SCHOOL LAUNCH · EARTH SCIENCE K–8

Grade 5 Earth Science: The Sky: Sun, Moon and Stars

A year of true stories about the sky, from Eratosthenes measuring the earth with a shadow and Galileo turning his telescope on the mountains of the Moon to Herschel’s new planet, Kepler’s ellipses, Newton’s apple, the railroad clocks of 1883 and Voyager’s last look home, each one taken apart to see how it was figured out and then tried with a stick, a string, a lamp and a notebook in the backyard.

First edition

> *“In the beginning God created the heaven and the earth.” (Genesis 1:1, KJV)*

Course guide

This course follows the sky through one school year in eight units: day and year, the Moon, the planets, the stars, Kepler and Newton, telescopes, seasons and the calendar, and navigation by the sky. Each unit is built around real moments: Eratosthenes comparing shadows in Syene and Alexandria, Galileo sketching the craters and mountains of the Moon in 1609, William Herschel spotting Uranus from his garden in Bath in 1781, the railroads setting the clocks of a continent in 1883, Johannes Kepler wrestling with the orbit of Mars, Isaac Newton asking why the Moon does not fall, Pope Gregory's calendar of 1582, and Voyager 1 turning its camera back toward the earth in 1990.

Every lesson follows the same path. First comes **the story**. Then **how they figured it out**: what puzzled them, what they watched, what they measured and what they got wrong before they got it right. Then **the big idea** underneath, explained for a fifth grader: rotation and revolution, phases, eclipses, orbits, gravity, light-years, tilt and seasons. Last, the student **observes and measures** for himself or herself: shadow lengths on a stick, Moon sketches night after night, an ellipse drawn with two pins and a loop of string, a scale model of the solar system paced out down a long road, a simple telescope and a cardboard astrolabe.

The thread of the year is **reading the sky**. People have always used the Sun, Moon and stars to tell the time, keep the calendar, find their way and wonder at their Maker. The course moves from the simplest observation, a shadow that shortens and lengthens through the day, to the great discoveries of Kepler and Newton, and ends with sailors steering by Polaris and the Southern Cross and the wise men following the star to Bethlehem. An optional ninth unit, the **Field Lab**, gathers the best outdoor work of the year: a sundial in the yard, a star map night, a month of Moon sketches and a scale solar-system walk.

The course begins where the Bible begins: "In the beginning God created the heaven and the earth." (Genesis 1:1). The Sun, Moon and stars were made "for signs, and for seasons, and for days, and years" (Genesis 1:14), and the great astronomers of the past, Kepler and Newton among them, studied the heavens because they believed an orderly God had made an orderly world that could be understood. Scripture appears where it fits, from Psalm 19 to the stars of Job 38, and the student learns that careful measuring and honest wonder belong together.

WHO IT IS FOR

Written for students in grade 5 (about ages 10–11) who read on their own, can multiply and divide, measure with a ruler and read a simple table or bar graph. A parent or teacher reads along, helps with evening observing and supervises every experiment that uses a lamp, a lens or sunlight. Nothing needs to be bought beyond ordinary household things: a flashlight, a ball, string, pins, a protractor, cardboard, a meter stick or yardstick and a notebook. A pair of binoculars helps but is never required.

HOW TO USE THIS COURSE

The weekly rhythm. The year has 32 lessons, one a week, in eight units of four, plus the optional Field Lab. Session 1 (about 45 minutes) is the warm-up, the story, the core ideas and the picture study. Session 2 (about 45 minutes) is the experiment, the worked examples, the practice and the field notebook. Some lessons ask for a few extra minutes outdoors in the evening or at noon; plan these on clear days and move them a day or two when the weather will not cooperate.

The ★ quarter path. Ten lessons are marked ★: Eratosthenes, Galileo and the Moon, the wanderers, the scale-model walk, the number of the stars, Kepler, ellipses with string and pins, the simple refractor, tilt and the seasons, and Polaris. A family that wants a one-quarter course can teach only these ten, one a week, and still cover the heart of the year.

The field notebook. Use one graph-paper composition book for the whole year. Every experiment ends with something observed or measured and written down: a shadow table, a Moon sketch with the date and time, a planet scale chart, a star map, an ellipse, a sundial reading. Date every page, note the weather and the time, and write one sentence about what surprised you. Honest records matter more than neat answers.

Experiments and safety. Each lesson names a variable to change and a control to keep the same, so the student learns to test one thing at a time. *Never look directly at the Sun*, with the eyes, binoculars or a telescope, not even during an eclipse; use a pinhole viewer or watch shadows instead. An adult handles lenses near sunlight, hot lamps and any work with pins and knives, and goes along on every evening outing.

Worked examples, practice and unit reviews. Each lesson has two worked examples that show every step, then eight practice items, including a data table or graph to read and an experiment to design. Answers are given so the student can check his or her own work and the parent can see where to help. Each unit ends with a 10-item quiz worth 50 points and a unit project, such as a working sundial, a phases flip-book, a planet poster, a star map, a model orbit or a cardboard astrolabe. Keep the unit projects in one folder for the year.

A word about time. The course is written from a Christian view of creation (Genesis 1:1) and the Flood (Genesis 6–9). Deep-time names such as “Jurassic” or “Ice Age” are taught as museum words so students can read any sign or textbook. Wherever they come up, as in the lesson on light-years and distant starlight, a ⏳ **Thinking About Time** box sets out what the sign says, what we observe, and how Christians read it.

SCOPE AND SEQUENCE

Unit 1: Day and Year (1–4)

Eratosthenes measures the earth with shadows; sundials and telling time by the Sun; the earth’s rotation and revolution; and how the railroads gave North America standard time zones in 1883.

Unit 2: The Moon (5–8)

Galileo sees mountains and craters on the Moon in 1609; why the Moon has phases; how eclipses of the Sun and Moon happen; and how the Moon's pull raises the tides.

Unit 3: The Planets (9–12)

The "wanderers" the ancients watched move among the stars; the true sizes and distances of the solar system in a walking scale model; Herschel's discovery of Uranus in 1781; and Voyager's Pale Blue Dot.

Unit 4: The Stars (13–16)

Counting the stars and the God who names them (Psalm 147:4); Orion and the Pleiades in the Bible (Job 38:31); what a star's color tells us; and light-years, with a ⏳ box on distant starlight.

Unit 5: Kepler and Newton (17–20)

Johannes Kepler finds that planets move in ellipses; drawing ellipses with string and pins; Isaac Newton connects the falling apple to the orbiting Moon; and simple experiments with falling objects and gravity.

Unit 6: Telescopes (21–24)

How lenses gather light and the student builds a simple refractor; the Hubble and Webb space telescopes; great observatories on mountaintops; and how to observe the night sky safely and well.

Unit 7: Seasons and Calendar (25–28)

Why the earth's tilt, not its distance from the Sun, makes the seasons; solstices and equinoxes; the Julian calendar and the Gregorian reform of 1582; and how the dates of Passover and Easter follow the Moon.

Unit 8: Navigation by the Sky (29–32)

Finding north by Polaris and measuring latitude by its height; making and using a cardboard astrolabe; the Southern Cross for travelers below the equator; and the star the wise men followed (Matthew 2).

Unit 9: Field Lab (optional) (Any time)

Four outdoor projects that gather up the year: a working sundial in the yard, a star map night, a month of Moon sketches and a scale solar-system walk with family or friends.

MATERIALS

- **Field notebook (a graph-paper composition book)**: One for the whole year: shadow tables, Moon sketches, star maps, scale charts and experiment records.

- **A meter stick or yardstick, a 30-centimeter (12-inch) ruler and a measuring tape**: For shadow-stick measurements, scale models and the long solar-system walk. Metric first, with U.S. customary in parentheses.
- **A flashlight or a lamp with the shade removed, and a few balls of different sizes**: For modeling day and night, phases, eclipses and the seasons. A foam ball or an orange on a pencil makes a good Moon or earth.
- **String, push pins, a sheet of cardboard and a protractor**: For drawing ellipses, making a sundial and building a cardboard astrolabe.
- **Two magnifying glasses or simple lenses and a cardboard tube**: For building a simple refractor in Unit 6. Inexpensive lens kits work too but are not required.
- **A compass and a straight stick or dowel about 1 meter (3 feet) long**: For finding north, setting up a shadow stick and lining up the sundial.
- **Colored pencils, white and black paper, a pencil, scissors and tape**: For star maps, phases flip-books, planet posters and sketches.
- **A wall calendar and a free printable star chart for your latitude**: For tracking Moon phases, solstices and equinoxes, and finding constellations through the year.
- **Optional: a pair of binoculars and a red-light flashlight**: Binoculars show the Moon’s craters and the moons of Jupiter. Red light (or red cellophane over a flashlight) keeps night vision sharp. Never point binoculars at the Sun.

GRADING

Grades come from the experiments, the field notebook, the unit quizzes and the unit projects, because astronomy is learned by watching, measuring and recording. An experiment that did not turn out as predicted but is honestly recorded and explained earns full credit.

- Experiments (prediction, careful measuring, variable and control, explanation): 30%
- Field notebook (dated pages, times and weather, labeled tables and sketches): 20%
- Unit quizzes (10 items, 50 points each): 25%
- Unit projects: 25%

A 90–100, B 80–89, C 70–79, D 60–69. Below 60: redo the experiment or quiz with help.

- Grade the process, not just the result. Did the student predict, measure carefully, change only one thing at a time, record honestly and explain what happened?
- A notebook page earns full marks when it has a date, a time, a title, labeled columns or a labeled sketch, units of measure and one sentence about what the observation means.
- Cloudy weeks happen. If an observation cannot be made, the student records the weather and makes it up on the next clear night; this is not a lost grade.
- Unit quizzes may be done orally for a student who writes slowly; the parent writes down the answers.
- Keep each unit project in one folder. Together they make a fine record of the year and a good display for family or friends.

A NOTE TO PARENTS

You do not need to be an astronomer to teach this course. Read the story aloud together, look at the picture, and then step outside with your child to watch and measure. Ask “What do you see?”, “What do you think will happen next?” and “How do you know? Show me in your notebook.” Those three questions are most of what a good science teacher does.

Some of the best lessons happen after dark. Plan a few evenings each unit when the sky is clear, bring a blanket and a red flashlight, and let your child find the Moon, Orion or the Big Dipper before you point them out. Safety comes first: no one looks at the Sun, an adult handles lenses and lamps, and evening outings are always together.

Above all, the course hopes to raise a young person who looks up with wonder and works with care. “The heavens declare the glory of God; and the firmament sheweth his handywork” (Psalm 19:1). Kepler and Newton measured the sky because they expected to find order in it, and your child can share that same delight with a stick, a string and a patient eye.

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★ quarter path · ⏳ Thinking About Time box

UNIT 1

Day and Year

"The heavens declare the glory of God; and the firmament sheweth his handywork" (Psalm 19:1). This year you will study the sky as the great Christian astronomers did: by watching, measuring and recording. We begin with the two clocks God built into the world, the **day** and the **year**. On the fourth day of creation God made the lights in the heaven "for signs, and for seasons, and for days, and years" (Genesis 1:14), and in this unit you will learn how the turning earth and its trip around the sun give us both.

You will stand in ancient Alexandria with Eratosthenes as he measures the whole earth with a shadow, a known distance and a little geometry. You will build a sundial and gather a full day of shadow data. You will watch Foucault's great pendulum turn in Paris and act out rotation and revolution with a lamp and a ball. Finally, you will watch the clocks change on "the day of two noons" in 1883, when the railroads divided the country into time zones. In every lesson you will ask: **what does the shadow tell us?**

BEFORE YOU BEGIN

- Can measure lengths with a ruler in centimeters and inches
- Can multiply and divide by one- and two-digit numbers
- Can tell time on a clock with hands and add hours across noon and midnight
- Can find north, south, east and west outdoors or on a map

MASTERY CHECKLIST

- I can explain how Eratosthenes used two noon shadows and one distance to find the size of the earth.
- I can use a protractor to measure the sun's angle from a stick and its shadow drawn to scale.
- I can build a shadow-stick sundial, find solar noon and read a table or bar graph of shadow lengths.
- I can tell the difference between rotation and revolution and explain why the sun rises in the east.
- I can convert times between U.S. time zones and use the rule that 1 degree of longitude equals 4 minutes.
- I can design a simple experiment that changes one thing, keeps the others the same and measures the result.

OPTIONAL BOOKS AND RESOURCES

- **NASA Space Place** (https://spaceplace.nasa.gov/): Free. Short articles, games and make-and-do activities from NASA about the sun, the earth's motions, the Moon and the stars, written for children.

- **time.gov, from the National Institute of Standards and Technology** (https://www.time.gov/): Free. The official U.S. time for every time zone, shown on a map. Use it to set your clock before the solar-noon experiment in Lesson 1.4.
- **NOAA Solar Calculator** (https://gml.noaa.gov/grad/solcalc/): Free. A parent can click on your town to see the clock time of solar noon, sunrise and sunset on any date, and check your shadow-stick results.

1.1 Eratosthenes Measures the Earth (c. 240 B.C.) ★

OBJECTIVES

- Tell how Eratosthenes used two noon shadows, one known distance and geometry to measure the size of the earth.
- Explain why parallel sunlight makes different shadows on a round earth but the same shadow everywhere on a flat one.
- Measure a real noon shadow, draw it to scale and find the sun's angle with a protractor.

Warm-up. Go to a sunny window or step outside. Stand two pencils upright in lumps of clay on a flat book, a hand's width apart, and look at their shadows: they are the same length and point the same way. Now press the same two pencils onto a basketball or large ball, one on top and one partway down the side, and hold the ball still in the sunlight. Do the shadows still match? Write one sentence about what changed. (Never look at the sun; look only at the shadows.)

Video. Coming soon. Eratosthenes measuring the circumference of the earth with shadows at Alexandria and Syene; search NASA education, Smithsonian, Science Max, Homeschool Pop (Alternate) and classroom "Eratosthenes experiment" demonstrations with sticks and shadows.

KEY TERMS

sphere
A perfectly round three-dimensional shape, like a ball. The earth is very nearly a sphere.

circumference
The distance all the way around a circle or sphere. The earth's circumference is about 40,000 km (about 24,900 miles).

degree
A unit for measuring angles. A full circle has 360 degrees, written 360°.

parallel
Running side by side in the same direction and never meeting, like railroad rails. Sunlight reaches the earth in nearly parallel rays.

stadion
A Greek unit of length used by Eratosthenes (plural: stadia). Its exact length is not known for certain.

latitude
How far north or south of the equator a place is, measured in degrees from 0° at the equator to 90° at a pole.

CORE IDEAS

The story. About 240 years before Christ, the greatest library in the world stood in Alexandria, a busy port city on the Mediterranean coast of Egypt. Its chief librarian was a Greek scholar named **Eratosthenes** (air-uh-TOS-thuh-neez), who had been born in the city of Cyrene in North Africa. He wrote about mathematics, poetry, history and maps, and he loved a good puzzle. He came across a curious report about Syene, a town far up the Nile River that is called Aswan today. At noon on the longest day of the year, people said, the sun shone straight down into a deep well and lit the water at the very bottom. Upright posts cast no shadow at all. For a moment the sun stood directly overhead.

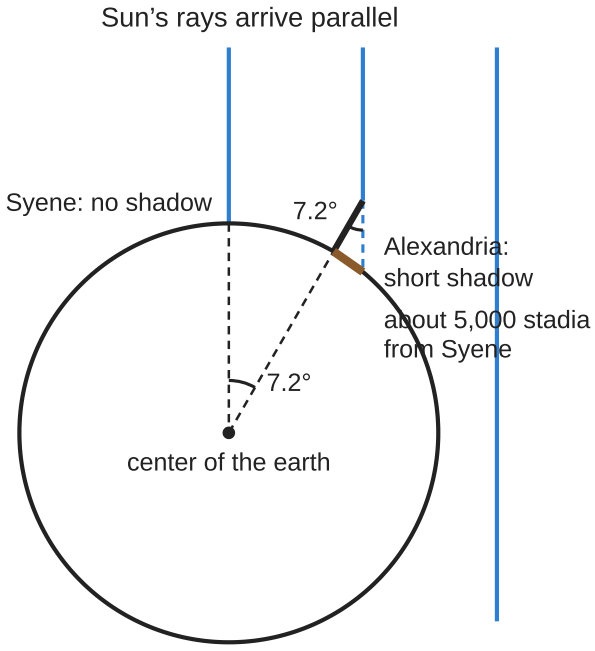
How they figured it out. Eratosthenes knew that in Alexandria, on that same day at noon, an upright pointer *did* cast a short shadow. Why the difference? The sun is so far away that its rays reach the earth almost exactly **parallel**, like the lines on notebook paper. If the earth were flat, parallel rays would make every noon shadow the same. Because the shadows were different, the ground between the two cities had to be curved. Eratosthenes measured the angle between the pointer and the sun's ray in Alexandria and found it was one-fiftieth of a full circle, or **7.2 degrees**. He knew a rule of geometry: when one straight line crosses two parallel lines, the matching angles are equal. So the angle at the center of the earth between Syene and Alexandria must also be 7.2 degrees, and the distance between the two cities must be one-fiftieth of the way around the whole earth. That distance was counted as about 5,000 **stadia**. Fifty times 5,000 is 250,000 stadia.

The big idea. With a pointer, a shadow, one known distance and careful thinking, Eratosthenes measured a world he could never walk around. How close did he come? Nobody knows exactly how long his stadion was, so scholars give different answers, but most agree he came remarkably close. Today we know the earth's **circumference** is about 40,000 kilometers (about 24,900 miles). His method rested on three ideas: the earth is a **sphere**, the sun is very far away, and its rays arrive parallel. Educated people already knew the earth was round. About a hundred years earlier, Aristotle had pointed out that the earth's shadow on the Moon during an eclipse is always curved, and that travelers who went south saw stars that could not be seen farther north. Eratosthenes went one step further. He measured *how big* the round earth is.

Try it and see. You can repeat his experiment. Stand a straight stick upright on level ground, and at noon by the sun measure the stick and its shadow. Draw both to scale on paper and measure the sun's angle with a protractor. Near the first day of spring or the first day of fall, the noon sun stands straight over the equator, so the shadow angle you measure is very nearly your **latitude**, your distance north of the equator in degrees. Every year, classes in many countries measure their noon shadows on the same day and share their results to work out the size of the earth together, just as Eratosthenes did with two cities.

God's handiwork. On the fourth day of creation God set lights in the sky "for signs, and for seasons, and for days, and years" (Genesis 1:14). Because the sun keeps such faithful order, a careful man could stand in Alexandria with a pointer and measure the world. Eratosthenes did not know the God of Israel, but he was reading a book written in light and shadow by the

Maker of heaven and earth. Every measurement of the sky in this course depends on that same steady order.



Parallel rays make no shadow at Syene and a short shadow at Alexandria. The angle at the pointer equals the angle at the earth’s center. (The angle is drawn larger than real so you can see it.)

PICTURE STUDY



Eratosthenes Teaching in Alexandria, Bernardo Strozzi, 1635 · Oil on canvas · Montreal Museum of Fine Arts, Montreal, Canada

Bernardo Strozzi was a painter from Genoa, Italy, who had once been a Capuchin friar. He painted with rich colors and loose, lively brushstrokes. Almost nineteen hundred years after Eratosthenes lived, Strozzi imagined him as an old teacher passing his knowledge on to the young.

No one knows what Eratosthenes really looked like, so this is a picture of an idea: that knowledge is handed down carefully from teacher to student. Strozzi dressed the scene in the clothes and colors he knew in his own day.

Look closely

- Find the teacher. How can you tell he is the one in charge of the lesson?
- Look at the students' faces and hands. Are they bored, puzzled or eager?
- Find where the light falls brightest. What does the painter want you to notice first?
- Look for books, papers or tools. What might a teacher of geometry and maps need?

Talk about it

1. If Eratosthenes were teaching these students about the size of the earth, what would he need to show them?
2. Why do you think Strozzi painted Eratosthenes as an old man with young students around him?
3. Who has taught you something you will remember all your life?

> **Safety first.** Never look at the sun, even for a moment and even through sunglasses. Look only at the shadows. Use pushpins or toothpicks carefully and keep them away from younger children.

EXPERIMENT: SHADOWS ON A ROUND WORLD

In this small experiment you will test Eratosthenes' big idea: parallel sunlight makes the same shadow everywhere on a flat surface but different shadows on a curved one. Then you will measure your own noon shadow, just as he did in Alexandria.

Question: Does the distance between two pointers on a ball change how different their shadows are? **Prediction:** Write yours before you start. **What we change:** the distance between the pointers. **What we keep the same:** the ball, the pointer height, the place and the time. **What we measure:** the length of the second pointer's shadow.

You will need

- A basketball, soccer ball or large playground ball
- Four toothpicks, all the same length, and small lumps of modeling clay
- A flat board or large hardcover book
- Ruler marked in millimeters, measuring tape, protractor
- A straight stick or yardstick exactly 100 cm (about 39 inches) long, or any straight stick you can measure

- Lab notebook, pencil and a sunny day

Steps

1. **Flat test.** Stand two toothpicks upright in clay on the flat board, 10 cm (4 inches) apart. Set the board flat in sunlight. Measure both shadows in millimeters and record them.
2. **Round test.** Set the ball on a towel or ring of clay so it cannot roll. Stand one toothpick on the ball and turn the ball slowly until that toothpick casts almost no shadow. This is your “Syene.”
3. Stand a second toothpick on the ball 5 cm (2 inches) away along the surface, toward the shady side. This is your “Alexandria.” Measure its shadow and record it.
4. Move the second toothpick to 10 cm (4 inches) and then 15 cm (6 inches) from Syene. Measure the shadow each time. Work quickly so the sun does not move much.
5. Make a table with columns: Distance from Syene (cm), Shadow length (mm).
6. **Your own noon shadow.** Near the middle of the day, stand the measured stick straight up on level ground (use a level or a string with a weight to check). Every 10 minutes, mark the tip of the shadow with a pebble and measure its length. The shortest shadow is the noon shadow.
7. On graph paper, draw the stick and the shortest shadow to scale (for example, 1 square = 10 cm). Draw a line from the top of the stick to the tip of the shadow. That line is the sun’s ray. Use the protractor to measure the angle between the stick and the ray at the top of the stick.
8. Write your conclusion: Was your prediction right? What did the flat test show? What did the round test show?

Tips

- If the ball tips, put it in a bowl or a roll of tape so it sits still.
- On the ball the shadows are short, so measure carefully with millimeters.
- Near the first day of spring (about March 20) or fall (about September 22), your measured angle should be close to your town’s latitude. Look up your latitude on a map and compare.

Check your work

- I kept the pointers, the ball and the place the same and changed only the distance.
- I can explain why the flat board shadows matched and the ball shadows did not.
- I drew my noon shadow to scale and measured the sun’s angle with a protractor.

FIELD NOTEBOOK

1. Copy the Eratosthenes diagram into your notebook from memory. Label Syene, Alexandria, the parallel rays, the center of the earth and both 7.2° angles.
2. Draw your noon stick and shadow to scale. Write the date, the time, the stick length, the shadow length and the angle you measured.

3. Write three sentences as if you were Eratosthenes writing a letter to a friend explaining what he found.

From history. Very little of what Eratosthenes wrote has survived. We know how he measured the earth mainly from a later Greek writer named Cleomedes, who explained the method in a book about the heavens and said Eratosthenes measured the shadow in a bowl-shaped sundial. Eratosthenes also drew one of the first world maps marked with lines like latitude and longitude, and he is often credited with being the first to use the word *geography*, which means "writing about the earth." Math students still learn his "sieve," a clever way of finding prime numbers.

WORKED EXAMPLES

Example 1. In Alexandria, Eratosthenes measured the sun's angle at noon as 7.2°. At Syene, the angle was 0°. Syene was about 5,000 stadia from Alexandria. How many stadia is it around the whole earth?

(Use the map or drawing "The angle at the pointer equals the angle at the center of the earth." shown earlier in this lesson.)

1. Because the sun's rays are parallel, the angle at the earth's center between the two cities is also 7.2°.
2. A full circle is 360°. Find how many 7.2° pieces fit in it: 360 ÷ 7.2 = 50. So the distance between the cities is 1/50 of the way around the earth.
3. Multiply the distance by 50: 5,000 stadia × 50 = 250,000 stadia.

Answer: About 250,000 stadia around the earth.

Example 2. Today we measure the straight-line distance from Alexandria south to Aswan (old Syene) as roughly 800 km (about 500 miles). Use Eratosthenes' fraction of 1/50 to estimate the earth's circumference in kilometers and miles. How does it compare with the modern value of about 40,000 km (about 24,900 miles)?

1. The two cities are 1/50 of the way around the earth, so multiply by 50.
2. Kilometers: 800 km × 50 = 40,000 km.
3. Miles: 500 miles × 50 = 25,000 miles.
4. Compare: 40,000 km matches the modern value, and 25,000 miles is only about 100 miles more than 24,900 miles.

Answer: About 40,000 km (about 25,000 miles), very close to the modern circumference.

PRACTICE

1. EASY Why did upright posts in Syene cast no shadow at noon on the longest day of the year?
2. EASY How many degrees are in a full circle? What fraction of a circle is 7.2°?
3. MEDIUM Suppose Eratosthenes had measured a shadow angle of 9° instead of 7.2°, with the same distance of 5,000 stadia. What would he have calculated for the earth's circumference?
4. MEDIUM Two towns lie due north and south of each other, 1,000 km (about 620 miles) apart. At noon on the same day, their sun angles differ by 9°. Estimate the earth's circumference.
5. MEDIUM Four classes measured the sun's angle at noon on the first day of spring:
   City A: 30°
   City B: 35°
   City C: 40°
   City D: 45°
   (a) Which city is farthest north? (b) Which is closest to the equator? (c) Cities A and D are on nearly the same north-south line. About how far apart are they?
6. HARD Design an experiment to test whether the height of a stick changes the sun's angle you measure at noon. Name what you change, what you keep the same and what you measure. What do you predict?
7. HARD Explain in two or three sentences why Eratosthenes needed the sun's rays to be parallel. What would go wrong if the sun were a lamp hanging just above Egypt?
8. CHALLENGE On the first day of spring, a student's 100 cm (about 39 inch) stick casts a noon shadow that is also 100 cm long. Draw it to scale. What is the sun's angle from the stick? About what is the student's latitude?

COMMON MISTAKES

- Thinking that people before Columbus believed the earth was flat. Educated people had known the earth was round since the days of the ancient Greeks, and Eratosthenes even measured its size about 240 years before Christ.
- Thinking the sun's rays spread out so much that they cannot be parallel. The sun is about 150 million km (93 million miles) away, so the rays that reach two cities on earth are almost exactly parallel.
- Thinking a shadow's length tells the sun's angle without knowing the stick's height. You need both the stick and the shadow to find the angle; a taller stick has a longer shadow but the same angle.

> **Make it a game · Shadow Detective.** A parent names a place and a moment, such as "Syene at noon on the longest day," "our yard at 8 in the morning," or "a flat board in Alexandria." You call out "No shadow," "Short shadow" or "Long shadow" and give one reason. Then switch: you name a place and time and the parent answers. Score a point for each correct answer with a good reason. First to seven points wins.

> **Scripture.** “It is he that sitteth upon the circle of the earth, and the inhabitants thereof are as grasshoppers; that stretcheth out the heavens as a curtain, and spreadeth them out as a tent to dwell in:” (Isaiah 40:22, KJV)

Eratosthenes was amazed at how big the earth is, about 40,000 km around. Yet Isaiah says that to God, who made it, all its people are like grasshoppers. Measuring the earth should make us wonder at the greatness of its Maker.

Practice answers

1. The sun was directly overhead, so its rays came straight down along the posts and there was no shadow to the side.
2. 360°. Since 360 ÷ 7.2 = 50, 7.2° is 1/50 of a circle.
3. 360 ÷ 9 = 40, so the cities are 1/40 of the way around. 5,000 × 40 = 200,000 stadia.
4. 360 ÷ 9 = 40. 1,000 km × 40 = 40,000 km (about 620 × 40 = 24,800 miles).
5. (a) City D, because the biggest angle means the farthest from the equator. (b) City A. (c) 45° − 30° = 15°, and 360 ÷ 15 = 24, so they are 1/24 of the way around: 40,000 ÷ 24 ≈ 1,670 km (about 1,040 miles).
6. Change: the stick height (for example 50 cm, 100 cm and 150 cm). Keep the same: the place, level ground, the day and the time (all at noon, measured within a few minutes), and the way the stick is held straight up. Measure: the shadow length, then draw each to scale and measure the angle. Prediction: taller sticks cast longer shadows, but the angle stays the same, because the sun’s rays are parallel.
7. His method assumed the rays hitting Syene and Alexandria point the same direction, so that any difference in the shadows came only from the curve of the earth. If the sun were a nearby lamp, its rays would spread out, and even a flat earth would give different shadows in different places, so the shadows would not tell the size of the earth. Because the sun is very far away, its rays are almost exactly parallel.
8. The stick and shadow make a right triangle with two equal sides, so the angle at the top of the stick is 45°. On the first day of spring the noon shadow angle is about equal to the latitude, so the student is at about 45° north latitude (about halfway between the equator and the North Pole).

1.2 A Sundial

OBJECTIVES

- Explain how a sundial tells time from the shadow of its gnomon and why the shadow moves across the dial.
- Find local solar noon by recording a shadow's length through the day and reading the data in a table or bar graph.
- Explain why a sundial and a clock do not always agree.

> **Warm-up.** On a sunny morning, stand a pencil upright in a lump of clay on a sheet of paper by a sunny window or outdoors. Trace the shadow and write the time beside it. Come back in 15 minutes and trace it again. Which way did the shadow move? Did it get longer or shorter? (Look only at the shadow, never at the sun.)

> **Video.** Coming soon. How a sundial works, the gnomon, shadow sticks and solar noon; search NASA Space Place, NOAA SciJinks, SciShow Kids, Science Max, Homeschool Pop (Alternate) and make-your-own-sundial demonstrations.

KEY TERMS

sundial
A device that tells time by the position of a shadow cast by the sun.

gnomon
The part of a sundial that casts the shadow (say NO-mon). On a good sundial its edge points toward the North Star.

solar noon
The moment each day when the sun is highest in the sky and shadows are shortest. In most of the United States the sun is then due south and shadows point due north.

hour lines
The lines marked on a sundial's face where the shadow falls at each hour.

sun time
Time told by the sun's real place in the sky, as a sundial shows it. Also called apparent solar time.

CORE IDEAS

The story. About seven hundred years before Christ, Hezekiah, king of Judah, lay sick in Jerusalem. The prophet Isaiah brought word that God would heal him and add fifteen years to his life. Hezekiah asked for a sign, and the sign was written in shadow. On the "dial of Ahaz," named for Hezekiah's father, King Ahaz, the shadow could go forward ten degrees or back ten degrees. Hezekiah chose the harder sign, and the Bible records that the LORD "brought the shadow ten degrees backward" (2 Kings 20:11). It was a wonder because

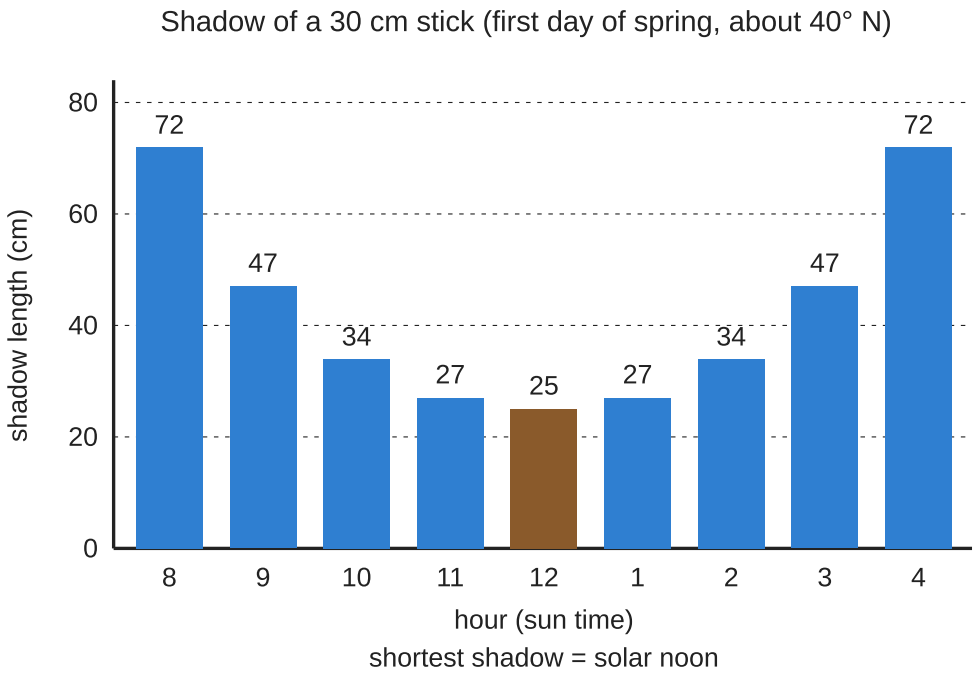
everyone in Jerusalem knew how a shadow normally behaves. It creeps steadily across the dial, always the same way, day after day. That faithful, steady creeping is what makes a **sundial** work.

How they figured it out. A shadow always points directly away from the sun. As the earth turns toward the east, the sun seems to rise in the east, climb across the southern sky and set in the west, so the shadow swings the opposite way. In the United States, a morning shadow points toward the west, the noon shadow points north, and an evening shadow points toward the east. The shadow is shortest at **solar noon**, when the sun is highest. Because the earth turns all the way around (360 degrees) in 24 hours, the sun seems to move 360 ÷ 24 = **15 degrees every hour**. Sundial makers learned to tilt the **gnomon**, the shadow-casting edge, so it points at the North Star. Its tilt from the ground then equals the place's latitude, and the **hour lines** stay right all year long. Many people think clock hands turn "clockwise" because sundial shadows in the northern half of the world turn that way.

The big idea. A sundial tells **sun time**, the time by the sun's real place in the sky. A clock keeps a steady, averaged time instead. Because the earth's path around the sun is slightly oval and the earth is tilted, the sun runs a little ahead of the clock at some times of year and a little behind at others. The difference grows to about a quarter of an hour: a sundial runs about 16 minutes fast in early November and about 14 minutes slow in mid-February. Clocks also follow time zones (Lesson 1.4), and in summer daylight saving time moves them ahead one hour, so solar noon often comes near 1:00 in the afternoon on the clock. The sundial is not wrong. It simply tells a different kind of time, the time written in the sky.

Try it and see. The simplest sundial is a *shadow stick*: a straight stick standing upright on level ground. Mark the tip of its shadow with a pebble every hour and write the time beside each pebble. By evening you will have a fan of marks. The shortest shadow shows solar noon and points to true north, so a shadow stick can also be a compass. If you keep your stick in the same place, you can come back next month and see that the noon shadow has changed length, because the sun's noon height changes with the seasons.

God's handiwork. "He appointed the moon for seasons: the sun knoweth his going down" (Psalm 104:19). For thousands of years, before there were any clocks with gears, people told time by the sun because God made it faithful. Farmers, soldiers, priests and travelers all trusted the shadow. A sundial is a small thank-you note to the Creator, a way of saying that His world keeps time.



A 30 cm (about 12 inch) stick's shadow near the first day of spring at about 40° north latitude. The shortest shadow marks solar noon, and the morning and afternoon bars match like mirror images.

PICTURE STUDY



Portrait of Nicolaus Kratzer, Hans Holbein the Younger, 1528 · Oil on oak panel · Louvre Museum, Paris

Nicolaus Kratzer was a German mathematician who served as astronomer to King Henry VIII of England. One of his jobs was making sundials, and he made a famous one for Corpus Christi College in Oxford. His friend Hans Holbein, one of the finest portrait painters who ever lived, painted him in 1528 at work at his table.

Kratzer holds an unfinished sundial with many flat faces. Each face points a different way, so the sun lights at least one face at almost any hour of the day. Holbein painted every tool so carefully that sundial experts today can recognize them.

Look closely

- Find the many-sided sundial in Kratzer's hand. How many faces can you see?
- Find the tools on the table and on the wall. Which ones might be used for drawing straight lines or measuring angles?
- Look at Kratzer's face. Does he look rushed, or patient and careful?
- Find where the light comes from in the painting. How does it help you see the tools?

Talk about it

1. Why would a sundial with many faces be useful?
2. Why do you think a king would want an astronomer who could make sundials?
3. What tools would be on your table if Holbein painted you doing your favorite kind of work?

> **Safety first.** Never look at the sun, even for a moment and even through sunglasses. Watch only the shadow. A parent should do any cutting with a craft knife, and you should push the stick into the ground carefully so it does not snap.

EXPERIMENT: A SHADOW-STICK SUNDIAL

You will turn a stick and some pebbles into a working sundial and collect a full day of real shadow data, the same kind of data sundial makers have gathered for thousands of years.

Question: How do a shadow's length and direction change during one day? **Prediction:** Write when you think the shortest shadow will come, by your clock. **What changes:** the time of day. **What we keep the same:** the stick, its place and how straight it stands. **What we measure:** the shadow's length in centimeters and the direction it points.

You will need

- A straight stick or dowel; 30 cm (about 12 inches) should stand above the ground
- A flat, sunny place in the yard (or a flowerpot of sand on a sunny patio)
- A string with a small weight tied on (a plumb line) to check that the stick is straight up
- Ten pebbles or craft sticks, and a marker
- Measuring tape in centimeters, a compass (optional)
- Lab notebook and pencil; graph paper for a bar graph

Steps

1. Push the stick into level ground until exactly 30 cm (about 12 inches) stands above the ground. Hang the plumb line beside it and adjust until the stick is straight up.

2. In your notebook, make a table with columns: Clock time, Shadow length (cm), Direction the shadow points.
3. Starting at 8:00 or 9:00 in the morning, mark the tip of the shadow with a pebble every hour. Write the hour on the pebble or on a craft stick beside it.
4. Each time, measure the shadow from the base of the stick to the tip and record it with its direction.
5. Around midday, measure every 10 minutes to find the very shortest shadow. Record the clock time. This is your local solar noon.
6. At the end of the day, make a bar graph of shadow length for each hour.
7. Leave the pebbles in place. Tomorrow, check the time by your sundial and compare it with a clock. How close is it?
8. Write your conclusion: When was the shortest shadow? Which way did the shadow point at noon? Was your prediction right?

Tips

- If you are on daylight saving time, do not be surprised if the shortest shadow comes near 1:00 in the afternoon.
- The noon shadow points true north, so draw an arrow on the ground there. You have found north without a compass.
- **Make it last:** cut a triangle of stiff cardboard whose slanted edge rises at an angle equal to your latitude (for example 40°). Glue it upright on a paper plate with the slanted edge pointing north, then mark the hour lines where its shadow falls each hour.

Check your work

- I kept the stick in the same place and straight up all day.
- I recorded at least six shadow lengths and directions.
- I found the time of solar noon and made a bar graph of my data.

FIELD NOTEBOOK

1. Draw your shadow-stick sundial from above, with the fan of pebble marks and the hour beside each one. Draw an arrow pointing north.
2. Copy your table of shadow lengths and make a neat bar graph from it. Circle the shortest bar and label it “solar noon.”
3. Draw the dial of Ahaz as you imagine it and write 2 Kings 20:11 underneath.

> **From history.** The Roman writer Pliny the Elder told how the city of Rome got its first public sundial. A Roman general brought one home from the city of Catania in Sicily in 263 B.C. and set it up in the forum. But a sundial must be made for the latitude where it stands, and Catania lies farther south than Rome. Pliny says the Romans followed its wrong hours for nearly a hundred years before someone set up a dial made for Rome itself.

WORKED EXAMPLES

Example 1. A class measured the shadow of a 30 cm stick each hour near the first day of spring:
8:00: 72 cm
9:00: 47 cm
10:00: 34 cm
11:00: 27 cm
12:00: 25 cm
1:00: 27 cm
2:00: 34 cm
3:00: 47 cm
4:00: 72 cm
(These are sun-time hours.) When was solar noon? At what two times was the shadow 47 cm? How much shorter was the noon shadow than the 8:00 shadow?

(Use the map or drawing "The same data as a bar graph. The bars are shortest at noon and match on each si" shown earlier in this lesson.)

1. Solar noon is when the shadow is shortest. The smallest number is 25 cm, at 12:00.
2. Find 47 cm in the table: it appears at 9:00 and at 3:00. Each is 3 hours from noon, one before and one after.
3. Subtract: 72 cm − 25 cm = 47 cm.

Answer: Solar noon was at 12:00. The shadow was 47 cm at 9:00 and 3:00. The noon shadow was 47 cm shorter than the 8:00 shadow.

Example 2. The sun seems to move across the sky as the earth turns. How many degrees does the sun seem to move in one hour? How many degrees does it move from 9:00 in the morning to 3:00 in the afternoon?

1. The earth turns all the way around, 360°, in 24 hours.
2. Degrees per hour: 360 ÷ 24 = 15° each hour.
3. From 9:00 to 3:00 is 6 hours.
4. 6 hours × 15° per hour = 90°.

Answer: 15° each hour, and 90° (a quarter of a full circle) from 9:00 to 3:00.

PRACTICE

1. EASY What is the part of a sundial that casts the shadow called?
2. EASY In the United States, which direction does the shadow of a stick point at solar noon? Which direction does it point early in the morning?
3. MEDIUM How many degrees does the sun seem to move across the sky in 4 hours?

4. MEDIUM Use the bar graph of the 30 cm stick. (a) How long was the shadow at 11:00? (b) How much longer was the 10:00 shadow than the noon shadow? (c) Why do the morning and afternoon bars match?
   (Use the map or drawing "Shadow of a 30 cm stick through one day." shown earlier in this lesson.)
5. MEDIUM Your town is at 35° north latitude. At what angle above the ground should the slanted edge of your sundial's gnomon rise, and which way should it point?
6. HARD In July your shadow stick shows its shortest shadow when the kitchen clock says 1:05 in the afternoon. Give two reasons the clock does not say 12:00.
7. HARD Design an experiment to find out whether the time of year changes the length of the noon shadow. Name what you change, what you keep the same and what you measure. How would you record your results?
8. CHALLENGE Explain in two or three sentences why a sundial in Australia has its hour marks running the opposite way around from a sundial in the United States.

COMMON MISTAKES

- Thinking the sun really travels around the earth each day. The sun only seems to move across the sky because the earth is turning toward the east.
- Thinking the noon shadow disappears everywhere. A stick has no noon shadow only in the tropics, on the days the sun passes straight overhead. Everywhere else, including all of the United States except Hawaii, there is always a noon shadow.
- Thinking a sundial is broken when it does not match the clock. A sundial tells sun time; clocks use time zones, daylight saving time and an averaged day, so the two can differ by an hour or more.

Make it a game · Human Sundial. Go outside on a sunny day. One player stands still as the gnomon. The other calls out a time, such as "9 in the morning," "noon" or "4 in the afternoon," and the gnomon points with one arm to where the shadow would fall: west in the morning, north at noon, east in the evening, and long or short. Then check your real shadow at that moment. Switch roles after five calls. Score a point for each correct direction.

Scripture. "And Isaiah the prophet cried unto the LORD: and he brought the shadow ten degrees backward, by which it had gone down in the dial of Ahaz." (2 Kings 20:11, KJV)

A sundial works because the shadow always moves the same way. The sign given to Hezekiah was a wonder exactly because God's ordinary order is so steady. The God who keeps the sun faithful every day is the same God who answers prayer.

Practice answers

1. The gnomon.
2. At solar noon it points north. Early in the morning it points toward the west, away from the rising sun in the east.
3. 4 × 15° = 60°.

4. (a) 27 cm. (b) 34 − 25 = 9 cm. (c) At 10:00 and 2:00 (and at each matching pair of times) the sun is the same height in the sky, once climbing and once going down, so the shadows are the same length.
5. At 35°, pointing north (toward the North Star).
6. First, daylight saving time sets clocks one hour ahead in summer. Second, clocks follow time zones and keep an averaged time, so solar noon in your exact town can come some minutes before or after noon on the clock, depending on where you are in your time zone and the time of year.
7. Change: the date (for example, measure on the 1st of each month for several months). Keep the same: the same 30 cm stick, the same level spot, the stick straight up, and measuring at solar noon (the shortest shadow) each time. Measure: the length of the noon shadow in centimeters. Record the date and length in a table and make a bar graph with one bar for each month.
8. In the United States the noon sun is in the southern sky, so shadows point north and swing from west through north to east, which is clockwise. In Australia, south of the tropics, the noon sun is in the northern sky, so shadows point south and swing from west through south to east, which turns the other way, counterclockwise. The hour marks must follow the way the shadow moves.

1.3 Rotation and Revolution

OBJECTIVES

- Tell the difference between the earth's rotation (one spin in about 24 hours, making day and night) and its revolution (one trip around the sun in about 365¼ days, making the year).
- Explain how Foucault's pendulum showed that the earth turns, and why the sun rises in the east.
- Use simple division and multiplication to find the earth's spinning speed at the equator and to explain leap years.

Warm-up. Stand in the middle of a room facing a lamp or a bright window, which will be your "sun." Turn slowly in place to your left (counterclockwise). Notice when the sun first comes into view at the edge of your eyes, and when it disappears. You just made a sunrise and a sunset by spinning. Now walk once in a big circle around a chair. Which motion made a "day," and which made a "year"?

Video. Coming soon. Earth's rotation and revolution, day and night, and the Foucault pendulum; search NASA Space Place, NASA education, Smithsonian, SciShow Kids, Science Max, Homeschool Pop (Alternate) and museum Foucault pendulum footage.

KEY TERMS

axis
An imaginary line through the North and South Poles that the earth spins around.

rotation
The spinning of the earth on its axis. One rotation takes about 24 hours and gives us day and night.

revolution
One complete trip of the earth around the sun. One revolution takes about 365¼ days, one year.

orbit
The curved path one body in space follows around another, like the earth's path around the sun.

leap year
A year with an extra day, February 29, added about every four years to make up the extra quarter day in each revolution.

Foucault pendulum
A long, heavy pendulum whose swing slowly turns as the earth rotates beneath it (say foo-KOH).

CORE IDEAS

The story. In 1851 a French scientist named **Léon Foucault** invited the people of Paris to come and see the earth turn. Inside the Panthéon, a great domed building, he hung an iron ball of about 28 kilograms (about 62 pounds) from a wire about 67 meters (220 feet) long. A pin under the ball scratched a line in a ring of sand on the floor each time it swung. Crowds gathered and waited. Swing after swing, the line in the sand slowly crept around the ring. Nobody was pushing the pendulum sideways. What was turning?

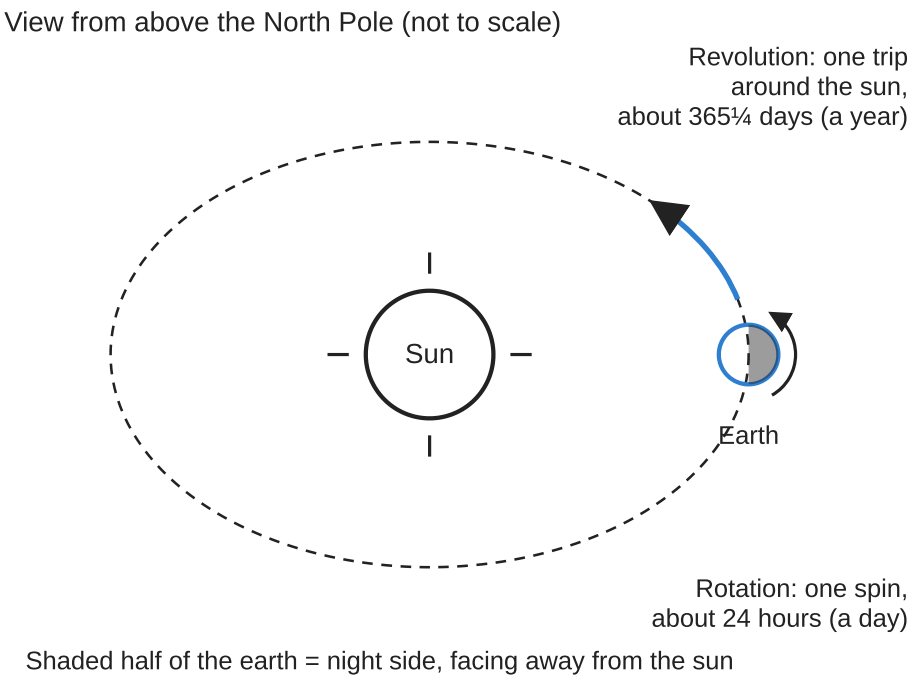
How they figured it out. A heavy pendulum keeps swinging back and forth in the same direction. But the floor under it is attached to the spinning earth. So as the hours pass, the floor turns underneath the pendulum, and to the people standing on that floor the swing seems to turn the other way. In Paris the swing turned about 11 degrees every hour and needed about 32 hours to go all the way around. At the North Pole it would go around in about one day; at the equator it would not turn at all. Foucault's pendulum gave plain, everyday proof that the earth turns. Today you can see Foucault pendulums swinging in science museums and university buildings all over the world.

The big idea. The earth moves in two ways at once. First, it spins on its **axis**, an imaginary line through the North and South Poles. This spin is called **rotation**, and one rotation takes about 24 hours. The half of the earth facing the sun has day, and the half facing away has night. The earth spins toward the east, so the sun seems to rise in the east and set in the west. At the equator the ground is moving about 1,670 kilometers per hour (about 1,040 miles per hour)! We do not feel it because the motion is smooth and steady, the way you cannot feel a smooth airplane flight with your eyes closed, and the air spins right along with us.

The second motion. At the same time, the earth travels around the sun on a nearly circular path called its **orbit**, about 150 million kilometers (93 million miles) from the sun. One complete trip is a **revolution**, and it takes about 365¼ days, which is one year. To make the trip the earth races along at about 30 kilometers (19 miles) every second. That leftover quarter of a day adds up: after four years it makes a whole extra day, so about every four years the calendar adds February 29, a **leap year**. Seen from high above the North Pole, the earth both spins and orbits counterclockwise. In 1543 the Polish astronomer Nicolaus Copernicus published a book arguing that the earth goes around the sun; later astronomers found the proof.

Try it and see. With a lamp for the sun and a ball for the earth, you can act out both motions. Put a sticker on the ball for your home. Spin the ball slowly toward the east and watch your sticker move from night into morning, through noon and into evening. Then carry the ball in a big circle around the lamp while you keep spinning it. You will quickly see that the earth makes about 365 spins for every one trip around the sun.

God's handiwork. After the Flood, God promised Noah that "day and night shall not cease" (Genesis 8:22). Every sunrise is that promise kept. The earth's steady spin and its faithful yearly path are the clock and calendar God built into creation.



Seen from above the North Pole, the earth rotates (spins) and revolves (orbits) counterclockwise. The half facing away from the sun has night. Sizes and distances are not to scale.

PICTURE STUDY



A Philosopher Lecturing on the Orrery, Joseph Wright of Derby, about 1766 · Oil on canvas · Derby Museum and Art Gallery, Derby, England

An *orrery* is a clockwork model of the solar system. When you turn its handle, little brass planets go around a center that stands for the sun, and moons go around their planets. Joseph Wright, an English painter from the town of Derby, loved to paint people lit by a single strong light.

Here the only light comes from a lamp hidden in the middle of the orrery, standing in for the sun. Just as the real sun lights the side of the earth that faces it, the lamp lights the faces turned toward it and leaves the backs of heads in shadow. Wright made the painting itself a lesson in day and night.

Look closely

- Find where the light is coming from. Can you see the lamp itself, or is something blocking it?
- Look at the faces of the children. Which side of each face is lit, and which side is in shadow?
- Find the brass rings and little balls of the orrery. Which might stand for planets, and which for their paths?
- Find the man who is taking notes. Why might he be writing during the lecture?

Talk about it

1. How is this room like the earth, with a day side and a night side?
2. If you turned the handle of the orrery, what two motions would the little earth make?
3. Why do you think the painter chose to show a lesson at night by lamplight?

> **Safety first.** Use a lamp with an LED bulb if you can. Older bulbs get hot enough to burn, so do not touch the bulb, keep paper and the ball from resting on it, and keep cords out of walkways. Ask an adult before moving a lamp or removing its shade.

EXPERIMENT: DAY, NIGHT AND A YEAR IN THE LIVING ROOM

You will build a model of the earth and sun to see rotation and revolution, and then make a small Foucault pendulum to see why a swinging weight can show that the floor is turning.

Question: Does a pendulum keep swinging the same direction when the stand under it is turned slowly? **Prediction:** Write yours first. **What we change:** how far we turn the stand. **What we keep the same:** the weight, the string length and how far we pull it back. **What we measure:** which way the swing points compared with the room and compared with the stand.

You will need

- A lamp without a shade (LED bulb if possible) in a darkened room
- A ball or globe, a small sticker and a pencil or chopstick to push through for an axis (optional)
- A lazy Susan turntable, or a large plate on a smooth table that can be turned slowly
- A small stand to hang the pendulum: two stacks of books with a ruler or yardstick across the top, or a chair turned upside down on the turntable
- String about 50 cm (20 inches) long and a small weight such as a metal washer, nut or fishing sinker

- Masking tape, lab notebook and pencil

Steps

1. **Day and night.** Darken the room and turn on the lamp. Put a sticker on the ball for your home. Hold the ball at arm's length from the lamp and spin it slowly counterclockwise (as seen from above the top of the ball).
2. Watch the sticker. Call out "sunrise," "noon," "sunset" and "midnight" as it moves. Which side of the ball does the sun "rise" on?
3. **A year.** Keep spinning the ball while you walk slowly in a big counterclockwise circle around the lamp. Count your spins. (You will not reach 365, but you will see why there are so many days in one year.)
4. **The pendulum.** Build your stand on the turntable so the weight hangs in the middle, just above the turntable's surface. Put a strip of masking tape across the turntable under the weight, and another strip on the table beside it pointing the same way.
5. Pull the weight back along the tape and let it go gently, with no sideways push. Let it swing.
6. Very slowly turn the turntable a quarter turn (90°). Watch the swing. Does it follow the tape on the turntable, or does it keep swinging in line with the tape on the table?
7. Repeat with a half turn (180°). Record what you saw in a table: How far I turned, Direction of swing compared with the room, Direction of swing compared with the turntable tape.
8. Write your conclusion: How is the turntable like the earth? How is your pendulum like Foucault's?

Tips

- Turn the turntable slowly and smoothly; a jerk will shake the stand and start the weight wobbling.
- A heavier weight on a longer string keeps swinging longer and works better.
- An observer riding on the turntable (like an ant) would think the pendulum was turning, just as the crowds in Paris saw the swing turn.

Check your work

- I can show rotation and revolution with a ball and a lamp and say which one makes a day and which one makes a year.
- I kept the weight, string and release the same and changed only how far I turned the stand.
- I can explain why Foucault's swing seemed to turn even though nothing pushed it.

FIELD NOTEBOOK

1. Draw the earth and sun as seen from above the North Pole. Draw an arrow for rotation and an arrow for revolution, and shade the night side.

2. Draw Foucault’s pendulum hanging from the dome of the Panthéon, with the ring of sand on the floor. Label the wire, the iron ball and the sand.
3. Make a two-column chart: Rotation and Revolution. Under each, write what it is, how long it takes and what it gives us.

From history. Copernicus said the earth goes around the sun, but for almost three hundred years no one could measure the proof directly. If the earth moves, nearby stars should seem to shift a tiny bit against faraway stars as we look from opposite sides of our orbit, the way your thumb seems to jump when you look at it with one eye and then the other. The shift is so small that it took until 1838 for the German astronomer Friedrich Bessel to measure it, for a star called 61 Cygni. Thirteen years later, Foucault’s pendulum gave an everyday proof of the earth’s other motion, its spin.

WORKED EXAMPLES

Example 1. The distance around the earth at the equator is about 40,000 km (about 24,900 miles). The earth makes one rotation in about 24 hours. How fast is a person standing on the equator moving because of the earth’s spin?

(Use the map or drawing “Rotation carries a person on the equator all the way around the earth each day.” shown earlier in this lesson.)

1. In one rotation, a point on the equator travels all the way around: about 40,000 km.
2. Speed = distance ÷ time = 40,000 km ÷ 24 hours ≈ 1,667 km per hour.
3. In miles: 24,900 miles ÷ 24 hours ≈ 1,038 miles per hour.

Answer: About 1,670 km per hour (about 1,040 miles per hour).

Example 2. One revolution of the earth takes about 365¼ days, but a normal calendar year has 365 days. How much time is left over after 1 year, 2 years, 3 years and 4 years? What does the calendar do about it?

1. Each year leaves about ¼ day extra.
2. After 1 year: ¼ day. After 2 years: ½ day. After 3 years: ¾ day.
3. After 4 years: 4 × ¼ = 1 whole day.
4. So about every four years the calendar adds one day, February 29. That year has 366 days and is called a leap year (for example, 2024 and 2028).

Answer: After 4 years the extra quarter days add up to 1 whole day, so a leap year adds February 29.

PRACTICE

1. EASY Match each word with its meaning: (a) rotation (b) revolution. Meanings: one trip around the sun; one spin on the axis.
2. EASY Which motion gives us day and night? Which motion gives us the year? About how long does each take?
3. MEDIUM The earth travels about 30 km (about 19 miles) along its orbit every second. How far does it travel in one minute?
4. MEDIUM Students recorded the direction of a Foucault pendulum's swing in Paris:
   Start: 0°
   After 2 hours: 23°
   After 4 hours: 45°
   After 6 hours: 68°
   After 8 hours: 90°
   (a) About how many degrees does the swing turn each hour? (b) Predict the direction after 16 hours. (c) About how many hours does a full turn of 360° take?
5. MEDIUM The earth spins toward the east. Explain why this makes the sun rise in the east.
6. HARD Foucault used a very long pendulum. Design an experiment to test whether the length of a pendulum's string changes how long one swing takes. Name what you change, what you keep the same and what you measure.
7. HARD The ground at the equator moves about 1,670 km per hour, yet we do not feel it. Explain why in two or three sentences.
8. CHALLENGE Imagine the earth spun the opposite way, toward the west, but still went around the sun the same way. (a) Where would the sun rise? (b) A child is born on February 29, 2028. In which years from 2029 through 2040 will the child have a real February 29 birthday?

COMMON MISTAKES

- Thinking day and night happen because the sun goes around the earth each day. Day and night come from the earth's rotation on its axis.
- Thinking day and night come from the earth going around the sun. One trip around the sun takes a whole year; it is the daily spin that makes day and night.
- Mixing up the two words. A memory trick: rotation is a spin, like a top that rotates in place; revolution is a trip around something, like a horse on a carousel going around the center.

Make it a game · Rotate or Revolve. Set a chair in the middle of the room as the sun. A caller shouts "Rotate!" or "Revolve!" On "Rotate," spin once in place. On "Revolve," walk once around the chair. On "Both!" spin while walking around the chair, counterclockwise for both. The caller can also shout "Day!" (rotate) or "Year!" (revolve). Anyone who does the wrong motion becomes the next caller.

Scripture. "While the earth remaineth, seedtime and harvest, and cold and heat, and

> summer and winter, and day and night shall not cease.” (Genesis 8:22, KJV)

Day and night come from the earth’s rotation; summer and winter come with its yearly revolution. God promised that both would keep going as long as the earth remains, and every sunrise and every new year shows He keeps His word.

