MY ANGLE ON COOLING

THE EFFECT OF DISTANCE AND INCLINATION

GRADE LEVEL
5 - 8

DURATION
1-2 45-minute periods

ESSENTIAL QUESTION
How do distance and inclination affect the amount of heat received from a heat source?

Lesson 3 of
Grades 5-8 Component
of *Staying Cool*

LESSON OVERVIEW

LESSON SUMMARY

In this lesson, students discover that it is possible to cool an object in the presence of a heat source by increasing the distance from it or by changing the angle at which it is faced. The students conduct an experiment that measures how the heat experienced by a test object changes as the distance or the viewing angle changes. The students learn to distinguish which effect is more important for determining the seasons on Earth. They learn how the MESSENGER mission to Mercury takes advantage of these passive cooling methods to keep the spacecraft comfortable in a high-temperature environment.

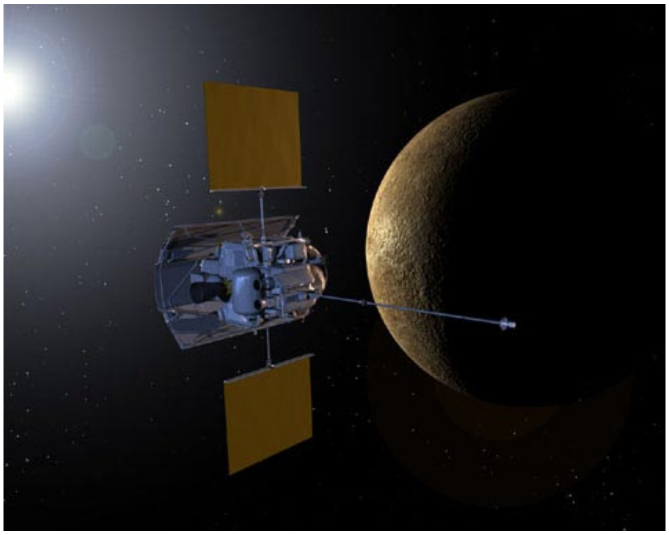


Figure 1.
The MESSENGER spacecraft with its solar panels angled toward the Sun for safe power generation.
(Picture credit: messenger.jhuapl.edu/the_mission/artistimpression/orbitwithsun_br.html)

OBJECTIVES

Students will be able to:

- Set up an experiment to test the effect of distance and inclination.
- Explain how distance and inclination affect heat.
- Graph their data.
- Identify situations where these concepts apply, such as the seasons on Earth and the MESSENGER mission.

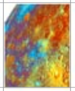
This lesson was developed by the National Center for Earth and Space Science Education (http://ncesse.org).

CONCEPTS

- Sunlight can be felt as heat when it interacts with matter.
- The intensity of light decreases as the distance from the light source increases.
- The angle at which a light source is viewed affects the intensity of light to which the object is exposed and therefore the amount of heat generated in the object.
- Seasons on Earth are caused by the (23.5°) tilt of the Earth's rotational axis, and by the resulting changes in the angle of sunlight arriving in different parts of the world at different times on the year.

MESSENGER MISSION CONNECTION

Because Mercury is much closer to the Sun than the Earth, a spacecraft studying the planet is exposed to more sunlight than objects on Earth. Two cooling methods used by the MESSENGER mission are making sure the solar panels do not view the Sun face-on, and keeping the distance from the sunlit areas of Mercury's surface large enough to limit the amount of radiation received from the surface.



STANDARDS & BENCHMARKS

NATIONAL SCIENCE EDUCATION STANDARDS

Standard D3 Earth in the solar system

- The sun is the major source of energy for phenomena on the earth's surface, such as growth of plants, winds, ocean currents, and the water cycle. Seasons result from variations in the amount of the sun's energy hitting the surface due to the tilt of the earth's rotation on its axis and the length of the day.

Related Standards

Standard B3 Transfer of energy

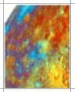
- The sun is a major source of energy for changes on the earth's surface. The sun loses energy by emitting light. A tiny fraction of that light reaches the earth, transferring energy from the sun to the earth. The sun's energy arrives as light with a range of wavelengths, consisting of visible light, infrared, and ultraviolet radiation.

Standard G2 Nature of science

- Scientists formulate and test their explanations of nature using observation, experiments, and theoretical and mathematical models. Although all scientific ideas are tentative and subject to change and improvement in principle, for most major ideas in science, there is much experimental and observational confirmation. Those ideas are not likely to change greatly in the future. Scientists do and have changed their ideas about nature when they encounter new experimental evidence that does not match their existing explanations.

AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE, PROJECT 2061

Benchmark 12C3 Read analog and digital meters on instruments used to make direct measurements of length, volume, weight, elapsed time, rates, and temperature, and choose appropriate units for reporting various magnitudes.



SCIENCE OVERVIEW

There are many different ways to cope with being in the presence of a hot object. A familiar one is to move away from it so that you do not feel its heat as strongly. Another is to change your position so that you do not face the hot object directly. It is also possible to use other cooling methods—such as air conditioning—but they can be more complicated and more expensive (though often also more efficient) than these simple methods.

Just as we prefer to work in a comfortable environment, it is important to make sure spacecraft components are kept at temperatures where they can operate normally during the mission. Using simple cooling or heating methods can greatly improve the cost-effectiveness of missions heading to very hot or very cold environments. In this lesson, we discuss how the amount of heat felt by an object can be altered by changing its distance or the angle at which the source of heat is faced.

The idea of using passive heating and cooling methods in the presence of a heat source can be demonstrated with the example of a campfire. If you hold your hands near a fire, they will warm up. The closer your hands are to the heat, the warmer they feel. If your hands are turned at an angle, only partially toward the fire, the heat received by your palms is less than if you were to hold your hands directly facing the fire. Therefore, you are able to conclude that the amount of heat felt depends on both the distance from the heat source and the angle at which your hands are inclined toward that source. If your hands become too warm, there are effective ways to cool them passively. For example, they can be moved farther from the heat, or the angle at which the hands are held can be increased.

How Heat Travels

Heat passes from one substance or object to another by three methods—conduction, convection, and radiation. Although conduction and convection need media through which to travel, heat transmitted via radiation does not need any intervening material, though it also works through some material. The Sun sends its energy through the vacuum of space via radiation, but sunlight also travels through material—the atmosphere—before reaching the surface of Earth.

Sunlight

Sunlight is the source of almost all energy on Earth. It affects many aspects of life on Earth, from allowing temperatures on our planet to remain hospitable for life to providing energy for photosynthesis. When sunlight interacts with matter, its energy is felt in various ways. For example, we can feel the warmth generated by sunlight on our skin when we stand outside on a sunny day. At the speed of light (300,000 km/s or 186,000 miles/s in a vacuum such as space), it takes about eight minutes for sunlight emitted from the Sun to reach Earth.

Sunlight is not always beneficial, however. If we stay in sunlight too long, the Sun's ultraviolet radiation may cause sunburn, which over time and with repeated exposure can develop into skin cancer. The Sun can also heat and damage items left in the sunlight. We can protect these items by placing them in shade or turning them so that they are not exposed to sunlight face-on. One thing we cannot do is change the distance of the items from the Sun since any change we could make on Earth is minimal compared with the distance from the Earth to the Sun.

The Effect of Distance on Heat

The idea of cooling by increasing the distance to a heat source radiating energy is based on the "inverse square law." This law states that the intensity of radiation to which an object is exposed depends on its distance from the source, R, as $1/R^2$ (see Figure 2). For example, Earth is one AU away from the Sun (Astronomical Unit = average Sun-Earth distance: about 150 million kilometers, or 93 million miles). Mercury's orbit gets to within 0.3 AU from the Sun. This means that a spacecraft studying the planet Mercury (such as MESSENGER) is exposed to as much as 11 times the sunlight that it would normally experience in space near Earth ($1/0.3^2 = 11$). Note that the inverse square law applies to light and heat transmitted by radiation, but not to heat traveling by other means (such as hot air currents moving from one place to another or heat conducted through material). The inverse square law is based on the fact that radiation spreads out in all directions in space from its source. By the time it has traveled a distance R, the radiation has spread over an area $4\pi R^2$, (the surface area of a sphere with radius R), and the intensity has therefore fallen as $1/R^2$ from its original value.

