Document ID: 03_18_08_1
Date Received: **Date Revised**: **Date Accepted**:
Curriculum Topic Benchmarks: S1.3.5, M3.3.7, M3.3.14 M3.3.12, M4.3.3, M4.3.14
Grade Level: Middle School [6-8], High School [9-12]
Subject Keywords: solar energy, temperature, season, tilt, inclination
Rating: Moderate

Why is Summer Hot?

By: Stephen J Edberg, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, M/S 301-486, Pasadena CA 91011
e-mail: Stephen.J.Edberg@jpl.nasa.gov

From: The PUMAS Collection http://pumas.jpl.nasa.gov

It is quite common for people to believe that summer is warmer than winter, basing the explanation on the belief that Earth is closer to the Sun during the summer than in the winter. Even a sizable fraction of Harvard graduates carry this belief (Schneps, 1987, mentioned in Green, 2003). In reality, this is exactly opposite the situation in the northern hemisphere. The separation of Earth and Sun is greatest at the beginning of July and least at the beginning of January. More direct sunlight and the greater duration of daytime in summer months makes summer warmer than winter. This activity, effective outdoors or indoors, will demonstrate how more direct sunlight leads to seasonal temperature variations.

This activity demonstrates how insolation is affected by latitude by using a pair of thermometers, each taped to some cardboard, placed outside on a sunny day. A globe can also be used, outdoors or indoors.

OBJECTIVE: Understand seasonal variations in temperature are the result of the heating of the Sun as a function of its peak angle and length of the day.

APPARATUS:

(1) Two **laboratory thermometers** that can be read to 1˚ C.
(2) **Corrugated cardboard** strip, long enough and wide enough to mount two thermometers to it lengthwise (Fig. 1). Approximate length 1 m, width 5 cm. The corrugation should be parallel to the width of the strip, so folding the cardboard makes a hinge. A more elaborate and permanent design can be made with materials such as wood or plastic, with good metal hinges, if desired.
(3) **Tape** or other material (aquarium cement, for example) to fix the thermometers to the cardboard backing (or the globe, below).
(4) **Short flat head nail** (optional), about 5 cm long, to indicate the orientation of a thermometer towards the Sun by minimizing its shadow.

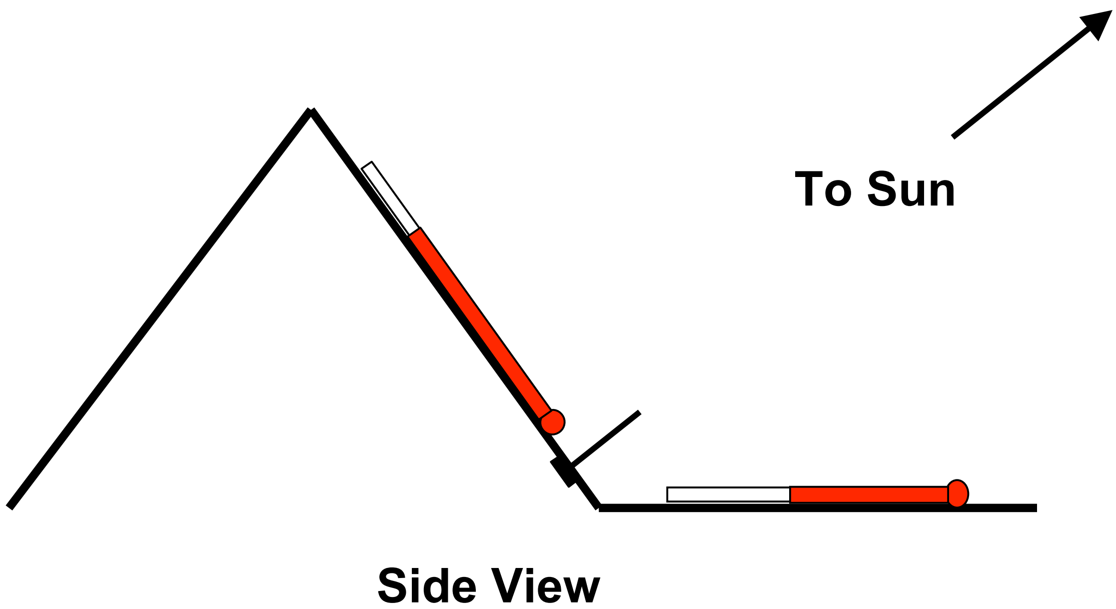

Fig. 1. This side view shows the cardboard thermometer mounting strip in its measurement position. Thermometers are attached to the middle section and the ground section. The prop section holds the middle section so it intercepts maximum sunlight. A (stylized) nail is pushed through the cardboard below the middle section's thermometer for use in orienting the assembly directly towards the Sun by minimizing the nail's shadow. Dimensions are roughly 30 cm per section but they only need to surround and protect the thermometers with some margin; size the strip and its sections based on the length of the thermometers.