Practice answers

1. (a) Rotation is one spin on the axis. (b) Revolution is one trip around the sun.
2. Rotation gives day and night and takes about 24 hours. Revolution gives the year and takes about 365¼ days.
3. 30 km × 60 = 1,800 km each minute (19 miles × 60 = 1,140 miles).
4. (a) 90° ÷ 8 hours ≈ 11° per hour. (b) Twice 8 hours gives twice 90°, so about 180°. (c) Twice 180° is 360°, so about 32 hours.
5. As the earth spins eastward, your side of the earth turns toward the sun from the east first. The sun comes into view over the eastern horizon, seems to climb, and later disappears in the west as your side turns away.
6. Change: the string length (for example 25 cm, 50 cm and 100 cm). Keep the same: the weight, how far you pull it back, and how you let it go (no push). Measure: the time for 10 complete swings with a stopwatch, then divide by 10 for one swing. Repeat each length three times and take the average. (Longer strings swing more slowly.)
7. We feel speeding up, slowing down and bumps, not steady motion. The earth spins smoothly and steadily, and we, the air, the houses and everything around us move along with it, just as you can pour a drink calmly on a smooth airplane flight.
8. (a) The sun would rise in the west and set in the east. (b) Leap years come every four years: 2032, 2036 and 2040.

1.4 Time Zones and the Railroads (1883)

OBJECTIVES

- Explain why every town once kept its own local sun time and why that caused trouble for the railroads.
- Tell how the railroads' standard time of November 18, 1883 divided the country into time zones about 15 degrees of longitude wide, one hour apart.
- Convert times between U.S. time zones and use the rule that 1 degree of longitude equals 4 minutes of sun time.

Warm-up. Find a globe or a world map. Put your finger on your town. Now think: when it is noon by the sun where you live, is the sun already setting somewhere else? Is it still rising somewhere else? Shine a flashlight on the globe from one side and turn the globe slowly toward the east to check. Write down one place where the sun has already set and one where it has not yet risen.

Video. Coming soon. History of standard time and time zones, the railroads in 1883 and the Day of Two Noons; search Smithsonian, Library of Congress, NIST time and frequency, railroad museums, Homeschool Pop (Alternate) and short history-of-time documentaries.

KEY TERMS

longitude
How far east or west a place is, measured in degrees from the prime meridian.

meridian
An imaginary line on the globe running from the North Pole to the South Pole. Every place on one meridian has solar noon at the same moment.

prime meridian
The meridian at 0° longitude, which runs through Greenwich, England. It was chosen as the world's starting line in 1884.

local sun time
Time set by the sun in one exact place, so that 12:00 is that place's solar noon.

standard time
One agreed clock time used by everyone across a wide area, even though solar noon comes at slightly different moments across it.

time zone
A region that keeps the same standard time. Neighboring zones in the United States usually differ by one hour.

CORE IDEAS

The story. On Sunday, November 18, 1883, people in towns across the United States and Canada gathered near jewelers' windows, railroad stations and telegraph offices to watch the clocks. At a set moment, telegraph wires carried an exact time signal, and clocks everywhere were moved to a new "standard time." In New York City the clocks were set back about four minutes. In many towns whose clocks were set back, the hands came around to twelve a second time, and people called it "the day of two noons." From that day on, the railroads ran on just four time zones, Eastern, Central, Mountain and Pacific, instead of dozens of different times.

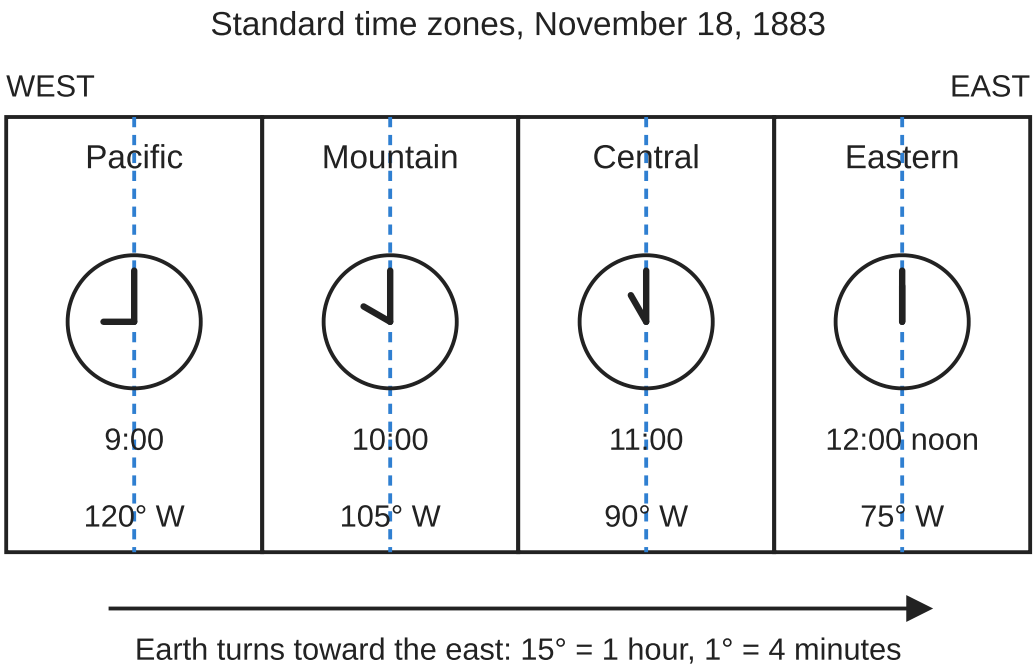
The problem. Before 1883, every town kept its own **local sun time**, setting its clocks so that 12:00 came at its own solar noon. Because the earth turns toward the east, the sun reaches its highest point a little earlier in towns farther east. Noon in Boston came about 12 minutes before noon in New York. That did not matter much when people traveled by horse. But trains crossed many towns in a single day, and each railroad kept the time of its own home city. A large station might have several clocks on the wall, each showing a different railroad's time. Travelers missed connections, and timetables were a puzzle. Worse, trains that shared one track had to know exactly when the other train would pass. In 1853 a collision in Rhode Island, blamed partly on a conductor's slow watch, pushed New England railroads to make strict rules about clocks.

How they figured it out. William F. Allen, a railroad engineer who edited the official railway timetable guide, worked out the plan for the railroads' General Time Convention. The idea came straight from the sky. The earth turns 360 degrees in 24 hours, so it turns **15 degrees every hour**. Allen's zones were each about 15 degrees of **longitude** wide, centered on the **meridians** at 75°, 90°, 105° and 120° west. Each zone's clocks showed the sun time of its center line, and each zone was exactly one hour different from its neighbor. A town no longer kept its own sun time, but its clocks were never more than about half an hour off from it.

The big idea. Since 15 degrees make one hour, **1 degree of longitude makes 4 minutes** of sun time (60 ÷ 15 = 4). Going east, clocks move later; going west, they move earlier. When it is noon Eastern Time, it is 11:00 Central, 10:00 Mountain and 9:00 Pacific. In October 1884, delegates from more than twenty nations met in Washington, D.C., at the International Meridian Conference and chose the meridian through Greenwich, England, as the **prime meridian**, 0° longitude, the starting line for measuring longitude and time all over the world. The United States Congress made the time zones law in 1918. Today the country uses more zones, including Alaska and Hawaii-Aleutian Time, and the zone lines zigzag along state and county borders so that a town is not split down the middle.

In the world today. Your phone and many clocks set themselves by radio or internet signals traced back to atomic clocks, which keep time more steadily than the turning earth itself. You can see the official time of every U.S. zone at time.gov, run by the National Institute of Standards and Technology. Yet every one of those zones still rests on the same simple fact Allen used: the turning earth carries noon westward at 15 degrees every hour.

God’s handiwork. The railroads could agree on one time because the earth turns with such steady faithfulness. Scripture reminds us that our time is a gift to be used wisely: “So teach us to number our days, that we may apply our hearts unto wisdom” (Psalm 90:12).



The four time zones of 1883, drawn as straight strips. Each is about 15° of longitude wide and one hour from its neighbor. Real zone boundaries zigzag along state and county lines.

PICTURE STUDY



The Gare Saint-Lazare, Claude Monet, 1877 · Oil on canvas · Musée d’Orsay, Paris

Claude Monet was a French painter who loved to paint light, air and weather. In 1877 he set up his easel inside the Saint-Lazare railroad station in Paris and painted it again and again, at different times of day. He painted quickly, with short dabs of color, to catch the steam before it drifted away.

In the 1870s the railroad was the fastest way to travel on land, and a great station like this one was a busy, noisy, smoky place where hundreds of people had to arrive and leave on time. Railroads all over the world needed clocks everyone could trust.

Look closely

- Find the locomotives. How many can you see? Which one looks closest to you?
- Look at the steam and smoke. What colors did Monet use for them? Are they only gray and white?
- Find the iron and glass roof. How does the sunlight get into the station?
- Look for people on the platforms. What might they be waiting for?

Talk about it

1. Why would a busy station like this need every train and every clock to keep exactly the same time?
2. Monet painted the station at different times of day. How might the light look different at sunrise and at noon?
3. What problems might happen if the engineer on one train and the station master each kept a different time?

> **Safety first.** Never look at the sun while doing the shadow-stick part of the project; watch only the shadow.

EXPERIMENT: SUN NOON OR CLOCK NOON?

You will find the exact moment of solar noon in your own yard and compare it with the clock, then make a set of time-zone clocks to show how the railroads solved the problem of many local times.

Question: Does solar noon in my town come at exactly 12:00 on the clock? **Prediction:** Write your guess, earlier, later or exactly on time, and by how many minutes. **What changes:** the clock time. **What we keep the same:** the stick, its place and its straightness. **What we measure:** the length of the shadow every 5 minutes.

You will need

- Your shadow stick from Lesson 1.2, standing straight up in a sunny, level place
- A clock or phone set to the official time (check it at time.gov)
- Measuring tape in centimeters, pebbles
- An atlas or map with longitude lines, or a parent’s help to look up your town’s longitude

- Four paper plates, brass fasteners and cardstock for clock hands, markers
- Lab notebook and pencil

Steps

1. Start about 30 minutes before you expect solar noon (around 11:30 in winter, or around 12:30 on daylight saving time in summer).
2. Every 5 minutes, mark the shadow tip with a pebble, measure its length and record the clock time in a table: Clock time, Shadow length (cm).
3. Keep going until the shadow has clearly started to grow longer again. The shortest measurement is your solar noon. Record its clock time.
4. Look up your town's longitude and which time zone you are in. The center meridians are 75° W (Eastern), 90° W (Central), 105° W (Mountain) and 120° W (Pacific).
5. Find how many degrees east or west of your zone's center meridian you are. Multiply by 4 to get minutes. If you are west of the center, solar noon should come later than 12:00; if east, earlier. (Add one hour if you are on daylight saving time.)
6. Compare your measured solar noon with your calculation. Remember that the sun can also run up to about a quarter hour ahead of or behind the clock at different times of year (Lesson 1.2).
7. Make four paper-plate clocks labeled Pacific, Mountain, Central and Eastern. Set the Eastern clock to 12:00 and set the other three correctly. Hang them on the wall in order from west to east, like a railroad station in 1883.
8. Write your conclusion: Did solar noon come at 12:00 on the clock? How many minutes off was it, and why?

Tips

- Near noon the shadow changes length very slowly, so measure carefully in millimeters if you can.
- Several measurements close together may tie for shortest. Choose the middle one.
- Example: Denver is near 105° W, right on the Mountain Time center line, so its winter solar noon comes close to 12:00 on the clock.

Check your work

- I measured the shadow every 5 minutes without moving the stick.
- I found my town's solar noon by the clock and compared it with my calculation.
- I set four time-zone clocks correctly and can explain why they differ by one hour.

FIELD NOTEBOOK

1. Draw a train station wall in 1882 with three clocks showing three different times. Below it, draw the same wall after November 18, 1883 with one clock for each time zone.
2. Copy the time-zone strip diagram and add a star for your own town. Write your zone and your longitude beside it.

3. Record your solar-noon table and circle the shortest shadow. Write the clock time of your solar noon.

From history. The prime meridian at Greenwich was not chosen by accident. The Royal Observatory at Greenwich, founded in 1675, had spent two centuries making careful star measurements, and most of the world's sea charts already measured longitude from Greenwich. At the International Meridian Conference in Washington, D.C., in 1884, the delegates voted to make Greenwich the starting line for the whole world. France did not vote for it and kept using Paris time for many more years before finally switching.

WORKED EXAMPLES

Example 1. It is 12:00 noon Eastern Time. What time is it in the Central, Mountain and Pacific zones? A train leaves New York at 8:00 in the morning Eastern Time and runs 18 hours to Chicago, which is on Central Time. What does the clock in Chicago say when it arrives?

(Use the map or drawing "Moving west one zone means setting the clock back one hour." shown earlier in this lesson.)

1. Each zone to the west is one hour earlier. Central: 12:00 − 1 hour = 11:00. Mountain: 10:00. Pacific: 9:00.
2. Add the trip time in Eastern Time: 8:00 in the morning + 18 hours = 2:00 the next morning, Eastern Time.
3. Chicago is one zone west, so subtract 1 hour: 2:00 − 1 hour = 1:00 in the morning.

Answer: Central 11:00, Mountain 10:00, Pacific 9:00 in the morning. The train arrives in Chicago at 1:00 in the morning, Central Time, the next day.

Example 2. Town A lies on the meridian at 75° W, the center of the Eastern zone. Town B lies at 80° W, also in the Eastern zone. When the clock in both towns says 12:00 noon (standard time), what is the local sun time in Town B?

1. Find the difference in longitude: 80° − 75° = 5°.
2. Each degree is 4 minutes of sun time: 5 × 4 = 20 minutes.
3. Town B is farther west, so its sun is behind. At 12:00 on the clock, the sun in Town B has not yet reached its highest point.
4. Local sun time in Town B: 12:00 − 20 minutes = 11:40.

Answer: 11:40 by the sun. Town B's solar noon comes 20 minutes later, at about 12:20 on the clock.

PRACTICE

1. EASY How many degrees does the earth turn in one hour? Show how you know.
2. EASY Name the four time zones the railroads began using on November 18, 1883, from east to west.
3. MEDIUM It is 3:00 in the afternoon in Atlanta (Eastern Time). What time is it in Los Angeles (Pacific Time)?
4. MEDIUM Two towns are 6 degrees of longitude apart. How many minutes apart are their solar noons? Which town has solar noon first?
5. MEDIUM Before 1883, each city kept its own sun time. This table shows the local sun time in four cities at the moment the sun was highest over the 75° W meridian:
   Boston, 71° W: 12:16
   New York, 74° W: 12:04
   Washington, 77° W: 11:52
   Pittsburgh, 80° W: 11:40
   (a) Which city was farthest east? (b) How many minutes apart were the clocks of Boston and Pittsburgh? (c) Check one row using the 4-minutes-per-degree rule.
6. HARD You want to find out whether the clock time of solar noon in your yard changes from week to week. Design the experiment. Name what you change, what you keep the same and what you measure.
7. HARD In two or three sentences, explain why the railroads, more than farmers or shopkeepers, needed standard time.
8. CHALLENGE A train leaves Chicago (Central Time) at 9:00 in the evening and travels 18 hours to Denver (Mountain Time). What does the clock in Denver say when it arrives? Show your steps.

COMMON MISTAKES

- Thinking time zones were made up for no reason. They come from the turning earth: 15 degrees of turning is one hour, so each zone is about 15 degrees wide.
- Setting the clock the wrong way. Traveling east, you move your clock later (ahead); traveling west, you move it earlier (back).
- Thinking every place in a time zone has solar noon at exactly 12:00. Only places on the zone’s center meridian do (and even there the sun can run a little fast or slow during the year). Places east of the center have solar noon earlier, and places west of it later.

Make it a game · Station Master. Hang your four paper-plate time-zone clocks on the wall. The caller sets one clock to any time, for example Mountain 4:00. The station master has ten seconds to set the other three clocks correctly. Then the caller names a train trip, such as “Leave Eastern at 7:00, ride 5 hours, arrive in Central,” and the station master announces the arrival time. Score one point for each correct clock and each correct arrival. Switch roles and play to ten points.

Scripture. “So teach us to number our days, that we may apply our hearts unto wisdom.”

> (Psalm 90:12, KJV)

The railroads learned to count minutes carefully, because a few minutes could mean a missed train or worse. Moses prayed that God would teach us to count our days carefully too, so that we use the time He gives us wisely.

Practice answers

1. 15 degrees, because 360° ÷ 24 hours = 15° per hour.
2. Eastern, Central, Mountain and Pacific.
3. Pacific is 3 hours behind Eastern, so it is 12:00 noon.
4. 6 × 4 = 24 minutes. The town farther east has solar noon first.
5. (a) Boston (its clock was the latest, and it has the smallest west longitude). (b) 12:16 − 11:40 = 36 minutes. (c) Example: Pittsburgh is 80° − 75° = 5° west, and 5 × 4 = 20 minutes earlier, so 12:00 − 20 minutes = 11:40. (Boston is 4° east: 4 × 4 = 16 minutes later, 12:16.)
6. Change: the date (measure once a week for six weeks). Keep the same: the same stick in the same level spot, kept straight up; the same clock checked against time.gov; and the same method (shadow measured every 5 minutes around midday). Measure: the clock time of the shortest shadow each week. Record the date and clock time of solar noon in a table and look for a pattern.
7. Trains traveled through many towns in one day, and every town’s sun time was a little different, so timetables were confusing and passengers missed connections. Trains sharing one track had to know exactly when other trains would pass, so a difference of even a few minutes could cause a collision. One standard time for a whole zone let everyone use the same clock.
8. 9:00 in the evening + 18 hours = 3:00 the next afternoon, Central Time. Denver is one zone west, so subtract 1 hour: 2:00 in the afternoon, Mountain Time, the next day.

Unit 1 review

Answer each question. Show your work for calculations and use complete sentences for explanations. The quiz is worth 50 points in all: 10 questions, 5 points each.

1. (5 pts) At noon on the longest day of the year, an upright post in Syene cast no shadow, but a pointer in Alexandria cast a short shadow. What did this tell Eratosthenes about the shape of the earth, and why?
2. (5 pts) Eratosthenes measured a shadow angle of 7.2° in Alexandria. The distance to Syene was about 5,000 stadia. Show how he found the size of the earth.
3. (5 pts) Two towns due north and south of each other are 500 km (about 310 miles) apart, and their noon sun angles differ by 4.5°. Estimate the earth's circumference.
4. (5 pts) Name the part of a sundial that casts the shadow. In the United States, which direction does a stick's shadow point at solar noon, and is it longest or shortest then?
5. (5 pts) A student recorded a stick's shadow: 9:00, 52 cm; 10:00, 38 cm; 11:00, 30 cm; 12:00, 28 cm; 1:00, 30 cm; 2:00, 38 cm. (a) When was solar noon? (b) How many degrees does the sun seem to move between 10:00 and 2:00?
6. (5 pts) Define rotation and revolution. Tell how long each takes and what each one gives us.
7. (5 pts) Explain why the calendar adds February 29 about every four years.
8. (5 pts) What did Foucault's pendulum in Paris show, and how? Then name what you would change, keep the same and measure in an experiment to test whether string length changes how long a pendulum takes to swing.
9. (5 pts) It is 4:00 in the afternoon in Chicago (Central Time). What time is it in New York (Eastern), Denver (Mountain) and San Francisco (Pacific)?
10. (5 pts) Why did the railroads adopt standard time zones on November 18, 1883? Why is each zone about 15 degrees of longitude wide?

Unit project: my sky clock notebook

Make a small science notebook that shows how the sky keeps time. Include: your noon-shadow drawing with the sun's angle measured by protractor (Lesson 1.1); your full-day shadow table and bar graph with solar noon circled (Lesson 1.2); a labeled diagram of rotation and revolution and your pendulum results (Lesson 1.3); and your solar-noon-versus-clock-noon results with a time-zone strip map showing your own town (Lesson 1.4). Finish with a one-page letter to Eratosthenes explaining what you measured and what you learned about the God who set the lights in the sky "for days, and years."

- **Measurement**: Shadow lengths, angles and times are measured carefully, with units, dates and clock times recorded.
- **Data and graphs**: Tables are complete, the bar graph has labeled axes and a title, and solar noon is correctly found.
- **Explanation**: The diagrams and letter correctly explain parallel rays, rotation and revolution, and why time zones are 15° wide.

- **Care**: The notebook is neat, labeled and easy to follow, with drawings done carefully.

Answer key

1. It told him the earth's surface is curved (round). The sun's rays arrive parallel, so on a flat earth every noon shadow would be the same. Different shadows in different places mean the ground is curved between them.
2. 360 ÷ 7.2 = 50, so the distance between the cities is 1/50 of the way around the earth. 5,000 × 50 = 250,000 stadia.
3. 360 ÷ 4.5 = 80. 500 km × 80 = 40,000 km (310 × 80 = 24,800 miles).
4. The gnomon. At solar noon the shadow points north and is the shortest of the day.
5. (a) 12:00, the time of the shortest shadow (28 cm). (b) 4 hours × 15° per hour = 60°.
6. Rotation is the earth spinning on its axis; it takes about 24 hours and gives us day and night. Revolution is the earth's trip around the sun; it takes about 365¼ days and gives us the year.
7. One revolution takes about 365¼ days, but a normal year has 365 days. The extra quarter day each year adds up to 4 × ¼ = 1 whole day after four years, so a leap year adds one day.
8. It showed that the earth rotates: the pendulum kept swinging in the same direction while the floor turned underneath it, so the swing seemed to turn slowly around the ring of sand. Experiment: change the string length; keep the weight, the pull-back distance and the release the same; measure the time for 10 swings.
9. New York 5:00, Denver 3:00 and San Francisco 2:00 in the afternoon.
10. Before 1883 every town kept its own sun time, and railroads kept dozens of different times, which made timetables confusing and train travel less safe. Zones are about 15° wide because the earth turns 360° in 24 hours, which is 15° each hour, so each zone is one hour apart.

UNIT 2

The Moon

The Moon is the nearest of all the lights God set in the heaven, and the easiest to study. You can see it with your own eyes, sketch it with a pencil, and watch it change every night. In this unit you will look at the Moon the way the great observers did, with patience, careful drawings and a measuring mind. You will learn what the Moon is made of, why its shape changes through the month, why it sometimes turns red or blots out the Sun, and how it lifts the oceans twice a day.

You will stand beside Galileo in Padua in 1609 as his homemade telescope shows mountains and craters on the Moon. You will ride with the Apollo 8 astronauts as Earth rises over the Moon on Christmas Eve, 1968. You will read Edmond Halley's map of the eclipse of 1715 and walk the shore of the North Sea with the monk Bede, who noticed that the tides keep time with the Moon. In every lesson you will build a model, measure a shadow or read a table, and ask the scientist's question: **How do we know?**

BEFORE YOU BEGIN

- Knows that Earth spins once a day (day and night) and travels around the Sun once a year (Unit 1)
- Can measure lengths in centimeters with a ruler and record results in a table
- Can add and subtract times in hours and minutes
- Can divide large numbers with a calculator or by long division

MASTERY CHECKLIST

- I can tell how Galileo discovered mountains and craters on the Moon and explain why shadows show them best near the terminator.
- I can explain that half the Moon is always lit and that the phases come from how much of that lit half we see.
- I can name and draw the eight phases in order and predict phases and moonrise times.
- I can explain solar and lunar eclipses, which phase goes with each, and why they do not happen every month.
- I can explain how the Moon's gravity makes tides, including spring and neap tides, and read a tide table.
- I can design a fair test by changing one thing, keeping the rest the same and measuring the result.

OPTIONAL BOOKS AND RESOURCES

- **NASA Moon (Earth's Moon) website** (https://moon.nasa.gov/): Free. Photographs, Moon maps, a daily Moon-phase guide and facts checked by NASA scientists. Use it for Lessons 2.1 and 2.2 and the portfolio Moon map.

- **NASA Eclipse Web Site** (https://eclipse.gsfc.nasa.gov/): Free. Tables and maps of past and future solar and lunar eclipses. Look up the next lunar eclipse you can see from home (Lesson 2.3).
- **NOAA Tides and Currents** (https://tidesandcurrents.noaa.gov/): Free. Real tide predictions for hundreds of U.S. coastal stations. Choose a station, print a week of high and low tides and graph them for Lesson 2.4.

2.1 Galileo Sees Mountains on the Moon (1609) ★

OBJECTIVES

- Tell how Galileo used a telescope in 1609 to discover that the Moon has mountains, valleys and craters.
- Explain why the Moon shines and why shadows near the terminator make mountains and craters easy to see.
- Measure shadows in a model and use a shadow-to-height ratio to find the height of a model mountain, the way Galileo reasoned about the Moon.

Warm-up. Crumple a sheet of aluminum foil into a loose ball, then gently flatten it on a plate so it is bumpy. In a dark room, shine a flashlight straight down on it from above. Now hold the flashlight low, almost level with the table, and shine it across the foil from one side. Which way shows the bumps and hollows better? Why do you think so?

Video. Coming soon. Galileo's 1609 telescope and his drawings of the Moon; Moon craters, maria and the terminator through binoculars or a small telescope. Search NASA (Moon and Lunar Reconnaissance Orbiter), NASA Goddard Scientific Visualization Studio, Smithsonian National Air and Space Museum, Museo Galileo, SciShow Kids and Homeschool Pop (Alternate).

KEY TERMS

telescope
An instrument with lenses or mirrors that gathers light and makes faraway things look larger and brighter.

magnify
To make something look bigger than it looks to the eye alone. A telescope that magnifies 20 times makes the Moon look 20 times wider.

terminator
The line on the Moon between the sunlit part and the dark part. Standing on the terminator, you would see the Sun rising or setting.

crater
A round, bowl-shaped hollow with a raised rim on the surface of the Moon or a planet.

maria
The large, dark, smooth plains on the Moon (one is a mare). The word is Latin for "seas," but they are plains of dark rock with no water.

reflect
To bounce light back. The Moon makes no light of its own; moonlight is sunlight reflected from the Moon's rocky surface.

CORE IDEAS

The story. In the summer of 1609, Galileo Galilei, a professor of mathematics at the University of Padua in Italy, heard that a Dutch spectacle maker had made a tube with two lenses that made faraway things look near. Galileo did not wait to buy one. He ground his own lenses and built his own telescopes, each better than the last. By the end of that year one of them made things look about 20 times wider. From late November through December of 1609, on clear nights, he pointed it at the Moon. Night after night he watched and made careful drawings in brown ink wash. In March 1610 he published what he had seen in a small book called *Sidereus Nuncius*, *The Starry Messenger*.

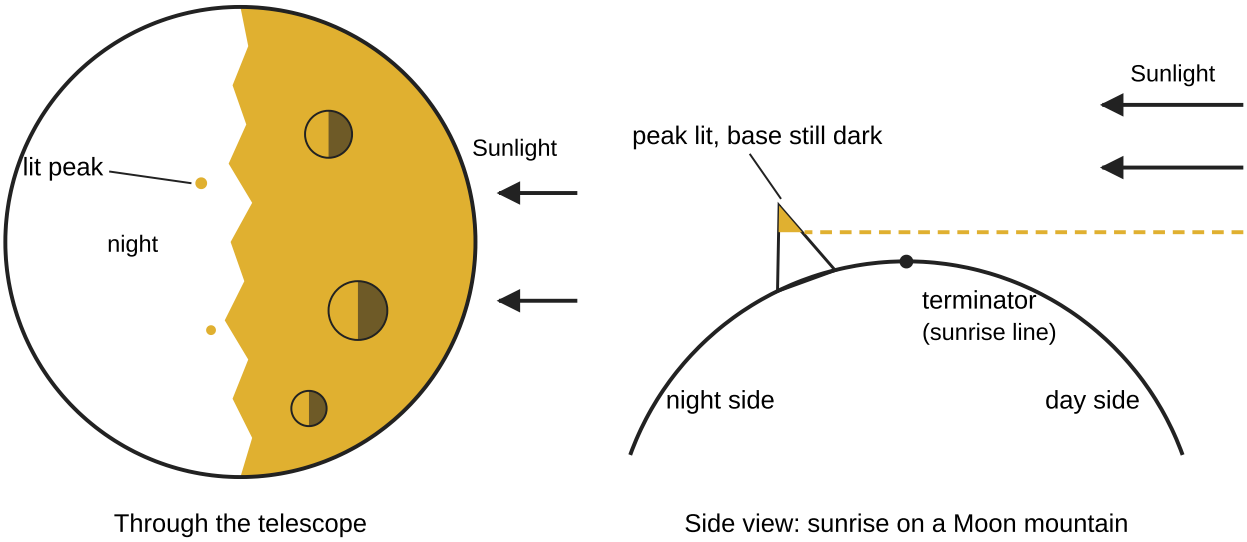
How they figured it out. Many learned men of Galileo's day, following the old Greek teacher Aristotle, taught that the Moon was a perfectly smooth, polished ball. Galileo saw something else. The **terminator**, the line between the Moon's bright part and its dark part, was not smooth. It was jagged and rough. Out in the dark part, a little beyond the terminator, he saw tiny points of light. Night by night they grew and joined the bright part. Galileo remembered how mountain tops on Earth catch the first rays of sunrise while the valleys below are still dark. These bright points must be the tops of mountains on the Moon! He also saw round hollows whose shadows lay on the side away from the Sun and grew shorter as the Sun rose higher over them. By measuring how far a lit peak stood from the terminator and using geometry, he worked out that the Moon's mountains were at least as tall as the highest mountains on Earth, and he thought they were even taller. The Moon, he concluded, is rough and rugged, with mountains and valleys, much like our own world.

The big idea. The Moon is a ball of rock about one-fourth as wide as Earth: about 3,475 kilometers (2,159 miles) across. Its average distance from Earth is about 384,400 kilometers (238,900 miles). It makes no light of its own. Moonlight is sunlight **reflected** off gray rock and dust. Through even ordinary binoculars you can see the dark **maria**, smooth plains of dark rock that early astronomers took for seas, and the bright, rough highlands full of **craters**. The Moon has no air, no liquid water and no weather, so its craters and mountains stay sharp, and the footprints astronauts left there in 1969 and the early 1970s are still there. The same side of the Moon always faces Earth, so you see the same "face" every month.

Try it and see. Shadows are the secret. When the Sun is low in the sky, shadows are long, and long shadows show every bump. That is why the best place to look for lunar mountains and craters is near the terminator, where the Sun is rising or setting on the Moon. At full moon, the Sun shines straight down on the side facing us, shadows almost disappear, and the Moon looks flat and bright. So the best nights to look are around first quarter, when the Moon is half lit. Rest your binoculars on a fence or a car roof, or lean against a wall, to hold them steady. Then look along the terminator and sketch what you see, just as Galileo did.

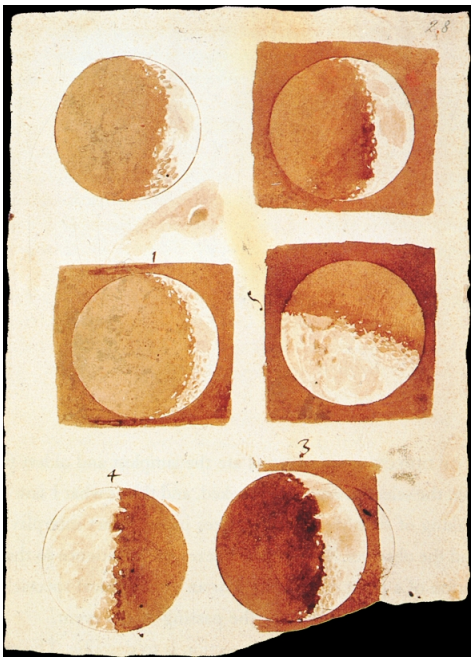
God's handiwork. Galileo was amazed to see God's handiwork more clearly than anyone before him. He wrote that the Bible and the book of nature both come from God, and so the two cannot truly disagree. When David looked up at night, he wrote, "When I consider thy heavens, the work of thy fingers, the moon and the stars, which thou hast ordained" (Psalm

8:3). A telescope did not make the Moon any less wonderful. It showed that the Moon is a real place, with mountains and plains, made and set in its path by the Creator. Your own careful looking and drawing is the same kind of work Galileo did.



What Galileo saw (left) and why (right): just beyond the terminator, a high peak catches sunlight while the ground around it is still in night.

PICTURE STUDY



Drawings of the Moon, Galileo Galilei, 1609 · Brown ink wash on paper · Biblioteca Nazionale Centrale (National Central Library), Florence, Italy

These are some of the very first pictures ever made of the Moon as seen through a telescope. Galileo was not only a mathematician; he had studied drawing as a young man and knew how light and shadow show the shape of things. He painted these small studies with a brush and brown ink thinned with water, working at night from what he saw in the eyepiece.

Look closely at the edge between light and dark. Galileo drew it ragged on purpose, because that is what he saw. Some of these drawings were later made into engravings for *The Starry Messenger*, so that readers all over Europe could see the Moon's mountains and hollows for themselves.

Look closely

- Find the terminator, the edge between the lit and dark parts. Is it smooth or rough?
- Look for small bright spots out in the dark part. What did Galileo decide they were?
- Find a dark round spot in the bright part. On which side of it is the shadow?
- Compare two drawings. How is the amount of the Moon that is lit different?

Talk about it

1. Why did Galileo use only light and shadow, and no outlines, to show the mountains?
2. Why do you think people believed Galileo once they could look through a telescope themselves?
3. What would you want to draw if you were the first person to look at something through a telescope?

> **Safety first.** Never point binoculars or a telescope at the Sun or anywhere near it, not even for a moment; it can blind you instantly. Look at the Moon only after the Sun has set or when the Sun is well out of view, and have an adult help. When you measure shadows outdoors, look down at the shadows, never up at the Sun.

EXPERIMENT: MOUNTAINS, SHADOWS AND A MODEL MOON

Galileo could not visit the Moon, so he reasoned from light and shadow. You will build small clay mountains, light them like the Sun at different heights, and measure their shadows. Then you will use a shadow to find the height of a mountain you have not measured, the same idea Galileo used.

Question: How does the height of the "Sun" in the sky change the length of a mountain's shadow? **Prediction:** Write what you think will happen before you start.

You will need

- Modeling clay or play dough
- A flashlight (a small LED flashlight with a narrow beam works best)
- Two rulers (centimeters)
- A stack of books to rest the flashlight on
- A sheet of white paper or poster board

- A ball (a small foam ball or an orange) and small clay bumps for the model Moon
- Pencil and lab notebook

Steps

1. Make a cone-shaped clay mountain exactly 3 cm tall. Set it on the white paper in a dark room.
2. Lay a ruler flat on the paper. Place the flashlight on a stack of books 30 cm from the mountain, with its bulb 10 cm above the table, pointing at the mountain.
3. Measure the shadow from the base of the mountain to the tip of the shadow. Record it in a table: Light height (cm), Shadow length (cm).
4. Raise the light to 15 cm, then 20 cm, then 30 cm, keeping the distance at 30 cm each time. Measure and record the shadow each time.
5. **What we change:** the height of the light. **What we keep the same:** the mountain, its distance from the light and the flashlight. **What we measure:** the shadow length.
6. Now make a second mountain of a different height, but do not measure it. On a sunny morning or late afternoon, carry both mountains outside on a board and set them side by side. Measure both shadows. Use the shadow ratio from your first mountain (shadow ÷ height) to predict the height of the second. Then measure it to check.
7. Make a model Moon: press small clay bumps and rims onto the ball. Shine the flashlight from the side so half the ball is lit. Look along the line between light and dark. Can you see bright tips of bumps standing in the dark part, like Galileo's peaks?

Tips

- Keep the flashlight from moving while you measure. Tape it to the books if needed.
- Measure to the darkest tip of the shadow. A fuzzy edge is normal; choose the middle of the fuzzy part each time.
- The ratio trick works in sunlight because the Sun is so far away that its rays arrive almost parallel, so every object nearby gets the same shadow ratio. A nearby flashlight spreads its rays out, so taller and shorter mountains do not share one ratio. That is why the second part is done outdoors.

Check your work

- My table shows shadows getting shorter as the light gets higher.
- I used a shadow ratio to predict the height of a second mountain and checked it.
- I can explain why mountains on the Moon show up best near the terminator.

FIELD NOTEBOOK

1. On a night near first quarter, look at the Moon through steady binoculars and draw a circle with the lit half. Shade the dark maria you see and mark the terminator. Write the date, time and what you used to look.
2. Copy one of Galileo's Moon drawings with a pencil, using only shading, no outlines. Label the terminator, a lit peak and a crater shadow.

3. Draw your clay mountain and its shadow at two light heights side by side, with measurements written on each.

From history. Galileo was not quite the first. In England, Thomas Harriot pointed a telescope that magnified about 6 times at the Moon in the summer of 1609, months before Galileo, and made a rough sketch. But Harriot did not publish it, and his first drawing did not show mountains. After he read *The Starry Messenger*, Harriot made much better Moon maps of his own. Galileo's gift was not only seeing first, but explaining what he saw and sharing it with the world.

WORKED EXAMPLES

Example 1. The Moon is about 384,400 km (238,900 mi) away. Galileo's best telescope made things look about 20 times wider. How close did the Moon seem through his telescope?

1. Making something look 20 times wider is like seeing it from 20 times closer.
2. Divide the distance by 20: 384,400 km ÷ 20 = 19,220 km.
3. In miles: 238,900 mi ÷ 20 = 11,945 mi, about 11,900 mi.

Answer: About 19,220 km (about 11,900 mi) away, still very far, but close enough to see mountains and craters.

Example 2. Outdoors in the late-afternoon sun, a 4 cm clay mountain casts a 10 cm shadow. At the same moment, a second mountain beside it casts a 15 cm shadow. How tall is the second mountain?

1. Find the shadow ratio for the first mountain: 10 cm ÷ 4 cm = 2.5. Each centimeter of height makes 2.5 cm of shadow.
2. The sunlight strikes both mountains at the same angle at the same moment, so the second mountain has the same ratio.
3. Height = shadow ÷ ratio = 15 cm ÷ 2.5 = 6 cm.
4. Check: 6 cm × 2.5 = 15 cm. ✓

Answer: 6 cm tall (about 2.4 in). Galileo used the same idea, light and shadow plus geometry, to estimate the heights of the Moon's mountains.

PRACTICE

1. EASY What did Galileo see along the Moon's terminator, and what did he conclude?
2. EASY Where does moonlight come from?
3. MEDIUM The Moon is about 3,475 km (2,159 mi) across and Earth is about 12,742 km (7,918 mi) across. About how many Moons could be lined up across Earth?

4. MEDIUM A student measured the shadow of a 3 cm clay mountain with the light 30 cm away at different heights:
   Light height 10 cm → shadow 12.9 cm
   Light height 15 cm → shadow 7.5 cm
   Light height 20 cm → shadow 5.3 cm
   Light height 30 cm → shadow 3.3 cm
   (a) What happens to the shadow as the light gets higher? (b) On the Moon, where would you expect the longest shadows: near the terminator or in the middle of the lit part?
5. MEDIUM Experiment design: You want to test whether taller clay mountains cast longer shadows. What will you change? Name two things you must keep the same. What will you measure?
6. HARD Your friend wants to see craters through binoculars and says, “Let’s wait for the full moon, when the Moon is brightest.” In two or three sentences, explain why that is not the best plan.
7. HARD Ordinary binoculars magnify about 10 times. How close does the Moon seem through them? Use 384,400 km (238,900 mi).
8. CHALLENGE Make an Earth-Moon model. If Earth is a ball 24 cm (about 9.4 in) wide, how wide should the Moon ball be, and how far apart should they be? Use Earth 12,742 km, Moon 3,475 km and distance 384,400 km.

COMMON MISTAKES

- Thinking Galileo invented the telescope. Spectacle makers in the Netherlands made the first ones in 1608; Galileo built better ones himself and was among the first to use them to study the sky.
- Thinking the Moon makes its own light. Moonlight is sunlight reflected off the Moon’s gray rock.
- Thinking the dark maria are seas of water. They are plains of dark rock; the Moon has no liquid water on its surface.

> **Make it a game · Shadows Under the Towel.** While the child looks away, a parent hides three or four small objects (a spoon, a coin, a bottle cap, a toy) under a thin dish towel on the table. Turn off the lights. The child may not touch, only shine a flashlight across the towel from a low angle and from straight above. From the shadows, the child guesses each object’s shape and size. One point for each correct guess. Then switch roles.

> **Scripture.** “When I consider thy heavens, the work of thy fingers, the moon and the stars, which thou hast ordained;” (Psalm 8:3, KJV)

David “considered” the heavens: he looked carefully and thought about what he saw. A telescope lets us consider the Moon even more closely, and what we find is still the work of God’s fingers.

Practice answers

1. He saw that the terminator was jagged, with bright points of light out in the dark part and hollows with shadows in the lit part. He concluded that the Moon has mountains, valleys and craters and is not a perfectly smooth ball.
2. From the Sun. The Moon makes no light of its own; it reflects sunlight off its rocky surface.
3. 12,742 ÷ 3,475 ≈ 3.7, so between 3 and 4 Moons; the Moon is about one-fourth as wide as Earth.
4. (a) The shadow gets shorter as the light gets higher. (b) Near the terminator, because there the Sun is low in the Moon’s sky, like sunrise or sunset.
5. Change: the height of the mountain (for example 2 cm, 4 cm, 6 cm). Keep the same: the height of the light, the distance from the light to the mountain, and the same flashlight (any two). Measure: the length of each shadow.
6. At full moon the Sun shines straight down on the side facing us, so there are almost no shadows and the Moon looks flat. Craters and mountains show best near the terminator, where the Sun is low and shadows are long, so a night near first quarter is better.
7. 384,400 km ÷ 10 = 38,440 km (238,900 mi ÷ 10 = 23,890 mi).
8. Scale: 24 cm stands for 12,742 km. Moon: 24 × 3,475 ÷ 12,742 ≈ 6.5 cm (about 2.6 in), about the size of a tennis ball. Distance: 384,400 ÷ 12,742 ≈ 30 Earth-widths, so 30 × 24 cm = 720 cm = 7.2 m (about 24 ft).

2.2 Phases Explained

OBJECTIVES

- Explain that half of the Moon is always lit by the Sun and that phases come from how much of that lit half we see from Earth.
- Name and draw the eight phases of the Moon in order and tell whether the Moon is waxing or waning.
- Use the 29½-day lunar month and the Moon's daily delay of about 50 minutes to predict phases and moonrise times.

Warm-up. Hold a ball (an orange or an apple works) at arm's length in a room with one bright window or one lamp. Turn slowly in a circle, keeping your eyes on the ball. Watch how the bright part of the ball changes shape as you turn. Without turning on any other light, can you make the ball look like a thin crescent? Like a full circle?

Video. Coming soon. Why the Moon has phases, shown with a lamp-and-ball model or animation; the Apollo 8 Earthrise photograph. Search NASA (Moon and Apollo 8), NASA Goddard Scientific Visualization Studio (Moon phase and libration), NOAA SciJinks, Science Max, SciShow Kids and Homeschool Pop (Alternate).

KEY TERMS

phase
The shape of the lit part of the Moon as we see it from Earth on a certain night.

waxing
Growing. A waxing Moon shows more of its lit side each night, from new moon toward full moon.

waning
Shrinking. A waning Moon shows less of its lit side each night, from full moon toward new moon.

crescent
A phase when less than half of the Moon's face looks lit, shaped like a curved fingernail.

gibbous
A phase when more than half but not all of the Moon's face looks lit.

lunar month
The time from one new moon to the next, about 29½ days.

CORE IDEAS

The story. On December 24, 1968, three American astronauts, Frank Borman, Jim Lovell and Bill Anders, became the first people ever to circle the Moon. Their spacecraft, Apollo 8, went around it ten times. On one trip around, Earth came up over the gray lunar horizon,

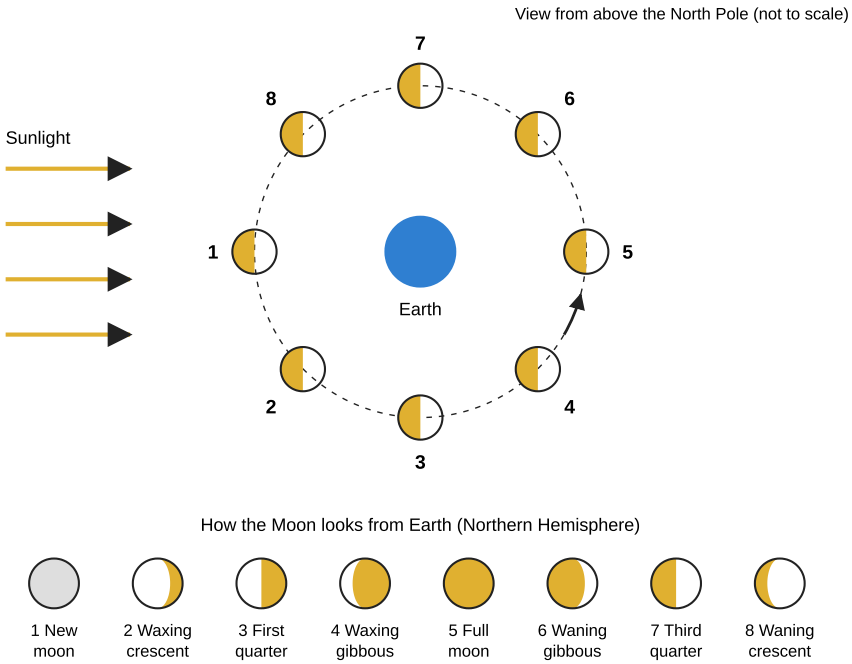
blue and white against the black sky. Anders grabbed his camera and took the photograph now called *Earthrise*. Look closely at that picture and you will see something surprising: Earth was not a full circle. Only part of it was lit. The rest was in night. From the Moon, Earth has phases too! That same Christmas Eve, the three men took turns reading Genesis 1 aloud on television to the people back home, beginning, “In the beginning God created the heaven and the earth.”

How they figured it out. People did not need a spacecraft to understand phases. More than two thousand years ago, Greek thinkers such as Anaxagoras reasoned that the Moon has no light of its own and is lit by the Sun. You can see the clue yourself. Look at a thin crescent Moon just after sunset, low in the west. Its bright, rounded edge always points toward where the Sun has just gone down. The lit side of the Moon always faces the Sun. As the Moon travels around Earth, we look at that lit side from different angles. Sometimes we see it straight on, sometimes from the side, and sometimes hardly at all.

The big idea. The Sun always lights half of the Moon, just as it always lights half of Earth (that is day and night). The **phase** we see depends on how much of that sunlit half faces us. At **new moon**, the Moon is between Earth and the Sun, its lit side faces away, and we see nothing. Then, night by night, the Moon is **waxing**: a thin **crescent**, then the **first quarter** (half the face lit), then **gibbous**, then **full moon**, when the Moon is on the far side of Earth from the Sun and we see its whole lit face. After that it is **waning**: gibbous, **third quarter**, crescent, and new again. One whole cycle, a **lunar month**, takes about 29½ days. In the Northern Hemisphere, a waxing Moon is lit on the right and a waning Moon is lit on the left. Earth’s shadow has nothing to do with the phases; that is a different event, an eclipse.

Try it and see. The Moon moves along its orbit about 12 to 13 degrees a day, so it rises about 50 minutes later each day, on average. That is why the full moon rises in the east just as the Sun sets in the west, while the first quarter Moon is already high in the south at sunset, and you can often see it in the afternoon. A third quarter Moon rises around midnight and is still up in the morning sky when you go to school. The Moon also spins exactly once each time it goes around Earth, so it always keeps the same face toward us. The “far side” is not dark; it gets just as much sunlight as the near side, at different times.

God’s handiwork. On the fourth day of creation God made the lights in the heaven “for signs, and for seasons, and for days, and years” (Genesis 1:14). The Moon’s phases are a calendar anyone can read, even a shepherd with no books. In ancient Israel each month began when the first thin crescent was seen after the new moon, and the great feasts were counted from it. The Moon never forgets its schedule. The phases you see this month will come again, in the same order, next month.



Half of the Moon is always lit by the Sun (top). The numbered shapes (bottom) show how much of that lit half we see from Earth at each place in the Moon's orbit.

PICTURE STUDY



Earthrise, William Anders, Apollo 8 astronaut, NASA, December 24, 1968 · Color photograph on 70 mm film · NASA (public domain)

This is a photograph, not a painting, but it is one of the most famous pictures ever made. Bill Anders took it from the Apollo 8 spacecraft as it came around the Moon on Christmas Eve, 1968. When Earth came into view, Anders quickly asked for a roll of color film. The three men had trained to photograph the Moon, but the view of home caught them by surprise.

The photograph is usually shown with the Moon’s surface at the bottom, as if Earth were rising like the Sun. In space there is no real up or down, and the astronauts saw Earth beside the lunar horizon. Either way, the picture shows Earth the way it looks from the Moon: part in daylight and part in night, a phase.

Look closely

- Find the part of Earth that is lit and the part in shadow. Where must the Sun be?
- Look at the edge between light and dark on Earth. That is Earth’s terminator. What is happening to the people living along that line?
- Look at the Moon’s surface in the front of the picture. What shapes can you find?
- Compare the colors of Earth and the Moon. Why do you think Earth looks so much brighter and more colorful?

Talk about it

1. If an astronaut on the Moon sees a “full Earth,” what phase would we see the Moon in from Earth at that time?
2. Why do you think this photograph made so many people stop and think about God and home?
3. If you could take one picture from space, what would you want it to show?

> **Safety first.** Lamp bulbs can get hot. Use an LED bulb if you can, take off the lampshade only with an adult’s help, and do not touch the bulb.

EXPERIMENT: MOON PHASES IN YOUR LIVING ROOM

You will make the phases yourself with a lamp, a ball and your own head. The lamp is the Sun, the ball is the Moon, and your head is Earth. Your eyes are a person on Earth looking up.

Question: What makes the Moon’s shape change through the month? **Prediction:** Before you begin, write whether you think the shape changes because of Earth’s shadow, because of clouds, or because we see the Moon’s lit half from different angles.

You will need

- A lamp with the shade removed (an LED bulb is best), placed at about head height
- A light-colored ball about 7 to 10 cm (3 to 4 in) wide: a foam craft ball, a tennis ball or an orange
- A pencil or craft stick pushed into the ball as a handle
- A dark room
- Lab notebook, pencil and a paper with eight circles drawn on it

Steps

1. Stand about 2 meters (about 6 feet) from the lamp. Hold the ball at arm's length, a little above your head so your head does not block the light.
2. Face the lamp with the ball in front of your face. The lit side faces away from you. This is position 1, new moon. In circle 1, draw what you see.
3. Turn your whole body slowly to the left (counterclockwise), one-eighth of a turn at a time, keeping the ball at arm's length in front of you. At each stop, draw the shape of the lit part you see.
4. At position 3 (facing sideways to the lamp) you should see half the ball lit: first quarter. At position 5 (back to the lamp, ball above your head's shadow) you should see it all lit: full moon.
5. Keep turning until you are back at new moon. Label your eight drawings: new, waxing crescent, first quarter, waxing gibbous, full, waning gibbous, third quarter, waning crescent.
6. Test the shadow idea: lower the ball at full moon so it passes into the shadow of your head. What happens? (You have made a model eclipse, the subject of the next lesson.)
7. **What we change:** where the Moon is in its orbit. **What we keep the same:** the lamp's place, the arm's length and the ball. **What we record:** the shape of the lit part at each position. Write one sentence: Was your prediction right?

Tips

- Keep the ball slightly higher than your head, or your head's shadow will spoil the full moon.
- Move slowly. The in-between phases, crescent and gibbous, are easy to miss.
- Notice that the lamp lights half the ball the whole time. Only your view of it changes.

Check your work

- I drew all eight phases in order and labeled them.
- I can show that half the ball is always lit.
- I can explain why Earth's shadow does not cause the phases.

FIELD NOTEBOOK

1. Start a Moon log: on five clear evenings this week, draw the Moon's shape and write the date, the time and which direction you faced (east, south or west).
2. Draw the eight phases around a circle with the Sun's light coming from one side, and color the lit half of every Moon.
3. Copy the shape of Earth in the *Earthrise* photograph and label Earth's day side, night side and terminator.

> **From history.** Our word "month" comes from the Old English word for moon, because people have always counted time by the Moon's phases. In ancient Israel, watchmen looked for the first thin crescent after the new moon, and when it was seen, a new month

began. The psalmist wrote, “Blow up the trumpet in the new moon, in the time appointed, on our solemn feast day” (Psalm 81:3).

WORKED EXAMPLES

Example 1. A calendar shows a new moon on March 1. About when will the next first quarter, full moon, third quarter and new moon come?

(Use the map or drawing “Each step between numbered positions takes about 3 or 4 days; each quarter of th” shown earlier in this lesson.)

1. A lunar month is about 29½ days. Each quarter of it is about 29.5 ÷ 4 ≈ 7.4 days.
2. First quarter: March 1 + 7.4 days ≈ March 8.
3. Full moon: March 1 + 14.8 days ≈ March 16.
4. Third quarter: March 1 + 22.1 days ≈ March 23.
5. Next new moon: March 1 + 29.5 days ≈ March 30 or 31.

Answer: First quarter about March 8, full moon about March 16, third quarter about March 23, and new moon again about March 30 or 31. (Real dates can shift by a day because the Moon’s speed changes a little.)

Example 2. At sunset you see a Moon high in the south with its right half lit. What phase is it, and about when will it set?

1. Half the face lit means a quarter Moon. Lit on the right (Northern Hemisphere) means waxing, so it is first quarter.
2. A first quarter Moon is 90 degrees, a quarter of a circle, east of the Sun in the sky.
3. Earth turns a quarter of a circle in about 6 hours. So the Moon is about 6 hours behind the Sun and sets about 6 hours after sunset.
4. If sunset is 6:00 p.m., the Moon sets around midnight.

Answer: First quarter. It sets about 6 hours after the Sun, around midnight if the Sun set at 6:00 p.m.

PRACTICE

1. EASY List the eight phases of the Moon in order, starting with new moon.
2. EASY How much of the Moon is lit by the Sun at full moon? At new moon? At first quarter?
3. MEDIUM A student recorded moonrise times on four nights in a row:
   Day 1: 6:10 p.m.
   Day 2: 6:58 p.m.
   Day 3: 7:49 p.m.

Day 4: 8:40 p.m.
(a) How many minutes later did the Moon rise each day? (b) What is the average delay? (c) Predict moonrise on Day 5.

4. MEDIUM Early one morning before sunrise you see a thin crescent low in the east, lit on its left side. What phase is it? Will it be new moon or full moon next?
5. MEDIUM Experiment design: Jonah wonders whether a bigger ball shows different phase shapes in the lamp model. What should he change? Name two things he should keep the same. What should he record?
6. HARD Your little brother says, “The phases happen because Earth’s shadow covers part of the Moon.” In two or three sentences, explain why that cannot be right.
7. HARD A full moon rises at 6:00 p.m. If the Moon rises about 50 minutes later each day, about what time will it rise 7 days later? What phase will it be then?
8. CHALLENGE An astronaut standing on the near side of the Moon looks at Earth during our new moon. What does Earth look like to the astronaut: new, half, or full? Explain.

COMMON MISTAKES

- Thinking Earth’s shadow causes the phases. The phases come from viewing the Moon’s always-lit half from different angles; Earth’s shadow touches the Moon only during a lunar eclipse.
- Thinking the Moon is out only at night. The Moon is above the horizon about half of each day, and you can often see it in the daytime, especially near first and third quarter.
- Calling the far side of the Moon the “dark side.” The far side gets just as much sunlight as the near side; we simply never see it from Earth because the same face always points toward us.

> **Make it a game · Phase Flash.** A parent draws the eight phases on eight index cards and shuffles them. The child has one minute to lay them out in order from new moon around to waning crescent. Then the parent holds up one card at a time and asks a question about it: “Waxing or waning?” “Does it rise at sunset, noon or midnight?” “What comes next?” One point for each right answer. Beat your score next time.

> **Scripture.** “He appointed the moon for seasons: the sun knoweth his going down.” (Psalm 104:19, KJV)

The Moon’s phases keep perfect time because God appointed them. Every month you can watch the same orderly pattern He set in place.

Practice answers

1. New moon, waxing crescent, first quarter, waxing gibbous, full moon, waning gibbous, third quarter, waning crescent.
2. Half of the Moon every time. Only the amount of the lit half that we can see from Earth changes.

3. (a) 48 minutes, 51 minutes, 51 minutes. (b) (48 + 51 + 51) ÷ 3 = 150 ÷ 3 = 50 minutes. (c) About 8:40 + 50 minutes = 9:30 p.m.
4. A waning crescent. New moon comes next, in a few days.
5. Change: the size of the ball (for example a ping-pong ball and a basketball). Keep the same: the lamp and its place, the distance from the lamp, the arm's length and the positions where he stops (any two). Record: the shape of the lit part at each position. (He will find the shapes are the same; size does not change the phases.)
6. Earth's shadow always points straight away from the Sun, but at a quarter or crescent Moon the Moon is off to the side of Earth, nowhere near that shadow. The phases come from seeing different amounts of the Moon's sunlit half as it goes around us. Earth's shadow falls on the Moon only during a lunar eclipse, at full moon.
7. 7 × 50 = 350 minutes = 5 hours 50 minutes, so about 11:50 p.m. Seven days after full moon it is about third quarter, which rises around midnight. ✓
8. Full. At new moon the Moon is between Earth and the Sun, so the astronaut is looking back at Earth's whole sunlit side. Earth's phases are always the opposite of the Moon's phases.

2.3 Eclipses

OBJECTIVES

- Explain how a solar eclipse and a lunar eclipse happen, and tell which Moon phase goes with each.
- Explain why eclipses do not happen every month and why the Sun and Moon look almost the same size in our sky.
- Describe how to watch a solar eclipse safely and measure how a shadow changes in a model.

Warm-up. Close one eye and hold a coin at arm's length toward a ceiling light or lamp (not the Sun). Slowly bring the coin closer to your eye until it just covers the light. How can a small coin hide a big lamp? What would happen if the coin were farther away?

Video. Coming soon. How solar and lunar eclipses work, the April 8, 2024 total solar eclipse, the red Moon of a total lunar eclipse, and safe eclipse viewing with pinhole projectors. Search NASA (eclipses and NASA Science Live), NASA Goddard Scientific Visualization Studio, NOAA SciJinks, Exploratorium eclipse coverage, Science Max and SciShow Kids.

KEY TERMS

solar eclipse
When the Moon passes between the Sun and Earth and its shadow falls on Earth, hiding all or part of the Sun. It can happen only at new moon.

lunar eclipse
When Earth passes between the Sun and the Moon and Earth's shadow falls on the Moon. It can happen only at full moon.

umbra
The dark inner part of a shadow, where the light is blocked completely. Inside the Moon's umbra you see a total solar eclipse.

penumbra
The lighter outer part of a shadow, where only part of the light is blocked. Inside the Moon's penumbra you see a partial eclipse.

totality
The time during a total eclipse when the Sun (or, in a lunar eclipse, the Moon) is completely covered by the shadow.