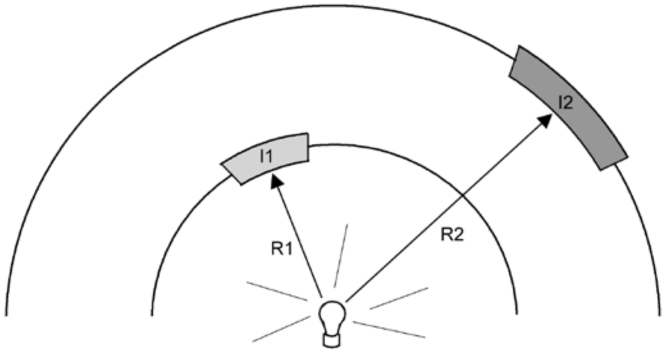


Figure 2. Intensity (I) of radiation falls off as a square of the distance from the source of radiation: $I_2/I_1 = (R_1/R_2)^2$.

The Effect of Viewing Angle on Heat

The angle at which a radiant heat source is viewed also changes the amount of heat experienced by the object. This is because the amount of radiation received by the object decreases when it is tilted away from the source (see Figure 3). Because the same amount of radiation is now spread over a larger area, the intensity (the amount of radiation per unit area) received by the object is smaller than if it were viewing the source face-on. You can calculate the intensity of radiation experienced by the object based on the viewing angle, but the mathematical treatment of the problem is not necessary for this lesson.

You can try a simple demonstration of this effect by shining a flashlight at a wall (see Figure 4). If you point the flashlight so that it is perpendicular to the wall, you can see a bright circle of light created on the wall. If you tilt the flashlight, the circle on the wall changes to an oval, and the lighted area becomes dimmer. The more you tilt the flashlight, the larger the lighted area becomes. The light received per unit area decreases, and therefore the light appears dimmer.

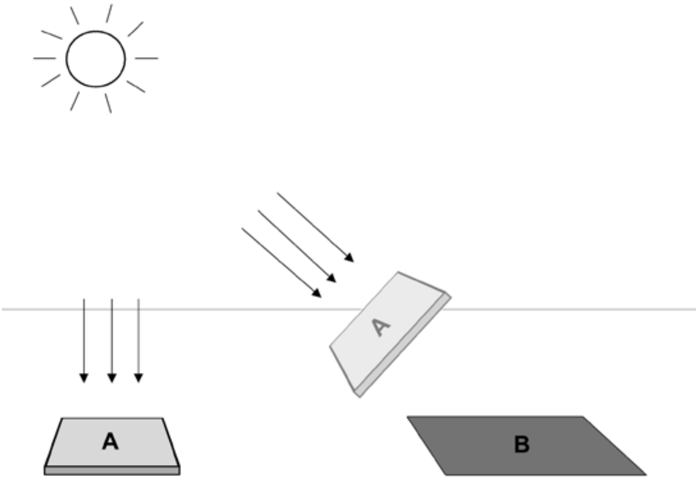


Figure 3. Effect of the viewing angle on the amount of radiation received from the Sun. Sunlight is spread over a larger area (B on right) when it strikes the ground at an angle than when it strikes the ground face-on (area A on left). If the surface were tilted toward the incoming sunlight face-on (dotted area A on right), the intensity of sunlight would be the same as the intensity on area A. (Note: the distance to the Sun appears different in the picture in the two cases, but it is just to make both images fit in the same picture; in reality the distance from the Sun for objects on the surface of Earth is basically the same wherever they are.)

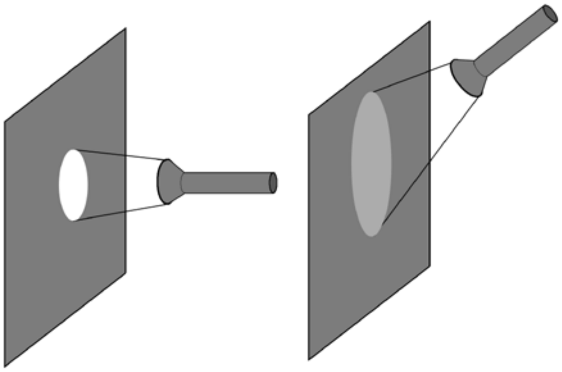


Figure 4. Shining a flashlight on a wall to demonstrate the effect of the viewing angle. When the flashlight is tilted (right-hand case), the light is spread over a larger area, and the amount of light received by unit area is reduced.

Seasons on Earth

An important example of the effect of the viewing angle is the seasons on Earth.

The angle between the equatorial plane and the orbital plane of the Earth is 23.5° (see Figures 5 and 6). The corresponding tilt of the rotational axis is called the obliquity of the Earth. The orientation of the Earth's rotational axis does not change as our planet orbits the Sun—the northern end of the axis points toward a star called Polaris, also called the North Star, in the constellation Ursa Minor, throughout the year.

The tilt of the rotational axis—and the resulting change in the direction of the arriving sunlight during the year—has the following effects on the amount of sunlight received by different regions on the surface of the Earth:

- The angle at which the sunlight strikes the Earth changes throughout the year: during the summer, the angle between the surface and the arriving sunlight is greater than during the winter. For an observer standing on the surface of the Earth, this effect can be seen as the Sun's position in the sky at local noon being higher during summer than during winter.
- There are more hours of daylight during summer than during winter.

The first effect is connected with the viewing angle toward a light or radiant heat source. If the sunlight arrives on the surface of Earth from directly overhead, sunlight heats a given place at maximum intensity. If the sunlight arrives at an angle, the same amount of sunlight is spread over a larger area, and the amount of radiation received by the same place is smaller (just as in the flashlight demonstration). Sunlight arriving at an angle also has to travel through more of the Earth's atmosphere, and more of the energy of the sunlight is lost before it arrives at the surface.

The magnitude of the second effect depends on the part of the Earth. At the equator, the number of daylight hours does not change during the year, while at the poles the days change from 24 hours of daylight in the summer to 24 hours of night in the winter. Although the length of daylight has

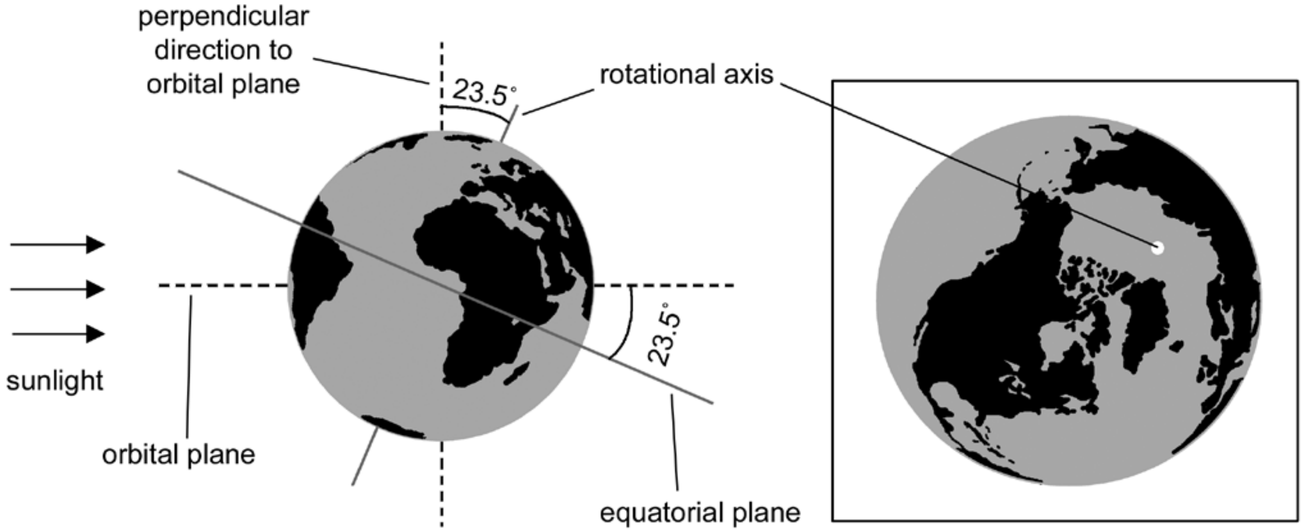


Figure 5. Definitions of terms used to describe Earth's orientation in space. Rotational axis is the geometric axis around which the Earth rotates once a day. The equatorial plane is the geometric plane going through the Earth at the equator. It is perpendicular (at 90° angle) to the rotational axis. The orbital plane of the Earth (also called the ecliptic), is the geometric plane in which the orbit of Earth around the Sun is located. The angle between Earth's equatorial and orbital planes is 23.5°; or, the rotational axis is tilted 23.5° from the perpendicular direction of the orbital plane. (Note that the sunlight arriving on Earth is always parallel to the orbital plane but does not always come from the same direction with respect to the orientation of the Earth. By the way the sunlight is falling on Earth in this figure, it would be winter in the northern hemisphere and summer in the southern hemisphere.)

an effect on temperature (and climate), it is not nearly as noticeable as the effect of the angle of sunlight—remember that the arctic summer is still cool when compared with the tropics, even when the poles get 24-hour sunlight.

