11.2: The Tilted Axis Model of the Seasons

The tilt of the Earth's axis is one of those 'gradual discoveries' that have their origins in antiquity and crop up independently in many cultures. Study of the ***ecliptic*** – the path of the Sun across the sky each day, and the observation of the zodiacal constellations are just two ways in which can discover the tilt of the Earth's axis. One can also do this with nothing more than a vertical stick and a bit of string, observing the angle created by the shadow cast by the stick and how it varies through the year. These observations from cultures around the world date back at least 3000 years, if not more.

Discovering that the Earth's axis it tilted is quite different from discovering how that fact fits into a coherent model of the solar system. Copernicus was the first modern scientist who discussed how the tilt of the Earth's axis fitted into a scientific model of the solar system. It wasn't until Tycho Brahe made extremely precise measurements of the position of the Sun, Moon, and planets in the sky and Johannes Kepler put those observations into the context of an exact mathematical model that we understood, and measured, the tilt of the Earth's axis with modern precision.

Academic Standards

Science and Engineering Practices

- Asking questions and defining problems.
- Developing and using models.
- Planning and carrying out investigations.
- Analyzing and interpreting data.
- Using mathematics.
- Constructing explanations.
- Argument from evidence.

Crosscutting Concepts

- Patterns in nature.
- Cause and effect.
- Systems and system models.
- Energy flows, cycles, and conservation.
- Stability and change.

Next Generation Science Standards

- Space systems (K-5, 6-8, 9-12).
- Structure and function (K-5, 6-8, 9-12).
- Waves and electromagnetic radiation (6-8, 9-12).
- The Earth-Moon system (6-8, 9-12).
- Gravitation and orbits (6-8, 9-12).

For the Educator

Facts you need to know

1. The Earth's axis is tilted 23.5 degrees with respect to the Sun's equator which is also the plane of the solar system.
2. The direction in which the Earth's axis points in space ***does not change***. We can tell this because the location of ***Polaris***, the northern pole star, does not change in the sky.
3. Since the direction of the Earth's axis in space does not change, we find that sometimes our hemisphere is ***tilted toward the Sun***; while at other times of the year, our hemisphere is ***tilted away from the Sun.***
4. It is the ***change in solar angle*** which causes the change in the seasons and our weather – not the distance between the Earth and the Sun.[1]

Teaching and Pedagogy

It was known from ancient times that the ***ecliptic*** – the line in the sky which describes the path of the Sun, the Moon, and all the planets as well as the constellations of the zodiac – was tipped at an angle to the line of the celestial equator. There were numerous different explanations for this, none of them particularly noteworthy. Only with the modern idea of the spinning Earth put forward by Copernicus was the proper explanation of the ***celestial poles*** and the ***celestial equator*** arrived at. The cosmos has no natural pole or equator – it is the spinning Earth that defines them for those of us who live here. If you lived on another planet like Mercury or Mars, there would be different pole stars and a different celestial equator!

The modern concept of the Earth's tilted axis being a primary cause of the seasonal changes was developed after Copernicus published his heliocentric theory in 1543. When Copernicus realized that it was the spinning Earth that in effect created the celestial poles and equator, it was a short leap to realize that all the planets orbiting the Sun in the same plane creates the ecliptic. Our solar system is essentially flat, with all the planets orbiting essentially in the same plane. This is not a coincidence and physics gives us good reason to expect that this should be so, but we must leave that explanation for another time!

In effect, it is the motions of the Earth, both spinning on its axis and orbiting the Sun, that make the motions of all the objects in the sky appear as they do. The brilliance of Copernicus was that he was able to look at the sky with just his eyes and deduce what the motions of the stars, Sun, and Moon told him about how the Earth moves and spins through space. One must learn a good bit about astronomy to appreciate the genius of Copernicus! For your classes, the important part to remember is that Copernicus hypothesized that it was indeed the tilt of the Earth's axis that caused the change in the seasons – not the change is the distance from the Earth to the Sun! This next activity will focus on modeling that idea and seeing what predictions our new model makes.

