch would not agree with yours. Hence, if everybody were to set their watches to local solar time at their current positions, then a traveler heading east or west would experience a gradual change in local time. Suppose a traveler starting in Milwaukee with his watch set to read solar time in Milwaukee moves east along the 43° N parallel of latitude (which passes through Milwaukee). The 43° N parallel of latitude is a circle of circumference about 29,260 km. Since there are 24x60x60 seconds in a day, then when the traveler goes east for 29,260/(24x60x60) = .34 km, his watch would read one second behind local solar time at his new location. When the traveler goes east for 29,260/(24x60) = 20.32 km, his watch would read one minute behind local solar time at his new location. If the traveler were to go east for 29,260/24 = 1219.17 km, his watch would read one hour behind local solar time at his new location.

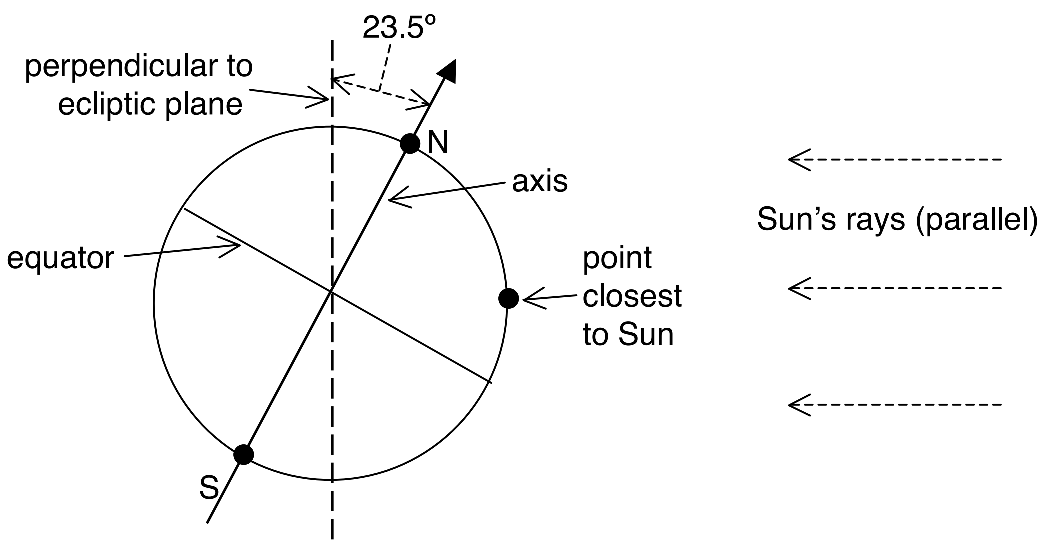
A system in which everyone kept local solar time would be very inconvenient because a small displacement east or west would create disagreements about local time. For example, solar noon in Madison occurs 6 minutes later than solar noon in Milwaukee. So if you lived in Madison and set your watch to Madison solar time; and you drove to Milwaukee to catch a plane to Djakarta that finished boarding at 3:00 pm Milwaukee solar time arriving at the gate in what you thought was enough time at 2:59 pm Madison solar time, you would be 5 minutes late! To avoid such confusion and disagreements, standard time zones were created. There are 24 standard time zones – one for each hour of the day. Since a trip around any parallel of latitude traverses 360 degrees of longitude, then the width of each time zone is approximately 360/24 = 15° of longitude. Running through the center of each standard time zone is a meridian of longitude whose longitude coordinate is a multiple of 15°, and solar time along this central meridian of longitude determines standard time within the entire time zone. Hence, the 24 central meridians of the various time zones have longitudinal coordinates: 0° (the prime meridian), 15° E, 30° E, 45° E, … , 165°, 180° E = 180° W (the international date line), 165° W, … , 45° W, 30° W, 15° W. The time zone containing the prime meridian is about 15° wide and ranges in longitude from about 7.5° W to 7.5° E. Standard time within this time zone is simply solar time at Greenwich, England on the 0° meridian; this time is called *Greenwich Mean Time* (abbreviated *GMT*). Milwaukee, which has a longitude of 87.9° W, lies in the Central Standard Time zone. The central meridian of the Central Standard Time zone has longitudinal coordinate 90° W, and the time zone ranges in longitude from about 82.5° W to 97.5° W. Central Standard Time, the time we keep in Milwaukee, is simply solar time at any point on the 90°W meridian of longitude.