Let us consider how the Earth is affected as it goes through one revolution around the Sun (one year). You can use Figure 6 as a guide; we will start at the top of the figure and proceed counter-clockwise. The situation is described from the perspective of the northern hemisphere.

On the spring equinox (on or about March 20), the Earth's rotational axis is perpendicular to the direction of the arriving sunlight. (Remember that the rotational axis is always pointing toward the North Star, but during the equinox the angle between the Sun, the Earth, and the North Star is 90˚.) At this time, both northern and southern hemispheres are half in sunlight, half in darkness, and the length of daylight is more or less equal (about 12 hours) in all parts of the world.

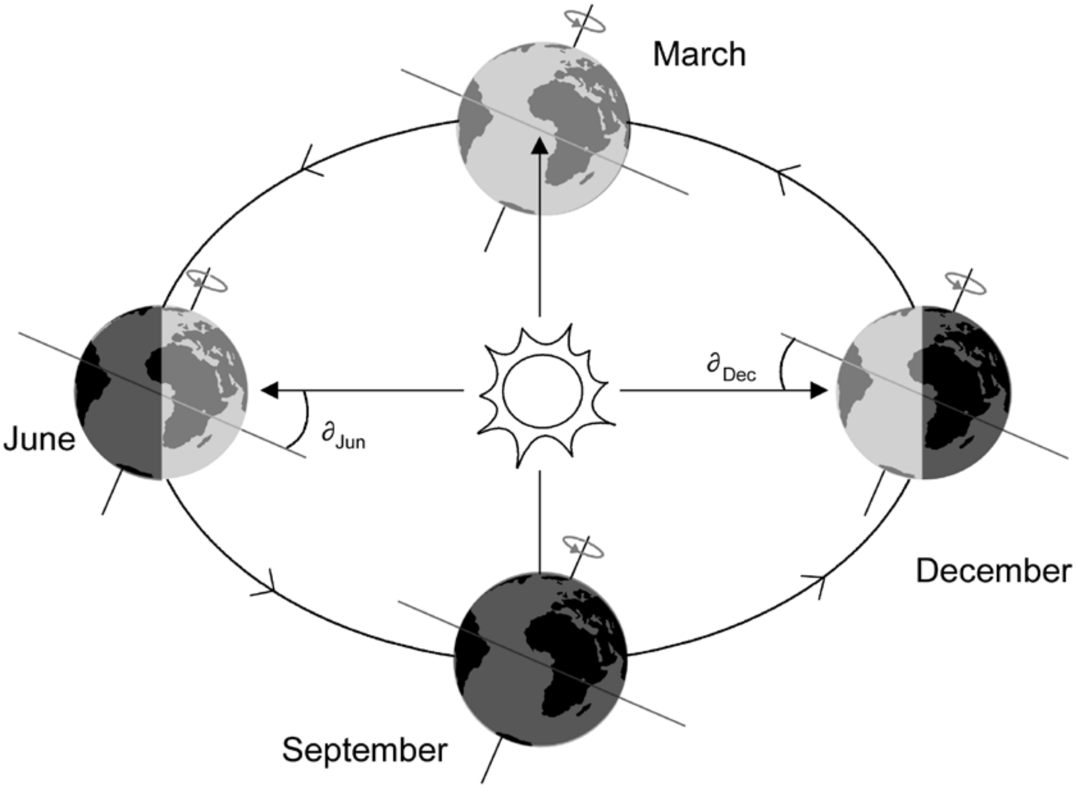


Figure 6. The inclination of Earth's rotational axis ("tilt") explains why the summer starts in June in the northern hemisphere. At this time, the Sun's rays strike the northern hemisphere most directly: the angle between arriving sunlight and Earth's equator is $\partial_{Jun} = 23.5^o$*. The tilt does not change, so in the winter the Sun's rays strike the surface at a low angle:* ∂_{Dec} *is* -23.5^o *(minus sign since the northern end of the rotational axis is pointed away). On the equinoxes (March and September), the sunlight arrives at the equator exactly perpendicular to it,* $\partial_{Mar} = \partial_{Sep} = 0^o$ *(these angles are not drawn in the picture). The seasons occur in the opposite times of the calendar year in the southern hemisphere.*
NOTE: Figure not drawn to scale.

During spring and summer months, more than half of the northern hemisphere is in sunlight at any given time, and the days are longer than the nights. The North Pole is in sunlight all the time, and as the spring progresses, regions in lower (but still arctic) latitudes experience 24-hour sunlight, as well. On the summer solstice (on or about June 21), the angle between the rotational axis and the direction of the arriving sunlight is smallest (see Figure 6). Regions above the Arctic Circle (at 66.5° latitude and above) have 24-hour sunlight during this time. After the summer solstice, the number of daylight hours dwindles toward the winter, and the limiting line of regions with 24-hour sunlight moves back toward the pole.

On the autumnal equinox (on or about September 23), the Earth's rotational axis is perpendicular to the arriving sunlight again, and the northern and southern hemispheres both are half in sunlight, half in darkness.

As the autumn progresses, less than half of the northern hemisphere receives sunlight, as the North Pole is directed away from the Sun. In fact, no sunlight reaches the North Pole from this point until the spring, and a six-month long night begins. The limiting line of regions receiving no sunlight moves down from the pole as the autumn progresses, until the winter solstice (on or about December 21), when regions above the Arctic Circle receive no sunlight. From the solstice on toward the summer, the number of daylight hours increases, and the limiting line of no sunlight during the day moves back toward the pole. On the spring equinox, the cycle begins again.

The seasons follow the same pattern in the southern hemisphere, but there they are reversed. During the summer in the northern hemisphere, it is winter in the southern hemisphere, and vice versa. This is because when the angle between the North Pole and the Sun is the smallest, the angle between the South Pole and the Sun is the largest, and vice versa (see Figure 6).

The apparent position of the Sun at a given time of day changes during the course of the year. (Remember that the Sun does not actually move—it appears to move in the sky during the day because of the Earth's rotation.) The highest position of the Sun in the sky during a day occurs at local noon, but the position of the Sun at noon varies during the year. It is highest on the summer solstice in June and lowest on the winter solstice in December in the northern hemisphere, and exactly opposite in the southern hemisphere. The highest position that the Sun can reach depends on the observer's latitude. If you live between 23.5° latitude and the North (or South) Pole, subtract your latitude from 90.0° and add 23.5° in order to determine the Sun's highest position in the sky viewed from your hometown. For example, if your hometown is Orlando, Florida, which has a latitude of 28.5°, the Sun will be at an angle of 85.0° from the horizon at local noon on the summer solstice. Alternatively, if your hometown is Seattle, Washington, at a latitude of 47.5°, the Sun's angle will be 66.0° at local noon on the summer solstice. Note that the names for the solstices and equinoxes are based on northern hemisphere seasons and it can become a little confusing when talking about the seasons in the southern hemisphere at the same time.

It is a common misconception that the seasons on Earth are caused by the Earth being closer to the Sun in the summer than in the winter. THIS IS WRONG! The Earth orbits the Sun in a nearly circular orbit: the average distance from the Earth to the Sun is 1.00 AU (about 150 million kilometers, or 93 million miles). The closest distance that the Earth gets to the Sun (perihelion) is 0.98 AU, and the farthest (aphelion) is 1.02 AU. The change is small and, in fact, the Earth is actually farther away from the Sun during the summer in the northern hemisphere than it is during the winter. This clearly demonstrates how important the 23.5˚ tilt of the rotational axis is to the existence of seasons here on Earth. There are planets for which the changes in the distance around the Sun are larger and therefore a more important factor in determining their seasons. For example, the tilt of the rotational axis of Mars (25˚) is approximately the same as Earth's, but the distance from the Sun changes from 1.41 AU to 1.64 AU (with an average distance of 1.52 AU). The change in the distance is much larger than for Earth, and the resulting influence on the seasons much greater. *IF* Earth's rotational axis were not tilted, the seasons on Earth would be caused by the varying distance, but in this case, the seasonal changes would be nowhere near as significant as they are now. Since the Earth's rotational axis is tilted, contemplating about this is just a fun "What if…?" exercise. It is important to stress that on the Earth, the seasons are caused by the tilt of the Earth's rotational axis, not the changing distance from the Sun.