(5) **Globe** (12 inch [30 cm] or greater diameter); optional. A large ball can also be used, but having oceans and continents visible reduces the abstraction of this demonstration.

(6) **Cardboard sheet,** optional, with a circular hole closely matching the diameter of the globe. This will be used to provide a plane to mimic the horizon.

(7) **String,** optional, length somewhat greater than one-half of the circumference of the globe (i.e., > π x [globe radius]).

(8) **Ruler** or **meter stick** for measuring the length of the string.

(9) Five (or more) **small thermometers** (no larger than 2-4 cm length), optional. The small thermometers are attached to the globe at the equator and at two higher latitudes in each hemisphere. Aquarium and pet stores sell small LCD thermometers (with limited temperature range, so test one first to confirm the temperature range is adequate). Very short dyed-alcohol thermometers can also be found.

(10) **Desk lamp with tungsten bulb** (optional, to do this experiment indoors during inclement weather). Fluorescent and LED lamps do not emit enough heat (they're too efficient at generating light!) to warm the thermometers.

PROCEDURE:

Fold the cardboard strip into three sections, roughly equal in length (Figure 1). One end section becomes the prop to hold the middle section thermometer oriented toward the Sun. The other end section is the "ground section" that holds a thermometer flat on the ground. Attach the thermometers to the middle section and ground section with tape, giving them a few centimeters of space from the ends of their sections. A short nail, if desired, can be pushed through the back of the middle section. Avoid interference with the thermometer or shadowing the thermometer during the experiment.

Lay the cardboard strip on the ground with the ground section end towards the Sun. Elevate the middle section with the prop section. Use the shadow of the nail to check the orientation. When the nail's shaft shadows only itself, not the cardboard, the middle section is perpendicular ("normal") to the direction to the Sun. Give the thermometers a chance to equalize: each thermometer's working fluid should settle at one temperature, after a minute or so. Observe that the propped thermometer is much warmer than the one on the ground.

Caveats: This demonstration is much more effective on cold sunny days than on warm sunny days. It is better done early or late in the day when the Sun is closer to the horizon, not around noon. On warm days and at mid-day heating by conduction from the ambient air can reduce the apparent difference between warming caused by sunlight radiating directly onto a thermometer and warming due to sunlight falling at an angle.

You can actually do this experiment indoors on a rainy day if you use a good spotlight (make sure you use a tungsten bulb, not fluorescent or LED) equidistant from the two thermometer bulbs with the geometry otherwise copying natural solar illumination.

<u>Variation</u>: Use some small thermometers and a globe. Tape small thermometers to the equator, to similar mid-latitudes in both hemispheres, and to similar polar latitudes in both hemispheres on the same meridian of longitude on the globe. Illuminate the globe with sunlight outdoors or with a close spotlight or desk lamp indoors; make sure you use a tungsten bulb, not fluorescent or LED.

Start with artificial or actual sunlight falling on the equator (vernal and autumnal equinox). (If artificial lighting is being used, maximize the distance between source and globe. This minimizes the warming resulting from the globe's bulge [due to its spherical shape] being closer to the lamp.) Allow the thermometers to equilibrate (probably less than two minutes for LCD thermometers). The difference in temperatures at different latitudes will be apparent. Now tilt the globe with one pole towards the light source (or move the lamp) and wait for the thermometers to equilibrate again (Figure 2). The hemisphere getting more direct light (summer solstice) will be warmer than before while the thermometers in the opposite hemisphere will be cooler. Repeat with the same pole tilted away (winter solstice) from the source. The thermometers will change their temperatures to match the change in desktop-season. Since the distance from light source to globe has not changed, the changes in temperature must be due to the angle of the sunlight falling on the thermometers, and hence Earth's surface.