Standard time zones in the U.S. were first introduced by railroads in 1883 to avoid confusion in interpreting train schedules. They became codified by law in the U.S. in 1918. In most time zones, the standard time differs from Greenwich Mean Time by several whole hours. Since 90° = 6x15°, then Central Standard Time is 6 whole hours behind GMT. There are a few regions in the world that have slightly anomalous standard time zones in which the standard time differs from GMT by several whole hours plus a half hour. For example, standard time in India is 5 hours and 30 minutes ahead of GMT. This choice allows the entire country of India to have a single time zone. Otherwise, the natural divider between two time zones would run through the center of the country and split it into two time zones. Similarly standard time in Afghanistan is 4 hours and 30 minutes ahead of GMT. Standard time in Newfoundland is 3 hours and 30 minutes behind GMT. Standard time in the Marquesas Islands in the south Pacific is 9 hours and 30 minutes behind GMT. Australia is divided into three standard time zones: east, central and west. Standard time in the western zone is 8 hours ahead of GMT, standard time in the eastern zone is 10 hours ahead of GMT, and standard time in the central zone is 9 hours and 30 minutes ahead of GMT!

Activity 7. Each group should solve the problem posed in parts **a)** and **b)** of this activity and report its conclusions to the class.

Consider the Earth on the day of the summer solstice (when the north end of the Earth's axis points toward the Sun more than on any other day of the year). Recall that the Earth's axis deviates from the perpendicular to the ecliptic plane by an angle of 23.5°. At any particular moment of time, there is one point on the Earth's surface that is closest to the Sun. As the Earth rotates about its axis, the point closest to the Sun traces out a curve on the Earth's surface. This curve consists of all the points on the Earth's surface that are closest to the Sun at some moment of time on the day of the summer solstice.

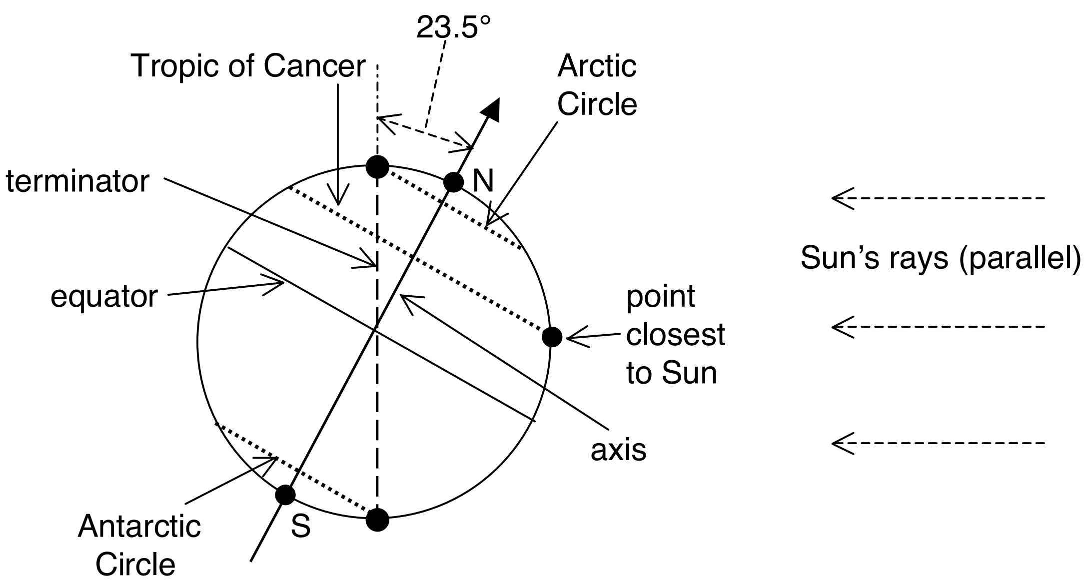
a) Describe the curve on the Earth's surface made up of the points that are closest to the Sun at some moment of time on the day of the summer solstice. Formulate your description in terms of familiar curves: parallels of latitude or meridians of longitude. Be as precise as possible: give latitude or longitude coordinates.