Orbits, Planets, and Satellites

There are two angles that are important for the current discussion with regards to planets: obliquity and inclination angle. The planet's obliquity describes the angle between the equatorial plane and the orbital plane (or the "tilt" of the planet). The Earth's obliquity, as discussed earlier, is 23.5˚. If a planet's obliquity is 0˚, the planet "spins upright" on its orbit around the Sun, and the Sun appears to be at the same height in the sky at noon each day during the year. Note that this height depends on the latitude of where you are—at the equator, the Sun would appear to be directly overhead at noon every day during the year, while at the latitude of 30˚, it would get to be 60˚ above the horizon. Mercury's obliquity, for example, is very close to 0˚.

Inclination is a way to describe how an object deviates from a horizontal position or how two geometric lines or planes differ in their direction. Inclination angle is one of the basic parameters describing the orbit of an object around another object—it describes the angle between the orbit of the object and some reference plane. For Earth-orbiting satellites, the reference plane is the Earth's equatorial plane. For a planet orbiting the Sun, the reference plane is the ecliptic (the plane of the Earth's orbit). Since the ecliptic is defined as the Earth's orbital plane, the inclination of Earth's orbit is 0°.

The inclination of the orbit of artificial satellites (remember that moons are natural satellites) determines how they can view the Earth (see Figure 7). A satellite in a geostationary orbit is always in the same position in the sky as seen from the surface of the rotating Earth. That is, the orbital period of the satellite is the same as the rotational period of the Earth. Geostationary orbits are in the equatorial plane of the Earth. Polar-orbiting satellites fly over the Earth close to the north-south direction, passing over or near the poles. Satellites in polar orbits can see the entire surface of the Earth, not just the areas near the equator. Inclined orbits fall between these two extremes: they have an inclination angle between 0° (equatorial orbit) and 90° (polar orbit). The orbit of the satellite is determined based on its intended use.

MESSENGER, Distance, and Inclination

The MESSENGER mission to Mercury poses a

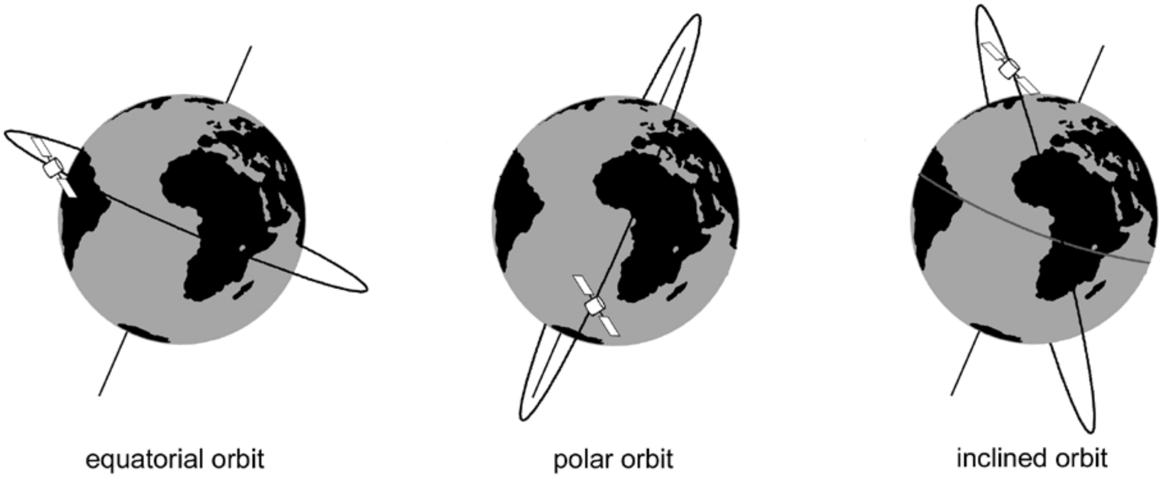


Figure 7. Satellite orbits. Equatorial orbit is in the equatorial plane of the Earth. Geostationary orbit is a version of an equatorial orbit where the satellite stays over one specific place on Earth. A satellite on a polar orbit flies over the poles and sees the whole Earth. Inclined orbit is between these two extremes; the inclination of the orbit in the figure is about 60°. [Note: satellite and its orbit not drawn to scale.]

great engineering challenge because of the close distance of the planet to the Sun. During the mission, the spacecraft will be exposed to 5-11 times the amount of sunlight that it would near Earth, depending on where Mercury is in its orbit around the Sun. Since the Earth's atmosphere allows only about half of solar radiation to pass through, the MESSENGER spacecraft will be exposed to more than 20 times the amount of solar radiation as it would on the surface of Earth. (Note that spacecraft operating in orbit around Earth but above the atmosphere also need to worry about heat and radiation—for MESSENGER, this will be a much greater problem.) This exposure to extreme heat and radiation could seriously damage components of the spacecraft. In order to limit the amount of sunlight falling on the spacecraft, it will use several cooling methods, such as a sunshade that is pointed toward the Sun at all times. As a result, the sensitive instruments aboard the spacecraft can operate in a safe temperature range, from a few degrees below 0°C (32°F) to 33°C (91°F).

The consideration of distance from a hot source also affects the choice of MESSENGER's orbit around Mercury. The sunlit side of Mercury heats up in the baking sunlight and emits infrared radiation into space as a result. The surface also reflects some solar radiation back into space. The spacecraft's orbit around Mercury has been designed so that its closest approach to the planet is away from the most sun-baked region of the surface and so that it flies quickly over the sunlit areas. This is achieved by an orbit where the periapsis (the closest point to the surface of Mercury, and also the part of the orbit where the spacecraft's speed is at its highest) is at a high latitude and the apoapsis (the farthest point of the orbit, and also the part of the orbit where the spacecraft's speed is at its lowest) is far away from the surface of Mercury. In this manner, infrared radiation received by the spacecraft can be kept at safe levels.

Inclination is important for MESSENGER in several ways. First, the orbit of the spacecraft will be highly inclined, a near polar orbit; the inclination angle is about 80°. As the spacecraft orbits the planet once every 12 hours, it can view a swath of the planet's surface in the north-south direction. As the planet rotates, the spacecraft can view the whole planet's surface during successive orbits. If the orbit were not highly inclined, the spacecraft would not be able to observe the polar regions at high resolution. The near polar orbit also makes it possible for the closest approach to the planet's surface to be at a high latitude, away from the most sun-baked regions, as described above.

Another consideration of inclination is in the design of the solar panels that provide power to the spacecraft. At Mercury's distance from the Sun, the solar panels can receive more sunlight than they can handle. One way to deal with the problem is to spread out the cells enough so that they can radiate their heat into space as infrared light. In MESSENGER's two solar panels, 70% of the area is covered with mirrors, while only 30% has actual solar cells generating energy. Another approach, this one using inclination to stay cool, is to keep the solar panels from facing the Sun directly. Using this method, the temperature of the solar panels can be reduced by about 100˚C, in addition to the 125˚C cooling effect given by the spread-out design. Combined, these passive cooling methods will keep the solar panel temperatures at around 150˚C (300˚F) instead of the more than 400˚C (750˚F) they could experience otherwise.

The third important aspect of inclination for the mission is the fact that Mercury's rotation axis is not tilted. This means that as Mercury moves around its orbit during its year, the Sun appears to reach the same height in the sky at noon each day—for example, directly overhead at the equator. At Mercury's poles, this means that the Sun appears very low in the horizon every day, all year round, apparently just crawling around the horizon as the planet rotates. This is not an important effect for the MESSENGER spacecraft itself, but it is the basis for one of the central science questions the mission is trying to answer. The low angle at which sunlight arrives at Mercury's poles makes it possible for ice to exist in permanently shaded craters that never see sunlight. Confirming or rejecting the idea of the existence of ice, suggested by Earth-based radar observations of Mercury, is one of the principal scientific goals of the MESSENGER mission.

Lesson Plan: Determining the Effect of Distance (Part 1) and Inclination (Part 2)

In the activity at the heart of this lesson, the students will measure the effect of distance and inclination on the amount of heat felt by an object. In Part 1, the students set up two thermometers at different distances from a light bulb and record their temperatures to determine how distance from a heat source affects temperature (see Figure S1 on Student Worksheet 1). In Part 2, students construct a device designed to measure the temperature as a function of viewing angle toward the Sun by placing a thermometer inside a black construction paper sleeve, and placing the device at different angles toward the Sun (see Figure S2 on Student Worksheet 1).