CORE IDEAS

The story. In the spring of 1715, the English astronomer Edmond Halley, the same Halley whose name is on a famous comet, knew that the Moon's shadow was about to sweep across

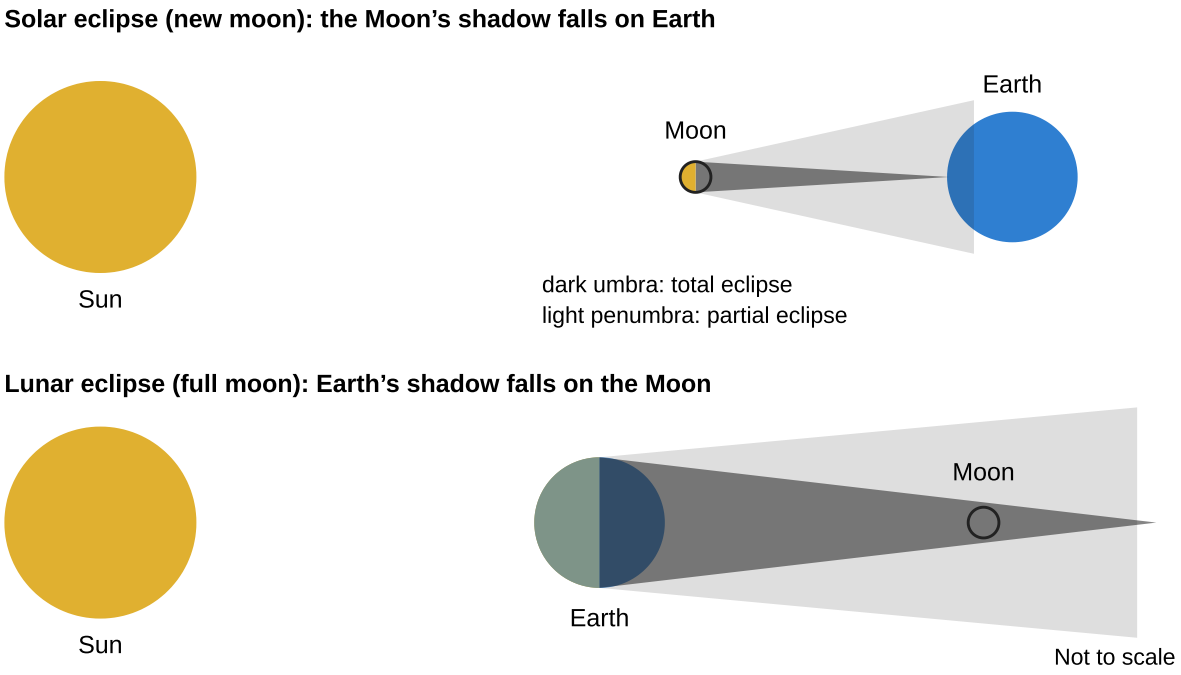
England. The eclipse would come on the morning of May 3, 1715 (April 22 by the old calendar England still used). Halley did not want people to be frightened or to think it was an evil sign. So he printed a map showing the path where the Sun would be completely covered, right over London, and he asked curious people everywhere to watch and write down exactly when the darkness came and how long it lasted. On that morning the sky went dark, stars came out, and the Sun's pearly outer glow shone around the black Moon. Halley's prediction was right to within about four minutes.

How they figured it out. Halley could predict the eclipse because he knew how the Moon moves. Long before, Babylonian sky-watchers had kept records of eclipses for many lifetimes and noticed that they repeat in a pattern about every 18 years and 11 days. Halley gave that pattern the name *saros*. He also used his friend Isaac Newton's new laws of motion and gravity to work out the Moon's path more exactly. After the eclipse he collected the reports people sent in and drew a corrected map. Careful records from many observers, checked against a prediction: that is how science grows.

The big idea. An eclipse is a shadow falling on something. In a **solar eclipse**, the Moon passes between the Sun and Earth, and the Moon's shadow falls on Earth. That can happen only at new moon. People inside the dark **umbra**, a path usually about 160 kilometers (100 miles) wide, see a total eclipse; people in the wider, lighter **penumbra** see only part of the Sun covered. **Totality** never lasts more than about 7½ minutes. In a **lunar eclipse**, Earth passes between the Sun and the Moon, and Earth's shadow falls on the Moon. That can happen only at full moon, and everyone on the night side of Earth can see it. The Moon does not vanish. It turns a coppery red, because a little sunlight bends through Earth's air, which scatters away the blue light and lets the red reach the Moon. Why not an eclipse every month? The Moon's path is tilted about 5 degrees, so most months its shadow passes just above or below Earth.

In the world today. Here is a wonder: the Sun is about 400 times wider than the Moon, but it is also about 400 times farther away. So in our sky they look almost exactly the same size, and the Moon can just cover the Sun. When the Moon is a little farther away than usual, it looks slightly too small and leaves a bright ring of Sun around it, an *annular* eclipse. On April 8, 2024, millions of people in Mexico, the United States and Canada stood in the Moon's umbra and watched a total eclipse. The next total eclipses to cross the lower 48 states will come in 2044 and 2045. A total lunar eclipse comes to most places every few years, and you can watch it with no special equipment at all.

God's handiwork. "And God made two great lights; the greater light to rule the day, and the lesser light to rule the night" (Genesis 1:16). The Sun and Moon are very different in size, yet they fit so well in our sky that the Moon can cover the Sun like a lid on a jar. Because of that fit, astronomers have learned a great deal about the Sun's faint outer glow, the corona, which normally hides in the Sun's glare. Eclipses run on a schedule so faithful that astronomers can tell you where the Moon's shadow will fall many years from now.



Solar eclipse (top): the Moon's shadow falls on Earth at new moon. Lunar eclipse (bottom): Earth's shadow falls on the Moon at full moon. Sizes and distances are not to scale.

PICTURE STUDY



Astronomers Studying an Eclipse, Antoine Caron, 1570s · Oil on panel · J. Paul Getty Museum, Los Angeles

Antoine Caron was a French painter who worked for the royal court of France. In this painting, scholars in robes gather in a city square with instruments for measuring the sky: globes, rings and compasses. Some point upward toward an eclipse, while others are busy measuring and talking.

Some art historians think the painting shows Dionysius, the Athenian judge who believed Paul's preaching (Acts 17:34). An old story says Dionysius saw the sky grow dark at the time of the Crucifixion. That darkness could not have been an ordinary solar eclipse. Jesus was crucified at Passover, which comes at full moon, when the Moon is on the far side of Earth from the Sun, and the Gospels say the darkness lasted about three hours, much longer than any eclipse.

Look closely

- Find the dark disk in the sky. Who is pointing at it?
- Find at least three instruments the astronomers are using. What do you think each one measures?
- Look at the buildings. Do they look like a real city or an imagined one?
- Find someone who is not looking at the sky. What is that person doing instead?

Talk about it

1. Why do you think the painter filled the scene with instruments and books, not just people staring?
2. If you were in this crowd, what would you want to measure or record?
3. How is watching an eclipse with a group of people different from watching it alone?

> **Safety first.** Never look at the Sun, even when most of it is covered by the Moon. Sunglasses, smoked glass and camera screens are not safe. Use only certified eclipse glasses (marked ISO 12312-2) or a pinhole projector with your back to the Sun, and always with an adult. Never use binoculars or a telescope to look at the Sun unless it has a proper solar filter fitted by an adult. A lunar eclipse is completely safe to watch with your eyes, binoculars or a telescope. A hot lamp bulb should not be touched.

EXPERIMENT: MAKE AN ECLIPSE AND MEASURE THE SHADOW

You will make both kinds of eclipse with a lamp and two balls, then run a small experiment on the shadow itself. Why does a total solar eclipse cover only a narrow path? Why are some eclipses a ring instead of a total? The shadow will show you.

Question: How does the dark center of a ball's shadow change as the screen moves farther from the ball? **Prediction:** Write whether you think the dark center will grow, shrink or stay the same.

You will need

- A lamp with the shade removed, or a bright flashlight (LED is best)
- A small ball about 2 cm (about 3/4 in) wide on a stick (a marble in clay on a pencil or a bead on a skewer) for the Moon
- A larger ball about 8 cm (3 in) wide for Earth (a foam ball or an orange)
- A white index card or stiff paper for a screen

- A ruler in centimeters, tape, lab notebook and pencil

Steps

1. **Solar eclipse.** In a dark room, line up the lamp, the small Moon ball and the Earth ball. Hold the Moon between the lamp and Earth. Find the Moon's little shadow on Earth. Move the Moon a little above the line. Does the shadow miss Earth? That is why there is not an eclipse every month.
2. **Lunar eclipse.** Now put Earth between the lamp and the Moon. Slide the Moon slowly into Earth's shadow and watch it darken.
3. **The shadow experiment.** Tape the small ball on its stick to a table about 50 cm (20 in) from the lamp. Hold the white card 10 cm behind the ball, facing the lamp.
4. Look for the very dark center of the shadow (the umbra) and the lighter fuzzy ring around it (the penumbra). Measure the width of the dark center and record it.
5. Move the card to 20 cm, 30 cm, 40 cm and 50 cm behind the ball. Measure the dark center each time.
6. **What we change:** the distance from the ball to the card. **What we keep the same:** the lamp, the ball and the distance from the lamp to the ball. **What we measure:** the width of the dark center.
7. Make a bar graph of your results. Write a sentence explaining how your graph matches the narrow path of a total solar eclipse.

Tips

- A small, bright bulb gives a sharper shadow than a big frosted one.
- If the dark center disappears, you are past the tip of the umbra. Write that down; it is an important result, like an annular eclipse.
- Keep the card straight, facing the lamp, every time you measure.

Check your work

- I made both a solar and a lunar eclipse with my model and can tell them apart.
- My table and bar graph show how the dark center changed with distance.
- I can explain why most months have no eclipse.

FIELD NOTEBOOK

1. Draw the Sun, Moon and Earth lined up for a solar eclipse and again for a lunar eclipse. Label the umbra and penumbra and write the Moon phase under each.
2. Draw a total lunar eclipse in colored pencil, showing the Moon's coppery red color. If one happens where you live this year, draw it from life and write the date and time.
3. Make a step-by-step drawing showing how to build a pinhole projector from a cereal box, with a warning written at the top: "Never look at the Sun."

> **From history.** In 1504, Christopher Columbus and his crew were stranded on the island of Jamaica after their worm-eaten ships could sail no farther. When the local people

> stopped bringing them food, Columbus checked an almanac of sky tables made by the German astronomer Regiomontanus and saw that a total lunar eclipse would come on the night of February 29, 1504. He told the island leaders that God would darken the Moon as a sign. When the Moon rose red and dim, they were alarmed and agreed to bring food again. Columbus's son Ferdinand, who was there, later wrote down the story.

WORKED EXAMPLES

Example 1. The Sun is about 1,392,000 km (865,000 mi) wide and about 150,000,000 km (93,000,000 mi) away. The Moon is about 3,475 km (2,159 mi) wide and about 384,400 km (238,900 mi) away. How many times wider is the Sun? How many times farther away? What does that tell you?

(Use the map or drawing "Because the Sun and Moon look about the same size, the Moon's umbra just reaches" shown earlier in this lesson.)

1. Width: 1,392,000 ÷ 3,475 ≈ 400.6, so about 400 times wider.
2. Distance: 150,000,000 ÷ 384,400 ≈ 390.2, so about 390 times farther.
3. Something that is 400 times wider but about 400 times farther away looks about the same size.

Answer: The Sun is about 400 times wider and about 390 times farther, so the Sun and Moon look nearly the same size in our sky. That is why the Moon can just cover the Sun in a total eclipse.

Example 2. At one town during a total solar eclipse, the partial eclipse began at 12:10 p.m., totality lasted from 1:27 p.m. to 1:31 p.m., and the partial eclipse ended at 2:47 p.m. How long did the whole eclipse last? How long was totality?

1. Whole eclipse: from 12:10 p.m. to 2:47 p.m. From 12:10 to 2:10 is 2 hours; from 2:10 to 2:47 is 37 minutes.
2. Whole eclipse = 2 hours 37 minutes.
3. Totality: from 1:27 p.m. to 1:31 p.m. is 4 minutes.

Answer: The whole eclipse lasted 2 hours 37 minutes, but totality lasted only about 4 minutes. Most of an eclipse is the partial part, when eclipse glasses must stay on.

PRACTICE

1. EASY At which phase of the Moon can a solar eclipse happen? At which phase can a lunar eclipse happen?
2. EASY What is the difference between the umbra and the penumbra?
3. MEDIUM If there is a new moon every month, why is there not a solar eclipse every month?

4. MEDIUM In the shadow experiment, a student recorded:
   Card 10 cm behind ball → dark center 1.6 cm wide
   20 cm → 1.2 cm
   30 cm → 0.8 cm
   40 cm → 0.4 cm
   (a) By how much does the dark center shrink for each 10 cm? (b) Predict what happens at 50 cm. (c) What kind of solar eclipse does that match?
5. MEDIUM Experiment design: Abigail wants to find out whether a bigger ball makes a longer dark center (umbra). What should she change? Name two things she must keep the same. What should she measure?
6. HARD Why have far more people seen a total lunar eclipse than a total solar eclipse?
7. HARD Your neighbor plans to watch the partial part of a solar eclipse through two pairs of dark sunglasses. In two or three sentences, tell your neighbor why that is dangerous and what to do instead.
8. CHALLENGE Suppose the Moon were twice as far from Earth as it is now. Could we still have total solar eclipses? Explain.

COMMON MISTAKES

- Thinking there is an eclipse every month. The Moon's orbit is tilted about 5 degrees, so the Sun, Moon and Earth line up exactly only a few times a year.
- Thinking it is safe to look at the Sun during a partial eclipse, or through sunglasses. Only certified eclipse glasses or a pinhole projector are safe.
- Mixing up a lunar eclipse with a new moon. At new moon the Moon's lit side faces away from us; in a lunar eclipse a full moon passes into Earth's shadow and turns red.

> **Make it a game · Line Up!.** Three players (or three objects: a flashlight, an orange and a grape) stand for the Sun, Earth and Moon. A caller shouts "Solar eclipse!", "Lunar eclipse!", "New moon!", "Full moon!" or "First quarter!" and the players race to stand in the right arrangement. The Moon player must also call out the phase. Score a point for each correct line-up in under ten seconds, then trade places.

> **Scripture.** "And God made two great lights; the greater light to rule the day, and the lesser light to rule the night: he made the stars also." (Genesis 1:16, KJV)

The greater light and the lesser light are very different in size, yet they look almost the same in our sky. Eclipses show how carefully the heavens are arranged.

Practice answers

1. A solar eclipse happens only at new moon. A lunar eclipse happens only at full moon.
2. The umbra is the dark center of a shadow, where the light is completely blocked. The penumbra is the lighter outer part, where only some of the light is blocked.
3. The Moon's path around Earth is tilted about 5 degrees, so at most new moons the Moon passes a little above or below the line between the Sun and Earth, and its shadow misses

Earth.

4. (a) It shrinks by 0.4 cm for every 10 cm. (b) At 50 cm the dark center would be 0 cm: it disappears and only the lighter penumbra is left. (c) An annular eclipse, when the Moon is a bit farther away and its umbra does not reach Earth, so a ring of Sun shows around the Moon.
5. Change: the size of the ball. Keep the same: the lamp, the distance from the lamp to the ball and the way she holds the card (any two). Measure: how far behind the ball the dark center reaches before it disappears (or its width at the same card distance).
6. A total lunar eclipse can be seen from the whole night side of Earth at once, and it lasts a long time. A total solar eclipse can be seen only inside the Moon’s narrow umbra, a path usually about 160 km (100 mi) wide, and only for a few minutes.
7. Even a thin sliver of the Sun is bright enough to burn the back of the eye, and sunglasses do not block enough light. Use certified eclipse glasses marked ISO 12312-2, or a pinhole projector with your back to the Sun. Take the glasses off only during totality, and only inside the path of totality, then put them back on as soon as the Sun begins to reappear.
8. No. Twice as far away, the Moon would look only half as wide as it does now, so it would look much smaller than the Sun. It could cover only the middle of the Sun, and every central eclipse would be a ring (annular), never total.

2.4 Tides and the Moon

OBJECTIVES

- Explain how the Moon’s gravity makes two bulges of ocean water and why most coasts have two high tides and two low tides about every 24 hours and 50 minutes.
- Tell how spring tides and neap tides follow the Moon’s phases.
- Read a tide table to find tide times and the tide range, and design a fair test with a model beach.

Warm-up. Fill a shallow pan or baking dish halfway with water and set it on a table. Gently tip one end up about 1 cm and then set it down, slowly, back and forth. Watch the water at the low end creep up the side and slide back. Where on Earth does water rise and fall like this every day, without anyone tipping anything?

Video. Coming soon. What causes ocean tides, spring and neap tides, and time-lapse footage of the tides in the Bay of Fundy or at Mont-Saint-Michel. Search NOAA Ocean Service and NOAA SciJinks, NASA Space Place, Smithsonian Ocean, SciShow Kids, Homeschool Pop (Alternate) and coastal nature footage.

KEY TERMS

tide
The regular rise and fall of the sea along the shore, caused mostly by the Moon’s gravity.

gravity
The pull that every object has on every other object. The closer two objects are, the stronger the pull.

tide range
The difference in height between high tide and the low tide that comes next.

spring tide
An extra-large tide range that comes near new moon and full moon, when the Sun and Moon pull in a line. It has nothing to do with the season of spring.

neap tide
A small tide range that comes near first and third quarter, when the Sun and Moon pull at right angles to each other.

CORE IDEAS

The story. About the year 725, a monk named Bede was writing a book at the monastery of Jarrow, in the north of England, close to where the River Tyne meets the North Sea. He called it *The Reckoning of Time*, and it explained how to count days, months and years by the Sun and Moon. Bede lived beside the sea, and he watched it closely. He wrote that the tides keep company with the Moon: high tide comes a little later each day, just as the Moon rises a

little later each day. The tides grow larger around new moon and full moon and smaller in between. He also noticed something even more careful: along the same stretch of coast, high tide reaches one harbor at a different time than another. Bede did not know why the Moon and sea moved together, but he was sure that they did, because he had looked.

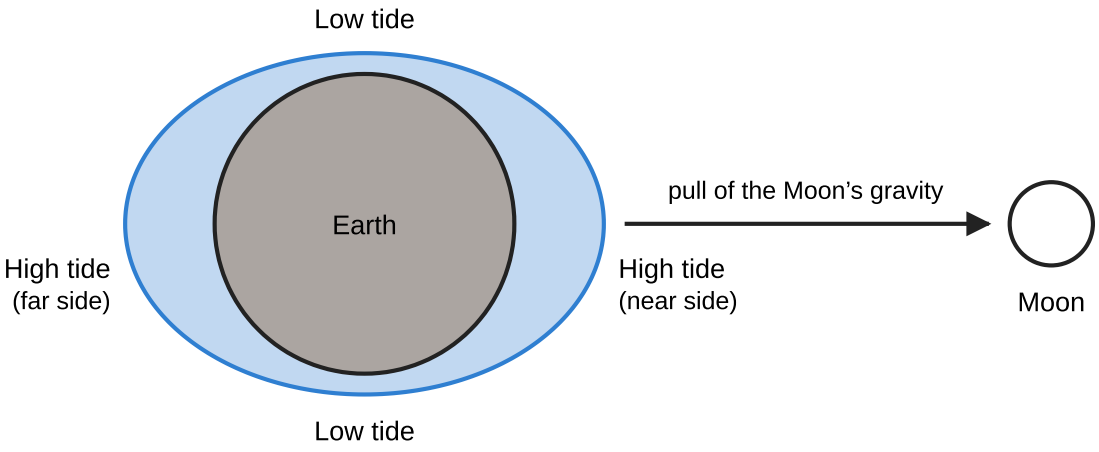
How they figured it out. Almost a thousand years later, in 1687, Isaac Newton explained the reason: gravity. The Moon pulls on the whole Earth, but its pull is strongest on the side nearest the Moon and weakest on the side farthest away. So the ocean on the near side is pulled toward the Moon a little more than the solid Earth is, and it heaps up in a bulge. On the far side, the solid Earth is pulled toward the Moon a little more than that far ocean water is, so the water there is left behind in a second bulge. Earth gets two bulges of water, one toward the Moon and one away from it.

The big idea. Earth spins once a day underneath those two bulges. As your beach turns into a bulge, the water rises: high tide. As it turns into the low places between the bulges, the water falls: low tide. Because the Moon moves along its orbit while Earth spins, it takes about 24 hours and 50 minutes for a place to come back under the Moon. So most coasts have two high tides and two low tides in about 24 hours and 50 minutes, and high tide comes about 50 minutes later each day, the same delay as moonrise. The Sun makes tides too, but they are less than half as strong as the Moon's. At new moon and full moon, the Sun and Moon pull in a line and the tide range is largest: **spring tides**. At first and third quarter they pull at right angles, and the range is smallest: **neap tides**.

In the world today. The shape of the coast makes a huge difference. In the long, funnel-shaped Bay of Fundy in Canada, the tide can rise and fall more than 15 meters (50 feet), the largest tide range in the world. Along much of the Gulf of Mexico, the range is often less than 1 meter (about 3 feet). Fishermen, ship captains and families heading to the beach all use tide tables. In the United States, NOAA keeps tide gauges along the coasts and publishes tide predictions for each station months ahead. Where the shore is gentle and flat, a small rise in water can move the shoreline a long way, and the tide can come in faster than a person can walk.

God's handiwork. The prophet Jeremiah wrote of "the LORD, which giveth the sun for a light by day, and the ordinances of the moon and of the stars for a light by night, which divideth the sea when the waves thereof roar" (Jeremiah 31:35). An "ordinance" is a fixed rule. Twice a day, all over the world, the sea obeys the rule God set for it. The tides wash and stir the shallow coastal waters, fill tide pools with crabs, sea stars and snails, and carry ships in and out of harbors. The same Moon that marks the months also moves the oceans.

Two bulges of ocean water (shape greatly exaggerated)



The Moon's gravity makes two bulges of water, one facing the Moon and one on the far side. As Earth spins, each coast passes through both bulges and both low places every day. The bulges are drawn much bigger than they really are.

PICTURE STUDY



Fishermen at Sea, J. M. W. Turner, 1796 · Oil on canvas · Tate Britain, London

Joseph Mallord William Turner was only about twenty-one when he painted this moonlit sea. It was the first oil painting he showed at the Royal Academy in London, and it made people take notice of the young artist. The scene is set off the Needles, a row of chalk rocks off the Isle of Wight on the south coast of England, where strong tides race through the channel.

Turner loved light more than almost anything. Here the cold silver light of the Moon breaks through the clouds and falls on the water, while a fishermen's lantern glows warm and small in the boat. Fishermen on such a coast had to know the tides and the Moon well, because both decided when it was safe to go out and come home.

Look closely

- Find the Moon. What phase do you think it is? How can you tell?
- Follow the path of moonlight across the waves. Where is it brightest?
- Find the two kinds of light in the picture: moonlight and lantern light. How are their colors different?
- Look at the boat and the waves. Does the sea look calm or dangerous?

Talk about it

1. If this is a full moon, would the tides that night be spring tides or neap tides?
2. Why would fishermen need to know when high tide and low tide would come?
3. How does Turner make you feel the cold and the motion of the sea?

> **Safety first.** Use only a shallow pan of water indoors and wipe up spills so no one slips. At a real beach, always go with an adult and check the tide table first. Tides can rise quickly over flat sand and around rocks, so never walk out onto a sandbar, mudflat or rock point where a rising tide could cut you off, and never turn your back on the waves.

EXPERIMENT: TIDE ON A MODEL BEACH

Why does the tide come in a long way on some beaches and only a little on others? You will build a model beach and raise the "tide" by the same amount on a gentle slope and on a steep slope, then measure how far the water's edge moves.

Question: When the water rises by the same height, does the water's edge move farther up a gentle beach or a steep beach? **Prediction:** Write your guess before you start.

You will need

- A long baking pan or clear plastic storage tub
- Damp sand, soil or modeling clay to build a beach (or a flat board or tray lid to make a ramp)
- A measuring cup and a pitcher of water
- A ruler in centimeters and a second ruler or craft stick to stand up in the water
- Masking tape and a marker
- Towels, lab notebook and pencil

Steps

1. Build a smooth, gentle beach at one end of the pan that slopes down to the other end. A long, low ramp works best.

2. Tape a ruler upright at the deep end. Pour in water until it is 2 cm deep at the ruler. Mark the water's edge on the beach with a toothpick or a small piece of tape. This is low tide.
3. Add water slowly until the ruler reads 3 cm, a rise of 1 cm. Mark the new edge. Measure along the beach how far the edge moved and record it.
4. Add water to 4 cm and then 5 cm, marking and measuring each time.
5. Pour out the water, rebuild the beach steeper (prop the ramp higher), and repeat the same steps starting from 2 cm.
6. **What we change:** the slope of the beach. **What we keep the same:** the pan, the starting depth and each 1 cm rise of water. **What we measure:** how far the water's edge moves along the beach.
7. Record your results in a table with columns: Water depth (cm), Edge moved on gentle beach (cm), Edge moved on steep beach (cm). Write a sentence telling which beach would be more dangerous for a person walking far out at low tide, and why.

Tips

- Pour slowly against the side of the pan so you do not wash away the beach.
- Measure along the slope of the beach, from the low-tide mark to each new mark.
- For a second activity, look up a real NOAA tide prediction for a coastal town and graph one day of high and low tides.

Check your work

- My table shows how far the water's edge moved on both beaches.
- I changed only one thing, the slope, and kept everything else the same.
- I can explain why the tide can come in so far on a flat shore.

FIELD NOTEBOOK

1. Draw Earth with two water bulges and the Moon. Label high tide, low tide, the near-side bulge and the far-side bulge.
2. Draw two small diagrams: the Sun, Earth and Moon lined up for a spring tide, and at right angles for a neap tide. Write the Moon phase under each.
3. If you visit a beach, sketch the high-tide line of seaweed and shells and draw three creatures or plants you find living between high and low tide. Write the date, the time and the Moon's phase.

> **From history.** In 1872 the Scottish scientist William Thomson, later Lord Kelvin, a devout Christian, built the first tide-predicting machine. It used gears, wheels and a long wire running over pulleys to add together the separate "pulls" that make up the tide at a harbor. A pen then drew a whole year of tides in a few hours, work that had taken people weeks by hand. In the United States, William Ferrel built a tide machine for the U.S. Coast and Geodetic Survey, and tide-predicting machines were used to make tide tables until computers took over in the 1960s.

WORKED EXAMPLES

Example 1. At a harbor, high tide comes at 6:15 a.m. If high tides are about 12 hours 25 minutes apart, when will the next two high tides come?

(Use the map or drawing "A spot on Earth passes through one bulge and then the other about every 12 hours" shown earlier in this lesson.)

1. Add 12 hours to 6:15 a.m.: 6:15 p.m.
2. Add 25 more minutes: 6:15 p.m. + 25 minutes = 6:40 p.m.
3. Add 12 hours 25 minutes again: 6:40 p.m. + 12 hours = 6:40 a.m.; + 25 minutes = 7:05 a.m. the next day.
4. Check: from 6:15 a.m. one day to 7:05 a.m. the next is 24 hours 50 minutes, the length of a tidal day. ✓

Answer: About 6:40 p.m. the same day and about 7:05 a.m. the next morning, 50 minutes later than the day before.

Example 2. A tide table shows high tide at 3.2 m (10.5 ft) and the next low tide at 0.4 m (1.3 ft). What is the tide range in meters and in feet?

1. Tide range = high tide height − low tide height.
2. In meters: 3.2 m − 0.4 m = 2.8 m.
3. In feet: 10.5 ft − 1.3 ft = 9.2 ft. (Check: 2.8 m × 3.28 ft per meter ≈ 9.2 ft. ✓)

Answer: The tide range is 2.8 m (about 9.2 ft).

PRACTICE

1. EASY On most coasts, how many high tides and how many low tides come in about one day?
2. EASY At which Moon phases do spring tides come? At which phases do neap tides come?
3. MEDIUM Low tide at a beach is at 11:30 a.m. About when will the next low tide be? (Low tides are also about 12 hours 25 minutes apart.)
4. MEDIUM Here is a sample tide table for one harbor on four days:
   New moon: high 3.6 m, low 0.1 m
   First quarter: high 2.6 m, low 1.0 m
   Full moon: high 3.5 m, low 0.2 m
   Third quarter: high 2.7 m, low 1.1 m
   (a) Find the tide range for each day. (b) Which days have spring tides? (c) Which have neap tides?
5. MEDIUM Experiment design: In the model beach project, Daniel wants to test whether a sand beach and a pebble beach of the same slope let the water's edge move the same

distance. What should he change? Name two things to keep the same. What should he measure?

6. HARD Why does high tide come about 50 minutes later each day? Connect your answer to the Moon.
7. HARD In the Bay of Fundy the tide range can be about 15 m. If a two-story house is about 7.5 m (about 25 ft) tall, how many houses stacked up would match the tide range? About how many feet is 15 m?
8. CHALLENGE Your friend says, “I understand why water bulges on the side facing the Moon, but there should not be a high tide on the far side.” In two or three sentences, explain the far-side bulge.

COMMON MISTAKES

- Thinking the wind causes the tides. Wind makes waves, but the regular rise and fall of the tide comes from the gravity of the Moon and Sun.
- Thinking there is only one high tide a day, when the Moon is overhead. Most coasts have two, one from each bulge.
- Thinking spring tides happen only in the spring. Spring tides come twice every month, near new moon and full moon; the name means the water “springs up” higher.

Make it a game · Tide Clock Race. A parent calls out a high tide time, such as “High tide at 2:10 p.m.!” The child must call out the next low tide (about 6 hours 12 minutes later), the next high tide (12 hours 25 minutes later) and tomorrow’s first high tide (about 50 minutes later than today’s). One point for each time within 10 minutes. Then the parent names a Moon phase and the child shouts “Spring!” or “Neap!” for a bonus point.

Scripture. “Thus saith the LORD, which giveth the sun for a light by day, and the ordinances of the moon and of the stars for a light by night, which divideth the sea when the waves thereof roar; The LORD of hosts is his name:” (Jeremiah 31:35, KJV)

God set fixed “ordinances” for the Moon, and the sea answers them every day. The tides are one of the clearest signs that the heavens and the oceans are ruled by one faithful Lord.

Practice answers

1. Two high tides and two low tides in about 24 hours and 50 minutes.
2. Spring tides come near new moon and full moon. Neap tides come near first quarter and third quarter.
3. 11:30 a.m. + 12 hours = 11:30 p.m.; + 25 minutes = 11:55 p.m.
4. (a) New moon 3.5 m; first quarter 1.6 m; full moon 3.3 m; third quarter 1.6 m. (b) New moon and full moon have spring tides (largest ranges). (c) First and third quarter have neap tides (smallest ranges).
5. Change: the beach material (sand or pebbles). Keep the same: the slope, the pan, the starting water depth and each 1 cm rise (any two). Measure: how far the water’s edge moves along the beach for each rise.

6. The tidal bulges stay lined up with the Moon. While Earth spins once, the Moon moves forward along its orbit, so Earth must turn about 50 extra minutes to bring a place back under the Moon. That is the same reason the Moon rises about 50 minutes later each day.
7. 15 m ÷ 7.5 m = 2 houses stacked. 15 m × 3.28 ≈ 49 ft, about 50 feet.
8. The Moon’s pull gets weaker with distance. It pulls hardest on the near-side water, a little less on the center of Earth and least on the far-side water. So the solid Earth is pulled toward the Moon a little more than the far-side water is, and that water is left behind as a second bulge.

Unit 2 review

Answer each question. Show your work for calculations and use complete sentences for explanations. Draw a diagram if it helps. The quiz is worth 50 points.

1. (5 pts) In 1609 Galileo saw bright points of light in the dark part of the Moon, just beyond the terminator. What were they, and what did they show him about the Moon?
2. (5 pts) Outdoors in sunlight, a 5 cm clay mountain casts a 15 cm shadow. At the same moment, a clay crater rim beside it casts a 6 cm shadow. How tall is the crater rim? Show your work.
3. (5 pts) Explain what causes the phases of the Moon. Use the words “half” and “lit” in your answer.
4. (5 pts) From the Northern Hemisphere you see a Moon with more than half its face lit, bright on the left side. Name the phase. Is it waxing or waning, and which major phase comes next?
5. (5 pts) A new moon falls on June 2. About when is the next full moon? About when is the next new moon? (A lunar month is about 29½ days.)
6. (5 pts) Draw or describe the order of the Sun, Earth and Moon in (a) a solar eclipse and (b) a lunar eclipse. Name the Moon phase for each.
7. (5 pts) Give two reasons eclipses are special: (a) why there is not an eclipse every month, and (b) why the Moon can just cover the Sun.
8. (5 pts) Name two safe ways to watch the partial part of a solar eclipse, and one way that is not safe. Why does a totally eclipsed Moon look red?
9. (5 pts) High tide at a harbor is at 9:20 a.m. Using 12 hours 25 minutes between high tides, when is the next high tide? About when is the first high tide the next morning?
10. (5 pts) A tide table shows: Day A high 3.4 m, low 0.3 m; Day B high 2.5 m, low 1.1 m. Find each tide range. Which day is a spring tide, and which Moon phases could it be?

Unit project: my moon guidebook

Make a small hand-bound guidebook to the Moon, the kind a young astronomer could carry outside at night. Include: (1) a labeled drawing of the Moon’s face from your own binocular or naked-eye sketches, showing the maria, a few craters and the terminator; (2) a phase wheel showing all eight phases in order, with when each one rises; (3) diagrams of a solar and a lunar eclipse with the umbra and penumbra labeled and a safety page on how to watch the Sun safely; (4) a tide page with a two-bulge diagram and a graph of one real week of high and low tides from NOAA for a coastal town. Finish with a page of your project data tables from this unit and one paragraph on what the Moon teaches you about the order God built into the heavens.

- **Accuracy**: Phases are in the right order and lit on the correct side, eclipse diagrams show the right line-up and phase, and the tide diagram shows two bulges.
- **Observation and data**: Moon sketches are drawn from real observation with dates and times, and project tables and the tide graph are complete, labeled and in correct

units.

- **Explanation**: Short captions and the closing paragraph explain phases, eclipses and tides in the student's own words, using the key terms correctly.
- **Care**: The guidebook is neat, readable and carefully illustrated, with a clear cover and table of contents.

Answer key

1. They were mountain tops catching sunlight while the ground below was still dark, like peaks on Earth at sunrise. They showed that the Moon is rough, with mountains and valleys, not a perfectly smooth ball.
2. Ratio: 15 ÷ 5 = 3 cm of shadow per cm of height. Rim height = 6 ÷ 3 = 2 cm (about 0.8 in).
3. The Sun always lights half of the Moon. As the Moon goes around Earth, we see different amounts of that lit half, from none at new moon to all of it at full moon. Earth's shadow does not cause the phases.
4. Waning gibbous. It is waning; third quarter comes next.
5. Full moon about half a lunar month later: June 2 + about 15 days ≈ June 16 or 17. Next new moon: June 2 + 29½ days ≈ July 1 or 2.
6. (a) Sun, Moon, Earth: the Moon is in the middle and its shadow falls on Earth; new moon. (b) Sun, Earth, Moon: Earth is in the middle and its shadow falls on the Moon; full moon.
7. (a) The Moon's orbit is tilted about 5 degrees, so most months the Moon passes above or below the Sun-Earth line. (b) The Sun is about 400 times wider than the Moon but also about 400 times farther away, so they look nearly the same size.
8. Safe: certified eclipse glasses (ISO 12312-2) and a pinhole projector with your back to the Sun. Not safe: sunglasses, smoked glass, or looking straight at the Sun (or through binoculars without a solar filter). The eclipsed Moon looks red because a little sunlight bends through Earth's air, which scatters away blue light and lets red light reach the Moon.
9. 9:20 a.m. + 12 h 25 min = 9:45 p.m. Next morning: 9:45 p.m. + 12 h 25 min = 10:10 a.m., about 50 minutes later than the day before.
10. Day A: 3.4 − 0.3 = 3.1 m. Day B: 2.5 − 1.1 = 1.4 m. Day A has the larger range, so it is a spring tide, near new moon or full moon. (Day B is a neap tide, near first or third quarter.)

UNIT 3

The Planets

Long ago, people who watched the night sky noticed that a few bright lights did not stay put. While the stars kept their places, these lights drifted slowly along the Sun's path, and Mars sometimes even seemed to loop backward. The Greeks called them "wanderers," and in this unit you will learn why they wander, how Nicolaus Copernicus explained the backward loop, and how to find the planets in the sky yourself. "The heavens declare the glory of God" (Psalm 19:1), and the planets declare it with their faithful order.

Then you will take a long walk: a true scale model of the solar system, with an orange-sized Sun, a sand-grain Earth 10 meters away and a peppercorn Neptune about 300 meters down the path. You will join William Herschel and his sister Caroline in their garden in Bath, England, on the night in 1781 when a homemade telescope revealed a brand-new planet. Finally you will ride along with Voyager 1 to the edge of the solar system and look back at the Earth as a pale blue dot, and you will read what King David wrote about how small we are and how much God cares for us (Psalm 8:3–4).

BEFORE YOU BEGIN

- Can multiply and divide whole numbers and decimals by 10 and by other one- and two-digit numbers (with a calculator for large numbers)
- Knows that Earth spins once a day and travels around the Sun once a year (Unit 1)
- Knows that the Moon shines by reflected sunlight (Unit 2)
- Can measure distances with a tape measure in meters and centimeters

MASTERY CHECKLIST

- I can explain why the planets were called "wanderers" and name the five planets seen without a telescope.
- I can tell a planet from a star and explain why Mars sometimes seems to move backward.
- I can build a scale model of the solar system and change distances in AU into model meters.
- I can tell how William Herschel discovered Uranus in 1781 and the two clues that it was not a star.
- I can calculate how long a radio signal takes to travel from a spacecraft and explain what the Pale Blue Dot photograph shows.
- I can name what I changed, what I kept the same and what I measured in a fair test.

OPTIONAL BOOKS AND RESOURCES

- **NASA Solar System Exploration** (https://science.nasa.gov/solar-system/): Free. NASA's pages on each planet, with facts, photographs from spacecraft and diagrams. Use them to check the planet data in this unit.

- **NASA Skywatching** (https://science.nasa.gov/skywatching/): Free. NASA's monthly "What's Up" guide tells which planets are visible this month, where to look and when. Use it for the planet-hunting sketches in Lesson 3.1.
- **Voyager mission home page (NASA Jet Propulsion Laboratory)** (https://voyager.jpl.nasa.gov/): Free. The story of both Voyager probes, the Golden Record, and where the spacecraft are right now (Lesson 3.4).

3.1 The Wanderers ★

OBJECTIVES

- Explain why people long ago called the planets “wanderers” and name the five planets that can be seen without a telescope.
- Tell two ways a planet is different from a star and explain Mars’s backward loop as Earth passing Mars on an inside lane.
- Read a table of planet data and compare how long each planet takes to go around the Sun.

Warm-up. Set twelve coins on a table in a scattered pattern. These are your “stars.” Add one button among them: your “planet.” Study the pattern for ten seconds and close your eyes. A parent slides the button a little way to a new spot and leaves every coin alone. Open your eyes. Can you find the one thing that wandered? That is exactly how people long ago found the planets.

Video. Coming soon. Planets as wanderers and the retrograde motion of Mars explained for kids; search NASA Space Place, NASA Jet Propulsion Laboratory skywatching (“What’s Up”), Homeschool Pop (Alternate), Science Max and planetarium channels.

KEY TERMS

planet
A large, round world that travels around the Sun and shines by reflecting sunlight. The word comes from the Greek word for “wanderer.”

orbit
The curved path one object follows around another, such as Earth’s path around the Sun.

solar system
The Sun and everything that travels around it: eight planets, their moons, dwarf planets, asteroids and comets.

ecliptic
The narrow path across the sky that the Sun seems to follow through the year. The Moon and planets always stay close to it.

retrograde motion
The way a planet such as Mars seems to stop and slide backward among the stars for a while, because Earth is passing it.

CORE IDEAS

The story. In the spring of 1543, in the little town of Frombork near the Baltic coast of Poland, an old church officer named Nicolaus Copernicus lay ill in bed. For many years he had watched the sky, measured the places of the planets and worked on a large book. That

year it was finally printed in Nuremberg, Germany, with the title *On the Revolutions of the Heavenly Spheres*. An old story says a printed copy was placed in his hands near the day he died, May 24, 1543. The book made a bold claim: the Earth is not standing still in the middle of everything. It is one of the planets, and with them it travels around the Sun.

How they figured it out. Long before Copernicus, shepherds, sailors and farmers noticed that almost all the lights of the night sky keep their places. The stars of a constellation wheel across the sky together, night after night. But five bright lights do not. Over a few weeks they drift slowly among the stars. The Greeks called them *planētēs*, "wanderers," and that is where our word **planet** comes from. They are Mercury, Venus, Mars, Jupiter and Saturn. The wanderers never stray far from one narrow road across the sky, the **ecliptic**, which the Sun and Moon follow too. Mars did something stranger still. About every two years it slows down, stops, slides backward for about two months, stops again and then goes on its way. This is called **retrograde motion**. Around A.D. 150 in Alexandria, Egypt, the astronomer Ptolemy explained it with small circles riding on bigger circles around the Earth. Copernicus gave a simpler answer: Earth runs on an inside lane and moves faster than Mars. When Earth catches up and passes Mars, Mars seems to slide backward against the far-off stars, the way a slow truck seems to drift backward against distant hills when your car passes it. Mars never really goes backward at all.

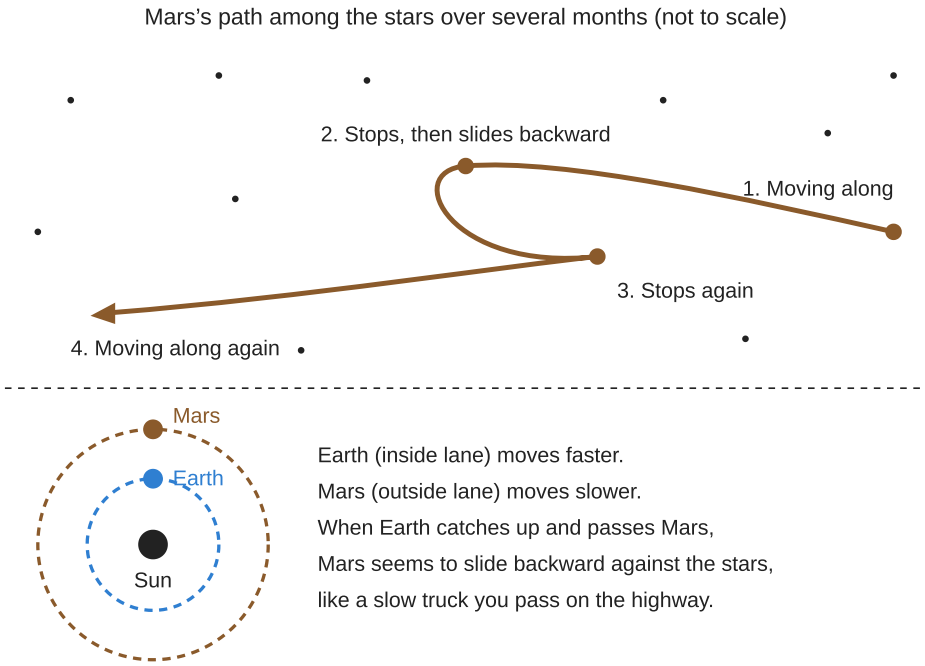
The big idea. Today we call the Sun and everything that travels around it the **solar system**. Eight planets follow paths called **orbits**. The four nearest the Sun, Mercury, Venus, Earth and Mars, are small and rocky. The four outer planets, Jupiter, Saturn, Uranus and Neptune, are giants made mostly of gas and ice, with no solid ground to stand on. (Pluto, found in 1930, is now called a dwarf planet.) A star such as our Sun makes its own light. A planet makes none; it shines because sunlight bounces off it, just as moonlight is really sunlight. Planets also tend to shine with a steadier light than stars. The stars are so far away that each one is a tiny point, and moving air makes points twinkle. A planet is close enough to be a very small disk, so its light is steadier. Finally, the closer a planet is to the Sun, the faster it moves and the shorter its year. Mercury goes around in 88 days. Saturn takes about 29 and a half of our years.

Because Mercury and Venus travel inside Earth's orbit, we always see them near the Sun in our sky. They show up low in the west after sunset as an "evening star" or low in the east before sunrise as a "morning star," but never high in the south at midnight. Mars, Jupiter and Saturn travel outside Earth's orbit, so when Earth is between them and the Sun, they can shine all night long.

Try it and see. To catch a wanderer yourself, check a monthly skywatching guide, such as NASA's "What's Up," to learn which planets are out this month. Venus is the brightest light in the night sky after the Moon. Jupiter is bright and creamy white, Mars glows orange-red, and Saturn shines a steady pale gold. Draw the planet together with the stars near it, then draw it again every few nights. In a few weeks your drawings will show that it has moved.

God's handiwork. The wanderers seemed lawless at first, but the more carefully people watched, the more order they found. Every planet keeps its own road and its own pace, so

faithfully that astronomers can tell you where Mars will be on your birthday years from now. Copernicus wrote that the world was built for us by the best and most orderly Workman of all. King David said it first: “The heavens declare the glory of God.”



Mars seems to loop backward among the stars when Earth, on the faster inside lane, passes it.

PICTURE STUDY



Astronomer Copernicus, or Conversations with God, Jan Matejko, 1872 · Oil on canvas · Jagiellonian University Museum, Kraków, Poland

Jan Matejko was the most famous painter of Polish history. He painted the great astronomer in 1872 and first showed the picture in 1873, four hundred years after Copernicus was born. It shows him on a balcony in Frombork, the town where Copernicus served the cathedral and studied the sky. Matejko did not see this moment himself, of course. He imagined it, and he gave the painting a title that shows what he believed Copernicus was doing when he studied the heavens: talking with God.

Look closely

- Find Copernicus's face. Where is he looking, and what is he doing with his hand?
- Look at the objects around him. What tools of an astronomer can you find?
- Find the cathedral in the background. What does it tell you about where Copernicus lived and worked?
- Look at the sky. Is it mostly dark or mostly light? How does the painter make Copernicus stand out?

Talk about it

1. Why do you think Matejko called this painting "Conversations with God"?
2. Copernicus spent years measuring before he wrote his book. Why does careful watching matter before making a big claim?

> **Safety first.** Never look at the Sun, even when it is low near the horizon, and never point binoculars or a telescope near it. When hunting for Venus or Mercury in the evening, wait until the Sun has fully set. Go out at night only with an adult, and watch your footing in the dark.

EXPERIMENT: PASSING MARS: A BACKWARD-LOOP WALK

Question: Why does Mars sometimes seem to go backward? You will act out Earth and Mars with a partner and find out. **Prediction:** before you begin, write whether you think Mars will ever seem to slide backward if both planets always walk forward.

What we change: how fast "Earth" walks (faster than Mars, the same as Mars, or standing still). **What we keep the same:** the two circles, the row of star notes and Mars's pace. **What we measure:** which star note Mars lines up with at each step. **Record:** a table of the star numbers.

You will need

- Sidewalk chalk (outdoors) or two long pieces of string (indoors)
- A ball, pot or lamp to stand for the Sun
- 10 sticky notes or paper squares numbered 1 to 10
- A partner and a caller to clap the beat
- Notebook and pencil

Steps

1. Place the Sun in the middle of an open space. Draw a circle around it 1 meter (about 3 feet) from the Sun for Earth’s lane, and a second circle 1.5 meters (about 5 feet) from the Sun for Mars’s lane. (Mars really is about 1.5 times as far from the Sun as Earth.)
2. Stick the ten numbered notes in a row along a wall or fence several meters beyond the circles. These are the faraway stars.
3. Earth and Mars stand on their circles on the same side of the Sun, a quarter turn apart, with Mars ahead. Both will walk counterclockwise.
4. The caller claps slowly. On each clap, Mars takes one heel-to-toe step and Earth takes two. After each step, Earth stops, points at Mars and calls out the number of the star note seen just beyond Mars along that pointing line.
5. Record the star numbers in a table: Step, Star number. Keep going until Earth has passed Mars and is well ahead.
6. Look at your list. Did the numbers move one way, turn back for a while, then move on again? Circle the steps where Mars seemed to go backward.
7. Change only Earth’s speed: do it again with Earth taking one step per clap like Mars, and then with Earth standing still. Record both tables.
8. Write a sentence: When did Mars seem to go backward, and why?

Tips

- Keep Mars’s steps small and even. The experiment is only fair if Mars walks the same way every time.
- If the numbers jump around, slow down and let Earth sight along an outstretched arm before calling the number.

Check your work

- I can show with my body why Mars seems to slide backward.
- I can explain that Mars never really reverses in its orbit.
- I can name what I changed, what I kept the same and what I measured.

FIELD NOTEBOOK

1. Draw a planet you find in the sky with the three or four nearest stars around it. Write the date and time. Draw it again on two more nights and circle how it moved.
2. Make a two-column chart titled “Planet or Star?” and list every clue you know for telling them apart.
3. Draw the eight planets in order from the Sun. Shade the four rocky planets brown and the four giants blue, and label each one.

> **From history.** In 1610 Galileo Galilei turned his telescope on Venus and watched it over several months. He saw it show phases, from a small round disk to a large thin crescent, just as the Moon does. That fit Copernicus’s idea that Venus travels around the Sun, and it could not be explained by Ptolemy’s arrangement, in which Venus always stayed between the Earth and the Sun.

WORKED EXAMPLES

Example 1. Mercury goes around the Sun in 88 days. Earth takes 365 days. How many times does Mercury go around the Sun in one Earth year?

1. We want to know how many 88-day trips fit into 365 days, so we divide.
2. 365 ÷ 88 = 4.1 (88 × 4 = 352, with 13 days left over).
3. So Mercury makes 4 full trips and starts a fifth before Earth finishes one.

Answer: About 4 times (4.1 Mercury years in one Earth year).

Example 2. Mars takes 687 Earth days to go around the Sun. If you are 10 Earth years old, about how old are you in Mars years?

1. First find your age in days: 10 years × 365 days = 3,650 days.
2. Next find how many Mars years fit into that: 3,650 ÷ 687 = 5.3.
3. Check: 687 × 5 = 3,435 days, which is less than 3,650, and 687 × 6 = 4,122, which is more. So the answer is between 5 and 6.

Answer: About 5.3 Mars years old. A Mars year is almost twice as long as an Earth year, so your Mars age is a little more than half your Earth age.

PRACTICE

1. EASY What does the word “planet” mean in Greek, and why did people give the planets that name?
2. EASY Name the five planets you can see without a telescope.
3. EASY Where does a planet’s light come from? Where does a star’s light come from?
4. MEDIUM Use the table.
   Planet | Distance from Sun (Earth = 1) | Time to go around the Sun
   Mercury | 0.4 | 88 days
   Venus | 0.7 | 225 days
   Earth | 1.0 | 365 days
   Mars | 1.5 | 687 days
   Jupiter | 5.2 | about 12 years
   Saturn | 9.5 | about 29 years
   (a) Which planet in the table has the longest year? (b) What pattern do you see between distance and the length of a year? (c) How many days shorter is Venus’s year than Earth’s?
5. MEDIUM Why will you never see Venus high in the sky at midnight?
6. MEDIUM In two or three sentences, explain why Mars sometimes seems to move backward among the stars.

7. HARD A student wants to test whether Earth's speed changes how far Mars seems to slide backward in the Passing Mars walk. What should the student change? Name two things to keep the same. What should she measure?
8. CHALLENGE Jupiter takes about 12 years to go once around the Sun, passing through the 12 constellations along the ecliptic. About how long does Jupiter stay in each constellation? If you see Jupiter in the constellation Leo when you are 10, about how old will you be when it is back in Leo?

COMMON MISTAKES

- Thinking planets make their own light like stars. Planets shine only by reflected sunlight.
- Thinking Mars really turns around in its orbit. It only seems to go backward because Earth is passing it.
- Thinking the planets are scattered all over the sky. They always stay near the ecliptic, the Sun's path.

> **Make it a game · Wanderer Hunt.** Lay a long string across the table as the ecliptic and scatter coins around it as stars. Put a button on the string as a planet. Each round, close your eyes while your parent moves the button a short way along the string, usually forward but sometimes backward. Open your eyes and point to where it went. If it went backward, shout "Retrograde!" and explain why to score a bonus point. First to ten points wins.

> **Scripture.** "The heavens declare the glory of God; and the firmament sheweth his handywork." (Psalm 19:1, KJV)

The planets keep their roads so faithfully that we can predict them years ahead. Their order points to the faithful God who set them in their courses.

Practice answers

1. It means "wanderer." The planets drift slowly among the stars from night to night, while the stars keep their places in their constellations.
2. Mercury, Venus, Mars, Jupiter and Saturn.
3. A planet reflects sunlight; it makes no light of its own. A star, like the Sun, makes its own light.
4. (a) Saturn. (b) The farther a planet is from the Sun, the longer it takes to go around. (c) 365 − 225 = 140 days shorter.
5. Venus travels inside Earth's orbit, so from Earth it always appears fairly near the Sun in the sky. We see it only in the west after sunset or in the east before sunrise. At midnight the Sun is on the far side of the Earth, and so is Venus.
6. Earth travels on an inside lane and moves faster than Mars. When Earth catches up and passes Mars, our line of sight to Mars swings back across the faraway stars, so Mars seems to slide backward for a while. Mars itself keeps moving forward the whole time.

7. Change: Earth’s speed (for example, two steps per clap, then three steps per clap). Keep the same (any two): the size of both circles, Mars’s speed, the row of star notes and where it stands, the starting positions, the person pointing. Measure: how many star numbers Mars seems to slide backward, counted from the table.
8. About 1 year in each constellation (12 years ÷ 12 constellations). It returns to Leo after about 12 years, when you are about 22.

3.2 Scale Model on a Long Walk ★

OBJECTIVES

- Build a model of the solar system that uses one scale for both the sizes of the planets and the distances between them.
- Use multiplication and division to change real distances (in astronomical units) and real sizes into model meters and millimeters.
- Explain why most book pictures and models of the solar system are not to scale, and describe how much empty space lies between the planets.

Warm-up. Put an orange on the floor at one end of a hallway. It is the Sun. Now take a peppercorn, which will stand for Earth, and set it down where you think Earth belongs if the orange is the Sun. Mark your guess with a piece of tape and write your name on it. Leave it there until the end of the lesson.

Video. Coming soon. Solar system scale model walk and how far apart the planets really are; search NASA Space Place, NASA Jet Propulsion Laboratory education, Smithsonian National Air and Space Museum, Science Max, Homeschool Pop (Alternate) and university planetarium channels.

KEY TERMS

scale model
A copy of something that is bigger or smaller than the real thing but keeps every part in the same proportion.

scale
The rule that links the model to the real thing, such as “1 AU = 10 meters.” Every part of the model must use the same scale.

astronomical unit (AU)
The average distance from Earth to the Sun, about 150 million kilometers (93 million miles). Astronomers use it as a measuring stick for the solar system.

diameter
The distance straight across a circle or ball through its center.

orrery
A machine with gears that shows the planets moving around the Sun. Its sizes and distances are almost never to scale.

CORE IDEAS

The story. In 1989 an astronomy writer named Guy Ottewell published a short guide with a delightful title: *The Thousand-Yard Model, or, The Earth as a Peppercorn*. He told teachers to take a ball about 20 centimeters (8 inches) across for the Sun and a peppercorn for the

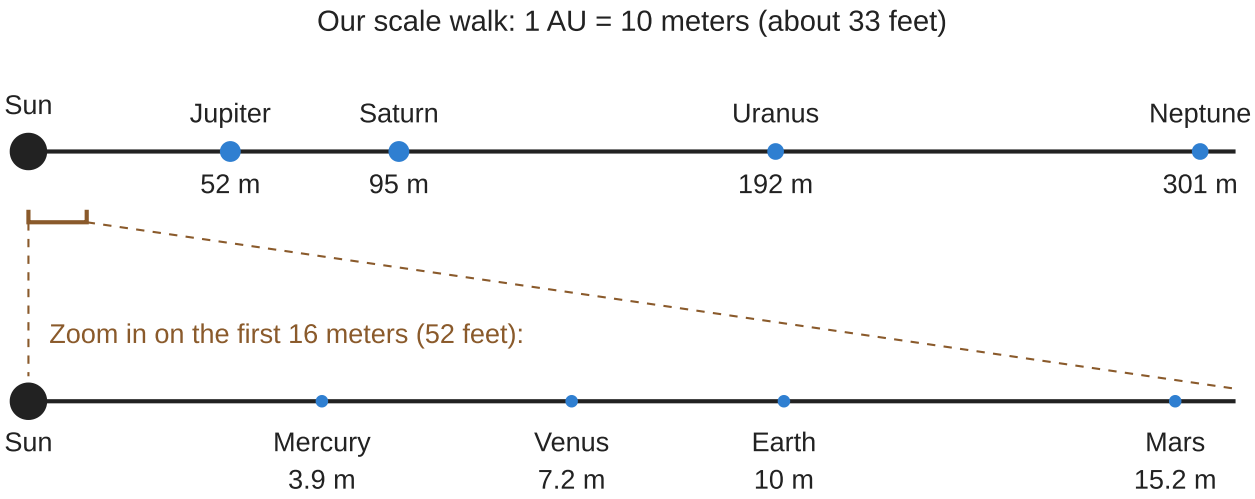
Earth, then go outside and walk. Earth goes about 26 long paces from the Sun. The outermost worlds end up nearly a thousand paces away. Classes all over the world have taken that walk since, and most walkers are amazed at the end by how big, and how empty, the solar system turns out to be.

How they figured it out. The secret of a true **scale model** is to choose one rule and use it for everything. Astronomers measure the solar system with the **astronomical unit**, or AU: the distance from Earth to the Sun, about 150 million kilometers (93 million miles). Mars is about 1.5 AU from the Sun, Jupiter 5.2 AU and Neptune about 30 AU. For our walk we will use the **scale** 1 AU = 10 meters (about 33 feet). To place each planet, multiply its distance in AU by 10 to get meters. Sizes follow the same rule. The Sun is about 1.4 million kilometers across, which at our scale is a ball 9.3 centimeters (3.7 inches) across, about the size of a softball or a large orange. The Sun is about 109 times as wide as Earth, so model Earth is 9.3 cm ÷ 109, less than 1 millimeter across: a speck like a grain of sand.

The big idea. Here is our whole walk. Mercury, a speck about the size of a grain of salt, sits 3.9 meters from the Sun. Venus and Earth, both grains of sand, sit at 7.2 and 10 meters. Mars, a smaller speck, is at 15 meters. All four rocky planets fit inside a large classroom. Then the long walk begins. Jupiter, a pea about 1 centimeter across, waits 52 meters from the Sun. Saturn, a slightly smaller pea, is at 95 meters. Uranus and Neptune, each the size of a peppercorn, stand at 192 and 301 meters. Neptune is about 300 meters (nearly 1,000 feet) from the Sun, the length of more than three football fields. Almost the whole solar system is empty space. That is why pictures in books and the gears of an **orrery** squeeze the planets close together and make them far too big: a picture drawn to true scale would show a dot for the Sun and nothing else you could see.