the summer solstice

b) The curve you described in part **a)** of this problem (made up of the points on the Earth's surface that are closest to the Sun at some moment of time during the day of the summer solstice) is called the *Tropic of Cancer*. Suppose you are standing at a point A on the Tropic of Cancer at solar noon on the day of the summer solstice, and you look at the position of the Sun in the sky. There is something special about the position of the Sun in the sky. All the points on the meridian of longitude that contains the point A experience solar noon at the same instant. However, A is the only point on this meridian of longitude that also lies on the Tropic of Cancer. The position of the Sun in the sky at solar noon on the day of the summer solstice has a special property that is seen only from A and not from any other point of the meridian of longitude containing A. What is this special property?

The Tropic of Cancer is one of three curves on the surface of the Earth that warrant attention on the day of the summer solstice. The other two interesting curves are the *Arctic Circle* and the *Antarctic Circle*. To describe these two curves, first recall that the terminator – the curve which divides daytime from nighttime – is a great circle on the surface of the Earth which moves as the Earth rotates. At every moment of time on the day of the summer solstice, the terminator has a northernmost point and a southernmost point. As the Earth rotates and the terminator moves, the northernmost and southernmost points of the terminator also move along the Earth's surface. In this way, two curves are generated. The Arctic Circle is the curve consisting of all points on the Earth's surface that are northernmost points of the terminator at some moment of time on the day of the summer solstice. Similarly, the Antarctic Circle is the curve consisting of all points on the Earth's surface that are southernmost points of the terminator at some moment of time on the day of the summer solstice.



the summer solstice

Activity 8. Each group should solve the problem posed in parts **a)**, **b)** and **c)** of this activity and report its conclusions to the class.

a) Describe the Arctic and Antarctic circles in terms of familiar curves: parallels of latitude or meridians of longitude. Be as precise as possible: give latitude or longitude coordinates.

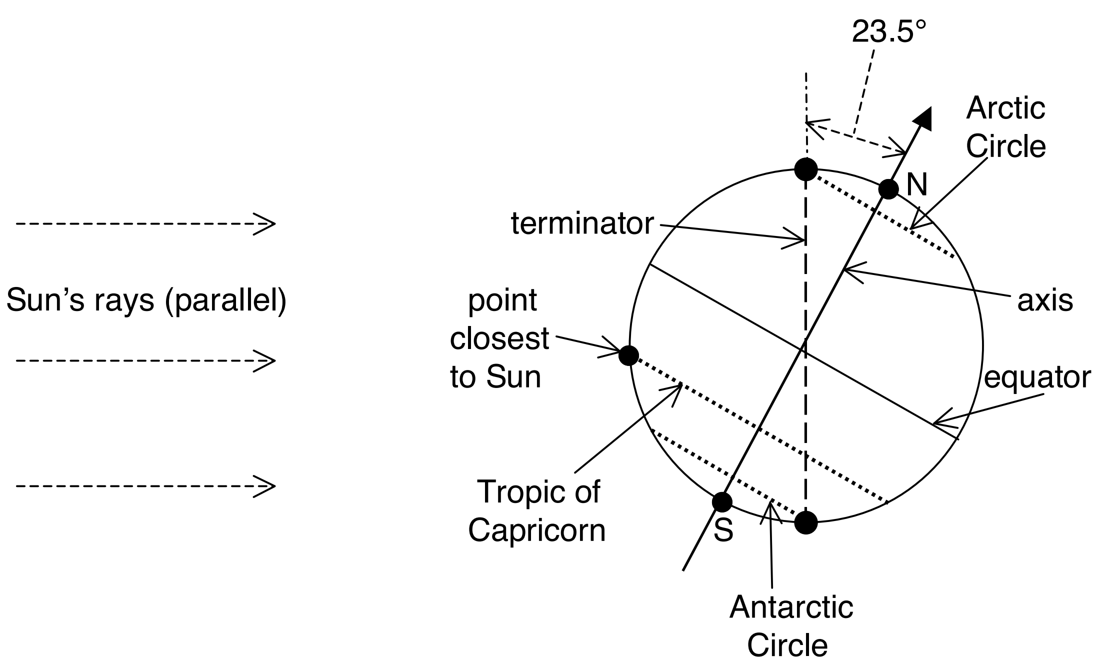
b) Suppose you are standing at a point on the Earth's surface that is north of the Arctic Circle on the day of the summer solstice, and you watch the position of the Sun in the sky for the entire day. You will witness a phenomenon that can't been seen from any point on the Earth's surface that is south of the Arctic Circle. What is it?