Preparation

- Make copies of the student worksheets and MESSENGER information sheet (one per student).

Points to consider in preparation of the experiment to ensure maximum results:

- To make Part 1 work more efficiently, you may want to blacken the thermometer bulbs. You can do this before the lesson or with the students. If you use paint, it must be done a day or more in advance. If you use spray paint, cover the tops of the thermometers with masking tape, leaving just the bulbs bare. After spray-painting the bulbs, remove the masking tape. Alternatively, you can use a permanent marker to blacken the bulbs. Blackened bulbs absorb the light more efficiently and make the experiment work better. (This effect will not matter for Part 2 of the experiment since the thermometer bulbs will already be covered by black construction paper.)

- Use at least a 100-Watt light bulb for Part 1 of the experiment. Be careful though—the stronger your light bulb, the hotter the lamp becomes!

- It is most efficient to perform Part 1 in a room with curtains or shades closed and the overhead lights turned off. That way the effect of the light from the lamp is most pronounced and the effect of distance can be seen better.

Materials

Per student:

- Thermometer (scale at least up to 50°C, preferably up to 100°C)
- 1 sheet of black construction paper
- 1 piece of cardboard the same size as the construction paper
- Bricks or blocks to prop up cardboard
- Graphing paper

Per group of three (Part 1):

- Desk lamp or flood lamp (without lampshade)
- 2 meter sticks
- Masking tape
- Stopwatch
- Chair and books or blocks to prop up the lamp (if needed)

Per group of five (Part 2):

- Scissors or knife (to cut slit in paper)
- 2-5 meter sticks
- Masking tape
- Stopwatch
- Colored pencils

Per class:

- Blackboard or flipchart with markers

- If you have a classroom that receives direct sunlight, you do not need to take the students outside to perform Part 2—you can do the experiment in the classroom. Performing Part 2 inside is preferable on a warm or windy day. Variable wind conditions may change the thermometer readings during the experiment. On a warm day, the thermometer readings may reach over the scale; this can be avoided by using a thermometer with scale reaching 100˚C.

Teaching Tip

If you do not have time for both activities in the classroom, you may want to conduct Part 1 as a demonstration. You could conduct the Warm-up while the lamp is heating the thermometers. You could also break the lesson into two periods by performing the Warm-up and Part 1 in the first period, and Part 2 and the discussion in the second period.

WARM-UP & PRE-ASSESSMENT

1. Begin by asking the students how we on Earth feel the effects of the Sun. Ask them how we can feel heat from the Sun, and remind them of (or introduce them to) the idea of heat transfer through radiation.

2. Ask students if they think that Mercury, the closest planet to the Sun, will receive more or less heat from the Sun. Ask questions about other planets as well.

3. Most middle school students are familiar with the concept of distance from a light source affecting the amount of heat felt by an object. For example, if you get close to a campfire, it feels hot more quickly than if you are far away. To introduce the idea of inclination also playing a role, ask students what they would do if they wanted to warm their hands by the campfire. They should hold their hands out flat as if toward the fire. Ask them why they would hold their hands toward the fire, and not at an angle. This will get them thinking about the effects of inclination. Ask them how they would get their hands warm the quickest: facing the fire and close to it, facing the fire and far from it?

Teaching Tip

Use a KWL Chart to determine what students KNOW about heat from distance and angles, and how these things effect seasons on Earth; what they WANT to find out; and what they have LEARNED after conducting the experiment. This is a good way to connect new ideas with old ideas, and may increase students' retention and understanding of the new concepts.

4. Ask the students which they think has a bigger effect, distance or angle? Brainstorm ideas of how the students can measure the effects of the campfire. Ask them how they could measure the effect of the distance from heat as well as the inclination. They should come up with the idea of a thermometer to measure the temperature. Ask if this would work to measure the effects of distance and inclination of the Sun. Since we cannot measure the effects of distance from the Sun when staying on Earth, guide them to the idea of using a lamp to show the difference between near and far.

Teaching Tip

Come up with your own analogies for distance and inclination, or ask the students to do so as an extra activity. Be creative, and personalize your analogy so that it relates to things that students can understand depending on their location, age, etc.

PROCEDURES

Part 1: Effect of distance

1. Place students into groups of three, each student with a different role: Time Keeper, Temperature Monitor, and Recorder. Give each group the materials necessary to make the experiment. Hand out copies of Student Worksheet 1 and have the students follow the instructions on the worksheet to set up the experiment.
2. Tables work best for this part of the experiment, but the floor will do if there are not enough tables or space.

Teaching Tip

We suggest placing the thermometers on separate tables so that students realize that distance is causing the temperature difference, and not by light falling on the farther thermometer being "blocked" by the closer one.

Teaching Tip

One way to set up the experiment is to set the lamp on a chair next to the tables. Put the 0 cm end of the meter stick at the edge of each table and adjust the lamp so that the light bulb is close to the edge of the tables. Books or blocks can be used to adjust the height of the lamp.

Teaching Tip

You may want to check each group's set-up to make sure that they have the correct lamp and thermometer placement. Make sure that the thermometer bulbs are facing the lamp, or the experiment will not work properly.

3. Make sure that the light is pointing directly toward the far end of the meter stick, as close to the table as possible. (See Figure S1 in Student Worksheet 1.) Have the students secure the lamp in place if necessary.
4. The thermometers should read the same temperature at the beginning of the experiment. (Hint: Make sure the thermometers have been stored at room temperature. If they have not, have the students wait five minutes for them to read the same temperature.)

Part 2: Effect of inclination

1. Place students into groups of five, and designate one student to be the Time Keeper. Assign each student in the group an angle: 60˚, 75˚, 90˚, 105˚, and 120˚.

Teaching Tip

If you do not have enough thermometers for every student, you can keep students in their groups of three from Part 1 and have each group measure the temperature of only one angle. In this case the results must be combined from all groups to see the desired effect.

2. Review with the students how to read a protractor. Remind the students that the angle is measured from the horizontal direction.
3. Have students follow procedures 1 and 2 in Part 2 of Student Worksheet 1 to construct the thermometer device.
4. Have the students bring the constructed thermometer devices outside and put them in shade for about five minutes before beginning the experiment; long enough so that they read the same outside temperature.
5. Have the students follow the remaining procedures in Student Worksheet 1.

Teaching Tip

The black construction paper on top of the thermometer is important for two reasons. Since it is flat, the effects of inclination are easily observable (as opposed to simply using a round thermometer bulb). Secondly, the black paper absorbs light better than would white paper, which is also why the bulbs should be blackened for the first part of the experiment.

DISCUSSION & REFLECTION

1. Have the students report on their distance experiment. Did everyone get the same result—that the thermometer farther away had a lower temperature? If not, discuss reasons why this might have happened. What would the temperature be if another thermometer was placed between the two? Further away? Explain the result as the idea that the intensity of light decreases as the distance increases. You can also discuss the "inverse square law": the intensity falls off rapidly when the distance increases. See Extensions for other possibilities with this experiment.

2. Ask the students which angle from the Sun had the highest temperature. Does this confirm their initial idea of viewing angle affecting the amount of heat felt?

3. Ask the students to discuss their results. With which effect (distance or inclination) did they find the biggest difference in their experiments? Do the students think these results can be directly compared with each other?

   [A: The results cannot be directly compared because the light source is different and there is no data available to the students to tell exactly how different or alike they are. The point is that which effect works better depends on the particular situation. If we are on the ground at Earth, talking about sunlight, we need to use inclination; distance will not help. If we are in the presence of a light bulb in a room, moving closer or farther away works best.]

4. Ask the students how their results could relate to the seasons on Earth. Which effect (distance or inclination) do they think is more important in determining the seasons? Explain that the Sun's distance from Earth does not change enough to cause a significant change in temperature. If the distance does not change, but the angle does, then the angle must be the more important effect in determining the seasons. If the students insist that seasons are caused by the distance of the Earth from the Sun, ask them if that model can explain why it is winter in the southern hemisphere while it is summer in the northern hemisphere. Can it also explain why the poles are so much colder than the equator?

5. Remind the students why the Sun appears to move in the sky during the day—because the Earth rotates, the Sun appears to move even though it does not. Ask the students how high in the sky the Sun is at noon in the summer versus how high it is at noon in the winter. Make a connection between the tilt of the Earth and the weather in the summertime, as well as for winter.

6. Explain or review the cause of the seasons with the students. You can make copies of the figures in the Science Overview if it would assist in your explanation, or you can find alternative figures and/or videos on the Internet (refer to Internet Resources & References).