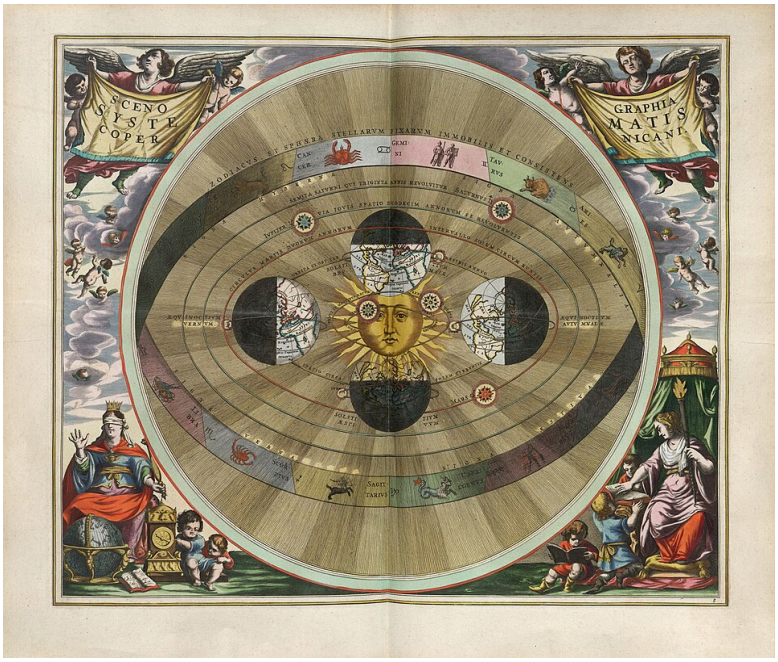
Try it and see. Before the walk, measure your own pace. Mark 10 meters with a tape measure, walk it with normal steps and count. If you take 13 steps, each pace is about 10 ÷ 13 = 0.77 meters. Then you can pace off every planet. When you reach Neptune, turn around and look back. The Sun will be a small round speck far away, and Earth will be invisible. At this same scale, the nearest star beyond the Sun would sit about 2,700 kilometers (1,700 miles) away, roughly the distance from New York to Denver.

God’s handiwork. The prophet Isaiah asked who “meted out heaven with the span,” that is, who measured the sky with the width of His hand (Isaiah 40:12). A span is the stretch from the tip of the thumb to the tip of the little finger. Your walk to Neptune takes several minutes of steady stepping, and you have walked across only a sliver of the heavens. To the Lord who made them, the whole of it is measured as easily as you measure a book with your hand. Standing at Neptune and looking back toward a tiny Sun is a good place to feel both how small we are and how great He is.



Our scale walk, with 1 AU = 10 meters. The four rocky planets fit in the first 16 meters; Neptune is more than 300 meters away.

PICTURE STUDY



Scenographia Systematis Copernicani (The Copernican System), Andreas Cellarius, 1660 · Hand-colored engraving, from the star atlas *Harmonia Macrocosmica* · Published in Amsterdam by Johannes Janssonius; copies are held in many libraries

Andreas Cellarius was a schoolmaster and mapmaker who lived in the Netherlands. In 1660 he published *Harmonia Macrocosmica*, one of the most beautiful star atlases ever printed. Its pictures were engraved on copper and colored by hand. This plate shows the arrangement Copernicus described, with the Sun in the middle and the planets traveling around it.

Like nearly every picture of the solar system made before or since, it is not to scale. The orbits are drawn neatly spaced so that everything fits on one page. After your scale walk, you will be able to see exactly what the artist had to squeeze.

Look closely

- Find the Sun. What did the artist put at the very center?
- Count the rings around the Sun. How many planets did people know about in 1660?
- Look at the spacing between the rings. Are they spread out evenly? How does that compare with your scale walk?
- Look at the outer edge of the picture. What did the artist place out there beyond the planets?

Talk about it

1. Why do you think Cellarius drew the orbits evenly spaced instead of to true scale?
2. If you redrew this plate to the scale of your walk, with Saturn at the edge of the page, where would Earth's ring be?

> **Safety first.** Do the walk on a sidewalk, park path or empty field with an adult, away from traffic, and stay together. Keep tiny planet models such as peppercorns and beads away from little brothers and sisters who might put them in their mouths. Never look at the Sun.

EXPERIMENT: THE LONG WALK: A SCALE SOLAR SYSTEM

Question: How far apart are the planets compared with their sizes? **Prediction:** before you start, each person guesses how far from the Sun Neptune will be and writes it down.

What we change: the planet we are placing. **What we keep the same:** one scale for everything (1 AU = 10 meters), the same walker and the same normal pace. **What we measure:** paces and meters to each planet. **Record:** a table of planet, model distance, paces and model size.

You will need

- A ball about 9 centimeters (3.5 inches) across for the Sun: a softball, orange or grapefruit
- 8 index cards and a fine-point pen
- 2 peas or 1-centimeter beads (Jupiter and Saturn) and 2 peppercorns (Uranus and Neptune), taped to cards
- 8 sticks, flags or stones to mark the planets
- A tape measure or a string exactly 10 meters long
- Notebook, pencil and calculator

Steps

1. Make the planet cards. On four cards, make tiny dots with a sharp pen for Mercury, Venus, Earth and Mars (Mercury and Mars the smallest, Venus and Earth a little bigger). Tape a pea or bead to the Jupiter and Saturn cards and a peppercorn to the Uranus and Neptune cards. Label each card with the planet's name and distance.
2. Measure your pace: walk the 10-meter string or tape with normal steps and count. Divide 10 by your count to find your pace length.
3. Copy this table into your notebook and fill in the paces column: Mercury 3.9 m, Venus 7.2 m, Earth 10 m, Mars 15.2 m, Jupiter 52 m, Saturn 95 m, Uranus 192 m, Neptune 301 m. Paces = meters ÷ your pace length.
4. Set the Sun at the starting point. Pace off each planet in a straight line from the Sun, set its card under a marker stone, and stand there a moment to look back.
5. At Jupiter, look back at the Sun and at the four rocky planets bunched near it. Write one sentence about what you see.
6. At Neptune, look back again. Can you still see the Sun? Can you see Earth? Record what you notice.
7. Compare your Neptune prediction with the real model distance. Then walk back to the hallway warm-up and check your Earth guess against 10 meters (and remember that the hallway orange was a little bigger than our model Sun).

Tips

- If you run out of straight path, the planets do not need to be in a line. Each one only needs to be the right distance from the Sun.
- A bicycle odometer, a long walking route on a map, or counting sidewalk squares can help on a long walk.

Check your work

- I used one scale for every planet's size and distance.
- I can change AU into model meters by multiplying by 10.
- I can describe how empty the solar system is.

FIELD NOTEBOOK

1. Draw a long strip of paper as a map of your walk. Mark the Sun and each planet and write how many paces each one was from the Sun.
2. Draw the model Sun, Jupiter and Earth side by side at their model sizes: 93 mm, about 10 mm and less than 1 mm across. Label each.
3. Write a short postcard from Neptune telling a friend back on Earth what the Sun looks like from out there.

> **From history.** In 2001 the Smithsonian opened Voyage, a model of the solar system at one ten-billionth of its true size, along the National Mall in Washington, D.C. At that scale the Sun is about the size of a grapefruit and Earth is smaller than the head of a pin, about

15 meters (50 feet) away. Visitors walk from planet to planet past the great museums, reading a sign at each stop.

WORKED EXAMPLES

Example 1. Our scale is 1 AU = 10 meters. Saturn is 9.5 AU from the Sun. How far from the model Sun do we put Saturn? About how many feet is that? If your pace is 0.75 meters, how many paces is it?

(Use the map or drawing "Find Saturn at 95 meters on the top line." shown earlier in this lesson.)

1. Multiply the distance in AU by 10: 9.5 × 10 = 95 meters.
2. One meter is about 3.28 feet: 95 × 3.28 = 311.6, about 312 feet.
3. Paces: 95 ÷ 0.75 = 126.7, about 127 paces.

Answer: Saturn goes 95 meters (about 312 feet) from the Sun, about 127 paces.

Example 2. In our model the Sun is a ball 9.3 centimeters across. The real Sun is about 109 times as wide as the real Earth. How big is model Earth?

1. Because every part uses the same scale, model Earth must also be 109 times smaller than model Sun.
2. 9.3 cm ÷ 109 = 0.085 cm.
3. There are 10 millimeters in a centimeter: 0.085 × 10 = 0.85 mm.

Answer: Model Earth is about 0.85 millimeters across, less than 1 millimeter: about the size of a grain of sand.

PRACTICE

1. EASY What is an astronomical unit (AU), and about how long is it?
2. EASY Using 1 AU = 10 meters, where does Mars go if it is 1.5 AU from the Sun?
3. MEDIUM Uranus is 19.2 AU from the Sun. How far from the model Sun is it? How far is it from model Saturn, at 95 meters?
4. MEDIUM Use the table of model distances.
   Planet | Model distance from Sun
   Mercury | 3.9 m
   Venus | 7.2 m
   Earth | 10 m
   Mars | 15.2 m
   Jupiter | 52 m
   Saturn | 95 m
   Uranus | 192 m

Neptune | 301 m
(a) How many planets are within 16 meters of the Sun? (b) Which two neighboring planets have the biggest gap between them, and how big is it? (c) How far apart are Earth and Mars?

5. MEDIUM The Sun is about 9.7 times as wide as Jupiter. Our model Sun is 9.3 centimeters across. About how wide is model Jupiter?
6. HARD Explain in two or three sentences why most pictures of the solar system in books are not drawn to scale.
7. HARD A student thinks walking faster makes paces longer, which would throw off the scale walk. Design a fair test. What should be changed? Name two things to keep the same. What should be measured?
8. CHALLENGE The Smithsonian's Voyage model on the National Mall in Washington, D.C., uses a larger scale: 1 AU is about 15 meters. Neptune is about 30 AU from the Sun. How far from the model Sun is Neptune in Voyage? How much farther is that than in our walk?

COMMON MISTAKES

- Thinking the planets are evenly spaced, as in many pictures. The outer planets are much farther apart than the inner ones.
- Thinking the planets are close to the Sun in size. The Sun is about 109 times as wide as Earth and about 10 times as wide as Jupiter.
- Using one scale for sizes and another for distances, then calling it a scale model. A true scale model uses one rule for everything.

> **Make it a game · Guess the Gap.** One player names two planets. Everyone else writes a guess of how far apart they are in the scale walk, in meters. Check with the table of model distances; the closest guess wins a point, and an exact answer wins two. Then the winner names the next pair. Play to seven points, and try to spot which gaps fool everyone.

> **Scripture.** "Who hath measured the waters in the hollow of his hand, and meted out heaven with the span, and comprehended the dust of the earth in a measure, and weighed the mountains in scales, and the hills in a balance?" (Isaiah 40:12, KJV)

It takes you minutes of walking to cross a tiny model of the solar system. God measures the whole heaven with the span of His hand.

Practice answers

1. The average distance from Earth to the Sun, about 150 million kilometers (93 million miles).
2. 1.5 × 10 = 15 meters from the Sun (about 49 feet).
3. 19.2 × 10 = 192 meters from the Sun. 192 − 95 = 97 meters beyond Saturn.
4. (a) Four: Mercury, Venus, Earth and Mars. (b) Uranus and Neptune: 301 − 192 = 109 meters. (c) 15.2 − 10 = 5.2 meters.

5. 9.3 ÷ 9.7 = 0.96 cm, about 1 centimeter (0.4 inch), the size of a pea.
6. The planets are tiny compared with the huge distances between them. If a page were drawn to scale with Neptune at the edge, the Sun would be a tiny dot and the planets would be far too small to see. So artists squeeze the orbits together and draw the planets much too big so we can see them.
7. Change: walking speed (slow walk versus fast walk). Keep the same (any two): the same person, the same shoes, the same flat path, the same measured distance such as 20 meters. Measure: the number of paces to cover the distance, repeated three times at each speed and averaged. If the fast walk takes fewer paces, the paces are longer when walking fast.
8. 30 × 15 = 450 meters (about 1,480 feet). Our walk put Neptune at about 300 meters, so Voyage’s Neptune is about 150 meters farther.

3.3 Herschel Finds Uranus (1781)

OBJECTIVES

- Tell how William Herschel, a music teacher in Bath, England, found the planet Uranus with a telescope he built himself on March 13, 1781.
- Explain the two clues that showed Uranus was not a star: it looked like a small disk, and it moved among the stars.
- Describe Uranus and compare its distance and year with Saturn’s, and design a fair test of how distance and magnification help us see a disk.

Warm-up. Tape a page of newspaper or a cereal box to a wall. Walk to the far side of the room and look at the smallest print. Can you tell letters from dots? Walk slowly closer and stop the moment you can see that the specks are really shapes. Measure how far away you are. Telescopes do the same thing for the sky: they help us tell a tiny shape from a mere point of light.

Video. Coming soon. William and Caroline Herschel and the discovery of Uranus in 1781, plus Voyager 2 images of Uranus; search NASA Science, NASA Jet Propulsion Laboratory, Royal Museums Greenwich, Smithsonian National Air and Space Museum and planetarium channels.

KEY TERMS

reflecting telescope
A telescope that uses a curved mirror, instead of a lens, to gather light and form an image.

magnification
How many times bigger a telescope or magnifying glass makes something look.

comet
A small, icy body that travels around the Sun. Near the Sun it often shows a fuzzy head and a long glowing tail.

Uranus
The seventh planet from the Sun, a pale blue-green giant tipped over on its side. It was the first planet found with a telescope.

ice giant
A giant planet, such as Uranus or Neptune, made mostly of water, ammonia and methane ices around a small rocky center, under a thick layer of gas.

CORE IDEAS

The story. On the night of March 13, 1781, in the narrow garden behind his house at 19 New King Street in Bath, England, William Herschel was doing what he loved best: sweeping the sky with a telescope he had built with his own hands. Herschel had been born in

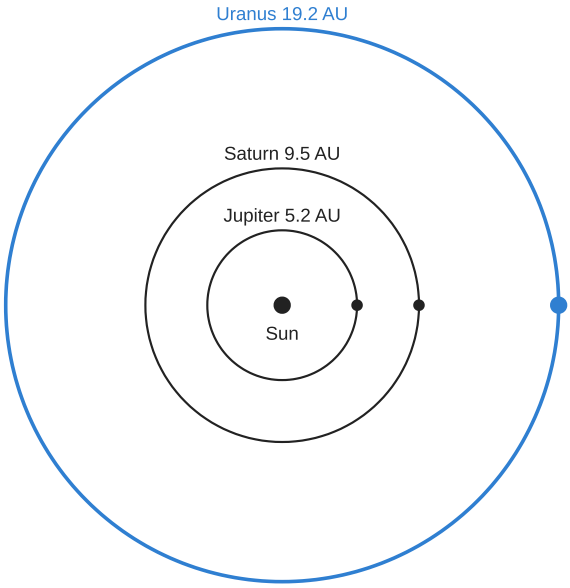
Hanover, Germany, in 1738 and came to England as a young musician. In Bath he played the organ at the Octagon Chapel, wrote music and taught pupils all day. At night he became an astronomer. His sister Caroline, who had joined him from Germany in 1772, helped him grind and polish telescope mirrors, sometimes feeding him bites of food while he worked for hours without stopping. That night, between ten and eleven o'clock, among the stars near the constellation Gemini, he noticed one "star" that did not look quite right.

How they figured it out. Herschel's telescope was a **reflecting telescope** about 2 meters (7 feet) long with a mirror about 16 centimeters (6.2 inches) across. Through it, the stars all looked like sharp points. This object looked like a tiny round disk. When Herschel switched to an eyepiece with greater **magnification**, it grew larger, while the stars stayed points. That was his first clue. A few nights later came the second: it had moved a little among the stars. Herschel reported that he had found a **comet**. But this "comet" had no fuzzy head and no tail. Astronomers in other countries, among them Anders Lexell in Russia, worked out its path. It moved in a nearly round orbit about twice as far from the Sun as Saturn. It was not a comet at all. It was a new planet, the first ever found with a telescope. Other astronomers had seen it before; John Flamsteed had even listed it as a star in 1690. But they had not looked carefully enough, night after night, to see that it was a wanderer.

The big idea. In one night Herschel doubled the size of the known solar system. Saturn, the farthest planet anyone knew, is about 9.5 AU from the Sun. **Uranus** is about 19.2 AU away, about 2.9 billion kilometers (1.8 billion miles). It is about four times as wide as Earth and takes 84 Earth years to go once around the Sun. Uranus is an **ice giant**: mostly water, ammonia and methane ices under a deep blanket of hydrogen and helium gas. The methane gas in its air soaks up red light, which gives the planet its pale blue-green color. Strangest of all, Uranus is tipped over on its side, so it seems to roll around the Sun like a ball rather than spin like a top.

In the world today. Herschel wanted to name the planet *Georgium Sidus*, "George's Star," in honor of King George III. The king gave him a yearly salary so he could give up teaching music and study the sky full time. The German astronomer Johann Bode suggested the name Uranus, after the sky god of the old Greek stories, and that name won out. In 1846 astronomers found the eighth planet, Neptune, by a different route: the French mathematician Urbain Le Verrier noticed that Uranus was being tugged slightly off its expected path, calculated where an unseen planet must be, and Johann Galle in Berlin found Neptune very close to that spot. Only one spacecraft has ever visited Uranus: Voyager 2, which flew past it in January 1986.

God's handiwork. Uranus had been rolling around the Sun all along, faithfully, unseen by anyone who knew what it was. It took a patient man with a homemade telescope, looking carefully, to find it. "The works of the LORD are great, sought out of all them that have pleasure therein" (Psalm 111:2). Science is a kind of seeking. God hides wonders in His creation, and He gives people the joy of finding them.

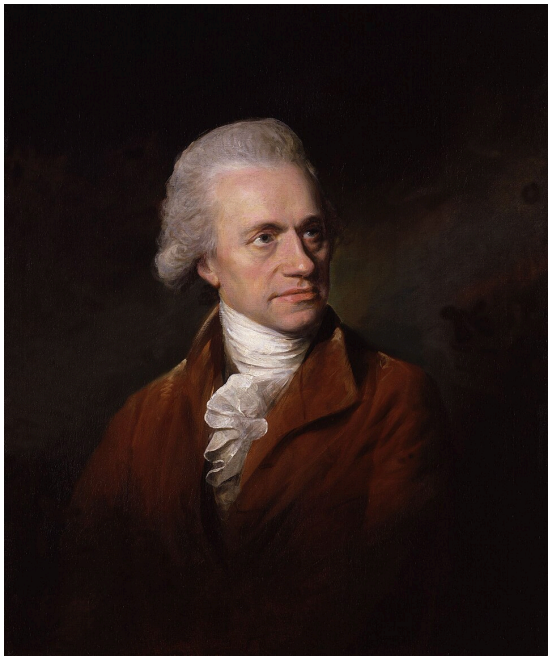


Uranus orbits about twice as far from the Sun as Saturn.

AU = the distance from Earth to the Sun. Earth's orbit would be a tiny circle near the Su

Uranus orbits about twice as far from the Sun as Saturn. Herschel's discovery doubled the size of the known solar system.

PICTURE STUDY



Sir William Herschel, Lemuel Francis Abbott, 1785 · Oil on canvas · National Portrait Gallery, London

Lemuel Francis Abbott was an English portrait painter who painted many famous men of his day, including the naval hero Horatio Nelson. He painted William Herschel in 1785, four years after the discovery of Uranus. By then Herschel had left his work as a music teacher in Bath and moved near Windsor Castle to be the King's astronomer.

A portrait painter tries to show not only what a person looked like, but what kind of person he was. Look closely to see what Abbott wanted you to know about Herschel.

Look closely

- Look at Herschel’s face and eyes. What words would you use to describe his expression?
- Look at his clothes. Do they look like the clothes of a poor musician or of an important man? What had changed in his life?
- Look for anything in the painting besides Herschel himself. What has the painter included, and what has he left out?
- Notice where the light falls. What part of the painting does it lead your eye to first?

Talk about it

1. If you were painting Herschel, what objects would you put in the picture to tell his story?
2. Herschel spent long nights sweeping the sky one patch at a time. What does his discovery teach about patience?

> **Safety first.** Never point binoculars, a telescope or a magnifying glass at the Sun. Even a quick look can blind you in an instant. Use binoculars only on the indoor test card and on the night sky.

EXPERIMENT: POINT OR DISK? A SEEING EXPERIMENT

Herschel knew Uranus was not a star because it showed a tiny disk while the stars stayed points. In this experiment you will find out how distance and magnification change whether you can tell a disk from a dot.

Question: How close must you be to tell a tiny dot from a tiny ring, with and without binoculars? **Prediction:** write your guess for each. **What we change:** your distance from the card, and whether you use binoculars. **What we keep the same:** the same card, the same light, the same person looking. **What we measure:** the greatest distance at which you can tell which mark is the ring. **Record:** a data table.

You will need

- A white index card
- A fine black pen and a ruler
- Tape and a wall or door in a well-lit room or hallway
- A tape measure
- Binoculars or a magnifying glass (optional)
- A partner, notebook and pencil

Steps

1. On the card, about 3 centimeters (just over 1 inch) apart, make two marks of the same width: a solid dot about 2 millimeters across, and a small open ring about 2 millimeters across. Your partner should not tell you which side has which.
2. Tape the card at eye level on a wall. Stand 15 meters (about 50 feet) away, or as far as the room allows.
3. Walk slowly toward the card. Stop the moment you can tell which mark is the ring. Measure your distance from the card and record it.
4. Repeat two more times, with your partner switching the card around (or making a new card) so you cannot remember. Find the average of your three distances.
5. Now do the same with binoculars or a magnifying glass. Start far back, walk forward and record the distance three times.
6. Make a data table with columns: Trial, Eyes only (meters), With binoculars (meters). Circle the averages.
7. Write two sentences: How did magnification help? How is this like what Herschel saw when he changed eyepieces?

Tips

- Keep the light the same for every trial. A brighter or darker room is a different experiment.
- If you have no binoculars, try the test again with a larger ring and dot, 4 millimeters across, and see how the distance changes.

Check your work

- I can name what I changed, what I kept the same and what I measured.
- I can explain how magnification helps tell a disk from a point.
- I can explain Herschel's two clues that Uranus was not a star.

FIELD NOTEBOOK

1. Draw what Herschel might have seen in his eyepiece: a field of sharp star points and one tiny round disk. Label the disk "Uranus, March 13, 1781."
2. Make a two-panel drawing of the same patch of stars on two different nights, with one "star" that has moved. Ask someone to find the wanderer.
3. Draw Uranus tipped on its side, with its rings and an arrow showing how it rolls as it travels around the Sun.

> **From history.** Caroline Herschel became a great astronomer in her own right. She swept the sky with her own small telescope and discovered eight comets. In 1787 King George III granted her a yearly salary as William's assistant, making her one of the first women ever paid to do scientific work. In 1828 the Royal Astronomical Society awarded her its Gold Medal for her catalog of star clusters and nebulae.

WORKED EXAMPLES

Example 1. Uranus takes 84 Earth years to go once around the Sun. Herschel found it in 1781. In what years did it come back to the same place in its orbit? How many full trips has it made by 2026?

1. Add 84 years at a time: 1781 + 84 = 1865. 1865 + 84 = 1949. 1949 + 84 = 2033.
2. So Uranus came back to its 1781 place in 1865 and 1949, and will return again in 2033.
3. From 1781 to 2026 is 2026 − 1781 = 245 years. 245 ÷ 84 = 2.9.

Answer: It returned in 1865 and 1949. By 2026 it has made 2 full trips and is nearly done with its third, which ends in 2033.

Example 2. Saturn is about 9.5 AU from the Sun and Uranus about 19.2 AU. How many times as far from the Sun as Saturn is Uranus? What did Herschel's discovery do to the size of the known solar system?

(Use the map or drawing "Compare the Saturn circle with the Uranus circle." shown earlier in this lesson.)

1. Divide the larger distance by the smaller: 19.2 ÷ 9.5 = 2.02.
2. So Uranus is about 2 times as far from the Sun as Saturn.
3. Before 1781, Saturn marked the edge of the known solar system. Now the edge was twice as far out.

Answer: Uranus is about twice as far from the Sun as Saturn, so Herschel doubled the size of the known solar system.

PRACTICE

1. EASY Where and when did William Herschel discover Uranus?
2. EASY What did Herschel first think he had found?
3. MEDIUM Give the two clues that showed Herschel the object was not a star.
4. MEDIUM Use the table.
   Object | Year found | Found by | How it was found
   Uranus | 1781 | William Herschel | seen through his telescope
   Ceres (dwarf planet) | 1801 | Giuseppe Piazzi | seen through a telescope
   Neptune | 1846 | Johann Galle | searched where Le Verrier's math predicted
   Pluto (dwarf planet) | 1930 | Clyde Tombaugh | compared photographs of the sky
   (a) How many years passed between the discovery of Uranus and of Neptune? (b) Which object was found by first predicting its place with mathematics? (c) Which objects in the table are not counted as planets today?

5. MEDIUM Uranus is about 4 times as wide as Earth. Earth is about 12,756 kilometers across. About how wide is Uranus?
6. HARD In the Point or Disk experiment, a student tests with binoculars in a bright room and without binoculars in a dim room, then says the binoculars helped. Why is this not a fair test? How should it be fixed?
7. HARD John Flamsteed saw Uranus in 1690 but listed it as a star. Explain in two or three sentences why he missed that it was a planet.
8. CHALLENGE Uranus goes all the way around the Sun, 360 degrees, in 84 years. About how many degrees does it move in one year? About how much in one week?

COMMON MISTAKES

- Thinking Herschel was a trained, paid astronomer. He was a musician and music teacher who studied the sky as a hobby and built his own telescopes.
- Thinking a telescope makes stars look bigger. Stars are so far away that they stay points; only nearer objects such as planets show a disk.
- Thinking Uranus can never be seen without a telescope. In a very dark sky, sharp eyes can just barely glimpse it as a faint star, which is why it was mistaken for one for so long.

Make it a game · Blink and Find. Draw a field of 25 dots on two sheets of paper, exactly the same, except move one dot a little on the second sheet. Trade with your partner. Flip back and forth between the two sheets and race to find the wanderer. In 1930 Clyde Tombaugh found Pluto by flipping between two photographs of the sky in just this way. Each find scores a point; make the moves smaller as you get better.

Scripture. “The works of the LORD are great, sought out of all them that have pleasure therein.” (Psalm 111:2, KJV)

Herschel and his sister took great pleasure in seeking out God’s works night after night, and their patience was rewarded with a whole new world.

Practice answers

1. In the garden of his house in Bath, England, on March 13, 1781.
2. A comet.
3. (1) It looked like a small disk, and it grew larger at higher magnification, while stars stayed points. (2) Over a few nights it moved among the stars.
4. (a) 1846 − 1781 = 65 years. (b) Neptune. (c) Ceres and Pluto, which are dwarf planets.
5. 4 × 12,756 = 51,024, about 51,000 kilometers (32,000 miles). (The measured value is about 51,118 km.)
6. Two things were changed at once, the binoculars and the light, so we cannot tell which one made the difference. Keep the light the same for every trial and change only whether binoculars are used. Repeat each test several times and compare the averages.
7. Uranus is faint and moves very slowly, and through Flamsteed’s instrument it looked like just another point of light. He did not watch it night after night to see that it moved. Herschel’s

better telescope showed a disk, and his follow-up nights showed the motion.

8. 360 ÷ 84 = about 4.3 degrees per year. 4.3 ÷ 52 = about 0.08 degree per week, a tiny amount. That is why careful watching over several nights was needed to see it move.

3.4 Voyager's "Pale Blue Dot"

OBJECTIVES

- Tell the story of the Voyager space probes and the "Pale Blue Dot" photograph Voyager 1 took of Earth on February 14, 1990.
- Calculate how long a radio signal takes to travel from a distant spacecraft and how far a spacecraft travels in a day.
- Explain how small Earth looks from the edge of the solar system, and compare that view with what Psalm 8 says about God's care for people.

Warm-up. Put one grain of salt or sugar on a dark plate or a dark piece of paper on the floor. Look at it from close up, then take one step back at a time. How many steps until you lose it? Now imagine looking for the whole Earth from far beyond Neptune.

Video. Coming soon. Voyager 1 and Voyager 2 missions, the Family Portrait and Pale Blue Dot image, and the Golden Record; search NASA, NASA Jet Propulsion Laboratory, Smithsonian National Air and Space Museum and NASA Space Place.

KEY TERMS

space probe
A robot spacecraft with no people aboard, sent to explore space and send back pictures and measurements by radio.

flyby
A trip in which a probe passes close by a planet or moon and takes pictures without stopping or landing.

radio signal
An invisible wave that travels at the speed of light, about 300,000 kilometers (186,000 miles) per second, used to send messages and pictures across space.

pixel
One tiny square of color in a digital picture. A picture is made of many thousands of pixels.

interstellar space
The space between the stars, beyond the region where the Sun's steady outflow of particles, called the solar wind, holds sway.

CORE IDEAS

The story. On February 14, 1990, a small spacecraft named Voyager 1 was racing away from home more than 6 billion kilometers (3.7 billion miles) from the Sun, well beyond the orbit of Neptune. That day its controllers on Earth had it do something it had never done before: turn around and look back toward home. Its camera took 60 pictures, making a "family portrait" of the planets. In one of them, inside a streak of scattered sunlight, sits a single

faint speck. That speck is the Earth, smaller than one pixel of the picture. The astronomer Carl Sagan, who had urged NASA to take the photograph, named it the “Pale Blue Dot.” He later wrote, “Look again at that dot. That’s here. That’s home. That’s us.” Shortly afterward, Voyager 1’s cameras were switched off to save power. They have never been turned on again.

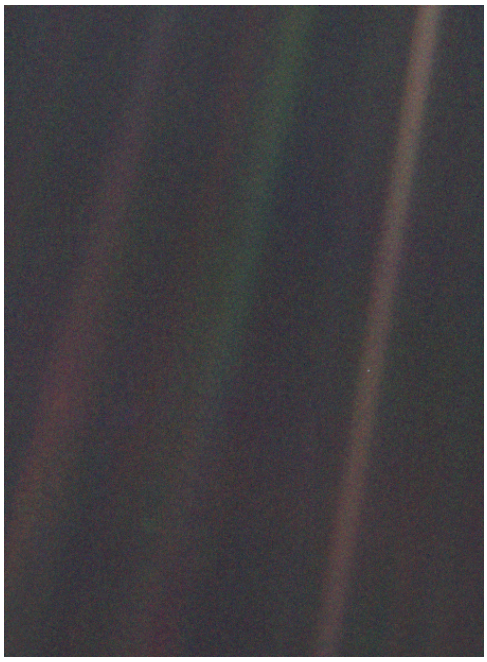
How they figured it out. Two Voyager **space probes** were launched from Cape Canaveral, Florida, in 1977: Voyager 2 on August 20 and Voyager 1 on September 5. They were sent at a rare time when the four giant planets were lined up so that a probe could swing past one and be flung on toward the next by that planet’s gravity. On their **flybys**, the Voyagers found active volcanoes on Jupiter’s moon Io, photographed the thin rings of Jupiter, and showed that Saturn’s rings are made of thousands of narrow ringlets. Voyager 2 went on to make the only visits ever made to Uranus, in 1986, and Neptune, in 1989. Every photograph was sent home as a long string of numbers carried by a faint **radio signal**. Even moving at the speed of light, the signal from Voyager 1 on the day of the Pale Blue Dot took about five and a half hours to reach Earth. Giant dish antennas in California, Spain and Australia listened for it.

The big idea. Picture the scale walk from Lesson 3.2, where 1 AU is 10 meters. Voyager 1 on that day was about 40 AU from the Sun, so in the model it would stand about 400 meters away, a hundred meters past Neptune, looking back at an orange-sized Sun and trying to spot a grain of sand 10 meters from it. Earth was so close to the Sun in the camera’s view that sunlight scattering inside the camera made the bright streaks that run across the picture. Mercury was lost in the Sun’s glare, and Mars was hidden by scattered sunlight. Earth, the only world we know that is full of oceans, forests and living things, was a speck you could almost cover with the point of a pin.

In the world today. The Voyagers are still traveling. Voyager 1 crossed into **interstellar space** in 2012, and Voyager 2 followed in 2018. They are the most distant objects people have ever made. Their power supplies grow weaker every year, so engineers switch off one instrument after another to keep the rest working. Today a radio message to Voyager 1 takes nearly a whole day to arrive. Each probe also carries a gold-plated copper record with sounds and pictures of Earth, in case anyone ever finds it.

God’s handiwork. Long before any spacecraft, King David looked up at the night sky and felt how small people are: “When I consider thy heavens, the work of thy fingers, the moon and the stars, which thou hast ordained; What is man, that thou art mindful of him?” (Psalm 8:3–4). The Pale Blue Dot shows just how small our home is. But the psalm does not stop at smallness. It goes on to say that God made man “a little lower than the angels” and crowned him “with glory and honour” (Psalm 8:5). The great God who made the heavens knows that tiny dot by name, and He cares for every person on it.

PICTURE STUDY



Pale Blue Dot, Voyager 1 spacecraft, NASA Jet Propulsion Laboratory, February 14, 1990 · Digital photograph made by combining images taken through color filters with Voyager 1's narrow-angle camera · NASA Jet Propulsion Laboratory archives, Pasadena, California (public domain)

This is not a painting but a photograph, taken by a robot camera about 6 billion kilometers (3.7 billion miles) from home. Engineers on Earth sent the commands, Voyager 1 took the pictures, and the pictures traveled back to Earth by radio in the weeks that followed. The bands of light are sunlight scattered inside the camera, because the camera was pointed not far from the Sun.

When people look at a famous painting, they look for what the artist put at the center. Here the most important thing in the picture is the smallest thing in it.

Look closely

- Find the pale blue dot. How long did it take you? Would you have noticed it if no one had told you to look?
- Look at the streaks of light. Where do they come from?
- Notice how much of the picture is empty and dark. What does that tell you about space?
- Think about what is inside that dot: every ocean, every mountain, every person who has ever lived.

Talk about it

1. Why do you think so many people around the world have found this picture so moving?
2. How does Psalm 8 help a Christian think about this picture?

EXPERIMENT: HOW FAR UNTIL IT VANISHES?

From Voyager’s camera, Earth shrank to less than a pixel. In this experiment you will find out how size changes the distance at which a small object disappears from sight.

Question: Does a bigger dot stay visible from farther away, and how much farther? **Prediction:** write your guess. **What we change:** the size of the object. **What we keep the same:** the same dark background, the same lighting, the same person looking, the same place to stand. **What we measure:** the distance at which the object can no longer be seen. **Record:** a data table and a bar graph.

You will need

- Three small light-colored objects of different sizes: a grain of salt, a sesame seed and a dried pea (or white beads of three sizes)
- A sheet of black or dark blue paper
- A ruler and a tape measure
- Masking tape for marking distances
- A partner, notebook, pencil and graph paper

Steps

1. Measure each object across with the ruler, as well as you can, and record the sizes in millimeters.
2. Tape the dark paper flat on a table in a room with steady light, and place the smallest object in the middle.
3. Start right beside the table. Walk straight backward one step at a time, keeping your eyes on the object. Stop when you can no longer see it, and have your partner measure your distance from the paper.
4. Repeat three times and average your distances. Your partner can secretly move the object a little, or remove it, so you have to really look.
5. Do the same with the middle-sized object and then the largest. Keep everything else exactly the same.
6. Make a data table with columns: Object, Size (mm), Trial 1, Trial 2, Trial 3, Average distance (m). Then draw a bar graph of the average distances.
7. Write two sentences: What pattern did you find? What does it tell you about how tiny Earth must look from 6 billion kilometers away?

Tips

- Do not squint or change your glasses between trials; the same eyes must look the same way each time.
- A long hallway works well. If you run out of room with the pea, record “more than” the longest distance you could reach.

Check your work

- I kept everything the same except the size of the object.
- I made a data table and a bar graph from my measurements.
- I can explain why Earth looked like a dot smaller than a pixel to Voyager 1.

FIELD NOTEBOOK

1. Draw a timeline of the Voyager journeys: launches in 1977, Jupiter in 1979, Saturn in 1980 and 1981, Uranus in 1986, Neptune in 1989 and the Pale Blue Dot in 1990.
2. Draw a dark square with one tiny blue dot in a streak of light. Beneath it, copy Psalm 8:3–4.
3. Design your own golden record: list five sounds and five pictures you would send to show someone what Earth is like, and explain one choice.

From history. Each Voyager carries a gold-plated copper phonograph record, packed with a needle and pictures showing how to play it. It holds greetings spoken in 55 languages, sounds of Earth such as wind, rain, birds and a mother’s kiss, more than a hundred pictures, and music from many lands, including music by Johann Sebastian Bach. Bach, a faithful Lutheran church musician, often wrote “Soli Deo Gloria,” glory to God alone, at the end of his works, so his music now travels between the stars bearing that dedication.

WORKED EXAMPLES

Example 1. On the day of the Pale Blue Dot, Voyager 1 was about 6 billion kilometers from Earth. Radio signals travel about 300,000 kilometers each second. How long did the pictures take to reach Earth?

1. Time = distance ÷ speed: 6,000,000,000 km ÷ 300,000 km per second.
2. Cancel five zeros from each number: 60,000 ÷ 3 = 20,000 seconds.
3. Change to hours: there are 60 × 60 = 3,600 seconds in an hour. 20,000 ÷ 3,600 = 5.56 hours.
4. 0.56 hour × 60 = about 33 minutes.

Answer: About 20,000 seconds, or about 5 hours 33 minutes.

Example 2. Voyager 1 travels about 17 kilometers every second. How far does it go in one hour? In one day? The Moon is about 384,000 kilometers from Earth; about how many Earth-to-Moon trips is one day of Voyager travel?

1. One hour has 3,600 seconds: 17 × 3,600 = 61,200 kilometers per hour (about 38,000 miles per hour).
2. One day has 24 hours: 61,200 × 24 = 1,468,800 kilometers, about 1.5 million kilometers.
3. Compare with the Moon's distance: 1,468,800 ÷ 384,000 = 3.8.

Answer: About 61,200 km in an hour and about 1.5 million km in a day, nearly 4 times the distance from Earth to the Moon.

PRACTICE

1. EASY What is a space probe?
2. EASY Which spacecraft took the Pale Blue Dot picture, and on what date?
3. MEDIUM Use the table of Voyager 2's flybys.
   Planet | Year of flyby
   Jupiter | 1979
   Saturn | 1981
   Uranus | 1986
   Neptune | 1989
   (a) How many years passed between the Saturn and Uranus flybys? (b) Voyager 2 was launched in 1977. How many years did it take to reach Neptune? (c) Which gap between flybys was the longest, and why does that make sense?
4. MEDIUM When Voyager passed Saturn, it was about 1.4 billion kilometers from Earth. Radio travels about 300,000 kilometers per second. About how many minutes did a signal from Saturn take to reach Earth?
5. MEDIUM In the scale walk where 1 AU = 10 meters, Voyager 1 was about 40 AU from the Sun when it took the Pale Blue Dot. How far from the model Sun would it be? How far past model Neptune (301 meters) is that?
6. HARD Why does the Pale Blue Dot photograph have bright streaks of light across it?
7. HARD In the How Far Until It Vanishes experiment, a student tests the salt grain on black paper and the pea on white paper. Is this a fair test? What is the variable that should change, and what must be kept the same?
8. CHALLENGE Carl Sagan used the Pale Blue Dot to say that people are very small in a very big universe. Psalm 8 also speaks of smallness. In three or four sentences, explain what David adds in Psalm 8 that the picture alone cannot show.

COMMON MISTAKES

- Thinking Voyager took the picture from outside our galaxy or near another star. It was still inside the solar system, a little beyond Neptune's distance.
- Thinking radio messages to spacecraft arrive instantly. Even at the speed of light they take hours, and now nearly a full day, to reach Voyager 1.
- Thinking the colored streaks in the picture are real beams in space. They are sunlight scattered inside the camera.

Make it a game · Radio Delay. One player is Mission Control and the other is Voyager, standing across the yard or at the far end of the house. Mission Control gives a simple command, such as "Turn left and take three steps." A timekeeper counts five seconds before Voyager may hear and obey, and five more before Voyager's reply of "Done!" counts. Try to steer Voyager to a hidden "planet" (a sock) using as few commands as possible. Then try a ten-second delay and see how much harder it gets.

Scripture. "When I consider thy heavens, the work of thy fingers, the moon and the stars, which thou hast ordained; What is man, that thou art mindful of him? and the son of man, that thou visitest him?" (Psalm 8:3–4, KJV)

From the edge of the solar system, Earth is a dot smaller than a pixel. Yet the God who made the heavens is mindful of every person on that dot.

Practice answers

1. A robot spacecraft with no people aboard that explores space and sends back pictures and measurements by radio.
2. Voyager 1, on February 14, 1990.
3. (a) 1986 − 1981 = 5 years. (b) 1989 − 1977 = 12 years. (c) Saturn to Uranus, 5 years. That makes sense because Uranus's orbit is about 10 AU beyond Saturn's, more than twice as far as the jump from Jupiter to Saturn (about 4 AU). (The jump to Neptune was about as long, but Voyager 2 had picked up speed swinging past Uranus.)
4. 1,400,000,000 ÷ 300,000 = about 4,667 seconds. 4,667 ÷ 60 = about 78 minutes, or about 1 hour 18 minutes.
5. 40 × 10 = 400 meters from the Sun, about 99 meters (roughly 100 meters) past Neptune.
6. From so far away, Earth appeared very close to the Sun in Voyager's view. The camera was pointed not far from the Sun, and sunlight bounced and scattered inside the camera, making the bright bands. Earth happened to sit in one of them.
7. No. Two things changed at once, the object's size and the background color, so we cannot tell which caused the difference. Only the size of the object should change. The background, lighting, person looking and starting place must stay the same.
8. Sample answer: The picture shows how tiny Earth is, and David agrees that people seem small when he considers the heavens. But David also says that God is mindful of man and visits him, and that God crowned man with glory and honour. A photograph can show size, but it cannot show that we are loved and cared for by the God who made the heavens. Our worth comes from Him, not from our size.

Unit 3 review

Answer each question. Show your work for calculations and use complete sentences for explanations. The review is worth 50 points.

1. (5 pts) Why did people long ago call the planets “wanderers”? Name the five planets they could see without a telescope.
2. (5 pts) Give two differences between a planet and a star as we see them in the night sky.
3. (5 pts) Explain why Mars sometimes seems to move backward among the stars.
4. (5 pts) In a scale model where 1 AU = 10 meters, how far from the model Sun does Jupiter go if it is 5.2 AU from the Sun? About how many feet is that? (1 meter is about 3.28 feet.)
5. (5 pts) Use the model distances: Earth 10 m, Mars 15.2 m, Saturn 95 m, Uranus 192 m. How far apart are Earth and Mars in the model? Saturn and Uranus? What does this show about the inner and outer solar system?
6. (5 pts) Explain why pictures of the solar system in books are almost never drawn to scale.
7. (5 pts) Who discovered Uranus, where, and in what year? What did he first think it was?
8. (5 pts) Uranus is about 19.2 AU from the Sun and Saturn about 9.5 AU. How did Herschel’s discovery change the size of the known solar system? Show your work.
9. (5 pts) Voyager 2 passed Uranus at about 3 billion kilometers from Earth. Radio travels about 300,000 kilometers per second. About how long did its signals take to reach Earth? Give your answer in seconds and in hours.
10. (5 pts) What does the Pale Blue Dot photograph show, and how does Psalm 8:3–4 help us think about it?

Unit project: my solar-system trail guide

Make an illustrated trail guide for a scale solar-system walk near your home, using the scale 1 AU = 10 meters. Include a hand-drawn map of your route with the Sun and all eight planets marked, a page for each planet showing its model size, model distance and paces from the Sun, and one fact from this unit (such as Mars’s backward loop, Herschel’s discovery of Uranus or Voyager’s visit). Add your Passing Mars data table, your Point or Disk table, and your How Far Until It Vanishes bar graph, and finish with a final page showing the Pale Blue Dot with Psalm 8:3–4 copied beneath it.

- **Accuracy**: Every model distance and size uses the same scale and is calculated correctly; planets are in the right order and labeled.
- **Records**: The three experiment tables and the bar graph are complete, dated and clearly labeled, with what was changed, kept the same and measured.
- **Explanation**: Planet pages explain clearly why the planets wander, how Uranus was found and what Voyager showed, in the student’s own words.
- **Care**: The guide is neat, colorful and easy for another family to follow on a real walk.

Answer key

1. The planets drift slowly among the stars from night to night, while the stars keep their places. The five are Mercury, Venus, Mars, Jupiter and Saturn.
2. Any two: a planet shines by reflected sunlight, while a star makes its own light; a planet moves among the stars over weeks, while stars keep their places; a planet usually shines with a steadier light, while stars twinkle more; planets always stay near the ecliptic.
3. Earth travels on an inside lane and moves faster than Mars. When Earth catches up and passes Mars, Mars seems to slide backward against the faraway stars, like a slower car you pass on the highway. Mars never really moves backward.
4. 5.2 × 10 = 52 meters. 52 × 3.28 = about 171 feet.
5. Earth to Mars: 15.2 − 10 = 5.2 m. Saturn to Uranus: 192 − 95 = 97 m. The inner planets are crowded close together, while the outer planets are spread very far apart.
6. The planets are tiny compared with the distances between them. Drawn to true scale, the Sun would be a dot and the planets would be far too small to see, so artists squeeze the orbits together and draw the planets much too big.
7. William Herschel, a musician and music teacher, in the garden of his house in Bath, England, in 1781 (March 13). He first thought it was a comet.
8. 19.2 ÷ 9.5 = about 2. Uranus is about twice as far from the Sun as Saturn, which had been the farthest known planet, so the known solar system doubled in size.
9. 3,000,000,000 ÷ 300,000 = 10,000 seconds. 10,000 ÷ 3,600 = about 2.8 hours (about 2 hours 47 minutes).
10. Taken by Voyager 1 on February 14, 1990, from about 6 billion kilometers away, it shows Earth as a tiny speck, smaller than one pixel, in a streak of sunlight. Psalm 8 agrees that people seem small beside the heavens God made, but it says God is mindful of us and cares for us, so our worth comes from Him, not from our size.

UNIT 4

The Stars

"He telleth the number of the stars; he calleth them all by their names" (Psalm 147:4). In this unit you will look up at the night sky the way real astronomers do: counting, measuring, sorting and asking careful questions. You will meet the star counters of the past, from Ptolemy in Alexandria to Johannes and Elisabeth Hevelius on their rooftop observatory, and learn how scientists estimate numbers far too large to count by sampling a small patch of sky.

Then you will find Orion and the Pleiades, the very star groups God named when He spoke to Job, and learn the difference between a constellation we imagine and a star cluster that really travels together. You will discover with Annie Jump Cannon that a star's color tells its temperature, and with Friedrich Bessel that parallax can measure the distance to a star. Finally you will learn what a light-year is, and think honestly about the distant starlight question and the ways creation scientists answer it.

Most of the projects happen outdoors on clear winter evenings, when Orion is high. Plan two or three observing nights with an adult, and keep every count, sketch and table in one sky notebook for your portfolio.

BEFORE YOU BEGIN

- Can multiply and divide whole numbers and find an average
- Can read a simple bar graph and a data table
- Knows that Earth spins once a day and goes around the Sun once a year (Units 1 and 3)
- Can name the variable, the things kept the same and the measurement in a simple experiment

MASTERY CHECKLIST

- I can explain how astronomers estimate the number of stars by sampling, and why city lights and dark adaptation change my count.
- I can find Orion, Betelgeuse, Rigel and the Pleiades, and use Orion's belt as a pointer.
- I can explain the difference between a constellation and a star cluster, and quote Job 38:31.
- I can tell a star's relative temperature from its color and list the star types O, B, A, F, G, K, M from hottest to coolest.
- I can explain parallax and define a light-year as a distance, and calculate how long light takes to come from the Sun.
- I can describe the distant starlight question fairly and explain two ways creation scientists answer it.

OPTIONAL BOOKS AND RESOURCES

- **Globe at Night** (https://globeatnight.org/): Free. A citizen-science project in which families match the stars they see in Orion (and other constellations) with charts and report how dark their sky is. A perfect partner for Lessons 4.1 and 4.2.
- **NASA Space Place** (https://spaceplace.nasa.gov/): Free. Short, accurate articles and activities for children on stars, light, the Sun and the speed of light.
- **Stellarium Web** (https://stellarium-web.org/): Free planetarium in a web browser. Set your town and date to see where Orion, the Pleiades and Sirius will be tonight before you go outside.

4.1 He Telleth the Number of the Stars (Psalm 147:4) ★

OBJECTIVES

- Tell how Hipparchus, Ptolemy and Johannes and Elisabeth Hevelius counted and listed the stars, and how the telescope showed far more stars than anyone had seen.
- Estimate a large number of stars by sampling: count a small patch, find the average, and multiply.
- Explain how city lights and dark-adapted eyes change how many stars we can see, and read a bar graph of star counts.

Warm-up. Sprinkle one spoonful of uncooked rice on a dark baking sheet. Without counting, guess how many grains there are and write your guess down. Now lay a ruler across the sheet to split it into 10 strips that are about the same size. Count the grains in just one strip and multiply by 10. Which number do you trust more: your guess or your sample? Keep your answer. Astronomers count stars in exactly this way.

Video. Coming soon. How many stars can we see, light pollution and dark skies, counting stars by sampling: search NASA Space Place, NASA Night Sky Network, Globe at Night, SciShow Kids, Homeschool Pop (Alternate) and Moody Science classics on the wonder of the heavens.

KEY TERMS

star
A huge, hot ball of glowing gas that makes its own light. The Sun is our nearest star.

star catalog
A careful list of stars that gives each star’s place in the sky and how bright it looks.

sample
A small part that is counted or measured carefully so that we can estimate the whole.

estimate
A careful, reasoned guess at a number that is too large or too hard to count one by one.

light pollution
Extra light from streetlights, buildings and signs that brightens the night sky and hides fainter stars.

dark adaptation
The way your eyes slowly grow more sensitive in the dark, so you see more stars after waiting 20 to 30 minutes.

CORE IDEAS

The story. Long ago God brought Abraham out of his tent at night and said, “Look now toward heaven, and tell the stars, if thou be able to number them” (Genesis 15:5). To “tell”

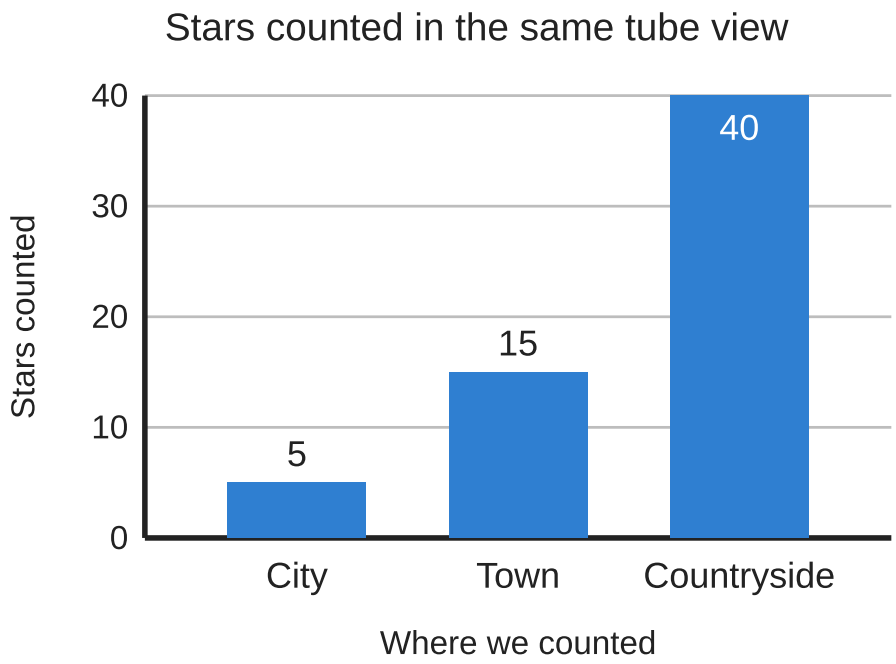
the stars meant to count them. People have tried ever since. On the island of Rhodes, the Greek astronomer **Hipparchus** made a list of about 850 stars. Nearly three hundred years later, in about A.D. 150, **Claudius Ptolemy** of Alexandria in Egypt wrote a great astronomy book that held a **star catalog** of 1,022 stars in 48 constellations. For more than a thousand years, that list was the best count anyone had.

How they figured it out. These men had no telescopes. They worked with their eyes, simple sighting tools and very dark skies. In 1610 Galileo Galilei turned his new telescope toward the heavens and saw that the sky was crowded with faint stars no one had ever seen. In the city of Danzig (today Gdańsk, Poland), **Johannes Hevelius** and his wife **Elisabeth** measured star positions night after night with large brass instruments. After Johannes died, Elisabeth finished their work and published it in 1690: a catalog of 1,564 stars and a beautiful star atlas. Today we know that about 9,000 stars in the whole sky are bright enough to see without a telescope. Half the sky is always below your feet, and stars near the horizon are dimmed by thick air, so on a very dark night you can see only about 2,000 to 3,000 stars at once.

The big idea. Telescopes keep showing more stars than anyone can count. Astronomers estimate that our own Milky Way holds a hundred billion stars or more, and there are billions of other galaxies. No one counts them one by one. Instead they **sample**: they count the stars in one small patch of sky, find the average of several patches, and multiply by the number of patches it would take to cover the whole sky. That gives an **estimate**, a careful reasoned number, not an exact count. Scientists are honest about this. Every star count you read is an estimate.

Try it and see. Two things change how many stars you see. The first is **light pollution**. In a city, the glow of lamps and signs washes out faint stars, and you may see only a few dozen. Out in the countryside, far from lights, the sky fills with thousands. The second is your own eyes. When you step from a bright house into the dark, your eyes need 20 to 30 minutes to grow fully sensitive. This is called **dark adaptation**. A single glance at a white phone screen undoes it, which is why astronomers use dim red flashlights. In the project you will measure both of these changes yourself, using a cardboard tube as your sampling window.

God’s handiwork. Psalm 147:4 says the Lord “telleth the number of the stars; he calleth them all by their names.” Astronomers with the finest telescopes on earth can only estimate. God knows the exact number and knows each star by name. Now read the verse just before it: “He healeth the broken in heart, and bindeth up their wounds” (Psalm 147:3). The same God who counts every star cares about one sad child. The size of the sky is not a reason to feel small and forgotten. It is a reason to trust the One who made it all and still knows you.



The same patch of sky, counted through the same tube in three places. The darker the sky, the more stars you see.

PICTURE STUDY



Johannes and Elisabeth Hevelius Observing with a Sextant, Drawn by Andreas Stech and engraved by Isaak Saal for Johannes Hevelius's book *Machina Coelestis*, 1673 · Engraving (book illustration) · Published in Danzig (Gdańsk), 1673; copies are kept in rare-book libraries

Johannes Hevelius was a brewer and city councilman in Danzig who loved the sky. He built an observatory on the rooftops of his houses and filled it with instruments he designed

himself. His wife Elisabeth worked beside him as a full partner, taking measurements and doing calculations.

This engraving from Hevelius's book shows the two of them measuring the distance between two stars with a great sextant. One person sights on one star and the other sights on a second star at the same moment. Thousands of careful measurements like this built their catalog of 1,564 stars.

Look closely

- Find the sextant. How big is it compared with the two people?
- Find the two sighting arms. Where is each person looking?
- Look at the room around them. What tells you they are working at night on a rooftop observatory?
- Look at their faces and hands. Do they look rushed or careful?

Talk about it

1. Why do you think it took two people to use this instrument?
2. Elisabeth finished and published the catalog after Johannes died. Why is finishing someone else's good work a way of loving them?
3. How is their careful work like your own star count with a tube?

> **Safety first.** Go outside at night only with an adult. Choose a safe, open place away from roads and water, check the ground for holes in daylight, and bring a flashlight covered with red cellophane. Dress warmly.

EXPERIMENT: STAR COUNT THROUGH A TUBE: DOES WAITING IN THE DARK HELP?

You will act like an astronomer and count stars by sampling. You will look through a cardboard tube so that you count the same small window of sky each time. Then you will test a question: do your eyes see more stars after they have waited in the dark?

You will need

- An empty paper towel tube (or a toilet paper tube)
- A notebook, pencil and clipboard
- A flashlight with red cellophane or a red balloon stretched over the end
- A watch or timer
- A clear, moonless night and an adult partner
- For a cloudy night: a black poster board, a white crayon and the rice from the warm-up

Steps

1. **Question.** Write: Will I count more stars through my tube after my eyes wait 20 minutes in the dark?
2. **Prediction.** Write what you think will happen and why.

3. **What we change:** the number of minutes your eyes have been in the dark (0, 5, 10 and 20 minutes). **What we keep the same:** the same tube, the same patch of sky (pick one bright star to center in the tube), the same observer and the same night. **What we measure:** the number of stars inside the tube's circle.
4. Rule a table with two columns: Minutes in the dark, Stars counted.
5. Turn off porch lights. Step outside from a lit room and right away center your star in the tube. Count every star you see inside the circle. That is your 0-minute count.
6. Wait in the dark. Use only the red flashlight to write. At 5, 10 and 20 minutes, aim at the same star and count again.
7. Make a bar graph of your results with minutes along the bottom and stars counted up the side.
8. **Second test (optional).** On another clear night, count the same patch of sky from a darker place, such as a park or a relative's farm. Compare the two counts.
9. Write a conclusion: Did my prediction match my data? What else might have changed the count?
10. **Cloudy night version.** Sprinkle rice on the black poster board as pretend stars. Count the grains inside the tube's circle in five different places, average them, and estimate the whole board as in the worked examples.

Tips

- Do not look at a phone or white light during the test. Even a few seconds will reset your eyes.
- Count each star only once. Count the bright ones first, then look for faint ones out of the side of your eye, which is more sensitive in the dark.
- If the Moon is up, your counts will be lower. Write the Moon's phase in your notes.

Check your work

- I named what I changed, what I kept the same and what I measured.
- My table and bar graph show my counts at each time.
- I can explain why my count is a sample and not the number of stars in the whole sky.

FIELD NOTEBOOK

1. Draw the circle of sky you saw through your tube at 20 minutes, with each star as a dot. Make bright stars bigger dots. Label the date, time, place and Moon phase.
2. Copy Psalm 147:4 in your best handwriting at the top of a page and draw a starry sky beneath it.
3. Make a timeline of star counters: Hipparchus (about 850 stars), Ptolemy (1,022 stars, about A.D. 150), Elisabeth and Johannes Hevelius (1,564 stars, 1690), and Galileo's telescope (1610).

> **From history.** In 1679 a fire swept through the Hevelius house and destroyed the rooftop observatory, its instruments and many books. Johannes, then nearly seventy, rebuilt and

kept observing. He died in 1687, and Elisabeth gathered his papers and saw the star catalog and the star atlas through to print in 1690. Many historians count her among the first women astronomers.

WORKED EXAMPLES

Example 1. Mara counted the stars in five tube views of the sky: 6, 4, 8, 5 and 7. Suppose it would take 400 tube views to cover the whole sky above her. Estimate how many stars she could see in her whole sky.

1. Add the five counts: 6 + 4 + 8 + 5 + 7 = 30 stars.
2. Find the average: 30 ÷ 5 = 6 stars per tube view.
3. Multiply by the number of views: 6 × 400 = 2,400 stars.
4. Check: this fits what astronomers say, about 2,000 to 3,000 stars on a very dark night.

Answer: About 2,400 stars. It is an estimate, because she counted only samples.

Example 2. Use the bar graph. A family counted stars through the same tube in a city, a town and the countryside. How many more stars did they see in the countryside than in the city? How many times as many?

(Use the map or drawing "Stars counted through the same tube in three places." shown earlier in this lesson.)

1. Read the bars: City = 5 stars, Town = 15 stars, Countryside = 40 stars.
2. How many more: 40 − 5 = 35 more stars.
3. How many times as many: 40 ÷ 5 = 8.
4. Explain: the stars did not change. The countryside sky was darker, so fainter stars could be seen.