Student Outcomes

What will the student discover?

1. This is yet another occasion where we see what seems to be a reasonable hypothesis turn out to be wrong. The idea that summer weather happens when Earth is closer to the Sun seems reasonable and sound, but in fact it isn't true.
2. It is important to help guide your students' thinking here. The children may be frustrated with finding their idea was not correct. It is important to emphasize that the ***process of science*** is working, even if the hypothesis does not.

What will your students learn about science?

Our two models of the changing seasons have done something new and amazing. Our models have advanced our knowledge in a new way by helping us to decide between two scientific theories. This point cannot be emphasized too strongly! We had two perfectly interesting models of how the solar system worked. Each of these models made predictions. A single experiment proves that one model's predictions are correct while another model's predictions are false.

As a result of what we have learned through experiments, we now know that one model should be kept while the other must be discarded. There is nothing here about politics, nationalities, fairness, beauty, simplicity, or even what we may or may not like; this is ***all about the data***. We do not do science to ***prove we are correct***; rather, we do science to ***become correct***.

One of our models correctly explains nature to us, it has more to teach us, and we should be able to continue to modify it and add new features to it as we learn even more. The other model cannot continue to lead us in the right direction, it cannot tell us new and interesting things. It is a misstep, a scientific misunderstanding; quite simply, it is incorrect and must be discarded.

There have been many times that learned men and women have become attached to a particular theory or model. The favored model is what people learned from their teachers when they were in school. As adults, these people may have taught young students about their favorite model with complete confidence for many years.

Sometimes models are beloved because they fit well into our culture, or our religion, other times leaders favor one model over another because it fits better with their political ideas about the world. In the end, none of these things matter, but the ***truth*** does matter. This is why Galileo was willing to go to prison rather than abandon the scientific model of Copernicus and the Sun-centered solar system.

At his trial, Galileo was given the alternative of a horrible tortuous death, or life in prison. In order to escape a terrible death, the Inquisition made Galileo kneel and publicly renounce everything he had learned about the solar system. Galileo was made to say that Copernicus was wrong, that the Earth was the center of the solar system, and that it was fixed in place and unmoving in the heavens. When his guards helped the old man rise from his knees to lead him away to prison, Galileo was heard to say: ***"Eppursimuove"***, (And yet, it moves.) With his last breath as a free man, Galileo paid homage to the truth; *simuove*, indeed.

Conducting the Activity

Materials

1. One ping-pong ball and poker chip
2. One large paper clip
3. One round toothpick
4. A length of string – about 12-inches.
5. Super glue
6. Wire cutters (The type known as diagonal cutters work best. Check with your custodian first, if they do not have one, your local home improvement store will.)
7. Regular pliers
8. One large sewing needle
9. Emery board or fine sand paper
10. Ping-pong Sun model
11. Construction paper (light colors work best)
12. Markers, paints, etc.

Building the Tilted Axis Model of the Seasons

1. Have your students decorate another ping-pong Earth model using paints or markers, but this time, we include the entire planet instead of just half of it. A coating of clear sealer will probably be helpful after they are finished.
2. **[Teacher]** Put a dot at the north and south poles of each model Earth. Hold the needle with the pliers and heat it well with a candle flame, then poke a hole in the ping-pong ball at the north and south poles.
3. Unfold your paper clip so that it is bent almost at a 90o angle, then the teacher uses the wire cutters to cut the paper clip as shown to make an axis for your model. Use super glue to attach the axis to the poker chip.
4. Use the wire cutters again to snip the last ¼-inch off of a round toothpick. Sand the cut end flat and glue it onto your ping-pong Earth wherever you live. This will indicate not only your location on the globe, but it will point to the zenith (straight up) in your location.
5. Slip the Earth model onto the paper clip axis you have prepared for it – your tilted Earth model is now complete.
6. Now trace a large circle on your construction paper to represent the Earth's orbit. You can do this with a classroom compass or simply trace around a plate or a bowl. While it is true that all planetary orbits are elliptical, Earth's orbit is so nearly circular that our distance from the Sun varies by less than 5% at any time of year!