7. Ask the students what would happen if the Earth was not tilted. Would distance then play a role in determining the seasons? Explain to them the situation on Mars (where the distance from the Sun varies quite a bit more than in the case of the Earth), and ask why they think the distance may make a difference there. (Answer: the changes in distance are larger than on Earth.)

8. Describe the MESSENGER mission and hand out the MESSENGER Information Sheet. How do the students think the concepts of this lesson are being used by the MESSENGER mission designers? You can assign the students to apply the concepts learned in the lesson to discuss the various cooling methods used by the MESSENGER mission (Student Worksheet 2). Note that the students need to understand how the location of the Sun in the sky appears to change on Earth during the year to answer question 3 in the worksheet.

Teaching Tip

An effective way to teach the cause of the seasons is to have the students act it out. Go to an open space with no desks or chairs. Choose one student to be the Sun and have the rest of the students stand around him in a circle. Every other student represents Earth at some time in its orbit around the Sun. Choose one point off in space to be the North Star, and have the students tilt their heads toward that point. Have them rotate on their "axes" and choose four students in the positions of the equinoxes and solstices as examples. You can use this activity to define terms, such as obliquity, ecliptic, inclination, etc.

Lesson Adaptations

- For students who may not be able to read thermometers, you could use thermal strips to observe changes in temperature.

- For students who may have problems with protractors, you can also see the effect of inclination more simply by making only two thermometer devices per group. One can be placed flat on the ground and the other can be propped to face the Sun. If you use this set-up, be sure that the students understand that the device facing the Sun receives the most sunlight of any configuration.

Extensions

- Further demonstrate the effects of distance and inclination with thermal strips that change color depending on temperature. Attach a thermal strip to a globe so that it runs along a line of longitude. Place the globe in the sunlight so that the equator is at an angle to the Sun's rays similar to the Earth's obliquity of 23.5°. After a few minutes there should be a noticeable difference between the color of the thermal strip at the equator and at the poles.

- Have the students design an experiment to determine which effect is more important in a given situation, distance or inclination.

- Have the students perform Part 1 of the experiment at various distances from the light bulb, and graph their results. (The x-axis should be labeled "Distance" and the y-axis should be labeled "Change in temperature.") Ask them to first draw a prediction line on the graph paper of what they expect to happen. Then have them plot their data and compare to their prediction. Next have them graph the $1/R^2$ law, and see how well their data fits the theory.

Curriculum Connections

- *Social Studies:* Have the students study how the seasons affect various parts of the world and their people. What kinds of jobs do people have that depend on the climate? How would you feel living at the North Pole? Or at the Arctic Circle? (HINT: At the Arctic and Antarctic Circles (latitude 66.5°), the highest position of the Sun is 47° above the horizon. Here, there is complete sunlight for one day each year, complete darkness for one day each year. At the poles, the Sun's highest position is 23.5° above the horizon. Here, the Sun is seen constantly during half of the year, not at all during the other half.)

- *Art and Design:* Have students draw pictures and/or diagrams of what causes seasons on Earth. They could construct their own three-dimensional model of the Earth to demonstrate the seasons.

- *Astronomy:* Students can examine the cause of seasons on other planets. For example, Mars has seasons that are significantly affected by the large differences in its distance from the Sun during one Mars year as well as by the tilt of its rotational axis, and Uranus has extreme seasons that are 20 years long due to its extreme axial tilt combined with its very long orbital period.

- *Creative Writing:* Have the students write a story about their life if they lived on a planet where there are no seasons.

CLOSING DISCUSSION

Remind students that they have demonstrated that the simple methods of increasing distance or changing the viewing angle can be effective in cooling in the presence of a heat source. Review with students how the tilt of Earth's axis is the cause for the seasons on Earth. Discuss why other planets are warmer or colder than the Earth, using the example of Mercury. Ask the students how they think its tilt (which is close to 0°) would affect the Mercurian seasons. Discuss how space exploration missions like MESSENGER can use the same concepts to make sure the mission is successful.

ASSESSMENT

4 points

- Student set up the experiment in Part 1 correctly, recorded results in Chart 1 on Student Worksheet 1, and graphed the data.
- Student set up the experiment in Part 2 correctly, recorded results in Chart 2 on Student Worksheet 1, and graphed the data.
- Student answered Part 1 and Part 2 questions completely and accurately.
- Student answered "Putting it Together" questions completely and accurately.

3 points

- Student met three of the four criteria from above.

2 points

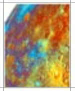
- Student met two of the four criteria from above.

1 point

- Student met one of the four criteria from above.

0 points

- No work completed.



INTERNET RESOURCES & REFERENCES

MESSENGER website

messenger.jhuapl.edu

American Association for the Advancement of Science, Project 2061 Benchmarks for Science Literacy

www.project2061.org/tools/benchol/bolintro.htm

Exploring Mars (Explanation of seasons on Mars vs. Earth)

www.exploringmars.com/science/climate.html

National Science Education Standards

www.nap.edu/html/nses/html/

University of Illinois: DATA (Demonstrations and Animations for Teaching Astronomy)

seasons animation

www.astro.uiuc.edu/projects/data/Seasons/

Views of the Solar System (Obliquity—the tilt of the rotational axis—of the nine planets)

www.solarviews.com/cap/misc/obliquity.htm

ACKNOWLEDGMENTS

The student activity in this lesson was inspired by the NASA SciFiles activity "Nice Angle" (scifiles.larc.nasa.gov/educators/activities/2001_2002/inclass/nice_angle.html), Harvard-Smithsonian Center for Astrophysics' High-Energy Division's "Fun in the Sun" activity "How Angle Spreads Sunlight" (hea-www.harvard.edu/scied/SUN/SunActivities.html#act3), and NASA TOPEX/Poseidon "Visit to an Ocean Planet" activity "Solar Energy and Distance" (topex-www.jpl.nasa.gov/education/activities/ts1enac2.pdf).

DISTANCE AND INCLINATION

Your group will perform two experiments.

The first experiment will measure how distance from a light source (in this case, a light bulb) can affect the amount of heat that an object receives.

The second experiment will measure how the angle (or inclination) at which the light source is viewed (in this case, the Sun) can affect the amount of heat received by an object.

Part 1: Effect of distance

For Part 1, you will have three members in your group. When making the measurements, you will perform different functions:

- "Time Keeper" will operate the stopwatch.
- "Temperature Monitor" will read temperatures in the thermometers.
- "Recorder" will record the results.

Your group will need the following materials for Part 1:

- 2 thermometers
- Desk lamp or flood lamp (without lampshade)
- 2 meter sticks
- Masking tape
- Stopwatch

WARNING

Do *not* look directly at the Sun!

Looking for even a few seconds can cause permanent damage to the eyes!
Note that sunglasses do *not* provide an adequate safeguard against looking directly at the Sun.

So remember to *never* look directly at the Sun!

Name ________________________________

Procedures:

1. Place each meter stick on a table. Place the tables side-by-side so that there is enough space between them to put the lamp, and so that the 0 end of the meter sticks are next to each other. (See Figure S1.)
2. Place the lamp between the tables, as close to the tables as possible. Move the meter sticks so that each 0 cm mark is next is next to the lamp (see Figure S1). Leave the lamp off.
3. Measure 10 cm out from the lamp on one table and tape a thermometer there so that the bulb of the thermometer is facing the lamp. Tape another thermometer at the 50 cm mark on the other table.
4. Record the temperatures of the thermometers to the nearest degree at the "0 minute" line in Chart 1 of this worksheet on Page 5.
5. Turn on the lamp and start the stopwatch. The Time Keeper keeps track of the time and tells the Temperature Monitor when it is time to check the temperature (see Chart 1 on Page 5). The Recorder writes the result in the chart on Page 5.
6. Record your results as indicated on the chart, for 10 minutes.