Answer: 35 more stars; 8 times as many stars in the countryside as in the city.

PRACTICE

1. EASY According to Psalm 147:4, what two things does God do with the stars?
2. EASY About how many stars in the whole sky are bright enough to see without a telescope? Why can you see only about 2,000 to 3,000 of them at one time?
3. MEDIUM Ptolemy's catalog listed 1,022 stars. The Hevelius catalog listed 1,564 stars. How many more stars did the Hevelius catalog list?
4. MEDIUM Sam counted 3, 5, 4 and 4 stars in four tube views. If 500 tube views cover his whole sky, estimate the number of stars he can see.

5. MEDIUM Read the table. Minutes in the dark: 0, 5, 10, 20. Stars counted in the tube: 4, 9, 14, 18. (a) Describe the pattern. (b) How many more stars were counted at 20 minutes than at 0 minutes?
6. HARD Plan an experiment to test whether a bright Moon hides stars. Name what you change, what you keep the same and what you measure.
7. HARD In two or three sentences, explain why astronomers estimate the number of stars instead of counting every one.
8. CHALLENGE Suppose you could count one star every second, day and night, without ever stopping. About how long would it take to count 100 billion stars? (There are about 31,536,000 seconds in a year.)

COMMON MISTAKES

- Thinking you can see millions of stars with your eyes alone. Even on the darkest night you see only about 2,000 to 3,000 at once.
- Thinking the stars "come out" at night. They are in the sky all day; the bright daytime sky hides them.
- Thinking a star count in a book is an exact count. Large star numbers are estimates made by sampling.

Make it a game · Estimation Station. A parent fills a clear jar with dried beans, pours a spoonful of rice on a tray, or scatters paper dots on a table. Each player first guesses the total. Then each player may count one sample (one row of beans, one ruler strip of rice) and make a new estimate by multiplying. Finally count the real total together. Closest estimate wins 2 points; best improvement from guess to estimate wins 1 point. Play three rounds.

Scripture. "He telleth the number of the stars; he calleth them all by their names." (Psalm 147:4, KJV)

Our best counts of the stars are estimates. God's is exact, and He names each one. The God of the countless stars is the same God who "healeth the broken in heart" in the verse before.

Practice answers

1. He tells (counts) the number of the stars, and He calls them all by their names.
2. About 9,000. At any moment half the sky is below the horizon, and stars low in the sky are dimmed by the thick air near the horizon.
3. 1,564 − 1,022 = 542 more stars.
4. Total 3 + 5 + 4 + 4 = 16; average 16 ÷ 4 = 4 stars per view; 4 × 500 = 2,000 stars (an estimate).
5. (a) The longer the eyes stayed in the dark, the more stars were counted, though the increase slowed down near the end (5 more, then 5 more, then 4 more over a longer wait). (b) 18 − 4 = 14 more stars.
6. Change: the Moon (count on a night near full Moon and on a night with no Moon in the sky). Keep the same: the place, the tube, the patch of sky, the observer, the time after dark and 20

minutes of dark adaptation, and only clear nights. Measure: the number of stars inside the tube. Repeat each count more than once and compare averages.

7. There are far too many stars to count one by one, and most are too faint to see without large telescopes. So astronomers count small samples of the sky, find the average, and multiply to estimate the whole. The answer is a careful estimate, not an exact count.
8. 100,000,000,000 ÷ 31,536,000 ≈ 3,171, so about 3,200 years of nonstop counting. Only God “telleth the number of the stars.”

4.2 Constellations in the Bible: Orion and the Pleiades (Job 38:31)

OBJECTIVES

- Find Orion, its bright stars Betelgeuse and Rigel, and the Pleiades in the winter sky, and use Orion's belt as a pointer.
- Explain the difference between a constellation (a pattern we see) and a star cluster like the Pleiades (stars that really travel together).
- Measure distances across the sky with a hand held at arm's length and use a table of rising times to predict when Orion is high in the sky.

Warm-up. Scatter about 15 dried beans or buttons on a dark tablecloth. Look for a shape: a kite, a bird, a letter. Trace it in the air with your finger and give it a name. Now have someone else look at the very same beans. Did they see the same shape? People of long ago did this with the stars, and many of their shapes are still used today.

Video. Coming soon. How to find Orion, Orion's belt and the Pleiades (Seven Sisters) in the winter sky, constellations versus star clusters: search NASA Space Place, NASA Night Sky Network, planetarium channels, Homeschool Pop (Alternate) and Moody Science classics.

KEY TERMS

constellation
A pattern of stars that people have named, and the region of sky around it. Astronomers divide the whole sky into 88 constellations.

asterism
A well-known star pattern that is not one of the 88 official constellations, such as the Big Dipper or Orion's belt.

star cluster
A family of stars that really are close together in space and move together, such as the Pleiades.

Orion
A bright constellation shaped like a hunter, with three stars in a row for his belt. In the Hebrew of Job it is called *Kesil*.

Pleiades
A small, tight cluster of bright blue-white stars in Taurus, also called the Seven Sisters. In the Hebrew of Job it is called *Kimah*.

degree
A unit for measuring angles and distances across the sky. A full circle has 360 degrees (360°).

CORE IDEAS

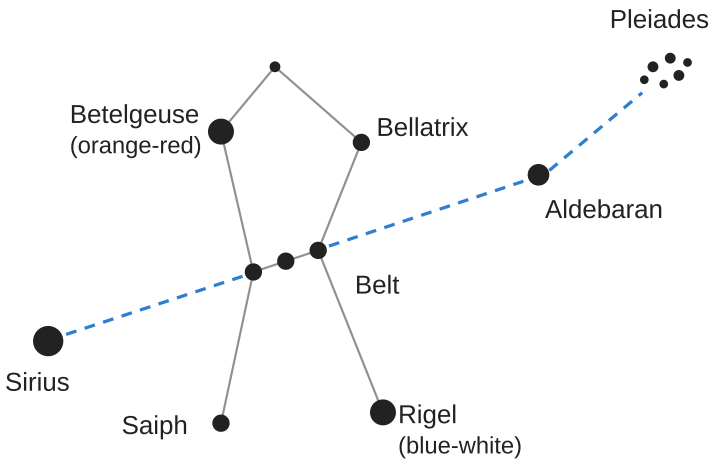
The story. Job had lost almost everything, and he wanted answers. Then God spoke to him "out of the whirlwind" and asked him questions no man could answer. One was about the stars: "Canst thou bind the sweet influences of Pleiades, or loose the bands of Orion?" (Job 38:31). Job knew these star groups. In Hebrew the Pleiades are *Kimah*, which may mean "heap" or "cluster," and Orion is *Kesil*. The same two groups appear in Job 9:9 and Amos 5:8, where the prophet calls the Pleiades "the seven stars." On a winter evening you can look up and see the very stars Job and Amos saw.

How they figured it out. In 1610, in Italy, Galileo pointed his small telescope at the Pleiades. Most people can see six or seven stars there. Galileo drew thirty-six. He turned to Orion's belt and sword and found dozens of stars hidden among the bright ones. He published the drawings in a little book called *The Starry Messenger*. Later astronomers learned to measure how stars move across the sky over many years. They found that the stars of the Pleiades all drift in the same direction at the same speed, like a family walking together. The Pleiades are a true **star cluster**, hundreds of stars held together by their own gravity.

The big idea. A **constellation** is a pattern people see, like a dot-to-dot picture. Its stars only look close together from Earth. Some are much farther away than others, and they are not held together. The three belt stars of Orion are at different distances from us and are not bound to each other as a group. So there is a real difference between the Pleiades, which are bound together, and Orion's belt, which is not. Many Bible readers have enjoyed noticing how well that fits the words "bind" and "loose" in Job 38:31. The main point of God's question is plain: Job could not hold the stars together or pull them apart, but God can. Today astronomers divide the whole sky into 88 constellations, the way a map divides a country into states.

Try it and see. From December through March, Orion stands in the southern sky on evenings in North America. Look for three bright stars in a short, straight row: the belt. Above the belt and to the left, at the hunter's shoulder, is **Betelgeuse**, which glows orange-red. Below the belt and to the right, at his foot, is **Rigel**, which shines blue-white. Follow the belt up and to the right to the orange star Aldebaran, and keep going about the same distance again to find the tiny misty dipper of the Pleiades. Follow the belt down and to the left to Sirius, the brightest star of the night. To measure the sky, hold your hand at arm's length. One finger is about 1° wide, and a closed fist is about 10°.

God's handiwork. Amos told Israel to "seek him that maketh the seven stars and Orion, and turneth the shadow of death into the morning" (Amos 5:8). The stars keep perfect time. Each night a star rises about 4 minutes earlier than the night before, so Orion moves steadily from the morning sky into the evening sky through the year. God set the lights in the heavens "for signs, and for seasons, and for days, and years" (Genesis 1:14). Farmers and sailors have used Orion and the Pleiades as a calendar for thousands of years. If you live in the Southern Hemisphere, Orion appears upside down to you and rides high in your summer evenings.



ORION (winter evening, facing south)

Orion as seen from North America on a winter evening. The belt points up and right to Aldebaran and the Pleiades, and down and left to Sirius.

PICTURE STUDY



The Flight into Egypt, Adam Elsheimer, 1609 · Oil on copper · Alte Pinakothek, Munich

Adam Elsheimer was a German painter who worked in Rome. He painted on small copper plates, and this picture is only about 31 by 41 centimeters (12 by 16 inches). It shows the Holy Family fleeing at night into Egypt (Matthew 2:13–14).

Elsheimer painted the night sky with great care. The Milky Way is shown as a band made of countless tiny stars, and many people believe this is the first painting to show it that way. Astronomers have also recognized real star groups in the sky, among them the Big Dipper and the constellation Leo, placed as they stood over Rome on a June night in 1609. He painted it in 1609, the same year Galileo first turned a telescope to the heavens.

Look closely

- Count the lights in the painting: the Moon, its reflection, Joseph's torch, the shepherds' fire. Which is brightest?
- Find the Milky Way. Does it look like a cloud or like many tiny dots?
- Search the upper right of the sky for the seven stars of the Big Dipper.
- Find Mary, the Child and Joseph. How small are they compared with the sky?

Talk about it

1. Why do you think Elsheimer made the people so small and the starry sky so large?
2. How might the stars have comforted Joseph on a dangerous night journey?
3. What does this painting say about God's care for His Son under the great sky?

> **Safety first.** Observe at night only with an adult, in a safe open place away from roads and water. Use a red flashlight. Binoculars are safe at night, but never point binoculars or any optical tool toward the Sun.

EXPERIMENT: ORION STAR VIEWER AND A PLEIADES COUNT

First you will make a pinhole star viewer of Orion so you can learn its shape indoors. Then you will go outside and run a small experiment: do binoculars show more stars in the Pleiades than your eyes alone?

You will need

- A paper cup or empty oatmeal canister, and a flashlight
- A pushpin and a nail (for larger holes), with an adult's help
- A copy of the Orion map in this lesson
- Binoculars (any size)
- Notebook, pencil and a red flashlight

Steps

1. **Part A: Make the viewer.** Trace the Orion map onto a circle of paper that fits the bottom of the cup. Tape it on the outside of the cup bottom.
2. With an adult, poke a hole through each star. Use the nail for bright stars (Betelgeuse, Rigel) and the pushpin for fainter ones. Remove the paper.
3. In a dark room, shine the flashlight into the open end of the cup and aim the bottom at the ceiling. Orion appears! Practice naming Betelgeuse, Rigel and the three belt stars.

(Remember the stars on the ceiling are reversed left to right, so check your viewer against the map.)

4. **Part B: The experiment.** Write the question: Will binoculars show more stars in the Pleiades than my eyes alone?
5. Write your prediction.
6. **What we change:** eyes alone or binoculars. **What we keep the same:** the same night, the same place, the same observer and 20 minutes of dark adaptation. **What we measure:** the number of stars counted in the Pleiades. Your eyes-alone count is the **control**, the result you compare against.
7. Find Orion, follow the belt up and to the right past Aldebaran, and find the Pleiades. Count the stars with your eyes alone three times and record each count.
8. Now count through binoculars three times. Record each count.
9. Find the average of each set of three. Make a two-bar graph and write a conclusion.

Tips

- Look slightly to the side of the Pleiades. The edge of your eye sees faint stars better in the dark.
- Brace your elbows on a car roof or fence rail to hold binoculars steady.
- Galileo drew thirty-six stars there. How close did you come?

Check your work

- My viewer shows Orion’s shape, and I can name Betelgeuse, Rigel and the belt.
- I recorded three counts with each method and found the averages.
- I can name my control and explain why I kept the night and place the same.

FIELD NOTEBOOK

1. Draw Orion as you see it in the real sky. Make Betelgeuse orange-red and Rigel blue-white, and write the date and time.
2. Draw the Pleiades with your eyes alone and again through binoculars, side by side.
3. Copy Job 38:31 and, underneath, write in your own words what God was asking Job.

> **From history.** In the second century, Ptolemy listed 48 constellations, including Orion and Taurus, the Bull that carries the Pleiades on its shoulder. As explorers sailed south, new patterns were added for the southern sky. In 1922 astronomers from many nations agreed on an official list of 88 constellations, and in 1930 they published exact boundaries for every one, drawn by the Belgian astronomer Eugène Delporte, so that every point in the sky belongs to exactly one constellation.

WORKED EXAMPLES

Example 1. Held at arm’s length, the distance from Betelgeuse to Rigel is about two fists. Orion’s belt is about three finger widths long. About how many degrees is each? About how many belt lengths would fit between Betelgeuse and Rigel?

(Use the map or drawing “Use your hand to measure the sky.” shown earlier in this lesson.)

1. One fist at arm’s length covers about 10°. Two fists: 2 × 10° = 20°.
2. One finger covers about 1°. Three fingers: 3 × 1° = 3°.
3. Belt lengths between the stars: 20° ÷ 3° ≈ 6.7, so about 6 or 7 belts.

Answer: Betelgeuse to Rigel is about 20°; the belt is about 3°; about 6 to 7 belt lengths fit between them.

Example 2. Each night a star rises about 4 minutes earlier than the night before. If a bright star in Orion rises at 10:00 p.m. tonight, at about what time will it rise 30 nights from now?

1. Minutes earlier: 30 nights × 4 minutes = 120 minutes.
2. Change to hours: 120 ÷ 60 = 2 hours.
3. Subtract: 10:00 p.m. − 2 hours = 8:00 p.m.

Answer: About 8:00 p.m., two hours earlier. That is why Orion appears earlier in the evening each month.

PRACTICE

1. EASY Which two star groups does God name in Job 38:31? What does He ask Job to do with each?
2. EASY What is the difference between a constellation and an asterism? Give an example of an asterism.
3. MEDIUM You have found Orion’s belt. Which way do you follow it to find the Pleiades? Which way to find Sirius? (Northern Hemisphere, evening)
4. MEDIUM At arm’s length the Pleiades look about two finger widths across. About how many degrees wide is the cluster? How many Pleiades could fit across one fist?
5. MEDIUM Read the table of when Orion stands highest in the south. December 15: midnight. January 15: 10:00 p.m. February 15: 8:00 p.m. (a) What is the pattern? (b) Predict the time for March 15. (c) Why will Orion be harder to see well then?
6. HARD Lily wants to test whether binoculars show more stars in the Pleiades than her eyes. Name the variable she changes, two things she must keep the same, what she measures and what her control is.

7. HARD In two or three sentences, explain how the Pleiades are different from the stars of Orion's belt.
8. CHALLENGE A pen pal in Australia says that Orion looks upside down to her and that she sees it in her summer. Explain why.

COMMON MISTAKES

- Thinking the stars of a constellation are near each other in space. Most only line up from where we stand.
- Calling the Pleiades the Little Dipper. The Pleiades look like a tiny dipper, but the Little Dipper is a different, much larger pattern that holds the North Star.
- Thinking you can see Orion in the evening all year. It is an evening star group of winter; in summer it is up only in daytime, hidden by the Sun's light.

Make it a game · Find the Hunter. One player uses the pinhole viewer to shine Orion on the ceiling in a dark room. The other player must point to and name Betelgeuse, Rigel and the belt, then point the way to the Pleiades and to Sirius. Score 1 point for each correct name and pointer. Then switch. For a harder round, a parent calls out "Show me 10 degrees!" or "Show me 3 degrees!" and you must show it with your hand at arm's length.

Scripture. "Canst thou bind the sweet influences of Pleiades, or loose the bands of Orion?" (Job 38:31, KJV)

God asked Job questions about things only God can do. No person can hold a star family together or pull a constellation apart. Job learned to trust the One who rules the stars.

Practice answers

1. The Pleiades and Orion. He asks whether Job can bind the sweet influences of the Pleiades and loose the bands of Orion.
2. A constellation is one of the 88 official named star patterns and regions of the sky. An asterism is a well-known pattern that is not an official constellation, such as the Big Dipper or Orion's belt.
3. Up and to the right, past the orange star Aldebaran, to reach the Pleiades. Down and to the left to reach Sirius.
4. About 2° (2 × 1°). A fist is about 10°, so about 10 ÷ 2 = 5 Pleiades across one fist.
5. (a) Each month Orion is highest about 2 hours earlier. (b) About 6:00 p.m. (c) At 6:00 p.m. in mid-March the sky is still bright with twilight, so Orion is hard to see at its highest; by full dark it is already sinking toward the west.
6. Variable: eyes alone or binoculars. Keep the same (any two): the same night, place, observer, time and length of dark adaptation. Measure: the number of stars counted in the Pleiades. Control: the count with her eyes alone.
7. The Pleiades are a true star cluster: hundreds of stars close together in space, moving together and held by their own gravity. Orion's belt stars only look close together from Earth; they lie at different distances and are not held together as a group.

8. She stands on the other side of the round Earth, south of the equator, so she faces north to see Orion and her “up” is turned around compared with ours, making Orion look upside down. The seasons are also reversed in the Southern Hemisphere, so the months when Orion is up in the evening (December through March) are her summer.

4.3 Star Colors

OBJECTIVES

- Tell how Annie Jump Cannon sorted hundreds of thousands of stars by their light, and name the star types O, B, A, F, G, K, M from hottest to coolest.
- Explain that a star's color shows its surface temperature: red stars are the coolest and blue-white stars are the hottest.
- Read a table and bar graph of star temperatures, compare them, and convert a temperature from Celsius to Fahrenheit.

Warm-up. Look at a toaster, an electric stove coil or an old-fashioned light bulb in a photo or, with a parent, in real life (do not touch). What color does the hot coil glow? Now think of a campfire: what color are the hottest coals at the bottom compared with the flickering tips? Write down your guess: is red the hottest color, or the coolest?

Video. Coming soon. Why stars have different colors, star temperature and color, prisms and spectra, Annie Jump Cannon and the Harvard star classifiers: search NASA Space Place, NASA Goddard, Smithsonian, SciShow Kids, Homeschool Pop (Alternate) and Science Max.

KEY TERMS

temperature
How hot or cold something is. Star temperatures are measured in degrees Celsius (°C) or Fahrenheit (°F).

glow (incandescence)
Light given off by something because it is very hot, like a toaster coil or the surface of a star.

prism
A clear wedge of glass or plastic that bends light and spreads it out into its colors.

spectrum
The band of colors made when light is spread out: red, orange, yellow, green, blue and violet. Star spectra also show thin dark lines.

spectral class
A star's type, named by a letter: O, B, A, F, G, K or M, in order from hottest to coolest. The Sun is a G star.

CORE IDEAS

The story. In 1896 a young woman named **Annie Jump Cannon** went to work at the Harvard College Observatory in Cambridge, Massachusetts. Every clear night, telescopes there took photographs of the sky on glass plates. In front of the camera sat a prism, so each

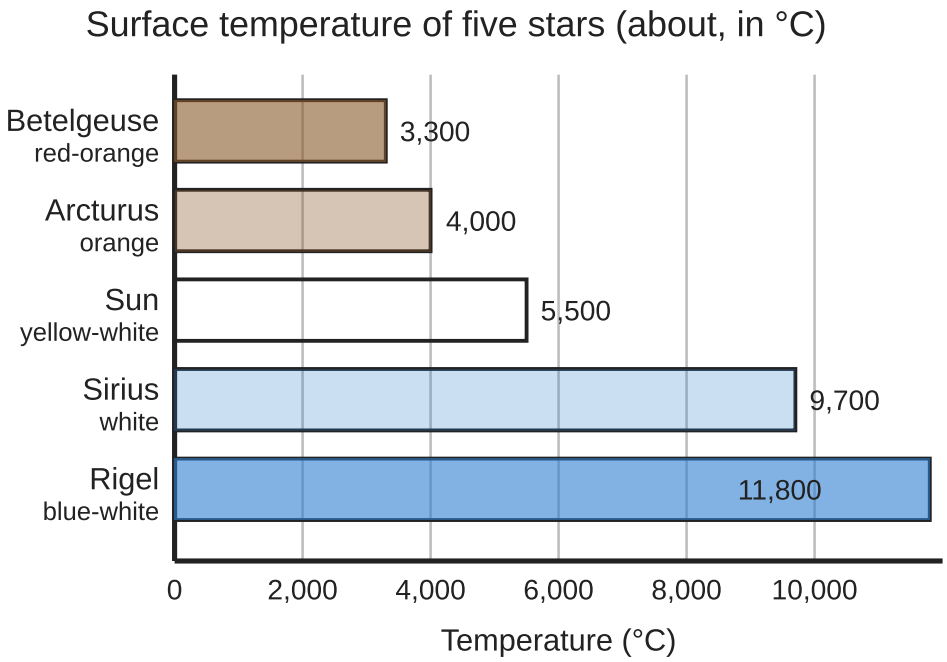
star showed up not as a dot but as a tiny strip of light crossed by dark lines. Cannon studied these strips through a magnifying glass, one after another, and sorted each star by its pattern of lines. She became so skilled that she could classify about three stars a minute. Over her life she classified roughly 350,000 stars, more than any other person, and many of them were printed in the great Henry Draper Catalogue, published from 1918 to 1924.

How they figured it out. A **prism** spreads white light into a **spectrum**, a rainbow of colors. Starlight spread this way shows the colors the star gives off most strongly and dark lines where certain colors are missing. Cannon arranged the star types in the order O, B, A, F, G, K, M, a list her system made famous. Astronomers around the world agreed to use it in 1922. A few years later other astronomers showed what her order really meant: it is a ladder of temperature. O stars are the hottest and M stars are the coolest. Students often remember the order with a silly sentence such as “Oh Be A Fine Friend, Keep Marching.”

The big idea. A star’s color tells its surface temperature. You can see the same thing on earth. When a blacksmith heats an iron bar, it first glows dull red, then orange, then yellow, and at last nearly white. Hotter means bluer and whiter. Stars follow the same rule. The **coolest** stars glow red or orange, around 3,300 °C (about 6,000 °F). The Sun, a G star, is about 5,500 °C (about 10,000 °F) at its surface; its light is nearly white, though it looks yellowish to us through our air. The **hottest** stars glow blue-white, at 10,000 °C (18,000 °F) and far above. So on a star, red means cooler and blue means hotter, the opposite of the faucet labels in your bathroom.

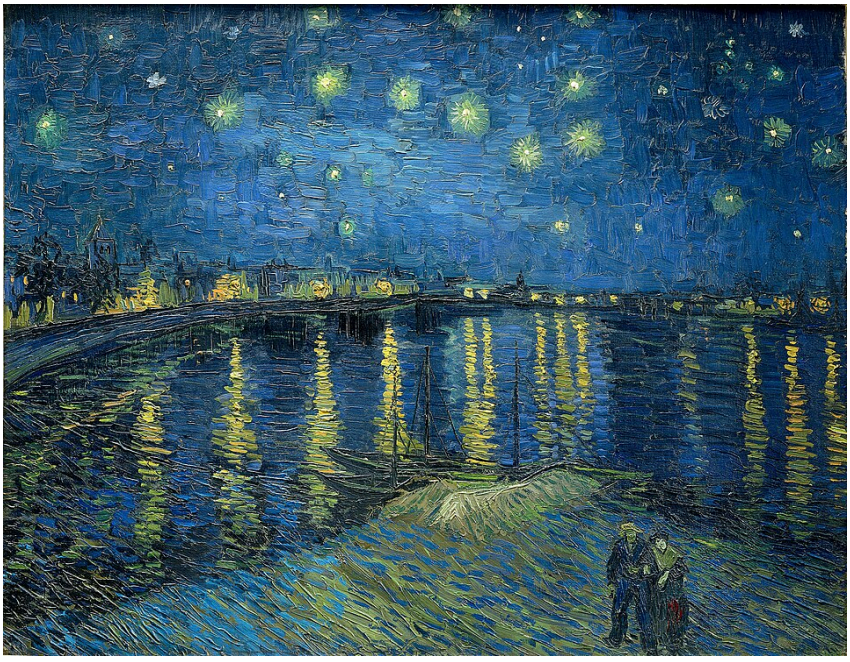
Try it and see. Look at Orion on a winter evening. **Betelgeuse**, at the upper left, is plainly orange-red. **Rigel**, at the lower right, is blue-white. Now you know that Rigel’s surface is much hotter. In spring and summer, compare orange **Arcturus** with blue-white **Vega**. Faint stars all look white because the color-seeing cells in your eyes need bright light to work, and in the dark you see mostly with cells that do not sense color. To bring out color, look at bright stars, or turn the focus of binoculars slightly so each star becomes a small colored disk.

God’s handiwork. The painter Vincent van Gogh wrote to his sister in 1888 that if you pay attention to the night sky you will see that some stars are lemon yellow and others pink, green or a bright forget-me-not blue. He was right that the stars are not all alike. The apostle Paul noticed the same thing: “one star differeth from another star in glory” (1 Corinthians 15:41). God did not make one star and copy it. He made each with its own color, size and brightness, and He gave us eyes and minds to discover what those colors mean.



Approximate surface temperatures of five stars. The bars get longer as the color goes from red toward blue-white.

PICTURE STUDY



Starry Night Over the Rhône, Vincent van Gogh, 1888 · Oil on canvas · Musée d'Orsay, Paris

Vincent van Gogh was a Dutch painter living in Arles, in the south of France. In September 1888 he set up his easel beside the Rhône River at night and painted what he saw. Above the river he painted the seven stars of the Big Dipper.

Van Gogh had a painter's eye for color. Around the same time he wrote to his sister that night is even more richly colored than day, and that some stars are lemon yellow while others glow pink, green or blue. Look closely and you will see that his stars and his lamps are not the same color.

Look closely

- Find the seven stars of the Big Dipper. Trace the bowl and the handle with your finger.
- Compare the color of the stars with the color of the gas lamps and their reflections. Which look warmer, and which look cooler?
- Look at how each star is painted with short strokes around it. How does Van Gogh make them seem to twinkle?
- Find the two people on the riverbank and the boats. Where is the brightest part of the picture?

Talk about it

1. The gas lamps glowed orange-yellow. From this lesson, what does that color tell you about how hot a flame is compared with a blue-white star?
2. Why might a painter see star colors that most people never notice?
3. If you painted tonight's sky, which star would you make a different color, and why?

> **Safety first.** Toasters and stove coils get hot enough to cause serious burns. An adult must run the toaster and stay with you. Never touch the coils, never put anything inside the toaster, and keep your face at least an arm's length away. Unplug the toaster as soon as you finish. Never look at the Sun to judge its color.

EXPERIMENT: RED-HOT TO ORANGE-HOT: WATCHING A COIL GLOW

Stars are too far away to heat up and watch, but a toaster coil follows the same rule of color and temperature. You will watch an empty toaster heat up in a dark room and record how its color changes as it gets hotter. Then you will compare your results with the stars.

You will need

- An empty toaster (an adult runs it)
- A dark room
- A timer
- Notebook, pencil, and red, orange and yellow colored pencils
- Optional: binoculars and a clear winter night to compare Betelgeuse and Rigel

Steps

1. **Question.** Write: How does the color of a heated wire change as it gets hotter?
2. **Prediction.** Write the order of colors you expect to see.

3. **What we change:** how long the coil has been heating (which makes it hotter). **What we keep the same:** the same toaster, the same dial setting, the same dark room and the same observer standing in the same place. **What we measure:** the color of the coil.
4. Rule a table with two columns: Seconds of heating, Color I see. Write 0, 10, 20, 30, 40, 50 and 60 down the first column.
5. Turn off the room lights. The adult pushes the lever down and starts the timer.
6. Every 10 seconds, write the color you see, such as none, dull red, red, bright orange-red. Color a small box beside each with your pencils.
7. As soon as the toast cycle ends or 60 seconds pass, the adult pops it up and unplugs it.
8. Compare: which color came first, when the coil was coolest? Which came last, when it was hottest? Did it ever reach yellow or white?
9. Write a conclusion that connects your toaster to Betelgeuse and Rigel. Which star is like the coil at 10 seconds? Which is hotter than any toaster could ever get?

Tips

- Your eyes see the dull red glow first in a very dark room, so give your eyes a minute in the dark before you start.
- A toaster coil never gets as hot as a star, so it stops at orange. Stars like the Sun and Rigel are thousands of degrees hotter.
- If you have a dimmable old-style (incandescent) bulb, you can see the same change: dim it down and the light turns orange; turn it up and it turns whiter.

Check your work

- I named what I changed, what I kept the same and what I measured.
- My table shows the color every 10 seconds.
- I can explain why a red star is cooler than a blue-white star.

FIELD NOTEBOOK

1. Draw a color ladder of the star types: O and B blue-white at the top, then A white, F yellow-white, G yellow-white (the Sun), K orange and M red at the bottom. Label it “hottest” at the top and “coolest” at the bottom.
2. Draw Orion with colored pencils, showing orange-red Betelgeuse and blue-white Rigel, and write which is hotter.
3. Copy 1 Corinthians 15:41 and draw three stars of different colors beside it.

> **From history.** In 1814 the German glassmaker Joseph von Fraunhofer passed sunlight through a fine prism and looked at it through a small telescope. He found that the Sun’s rainbow was crossed by hundreds of thin dark lines and mapped more than 500 of them, labeling the strongest with letters. These same kinds of lines, seen in the light of other stars, are what Annie Jump Cannon later used to sort the stars into types.

WORKED EXAMPLES

Example 1. Use the bar graph of star temperatures. List the five stars from coolest to hottest with their colors. Which star is closest in temperature to the Sun?

(Use the map or drawing "Star surface temperatures." shown earlier in this lesson.)

1. Read each bar: Betelgeuse 3,300 °C, Arcturus 4,000 °C, Sun 5,500 °C, Sirius 9,700 °C, Rigel 11,800 °C.
2. Order them, smallest number first: Betelgeuse (red-orange), Arcturus (orange), Sun (yellow-white), Sirius (white), Rigel (blue-white).
3. Find the differences from the Sun: Arcturus 5,500 − 4,000 = 1,500; Betelgeuse 5,500 − 3,300 = 2,200; Sirius 9,700 − 5,500 = 4,200; Rigel 11,800 − 5,500 = 6,300.
4. The smallest difference is 1,500 °C.

Answer: Coolest to hottest: Betelgeuse, Arcturus, Sun, Sirius, Rigel. Arcturus is closest to the Sun's temperature (1,500 °C cooler).

Example 2. The Sun's surface is about 5,500 °C. Convert this to degrees Fahrenheit using the rule: °F = °C × 9 ÷ 5 + 32.

1. Multiply by 9: 5,500 × 9 = 49,500.
2. Divide by 5: 49,500 ÷ 5 = 9,900.
3. Add 32: 9,900 + 32 = 9,932.
4. Round: about 10,000 °F.

Answer: About 9,932 °F, or roughly 10,000 °F.

PRACTICE

1. EASY Put these star colors in order from coolest to hottest: blue-white, red, yellow-white.
2. EASY What does a prism do to white light? What is the band of colors called?
3. EASY Betelgeuse is orange-red and Rigel is blue-white. Which has the hotter surface?
4. MEDIUM Use the data table (or the bar graph). Sirius is about 9,700 °C and Arcturus is about 4,000 °C. How much hotter is Sirius? What colors are the two stars?
5. MEDIUM The star types in order are O, B, A, F, G, K, M. The Sun is a G star. Which types are hotter than the Sun? Which are cooler?
6. HARD Ben has a lamp with an old-style bulb on a dimmer. He wants to test whether the light gets whiter as the bulb gets brighter and hotter. Name what he changes, two things he keeps the same, and what he observes.
7. HARD In two or three sentences, explain why most stars look white to us even though stars come in different colors.

8. CHALLENGE Betelgeuse's surface is about 3,300 °C. Convert this to °F using °F = °C × 9 ÷ 5 + 32. Then explain why calling a red star "red-hot" is true but misleading.

COMMON MISTAKES

- Thinking red is the hottest color because faucets mark hot water in red. For glowing objects and stars, red is the coolest glow and blue-white is the hottest.
- Thinking all stars are white. Many stars have clear colors, but our eyes cannot see color well in dim light.
- Thinking the Sun is a yellow ball. Its light is nearly white; our air scatters some blue light away, which makes it look yellowish, especially near sunrise and sunset.

Make it a game · O Be A Fine Star. Make seven cards labeled O, B, A, F, G, K and M, and color each one (O and B blue-white, A white, F and G yellow-white, K orange, M red). Shuffle them. Race the timer to lay them in order from hottest to coolest while saying the memory sentence. Then a parent calls out a star (Rigel, Sirius, Sun, Arcturus, Betelgeuse) and you hold up its color and say "hotter than the Sun" or "cooler than the Sun." Beat your best time.

Scripture. "There is one glory of the sun, and another glory of the moon, and another glory of the stars: for one star differeth from another star in glory." (1 Corinthians 15:41, KJV)

Paul saw what astronomers now measure: stars differ. Their colors, temperatures and brightness show the rich variety of the One who made them.

Practice answers

1. Red (coolest), yellow-white, blue-white (hottest).
2. A prism bends light and spreads it into its colors. The band of colors is called a spectrum.
3. Rigel. Blue-white stars are hotter than red stars.
4. 9,700 − 4,000 = 5,700 °C hotter. Sirius is white and Arcturus is orange.
5. Hotter: O, B, A and F. Cooler: K and M.
6. Change: the dimmer setting (low, medium, high). Keep the same (any two): the same bulb and lamp, the same dark room, the same observer standing in the same spot, looking through the same lampshade or none. Observe: the color of the light, recorded with colored pencils or color names at each setting. (He must not touch the hot bulb.)
7. Most stars are faint, and the cells in our eyes that see color need bright light to work. In dim light we see mainly with cells that do not sense color, so faint stars look white. Only bright stars, or stars seen through binoculars, show their colors clearly.
8. 3,300 × 9 = 29,700; 29,700 ÷ 5 = 5,940; 5,940 + 32 = 5,972, about 6,000 °F. It is true that a red star is fantastically hot, far hotter than any oven. But it is misleading because among stars, red means the coolest kind; blue-white stars are much hotter.

4.4 Light-Years: Distant Starlight and How Creationists Answer It

OBJECTIVES

- Explain how Friedrich Bessel used parallax in 1838 to measure the distance to a star, and show parallax with your own thumb.
- Define a light-year as a distance, and calculate how long light takes to travel from the Moon and the Sun.
- Describe the distant starlight question and explain, fairly and simply, several ways creation scientists answer it.

Warm-up. Hold your thumb up at arm's length in front of a doorframe or a picture on the wall. Close your left eye, then open it and close your right eye. Switch back and forth. What does your thumb seem to do? Now bring your thumb halfway to your nose and try again. Does it jump more or less? Write down what you notice. You have just discovered the trick that measured the first star distance.

Video. Coming soon. What is a light-year, the speed of light, stellar parallax explained with your thumb, Bessel and 61 Cygni, GPS clocks and relativity: search NASA Space Place, NASA Goddard, NASA JPL Education, Smithsonian, SciShow Kids, Science Max and Moody Science classics.

KEY TERMS

speed of light
How fast light travels: about 300,000 kilometers (186,000 miles) every second in empty space.

light-year
A unit of *distance*: how far light travels in one year, about 9.5 trillion kilometers (about 5.9 trillion miles). It is not a measure of time.

light-minute
How far light travels in one minute, about 18 million kilometers. The Sun is about 8 light-minutes away.

parallax
The way a nearby object seems to shift against a faraway background when you look at it from two different places. Closer objects shift more.

time dilation
The measured fact that clocks run at different rates depending on how fast they move and how strong the gravity around them is.

CORE IDEAS

The story. For thousands of years no one knew how far away the stars were. Then in 1838, in Königsberg, Prussia, the astronomer **Friedrich Bessel** announced that he had measured the distance to a faint star called **61 Cygni** in the constellation Cygnus, the Swan. He had watched it for more than a year with a special telescope called a heliometer, comparing its place with fainter stars near it. His answer: the star is so far away that its light takes about ten years to reach us. Modern measurements put it at about 11 light-years. At about the same time, two other astronomers measured the stars Alpha Centauri and Vega. People suddenly understood how enormous the heavens are.

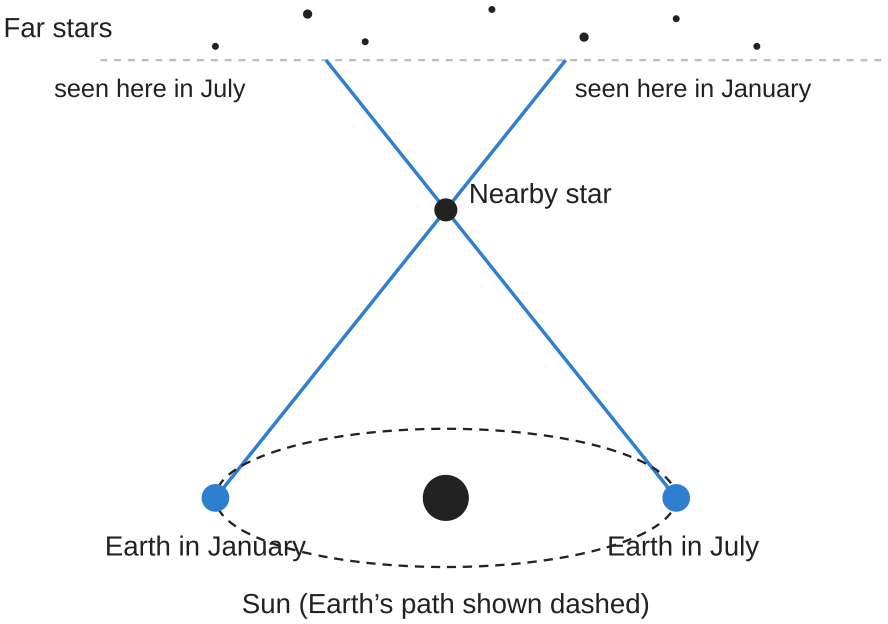
How they figured it out. Bessel used **parallax**, the same trick as your winking thumb. Your two eyes see your thumb from two places, so it seems to jump against the wall. Astronomers use the whole Earth as their two eyes. In January Earth is on one side of the Sun; in July it is about 300 million kilometers (186 million miles) away on the other side. A nearby star seems to shift a tiny bit against the farther stars behind it. The closer the star, the bigger the shift. Even for the nearest stars, the shift is smaller than the width of a coin seen from many kilometers away, which is why it took until 1838 to measure one.

The big idea. Light is the fastest thing there is: about 300,000 kilometers (186,000 miles) every second. Light from the Moon reaches us in a little over one second. Sunlight takes about 8 minutes. Star distances are so huge that astronomers measure them with a **light-year**, the distance light travels in one year, about 9.5 trillion kilometers (about 5.9 trillion miles). A light-year is a distance, not a time. The nearest star after the Sun, Proxima Centauri, is about 4.2 light-years away. Sirius is about 8.6 light-years away, so the Sirius you see tonight is the light that left it more than eight years ago.

The starlight question. Astronomers estimate that some galaxies are so far away that, if light crossed the whole distance at today's speed and by earth's clocks, the trip would take far longer than the history the Bible gives. Christians who believe God made the heavens and the earth in six days not long ago have thought hard about this. Creation scientists give several answers. **First**, God made a finished, working universe, and Genesis 1:17 says He set the stars in the heaven "to give light upon the earth," so Adam could see stars on his very first night. **Second**, time does not tick at the same rate everywhere. This is measured: clocks on GPS satellites run faster than clocks on the ground by about 38 millionths of a second each day, and engineers must correct for it. Some creation physicists think that when God "stretcheth out the heavens" (Isaiah 40:22), clocks out in space and clocks on earth could have run very differently. **Third**, scientists can measure light's round-trip speed, there and back, but no one has ever measured its one-way speed by itself, so some answers start there. Mainstream scientists have a light-travel puzzle of their own, called the horizon problem. The question is still being studied, and no answer is final.

God's handiwork. The prophet Isaiah wrote, "Lift up your eyes on high, and behold who hath created these things, that bringeth out their host by number: he calleth them all by names by the greatness of his might, for that he is strong in power; not one faileth" (Isaiah 40:26). Every new measurement has made the heavens bigger than people imagined. The

bigger the heavens, the greater the God who made them. Scientists should be honest about what they measure and what they assume, and children can ask good questions about both.



Parallax: from January and July, a nearby star seems to sit in two different places against the far background stars.

⏳ Thinking About Time

What the sign says. What the sign says: Many textbooks and planetarium shows say that some galaxies are millions or even billions of light-years away, so their light must have been traveling for millions or billions of years, which would mean the universe is very old.

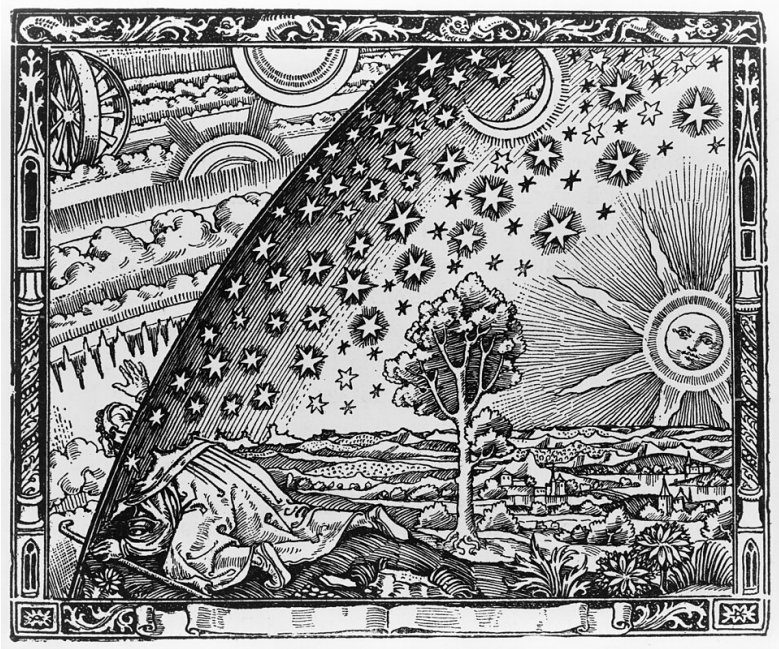
What we observe. What we observe: Starlight is arriving at earth right now. We can measure light's round-trip speed and the parallax of nearby stars. Distances to faraway galaxies are not measured with a ruler; they are worked out from how bright certain stars look and other clues, using assumptions. We also measure that clocks run at different rates in different gravity and at different speeds, as GPS satellites show every day.

How Christians read it. How Christians read it: God made the stars on the fourth day "to give light upon the earth" (Genesis 1:16–17), so their light could be seen from the start. Creation scientists suggest answers based on a finished creation, on clocks running at different rates as God stretched out the heavens, and on how light's speed is measured. These are honest attempts that are still being tested. Christians can hold them humbly, knowing God is truthful and His Word is reliable.

Try it. Look at Sirius on a winter night and say: "This light left the star more than eight years ago, and God knew its path all the way."

> *Genesis 1:16*

PICTURE STUDY



The Traveler at the Edge of the Sky (the "Flammarion engraving"), Unknown artist, from Camille Flammarion's book *L'atmosphère: météorologie populaire*, 1888 · Wood engraving (book illustration) · Published in Paris, 1888; copies are kept in libraries

This picture appeared in a popular science book by the French astronomer and writer Camille Flammarion. Its caption says that a missionary of the Middle Ages claimed he had found the place where the sky and the earth meet. The engraving shows the traveler poking his head through the sky to see what lies beyond.

The picture is a playful old tale, not real history. Educated people in the Middle Ages knew the earth was round. But the picture asks a good question: how far away is the sky, and what lies beyond? Bessel's parallax measurement in 1838 began to answer it.

Look closely

- Find the traveler. What is he holding, and what is he looking at?
- Find the Sun, the Moon and the stars. Where has the artist put them?
- Look at the strange wheels and shapes beyond the sky. What do you think the artist wanted them to mean?
- Compare the ordinary world on the left with the world beyond the sky. How are they different?

Talk about it

1. In this picture the stars are painted on a dome you could touch. What did Bessel discover that shows how wrong that idea is?

2. Why do you think this picture is still so popular more than a hundred years later?
3. What question about the sky would you most like to poke your head through and answer?

EXPERIMENT: THUMB PARALLAX: MEASURING DISTANCE BY A JUMP

Bessel measured how much a star seemed to jump as Earth moved around the Sun. You will measure how much a pencil seems to jump as you switch eyes. You will test how the jump depends on distance, just as the stars do.

You will need

- A meter stick or a tape measure taped flat along a wall at eye level
- A pencil with an eraser
- A second tape measure or ruler for measuring arm distance
- Masking tape to mark a spot on the floor
- A helper, notebook and pencil

Steps

1. **Question.** Write: How does an object's distance from my eyes change how far it seems to jump when I switch eyes?
2. **Prediction.** Write whether a close pencil or a far pencil will jump more.
3. **What we change:** the distance from your eyes to the pencil: 25 cm (about 10 in), 40 cm (about 16 in) and 60 cm (about 24 in). **What we keep the same:** your spot on the floor, 3 meters (about 10 feet) from the wall; the same pencil; the same observer; holding your head still. **What we measure:** how many centimeters the pencil seems to jump along the meter stick.
4. Stand on the tape mark facing the meter stick. Your helper holds the ruler from your nose so you can place the pencil exactly 25 cm from your eyes, lined up with the meter stick.
5. Close your left eye and read the number on the meter stick just behind the pencil eraser. Then close your right eye and read the new number. The difference is the jump.
6. Repeat at 40 cm and 60 cm. Do each distance twice and average the two jumps.
7. Record a table: Pencil distance (cm), Jump 1, Jump 2, Average jump.
8. Make a bar graph and write a conclusion. Explain how this is like Bessel measuring 61 Cygni, and why the stars' jumps are so tiny.

Tips

- Keep your head perfectly still and only switch which eye is open.
- Your numbers will not match a friend's exactly, because people's eyes are different distances apart. The pattern should match: closer means a bigger jump.
- For a person whose eyes are about 6.5 cm apart, the jump is roughly 70 cm at 25 cm, 40 cm at 40 cm and 25 cm at 60 cm.

Check your work

- I named what I changed, what I kept the same and what I measured.
- My table shows two trials at each distance and an average.
- I can explain why a closer star shows a bigger parallax shift.

FIELD NOTEBOOK

1. Draw the parallax diagram: the Sun, Earth in January and in July, a nearby star, and lines to two places among the far stars. Label each part.
2. Make a “light travel” strip: Moon about 1 second, Sun about 8 minutes, Proxima Centauri about 4.2 years, Sirius about 8.6 years. Draw each object along the strip.
3. Write the three creation answers to the starlight question in your own words, each in one sentence, and copy Isaiah 40:26 beneath them.

> **From history.** The first person to show that light has a speed was the Danish astronomer Ole Rømer, working at the Paris Observatory in 1676. He noticed that Jupiter’s moon Io slipped into Jupiter’s shadow a little later than predicted when Earth was far from Jupiter, and a little earlier when Earth was near. He reasoned that the light from Io needed extra time to cross the extra distance. Before Rømer, many thought light arrived instantly.

WORKED EXAMPLES

Example 1. The Sun is about 150,000,000 km (93,000,000 miles) from Earth. Light travels about 300,000 km each second. How long does sunlight take to reach us?

1. Divide distance by speed: 150,000,000 ÷ 300,000 = 500 seconds.
2. Change to minutes: 500 ÷ 60 = 8 minutes with 20 seconds left over (8 × 60 = 480; 500 − 480 = 20).
3. Check with miles: 93,000,000 ÷ 186,000 = 500 seconds. Same answer.

Answer: About 500 seconds, or 8 minutes 20 seconds. The Sun you see is the Sun as it was about 8 minutes ago.

Example 2. Show where the number “about 9.5 trillion kilometers in a light-year” comes from. Light travels 300,000 km each second. (You may use a calculator.)

1. One minute: 300,000 × 60 = 18,000,000 km.
2. One hour: 18,000,000 × 60 = 1,080,000,000 km.
3. One day: 1,080,000,000 × 24 = 25,920,000,000 km.
4. One year: 25,920,000,000 × 365 = 9,460,800,000,000 km.
5. Round: about 9.5 trillion km.

Answer: A light-year is about 9,460,800,000,000 km, roughly 9.5 trillion kilometers (about 5.9 trillion miles).

PRACTICE

1. EASY Is a light-year a measure of time or of distance? Explain in one sentence.
2. EASY About how fast does light travel? Give your answer in kilometers per second and miles per second.
3. MEDIUM The Moon is about 384,000 km from Earth. How many seconds does moonlight take to reach us? (Light: 300,000 km each second.)
4. MEDIUM Read the table of star distances. Proxima Centauri 4.2 light-years; Alpha Centauri A 4.4; Sirius 8.6; 61 Cygni 11.4; Vega 25. (a) Which is nearest? (b) How much farther is Vega than Sirius? (c) Is the light you see from 61 Cygni tonight older or younger than the light from Sirius?
5. MEDIUM In the thumb experiment, does your thumb seem to jump more when it is close to your face or at arm’s length? What does this tell astronomers about stars that show a big parallax shift?
6. HARD Plan a parallax experiment with a pencil and a meter stick on a wall. Name the variable you change, three things you keep the same, and what you measure.
7. HARD In three or four sentences, describe the distant starlight question and two ways creation scientists answer it. Name one real measurement that one of the answers uses.
8. CHALLENGE Proxima Centauri is about 4.2 light-years away. One light-year is about 9.5 trillion km. About how many kilometers away is Proxima Centauri? If a car drove 100 km every hour without stopping for a 90-year lifetime (about 790,000 hours), would it get there?

COMMON MISTAKES

- Thinking a light-year is a length of time. It is a distance: how far light goes in a year.
- Thinking we see stars exactly as they are right now. We see the light that left them some time ago, because even light needs time to travel.
- Thinking the starlight question has been closed for good. It is still being studied, and every view, including the mainstream one, works with assumptions it cannot directly

measure.

Make it a game · Light Race. Mark a starting line on the floor labeled Earth. Place sticky notes along a hallway: the Moon (1 step), the Sun (5 steps), Proxima Centauri (the far end of the hall). A parent calls out a place, and you call out how long its light takes to reach us (Moon about 1 second, Sun about 8 minutes, Proxima about 4.2 years, Sirius about 8.6 years) before you race to touch it. Then a parent calls "time or distance?" about a word such as light-year, minute or kilometer, and you shout the right answer. Score a point for each correct answer.

Scripture. "And God made two great lights; the greater light to rule the day, and the lesser light to rule the night: he made the stars also." (Genesis 1:16, KJV)

Five short words, "he made the stars also," cover trillions of kilometers of heaven. The next verse tells why: God set them in the heaven "to give light upon the earth." The far stars were made with us in mind.

Practice answers

1. Distance. It is how far light travels in one year.
2. About 300,000 kilometers per second, or about 186,000 miles per second.
3. 384,000 ÷ 300,000 = 1.28 seconds, a little over one second.
4. (a) Proxima Centauri. (b) 25 − 8.6 = 16.4 light-years farther. (c) Older: it left 61 Cygni about 11.4 years ago, while the light from Sirius left about 8.6 years ago.
5. It jumps more when it is close to your face. A star with a bigger parallax shift is closer to us than a star with a smaller shift.
6. Change: the distance from the eyes to the pencil. Keep the same (any three): where you stand, the distance to the wall, the same pencil, the same observer, keeping the head still. Measure: how many centimeters the pencil seems to jump along the meter stick when you switch eyes. Repeat trials and average.
7. Some galaxies are thought to be so far away that light traveling at today's speed by earth's clocks would take far longer than the Bible's history to get here. One answer is that God made a finished universe and set the stars to give light upon the earth from the beginning. Another is that clocks do not run at the same rate everywhere, so far less time may have passed on earth than in distant space. That idea rests on time dilation, which is measured every day in GPS satellite clocks. (A third answer looks at how the one-way speed of light is measured.)
8. 4.2 × 9.5 = 39.9, so about 40 trillion km. No. In 790,000 hours the car would go 100 × 790,000 = 79,000,000 km. That is only about one five-hundred-thousandth of the way (40,000,000,000,000 ÷ 79,000,000 ≈ 506,000). The stars are truly far away.

Unit 4 review

Answer each question. Show your work for calculations and use complete sentences for explanations. The test is worth 50 points, with 5 points for each question.

1. (5 pts) Quote Psalm 147:4 (or say it in your own words). What can God do with the stars that no astronomer can?
2. (5 pts) Ava counted 7, 5, 6 and 6 stars in four tube views. If 400 tube views cover her whole sky, estimate how many stars she can see. Is your answer exact?
3. (5 pts) Name two things that change how many stars you can see from your backyard, and explain each one.
4. (5 pts) Quote Job 38:31. Which two star groups does it name?
5. (5 pts) Explain the difference between a constellation like Orion and a star cluster like the Pleiades.
6. (5 pts) A star rises about 4 minutes earlier each night. If Rigel rises at 9:00 p.m. tonight, about when will it rise 15 nights from now? Show your work.
7. (5 pts) Betelgeuse is orange-red and Rigel is blue-white. Which star is hotter? Put the star types O, B, A, F, G, K, M in order and tell which type the Sun is.
8. (5 pts) Read the data: Arcturus about 4,000 °C; Sun about 5,500 °C; Sirius about 9,700 °C. How much hotter is Sirius than the Sun? Which star would look the most orange?
9. (5 pts) Is a light-year a time or a distance? Light travels 300,000 km each second, and the Sun is 150,000,000 km away. How long does sunlight take to reach us?
10. (5 pts) Explain how parallax shows that a star is close, and name two ways creation scientists answer the distant starlight question.

Unit project: my winter sky notebook

Make a sky notebook of at least six pages that records your own observations of the winter stars. Include: your tube star counts with a table and bar graph (Lesson 4.1); a hand-drawn chart of Orion and the Pleiades with Betelgeuse, Rigel, Aldebaran and Sirius labeled and your Pleiades count with eyes and with binoculars (Lesson 4.2); a colored star-type ladder and your toaster-coil color table (Lesson 4.3); and your pencil parallax table and a “light travel” strip (Lesson 4.4).

Finish with one page in your best handwriting that copies Psalm 147:4 and answers in a paragraph: What did I learn about the stars this winter, and what did it teach me about the God who made them?

- **Observations**: Every observing page gives the date, time, place and sky conditions, and the counts and colors were really observed by the student.
- **Accuracy**: Star names, positions, colors and temperatures are correct, and the parallax and light-travel numbers are calculated correctly.
- **Experiments and data**: Each experiment names what was changed, what was kept the same and what was measured, with neat tables, bar graphs and a short conclusion.

- **Reflection and care**: The closing paragraph connects what was learned to Psalm 147:4 in the student's own words, and the notebook is neat, colorful and easy to read.

Answer key

1. "He telleth the number of the stars; he calleth them all by their names." God knows the exact number of the stars and the name of each one; astronomers can only estimate the number.
2. Total 24; average 24 ÷ 4 = 6; 6 × 400 = 2,400 stars. It is an estimate made from samples, not an exact count.
3. Light pollution: lights from streets and buildings brighten the sky and hide faint stars. Dark adaptation: your eyes need 20 to 30 minutes in the dark to become most sensitive, and white light resets them. (The Moon's brightness and clouds are also acceptable.)
4. "Canst thou bind the sweet influences of Pleiades, or loose the bands of Orion?" It names the Pleiades and Orion.
5. A constellation is a pattern people see; its stars only look close together and lie at different distances. A star cluster is a true family of stars close together in space, moving together and held by their own gravity.
6. 15 × 4 = 60 minutes = 1 hour earlier, so about 8:00 p.m.
7. Rigel is hotter. The order from hottest to coolest is O, B, A, F, G, K, M. The Sun is a G star.
8. 9,700 − 5,500 = 4,200 °C hotter. Arcturus, the coolest of the three, would look the most orange.
9. A light-year is a distance (how far light goes in a year). 150,000,000 ÷ 300,000 = 500 seconds, which is 8 minutes 20 seconds.
10. As Earth moves around the Sun, a nearby star seems to shift against the far stars behind it; the bigger the shift, the closer the star (like a thumb that jumps more when close to your eyes). Creation answers (any two): God made a finished universe with the stars set to give light upon the earth from the start; clocks run at different rates in different places (time dilation, measured in GPS clocks), so less time may have passed on earth; and the one-way speed of light has never been measured by itself.

UNIT 5

Kepler and Newton

For thousands of years people watched the planets wander among the stars, but no one knew the true shape of their paths or what kept them moving. In this unit you will meet two men who found out. Johannes Kepler, a German mathematician who once hoped to be a minister, spent years in a “war” with the planet Mars until Tycho Brahe’s careful measurements showed him that planets travel in **ellipses**, not perfect circles. Isaac Newton, a quiet English scholar, watched an apple fall and asked whether the same pull reached all the way to the Moon. It did. He called it **universal gravitation**.

You will draw ellipses with string and pins, find out why the Moon is always falling but never lands, and test gravity yourself with falling paper, rolling balls and swinging pendulums, just as Simon Stevin and Galileo did. Along the way you will practice the habits of a real scientist: measuring carefully, changing one thing at a time, and trusting honest evidence over a favorite idea. Kepler believed that studying the heavens was a way of thinking God’s thoughts after Him, and by the end of this unit you will see why: the God who made the sky gave it laws that a child with a string and a pencil can begin to understand.

BEFORE YOU BEGIN

- Knows that Earth turns on its axis and travels around the Sun (Unit 1)
- Knows the names and order of the planets (Unit 3)
- Can measure lengths in centimeters and millimeters with a ruler
- Can multiply and divide whole numbers and simple decimals

MASTERY CHECKLIST

- I can tell how Kepler used Tycho Brahe’s measurements to discover that planets move in ellipses.
- I can state Kepler’s three laws of planetary motion in my own words.
- I can draw an ellipse with two pins and a string, label its foci and major axis, and find its eccentricity.
- I can explain, using Newton’s cannon, why the Moon keeps going around Earth.
- I can explain why a hammer and a feather fall together on the Moon, and tell the difference between mass and weight.
- I can plan a fair test that changes only one variable and read its results from a table or graph.

OPTIONAL BOOKS AND RESOURCES

- **NASA Space Place** (https://spaceplace.nasa.gov/): Free. NASA’s site for children, with short articles, pictures and activities about gravity, orbits, the Moon and the planets. A parent can search it for “orbit” or “gravity.”

- **NASA Science: Solar System** (https://science.nasa.gov/solar-system/): Free. Up-to-date facts and images for every planet and many comets, including distances from the Sun and the time each takes to orbit. Useful for checking numbers in your orbit drawings.