It is important to point out that Earth does not change its orientation with respect to the stars; its rotation axis always points towards Polaris, the North Star. Earth's orbital motion makes the Sun change its apparent maximum height at local noon as Earth goes around the Sun annually. This is due to the tilt of Earth's rotation axis with respect to the plane of its orbit around the Sun (Figure 2).

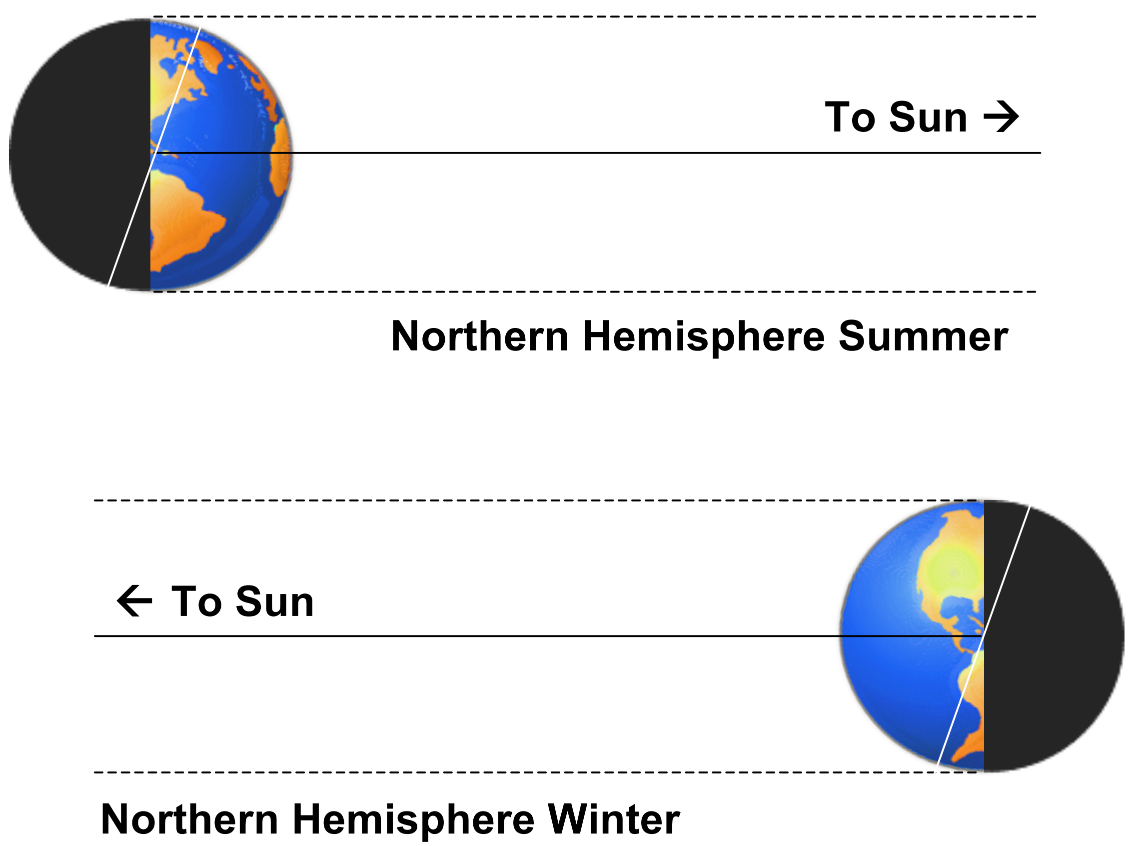

Fig. 2. Earth's hemispheres experience summer and winter on opposite sides of Earth's orbit around the Sun. The tilted white line represents Earth's rotation axis, which maintains the same orientation (towards the North Star, Polaris) as Earth goes around the Sun. During northern summer, the northern hemisphere is tilted towards the Sun and receives more direct sunlight. The north polar region is in continuous sunlight. During northern winter, on the other side of Earth's orbit, the northern hemisphere is tilted away from the Sun and receives less direct sunlight. The north polar region is in continuous night.