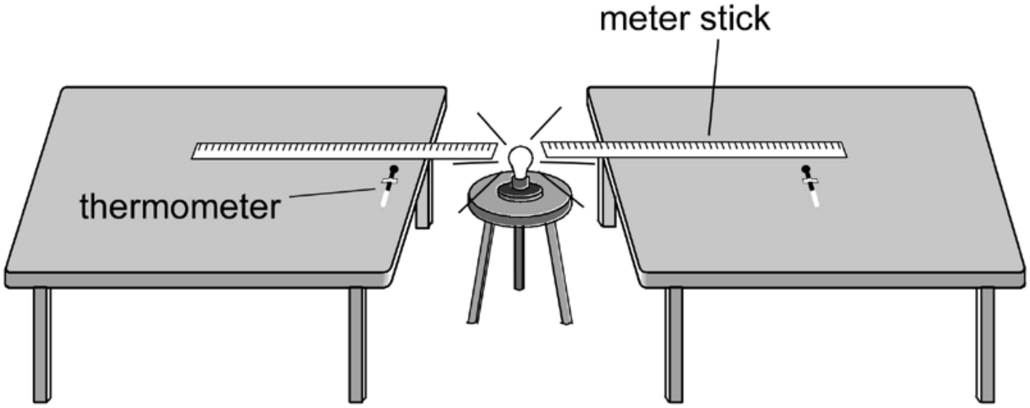


Figure S1. Setup for measuring the effect of distance from a light source.

Part 2: Effect of inclination

For Part 2, you will have five members in your group. One of you will be the Time Keeper for the entire group.

You will need the following materials:

Per student:

- Thermometer
- 1 sheet of black construction paper
- 1 piece of cardboard the same size as the construction paper
- Bricks or blocks to prop up cardboard
- Graphing paper
- Meter stick

Per group:

- Scissors or knife (to cut slit in paper)
- Masking Tape
- Stopwatch
- Colored pencils

Procedures:

1. Cut an inch-wide slit in the middle of the piece of black construction paper. Tape the paper to the cardboard. Place the thermometer into the slit in the construction paper so that the bulb is between the board and the paper, and the scale can be read without removing the thermometer. Tape the thermometer in place, making sure that you can still read the temperature. (See Figure S2, which shows the entire setup for the experiment.)

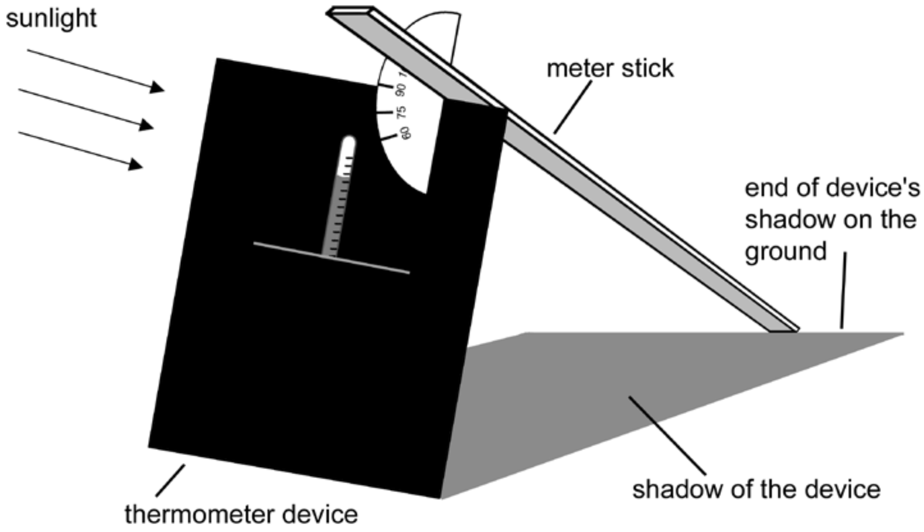


Figure S2: Setup for thermometer device.

2. Cut out the protractor provided for you on Page 8 of the worksheet and fold it along the dotted line. Place the protractor on top of the thermometer device (see Figure S2), and tape the flap down on the construction paper.

3. Bring the thermometer device, meter stick, Student Worksheet 1 and pencil out to the experiment site. Place the thermometer devices in the shade for five minutes so that they read the outside temperature.

4. Set the device on the ground facing the general direction of the Sun so that the slit in the black paper is horizontal with respect to the ground. Place the meter stick so that one end is resting on top of the thermometer device and the other end is at the edge of the device's shadow. The number on the protractor that the meter stick crosses is the angle between the thermometer device and the Sun. This means that when the meter stick crosses 90°, the device is at a 90˚ angle (face-on) toward the Sun. (See Figure S2.)

5. Each student in your group has been assigned an angle at which to monitor the temperature. Adjust the meter stick and thermometer device so that you are measuring the correct Sun angle. (See Figure S2.) *Remember to keep the end of the meter stick at the very edge of the cardboard's shadow.*

6. Use blocks or bricks to prop the cardboard and keep it at the correct angle.

7. Start the stopwatch. The Time Keeper keeps track of the time and tells each student in the group when to check his or her thermometer (every two minutes). Write the result in Chart 2.

8. After 10 minutes, return to your classroom and share your data among your group so that you can fill in the entire Chart 2.

9. Graph your data. Your x-axis should be labeled "Time" and your y-axis should be labeled "Temperature." Pick a color from your pencils to use for marking your own measurements from Chart 2. Once you have plotted your data points, connect them with a line. Repeat plotting for all angles in your group using different colors for each angle.

Chart 1 (Distance):

Time	Temperature of thermometer 1 at 10 cm (˚C)	Temperature of thermometer 2 at 50 cm (˚C)
0 minutes		
1 minute		
3 minutes		
5 minutes		
10 minutes		
Total change:		

Chart 2 (Time):

Time	60°	75°	90° (facing Sun directly)	105°	120°
0 minutes					
2 minutes					
4 minutes					
6 minutes					
8 minutes					
10 minutes					
Difference of angle from facing the Sun directly					

Part 1 – Refer to Chart 1

1. Which thermometer recorded the higher temperature? By how much?

2. Are the results what you expected? Why or why not?

3. How does the amount of heat you feel from a hot object depend on your distance?

4. Think of examples where the distance to a hot object is important.

Part 2 – Refer to Chart 2

1. a) At which angle was the greatest temperature recorded?

   b) What do you notice about the relationship in general between the temperature and the angle between the device and the Sun?

2. Is this what you would expect? Why or why not?

3. How does the amount of heat you feel from a hot object depend on the angle at which you face it?

4. Look at the graph you made. What are your observations of the temperatures at different angles? How does this graph tell you that inclination to the heat source is important?

5. Think of examples where your inclination to a hot object is important.

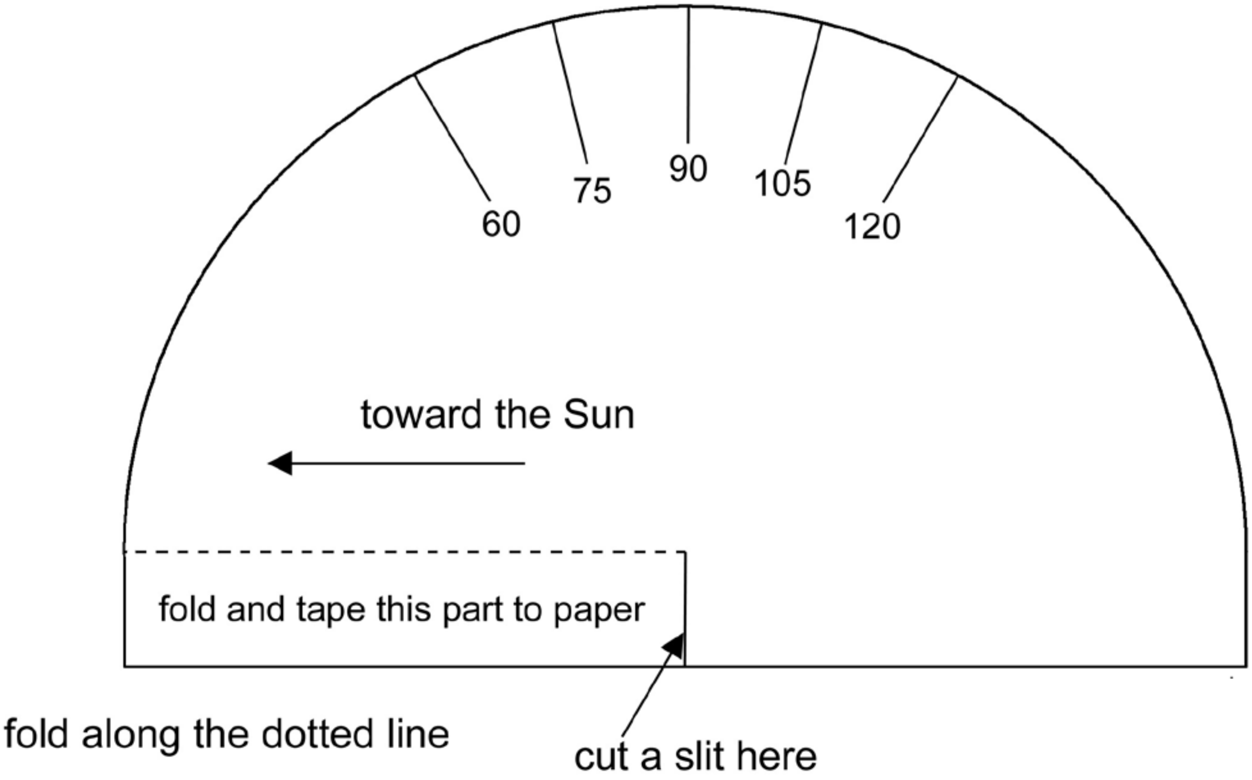
Putting it together

1. Which of these effects (distance or inclination) do you think is more important? Why? Is it always more important?

2. If you had to cool down something that was close to a heat source (like a light bulb, a fire, or the Sun), how would you do it? Based on this experiment, think of two different ways.