5.1 Kepler: Thinking God's Thoughts After Him ★

OBJECTIVES

- Tell how Johannes Kepler used Tycho Brahe's careful measurements of Mars to discover that planets travel in ellipses, not perfect circles.
- State Kepler's three laws of planetary motion in simple words and use them to explain when Earth moves fastest and slowest.
- Explain why Kepler saw astronomy as a way of honoring God, and why he trusted careful measurements more than a favorite idea.

Warm-up. Hold your little finger out at arm's length and look past it at a light switch across the room. Your fingertip covers about 1 degree of the sky. Now imagine slicing that fingertip into 8 thin strips and keeping just one. That sliver is about how big Kepler's "mistake" was in this lesson's story. Would you throw out a whole idea because of a gap that small? Talk it over, then find out what Kepler did.

Video. Coming soon. Johannes Kepler and Tycho Brahe, Kepler's three laws of planetary motion for kids, elliptical orbits: search NASA, NASA Space Place, Homeschool Pop (Alternate), SciShow Kids, Crash Course Kids and Moody Science classics.

KEY TERMS

astronomer
A scientist who studies the Sun, Moon, planets, stars and everything else in the sky.

orbit
The path one object in space follows around another, such as Earth's path around the Sun.

ellipse
A closed curve shaped like a stretched circle. Every planet's orbit is an ellipse.

observation
Something noticed and recorded carefully, often by measuring it, such as the exact place of Mars in the sky on a certain night.

law of nature
A rule that describes how some part of creation always behaves, such as Kepler's laws for how planets move.

CORE IDEAS

The story. On February 4, 1600, a thin, nearsighted German mathematics teacher named Johannes Kepler arrived at Benátky Castle near Prague to meet the most careful sky-watcher in the world. Tycho Brahe was a Danish nobleman who had spent more than twenty years measuring the exact places of the planets, night after night, from his observatory on the island of Hven. He used giant instruments of brass and wood but no telescope, because no

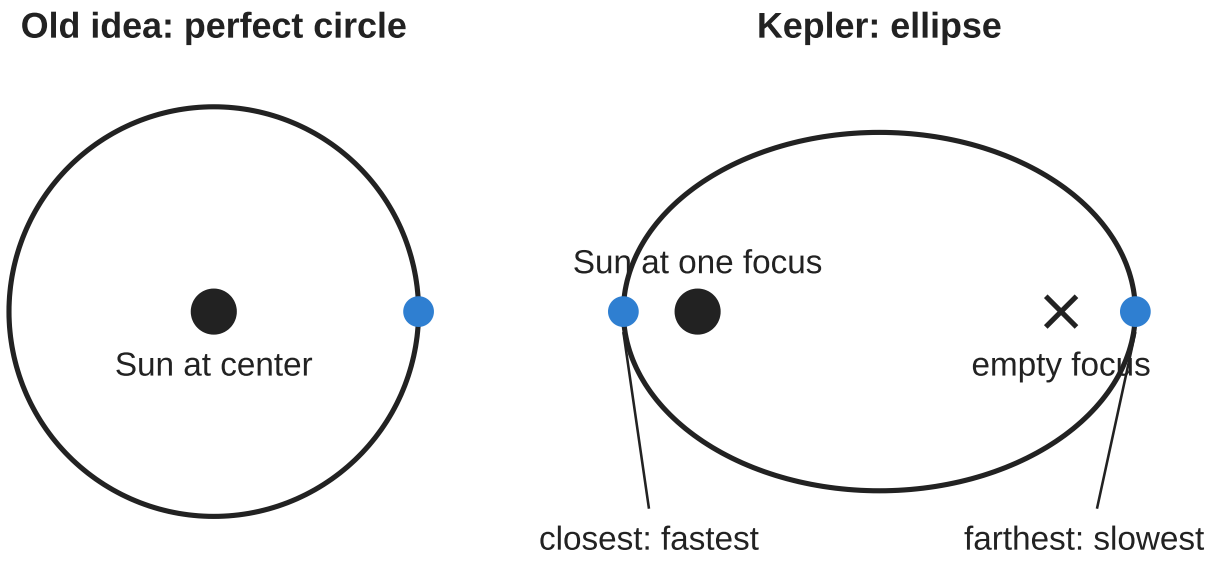
one had yet turned a telescope to the sky. Smallpox had weakened Kepler's eyes when he was three, so he could never have made such measurements himself. But he was a brilliant mathematician. Tycho had the numbers; Kepler had the mind to explain them. Tycho handed him the hardest planet of all: Mars. When Tycho died in 1601, Kepler became mathematician to the emperor and kept Tycho's precious records.

How they figured it out. For about two thousand years, astronomers had believed the heavens moved in perfect circles. Even Copernicus, who in 1543 put the Sun in the middle of the planets, still used circles. Kepler tried circle after circle for Mars. His best one came very close, but at some points it missed Tycho's measured position of Mars by 8 minutes of arc. That is less than one-seventh of a degree, about the width of a dime seen from 8 meters (26 feet) away. Many people would have called it close enough. Kepler did not, because Tycho's measurements were good to about 2 minutes of arc. A miss four times bigger than Tycho's possible error meant the circle was wrong. Kepler later wrote that those 8 minutes alone led the way to reforming all of astronomy. After years of calculating by hand, a struggle he called his "war" with Mars, he found the answer: Mars moves in an **ellipse**, with the Sun not at the center but at a special point off to one side. He published this in 1609 in his book *New Astronomy*.

The big idea. Kepler found three rules we now call **Kepler's laws of planetary motion**. First, every planet travels around the Sun in an ellipse, with the Sun at one of two special points called foci. Second, a planet speeds up when it swings closer to the Sun and slows down when it is farther away. Third, planets farther from the Sun take longer to go around, following an exact number pattern Kepler discovered in 1618. Earth obeys these laws. In early January it is closest to the Sun, about 147 million kilometers (91 million miles) away, and moves a little faster. In early July it is farthest, about 152 million kilometers (94.5 million miles) away, and moves a little slower. Earth's ellipse is so nearly round that you could not tell it from a circle in a drawing. Mars has a more stretched orbit, which is why Mars gave Kepler the clue.

God's handiwork. Kepler had studied at the University of Tübingen to become a Lutheran minister, but his teachers sent him to teach mathematics instead. At first he was disappointed. Later he decided that studying the sky was itself a way of serving God. In a letter he wrote that God made people in His own image so that they could understand the laws He built into the world, and he called astronomers priests of the most high God in the book of nature. People have summed up his view in a famous phrase: Kepler was "thinking God's thoughts after Him." Those exact words are a later summary, not a sentence from his books, but they fit him well. Because he believed a faithful, orderly God made the heavens, he expected to find laws there, and he refused to bend Tycho's honest numbers to fit a favorite idea.

Try it and see. A real scientist trusts careful measurements more than a shape that merely looks right. In this lesson's project you will measure round and oval objects in several directions to test whether they are truly circles. Then you will draw the orbits of Earth and Mars to scale and put the Sun in its proper place, a little off center, just as Kepler found it.



(The ellipse is stretched to show the idea. Real orbits are nearly round.)

The old idea and Kepler's discovery. The ellipse is stretched here so you can see it; real planet orbits are much rounder.

PICTURE STUDY



Frontispiece of the Rudolphine Tables (The Temple of Urania), Designed by Johannes Kepler; engraved by Georg Celer of Nuremberg, 1627 · Copper engraving (book illustration) · Printed in Ulm, Germany, 1627; copies of the book are kept in many rare-book libraries

When Kepler at last finished the great planet tables that Tycho Brahe had begun, he designed this title page himself. It shows a temple to Urania, the Greek muse of astronomy. The pillars stand for the astronomers of the past: rough log pillars for the earliest sky-

watchers, finer stone pillars for Hipparchus and Ptolemy, and the finest of all for Copernicus, who sits, and Tycho Brahe, who stands pointing up at a diagram of his own plan of the heavens.

Kepler put himself in a small panel at the base of the temple, working at a desk by candlelight. The tables were named for Emperor Rudolf II, who had employed both Tycho and Kepler, and they were printed at Ulm in 1627. They predicted the positions of the planets far better than any tables before them.

Look closely

- Find the pillars. Which look rough and old, and which look finely carved? Why might Kepler have drawn them that way?
- Find the standing man pointing upward. That is Tycho Brahe. What is he pointing at?
- Find the seated astronomer near him. That is Copernicus, who put the Sun in the middle of the planets.
- Look at the small panels in the base of the temple. Can you find the man working at a desk? That is Kepler himself.

Talk about it

1. Kepler gave Tycho the grandest place in the picture and put himself in a small corner. What does that tell you about how he valued Tycho’s measurements?
2. Why do you think Kepler showed the history of astronomy as a building with many pillars?
3. If you drew a pillar for yourself as a sky-watcher, what would you carve on it?

EXPERIMENT: CIRCLE OR NOT? MEASURING LIKE TYCHO

Question: How can you tell whether a shape that looks round is really a circle? A circle is the same width in every direction through its center. An ellipse is longer one way than the other. You will measure several round-looking objects in four directions, then draw Earth’s and Mars’s orbits to scale with the Sun in the right place.

Prediction: Before you measure, write down which objects you think are true circles. What we change: the object being measured. What we keep the same: the ruler, the person measuring and the rule of measuring straight across through the middle. What we measure: the width in four directions, in centimeters. Record everything in a table.

You will need

- Ruler marked in centimeters and millimeters
- Four round or oval things: a dinner plate, a jar lid, an oval serving platter or picture frame, and an egg or oval cracker
- Pencil, lab notebook and a sheet of poster board (or two sheets of paper taped together)
- A piece of string about 20 cm (8 in) long and a pushpin, or a drawing compass

- A sticker or coin for the Sun

Steps

1. Make a table with columns: Object, Width 1, Width 2, Width 3, Width 4, Biggest minus smallest, Circle?
2. Write your prediction for each object.
3. Lay the ruler across the first object through its middle and measure the widest distance, to the nearest millimeter. Turn the ruler about one-eighth of a turn and measure again. Do this four times in all, going around like spokes on a wheel.
4. Subtract the smallest width from the biggest. If the difference is 0 or 1 millimeter, call it a circle. If it is bigger, it is not a circle.
5. Repeat for every object and compare your results with your predictions.
6. Now draw orbits to scale. Make a dot in the middle of the poster board. Draw a circle around it with a radius of 10 cm (4 in) for Earth's orbit. Earth's orbit is so nearly round that a circle is a fine drawing of it.
7. Measure 1.7 mm (less than 1/16 inch) from the center dot and place the Sun there. That tiny step is how far the Sun sits from the middle of Earth's orbit at this scale.
8. Draw a second circle around the same center dot with a radius of 15 cm (6 in) for Mars. At this scale, the Sun belongs about 1.4 cm (a little over 1/2 inch) from the center of Mars's orbit. Mark that spot and compare it with where you put the Sun for Earth.
9. Write two sentences: Which orbit has the Sun farther off center? Why could Tycho's Mars measurements, and not Earth's, show Kepler that circles were wrong?

Tips

- Measure each width twice. If your two numbers do not agree, measure a third time. Tycho checked his measurements again and again.
- A circle seen at a slant looks like an ellipse. Measure the object itself, not how it looks from the side.
- Real orbits of Earth and Mars are not perfect circles, but they are so close that the off-center Sun is the part your drawing really needs to show.

Check your work

- I measured each object in four directions and recorded my numbers.
- I used my measurements, not just my eyes, to decide which objects are circles.
- I placed the Sun off center in my orbit drawing and can explain why.

FIELD NOTEBOOK

1. Draw Tycho Brahe's observatory instrument as you imagine it, with Tycho on one side and Kepler at a desk of papers on the other. Label it: "The numbers and the mind."
2. Write Kepler's three laws in your own words, each with a small sketch beside it.

3. Copy the circle and ellipse diagram from this lesson. Mark the Sun, the empty focus, the closest point and the farthest point.

From history. Kepler was curious about small things as well as large ones. In 1611 he wrote a little booklet called *The Six-Cornered Snowflake* as a New Year's gift for a friend in Prague who had helped him. In it he asked why every snowflake has six points, and he guessed that the answer had to do with how tiny particles of ice pack together. He could not prove it, but scientists later found that the six-sided shape of ice crystals really does come from the orderly way water molecules fit together.

WORKED EXAMPLES

Example 1. Kepler's best circle for Mars missed Tycho's measurements by 8 minutes of arc. Tycho's measurements were good to about 2 minutes of arc. How many times bigger was the miss than Tycho's possible error? How big is 8 minutes of arc in degrees?

1. Compare the two numbers by dividing: 8 ÷ 2 = 4. The miss was 4 times bigger than Tycho's possible error.
2. There are 60 minutes of arc in 1 degree, so 8 minutes of arc is 8/60 of a degree.
3. Simplify: 8/60 = 2/15, which is about 0.13 degree, a little more than one-eighth of a degree.

Answer: The miss was 4 times Tycho's possible error. 8 minutes of arc is 2/15 of a degree, about 0.13 degree.

Example 2. You draw Earth's orbit with an average radius of 10 cm and Mars's orbit with an average radius of 15 cm. For Earth, the Sun sits about 1/60 of the radius away from the center. For Mars, it sits about 1/11 of the radius away. How far from the center should you place the Sun in each drawing?

1. Earth: 10 cm ÷ 60 = about 0.17 cm. Change to millimeters: 0.17 cm × 10 = 1.7 mm.
2. Mars: 15 cm ÷ 11 = about 1.4 cm.
3. Compare: 1.4 cm is 14 mm, about 8 times farther off center than 1.7 mm.

Answer: About 1.7 mm off center for Earth and about 1.4 cm (14 mm) off center for Mars. Mars's orbit is much more lopsided, which is why it revealed the ellipse.

PRACTICE

1. EASY Who made the careful measurements of Mars that Kepler used, and where did he make most of them?
2. EASY What shape is every planet's orbit, and where is the Sun?
3. EASY According to Kepler's second law, where in its orbit does a planet move fastest?

4. MEDIUM This table shows Earth's distance from the Sun at four times of year, rounded to the nearest million kilometers. Early January: 147. Early April: 150. Early July: 152. Early October: 150. (a) When is Earth closest to the Sun? (b) How many million kilometers is the difference between farthest and closest? (c) When does Earth move fastest? (d) Is it summer in the United States when Earth is closest?
5. MEDIUM Put these planets in order from shortest to longest trip around the Sun, and tell which of Kepler's laws explains the order: Mars (687 days), Mercury (88 days), Earth (365 days), Venus (225 days).
6. MEDIUM You want to test whether a round tabletop is truly a circle. Describe a fair test. What will you change, what will you keep the same, and what will you measure?
7. HARD Tycho's measurements were good to about 2 minutes of arc. Change 2 minutes of arc to a fraction of a degree. If a careless observer could only measure to within 15 minutes of arc, could he have caught Kepler's 8-minute miss? Explain.
8. CHALLENGE In two or three sentences, explain why Kepler did not ignore the 8 minutes of arc, and how his belief about God shaped the way he did science.

COMMON MISTAKES

- Thinking planets move in perfect circles with the Sun at the exact center. Orbits are ellipses with the Sun at one focus, off to one side.
- Thinking Earth has summer when it is closest to the Sun. Earth is closest in early January, during winter in the Northern Hemisphere; seasons come from the tilt of Earth's axis.
- Thinking a planet moves at the same speed all the way around. It speeds up near the Sun and slows down far from it.

> **Make it a game · Circle or Ellipse?.** A parent holds up round and oval things one at a time: a plate, a coin, an egg, a lid, a cracker. Then the parent tilts a round plate so you see it at a slant. Call out "circle" or "ellipse" for what you see, and then say whether the object itself is a circle. Each correct call earns a point, and you earn a bonus point if you can state one of Kepler's three laws in your own words. Play to ten points.

> **Scripture.** "It is the glory of God to conceal a thing: but the honour of kings is to search out a matter." (Proverbs 25:2, KJV)

God hid the shape of the planets' paths in the sky, and it took years of patient searching to find it. Kepler counted that search an honor, and so can we whenever we measure carefully and learn how God's world works.

Practice answers

1. Tycho Brahe, a Danish nobleman, mostly at his observatory on the island of Hven.
2. An ellipse. The Sun is at one of the two foci, a point off to one side of the center.
3. At the point closest to the Sun. It moves slowest at the point farthest from the Sun.

4. (a) Early January. (b) 152 − 147 = 5 million kilometers. (c) Early January, when it is closest. (d) No. It is winter in the United States in January, so the seasons do not come from Earth’s distance to the Sun.
5. Mercury, Venus, Earth, Mars. Kepler’s third law: planets farther from the Sun take longer to go around.
6. Change: the direction across the table (measure in four or more directions). Keep the same: the tape measure, the person measuring, and the rule of measuring straight through the center at the widest point. Measure: the width in each direction to the nearest millimeter. If all the widths match, it is a circle; if one direction is longer, it is an ellipse or other oval.
7. 2 minutes of arc = 2/60 = 1/30 of a degree. No: an observer whose measurements could be off by 15 minutes could not tell an 8-minute miss from his own measuring errors. Only measurements as careful as Tycho’s could reveal it.
8. Kepler knew Tycho’s measurements were more accurate than 8 minutes, so the miss was a real clue that circles were wrong. He believed a faithful, orderly God made the heavens to follow laws people could understand, so he trusted honest measurements and kept searching until his idea matched them, instead of bending the numbers to fit a favorite idea.

5.2 Ellipses with String and Pins ★

OBJECTIVES

- Draw an ellipse with two pins, a string and a pencil, and name its foci and major axis.
- Explain why the length of the string sets the length of the ellipse, and how moving the pins changes its shape.
- Find the eccentricity of an ellipse by dividing the distance between the foci by the length of the ellipse, and compare the orbits of planets and a comet.

Warm-up. Lay a piece of string in a loop on the table. Push it into a circle, then a long thin oval, then a fat oval. Did the string get any longer or shorter? Now ask: if the string never changes length, what does change when the shape changes? Keep that question in mind for today’s lab.

Video. Coming soon. How to draw an ellipse with two pins and string (the gardener’s ellipse), foci and eccentricity of planet and comet orbits: search NASA, NASA Space Place, Science Max, Khan Academy, Numberphile and homeschool math and science channels.

KEY TERMS

ellipse
A closed curve where the distance from any point on it to one focus plus the distance to the other focus always adds up to the same number.

focus (plural: foci)
One of the two special points inside an ellipse. In a planet’s orbit, the Sun sits at one focus and the other is empty.

major axis
The longest line across an ellipse. It passes through both foci, and it is as long as the string used to draw the ellipse.

eccentricity
A number that tells how stretched an ellipse is: the distance between the foci divided by the length of the major axis. A circle has eccentricity 0.

circle
A special ellipse whose two foci sit at the same point, the center.

CORE IDEAS

The story. More than two hundred years before Christ, a Greek mathematician named Apollonius of Perga studied the curves you get by slicing a cone at different angles, and he gave one of them the name *ellipse*. For about eighteen centuries the ellipse was a shape in geometry books, not in the sky. Then came Johannes Kepler. In 1604 he wrote a book about

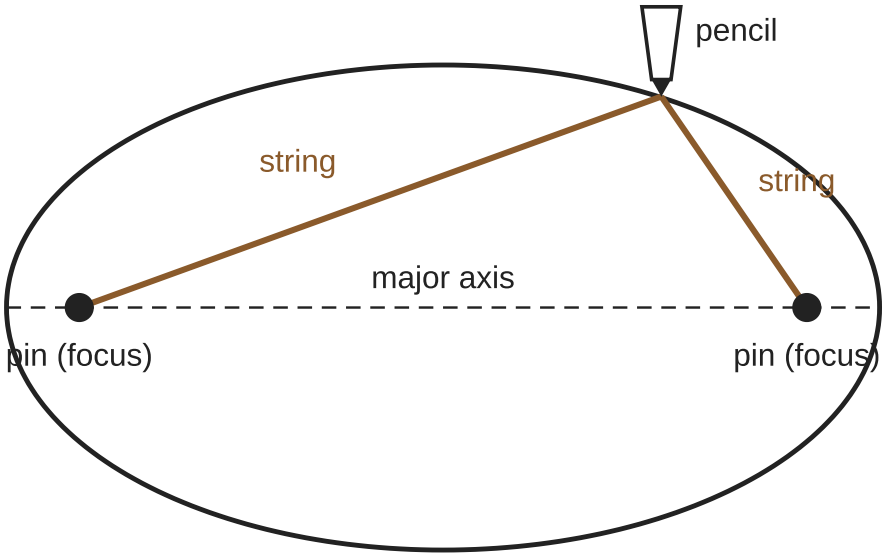
light and mirrors, and in it he called certain special points *foci*, from the Latin word for a hearth or fireplace, because a curved mirror can gather sunlight to a point hot enough to burn. Five years later, in 1609, Kepler announced that Mars travels in an ellipse with the Sun sitting at one focus. A shape mathematicians had studied just because it was beautiful turned out to be the path God had given the planets.

How they figured it out. You can draw an ellipse yourself with the same rule the planets follow. Push two pins into a piece of cardboard. Tie one end of a string to each pin, leaving some slack. Pull the string tight with the point of a pencil and move the pencil all the way around, keeping the string tight. The curve you draw is an ellipse, and the two pins are its **foci**. Here is the secret: at every point on the curve, the distance from the pencil to one pin plus the distance to the other pin equals the length of the string. The string never stretches or shrinks, so that sum never changes. Gardeners lay out oval flower beds the same way, with two stakes and a rope, which is why this is sometimes called the gardener's ellipse.

The big idea. The length of the string sets the length of the ellipse: the longest line across it, the **major axis**, is exactly as long as the string. The distance between the pins sets the shape. If both pins are in the same hole, you draw a circle. Move them apart and the ellipse gets flatter. Scientists measure this with a number called **eccentricity**: divide the distance between the foci by the length of the major axis. A circle has eccentricity 0. A very long, skinny ellipse has an eccentricity close to 1. Earth's orbit has an eccentricity of about 0.017, so it is very nearly a circle. Mars's is about 0.093, and Mercury's about 0.21. Halley's Comet travels on a long, narrow ellipse with an eccentricity of about 0.97, swinging close to the Sun and then far out past Neptune.

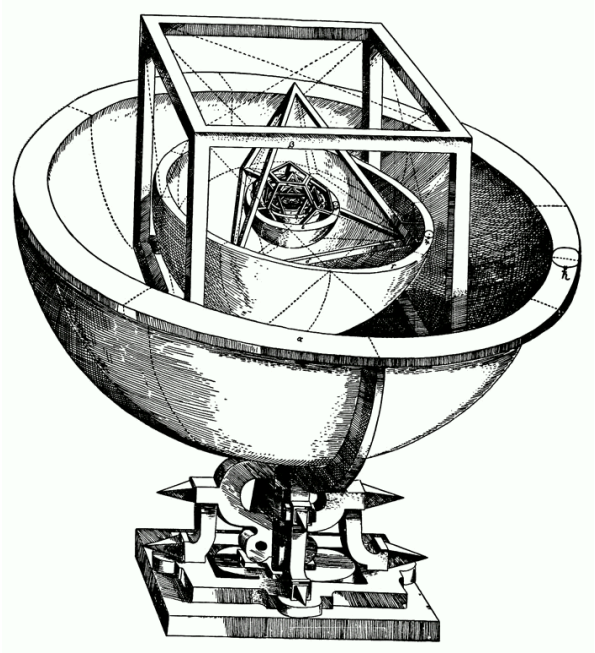
In the world today. Engineers who plan the paths of satellites and space probes still use Kepler's ellipses. A satellite circling Earth follows an ellipse with the center of Earth at one focus. Ellipses help on the ground too. Sound or light that starts at one focus of an ellipse-shaped surface bounces off the curve and comes together at the other focus. Some hospitals use machines with ellipse-shaped reflectors that send pulses of sound energy from one focus to a kidney stone placed at the other focus, breaking the stone into small pieces without surgery.

God's handiwork. Kepler was amazed that the planets obey the same geometry a child can draw with string. He believed geometry was part of God's own mind before the world was made, so of course His creation would follow it. When you trace an ellipse around two pins, you are drawing the very curve that Earth follows around the Sun every year.



Drawing an ellipse with two pins and a string. The two string pieces always add up to the same length.

PICTURE STUDY



Model of the Planetary Spheres, from The Secret of the Universe (Mysterium Cosmographicum), Johannes Kepler (design); engraved for his book, 1596 · Engraving (book illustration) · Printed in Tübingen, Germany; copies of the book are kept in many rare-book libraries

Before Kepler discovered ellipses, he had another idea that he loved. In his first book, published in 1596 when he was twenty-four, he imagined that the six planets known then rode on invisible spheres, and that God had spaced the spheres by fitting the five perfect solids (the cube, the four-sided pyramid called a tetrahedron, the twelve-sided

dodecahedron, the twenty-sided icosahedron and the eight-sided octahedron) one inside another between them. This engraving shows his model.

It is a beautiful idea, and Kepler was proud of it all his life. But when Tycho Brahe's careful measurements of Mars did not fit circles, Kepler followed the measurements and found the ellipse. A good scientist can love an idea and still let the evidence correct it.

Look closely

- Find the cube. It is the biggest solid, fitted between the outermost sphere, for Saturn, and the next sphere in, for Jupiter.
- Count how many spheres you can see nested inside each other.
- Look toward the very center. That is where Kepler placed the Sun.
- Notice the decorated stand and edges. Why might Kepler have wanted his model to look so fine?

Talk about it

1. Kepler's spheres are all perfect circles from the side. How is this model different from what he found later about Mars?
2. Have you ever had an idea you liked that turned out to be wrong when you tested it? What did you do?
3. Why is it good for a scientist to be willing to change his mind when careful measurements disagree with him?

> **Safety first.** Pushpins and thumbtacks are sharp. Push them into thick cardboard set on a cutting board or old magazine, never into a table, and keep them away from small children. An adult should help pull them out when you are done.

EXPERIMENT: ELLIPSE LAB: HOW DO THE PINS CHANGE THE SHAPE?

Question: If the string stays the same length, how does the distance between the pins change the shape of the ellipse? Prediction: Write what you think will happen to the length and the width as the pins move apart.

What we change: the distance between the pins (0, 4, 8 and 12 cm). What we keep the same: the string length between the pins (20 cm), the cardboard, the pencil and the way you hold it. What we measure: the length and the width of each ellipse, in centimeters. Record your results in a table.

You will need

- A sheet of thick corrugated cardboard about 30 cm by 40 cm (12 in by 16 in), with paper taped on top
- Two pushpins or thumbtacks
- Thin string that does not stretch, about 30 cm (12 in) long
- Sharp pencil, ruler and lab notebook

- Colored pencils (optional)

Steps

1. Draw a straight line across the middle of the paper. Mark a center point on the line.
2. Make your table: Pin distance (cm), Length (cm), Width (cm), Eccentricity.
3. Ellipse 1: push both pins into the center point, with one end of a 20 cm piece of string tied to each pin. Pull the middle of the string tight with the pencil and draw all the way around. Each half of the string is 10 cm, so you draw a circle. Measure the length and width.
4. Ellipse 2: push the pins into the line 2 cm on each side of the center, so they are 4 cm apart. Tie the string so the length from pin to pencil to pin is 20 cm. Hold the pencil straight up, keep the string tight and draw all the way around.
5. Ellipse 3: move the pins to 4 cm on each side of center (8 cm apart) and draw again with the same 20 cm of string.
6. Ellipse 4: move the pins to 6 cm on each side of center (12 cm apart) and draw again.
7. Measure the length of each ellipse along the line and the width across the middle. Divide the pin distance by the length to find each eccentricity.
8. Compare with your prediction. Then draw one more ellipse with the pins only 3 mm apart, about Earth's eccentricity at this size, and write whether you can tell it from a circle.

Tips

- Tying string to pins is fiddly. You can instead tape each end of the string down right beside each pin.
- Another way: tie the string into a loop and drop it over both pins. Then the length of the ellipse equals the length of the loop minus the distance between the pins.
- Keep the pencil straight up and the string just snug. If the string slips over the pin heads, your ellipse will come out lopsided.

Check your work

- I drew four ellipses and changed only the distance between the pins.
- I measured and recorded the length and width of each one.
- I can explain why every ellipse came out 20 cm long, and why the farther-apart pins made a flatter ellipse.

FIELD NOTEBOOK

1. Glue or copy your four lab ellipses on one page, nested together, and label each with its pin distance and eccentricity.
2. Draw Halley's Comet's long ellipse with the Sun at one focus. Mark where the comet moves fastest and where it moves slowest.
3. Draw the string-and-pins setup and label the foci, the string, the pencil and the major axis.

From history. Kepler used his laws to build a great book of planet tables, the *Rudolphine Tables*, published in 1627 and named for his old employer, Emperor Rudolf II. They predicted planet positions far better than any tables before. Using them, Kepler predicted that Mercury would pass across the face of the Sun in November 1631. Kepler died in 1630, but in Paris the astronomer Pierre Gassendi projected the Sun's image onto a screen and watched the little black dot of Mercury cross it, just as the tables said. It was the first time anyone had seen a transit of a planet across the Sun.

WORKED EXAMPLES

Example 1. You push two pins into cardboard 10 cm (4 in) apart and use 20 cm (8 in) of string from pin to pencil to pin. How long will the ellipse be? What is its eccentricity? How far past each pin does the ellipse reach?

(Use the map or drawing "The string from pin to pencil to pin always has the same total length." shown earlier in this lesson.)

1. The length of the ellipse (its major axis) equals the length of the string: 20 cm.
2. Eccentricity = distance between foci ÷ length = 10 ÷ 20 = 0.5.
3. The 20 cm length is made of the 10 cm between the pins plus two equal end pieces: 20 − 10 = 10 cm, and 10 ÷ 2 = 5 cm on each end.
4. Check with the string rule at the right end: the pencil is 5 cm from the right pin and 5 + 10 = 15 cm from the left pin. 5 + 15 = 20 cm, the length of the string.

Answer: The ellipse is 20 cm long, its eccentricity is 0.5, and it reaches 5 cm past each pin.

Example 2. You want to draw three orbits, each 20 cm long, with the right shape. How far apart should the pins be for Earth (eccentricity 0.017), Mars (0.093) and Halley's Comet (0.97)?

1. Eccentricity = pin distance ÷ length, so pin distance = eccentricity × length.
2. Earth: 0.017 × 20 cm = 0.34 cm, about 3 mm. That is smaller than the heads of two pushpins, so Earth's ellipse looks just like a circle.
3. Mars: 0.093 × 20 cm = 1.86 cm, about 1.9 cm.
4. Halley's Comet: 0.97 × 20 cm = 19.4 cm. The pins are almost as far apart as the string is long, so the ellipse is very long and skinny.

Answer: Earth: about 3 mm apart. Mars: about 1.9 cm apart. Halley's Comet: about 19.4 cm apart.

PRACTICE

1. EASY In the string-and-pins method, what do the two pins stand for?
2. EASY What shape do you draw if both pins go into the same hole?
3. MEDIUM Pins are 6 cm apart and the string from pin to pencil to pin is 12 cm. How long is the ellipse, and what is its eccentricity?
4. MEDIUM Ellipse A: pins 4 cm apart, string 20 cm. Ellipse B: pins 6 cm apart, string 12 cm. Find each eccentricity. Which ellipse is flatter?
5. MEDIUM A student's ellipse lab gave these results, all with 20 cm of string. Pins 0 cm apart: width 20.0 cm. Pins 4 cm apart: width 19.6 cm. Pins 8 cm apart: width 18.3 cm. Pins 12 cm apart: width 16.0 cm. (a) What happens to the width as the pins move apart? (b) How much narrower is the 12 cm ellipse than the circle? (c) What stayed the same for all four?
6. MEDIUM Eccentricities: Venus 0.007, Earth 0.017, Mars 0.093, Mercury 0.21, Halley's Comet 0.97. Which planet's orbit is the most nearly circular? Which planet's orbit is the most stretched? List all five from roundest to most stretched.
7. HARD Design an experiment to find out whether a longer string makes a longer ellipse. What will you change? What will you keep the same? What will you measure? What do you predict?
8. CHALLENGE Your string is 16 cm long from pin to pencil to pin. When the pencil is at the end of the ellipse nearest pin A, it is 3 cm from pin A. How far is it from pin B? How far apart are the two pins? Explain how you know.

COMMON MISTAKES

- Thinking any oval or egg shape is an ellipse. An egg is fatter at one end; an ellipse is the same on both ends and follows the string rule exactly.
- Thinking the Sun sits at the center of a planet's ellipse. It sits at one focus, and the other focus is empty.
- Thinking planet orbits are long, skinny ovals because textbook pictures draw them that way. Most planet orbits are very nearly circles; the pictures stretch them so you can see the idea.

Make it a game · Human Ellipse. Go out to a driveway or sidewalk with sidewalk chalk and a rope about 4 meters (13 feet) long. Two people stand still as the foci, each holding one end of the rope. The third person holds the middle of the rope tight with a piece of chalk and walks all the way around, drawing on the ground. Then the foci step closer together or farther apart and you draw again. Before each round, everyone guesses whether the new ellipse will be rounder or flatter. A correct guess earns a point.

Scripture. "Knowest thou the ordinances of heaven? canst thou set the dominion thereof in the earth?" (Job 38:33, KJV)

God asked Job whether he knew the laws, or "ordinances," of the heavens. People did not make those laws, but God lets us discover them. Every ellipse you draw shows one of His

ordinances for the sky.

Practice answers

1. The two foci of the ellipse. In a planet’s orbit, the Sun is at one focus.
2. A circle. Its eccentricity is 0.
3. 12 cm long (the same as the string). Eccentricity = 6 ÷ 12 = 0.5.
4. A: 4 ÷ 20 = 0.2. B: 6 ÷ 12 = 0.5. Ellipse B is flatter because its eccentricity is larger.
5. (a) The width gets smaller, so the ellipse gets flatter. (b) 20.0 − 16.0 = 4.0 cm narrower. (c) The length stayed 20 cm every time, because the string length stayed 20 cm.
6. Venus is the most nearly circular. Mercury is the most stretched of these planets. Roundest to most stretched: Venus, Earth, Mars, Mercury, Halley’s Comet.
7. Change: the string length (for example 12, 16, 20 and 24 cm). Keep the same: the distance between the pins, the cardboard, the pencil and how tightly you hold the string. Measure: the length of each ellipse along its major axis. Prediction: each ellipse will be exactly as long as its string, so a longer string makes a longer ellipse.
8. The two distances must add up to 16 cm, so the pencil is 16 − 3 = 13 cm from pin B. At the end of the ellipse, both pins lie on the same line as the pencil, so the pins are 13 − 3 = 10 cm apart.

5.3 Newton's Apple and the Moon

OBJECTIVES

- Tell the true story of Isaac Newton, the falling apple and his question about the Moon.
- Explain that the Moon stays in orbit because it is always falling toward Earth while moving sideways very fast, using Newton's cannon as a model.
- Use the rule that gravity grows weaker with distance (twice as far, one-fourth as strong) to compare the pull on an apple and on the Moon.

Warm-up. Hold a ball at shoulder height and let it drop. Now toss it gently forward and watch it land. Then toss it a little harder. Draw the three paths in your notebook. Every path ended on the floor, but each one curved. What would have to happen for a ball to curve all the way around the earth and never land?

Video. Coming soon. Isaac Newton, the apple, and why the Moon doesn't fall; Newton's cannonball thought experiment and orbits: search NASA, NASA Space Place, Science Max, Homeschool Pop (Alternate), SciShow Kids and Moody Science classics.

KEY TERMS

gravity
The pull that every object with mass has on every other object. Earth's gravity pulls things toward its center.

force
A push or a pull. Gravity is a pulling force.

inertia
The way an object keeps doing what it is doing, staying still or moving in a straight line at the same speed, until a force changes it.

mass
The amount of matter in an object. More mass means a stronger pull of gravity.

universal gravitation
Newton's discovery that the same gravity that pulls an apple to the ground reaches out into space and holds the Moon and the planets in their orbits.

CORE IDEAS

The story. In 1665 a deadly plague swept through England, and the University of Cambridge closed its doors. A quiet young student named Isaac Newton went home to Woolsthorpe Manor, his family's stone farmhouse in Lincolnshire. There, during 1665 and 1666, he thought hard about light, mathematics and motion. Many years later, in 1726, Newton drank tea under some apple trees with his friend William Stukeley. Stukeley wrote that Newton told him the idea of gravity had first come to his mind just like this, when an apple fell while he

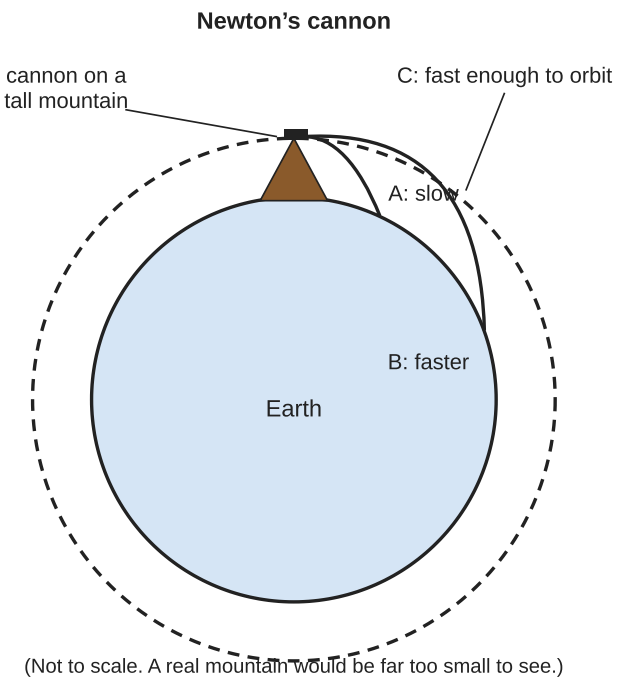
sat thinking in a garden. Notice what the story does *not* say: the apple did not bonk him on the head. That part was added by later storytellers. What matters is the question the apple raised.

How they figured it out. Newton wondered: if Earth's pull reaches to the top of the tallest tree and the highest mountain, does it reach all the way to the Moon? And if it does, why doesn't the Moon fall down? His answer was that the Moon *is* falling, all the time. Imagine a cannon on a very tall mountain, a picture Newton himself drew. Fire a cannonball slowly, and gravity bends its path down to the ground nearby. Fire it faster, and it lands farther away. Fire it fast enough, and the ground curves away beneath it as fast as it falls, so it falls all the way around the earth and never lands. That is an **orbit**. The Moon moves sideways at about 1 kilometer (0.6 mile) every second. Because of **inertia** it would fly off in a straight line, but gravity keeps bending its path around Earth.

The big idea. Newton figured out that gravity gets weaker with distance in a special way: twice as far away, the pull is one-fourth as strong; three times as far, one-ninth. The Moon is about 60 times as far from Earth's center as an apple in your yard, so Earth's pull on each kilogram of the Moon is 60 × 60 = 3,600 times weaker. An apple falls about 4.9 meters (16 feet) in its first second. The Moon, pulled 3,600 times more weakly, falls toward Earth only about 1.4 millimeters (about 1/20 inch) each second, and in one full minute it falls about as far as the apple falls in one second. When Newton checked numbers like these against the Moon's real path, they matched. The same force rules the apple and the Moon. He called it **universal gravitation**: every object pulls on every other, more strongly when it has more mass and more weakly when it is farther away.

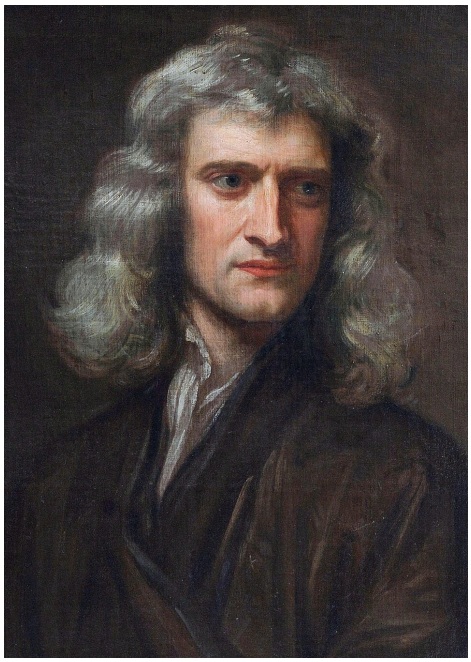
In the world today. In 1684 the astronomer Edmond Halley rode to Cambridge to ask Newton a question: if the Sun pulled on planets more weakly with distance in this way, what path would they follow? Newton answered at once: an ellipse. He had worked it out. Halley urged him to write it all down and paid to print the book himself. Newton's *Principia*, published in 1687, showed that gravity explains all three of Kepler's laws, the tides and the paths of comets. Today engineers use Newton's law of gravity to send spacecraft to the Moon and the planets, and to place weather and GPS satellites in orbit.

God's handiwork. Newton was a Christian who also wrote a great deal about the Bible. Near the end of the *Principia* he wrote that this most beautiful system of the Sun, planets and comets could only come from the counsel and dominion of an intelligent and powerful Being. One invisible law, given by God, reaches from a falling apple to the farthest planet.



Newton’s cannon. The faster the cannonball, the farther it goes before landing, until at last it falls all the way around the earth.

PICTURE STUDY



Portrait of Sir Isaac Newton, Sir Godfrey Kneller, 1689 · Oil on canvas · Private collection of the Earl of Portsmouth, England

Godfrey Kneller was the leading portrait painter in England, and he painted many kings, queens and great men. He painted Isaac Newton in 1689, two years after the *Principia* was published. Newton was forty-six years old and already famous among scholars.

Most gentlemen of that time wore big curled wigs in their portraits. Here Newton is shown with his own long hair, as if the painter wanted us to see the thinker himself and not his fine clothes.

Look closely

- Look at Newton’s eyes. Where is he looking? Does he seem to be thinking about something?
- Find the brightest parts of the painting. How does the painter use light and dark to draw your eye to the face?
- Look at his hair and clothes. Is he dressed in a showy or a plain way?
- Notice how plain the background is. What might the painter have added if he wanted to show Newton’s work?

Talk about it

1. This painting was made when Newton was forty-six. He thought about the apple and the Moon when he was about twenty-three. How long did it take him to publish his great book?
2. If you were painting Newton, what object would you put in the picture to tell people what he discovered?
3. Newton spent many quiet hours thinking. Why is quiet, careful thinking important for a scientist?

> **Safety first.** Throw balls only outdoors in an open space, away from windows, cars and people. Use a soft ball. Keep marbles away from babies and toddlers, who could choke on them.

EXPERIMENT: FALLING AROUND: NEWTON’S CANNON IN THE BACKYARD

Question: Does throwing a ball faster sideways change how far it travels before gravity brings it down? And what path does a rolling marble take when nothing pulls it into a curve?

Prediction: Write your guesses first. What we change: how hard you throw (soft, medium, hard), and later whether the marble has a wall to follow. What we keep the same: the ball, the starting height (your shoulder) and the direction (straight out, level). What we measure: how far the ball lands from your feet, in meters, and the path the marble takes. Record three throws at each speed.

You will need

- A soft ball, such as a tennis ball
- A measuring tape at least 10 meters (33 feet) long, or a long string marked every meter
- Small stones or chalk to mark landing spots
- A round cake pan, a sturdy paper plate with a raised rim, scissors (for an adult), a marble and a large sheet of paper

- Lab notebook and pencil

Steps

1. Part 1. Stand at a starting line outdoors. Hold the ball at shoulder height and throw it straight out, level with the ground, as softly as you can. A helper marks where it first lands.
2. Measure the distance from the starting line to the mark. Throw two more soft throws and record all three.
3. Repeat with three medium throws and three hard throws, always from shoulder height and always level.
4. Find the average for each speed: add the three distances and divide by 3.
5. Draw the three paths in your notebook, like Newton's cannon. Write: what happened to the distance as the throws got faster?
6. Part 2. Set the cake pan on a sheet of paper on a smooth floor. Roll the marble around the inside edge so it circles along the wall.
7. Now ask an adult to cut away about one-quarter of the rim of a paper plate with scissors. Set the plate on the paper, roll the marble around inside the rim, and watch which way it goes when it reaches the gap and the wall is no longer pushing it into a curve. Mark on the paper where it leaves.
8. Repeat five times. Sketch the path. Does it keep curving, or go off in a straight line? Write how this is like the Moon if Earth's gravity were suddenly switched off.

Tips

- In Part 1, the ball falls the same height every time, so it is in the air for about the same short time whether you throw softly or hard. The faster throw simply covers more ground in that time.
- In Part 2, the pan's wall plays the part of gravity, pulling the marble into a curve. Without it, inertia carries the marble straight ahead.
- If your throws are uneven, take more turns and keep the best three at each speed.

Check your work

- I changed only the speed of the throw and kept the height and ball the same.
- I measured and averaged my landing distances.
- I can explain, using my cannon drawing and my marble, why the Moon keeps going around Earth instead of falling down or flying away.

FIELD NOTEBOOK

1. Draw Newton under the apple tree at Woolsthorpe with the Moon rising in the sky behind him. Write his question underneath: Does the pull that brings down the apple reach the Moon?
2. Draw your own Newton's cannon diagram with a slow, a faster and an orbiting cannonball, and label each path.

3. Make a two-column chart called “Kepler and Newton.” Under Kepler, write what planets do. Under Newton, write why they do it.

From history. Edmond Halley used Newton’s laws to study comets. He noticed that bright comets seen in 1531, 1607 and 1682 followed nearly the same path, and he decided they were one comet traveling a long ellipse around the Sun. He predicted it would return around the end of 1758. Halley died in 1742 and did not live to see it, but on Christmas night, 1758, a German farmer and sky-watcher named Johann Palitzsch spotted the comet coming back. It has been called Halley’s Comet ever since.

WORKED EXAMPLES

Example 1. Gravity gets weaker with distance: at 2 times the distance it is 1/4 as strong, and at 3 times the distance it is 1/9 as strong. How strong is Earth’s pull at 10 times the distance? At 60 times the distance, where the Moon is?

(Use the map or drawing “The Moon is like the fastest cannonball: falling all the time, but never landing” shown earlier in this lesson.)

1. The rule: multiply the distance by itself, and the pull is 1 divided by that number. For 2 times as far: 2 × 2 = 4, so the pull is 1/4.
2. For 10 times as far: 10 × 10 = 100, so the pull is 1/100 as strong.
3. For 60 times as far: 60 × 60 = 3,600, so the pull is 1/3,600 as strong.

Answer: At 10 times the distance, the pull is 1/100 as strong. At the Moon’s distance, 60 times as far, it is 1/3,600 as strong.

Example 2. An apple dropped from rest falls about 4.9 meters (16 feet) in its first second. The Moon is 60 times farther from Earth’s center, so Earth’s pull on it is 3,600 times weaker. How far does the Moon fall toward Earth in one second? How far in one minute? (Falling distance grows with time × time: twice the time means 4 times the distance.)

1. In one second the Moon falls 3,600 times less than the apple: 4.9 m ÷ 3,600 = about 0.00136 m, which is about 1.4 mm (about 1/20 inch).
2. One minute is 60 seconds. Falling distance grows with time × time, so in 60 seconds the Moon falls 60 × 60 = 3,600 times as far as it does in 1 second.
3. 1.36 mm × 3,600 = about 4,900 mm, which is 4.9 meters.

Answer: About 1.4 mm in one second, and about 4.9 meters (16 feet) in one minute. The Moon falls in one minute about as far as an apple falls in one second, which is just what Newton’s idea predicts.

PRACTICE

1. EASY Why was Isaac Newton at home at Woolsthorpe Manor in 1665 and 1666 instead of at Cambridge?
2. EASY True or false: Newton said an apple hit him on the head. Explain.
3. EASY What does inertia make a moving object do if no force acts on it?
4. MEDIUM Copy and finish this table of how Earth’s pull changes with distance. Distance (times as far): 1, 2, 3, 4, 5. Strength of pull: 1, 1/4, 1/9, ?, ?
5. MEDIUM In Newton’s cannon, what happens to a cannonball fired (a) slowly, (b) faster, (c) fast enough?
6. MEDIUM Design an experiment to test whether swinging a ball on a string faster makes the pull on your hand stronger. Use a rubber band between your hand and the string. What will you change, keep the same and measure?
7. HARD A satellite orbits 2 times as far from Earth’s center as the ground is. Another orbits 20 times as far. How strong is Earth’s pull on each, compared with the pull at the ground?
8. CHALLENGE In three or four sentences, explain how Newton’s gravity and Kepler’s laws fit together.

COMMON MISTAKES

- Thinking there is no gravity in space. Earth’s gravity reaches the Moon and far beyond; astronauts float because they and their spacecraft are falling around Earth together.
- Thinking the Moon stays up because it is too far away for gravity to reach it. Gravity is what keeps the Moon from flying off in a straight line.
- Thinking only very big things like Earth have gravity. Every object with mass pulls on every other object; small objects simply pull too weakly for us to feel.

> **Make it a game · Gravity Says.** A parent calls out a distance, such as “three times as far!” and you must call back how strong gravity is there (“one-ninth!”) before the parent counts to five. Then the parent calls out a cannon speed, “slow,” “faster” or “fast enough,” and you act it out by walking a path that lands near, lands far or circles all the way around the room. Score a point for each right answer and play to ten.

> **Scripture.** “He stretcheth out the north over the empty place, and hangeth the earth upon nothing.” (Job 26:7, KJV)

The earth does not rest on pillars or on the back of a giant animal, as some ancient peoples imagined. It is held in its path around the Sun by the invisible pull God built into creation, the same pull Newton saw in a falling apple.

Practice answers

1. A plague closed the University of Cambridge, so he went home to his family’s farmhouse in Lincolnshire.

2. False. His friend William Stukeley wrote that Newton saw an apple fall while he sat thinking. The bump on the head was added later by storytellers.
3. Keep moving in a straight line at the same speed.
4. 4 times as far: $4 \times 4 = 16$, so 1/16. 5 times as far: $5 \times 5 = 25$, so 1/25.
5. (a) It curves down and lands near the mountain. (b) It lands farther around the earth. (c) The earth curves away beneath it as fast as it falls, so it goes all the way around in an orbit and never lands.
6. Change: how fast you swing the ball (slow, medium, fast, counted as turns in 10 seconds). Keep the same: the ball, the string length and the rubber band. Measure: how long the rubber band stretches at each speed, using a ruler or a helper. Prediction: the faster swing stretches the band more, showing a stronger pull is needed to keep the ball curving.
7. At 2 times: $2 \times 2 = 4$, so 1/4 as strong. At 20 times: $20 \times 20 = 400$, so 1/400 as strong.
8. Kepler described how the planets move: in ellipses with the Sun at one focus, faster when closer to the Sun, and slower and longer the farther out they are. Newton explained why: the Sun’s gravity pulls every planet, more weakly with distance, while inertia carries each planet sideways. When Halley asked what path such a pull would make, Newton showed it was an ellipse. Newton’s law of gravity explains all three of Kepler’s laws.

5.4 Gravity Experiments

OBJECTIVES

- Describe the falling-body experiments of Simon Stevin, Galileo and the Apollo 15 astronauts, and explain what they showed.
- Explain how air resistance makes some objects fall more slowly, and tell the difference between mass and weight.
- Plan and run a fair pendulum experiment, changing one variable at a time, and read the results from a table or bar graph.

Warm-up. Hold a book in one hand and a flat sheet of paper in the other, at the same height. Predict which will land first, then drop them together. Now crumple the paper into a tight ball and try again. Finally, lay a flat sheet of paper (smaller than the book) on top of the book and drop them together. What do you notice? What might be slowing the flat paper down?

Video. Coming soon. Apollo 15 hammer and feather drop on the Moon, Galileo's falling bodies and ramp experiments, pendulum experiments for kids: search NASA, Science Max, SciShow Kids, Homeschool Pop (Alternate), Moody Science classics and science-museum demonstration channels.

KEY TERMS

acceleration
Speeding up, slowing down or changing direction. A falling object accelerates: it goes faster every second.

air resistance
The push of air against a moving object. It slows light, spread-out objects like feathers and flat paper much more than heavy, compact ones.

mass
The amount of matter in an object. Your mass is the same on Earth and on the Moon.

weight
How hard gravity pulls on an object. Your weight on the Moon is about one-sixth of your weight on Earth.

pendulum
A weight hanging from a string or rod that swings back and forth under the pull of gravity.

fair test
An experiment in which you change only one thing (the variable), keep everything else the same, and measure the result.

CORE IDEAS

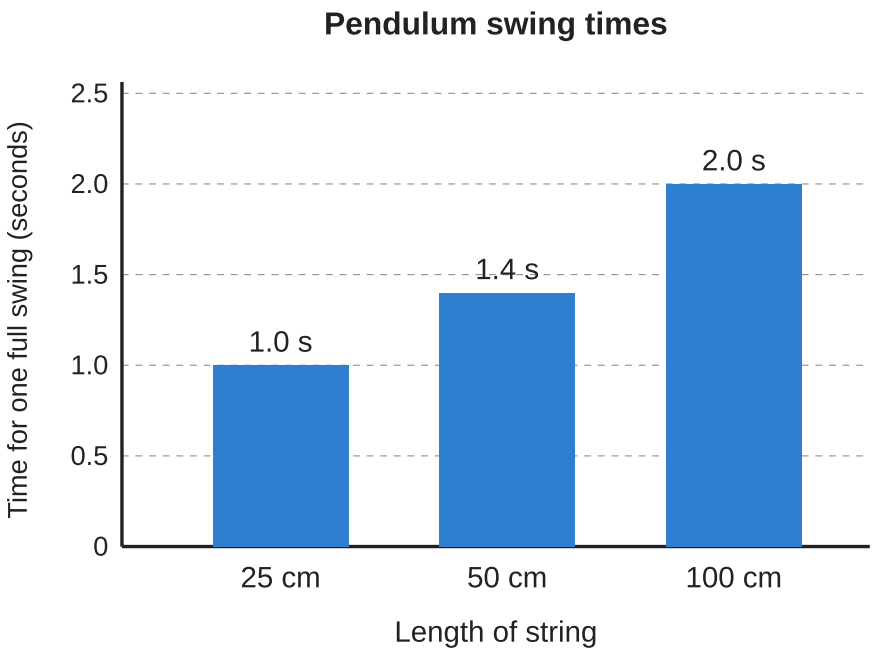
The story. On August 2, 1971, astronaut David Scott stood on the gray dust of the Moon during the Apollo 15 mission. A television camera was watching. In one hand he held a heavy geology hammer; in the other, a falcon feather. He held them out at the same height and let go. Down they drifted together and touched the ground at the same instant. Scott told the people watching on Earth that this proved Galileo had been right. Millions of people saw with their own eyes an experiment that had been argued about for nearly two thousand years.

How they figured it out. The ancient Greek thinker Aristotle taught that heavy things fall faster than light things, and for many centuries most scholars agreed. It seems sensible: a stone does fall faster than a leaf. But careful experimenters tested it. In 1586, in the Dutch city of Delft, the engineer Simon Stevin and a friend dropped two lead balls, one ten times heavier than the other, from about 9 meters (30 feet) up. They landed so close together that the two thuds sounded as one. In those same years Galileo Galilei, a professor in Italy, studied falling more carefully than anyone before him. Falling is very fast, so he slowed it down by rolling bronze balls down a long, smooth, grooved ramp, timing them with water flowing out of a tank. In his book of 1638 he reported a pattern: a ball rolls 1 unit in the first stretch of time, 4 units by the end of the second, 9 by the end of the third and 16 by the end of the fourth. Things that fall do not keep a steady speed; they **accelerate**, going faster and faster.

The big idea. Without air in the way, all objects fall with the same acceleration, no matter how heavy they are. On Earth, **air resistance** pushes against falling things. It barely slows a hammer or a crumpled ball of paper, but it greatly slows a feather or a flat sheet. On the Moon there is no air, so the feather fell like the hammer. The Moon's gravity is weaker than Earth's, about one-sixth as strong, so everything there falls more slowly and weighs less. Your **weight** would drop to one-sixth, but your **mass**, the amount of matter in you, would stay exactly the same. Galileo also studied the **pendulum**, and found something surprising: a pendulum's swing time depends on the length of its string, not on how heavy its weight is. Make the string 4 times as long, and each swing takes 2 times as long.

Try it and see. Good gravity experiments are **fair tests**. If you want to know whether a heavier pendulum swings faster, change only the weight. Keep the string length, the starting point and the way you time it the same. Because a single swing is too quick to time well with a stopwatch, time 10 swings and divide by 10. Then repeat each trial so that one slip of your thumb does not fool you. That is how Galileo worked, and how scientists still work today.

God's handiwork. Gravity never takes a day off. It worked the same for Stevin in Delft, for Galileo in Italy and for David Scott on the Moon. That steadiness is why experiments can be repeated and checked by anyone, anywhere. Scientists can trust that nature will behave tomorrow as it did today because the God who made it is faithful and upholds all things.



Pendulum swing times. Four times the length gives two times the swing time. The weight on the string does not matter.

PICTURE STUDY



Portrait of Galileo Galilei, Justus Sustermans, about 1636–1640 · Oil on canvas · National Maritime Museum, Greenwich, London

Justus Sustermans was a Flemish painter who worked for the grand dukes of Tuscany in Florence. He painted Galileo in about 1636, when Galileo was about seventy-two years old, living near Florence and finishing his last great book, *Two New Sciences*. That book, printed

in 1638, described his ramp experiments and his discoveries about falling bodies and pendulums.

By the time this portrait was made, Galileo's eyesight was failing, and within a few years he was blind. Yet he kept teaching and thinking, with younger students helping him write down his ideas.

Look closely

- Look at Galileo's face and beard. How old does he look? What feeling do you see in his eyes?
- Find the object in his hand. What is it, and why might he have wanted it in his portrait?
- Notice where the light falls. Which parts of the painting are brightest?
- Compare this portrait with the portrait of Newton from Lesson 5.3 and the tiny figure of Kepler at his desk in Lesson 5.1. What is the same? What is different?

Talk about it

1. Galileo did his most important falling experiments as a younger man but wrote them up when he was old. Why is it important for scientists to write down their experiments?
2. Galileo tested the old idea that heavy things fall faster. What old idea would you like to test?
3. Why do you think the painter showed Galileo with a telescope rather than a ramp or a pendulum?

> **Safety first.** Drop objects only from standing height on the floor; never climb on chairs, tables or ladders to drop things. Keep feet clear of heavy objects like books. Hang your pendulum from the edge of a sturdy table, not from a light fixture, and swing it where it cannot hit anyone.

EXPERIMENT: GALILEO'S PENDULUM LAB

Question: What changes how long a pendulum takes to swing: the length of the string or the weight hanging on it? Prediction: Write your guess for each before you begin.

Experiment 1 changes the length (25, 50 and 100 cm) and keeps the weight the same. Experiment 2 changes the weight (1 washer and 3 washers) and keeps the length the same. In both, keep the starting point (a small pull to the side, about 10 cm or 4 in) and the timing method the same. What we measure: the time for 10 full swings, in seconds.

You will need

- Strong thread or string, about 1.2 meters (4 feet)
- Three large metal washers or nuts of the same size
- A paper clip bent into a hook, tape and a sturdy table
- A stopwatch or a phone timer
- A meter stick or measuring tape, and a lab notebook

Steps

1. Make a table with columns: Length (cm), Number of washers, Time for 10 swings (s) for Trial 1, Trial 2 and Trial 3, Average, Time for 1 swing.
2. Tie the paper clip hook to one end of the string and hang one washer on it. Tape the other end to the edge of the table so that the distance from the table edge to the middle of the washer is 25 cm (10 in).
3. Pull the washer about 10 cm (4 in) to the side, keeping the string straight, and let go without pushing. A full swing is out and back to where it started.
4. Start the stopwatch as you let go and count 10 full swings. Stop the watch on the tenth. Record the time. Do two more trials.
5. Average the three trials, then divide by 10 to find the time for one swing.
6. Change the length to 50 cm (20 in) and then 100 cm (39 in), keeping one washer, and repeat. If your table is not high enough for 100 cm, tape the string to the top of a doorframe with an adult's help.
7. Experiment 2: set the length back to 50 cm and hang 3 washers instead of 1. Repeat the timing.
8. Make a bar graph of time for one swing against length. Write your conclusion: Which change mattered, length or weight?