THE UNDERLYING PRINCIPLES:

Solar energy falls on Earth's surface and is absorbed, warming the surface. If the energy falls with an angle of incidence that is not perpendicular (i.e., not normal) to the surface, the energy is spread over a larger area and will not warm the surface as rapidly. This is illustrated in Figure 3. At the equator during the vernal and autumnal equinoxes sunlight falls straight down on the surface. Sites at latitudes off the equator experience different levels of less-direct illumination. They always have the same amount of energy, per unit area coming from the Sun, but it is spread over a larger area than at the equator. The increase in area is a function of the latitude, φ. The length of the side of the triangle, h, represents the increase in area due to the latitude. Assuming a square with a 1 m side, the definition of cosine tells us that

$$h = 1/(\cos \varphi) \qquad (1)$$

The **Extension** describes how to make a paper cylinder that illustrates the size of the illuminated area off of the equator.

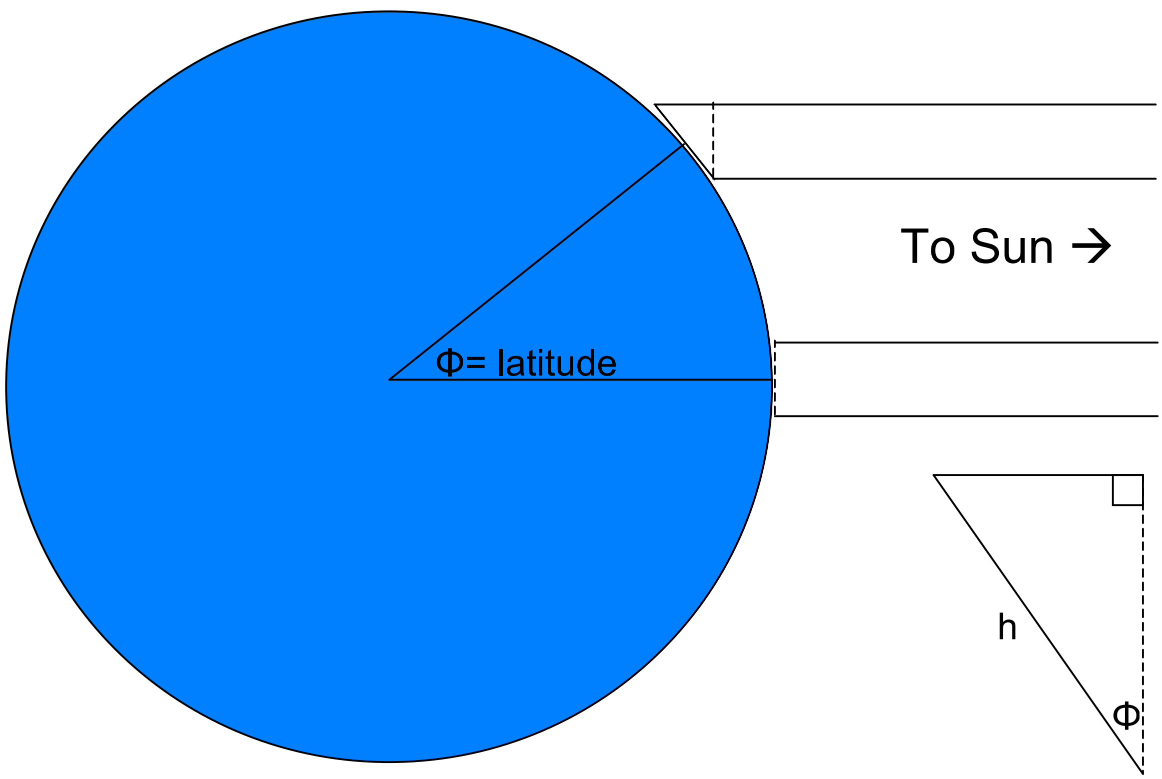

Fig. 3. An area on Earth's surface intercepting solar energy is warmed by it. If the receiving area is tilted with respect to the incoming rays, a larger area is warmed by the same amount of energy, so it warms more slowly. Higher latitudes warm more slowly than the equator. The triangle in the lower right is an enlargement of the high latitude triangle. The hypotenuse, h, is representative of the increase in area intercepting energy, compared to the equatorial value represented by the dashed line.

DISCUSSION:

More direct sunlight falling on a hemisphere warms it more than less direct sunlight. The duration of daylight also plays a role: longer days mean more sunlight and more warming during the summer. Longer days can be demonstrated with string and a horizon plane (one may be built right onto your globe stand, or it can be made from cardboard). Figure 4 illustrates on flat paper three situations (that are better demonstrated with the globe) and are described below.