3. If you wanted to heat something up very quickly, how would you do it? Based on this experiment, think of two different ways.

Use this protractor to measure the angle between arriving sunlight and the thermometer device.



STAYING COOL WITH MESSENGER

Answer the following questions based on the MESSENGER Information Sheet and the conclusions you drew from your experiments.

1. The MESSENGER spacecraft will study the planet Mercury. The distance from Mercury to the Sun is only one third of the distance from the Earth to the Sun. Why do you think the mission designers are concerned about keeping the spacecraft cool?

2. Think of some ways to keep the MESSENGER spacecraft cool near Mercury, based on what you learned from this experiment.

3. One curious property of the planet Mercury is that its axis is not tilted like Earth's is.

a. How high in the sky does the Sun appear at noon on the equator of Mercury?

b. How high in the sky does the Sun appear at noon at the poles?

4. Observations of Mercury have suggested that there might be water ice in deep craters near Mercury's poles even though the temperatures can get to be over 400°C (750°F) on the sunlit areas of the planet's surface. How do you think it is possible for ice to exist in the craters?

Name ________________________________

ANSWER KEY

Student Worksheet 1

Page 5

Charts will vary according to the students' measurements. Generally, the ending temperature of Thermometer 1 should be higher than that of Thermometer 2 in Chart 1, and the ending temperature at 90° angle should be the highest in Chart 2.

Pages 6-7

Part 1

1. Answers may vary, however Thermometer 1 (the one closer to the light bulb) should have changed more (i.e., have a higher temperature).
2. Answers will vary depending on the students' expectations.
3. The closer you are to a heat source, the more heat you feel.
4. Answers will vary. Examples may include being close to fire, stoves, etc. A wrong answer would be distance from the Sun at various locations on Earth. A correct answer with regard to the Sun would be the distances of different planets from the Sun.

Part 2

1. a) The 90° angle should have the highest temperature rise.

   b) The highest temperature rise occurs when the Sun is viewed face-on. The temperature rise becomes smaller when the difference of the angle from the face-on direction becomes larger.
2. Answers will vary depending on the students' expectations.
3. If you are facing a heat source directly, you will feel more heat than if you are inclined with respect to that source.
4. At all angles, the temperatures rise from their initial value. The temperature at 90° should reach the highest value in the end, the temperatures at 60° and 120°° the lowest (but similar to each other), and the temperatures at 75° and 105° angle should be in between the other values (but, again, similar to each other.) This should tell the students that inclination is a good way to keep the temperatures at a desired level, either cooler (inclined away) or warmer (faced toward the heat source) than they would be otherwise.

5. Answers will vary. Examples may include leaving objects in sunlight, avoiding sunburn, etc.

Putting it together

1. Answers will vary. It depends on the situation as to which is more important. For example, distance is more important if the change in distance is large (as with distances of planets from the Sun) but inclination is more important if the change in distance is small (as with Earth's seasons).
2. Answers may vary. However, the two ways demonstrated in this lesson are to move the object far away from the heat, and to incline the object with respect to the heat source.
3. Answers may vary. However, the two ways demonstrated in this lesson are to bring the object as close to a heat source as possible, and to angle the object so that it is directly facing a heat source.

Student Worksheet 2

Answers given below are based on the solutions used by the MESSENGER mission. The students may come up with other solutions—some of them may not work, but some might work quite well!

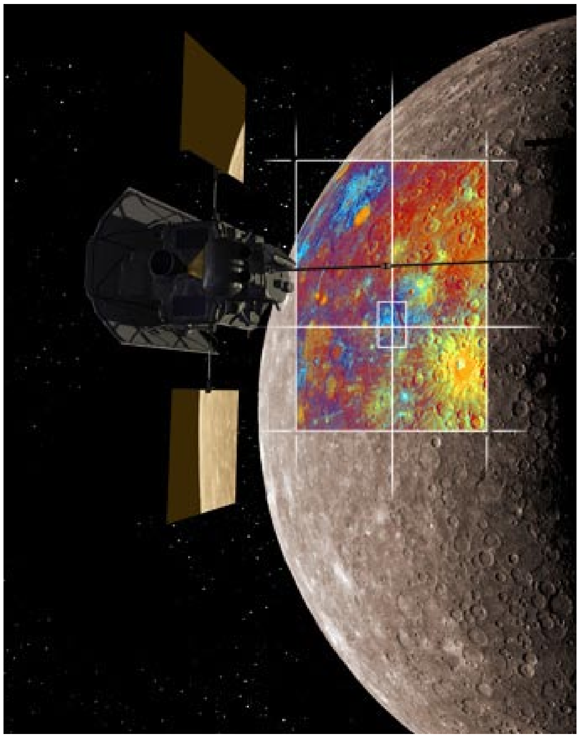
1. Mercury is so close to the Sun that the spacecraft will be exposed to much more sunlight than it would on Earth. This creates a high-temperature environment which can be dangerous to the spacecraft.
2. Answers may include: MESSENGER's orbit around Mercury is designed so that it is never very close to the hottest part of the planet's surface and so that it flies over the sunlit regions quickly. The solar panels are inclined when they face the Sun so that they don't heat up too much. (Note that you cannot change the distance from the Sun in this case effectively.) The solar panels are also partially covered with mirrors, but this is not discussed in the lesson, so the students will probably not know this. These are mentioned in the MESSENGER Information sheet, so the crucial point is in how well the students can explain the reasoning. The Information Sheet also mentions the sunshade—but it does not use the concept of cooling by distance or inclination, so it is not a correct answer to this question.

3. a) The Sun appears to be directly overhead at noon each day.

   b) At the poles, the sunlight always arrives at a grazing angle—the Sun just appears to crawl around the horizon all day, every day, all year round.

4. The low angle at which sunlight arrives at the poles means that there are craters on the surface whose bottoms have never seen sunlight. It is possible water ice could exist in these regions even if the temperatures in sunlit areas are high.

MESSENGER INFORMATION SHEET



The MESSENGER Mission to Mercury

MESSENGER is an unmanned U.S. spacecraft that was launched in 2004 and will arrive at the planet Mercury in 2011, though it will not land. Instead, it will make its observations of the planet from orbit. MESSENGER will never return to Earth, but will stay in orbit around Mercury to gather data until the end of its mission.

MESSENGER is an acronym that stands for “**ME**rcury **S**urface **S**pace **EN**vironment, **GE**ochemistry and **R**anging,” but it is also a reference to the name of the ancient Roman messenger of the gods: Mercury, who, it was said, wore winged sandals and was somewhat of a trickster.

MESSENGER will be the second spacecraft ever to study Mercury; in 1974 and 1975 Mariner 10 flew by the planet three times and took pictures of about half the planet’s surface. MESSENGER will stay in orbit around Mercury for about one Earth-year, during which time it will make close-up and long-term observations, allowing us to see the whole planet for the first time.

One of the biggest problems MESSENGER will face is the intense heat it will encounter at Mercury. Visible and infrared radiation from the Sun can be 11 times as strong as in space near Earth. Infrared radiation from the hot, sunlit side of Mercury’s surface becomes a second significant source of heat for the spacecraft. MESSENGER engineers have had to come up with various solutions for keeping the spacecraft from heating up too much. They have designed a sunshade which will be pointed at all times toward the Sun, so that MESSENGER’s instruments observing Mercury are always in the Sun’s shadow. MESSENGER’s orbit has been designed so that it does not get close to the hottest regions at Mercury’s surface, and the spacecraft’s solar panels are angled so that they do not look to the Sun face-on but are still able to generate sufficient power to the spacecraft.

For more information about the MESSENGER mission to Mercury, visit: messenger.jhuapl.edu/