Tips

- Measure the length to the middle of the washers, not just to the hook. When you add washers, the middle moves down a little; slide the tape to keep the length the same.
- Keep your swings small. Very wide swings take slightly longer and can spoil a fair test.
- Expect your times to be close to 1.0 second at 25 cm, 1.4 seconds at 50 cm and 2.0 seconds at 100 cm.

Check your work

- I changed only one thing in each experiment.
- I timed 10 swings, did three trials and found an average.
- I can explain from my data whether length or weight changes the swing time.

FIELD NOTEBOOK

1. Draw David Scott on the Moon dropping the hammer and the feather. Next to it, draw the same drop on Earth and show where air resistance acts.
2. Draw Galileo's ramp with a ball rolling down it. Mark the distances 1, 4, 9 and 16 at the end of each equal stretch of time.
3. Draw your pendulum setup and label the string length, the washer, the starting point and one full swing.

> **From history.** In 1798 the English scientist Henry Cavendish did a gravity experiment so delicate that he watched it through a telescope from outside the room, so that even the warmth of his body would not disturb it. He hung a rod with two small lead balls from a

thin wire and set two large lead balls nearby. The tiny pull of gravity between the balls twisted the wire ever so slightly. From that twist he worked out how strong gravity is and found that Earth as a whole is about five and a half times as dense as water. People called it “weighing the world.”

WORKED EXAMPLES

Example 1. On Galileo’s ramp, a ball rolls 10 cm (4 in) in the first second. Using his pattern of 1, 4, 9, 16, how far has it rolled in total after 2, 3 and 4 seconds? How far does it roll during each separate second?

1. Total distances follow 1, 4, 9, 16 times the first-second distance: 1 × 10 = 10 cm, 4 × 10 = 40 cm, 9 × 10 = 90 cm, 16 × 10 = 160 cm.
2. Distance during each separate second is the difference: 10 − 0 = 10 cm, 40 − 10 = 30 cm, 90 − 40 = 50 cm, 160 − 90 = 70 cm.
3. Notice the pattern 10, 30, 50, 70 grows by the odd numbers 1, 3, 5, 7. The ball covers more ground each second because it keeps speeding up.

Answer: Totals: 40 cm after 2 s, 90 cm after 3 s, 160 cm after 4 s. During each second: 10, 30, 50 and 70 cm.

Example 2. A bathroom scale on Earth reads 33 kg (72 lb) for a student. The Moon’s gravity is about one-sixth as strong as Earth’s. What would the same scale read on the Moon? What is the student’s mass on the Moon?

1. The scale measures how hard gravity pulls, which is weight. On the Moon, the pull is one-sixth as strong.
2. 33 ÷ 6 = 5.5, so the scale would read 5.5 kg. In pounds: 72 ÷ 6 = 12 lb.
3. Mass is the amount of matter. Going to the Moon does not remove any of the student, so the mass stays 33 kg.

Answer: The scale would read about 5.5 kg (12 lb) on the Moon, but the student’s mass would still be 33 kg.

PRACTICE

1. EASY When David Scott dropped a hammer and a feather on the Moon, which landed first? Why?
2. EASY Why does a flat sheet of paper fall more slowly than the same sheet crumpled into a ball?
3. EASY What is the difference between mass and weight?
4. MEDIUM Use the bar graph of pendulum swing times. (a) How long does one swing take with a 50 cm string? (b) What happens to the swing time when the string goes from 25

cm to 100 cm, four times as long? (c) Predict the swing time for a 400 cm string. *(Use the map or drawing "Pendulum swing times for three string lengths." shown earlier in this lesson.)*

5. MEDIUM A student wants to know whether a heavier pendulum swings faster. Design a fair test. What is the one thing to change? Name three things to keep the same. What should be measured?
6. MEDIUM A dog weighs 90 lb on Earth. About how much would it weigh on the Moon? Would its mass change?
7. HARD A student times 10 swings of a pendulum three times and gets 14.2 s, 13.8 s and 14.0 s. Find the average time for 10 swings and the time for one swing. Why is timing 10 swings better than timing just one?
8. CHALLENGE On Galileo's ramp, a ball rolls 5 cm in the first second. How far has it rolled in total after 3 seconds? How far does it roll during the third second alone?

COMMON MISTAKES

- Thinking heavier objects always fall faster. Without air resistance, heavy and light objects fall together; on Earth, shape and air make the difference.
- Thinking there is no gravity on the Moon. The Moon has gravity, about one-sixth as strong as Earth's; that is why the hammer and feather fell down at all.
- Thinking a heavier pendulum swings faster. The swing time depends on the length of the string, not the weight.

Make it a game · Drop Detective. A parent gathers pairs of safe objects: a sock and a shoe, a crumpled and a flat sheet of paper, a coin and a cotton ball, two balls of different weights. For each pair, you predict which will land first or whether they will tie, and say why (weight, shape or air resistance). Then drop them together from the same height while standing on the floor. Score one point for a correct prediction and a bonus point for a correct reason. The detective with the most points after eight pairs wins.

Scripture. "And he is before all things, and by him all things consist." (Colossians 1:17, KJV)

The word "consist" here means "hold together." Gravity is one of the ways God holds His world together, from the stones on the ground to the Moon in the sky, and its steady faithfulness is what makes our experiments work.

Practice answers

1. They landed together. The Moon has no air, so there was no air resistance to slow the feather.
2. The flat sheet spreads out and pushes against much more air, so air resistance slows it more. Its mass has not changed.
3. Mass is the amount of matter in an object and stays the same everywhere. Weight is how hard gravity pulls on it, so it changes from Earth to the Moon.
4. (a) About 1.4 seconds. (b) It doubles, from 1.0 second to 2.0 seconds. (c) 400 cm is 4 times 100 cm, so the time doubles again, to about 4.0 seconds.

5. Change: the weight (for example 1, 2 and 3 washers). Keep the same: the string length (measured to the middle of the weight), the starting point of the swing, the stopwatch and person timing, and the number of swings timed. Measure: the time for 10 swings, repeated three times and averaged.
6. 90 ÷ 6 = 15 lb on the Moon. Its mass would not change.
7. Average: (14.2 + 13.8 + 14.0) ÷ 3 = 42.0 ÷ 3 = 14.0 s. One swing: 14.0 ÷ 10 = 1.4 s. Your reaction time when starting and stopping the watch adds a small error. Spread over 10 swings, that error becomes 10 times smaller for each swing.
8. After 3 seconds: 9 × 5 = 45 cm. After 2 seconds it had rolled 4 × 5 = 20 cm, so during the third second it rolls 45 − 20 = 25 cm.

Unit 5 review

Answer each question. Show your work for calculations and use complete sentences for explanations. The review is worth 50 points.

1. (5 pts) Who was Tycho Brahe, and why were his measurements so important to Kepler?
2. (5 pts) State Kepler’s three laws of planetary motion in simple words.
3. (5 pts) Earth is closest to the Sun in early January and farthest in early July. When does Earth move fastest in its orbit? Does being closest cause summer in the United States? Explain.
4. (5 pts) You draw an ellipse with two pins 8 cm apart and 16 cm of string from pin to pencil to pin. How long is the ellipse, and what is its eccentricity?
5. (5 pts) Eccentricities: Earth 0.017, Mars 0.093, Halley’s Comet 0.97. Which path is most nearly a circle, and which is most stretched? Where is the Sun in each one?
6. (5 pts) Tell the true story of Newton and the apple. What question did it make him ask?
7. (5 pts) Use Newton’s cannon to explain why the Moon does not fall down to Earth or fly off into space.
8. (5 pts) The Moon is about 60 times as far from Earth’s center as an apple on the ground. How much weaker is Earth’s pull there? Show your work.
9. (5 pts) On the Moon, David Scott dropped a hammer and a feather together. What happened, and why? Why would the result be different on Earth?
10. (5 pts) A pendulum lab gave these results: 25 cm string, 1.0 s per swing; 50 cm, 1.4 s; 100 cm, 2.0 s. A second test at 50 cm with 3 washers instead of 1 gave 1.4 s. (a) What does length do to the swing time? (b) What does weight do? (c) In the second test, what was the variable and what was kept the same?

Unit project: my book of orbits and falling

Make a small illustrated book of at least six pages that tells the story of this unit. Include: a page on Kepler and Tycho with Kepler’s three laws; your ellipse lab drawings glued in with their pin distances and eccentricities; a scale drawing of Earth’s and Mars’s orbits with the Sun placed correctly; a Newton’s cannon diagram with a paragraph explaining why the Moon stays in orbit; and your pendulum lab table and bar graph with a written conclusion.

Finish with a closing page in your own words: what does it mean that Kepler was thinking God’s thoughts after Him, and how did your own measuring and testing in this unit show that God’s world follows steady laws?

- **Accuracy**: Kepler’s laws, the parts of an ellipse, Newton’s cannon and the facts about falling are stated and labeled correctly.
- **Records**: The ellipse and pendulum labs include complete tables, correct calculations, averages and a neatly labeled bar graph.
- **Explanation**: The written pages explain clearly why the Moon stays in orbit, why only one variable is changed in a fair test, and how Kepler and Newton fit together.

- **Care**: Drawings are neat and carefully measured, pages are in order, and the book is easy to read.

Answer key

1. Tycho Brahe was a Danish nobleman and astronomer who measured the positions of the planets very carefully for more than twenty years without a telescope. His measurements were so accurate (to about 2 minutes of arc) that Kepler could trust them when his circle model for Mars missed by 8 minutes of arc, which showed that circles were wrong.
2. (1) Every planet travels around the Sun in an ellipse, with the Sun at one focus. (2) A planet moves faster when it is closer to the Sun and slower when it is farther away. (3) Planets farther from the Sun take longer to go around it.
3. Earth moves fastest in early January, when it is closest. No: January is winter in the United States, so the seasons are not caused by distance from the Sun. They come from the tilt of Earth’s axis.
4. The ellipse is 16 cm long, the same as the string. Eccentricity = 8 ÷ 16 = 0.5.
5. Earth’s orbit is most nearly a circle; Halley’s Comet’s is the most stretched. In each, the Sun is at one focus of the ellipse, not at the center.
6. During the plague years of 1665 and 1666, Newton was home at Woolsthorpe Manor. He later told his friend William Stukeley that the idea of gravity came to him when he saw an apple fall while he sat thinking (it did not hit his head). It made him ask whether the same pull that brings down an apple reaches all the way to the Moon.
7. A slow cannonball curves down and lands; a faster one lands farther away; one fast enough falls all the way around the earth because the ground curves away as fast as it falls. The Moon moves sideways very fast. Inertia would carry it off in a straight line, but Earth’s gravity keeps pulling it into a curve, so it keeps falling around Earth in an orbit.
8. 60 × 60 = 3,600, so Earth’s pull is 3,600 times weaker (1/3,600 as strong) at the Moon’s distance.
9. They landed at the same time because the Moon has no air, and without air resistance all objects fall with the same acceleration. On Earth, air resistance would slow the light, spread-out feather much more than the hammer, so the hammer would land first.
10. (a) A longer string makes a longer swing time; four times the length gives twice the time. (b) Weight made no difference: 1 washer and 3 washers both took 1.4 s. (c) The variable was the weight (number of washers). The string length (50 cm), starting point and timing method were kept the same.

UNIT 6

Telescopes

For all the centuries before 1608, people saw the heavens only with their own eyes. Then a Dutch spectacle maker put two lenses in a tube, and the sky opened up. In this unit you will build your own two-lens telescope, just like the one Johannes Kepler described in 1611, measure the focal lengths of its lenses and test how much it magnifies. You will learn that a telescope's most important job is not to make things bigger but to **gather light**, so that we can see what God has made beyond the reach of our eyes.

Then you will follow telescopes as they grow: to the giant 40-inch refractor at Yerkes Observatory, to great mirrors on mountaintops in California, Hawaii and Chile, and finally above the air itself with the Hubble and Webb space telescopes. You will learn why observatories are built where they are, why they have turning domes and tracking mounts, and why Webb must be kept so cold. Last, you will become a real observer, like the comet hunter Charles Messier: letting your eyes adjust to the dark, using averted vision, measuring the sky with your hand and keeping a careful observing log.

Plan at least two clear evenings outdoors with an adult, one near first quarter Moon and one darker night without the Moon. Keep your lens measurements, experiment tables, sketches and observing log together in one notebook for your portfolio.

BEFORE YOU BEGIN

- Can multiply and divide whole numbers and simple decimals, and change millimeters to centimeters
- Can read a bar graph and a data table
- Knows that the earth turns once a day and that the Moon shows phases (Units 1 and 2)
- Can name the variable, the things kept the same and the measurement in a simple experiment

MASTERY CHECKLIST

- I can explain how a refractor's objective lens and eyepiece work, and calculate magnification by dividing their focal lengths.
- I can measure the focal length of a lens and build a simple two-lens telescope.
- I can explain why Hubble and Webb work above the air and compare their mirrors, the light they see and where they travel.
- I can explain what makes a good observatory site and why the largest telescopes use mirrors.
- I can use dark adaptation, averted vision, a red light and my hand ruler, and keep a complete observing log.
- I can name the one thing I changed, the things I kept the same and what I measured in my telescope experiments.

OPTIONAL BOOKS AND RESOURCES

- **NASA Webb Space Telescope site** (https://webb.nasa.gov/): Free. Webb's mirrors, sunshield and orbit explained, with pictures and the latest images (Lesson 6.2).
- **HubbleSite** (https://hubblesite.org/): Free. Hubble's story, its repair missions and a large gallery of images, including the Pillars of Creation (Lesson 6.2).
- **NASA Night Sky Network** (https://nightsky.jpl.nasa.gov/): Free. Find a local astronomy club and its public star parties, where volunteers let families look through large telescopes (Lessons 6.3 and 6.4).

6.1 Build a Simple Refractor ★

OBJECTIVES

- Explain how a refracting telescope uses an objective lens and an eyepiece to gather light and magnify, and tell how Hans Lipperhey and Johannes Kepler helped invent it.
- Measure the focal length of a lens and calculate magnification by dividing the focal length of the objective by the focal length of the eyepiece.
- Build a simple two-lens refractor and test how changing only the eyepiece changes the magnification.

Warm-up. Lay a sheet of newspaper on the table and put a piece of clear plastic wrap over it. Place one drop of water on the plastic and look at the letters under it. Now fill a round, clear drinking glass with water and look at a pencil through it. What happens to the size of the letters and the pencil? Last, hold a magnifying glass at arm's length and look through it at the far wall. Write down three things you notice. Curved, clear things bend light, and that is the whole secret of a telescope.

Video. Coming soon. How a refracting telescope works, convex lenses and focal length, build a cardboard telescope with two lenses, Hans Lipperhey and the first telescopes: search NASA Space Place, NASA JPL Education, Smithsonian National Air and Space Museum, Museo Galileo, SciShow Kids, Science Max and Homeschool Pop (Alternate).

KEY TERMS

refracting telescope (refractor)
A telescope that uses glass lenses to bend light and bring it to a focus.

convex lens
A lens that is thicker in the middle than at the edges. It bends light rays together toward a point.

focal length
The distance from a lens to the point where it brings light from a faraway object into focus.

objective lens
The big front lens of a telescope. It gathers light and makes a small, upside-down image inside the tube.

eyepiece
The small lens you put your eye to. It works like a magnifying glass to enlarge the image made by the objective.

magnification
How many times bigger a telescope makes something look. It equals the objective's focal length divided by the eyepiece's focal length.

CORE IDEAS

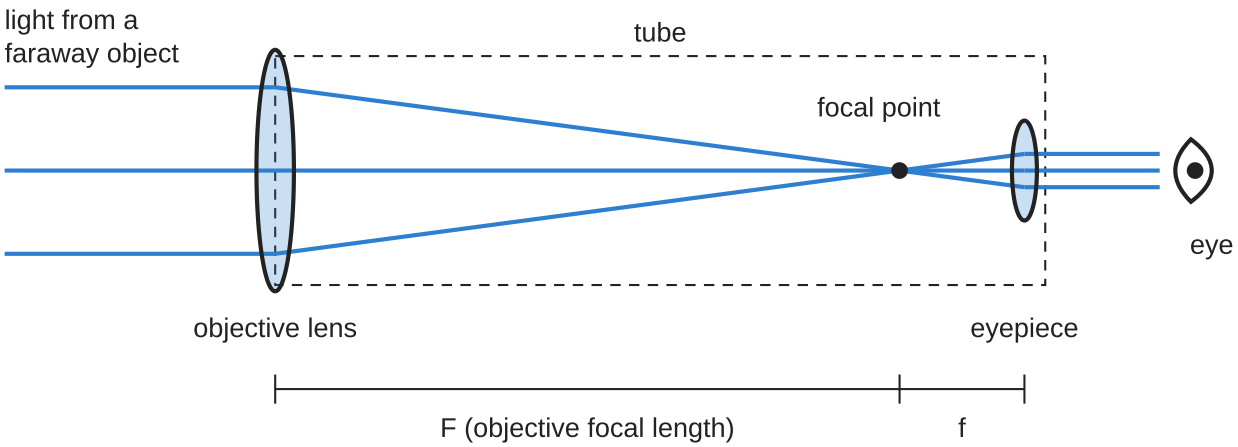
The story. In the fall of 1608, a spectacle maker named **Hans Lipperhey** traveled from the Dutch town of Middelburg to The Hague, where the leaders of the Netherlands met. He carried a tube with a glass lens at each end, and he asked for a patent, a promise that only he could make and sell it. Through his tube, a church tower far away looked about three times closer. The government did not give him the patent, because other spectacle makers soon said they had made such tubes too, and anyone who saw one could copy it. Within a year, spyglasses were being sold in Paris and Venice, and the Italian scientist Galileo had made his own and turned it to the sky.

How they figured it out. The spectacle makers had found the telescope by trying lenses together. The German astronomer **Johannes Kepler** wanted to know *why* it worked. Light travels in straight lines, but when it passes from air into glass at a slant, it bends. This bending is called **refraction**. A **convex lens**, thicker in the middle, bends all the rays from a faraway star or tower together toward one point. In 1611 Kepler published a book called *Dioptrice* that explained how lenses make images and described a new kind of telescope made with **two convex lenses**. It showed a wider view than the early spyglasses, though everything looked upside down. Others soon built it, and most refracting telescopes for looking at the sky still follow Kepler's plan.

The big idea. A refractor has two jobs. First, the large **objective lens** at the front gathers light, far more than the small opening of your eye, and bends it to make a tiny, upside-down image at its focal point inside the tube. Second, the small **eyepiece** near your eye acts like a magnifying glass and enlarges that tiny image. To find the magnification, divide the objective's focal length by the eyepiece's focal length. An objective of 500 millimeters (about 20 inches) with an eyepiece of 50 millimeters (about 2 inches) magnifies 500 ÷ 50 = 10 times. Swap in a 25-millimeter eyepiece and it magnifies 20 times. But the wider the objective, the more light it catches, and that is what lets you see faint stars. More magnification is not always better: the view gets dimmer, smaller and shakier.

Try it and see. You can measure a lens's focal length with a white card. Stand across the room from a bright window, hold the lens up, and move the card behind it until a sharp, tiny, upside-down picture of the window appears. The distance from lens to card is the focal length. A lens from drugstore reading glasses makes a fine objective, and its strength is printed on it in units called diopters: a +2.00 lens has a focal length of 1 ÷ 2 = 0.5 meter, or 500 millimeters. A small, strong magnifier makes a good eyepiece. Put them at the two ends of a paper tube, slide to focus, and you have built the same kind of instrument Kepler drew.

God's handiwork. Kepler also showed something wonderful about your own body. Inside each eye is a clear, living lens that bends light to make a small, upside-down picture on the back of the eye, and your brain turns it right side up. Unlike a glass lens, your eye's lens changes its shape to focus near and far. The Bible says, "It is the glory of God to conceal a thing: but the honour of kings is to search out a matter" (Proverbs 25:2). God hid moons, craters and countless stars beyond the reach of our eyes and then let people discover glass and lenses to search them out.



A simple refractor: the objective lens gathers light and brings it to a focus; the eyepiece magnifies that image. Magnification = F ÷ f.

PICTURE STUDY



Galileo Showing the Doge of Venice How to Use the Telescope, Giuseppe Bertini, 1858 · Fresco (paint on wet plaster) · Villa Andrea Ponti, Varese, Italy

In August 1609, Galileo carried one of his new telescopes to Venice and showed it to the Doge and the city's leaders. Merchants and sailors in a sea city understood at once how useful it would be to see ships far out at sea hours before they reached the harbor. The leaders rewarded Galileo with a better job and higher pay at the University of Padua.

About 250 years later, the Italian painter Giuseppe Bertini imagined this scene as a large fresco on the wall of a villa. A fresco is painted on fresh, wet plaster, so the colors soak into the wall and last for centuries.

Look closely

- Find the telescope. How long is it compared with the people? Who is holding or pointing it?
- Find the Doge, the ruler of Venice. How does the painter make him stand out from the crowd?
- Look at the faces of the men around Galileo. Who looks curious, who looks doubtful and who looks amazed?
- Look for the sky or the sea in the picture. Why might a sea city care so much about a spyglass?

Talk about it

1. Galileo's telescope worked much like the one you will build. What two lenses would be inside the tube?
2. Why do you think the leaders of Venice wanted the telescope for ships before anyone thought much about the stars?
3. If you could show a telescope to someone who had never seen one, what would you point it at first?

> **Safety first.** Never look at the Sun with your eyes, through your telescope or through any lens: it can blind you in an instant. A lens can focus sunlight into a spot hot enough to burn skin or start a fire, so measure focal lengths with a window or lamp, never the Sun, and store lenses out of sunlight. Ask an adult to help remove a lens from reading glasses and to handle any cutting with scissors or a craft knife.

EXPERIMENT: MY KEPLER TELESCOPE

You will measure two lenses, predict how much your telescope will magnify, build it from paper tubes, and then test your prediction. Then you will run a small experiment. **Question:** If I change only the eyepiece, does the magnification change the way the formula says? **What we change:** the eyepiece lens. **What we keep the same:** the objective lens, the target, its distance and the observer. **What we measure:** how many times bigger the target looks.

You will need

- An objective lens: one lens from drugstore reading glasses marked +1.50 to +2.50, or a wide magnifying glass with a long focal length (inexpensive science-fair telescope lens sets work best)
- One or two eyepiece lenses: small, strong magnifiers such as a jeweler's loupe or a small magnifying lens, with focal lengths from about 2 to 6 centimeters (about 1 to 2½ inches)
- A cardboard tube a little shorter than the objective's focal length (a wrapping-paper or mailing tube), plus poster board to roll a second tube that slides snugly inside it
- Masking tape, scissors, a meter stick or tape measure, a white index card

- Black paper or a black marker for the inside of the tubes
- A target sheet: a white paper with thick black stripes, each 2 centimeters (about ¾ inch) wide, with 2-centimeter white gaps

Steps

1. Write your prediction in your notebook: Which eyepiece will make things look bigger, the short one or the long one?
2. Measure each lens's focal length. Stand across the room from a bright window (never the Sun). Hold the lens up and move the white card behind it until a sharp, upside-down picture of the window appears. Measure from the lens to the card in millimeters. Do it three times and take the average.
3. Calculate your predicted magnification: objective focal length ÷ eyepiece focal length. Write it down.
4. Line the inside of the big tube and the poster-board tube with black paper or color them black, so stray light does not bounce around.
5. Tape the objective lens across one end of the big tube with its edges sealed. Tape the eyepiece across one end of the poster-board tube. Slide the eyepiece tube into the open end of the big tube.
6. Point the telescope at a faraway tree or rooftop. Slide the inner tube in and out until the view is sharp. Measure the distance between the two lenses. It should be close to the two focal lengths added together.
7. Tape the striped target to a wall or fence about 6 meters (20 feet) away. Rest the telescope on a chair back. Look at the target through the telescope with one eye and straight at it with your other eye. Count how many plain-eye stripes fit across one stripe seen in the telescope. That number is your measured magnification.
8. Change only the eyepiece (if you have a second one), refocus and measure again. Record a table with three columns: eyepiece focal length, predicted magnification, measured magnification.
9. On a clear evening, with an adult, look at the Moon. Sketch what you see.

Tips

- The view will be upside down. That is normal for a two-convex-lens telescope; astronomers don't mind, because there is no up or down in space.
- If you see colored fringes around bright objects, that is real too: different colors of light bend by slightly different amounts in glass.
- Hold the telescope against a door frame or chair back. At 10 times, every little shake is 10 times bigger too.
- Your measured magnification may differ from the prediction by one or two. Good scientists record what they measure, not what they hoped.

Check your work

- I can measure a lens's focal length with a card and a bright window.

- I can predict magnification with the formula and test it with a striped target.
- I can explain what the objective does and what the eyepiece does.

FIELD NOTEBOOK

1. Draw your telescope from the side. Label the objective lens, the eyepiece, the two tubes and the focal lengths you measured.
2. Copy the ray diagram of a refractor and trace the three light rays in colored pencil from the faraway object to your eye.
3. Sketch the Moon as seen through your telescope. Write the date, time, magnification and three things you could not see with your eyes alone.

From history. Two telescopes made by Galileo himself still survive in the Museo Galileo in Florence, Italy. Galileo learned to grind and polish his own lenses because the spectacle lenses he could buy were not good enough. His telescopes used a curved-in (concave) eyepiece, which showed things right side up, but they had a very narrow view: with his strongest telescope he could see only a small part of the Moon at a time. Kepler's two-convex-lens design gave astronomers a wider view.

WORKED EXAMPLES

Example 1. Abby uses a reading-glasses lens marked +2.00 as her objective and a small magnifier with a focal length of 50 millimeters as her eyepiece. What is the focal length of the objective, and how many times does her telescope magnify?

(Use the map or drawing "F = 500 mm, f = 50 mm, so magnification = 500 ÷ 50 = 10." shown earlier in this lesson.)

1. A lens marked in diopters has a focal length of 1 ÷ (diopters) meters: 1 ÷ 2.00 = 0.5 meter.
2. Change to millimeters: 0.5 meter × 1,000 = 500 millimeters.
3. Magnification = objective focal length ÷ eyepiece focal length = 500 mm ÷ 50 mm = 10.

Answer: The objective's focal length is 500 millimeters (about 20 inches), and the telescope magnifies 10 times (10×).

Example 2. For Abby’s telescope to focus on faraway things, the two lenses must be about one objective focal length plus one eyepiece focal length apart. How far apart should the lenses be, in centimeters and in inches? (1 inch = 2.54 centimeters)

1. Add the focal lengths: 500 mm + 50 mm = 550 mm.
2. Change to centimeters: 550 mm ÷ 10 = 55 cm.
3. Change to inches: 55 ÷ 2.54 ≈ 21.7 inches, about 22 inches.
4. So her tubes should slide so the lens-to-lens distance can be set a little shorter and a little longer than 55 cm, for example from 45 to 65 cm.

Answer: About 55 centimeters (about 22 inches) apart.

PRACTICE

1. EASY Which lens of a refractor gathers the light, and which lens do you put your eye to?
2. EASY Who asked the Dutch government for a patent on a telescope in 1608, and what did Kepler add in 1611?
3. MEDIUM A telescope has an objective with a focal length of 600 millimeters and an eyepiece with a focal length of 20 millimeters. What is its magnification?
4. MEDIUM You have an objective lens with a focal length of 900 millimeters. You want a magnification of 15 times. What eyepiece focal length do you need?
5. MEDIUM Read the table. Objective focal length: 500 mm.
   Eyepiece A: 50 mm, measured magnification 10
   Eyepiece B: 25 mm, measured magnification 19
   Eyepiece C: 10 mm, measured magnification 48
   (a) Which eyepiece magnifies most? (b) What magnification does the formula predict for B? (c) Which eyepiece will give the brightest, widest view?
6. HARD Two telescopes both magnify 20 times. One has an objective lens 5 centimeters wide, and the other has one 10 centimeters wide. Which will show more faint stars, and why?
7. HARD Design an experiment to test whether the width of the objective lens changes how many stars you can count in the Pleiades. Hint: you can cover the lens with a paper ring. Name what you change, what you keep the same and what you measure.
8. CHALLENGE Sam uses a reading-glasses lens marked +1.00 as the objective and a 40-millimeter eyepiece. Find (a) the objective’s focal length, (b) the magnification and (c) about how long the telescope must be, in centimeters and inches.

COMMON MISTAKES

- Thinking a telescope’s main job is to make things bigger. Its most important job is to gather more light than the eye can, so we can see faint things. The width of the objective matters most.

- Thinking more magnification is always better. Too much magnification makes the view dim, small and shaky, and it cannot show details the objective did not gather.
- Thinking an upside-down view means the telescope was built wrong. A telescope with two convex lenses always turns the image upside down; the objective makes it that way.

Make it a game · Lens Hunt. Set a timer for ten minutes and hunt the house for lenses: eyeglasses, a magnifier, a camera, binoculars, a door peephole, a water drop on a leaf, a glass marble. For each one, hold it close over a printed word. Score one point if it makes the word bigger (it is a convex lens) and one point if you can find its focal point on a card using a window. The player with the most points explains how a refractor works to the family.

Scripture. “It is the glory of God to conceal a thing: but the honour of kings is to search out a matter.” (Proverbs 25:2, KJV)

God filled the heavens with more than our eyes can see and gave people the curiosity and skill to search it out. Every telescope, from Lipperhey’s tube to the one you built, is a way of searching out the matter.

Practice answers

1. The objective lens (the big front lens) gathers the light. The eyepiece (the small lens) is the one you put your eye to.
2. Hans Lipperhey, a spectacle maker from Middelburg. In 1611 Kepler explained how lenses form images and described a telescope made with two convex lenses.
3. 600 ÷ 20 = 30 times (30×).
4. Eyepiece focal length = 900 ÷ 15 = 60 millimeters.
5. (a) Eyepiece C, the shortest focal length. (b) 500 ÷ 25 = 20, close to the measured 19. (c) Eyepiece A, the lowest magnification, gives the brightest and widest view.
6. The 10-centimeter telescope. Its lens is twice as wide, so its area is 2 × 2 = 4 times as large, and it gathers about 4 times as much light. Magnification is the same, but more light makes faint stars visible.
7. Change: the width of the opening, by covering the same objective with paper masks that have holes of different sizes (for example full lens, half width, quarter width). Keep the same: the lens, the eyepiece and magnification, the star cluster, the night and time, the observer and how long you look. Measure: the number of stars counted in the Pleiades for each opening. The full lens with no mask is the comparison (control).
8. (a) 1 ÷ 1.00 = 1 meter = 1,000 mm. (b) 1,000 ÷ 40 = 25 times. (c) 1,000 + 40 = 1,040 mm = 104 cm, about 41 inches long.

6.2 Hubble and Webb

OBJECTIVES

- Explain why astronomers put telescopes above the air, and tell how astronauts repaired the Hubble Space Telescope in 1993.
- Compare Hubble and Webb by mirror size, the kind of light each one sees and where each one travels, using a data table.
- Test with a pan of water how moving air blurs starlight, changing one variable and keeping the others the same.

Warm-up. Point a TV remote control at the camera of a phone or tablet and look at the screen while you press a button. On many devices (try the front, selfie camera if the back one shows nothing) you will see a flickering light that your eyes cannot see when you look straight at the remote. That light is **infrared**. Write down: What might a telescope see if it could see light that our eyes cannot?

Video. Coming soon. Hubble Space Telescope launch and the 1993 repair mission, James Webb Space Telescope unfolding its mirror and sunshield, infrared light explained, why stars twinkle: search NASA, NASA Goddard, NASA Webb, HubbleSite, ESA, NASA Space Place, SciShow Kids and Science Max.

KEY TERMS

space telescope
A telescope that works above the earth’s air, where the air cannot blur or block the light.

reflecting telescope (reflector)
A telescope that uses a curved mirror instead of a front lens to gather light and bring it to a focus. Hubble and Webb are reflectors.

infrared light
Light with longer waves than red light. Our eyes cannot see it, but we feel much of it as warmth. It can pass through clouds of dust.

orbit
The curved path one object follows around another, held by gravity.

twinkling
The quick shimmering of starlight caused by moving pockets of warmer and cooler air bending the light.

CORE IDEAS

The story. On April 24, 1990, the space shuttle *Discovery* lifted off from Kennedy Space Center in Florida carrying a telescope about the size of a school bus. The next day the astronauts lifted the **Hubble Space Telescope** out of the cargo bay with the shuttle’s robot

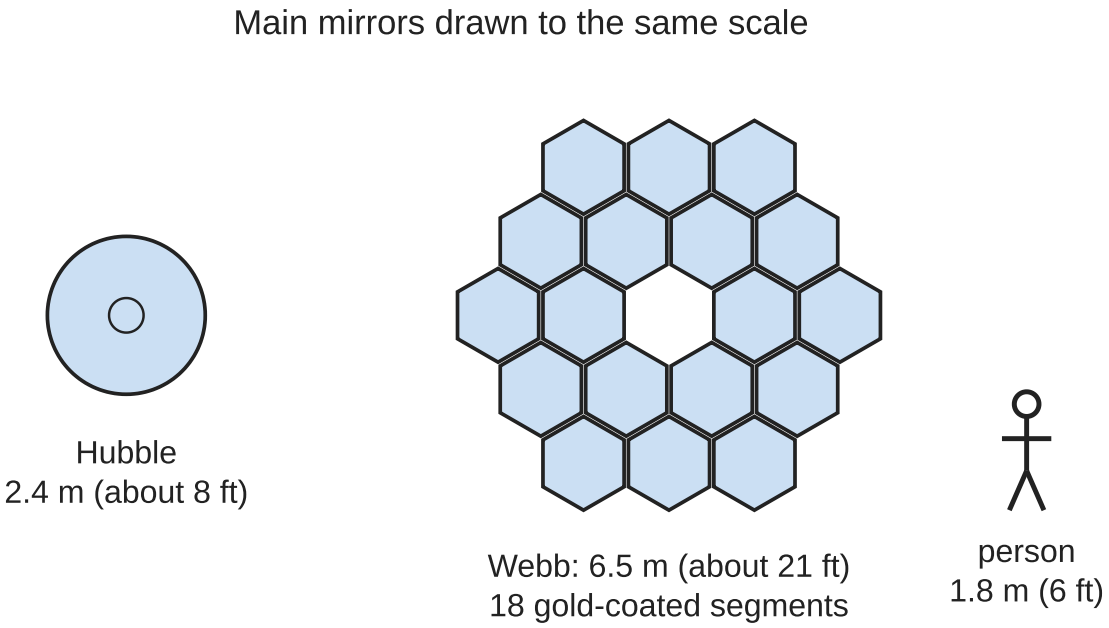
arm and set it free. Its main mirror was 2.4 meters (about 8 feet) across. But when the first pictures came down, they were blurry. Engineers found that the mirror had been ground to slightly the wrong shape near its edge, off by far less than the thickness of a human hair. In December 1993 the shuttle *Endeavour* caught up with Hubble. In five spacewalks, astronauts fitted it with small correcting mirrors that worked like a pair of eyeglasses and put in a new camera with the correction built in. The next pictures were sharp, and Hubble went on working for decades.

How they figured it out. Why go to all that trouble? Look at a star near the horizon on a cool night and it twinkles. Our **air** is always stirring, with pockets of warm and cool air that bend starlight one way and then another. Twinkling is pretty, but it smears the fine details astronomers want. Air also blocks some kinds of light completely. Hubble circles the earth about 540 kilometers (about 340 miles) up, above nearly all the air, once every 95 minutes. Because it is a **reflector**, with a curved mirror instead of a front lens, it can be large and light. Astronauts visited it five times to repair it and add new instruments.

The big idea. On December 25, 2021, an Ariane 5 rocket lifted off from Kourou, French Guiana, in South America, carrying the **James Webb Space Telescope**, named for James E. Webb, who led NASA during the years of the Apollo Moon program. Webb's gold-coated mirror is 6.5 meters (about 21 feet) across, too big to fit in any rocket, so it is made of 18 six-sided segments that were folded up for launch and unfolded in space like a flower. Webb sees mostly **infrared light**, which passes through clouds of dust that hide things from ordinary cameras. Because warm things glow in infrared, Webb must be very cold, colder than −220°C (−370°F). A five-layer sunshield about the size of a tennis court shades it from the Sun. Webb travels around the Sun about 1.5 million kilometers (about 1 million miles) from the earth, roughly four times as far away as the Moon, too far for astronauts to visit. NASA released its first full-color pictures in July 2022.

In the world today. Webb did not replace Hubble; the two work as partners. Hubble sees mostly visible light, the colors our eyes see, plus some ultraviolet and a little infrared. Webb sees deeper into the infrared. When both look at the same place, the pictures show different things. In 1995 Hubble photographed tall, dark clouds of gas and dust in the Eagle Nebula, which became known as the "Pillars of Creation." In 2022 Webb photographed the same pillars and showed many stars that the dust had hidden from Hubble. Thousands of scientists in many countries now study these pictures, and anyone can see them for free on NASA's websites.

God's handiwork. For thousands of years people saw only what the naked eye could catch through the stirring air. Now a mirror floating far beyond the Moon gathers light our eyes were never made to see, and the pictures are full of order and beauty: spirals, clusters, glowing clouds and countless galaxies. Isaiah wrote, "Lift up your eyes on high, and behold who hath created these things" (Isaiah 40:26). Every new telescope has shown more of the heavens, and every one has shown that the Maker is greater than we thought.



Hubble's and Webb's main mirrors drawn to the same scale, with a person for comparison.

⏳ Thinking About Time

What the sign says. What the sign says: NASA and many textbooks say Webb can see some of the first galaxies, so far away that their light has traveled for billions of years, showing the universe as it was not long after it began.

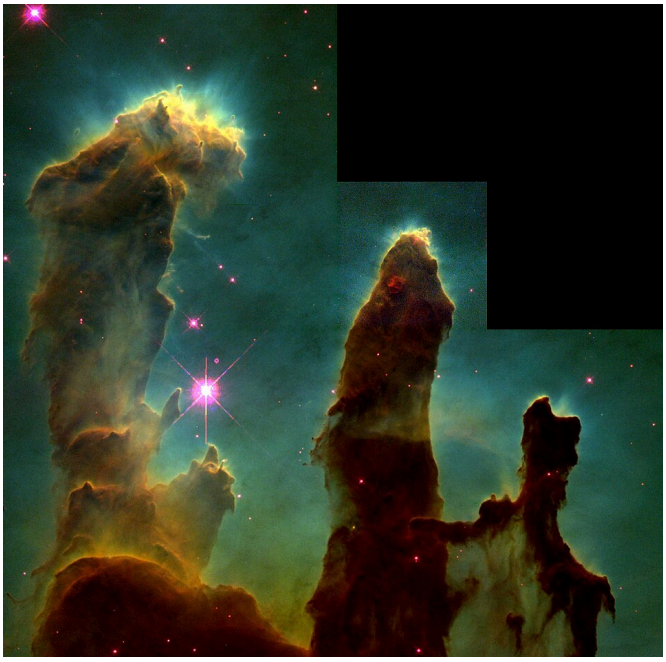
What we observe. What we observe: Webb's cameras record very faint, very red infrared light from small, distant galaxies. These distances are not measured with a ruler; they are worked out from how much the light has been stretched toward the red end of the rainbow, using assumptions about the history of the universe. Webb has also found far-off galaxies that look bigger and more developed than many astronomers expected, which has led to lively debate.

How Christians read it. How Christians read it: Christians who believe in a recent creation enjoy Webb's pictures as true views of what God made. They answer the distant-starlight question in the ways you met in Lesson 4.4, such as a finished creation and clocks running at different rates as God stretched out the heavens, and they point out that the ages given for these galaxies depend on starting assumptions, not on a clock anyone can read.

Try it. Look at a Webb deep-field picture online and count the galaxies in one small square of it. Then remember that each tiny smudge holds a great many stars, and God knows every one.

Isaiah 40:22

PICTURE STUDY



Pillars of Creation (Eagle Nebula), Hubble Space Telescope, NASA (image made by astronomers Jeff Hester and Paul Scowen), 1995 · Digital photograph from Hubble's Wide Field and Planetary Camera 2; colors stand for different kinds of light · NASA (public domain); copies on Wikimedia Commons

On April 1, 1995, Hubble's main camera took a set of pictures of a small part of the Eagle Nebula, a great cloud of gas and dust in the constellation Serpens, the Serpent. Astronomers put the pictures together and gave each kind of light a color. The result became one of the most famous space pictures ever made, and people began calling it the "Pillars of Creation."

The colors are real information, but they are chosen by the scientists: each color shows light from a different kind of gas. In 2022, the Webb telescope photographed the same pillars in infrared light. Compare the two pictures side by side if you can.

Look closely

- Count the pillars. Which one is tallest? What do their shapes remind you of?
- Look at the edges and tops of the pillars. Where is the brightest light, and where is it darkest?
- Find the small bumps and "fingers" at the tops of the pillars.
- Look at the background. How many separate stars can you find?

Talk about it

1. Why do you think the pillars look dark in the middle and bright at the edges?
2. If you compare Hubble's picture with Webb's, why can Webb show stars that Hubble's picture hides?
3. Why do you think this picture became so famous?

> **Safety first.** Use a sturdy glass or clear plastic baking dish on a table, not on the floor, and wipe up spilled water right away so no one slips. Do not point a remote or any light into anyone’s eyes.

EXPERIMENT: TWINKLE IN A PAN

Hubble flies above the air because moving air blurs starlight. You can see the same thing with water. **Question:** Does moving water make small letters harder to read than still water? **Prediction:** write yours. **What we change:** whether the water is still or stirred. **What we keep the same:** the chart, the water depth, the distance from your eye, the light and the reader. **What we measure:** the smallest line of letters you can read.

You will need

- A clear glass or plastic baking dish
- Water, about 5 centimeters (2 inches) deep
- A homemade letter chart: six lines of capital letters, from very large at the top to very small at the bottom, covered in clear tape or a plastic sleeve
- A spoon, a ruler or tape measure, a lamp
- Optional: poster board, scissors, a ruler and gold paper or a yellow crayon to make a folding model of Webb’s mirror

Steps

1. Number the lines of your chart 1 (biggest) to 6 (smallest). Lay the chart flat on the table and set the empty dish on top of it.
2. Pour in water to a depth of 5 centimeters (2 inches). Measure it with the ruler. Wait until the water is perfectly still.
3. Put your eye 50 centimeters (about 20 inches) above the dish. Have a helper measure. Write down the smallest line you can read. This is your control.
4. Have your helper stir the water gently in slow circles with the spoon, always at the same speed, then take the spoon out. Read the chart from the same height while the water still moves. Record the smallest line.
5. Repeat the still and stirred tests three times each and record all the numbers in a table.
6. Write a conclusion: Did stirring change how well you could read? How is the stirred water like the air above a telescope on the ground?
7. Optional: draw 18 hexagons about 4 centimeters (1½ inches) across on poster board, color them gold, and tape them in Webb’s pattern (a ring of 6 around an empty center, then a ring of 12). Cut the outer columns so they fold back and then swing open, just as Webb unfolded in space.

Tips

- Keep the lamp in the same place for every test. Changing the light would add a second variable.

- Read quickly but honestly. If you can read only some letters on a line, count the line above.
- On a clear night, compare a star low in the sky with one high overhead. Light from a low star passes through much more air, so it usually twinkles more.

Check your work

- I can explain why moving air blurs starlight.
- I can name the one thing I changed and three things I kept the same.
- I can explain why Hubble and Webb work above the air.

FIELD NOTEBOOK

1. Draw Hubble in orbit above the earth and Webb far away beyond the Moon. Label the distance of each and the size of each mirror.
2. Make a two-column chart, “Hubble” and “Webb,” and fill in launch year, rocket or shuttle, mirror size, main kind of light and where it travels.
3. Draw the “Pillars of Creation” with colored pencils and write one question you would ask an astronomer about them.

> **From history.** In 1946, more than ten years before the first satellite, the American astronomer Lyman Spitzer wrote a report explaining the advantages of an observatory above the earth’s air. People thought the idea was a dream, but Spitzer spent much of his life working for it, and he lived to see Hubble launched in 1990. The telescope was named for Edwin Hubble, an astronomer at Mount Wilson Observatory in California, who showed in the 1920s that some of the faint, fuzzy spirals in the sky are great star systems far beyond our own, which we now call galaxies.

WORKED EXAMPLES

Example 1. NASA gives the light-collecting area of Webb’s mirror as about 25 square meters and Hubble’s as about 4 square meters. About how many times as much light does Webb gather?

(Use the map or drawing “Webb’s mirror is about 2.7 times as wide as Hubble’s, and its collecting area is” shown earlier in this lesson.)

1. Light gathered depends on the area of the mirror, not just its width.
2. Divide the areas: 25 ÷ 4 = 6.25.
3. Round to a sensible number: about 6.

Answer: Webb gathers about 6 times as much light as Hubble.

Example 2. Hubble goes once around the earth every 95 minutes. About how many times does it go around in one day?

1. One day has 24 hours × 60 minutes = 1,440 minutes.
2. Divide by the time for one orbit: 1,440 ÷ 95 ≈ 15.2.
3. The extra 0.2 is only part of a trip, so in one day Hubble makes 15 full orbits and starts a 16th.

Answer: About 15 orbits a day, which means Hubble sees about 15 sunrises and 15 sunsets every day.

PRACTICE

1. EASY Give two reasons astronomers put telescopes in space.
2. EASY Which telescope was launched by the space shuttle *Discovery* in 1990, and which was launched on an Ariane 5 rocket on December 25, 2021?
3. MEDIUM Webb is about 1,500,000 kilometers from the earth. The Moon is about 384,000 kilometers away. About how many times farther away is Webb than the Moon?
4. MEDIUM Webb's mirror is 6.5 meters wide and Hubble's is 2.4 meters wide. How many times as wide is Webb's mirror? Round to one decimal place.
5. MEDIUM Use the table.
   Telescope | Mirror width | Main kind of light | Where it travels
   Hubble | 2.4 m | visible (some ultraviolet and infrared) | around the earth, about 540 km up
   Webb | 6.5 m | infrared | around the Sun, about 1.5 million km from the earth
   (a) Which telescope could astronauts reach to repair? (b) Which would be better for looking through a dusty cloud? (c) Which has the larger mirror?
6. HARD Explain why Webb needs a sunshield and must be kept so cold.
7. HARD Design an experiment with the "Twinkle in a Pan" setup to find out whether the depth of stirred water changes how blurry the letters look. Name what you change, what you keep the same and what you measure.
8. CHALLENGE Hubble travels at about 27,000 kilometers per hour (about 17,000 miles per hour). About how far does it travel in one 95-minute orbit?

COMMON MISTAKES

- Thinking Hubble is far out among the planets. It circles only about 540 kilometers (340 miles) above the ground, less than the driving distance from Washington, D.C., to Boston.
- Thinking space telescopes see better because they are closer to the stars. A few hundred kilometers makes no difference to the distance of a star; the gain comes from being above the air.

- Thinking Webb replaced Hubble. They work as partners: Hubble sees mostly visible light and Webb sees infrared, so each shows things the other cannot.

Make it a game · Hubble or Webb?. A parent reads clues one at a time: “launched by a space shuttle,” “gold mirror,” “visited by astronauts,” “sees mostly infrared,” “orbits the earth,” “sunshield the size of a tennis court,” “launched on Christmas Day,” “took the first Pillars of Creation picture.” The player shouts “Hubble!” or “Webb!” Each right answer earns a point; a wrong answer passes the clue to the next player. Add your own clues and play until someone reaches ten points.

Scripture. “Lift up your eyes on high, and behold who hath created these things, that bringeth out their host by number: he calleth them all by names by the greatness of his might, for that he is strong in power; not one faileth.” (Isaiah 40:26, KJV)

Hubble and Webb let us lift up our eyes higher than anyone before us. They find more stars and galaxies than people can count, yet God knows each one by name.

Practice answers

1. (1) Above the air, starlight is not blurred by moving pockets of warm and cool air, so pictures are sharper. (2) The air blocks some kinds of light, such as much ultraviolet and infrared, which a space telescope can see.
2. Hubble was launched by *Discovery* in 1990. Webb was launched on an Ariane 5 in 2021.
3. 1,500,000 ÷ 384,000 ≈ 3.9, so about 4 times as far.
4. 6.5 ÷ 2.4 ≈ 2.7 times as wide.
5. (a) Hubble, because it orbits close to the earth. (b) Webb, because infrared light passes through dust. (c) Webb.
6. Warm things give off infrared light. If Webb’s mirror and cameras were warm, their own glow would drown out the faint infrared light from distant objects. The five-layer sunshield blocks heat and light from the Sun (and the earth and Moon), keeping Webb colder than −220°C (−370°F).
7. Change: the depth of water, for example 2, 5 and 10 centimeters. Keep the same: the chart, the stirring speed and number of circles, the time you wait before reading, the eye height above the table, the light and the reader. Measure: the smallest line read for each depth, repeated three times. Compare with a still-water reading at each depth as the control. (This is like starlight passing through more air near the horizon.)
8. 95 minutes is 95 ÷ 60 ≈ 1.58 hours. 27,000 × 95 ÷ 60 = 42,750 kilometers, about 43,000 kilometers (about 26,600 miles) per orbit.

6.3 Observatories

OBJECTIVES

- Tell the story of the Yerkes Observatory and explain why the largest telescopes since then have used mirrors instead of lenses.
- Explain what makes a good observatory site (dark, dry, high and steady air) and read a bar graph of observatory heights.
- Explain why a telescope needs a turning mount and a dome with a slit, and measure how quickly the earth's turning carries a star or the Moon out of a telescope's view.

Warm-up. Turn a large mixing bowl upside down on the table. It is your observatory roof. Push a pencil "telescope" under its rim and try to point it at the ceiling light. What is in the way? Now imagine you are building a house just for a telescope. Write three answers: Where would you build it (city, valley or mountain)? What would its roof have to do? What would hold the telescope steady?

Video. Coming soon. Yerkes Observatory 40-inch refractor and rising floor, how an observatory dome opens and turns, Mauna Kea and the Keck telescopes, Mount Wilson and Palomar history, light pollution and dark-sky places: search NASA, NOIRLab, Keck Observatory, Smithsonian, the Yerkes Observatory, Mount Wilson Observatory, Science Max and SciShow Kids.

KEY TERMS

observatory
A building or group of buildings made for watching and measuring the sky, usually with large telescopes.

aperture
The width of a telescope's main lens or mirror. A bigger aperture gathers more light.

dome
The round, turning roof of an observatory. A slit opens so the telescope can look out, and the dome turns to keep the slit in front of it.

tracking mount
The stand that holds a telescope and turns it slowly to follow the stars as the earth spins.

light pollution
Unwanted light from streetlights, buildings and signs that brightens the night sky and hides faint stars.

CORE IDEAS

The story. In October 1897, scientists and guests gathered on a hill beside Geneva Lake in Williams Bay, Wisconsin, to dedicate the new **Yerkes Observatory**. A young astronomer

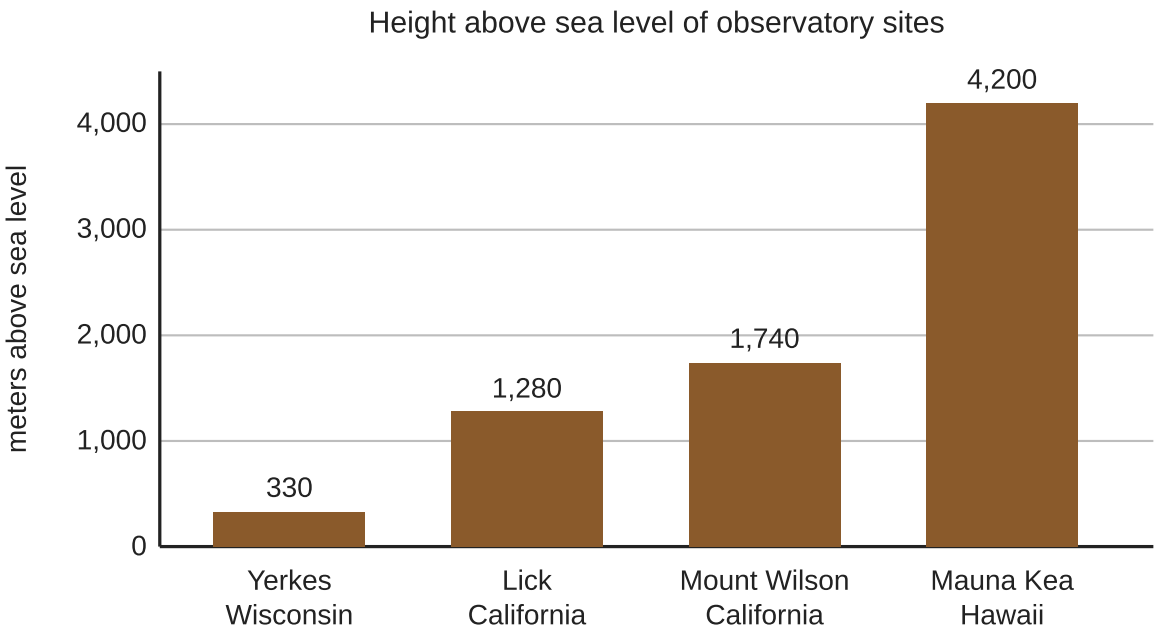
named **George Ellery Hale** had persuaded the Chicago businessman Charles Yerkes to pay for it. Under its great dome stood a telescope with a lens 40 inches (102 centimeters) across, ground and polished by the famous lens makers Alvan Clark and Sons of Massachusetts. Its tube was about 19 meters (63 feet) long. To reach the eyepiece, the astronomer stood on a huge round floor that rose and sank like an elevator. It is still the largest refracting telescope ever used for astronomy.

How they figured it out. Why has no one built a bigger refractor? A lens can be held only by its rim, because light must pass through the middle. A very large lens sags under its own weight and bends out of shape. Thick glass also soaks up some light and spreads colors apart. A **mirror** has none of these troubles: light bounces off its front, so it can be supported all across its back. Hale knew this, and he went on to build mirror telescopes on Mount Wilson in California, one 60 inches (1.5 meters) wide in 1908 and one 100 inches (2.5 meters) wide in 1917. He also planned a 200-inch (5-meter) telescope on Palomar Mountain, finished in 1948, ten years after he died. Today the two Keck telescopes in Hawaii each have a mirror 10 meters (33 feet) across, made of 36 six-sided segments, the same idea later used for Webb.

The big idea. Astronomers choose an observatory site with great care. The best sites are **dark**, far from city lights; **dry and clear**, with many cloudless nights; **high**, above the thickest, dampest air; and **steady**, where the air flows smoothly and does not shimmer. That is why so many observatories sit on mountains: Mauna Kea in Hawaii, about 4,200 meters (13,800 feet) high, and the very dry mountains of the Atacama Desert in Chile. Inside, the telescope sits on a **tracking mount**. The earth turns once a day, so the stars seem to move 15 degrees every hour, and the mount turns the telescope slowly to keep a star centered. The **dome** opens a slit at dusk, so the telescope can cool to the night air, and turns along with the telescope all night. Today most big telescopes feed cameras and computers rather than an eye at the eyepiece.

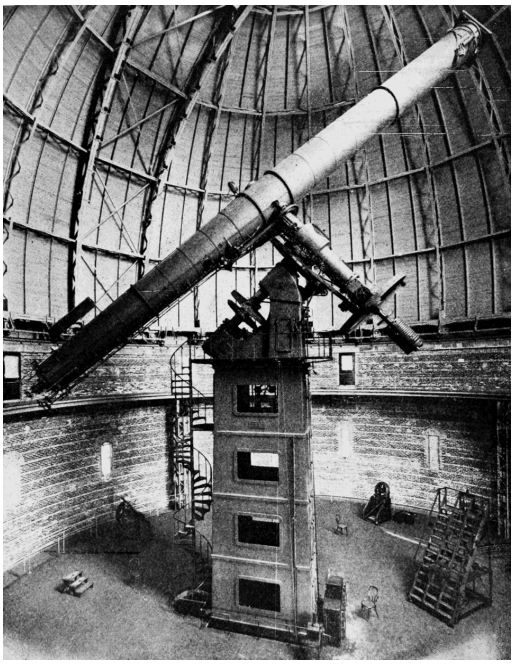
Try it and see. You can feel the earth turning with the telescope you built in Lesson 6.1. Rest it firmly on a chair back, center the Moon or a bright star, and do not touch it. Time how long it takes to drift out of view. Then try an empty paper-towel tube. The more a telescope magnifies, the smaller its view and the faster the sky slides out of it. That is the problem a tracking mount solves.

God’s handiwork. Night after night, in observatories around the world, astronomers measure the same stars rising, crossing and setting with clockwork faithfulness. “Day unto day uttereth speech, and night unto night sheweth knowledge” (Psalm 19:2). Many towns now protect their dark skies by shading streetlights so the light shines down instead of up. In 2001 Flagstaff, Arizona, home of Lowell Observatory, became the world’s first International Dark Sky City. Caring for the night sky is part of the dominion God gave people, to keep His works so that others can enjoy them too.



Heights above sea level of four famous observatory sites (rounded).

PICTURE STUDY



The Forty-Inch Telescope of the Yerkes Observatory, Unknown photographer; published in *Popular Science Monthly,* about 1901 · Black-and-white photograph (magazine illustration) · Published in *Popular Science Monthly,* volume 60 (1901–1902); copies in libraries

A few years after the Yerkes Observatory opened in 1897, a science magazine printed this photograph to show its readers the largest refracting telescope in the world. The long tube rises from a tall iron pier toward the opening in the dome, and the whole round room was built around it, with a floor that could rise and sink to carry the astronomer to the eyepiece.

Look at the picture the way an engineer would. Everything in it, from the heavy pier to the rising floor, was built to hold a 102-centimeter (40-inch) lens perfectly steady and point it exactly where the astronomer wanted.

Look closely

- Find the end of the tube where the big lens is and the end where the eyepiece is. Which end would the astronomer stand near?
- Look for anything that shows how big the telescope is, such as a person, a railing, a ladder or the eyepiece end, which stands about as high as a person's head when the floor is raised.
- Find the pier that holds the telescope up. Why must it be so heavy and strong?
- Look for the curved wall of the dome. Where would the slit open?

Talk about it

1. Why do you think the floor was built to rise and sink instead of using a ladder?
2. Why was this the last giant refractor rather than the first of many?
3. If you could spend one night at this telescope, what would you want to look at?

> **Safety first.** Observe only at night with an adult, and never point a telescope or tube toward the Sun, even near sunset. Bring a red flashlight, watch your footing in the dark, and stay away from roads.

EXPERIMENT: DRIFT TIMER: WHY TELESCOPES NEED A TURNING MOUNT

The earth's turning makes the sky slide past a telescope that is held still. You will measure how fast. **Question:** Does a telescope that magnifies more lose the Moon (or a star) faster? **Prediction:** write yours. **What we change:** the viewing tube (an empty paper-towel tube, then your telescope from Lesson 6.1). **What we keep the same:** the object, the night, the way the tube rests and starting with the object centered. **What we measure:** the time until the object leaves the view.