c) Suppose you are standing at a point on the Earth's surface that is south of the Antarctic Circle on the day of the summer solstice, and you watch the position of the Sun in the sky for the entire day. You will witness a phenomenon that can't been seen from any point on the Earth's surface that is north of the Antarctic Circle. What is it?

Activity 9. The class as a whole should solve the problems posed in parts **a)**, **b)**,**c)** and **d)** of this activity.

We now consider the Earth on the day of the winter solstice (when the north end of the Earth's axis points away the Sun more than on any other day of the year), and perform an analysis that is similar to the previous two problems. (Recall that the Earth's axis deviates from the perpendicular to the ecliptic plane by an angle of 23.5°.)

a) At any particular moment of time on the day of the winter solstice, there is one point on the Earth's surface that is closest to the Sun. As the Earth rotates about its axis, the point closest to the Sun traces out a curve on the Earth's surface. This curve consists of all the points on the Earth's surface that are closest to the Sun at some moment of time on the day of the winter solstice. This set is called the *Tropic of Capricorn.* Describe the Tropic of Capricorn in terms of familiar curves: parallels of latitude or meridians of longitude. Be as precise as possible: give latitude or longitude coordinates.



the winter solstice

b) Suppose you are standing at a point A on the Tropic of Capricorn at solar noon and you look at the position of the Sun in the sky. There is something special about the position of the Sun in the sky. All the points on the meridian of longitude that contains the point A experience solar noon at the same instant. However, A is the only point on its meridian of longitude that also lies on the Tropic of Capricorn. The position of the Sun in the sky at solar noon on the day of the winter solstice has a special property that is seen only from A and not from any other point of the meridian of longitude containing A. What is this special property?

c) Recall that the Arctic Circle was described as the curve consisting of all the northernmost points of the terminator at different times of the day of the **summer** solstice. Argue that the curve consisting of all the northernmost points of the terminator at different times of the day of the **winter** solstice is the same Arctic Circle. Similarly, recall that the Antarctic Circle was described as the curve consisting of all the southernmost points of the terminator at different times of the day of the **summer** solstice. Argue that the curve consisting of all the southernmost points of the terminator at different times of the day of the **winter** solstice is the same Antarctic Circle.

d) Suppose you are standing at a point on the Earth's surface that is north of the Arctic Circle on the day of the winter solstice, and you watch the position of the Sun in the sky for the entire day. You will witness a phenomenon that can't been seen from any point on the Earth's surface that is south of the Arctic Circle. What is it? Similarly, suppose you are standing at a point on the Earth's surface that is south of the Antarctic Circle on the day of the winter solstice, and you watch the position of the Sun in the sky for the entire day. You will witness a phenomenon that can't been seen from any point on the Earth's surface that is north of the Antarctic Circle. What is it?

Homework Problem 1. Review Activities 2 and 3. Find a point on the globe where the lengths of daytime and nighttime on the day of the winter solstice are the same as the lengths of daytime and nighttime in Milwaukee on the day of the summer solstice.