Exploring the Tilted Axis Model of the Seasons

1. Place the Sun in the center of your circle and the Earth on its circular orbit with the axis pointing toward the Sun. This represents the ***summer solstice*** and longest day of the year, June 21st; label this point on Earth's orbit as ***Summer***.
2. Advance anti-clockwise 90-degrees in orbit (¼ of the way around the Sun) and mark this position ***Autumn***, another 90-degrees brings us to ***Winter***, and the last position will be ***Spring.*** Label these locations on your construction paper orbit.
3. The important thing to remember when using this model is that the Earth's axis ***always points in the same direction***. We know this is true because the ***North Star*** never changes – if Earth's axis always pointed at the Sun, the pole star would change from month to month as our axis pointed to different directions out in space! If students do not understand why the Earth's axis stays pointed in one direction, it may be helpful to demonstrate the concept to them using a toy ***gyroscope***. When you spin the gyroscope, it will balance on the tip of your finger; move your finger how you will, the axis always points in the same direction, just as the Earth's axis does in real life!
4. After the students have had a chance to familiarize themselves with the model and see how the little toothpick representing their location spins on its axis, it is now time to use our piece of string to look at something important – the solar angle. Begin in the ***Summer*** position (the Earth's axis is pointing ***toward the Sun***) and spin your Earth model so that the toothpick also points toward the Sun. Your model now represents noon on mid-summer's day.
5. With your eye down near the table level, stretch the string horizontally from the Earth to the Sun; the string represents our horizon. Now look at the angle ***between the string and the toothpick***, this represents how high the Sun is off the horizon at noon on mid-summer's day. Make a note of this angle; older students may wish to estimate the angle using a protractor or cut a wedge of construction paper that fits this angle.
6. Now move your Earth around to the Winter position and use the string to measure the angle of the Sun off the horizon once more. The angle between the Sun and the horizon is ***significantly less!*** Our tilted Earth model has just made a new prediction: The angle of the Sun on the horizon should change with the seasons.

Discussion Questions

1. This model makes a very specific prediction about the distance between the Earth and the Sun – what is it? How do we know if this is true or not?
   - **Answer** A circular orbit predicts that Earth's distance from the Sun will not change through the year – and the size of the Sun's disk in the sky will also be consistent. We do not see the Sun changing in size in the sky from winter to summer indicating that this model is probably correct!
2. What actually does cause the change in the seasons?
   - **Answer:** The tilt of Earth's axis causes seasons to change. In the northern summer, our hemisphere is tilted toward the Sun, while in the winter months we are tilted away from it.
3. We hear that the seasons in the southern hemisphere are reversed from our northern hemisphere, winter in July, summer in December! Could our tilted axis model account for this?
   - **Answer:** Yes. When the northern hemisphere is tilted toward the Sun, the southern hemisphere must be tilted away. This effect accounts for the reversal of the seasons. This was first discussed in writing by Herodotus, a Greek historian in about 450 BC.

Supplemental Materials

Going Deeper

Can we add actual sunlight to our model? This little addition to activity #30 can be done in two simple ways, both amount to the same thing. Perhaps the easiest way is to use a flashlight. Darken your room a bit, and place the flashlight on the table so that it shines horizontally on the tilted Earth model – the flashlight will stand in for the Sun in this case. Adjust your model so that the Earth's axis is tipped directly toward the flashlight and rotate the Earth model slowly in an anti-clockwise direction. You will notice that the toothpick rotates gradually into the light (sunrise) and travels across as the Earth rotates until it disappears back into the darkness (sunset). Note how far you have to rotate the Earth between sunrise and sunset, this represents the hours of daylight that you experience.