Set up the plane so the globe's center is in the plane. The orientation of the plane should be varied: try the measurements described with the Earth's (globe's) poles in the horizon plane, with the horizon plane at some angle between the poles and equator, and the equator in the same plane as horizon plane. These positions correspond to an observer placed on the equator, placed at a middle latitude, and placed on the North Pole or South Pole (be sure to specify which during the demonstration and discussion).

For each position of the plane, use the string and a ruler or meter stick to measure the length of the latitude arc from one side of the horizon plane to the other. Lay the string along the "great circle" of the equator and along the "small circles" at 23.4˚ north and south of the equator (the Tropic of Cancer and the Tropic of Capricorn, respectively).

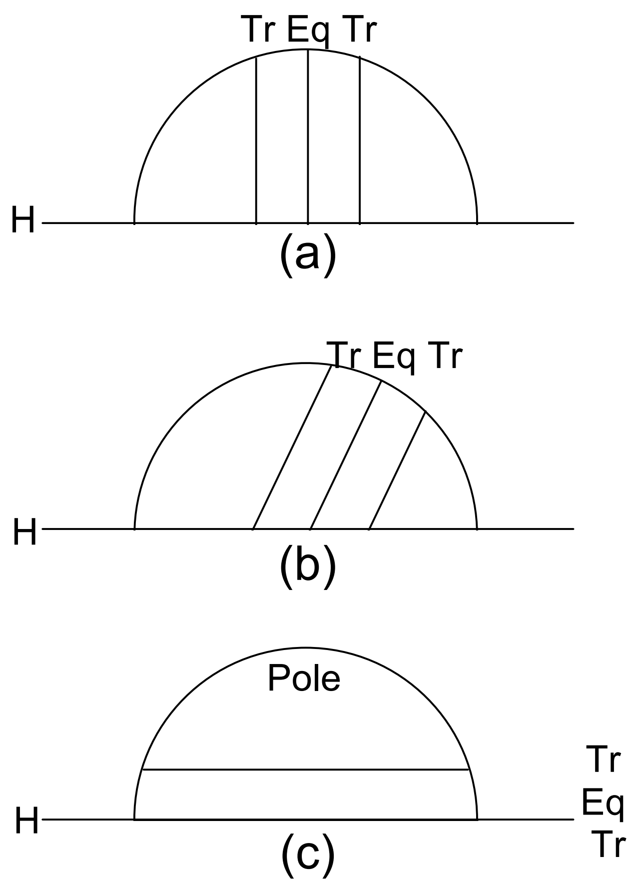

Fig. 4. In these three side-view perspectives, the horizon plane (H) for an observer on Earth's surface is represented by the horizontal line. The observer can see the sky above the plane while Earth blocks the view below. The equator (Eq) is centered between the Tropics of Cancer and Capricorn (Tr), represented by the three parallel lines (actually circles on a spherical planet). The Sun's position in the sky is limited to the span of the Tropics. (a) An observer on the equator would see the Sun during the day following an arc across the sky somewhere in the zone between the Tropics. Its daily arc from sunrise to sunset, at either Tropic extreme (solstice), is somewhat shorter than when it is above the equator. (b) An observer in temperate latitudes would observe the Sun following a daily arc much longer during the summer than during the winter, illustrated by the differing lengths of the Tropic lines above the horizon line (plane). (c) An observer at a pole sees the Sun continuously, at heights ranging from the horizon to the height of a Tropic line, for six months of the year. The Sun is not visible for the other six months of the year.

EXTENSION:

1) Students can construct a cylinder with a square cross-section to illustrate the effect of changing the angle of illumination (Figure 5 and Student Construction Sheet at the end of this activity). Inspection will immediately show that the area of the square end of the cylinder is smaller than the area of the end which has been sliced off at an angle. Alternatively, the square end can be placed on the rectangular portion of the discarded section to compare the areas.

The areas of the open ends of the cylinder can be calculated by measuring the length and width of the square (length = width) and of the rectangle and multiplying them:

$$\text{Area} = (\text{length}) \times (\text{width}) \qquad (2)$$

Divide the area of the rectangle into the area of the square to see the ratio of the areas.

$$\text{Area Ratio} = (\text{area of rectangle})/(\text{area of square}) \qquad (3)$$

To see the effect of the increased area at high latitudes, divide the Area Ratio into the solar constant (i.e., the solar energy per unit area reaching the top of Earth's atmosphere), 1.37 kW/m^2 (Bishop, 2007):

$$\text{Solar Energy Flux at Latitude} = 1.37\ [kw/m^2]/(\text{Area Ratio}) \qquad (4)$$

The solar energy will be less than 1.37 kW/m^2 for any latitude off of the equator.