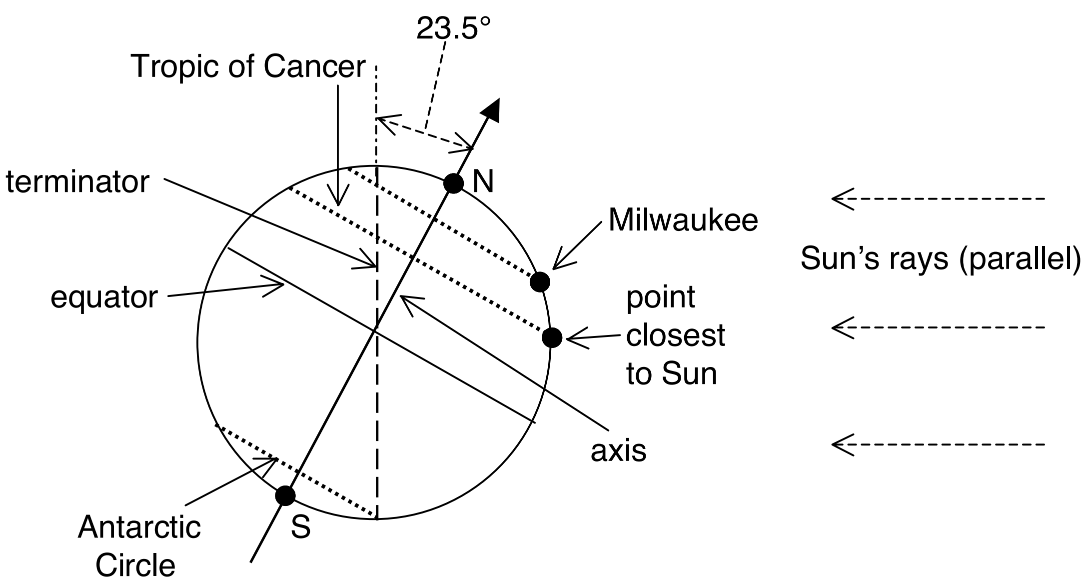
Homework Problem 2. Review Activities 2 and 4. Find a point on the globe where the lengths of daytime and nighttime on the day of the summer solstice are the same as the lengths of daytime and nighttime in Milwaukee on the day of the fall equinox.

Homework Problem 3. The longitude coordinate of downtown Milwaukee is 88° W. Here are the longitude coordinates of four other cities:

San Francisco	122° W
New York City	74° W
Paris	2° E
Shanghai	121° E

Tell how much earlier or later (in hours and minutes) solar noon occurs in each of these cities than it occurs in Milwaukee. Remember that one rotation of the Earth about its axis takes 24 hours, and longitude coordinates range from 180° W to 180°E (a total range of 360°).

Homework Problem 4. The latitude coordinate of Milwaukee is 43° N. At solar noon in Milwaukee on the day of the summer solstice, how many degrees above the horizon is the Sun? At this moment, is the Sun in the southern half or the northern half of the sky?



the summer solstice

Homework Problem 5. Noon in the Central Time Zone (when Daylight Savings Time is *not* in force) coincides with solar noon along the 90° W meridian of longitude. (The 90° W meridian of longitude passes near Madison. Hence, Central Standard noon and solar noon almost coincide in Madison.) The goal of this problem is to determine the time at which solar noon occurs in Milwaukee. Solar noon occurs in Milwaukee at the moment that Milwaukee's meridian of longitude (87°53´W) is closer to the Sun than any other meridian of longitude. Since the Earth rotates in an easterly direction (the East Coast sees the Sun before the West Coast), then the 87°53´ W meridian experiences solar noon before the 90° W meridian.

a) How much earlier does solar noon occur on the 87°53´W meridian of longitude than on the 90° W meridian of longitude?

Hint: The Earth rotates 360° in 24 hours. How long does it take the Earth to rotate 1°? What is the difference in degrees and minutes between 87°53´W and 90° W? How long does it take the Earth to rotate through this angle?

b) At what time of the day does solar noon occur in Milwaukee when Daylight Savings Time is not in force?

c) At what time of the day does solar noon occur in Milwaukee when Daylight Savings Time is in force?

Hint: At what time does solar noon occur on the 90° W meridian of longitude when Daylight Savings Time is in force? Remember: in spring we turn clocks ahead one hour.