Now adjust your Earth model so that the axis is tipped directly away from the flashlight. This represents the axis of the Earth tilted away from the Sun during the winter months. Once again, rotate your Earth model and see how far you must rotate the Earth to go from sunrise to sunset. If you have done everything carefully, you will notice that the length of the day in the winter months is significantly shorter that those in the summer months.

Ask your students how early it gets dark around Christmas time, and how long the night is before Christmas morning. Then ask them how long they have to wait to see fireworks on the 4^{th} of July! They will quickly realize that the predictions of the model fall in quite nicely with their own experiences – and explain how these changes in the length of daylight and darkness happen as we move through the year!

If you do not have a flashlight or do not want to dim the lights in your room, you can do this activity another way. Take a 3×5 index card (a piece from a manila folder will do) and cut out a U-shape just large enough to fit over the Earth model (and the attached toothpick!) and allow it to rotate freely. The cardboard represents the boundary between daylight and darkness. The side of the Earth that faces the Sun model is in daylight, the portion of our model on the other side of the card represents darkness. When the toothpick moves past the card onto the sunlit side, it is in daylight, and when it passes back onto the far side of the card, it will be in darkness. The change in the hours of daylight will be seen just as easily.

Being an Astronomer

Remember the ***Solar Clock and Calendar*** we built way back in Activity #1? Have you been keeping up with your observations? If you have, you are in for a wonderful experience! Any line from the tip of the gnomon stretched down to the tip of the shadow, shows the precise angle of the Sun in the sky. You can demonstrate this with one of the small student sundials and a flashlight in the classroom. Shine the light so that the pencil casts a shadow down onto the edge of the cardboard. Hold the light steady and stretch a string from the tip of the pencil down to the tip of the shadow – you string points directly back to your light source!

Have the students take their sundials and stretch a string from the pencil tip down to the first dot made back in September, then stretch the string to each dot in succession. The angle gets shallower until mid-December, then begins to increase again as you move into the spring months. Your solar clock and calendar ***proves by experiment*** that our tilted axis model of the Earth is correct.

The prediction made by the tilted axis model (the Sun's angle will change through the seasons) has been confirmed, while the prediction made by the original model (the Sun's angle will not change through the year) has been disproved.

Being a Scientist

Can you measure the angle of the Earth's axis with as much precision as Tycho Brahe and Johannes Kepler did in the 17th century? Potentially, all you need is a vertical stick and a protractor. If you know how to do some trigonometry, you can do this with just a vertical stick and a tape measure?

You will need to measure the angle of the Sun by measuring the angle between the tip of the shadow and the top of the vertical stick. You will need to do this on two different days, and at the ***same time*** of day. The required days are the ***winter solstice*** (December 21st) and the ***summer solstice*** (June 21st).

One these days, when the shadow falls perfectly along a north-south line, the Sun is crossing the ***meridian*** or center line of the sky. On the winter solstice, the Sun will be at its lowest angle above the horizon; while on the summer solstice, the Sun will be at its highest angle in the sky.

These two angles represent the extremes in the Sun's angle above the horizon. Keep in mind that in summer, we are tilted ***toward the Sun***, while in the winter we are ***tilted away from the Sun.*** By calculating the difference between these two angles – and then dividing the difference in half – we will measure the tilt of the Earth's axis.

The tilt of the axis measured by Tycho and Kepler is 23.5 degrees – meaning that the total difference in the solstice angles is 47 degrees. How close did your students come to this measurement?

Following Up

There are many good documentaries on Copernicus, Tycho, and Kepler. Find one of these videos to show in your class!

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1. The Earth's orbit is elliptical, meaning that the Earth is sometimes closer to the Sun, sometimes farther away. Even though the Earth's orbit is elliptical – the orbit is almost circular – the difference in the distance from Sun to Earth is very small, less than 1%, this change has virtually no effect on our weather. In fact, in the northern hemisphere, the Sun is closer to the Earth in the winter than in the summer! ↵