For a more mathematically advanced treatment of the situation the angle of the slice can be measured with a protractor or it can be calculated by measuring the length and width of the rectangular opening (since the cylinder is a square). The computed angle is:

$$\text{Angle} = \sin^{-1}(\text{width}/\text{length}) \qquad (5)$$

The angle from (5) can be used with Equation (1) and the solar constant to determine the insolation at the latitude demonstrated by the square cylinder.

2) According to Kaufmann (1991), Earth's

Mean distance from the Sun:	1.496×10^8 km
Maximum distance from the Sun:	1.521×10^8 km
Minimum distance from the Sun:	1.471×10^8 km

Students can calculate the percentage difference in Earth's distance compared to its mean distance. The answer is 1.7%, a small amount compared to the effect of illumination angle and duration of daylight between summer and winter solstices and the equinox everywhere except for a narrow band centered on the equator. (How narrow is the band?)

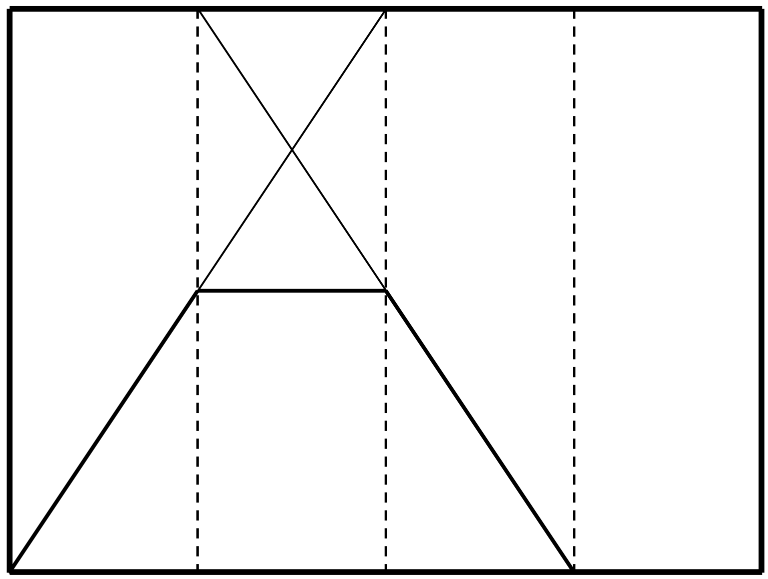

Fig. 5. Students can prepare a regular 8.5”x11” piece of paper to explore the effects of the angle of illumination on heating. Three folds are made (along the dashed lines) and two diagonal lines are penciled in (solid lines). Scissors are used to cut along the bold lines. See the Student Construction Sheet at the end of this activity for detailed instructions.

REFERENCES:

Bishop, R., 2007, “Some Astronomical and Physical Data” in *Observer’s Handbook 2008*, P. Kelly, ed., Royal Astronomical Society of Canada, Toronto.

Green, P. J., 2003, *Peer Instruction for Astronomy*, Pearson Education, Inc., Upper Saddle River, NJ.

Kaufmann, William J, *Universe*, 3rd Edition, W.H. Freeman, 1991.

Schneps, M. H., 1987, *A Private Universe*, a film available from Pyramid Films and Video, 2801 Colorado Avenue, Santa Monica, CA 90404.

ACKNOWLEDGMENT:

This publication was prepared by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

STUDENT CONSTRUCTION SHEET

To construct a square cylinder: First fold the paper into quarters along the dashed lines. Start by making the middle fold. Open the sheet. Now fold each outer edge inwards to the first fold. All the creases should be “hinged” to bring the paper faces together in the same direction.

With a ruler, draw straight diagonal lines across two quarters of the paper, as shown. Draw a connecting straight line from the intersection of the creases and the diagonal lines.

Use scissors to carefully cut the diagonal and connector lines.

Fold the outer two sections in to the original center-crease and tape them to each other at the top and bottom. Open the flattened paper into a cylinder with a square cross-section.