You will need

- Your telescope from Lesson 6.1
- An empty paper-towel tube
- A sturdy chair, fence rail or porch railing, plus masking tape or a folded towel to wedge the tubes steady
- A stopwatch or phone timer
- A notebook, pencil and red flashlight (cover a flashlight with red cellophane or red paper)
- Optional: an oatmeal canister, scissors and a paper plate to make a model observatory with a turning dome

Steps

1. Choose a night when the Moon or a bright star or planet is well above the trees. Go out with an adult and let your eyes adjust for a few minutes.
2. Rest the paper-towel tube on the chair back and wedge it with the towel or tape so it cannot move. Aim it so the object sits in the center of the circle you see.
3. Start the timer and take your hands away. Peek through the tube without bumping it. Stop the timer when the object has completely left the view. Record the time.
4. Repeat with your telescope: center the same object, fix the telescope in place, start the timer and stop it when the object leaves the view.
5. Do each test two more times and find the average time for each tube.
6. Write a conclusion: Which view lost the object faster? Use the words magnification and field of view.
7. Optional: cut a slit from the top of an oatmeal canister down one side, set it on a paper plate, and put a pencil “telescope” inside. Turn the dome to keep the slit in front of the pencil as you point it around the sky.

Tips

- Objects in the south (for people in the United States) drift fastest. Objects near the North Star drift very slowly. Use the same object for every test.
- Bumping the tube spoils a trial. If you bump it, start that trial over.
- The Moon drifts from east to west, the same way it rises and sets, so it leaves the view toward the west.

Check your work

- I can explain why the sky seems to move across a telescope’s view.
- I can name the variable I changed, the things I kept the same and what I measured.
- I can explain why observatories use tracking mounts and turning domes.

FIELD NOTEBOOK

1. Draw a cutaway of an observatory: the dome, the open slit, the telescope, the mount and the pier. Label each part and write what it does.
2. Draw a map of your town and mark the darkest place you can find to observe. Write two reasons it is darker than your house.
3. Record your drift-timer results in a neat table and draw a bar graph of the two average times.

> **From history.** James Lick, a wealthy California landowner and piano maker, left money to build a telescope more powerful than any that had ever been made. The Lick Observatory opened on Mount Hamilton, near San Jose, California, in 1888, with a refractor 36 inches (91 centimeters) across, the largest in the world until Yerkes. Lick had died in 1876, and by his wish his body was buried in the base of the pier that holds up the great telescope.

WORKED EXAMPLES

Example 1. Use the bar graph. How much higher is the Mauna Kea site than the Yerkes Observatory? Give the answer in meters and in feet. (1 meter ≈ 3.28 feet)

(Use the map or drawing "Read each bar against the scale on the left." shown earlier in this lesson.)

1. Read the bars: Mauna Kea is about 4,200 meters; Yerkes is about 330 meters.
2. Subtract: 4,200 − 330 = 3,870 meters.
3. Change to feet: 3,870 × 3.28 ≈ 12,700 feet.

Answer: Mauna Kea is about 3,870 meters (about 12,700 feet) higher than Yerkes.

Example 2. The earth turns once (360 degrees) in about 24 hours. A homemade telescope shows a piece of sky 2 degrees wide. About how long does a star near the celestial equator (the part of the sky that moves fastest) take to drift all the way across that view if the telescope is held still?

1. Find how far the sky turns each hour: 360° ÷ 24 hours = 15° per hour.
2. Find how long one degree takes: 60 minutes ÷ 15 = 4 minutes per degree.
3. Multiply by the width of the view: 2° × 4 minutes = 8 minutes.

Answer: About 8 minutes. A telescope that magnifies more, with a view only 1° wide, would lose the star in about 4 minutes.

PRACTICE

1. EASY Name four things that make a good observatory site.
2. EASY Why does an observatory dome have a slit, and why does the dome turn?
3. MEDIUM The Yerkes lens is 40 inches across. How many centimeters is that? (1 inch = 2.54 centimeters)
4. MEDIUM Use the bar graph of observatory heights. (a) Which site is highest? (b) How much higher is Mount Wilson than Lick? (c) About how many times as high as Mount Wilson is Mauna Kea?
   (Use the map or drawing "Heights above sea level of four observatory sites." shown earlier in this lesson.)
5. MEDIUM Air usually gets colder by about 6.5°C for every 1,000 meters you climb. If it is 22°C at the beach in Hawaii, about how cold is it at the top of Mauna Kea, 4,200 meters up? (This is why astronomers there wear winter coats.)
6. HARD Explain why the largest telescopes in the world are reflectors, not refractors like Yerkes.
7. HARD Design an experiment to find out whether magnification changes how fast the Moon drifts out of view of a telescope held still. Name what you change, what you keep the same, what you measure and your control.

8. CHALLENGE A Keck telescope mirror is 10 meters wide. The Yerkes lens is about 1 meter wide. About how many times as much light does a Keck telescope gather?

COMMON MISTAKES

- Thinking observatories are built on mountains to get closer to the stars. A few kilometers makes no difference to a star's distance. Mountains are chosen to get above thick, damp, shimmering air and away from city lights.
- Thinking a telescope looks through a glass window in the dome. The slit is open to the sky, because even clear glass would blur and dim the view.
- Thinking the stars move across the sky by themselves each night. Their nightly motion comes from the earth turning, which is why a telescope must turn to follow them.

Make it a game · Build the Best Observatory. Write site cards on slips of paper: "top of a dry mountain" (+3), "far from any city" (+3), "clear skies 300 nights a year" (+2), "steady ocean breeze" (+2), "next to a stadium with bright lights" (−3), "cloudy valley" (−2), "near a busy airport" (−1), "damp, foggy coast" (−2). Shuffle. Each player draws four cards and adds up the score, then explains why each card helps or hurts. Highest score gets to name the observatory. Play three rounds.

Scripture. "Day unto day uttereth speech, and night unto night sheweth knowledge." (Psalm 19:2, KJV)

An observatory is a place built to listen to the night. Every clear night the sky "sheweth knowledge" to anyone who watches carefully and records what they see.

Practice answers

1. Dark skies far from city lights; dry, clear weather with many cloudless nights; high elevation above the thickest air; steady, smooth air that does not shimmer.
2. The slit opens so the telescope can look out at the sky. The dome turns so the slit stays in front of the telescope as it points to different places and follows the stars.
3. 40 × 2.54 = 101.6 centimeters, about 102 centimeters.
4. (a) Mauna Kea, about 4,200 meters. (b) 1,740 − 1,280 = 460 meters. (c) 4,200 ÷ 1,740 ≈ 2.4 times as high.
5. 6.5 × 4.2 = 27.3°C colder. 22 − 27.3 = −5.3°C, about −5°C (about 23°F).
6. A lens can be held only at its edge, so a very large lens sags under its own weight; thick glass also absorbs light and spreads colors apart. A mirror reflects light from its front surface, so it can be supported all across its back, and it can be made in segments. So mirrors can be built much larger than lenses.
7. Change: the magnification, by using eyepieces of different focal lengths in the same telescope. Keep the same: the telescope and how it is fixed in place, the Moon, the night and time, starting with the Moon centered, the person timing. Measure: the time until the Moon leaves the view, three trials each, averaged. Control: the lowest magnification (or an empty tube with no lenses) to compare against.

8. Light gathered depends on area, which grows with the width times the width. 10 × 10 = 100 and 1 × 1 = 1, so a Keck mirror gathers about 100 times as much light as the Yerkes lens.

6.4 Night-Sky Observing

OBJECTIVES

- Tell how Charles Messier made his list of faint, fuzzy objects, and name several Messier objects a family can find with binoculars.
- Use the skills of a real observer: dark adaptation, averted vision, a red light, hand measurements of the sky and a careful observing log.
- Test whether looking slightly to the side of a faint star group lets you see more stars, keeping everything else the same.

Warm-up. Look at a lamp across the room. Now stretch your arm straight out, make a fist, and see how many fists tall the lamp is. Measure the doorway the same way, then the distance from the floor to the ceiling at the far wall. Write your measurements in “fists.” Tonight you will use the same hand ruler on the sky.

Video. Coming soon. Beginner stargazing with binoculars, how to measure the sky with your hand, dark adaptation and averted vision, Charles Messier and the Messier catalog, Jupiter’s moons through binoculars: search NASA Night Sky Network, NASA Space Place, NASA Hubble Messier catalog, Sky and Telescope beginner guides, local astronomy club videos, SciShow Kids and Science Max.

KEY TERMS

dark adaptation
The way your eyes slowly grow more sensitive in the dark. It takes about 20 to 30 minutes and is spoiled by bright white light.

averted vision
Looking slightly to one side of a faint object so its light falls on the part of the eye that sees best in dim light.

binoculars
Two small telescopes joined side by side, one for each eye. “10×50” means they magnify 10 times and each front lens is 50 millimeters wide.

Messier object
One of the star clusters, glowing clouds and galaxies on Charles Messier’s list, named with an M and a number, such as M45, the Pleiades.

observing log
A record of each observing session: date, time, place, sky conditions, instrument, what you saw and a sketch.

CORE IDEAS

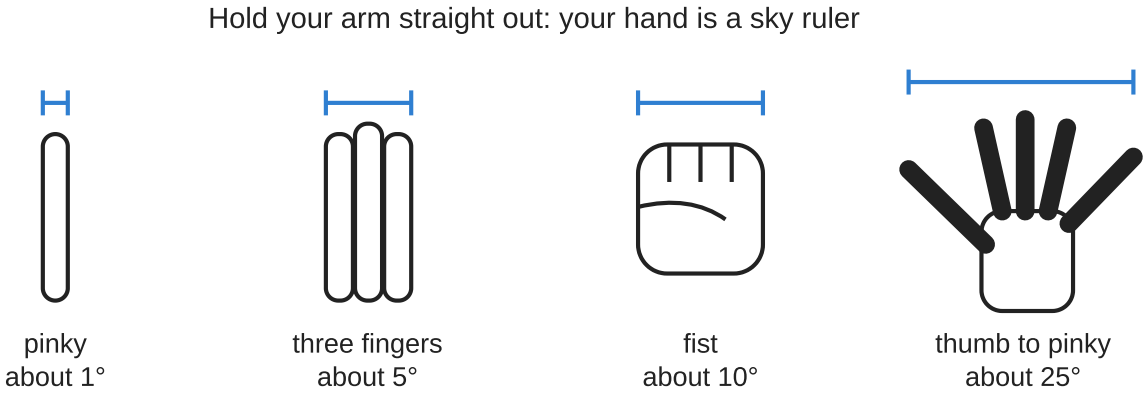
The story. On a night in 1758, a French astronomer named **Charles Messier** was following a comet from his small observatory on a rooftop in Paris. Near one of the horns of Taurus, the Bull, he found a faint, fuzzy smudge that looked just like a comet. But night after night it did not move against the stars, so it could not be a comet. Messier loved hunting comets, and in his life he discovered more than a dozen of them. He did not want to be fooled again, so he began a list of fuzzy things that were *not* comets. The final list he published in 1781 had 103 objects. Later astronomers added a few more that he had seen, so today the Messier list has 110. That first smudge is M1.

How they figured it out. Messier's trick was patience and good records. A comet creeps across the background stars from night to night; a star cluster or glowing cloud stays put. Only by writing down exactly where he saw each smudge, and checking again, could he tell them apart. Today the Messier objects are favorite targets for beginners, because many of them can be seen with binoculars: **M45**, the Pleiades, in the winter evening sky; **M42**, the Orion Nebula, a glowing patch in Orion's sword; **M31**, the Andromeda Galaxy, a faint oval of light on dark autumn nights; and **M13**, a ball of stars in Hercules in summer.

The big idea. A good observer trains the eyes as well as the telescope. Your pupils open wide within seconds of entering the dark, but your eyes keep growing more sensitive for 20 to 30 minutes. This is **dark adaptation**, and one glance at a bright phone screen spoils much of it, so astronomers use a dim red light. The center of your eye is packed with cells that see color and fine detail in bright light. Cells that work best in dim light are spread around the edges. So to see a faint smudge, look a little to one side of it. This is **averted vision**. To find your way, measure the sky with your hand held at arm's length: your pinky is about 1 degree wide, three fingers about 5 degrees, a fist about 10 degrees, and your spread hand from thumb to pinky about 25 degrees. From the horizon to straight overhead is 90 degrees, about nine fists. The full Moon is only about half a degree wide.

Try it and see. You do not need a large telescope to begin. A pair of 7×50 or 10×50 binoculars, steadied against a fence post or a lawn chair, shows craters on the Moon, many more stars in the Pleiades and, on many nights, the four largest moons of Jupiter as tiny points in a line. Your homemade telescope from Lesson 6.1 shows the Moon's craters too. Look at the Moon a few days before or after first quarter, not at full Moon: near the line between light and dark, the sun shines across the craters from the side and casts long shadows. Record every session in an **observing log**, as Messier did.

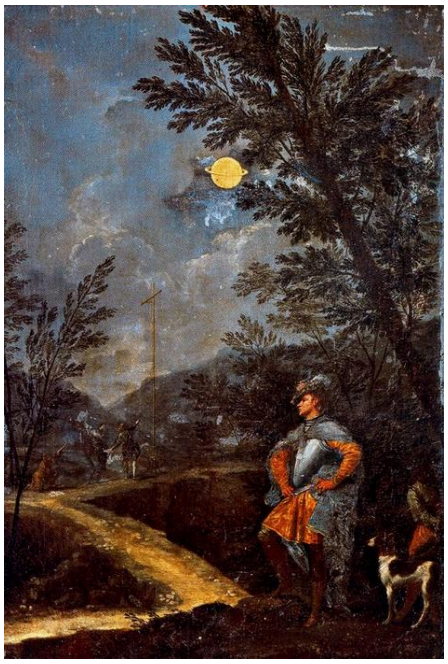
God's handiwork. The prophet Amos called on Israel to "seek him that maketh the seven stars and Orion" (Amos 5:8). The seven stars are the Pleiades, the same little cluster Messier listed as M45. When you sit outside in the dark, wait for your eyes to adjust and watch the faint stars appear one by one, you are seeing the same heavens Job, Amos and Messier saw. A careful observer learns to wait, to look closely and to write down what is really there.



Horizon to straight overhead is 90°, about 9 fists. The full Moon is about ½° wide.

Your hand at arm's length is a sky ruler. Adults and children get about the same angles, because longer arms go with bigger hands.

PICTURE STUDY



Astronomical Observations: Saturn, Donato Creti (with the heavenly body painted by Raimondo Manzini), 1711 · Oil on canvas · Pinacoteca Vaticana (Vatican Museums), Vatican City

In 1711 Count Luigi Ferdinando Marsili of Bologna, Italy, wanted his city to have an astronomical observatory. He asked the painter Donato Creti to make a set of eight small night paintings. Each shows people observing with a telescope, and each has a different heavenly body in the sky: the Sun, the Moon, Mercury, Venus, Mars, Jupiter, Saturn and a comet. Raimondo Manzini, a painter of tiny, detailed pictures, painted the heavenly bodies as they looked through the telescopes of the day.

The paintings were given to Pope Clement XI to win his support for the observatory, and in the years that followed Bologna built an observatory tower for its new Institute of Sciences.

The heavenly bodies are painted much larger than they really look, so that the viewer can see what the observers are seeing through their telescopes.

Look closely

- Find Saturn in the sky. How did the painter show its ring?
- Find the observers and their telescope. How long is the telescope compared with the people?
- Look at the landscape and the light. How does the painter make it feel like night?
- Compare the size of Saturn in the painting with how big a planet really looks to your eye. Why did the painter make it so large?

Talk about it

1. This painting was made to persuade someone to build an observatory. Do you think it would have persuaded you? Why?
2. Saturn's ring cannot be seen with the naked eye. What would you need to see it yourself?
3. If you painted a picture of your own observing night, what would you put in the sky?

> **Safety first.** Observe only with an adult. Never point binoculars or a telescope at the Sun or anywhere near it, even at sunset; it can blind you instantly. Choose a safe spot away from roads and water, bring a red flashlight, dress warmly and watch your step in the dark.

EXPERIMENT: LOOK STRAIGHT OR LOOK ASIDE?

You will run a real experiment on your own eyes and start your first observing log. **Question:** Do I see more stars in a faint star group when I look a little to the side of it? **Prediction:** write yours. **What we change:** where you aim your eye (straight at the group, or a little to one side). **What we keep the same:** the star group, the night, your place, how long your eyes have adjusted, how long you look and the observer. **What we measure:** the number of stars you count.

You will need

- A notebook ruled as an observing log (date, time, place, sky conditions, instrument, what I saw, sketch)
- A red flashlight (cover a flashlight with red cellophane or red paper)
- A timer, a lawn chair and a warm blanket
- Binoculars if you have them, and your telescope from Lesson 6.1
- Indoor backup for cloudy nights: black paper, a pin and a lamp

Steps

1. Choose a faint star group high in the sky: the Pleiades on fall, winter or early spring evenings, or the bowl of the Little Dipper in summer. Ask an adult to help you find it

with a free star chart.
2. Go outside, turn off all white lights and wait 20 minutes for your eyes to adjust. Use only the red light.
3. Look straight at the star group for 20 seconds and count the stars you can see. Record the number.
4. Rest for a few seconds. Now aim your eye a little to one side of the group, about one fist away, and count the stars you see in the group for 20 seconds. Record the number.
5. Repeat both ways two more times, switching back and forth. Find the average for each way.
6. If you have binoculars, steady them on the chair back and count again. Record it too.
7. Fill in a full log entry: date, time, place, clouds, Moon phase, instruments, your counts and a sketch of the group. Measure how high above the horizon it was in fists.
8. Cloudy night? Poke 30 pinholes of different sizes in black paper, hold it in front of a dim lamp in a dark room, sit across the room and run the same test.

Tips

- Count honestly. Some stars will seem to blink in and out; count only those you are sure of.
- Try looking to different sides (left, right, above, below). Many people find one side works best.
- A faint star can vanish when you stare straight at it and reappear when you look away. That is averted vision at work.

Check your work

- I can explain dark adaptation and averted vision.
- I can name what I changed, what I kept the same and what I measured.
- I can keep a complete observing log entry with a sketch.

FIELD NOTEBOOK

1. Draw the Moon through binoculars or your telescope a few days after first quarter. Shade the craters near the line between light and dark and label any you can name.
2. Watch Jupiter with steadied binoculars on three different nights. Each night, draw Jupiter as a dot and its moons as tiny dots in a line, and note how they have moved.
3. Make a page called “My Messier List” and record each Messier object you find, with the date, instrument and a small sketch.

> **From history.** Edward Emerson Barnard grew up poor in Nashville, Tennessee, and went to work in a photographer’s studio as a young boy. He saved his money, bought a small telescope and taught himself the sky. In the 1880s a businessman offered a prize of $200 for each new comet found by an American, and Barnard won it several times, enough to help pay for a house his friends called “Comet House.” He became one of the finest

observers in the world, first at Lick Observatory, where in 1892 he discovered a fifth moon of Jupiter, and later at Yerkes Observatory.

WORKED EXAMPLES

Example 1. On a dark night, the pupil of your eye opens to about 7 millimeters wide. Each front lens of a pair of 10×50 binoculars is 50 millimeters wide. About how many times as much light does one binocular lens gather as your eye?

1. Light gathered depends on area, which grows with the width times the width.
2. Binocular lens: 50 × 50 = 2,500. Eye: 7 × 7 = 49.
3. Divide: 2,500 ÷ 49 ≈ 51.

Answer: About 50 times as much light. That is why binoculars show many stars your eyes alone cannot.

Example 2. Ben stretches out his arm and measures Jupiter as 3 fists and 1 pinky above the horizon. (a) How high is Jupiter in degrees? (b) How many more degrees would it have to climb to be straight overhead?

(Use the map or drawing "Three fists and a pinky make about 31 degrees." shown earlier in this lesson.)

1. A fist is about 10° and a pinky is about 1°.
2. Add: 10° + 10° + 10° + 1° = 31°.
3. Straight overhead is 90° above the horizon: 90° − 31° = 59°.

Answer: (a) About 31° above the horizon. (b) About 59° more to reach straight overhead.

PRACTICE

1. EASY What is averted vision, and why does it work?
2. EASY Why did Charles Messier make his list of fuzzy objects?
3. MEDIUM What do the numbers on 7×50 binoculars mean? About how many times as much light does one 50-millimeter lens gather as a 7-millimeter pupil?
4. MEDIUM Using the hand ruler, how many degrees are 2 fists plus three fingers? How many full Moons, each about ½ degree wide, would fit side by side behind one fist?
5. MEDIUM Mia looked at Jupiter with binoculars on four nights and recorded the moons she saw.

   Night | Moons east of Jupiter | Moons west of Jupiter
   1 | 2 | 2
   2 | 1 | 3
   3 | 3 | 0
   4 | 1 | 2

(a) On which night did she see the most moons west of Jupiter? (b) On which nights did she see fewer than four moons in all? (c) Give a reason a moon might be missing.

6. HARD Explain why the Moon’s craters are easier to see a few days after first quarter than at full Moon.
7. HARD Design an experiment to find out whether resting binoculars on something steady lets you count more stars in the Pleiades than holding them in your hands. Name what you change, what you keep the same, what you measure and your control.
8. CHALLENGE The Moon rises about 50 minutes later each night, on average. If it rises at 7:10 p.m. on Monday, about what time will it rise on Thursday? Will that make Thursday a better or worse night for looking at faint stars early in the evening?

COMMON MISTAKES

- Thinking you need a big telescope to start observing. Your eyes, a hand ruler and a pair of steadied binoculars show hundreds of things, and many Messier objects.
- Thinking the full Moon is the best time to look at the Moon. Craters show best near the line between light and dark, where shadows are long.
- Thinking you will see faint objects as soon as you step outside. Your eyes need 20 to 30 minutes in the dark, and one look at a bright screen starts the clock over.

Make it a game · Sky Ruler Challenge. Indoors or out, one player names two things, such as the top of a tree and the chimney, or two bright stars. Everyone measures the angle between them with the hand ruler: pinky 1°, three fingers 5°, fist 10°, spread hand 25°. Write your answers secretly, then reveal. Anyone within 5 degrees of the average earns a point. Then take turns naming new pairs. Play to five points.

Scripture. “Seek him that maketh the seven stars and Orion, and turneth the shadow of death into the morning, and maketh the day dark with night: that calleth for the waters of the sea, and poureth them out upon the face of the earth: The LORD is his name:” (Amos 5:8, KJV)

When you find the Pleiades, the seven stars, and Orion on a winter night, remember that the One who made them is the One who turns night into morning. Observing is a way of seeking Him through what He made.

Practice answers

1. Looking a little to one side of a faint object. The cells that work best in dim light are spread around the edges of the eye, not in the center, so the faint light is easier to see off-center.
2. He was a comet hunter, and these faint smudges looked like comets. He listed them so that he and other comet hunters would not be fooled by them.
3. They magnify 7 times, and each front lens is 50 millimeters wide. (50 × 50) ÷ (7 × 7) = 2,500 ÷ 49 ≈ 51, so about 50 times as much light.
4. 10 + 10 + 5 = 25 degrees. A fist is 10 degrees, and 10 ÷ ½ = 20 full Moons.
5. (a) Night 2 (three moons). (b) Nights 3 and 4 (three moons each). (c) The moons circle Jupiter, so a moon can be hidden behind Jupiter, pass in front of it, or be too close to Jupiter’s glare to

see.

6. Near the line between the Moon’s light and dark parts, sunlight strikes the surface from the side, so crater walls and mountains cast long shadows that show their shape. At full Moon the sunlight shines straight down on the side facing us, so there are almost no shadows and the craters look flat. The full Moon is also so bright that it dazzles the eye.
7. Change: how the binoculars are held (handheld or rested on a fence post or chair back). Keep the same: the binoculars, the Pleiades, the night and time, the observer, the dark-adaptation time and how long you count (for example 30 seconds). Measure: the number of stars counted, three trials each way, averaged. Control: the handheld count, which is the usual way people use binoculars.
8. Monday to Thursday is 3 nights: 3 × 50 = 150 minutes = 2 hours 30 minutes. 7:10 p.m. + 2:30 = about 9:40 p.m. Thursday is better for faint stars early in the evening, because the bright Moon is not yet up to light the sky.

Unit 6 review

Answer each question. Show your work for calculations and use complete sentences for explanations. The quiz is worth 50 points.

1. (5 pts) Name the two lenses of a simple refractor and tell what each one does.
2. (5 pts) A telescope has an objective with a focal length of 750 millimeters and an eyepiece with a focal length of 25 millimeters. What is its magnification, and about how far apart must the lenses be?
3. (5 pts) Who asked for a patent on a telescope in 1608, and what kind of telescope did Kepler describe in 1611?
4. (5 pts) Why did astronomers put Hubble above the earth’s air? What went wrong with Hubble at first, and how was it fixed?
5. (5 pts) Give three differences between Hubble and Webb.
6. (5 pts) List four things that make a good place for an observatory, and explain why most of the largest telescopes are on mountains.
7. (5 pts) Explain why the Yerkes 40-inch lens is still the largest refractor used for astronomy, while mirror telescopes have grown to 10 meters.
8. (5 pts) The sky turns about 15 degrees every hour. A telescope held still shows a piece of sky 3 degrees wide. About how many minutes does a star near the celestial equator take to drift across it? What part of an observatory solves this problem?
9. (5 pts) Explain dark adaptation and averted vision, and tell why astronomers use a red flashlight.
10. (5 pts) Design an experiment to test whether you can count more stars in the Pleiades with 10×50 binoculars than with your eyes alone. Name what you change, what you keep the same and what you measure.

Unit project: my telescope and observing log

Present the telescope you built in Lesson 6.1 together with a lab report that shows the focal lengths you measured, your predicted and measured magnifications, and a labeled ray diagram. Add your experiment tables from “Twinkle in a Pan,” the drift timer and “Look Straight or Look Aside?”, each with the question, what you changed, what you kept the same, what you measured and your conclusion.

Finish with an observing log of at least three nights, including a sketch of the Moon’s craters, a hand-ruler measurement of a planet or star, and at least one Messier object or Jupiter’s moons. Close with a paragraph explaining how telescopes, from Lipperhey’s tube to Webb, have let people see more of the heavens God made.

- **Working instrument**: The telescope focuses on faraway objects, the lenses are measured, and the report correctly calculates magnification and lens spacing.
- **Experiments**: Each experiment names the variable, the things kept the same and the measurement, uses repeated trials and states an honest conclusion.

- **Observing log**: At least three complete entries with date, time, place, sky conditions, instrument, measurements and careful sketches.
- **Explanation and care**: The closing paragraph explains light gathering, why telescopes go to mountains and space, and gives God glory for His works; the notebook is neat and clearly labeled.

Answer key

1. The objective lens (the big front lens) gathers light and makes a small, upside-down image at its focal point. The eyepiece (the small lens by the eye) works like a magnifying glass to enlarge that image.
2. 750 ÷ 25 = 30 times. The lenses must be about 750 + 25 = 775 millimeters (77.5 centimeters, about 30 inches) apart.
3. Hans Lipperhey, a Dutch spectacle maker from Middelburg. Kepler described a telescope made with two convex lenses, which gives a wider view but shows things upside down.
4. Moving air blurs starlight (twinkling) and blocks some kinds of light, so above the air pictures are sharper and more kinds of light can be seen. At first Hubble's mirror had been ground to slightly the wrong shape, so its pictures were blurry. In December 1993 astronauts from the shuttle Endeavour added correcting mirrors and a new camera, like giving it eyeglasses.
5. Any three: Hubble's mirror is 2.4 meters wide and Webb's is 6.5 meters wide with 18 segments; Hubble sees mostly visible light and Webb sees mostly infrared; Hubble orbits the earth about 540 kilometers up and Webb travels around the Sun about 1.5 million kilometers from the earth; Hubble was launched by a space shuttle in 1990 and Webb by an Ariane 5 rocket in 2021; astronauts repaired Hubble but Webb is too far away to visit; Webb needs a sunshield to stay very cold.
6. Dark skies away from city lights; dry, clear weather; high elevation; steady air. Mountains rise above the thickest, dampest, most shimmering air and are often far from cities. They are not chosen to be closer to the stars.
7. A lens can be held only at its edge, so a bigger lens would sag under its own weight, and thick glass absorbs light and spreads colors apart. A mirror reflects light from its front, so it can be supported across its whole back and can be made of many segments.
8. 1 degree takes 60 ÷ 15 = 4 minutes, so 3 degrees take 3 × 4 = 12 minutes. A tracking mount turns the telescope to follow the stars (and the dome turns to keep the slit in front of it).
9. Dark adaptation: the eyes grow more sensitive over about 20 to 30 minutes in the dark. Averted vision: looking slightly to one side of a faint object, because the cells that see best in dim light are around the edges of the eye. A dim red light lets you read charts without spoiling your dark adaptation the way white light does.
10. Change: eyes alone or binoculars. Keep the same: the Pleiades, the night and time, the place, the observer, dark-adaptation time, how long you count (for example 30 seconds) and how the binoculars are steadied. Measure: the number of stars counted, three trials each, averaged. The eyes-alone count is the control.

UNIT 7

Seasons and Calendar

God made the lights in the heavens “for signs, and for seasons, and for days, and years” (Genesis 1:14). In this unit you will learn why the year has seasons and how people have counted the year by the Sun and the Moon. You will discover that summer and winter come from the steady 23.5° tilt of Earth’s axis, not from our distance to the Sun, and you will measure for yourself how slanting light spreads thin and how the noon Sun climbs and sinks through the year.

You will wait with Admiral Byrd through the dark Antarctic winter and watch the midwinter sunrise creep into the stone passage at Newgrange. Then you will turn from the sky to the calendar: Julius Caesar’s leap day, the ten dates that vanished in October 1582, and the careful arithmetic that keeps our calendar in step with the Sun. Finally you will learn how the spring full moon sets the dates of Passover and Easter, and why King Oswiu’s household once kept Easter twice in one year. In every lesson you will ask: **what is the Sun or Moon really doing, and how do we measure it?**

BEFORE YOU BEGIN

- Knows that Earth spins once a day and travels around the Sun once a year (Unit 1)
- Can name the phases of the Moon (Unit 2)
- Can add, subtract and multiply whole numbers and simple decimals, and subtract hours and minutes
- Can read a protractor and a simple data table

MASTERY CHECKLIST

- I can explain that the seasons come from the tilt of Earth’s axis, through sun angle and day length, and not from distance to the Sun.
- I can name the two solstices and two equinoxes with their dates and find the noon Sun height for a place when I know its latitude.
- I can locate the Tropic of Cancer, the Tropic of Capricorn and the Arctic Circle and tell what is special about each.
- I can use the Gregorian leap-year rule and explain why ten days were dropped in 1582.
- I can find the date of Easter from the full-moon rule and explain why the Hebrew calendar sometimes adds a thirteenth month.
- I can design a fair experiment that changes one thing, keeps the rest the same and measures the result.

OPTIONAL BOOKS AND RESOURCES

- **NASA Space Place: What Causes the Seasons?** (https://spaceplace.nasa.gov/seasons/): Free. A short, clear NASA page for children with diagrams of Earth’s tilt and sunlight. Good review for Lessons 7.1 and 7.2.

- **NOAA Solar Calculator** (https://gml.noaa.gov/grad/solcalc/): Free. Choose your town and any date to see sunrise, sunset and how high the Sun climbs at noon. Use it to check your noon Sun height calculations and to compare day lengths on the solstices and equinoxes.
- **U.S. Naval Observatory: Phases of the Moon** (https://aa.usno.navy.mil/data/MoonPhases): Free. Tables of the dates and times of new and full moons for any year. Use them in Lesson 7.4 to find the first full moon after March 21 and work out Easter.

7.1 Tilt and Seasons ★

OBJECTIVES

- Explain that Earth's axis is tilted about 23.5° and keeps pointing the same way in space as Earth travels around the Sun.
- Show with a flashlight that slanting light spreads the same energy over a larger area, and use sun angle and day length to explain summer and winter.
- Explain why the Northern and Southern Hemispheres have opposite seasons and why distance from the Sun does not cause the seasons.

Warm-up. Push a pencil through an orange, then tip the pencil a little so it leans toward one corner of the room. Set a lamp in the middle of a table and walk the orange slowly around it, keeping the pencil leaning toward that same corner the whole way. Stop at two opposite sides of the lamp. Which half of the orange, top or bottom, faces the lamp more at each stop?

Video. Coming soon. What causes the seasons: Earth's tilted axis, direct and slanting sunlight, and day length, explained with a globe and lamp (search NASA Space Place, NOAA SciJinks, Science Max, Homeschool Pop (Alternate), SciShow Kids).

KEY TERMS

axis
The imaginary line through the North and South Poles that Earth spins around once a day.

tilt
The lean of Earth's axis, about 23.5° from straight up-and-down compared with Earth's path around the Sun. The axis always points toward the North Star.

hemisphere
Half of the Earth. The equator divides Earth into the Northern Hemisphere and the Southern Hemisphere.

direct rays
Sunlight that strikes the ground nearly straight on, when the Sun is high. Direct rays pack their energy into a small area and warm the ground well.

season
One of the four parts of the year (spring, summer, fall, winter) with its own pattern of sun angle, day length and weather.

CORE IDEAS

The story. In March 1934, the American explorer Admiral Richard E. Byrd moved into a tiny wooden hut buried in the snow of the Ross Ice Shelf in Antarctica. He planned to spend the winter there alone, reading his weather instruments several times a day. By late April the

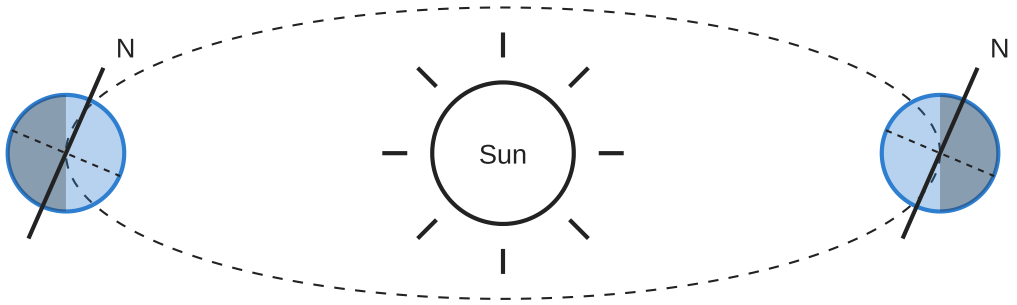
Sun had set for the last time, and it would not rise again until late August. Outside, the air grew colder than −50 °C (−58 °F). At that same time, on the other side of the world, farmers in Kansas were cutting wheat in June under a Sun that stayed up for nearly 15 hours a day. One planet and one Sun: so why was it the dark of winter for Byrd and the bright heat of summer in Kansas?

How they figured it out. People have always noticed that the noon Sun climbs high in summer and sinks low in winter. In 1543 the Polish astronomer Nicolaus Copernicus, a church canon in the town of Frombork, published *On the Revolutions of the Heavenly Spheres*. He taught that the Earth spins on its axis once a day and travels around the Sun once a year, with its axis tipped to one side, and he used that tipped axis to explain why the Sun's path across the sky changes through the year. Later astronomers measured the tilt carefully: Earth's axis leans about **23.5°** compared with its path around the Sun.

The big idea. Earth's tilted axis does not flip back and forth as we travel. All year long it points the same way in space, toward the North Star (see the diagram). So in June the Northern **Hemisphere** leans toward the Sun. The noon Sun rides high, its **direct rays** strike the ground nearly straight on, and the days are long. That is summer. In December the Northern Hemisphere leans away. The Sun stays low, its rays strike at a slant, and the days are short. That is winter. Two things work together: **the angle of the sunlight** and **the number of hours of daylight**. While the north has summer, the south has winter, which is why Byrd sat in darkness while Kansas baked. Near the poles the change is greatest; near the equator the noon Sun is always high and days stay close to 12 hours long all year.

Try it and see. Shine a flashlight straight down on graph paper and trace the bright spot. Then tilt the flashlight and trace again. The tilted spot is bigger, but it holds the same amount of light, so each square gets less. Slanting winter sunlight is spread out in the same way, and spread-out light warms the ground less. Many people think summer comes when Earth is closer to the Sun. In fact Earth is closest to the Sun in early January, about 147 million km (91 million mi) away, and farthest in early July, about 152 million km (94.5 million mi) away. If distance made the seasons, the whole Earth would have summer at the same time, and the north would have it in January!

God's handiwork. After the Flood, God promised Noah that "seedtime and harvest, and cold and heat, and summer and winter" would not cease while the earth remains (Genesis 8:22). The steady tilt of Earth's axis is one of the ways that promise is kept. Year after year the seasons return in order, so farmers know when to plant and when to reap, geese know when to fly south, and apple trees know when to bud. A farmer in Kansas and an explorer in Antarctica live under the same faithful Sun, on a world God set spinning with a steady lean.



Earth's axis points the same way all year. In June the Northern Hemisphere leans toward the Sun; in December it leans away. (Not to scale.)

PICTURE STUDY



The Hunters in the Snow (Winter), Pieter Bruegel the Elder, 1565 · Oil on wood panel · Kunsthistorisches Museum, Vienna, Austria

Pieter Bruegel the Elder was a Flemish painter who loved to show ordinary country people at work and play through the year. In 1565 he painted a set of large pictures about the times of the year for a merchant in Antwerp. Five of them survive, and this winter scene is the most famous.

Bruegel lived far north of the equator, where the winter Sun stays low and the days are short. Look for how he shows the cold, gray light of a short winter day, when the slanting rays of the Sun bring little warmth to the land.

Look closely

- Find the three hunters and their dogs coming home through the snow. Are they walking fast or slow? Do they look as if the hunt went well?
- Look down into the valley at the frozen ponds. How many people can you find skating or playing on the ice?
- Find the fire burning outside the inn on the left. Why would people gather around it?
- Look at the sky, the bare trees and the dark birds. Which colors did Bruegel use to make you feel the cold?

Talk about it

1. Where do you think the Sun is in this painting: high or low in the sky? How can you tell?
2. What would this same valley look like in July? Which two things about the sunlight would be different?
3. What do the people in the painting do to make the best of winter?

> **Safety first.** Never look directly at the Sun, even for a moment, and never shine a flashlight into anyone’s eyes. Lamp bulbs get hot, so do not touch them. Handle glass thermometers gently, and do the outdoor part with an adult.

EXPERIMENT: SUNBEAM SPREAD: A FLASHLIGHT ANGLE EXPERIMENT

Is slanting light really weaker light? You will shine the same flashlight on graph paper at three angles and count how many squares each spot covers. Our question: **Does the same light cover more squares when it strikes at a slant?** What we change: the angle of the flashlight. What we keep the same: the flashlight, its distance from the paper, the paper and the darkness of the room. What we measure: the number of squares inside each lit spot.

You will need

- A small flashlight with a narrow beam
- Graph paper with 1-centimeter squares, and tape
- Pencil, ruler and a protractor (or a cardboard triangle cut to the angles)
- A piece of string 30 cm (12 in) long
- Lab notebook
- For Part 2 (optional, a sunny day): two outdoor thermometers, two pieces of black construction paper, a piece of stiff cardboard and a stack of books

Steps

1. Write your prediction: “At 30° the spot will cover about ___ times as many squares as at 90°.”
2. Tape the graph paper to a table and darken the room. Mark a dot in the center of the paper.
3. Tie or tape the string to the front of the flashlight. Hold the flashlight straight down (90°) so the end of the string just reaches the center dot. This keeps the distance at 30 cm (12 in) every time.
4. Have a helper trace around the edge of the bright spot with a pencil. Label it “90°.”
5. Tip the flashlight to 60° from the table (check with the protractor), keep the string tight to the same center dot, and trace the spot. Label it “60°.” Do the same at 30°.
6. Count the whole squares inside each outline. Count squares that are about half inside as halves.
7. Make a table with three columns: Angle, Squares lit, Times as big as the 90° spot. Divide each count by the 90° count to fill in the last column.
8. Part 2 (sunny morning or late afternoon, with an adult): Lay one thermometer on black paper flat on the ground. Tape the other to black paper on cardboard and prop it on books so the card faces the Sun squarely (its shadow behind it is as small as possible). Do not look at the Sun. Read both thermometers after 15 minutes.
9. Write a conclusion: What happened to the size of the spot as the angle got lower? Which thermometer warmed more? How does this help explain winter?

Tips

- At 30° you should find the spot covers about twice as many squares as straight down. At 60° it is only a little bigger, about 1.15 times as many.
- The slanted spots are ovals, not circles. Trace the edge where the light is bright, not the faint glow beyond it.
- If your counts are close but not exact, that is normal. Real scientists repeat a measurement and take the average.

Check your work

- I kept the flashlight, distance and paper the same and changed only the angle.
- I recorded my counts in a table and compared each spot with the 90° spot.
- I can explain why slanting sunlight warms the ground less than direct sunlight.

FIELD NOTEBOOK

1. Draw the Sun with Earth on both sides of it, the axis leaning the same way in both drawings. Label June and December and write which hemisphere has summer at each spot.
2. Trace or copy your three flashlight spots side by side. Under each one write the angle and the number of squares.
3. For four weeks, copy the sunrise and sunset times from a newspaper or weather report once a week. Figure the day length and draw a bar for each week. Is the bar growing

or shrinking?

> **From history.** Our word *climate* comes from the Greek word *klima*, which means “slope” or “lean.” Greek geographers noticed that the farther north they traveled, the more the Sun’s noon rays slanted, and they divided the known world into bands called *klimata* according to that slant. They had found the key to hot and cold lands long before anyone knew that Earth travels around the Sun.

WORKED EXAMPLES

Example 1. A flashlight held straight down lights 12 squares on graph paper. Tipped to a low slant at the same distance, the same flashlight lights 24 squares. How does the amount of light on each square compare?

1. The flashlight gives out the same amount of light both times. Only the area changes.
2. Straight down, the light is shared by 12 squares, so each square gets 1/12 of the light.
3. At a slant, the light is shared by 24 squares, so each square gets 1/24 of the light.
4. 1/24 is half of 1/12, because 24 is twice 12.
5. Each square at the slant gets half as much light, so it would warm about half as much. Low winter sunlight works the same way.

Answer: Each square gets half as much light at the slant (1/24 instead of 1/12 of the light).

Example 2. This table shows about how long the daylight lasts in a town at 40° north latitude. How much longer is the longest day than the shortest day?
December 21: 9 h 20 min
March 20: 12 h 10 min
June 21: 15 h 0 min
September 22: 12 h 10 min

1. Find the longest day: June 21, with 15 h 0 min.
2. Find the shortest day: December 21, with 9 h 20 min.
3. Subtract. 15 h 0 min is the same as 14 h 60 min.
4. 14 h 60 min − 9 h 20 min = 5 h 40 min.
5. So on June 21 the Sun warms this town for 5 h 40 min more than on December 21, and its rays come in at a steeper angle too.

Answer: The longest day is 5 hours 40 minutes longer than the shortest day.

PRACTICE

1. EASY About how many degrees is Earth’s axis tilted? Toward which star does the north end of the axis point all year?
2. EASY It is December. Is it summer or winter in Australia? Explain in one sentence.
3. MEDIUM Earth is about 147 million km (91 million mi) from the Sun in early January and about 152 million km (94.5 million mi) in early July. Use these facts to show that distance does not cause the seasons.
4. MEDIUM Read the table of day lengths (rounded).
   Quito, Ecuador (on the equator): June 21, about 12 h 10 min; December 21, about 12 h 10 min.
   Anchorage, Alaska (61° north): June 21, about 19 h 20 min; December 21, about 5 h 30 min.
   (a) Which city has a bigger change in day length? (b) How big is that change?
5. MEDIUM Straight down, a flashlight lights 15 squares. At a slant it lights 30 squares. Which spot is brighter on each square, and by how much?
6. HARD Experiment design: A student wants to find out whether the angle of sunlight changes how warm a dark surface gets. Name (a) the one thing to change, (b) three things to keep the same, and (c) what to measure.
7. HARD Give two reasons summer days are warmer than winter days in the Northern Hemisphere.
8. CHALLENGE Suppose Earth’s axis were not tilted at all, but stood straight up compared with its path around the Sun. What would happen to the seasons? Explain.

COMMON MISTAKES

- Thinking summer comes because Earth is closer to the Sun. Earth is actually closest in early January, during northern winter. The tilt causes the seasons.
- Thinking Earth’s axis rocks back and forth, leaning toward the Sun in summer and away in winter. The axis points the same direction all year; it is Earth’s trip around the Sun that changes which hemisphere leans toward it.
- Thinking the whole Earth has summer at the same time. When it is summer in the Northern Hemisphere, it is winter in the Southern Hemisphere.

Make it a game · Tilt Walk. Tape a paper star high on one wall and call it the North Star. Set a lamp in the middle of the room. You are the Earth: hold a pencil leaning toward the star and keep it pointing there the whole time. Your parent calls out a month. Walk to the right place around the lamp, then say which season it is in the north and in the south. Score a point for each right answer; lose a point if your pencil stops pointing at the star. Play to ten.

Scripture. “While the earth remaineth, seedtime and harvest, and cold and heat, and summer and winter, and day and night shall not cease.” (Genesis 8:22, KJV)

God made this promise to Noah after the Flood. Every year the tilted Earth carries us through summer and winter again, a steady reminder that God keeps His word.

Practice answers

1. About 23.5°. It points toward the North Star (Polaris).
2. Summer. In December the Southern Hemisphere, where Australia is, leans toward the Sun, so it gets high, direct sunlight and long days.
3. If being closer made summer, the Northern Hemisphere would have summer in January, when Earth is closest. Instead the north has winter in January. Also, both hemispheres are the same distance from the Sun, yet they have opposite seasons. So the seasons come from the tilt, not the distance.
4. (a) Anchorage. (b) 19 h 20 min − 5 h 30 min = 13 h 50 min. Quito’s day length hardly changes at all.
5. The straight-down spot. The same light is spread over half as many squares, so each square gets twice as much light (1/15 compared with 1/30).
6. (a) The angle of the surface to the sunlight (one card facing the Sun squarely, one lying flat or tilted away). (b) Same kind and color of paper, same kind of thermometer, same time outdoors, same place and time of day, same starting temperature. (c) The temperature of each surface after the same number of minutes.
7. (1) The Sun is higher, so its rays strike more directly and pack more energy into each square meter. (2) The days are longer, so the ground has more hours to soak up sunlight and fewer hours of night to cool off.
8. There would be little or no change of seasons. Each place would get the same noon Sun height every day of the year, and day and night would each be about 12 hours long everywhere all year. Without the changing angle and changing day length, summer and winter would nearly disappear.

7.2 Solstices and Equinoxes

OBJECTIVES

- Name the two solstices and the two equinoxes with their approximate dates and describe what the Sun does on each.
- Calculate the noon Sun height on the solstices and equinoxes for a place whose latitude is known, and read a table of noon shadow lengths.
- Locate the Tropic of Cancer, the Tropic of Capricorn and the Arctic Circle and explain what makes each line special.

Warm-up. Find today's sunrise and sunset times in a newspaper, almanac or weather report. Subtract to find how long the Sun is up today. Now guess: will the day be longer or shorter one month from now? Write your guess down and check it in a month.

Video. Coming soon. Solstices and equinoxes: the Sun's changing path and noon height through the year, the tropics and the Arctic Circle, and the midwinter sunrise at Newgrange (search NASA, NOAA SciJinks, Science Max, Homeschool Pop (Alternate), and footage of the Newgrange winter solstice sunrise).

KEY TERMS

solstice
One of the two days each year when the noon Sun is highest or lowest in the sky: about June 21 and December 21. From Latin words meaning "the sun stands still."

equinox
One of the two days each year, about March 20 and September 22, when day and night are nearly equal everywhere on Earth. From Latin words meaning "equal night."

Tropic of Cancer
The line of latitude 23.5° north of the equator, where the noon Sun is straight overhead on the June solstice.

Tropic of Capricorn
The line of latitude 23.5° south of the equator, where the noon Sun is straight overhead on the December solstice.

Arctic Circle
The line of latitude 66.5° north. North of it, the Sun does not set on the June solstice and does not rise on the December solstice.

noon Sun height
How many degrees above the horizon the Sun stands at midday, when it is highest. Straight overhead is 90°.

CORE IDEAS

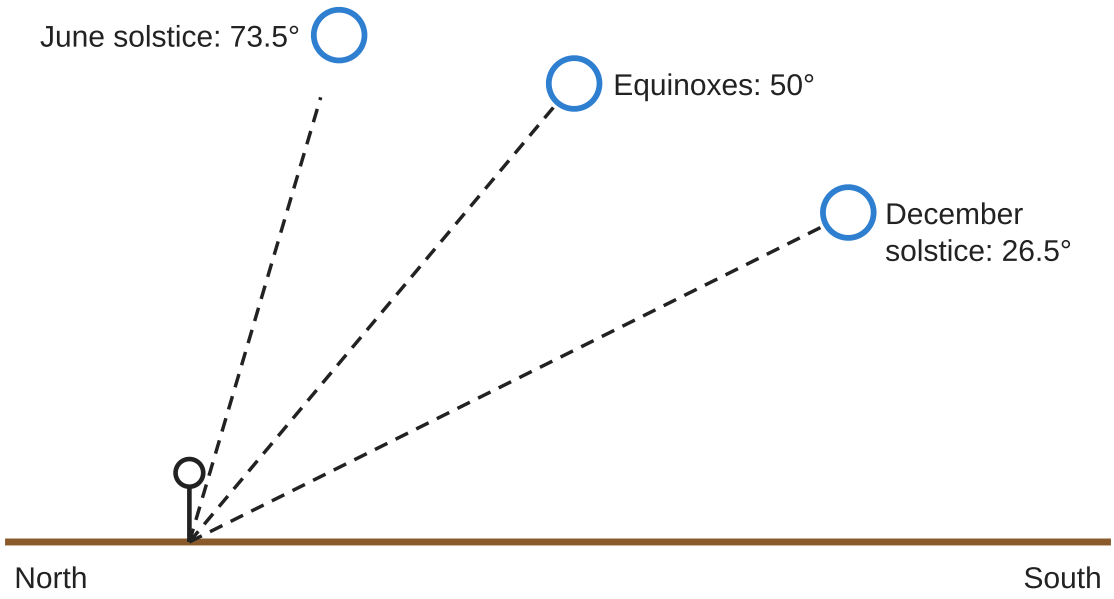
The story. Before dawn on December 21, 1967, the Irish archaeologist Professor Michael O'Kelly waited alone in a dark stone chamber deep inside Newgrange, a great grass-covered mound in the Boyne Valley of Ireland. Above the entrance, the builders long ago had left a strange stone-framed slot, now called the roof-box. O'Kelly wondered whether it had been made to let in the Sun. As the Sun rose, a thin beam of golden light slipped through the roof-box, crept up the stone passage, about 19 m (62 ft) long, and lit the floor of the chamber. After about 17 minutes it faded away. The people who built Newgrange left no writing, but they left a message in stone: they had aimed their passage at the sunrise on the shortest day of the year.

How they figured it out. Anyone who watches the sunrise from the same spot all year sees something wonderful. In winter the Sun rises far to the southeast. Each morning after midwinter it rises a little farther north, until in summer it rises far to the northeast. Then it turns and heads south again. At each turning point the Sun seems to pause for several days, rising in nearly the same place. The Romans called this a **solstice**, from *sol*, "sun," and *sistere*, "to stand still." Halfway between the solstices come the two **equinoxes**, from the Latin for "equal night," when day and night are each about 12 hours long.

The big idea. These four days mark four points on Earth's trip around the Sun. On the **June solstice** (June 20 or 21) the Northern Hemisphere leans most toward the Sun. At noon the Sun stands straight overhead along the **Tropic of Cancer**, 23.5° north of the equator. It is the longest day of the year in the north, and north of the **Arctic Circle** (66.5° north) the Sun does not set at all. On the **December solstice** (December 21 or 22) everything is reversed. The noon Sun is overhead on the **Tropic of Capricorn**, 23.5° south, the north has its shortest day, and north of the Arctic Circle the Sun does not rise. On the **March equinox** (about March 20) and the **September equinox** (September 22 or 23) neither hemisphere leans toward the Sun. The noon Sun is overhead at the equator, the Sun rises almost due east and sets almost due west, and day and night are nearly equal all over the Earth.

Try it and see. If you know your latitude, you can work out how high the noon Sun will climb on these days. On an equinox, the **noon Sun height** is 90° minus your latitude. On the June solstice, add 23.5°. On the December solstice, subtract 23.5°. In a town at 40° north, the noon Sun stands 50° high on the equinoxes, 73.5° high in June and only 26.5° high in December (see the diagram). A low Sun casts long shadows, so in that town a meter stick's noon shadow is more than six times as long in December as in June. (This simple rule works for places between the Tropic of Cancer and the Arctic Circle, which includes all of the lower 48 states.)

God's handiwork. On the fourth day of creation God made the lights in the heavens "for signs, and for seasons, and for days, and years" (Genesis 1:14). The solstices and equinoxes are like the four corner posts of the year. The psalmist says of the Sun, "His going forth is from the end of the heaven, and his circuit unto the ends of it" (Psalm 19:6). That circuit is so faithful that builders long ago could aim a stone passage at a single sunrise, and every December the light still finds its way in.



The noon Sun's height through the year in a town at 40° north latitude.

PICTURE STUDY



June, from the Très Riches Heures du Duc de Berry, The Limbourg brothers (Paul, Herman and Johan) and later painters, about 1412–1416 · Paint and gold on vellum (calfskin parchment) · Musée Condé, Chantilly, France

The *Très Riches Heures* ("Very Rich Hours") is a prayer book made for John, Duke of Berry, a French prince who loved beautiful books. Three brothers from the Netherlands, the Limbourg brothers, painted its pages. They died in 1416 before it was finished, and other artists completed it many years later.

The book opens with a calendar, one painted page for each month. Below, people do the work of that season. Above, a blue half-circle shows the Sun riding in a chariot and the star pictures of the zodiac that the Sun passes in front of during that month. The June page shows haymaking near the time of the summer solstice, outside the royal palace in Paris.

Look closely

- Find the men mowing with long scythes and the women raking the hay. Why would people cut hay in June, near the longest days of the year?
- Look at the blue half-circle at the top. Find the Sun in his chariot and the two star signs, the twins (Gemini) and the crab (Cancer).
- Find the tall, pointed chapel behind the palace wall. It is the Sainte-Chapelle in Paris, which still stands today.
- Look at the colors of the meadow and sky. How did the painters make the day feel bright and long?

Talk about it

1. The Tropic of Cancer is named for one of the star signs on this page. Which one, and why do you think that line got its name?
2. If the Limbourg brothers had painted a December page for the same place, how would the light and the work be different?
3. Why would farmers in the 1400s have cared so much about knowing the time of year?

> **Safety first.** Lamp bulbs get hot, so do not touch them and keep paper away from the bulb. Wooden skewers are sharp; let an adult push the skewer through the ball. Never look straight at the Sun when you go outside to compare with the real sky.

EXPERIMENT: THE DAY-LENGTH GLOBE

You will build a small tilted Earth and carry it around a lamp to see why the days are long in June and short in December. Our question: **How does the place in Earth’s orbit change how much of a day is spent in sunlight at 45° north?** What we change: the position of the globe around the lamp (June, September, December, March). What we keep the same: the tilt, the direction the axis points, the distance from the lamp and the lamp itself. What we measure: how many of 12 dots on the 45° north line are in the light.

You will need

- A foam ball about 8–10 cm (3–4 in) across, or an orange
- A wooden skewer or a long pencil for the axis
- A marker and a rubber band
- Twelve small stickers or marker dots
- A protractor and a ball of modeling clay
- A lamp with the shade removed, in a dark room
- A paper star taped high on one wall, and your lab notebook

Steps

1. Have an adult push the skewer straight through the ball from the North Pole to the South Pole.
2. Stretch the rubber band around the middle of the ball for the equator. Halfway between the equator and the North Pole, draw a circle with the marker. That is about 45° north.
3. Put 12 dots evenly spaced around the 45° north circle, like the hours on a clock face. Each dot stands for 2 hours of the 24-hour day.
4. Stand the skewer in the clay and use the protractor to tilt it about 23.5° from straight up. Turn the clay so the top of the skewer leans toward the paper star on the wall. Keep it leaning that way at every stop.
5. Write your prediction: at which stop will the most dots be in the light?
6. Place the globe at four stops around the lamp, the same distance away each time: the June stop (north end leaning toward the lamp), the September stop (a quarter of the way around), the December stop (north end leaning away) and the March stop.
7. At each stop, count the dots in the light. Count a dot right on the line between light and dark as one half.
8. Make a table: Stop, Dots in light, Hours of daylight (dots × 2).
9. Compare your model with real numbers. A city at 45° north really has about 15.5 hours of daylight in June, 12 at the equinoxes and 8.5 in December.

Tips

- You should find about 8 dots lit in June (about 16 hours), about 6 at the equinoxes (12 hours) and about 4 in December (8 hours). Close is good; the model is rough.
- Look at the North Pole at the June stop. Spin the ball slowly. Does the pole ever go into the dark? That is the midnight sun.
- If the axis drifts, you are measuring a different experiment. Check the star before each count.

Check your work

- I kept the tilt and the direction of the axis the same at every stop.
- I recorded the dots in light and turned them into hours of daylight.
- I can explain why the June solstice has the longest day in the north and the December solstice the shortest.

FIELD NOTEBOOK

1. Draw a large circle for Earth and mark the equator, the Tropic of Cancer, the Tropic of Capricorn and the Arctic Circle with their latitudes.
2. Make a year-wheel: a circle divided into four parts, with the two solstices and two equinoxes marked with their dates and a small drawing of the noon Sun’s height on each.

3. Sketch the view from a window where you can see the western sky. Once a week near sunset, without looking at the Sun itself, mark on your sketch about where it went down behind the trees or houses. Is the setting point moving north or south?

From history. The two tropics got their names from Greek astronomers. In their day the Sun at the June solstice stood in front of the stars of Cancer, the Crab, and at the December solstice in front of Capricornus, the Sea Goat. The word *tropic* comes from the Greek for "turning," because there the Sun turns back. The Greek astronomer Hipparchus discovered that the equinox points slowly creep along the background of stars. We now know the reason: Earth's axis slowly wobbles like the handle of a spinning top. Because of that creep, the June solstice Sun today stands in front of Taurus, near the border of Gemini, and the December solstice Sun in front of Sagittarius. The old names stayed.

WORKED EXAMPLES

Example 1. A town is at 40° north latitude. How high is the noon Sun on the equinoxes, on the June solstice and on the December solstice?

(Use the map or drawing "Noon Sun heights at 40° north." shown earlier in this lesson.)

1. Equinox rule: noon Sun height = 90° − latitude = 90° − 40° = 50°.
2. June solstice: add 23.5°. 50° + 23.5° = 73.5°.
3. December solstice: subtract 23.5°. 50° − 23.5° = 26.5°.
4. Check with the diagram: the June Sun is highest and the December Sun lowest, and the equinox Sun is halfway between. 73.5° − 50° = 23.5° and 50° − 26.5° = 23.5°.

Answer: 50° on the equinoxes, 73.5° on the June solstice and 26.5° on the December solstice.

Example 2. In the same town, a student stood a 1-meter stick straight up on level ground and measured its noon shadow on three days.
June 21: 30 cm (12 in)
March 20: 84 cm (33 in)
December 21: 200 cm (79 in)
(a) On which day was the shadow shortest? (b) About how many times longer was the December shadow than the June shadow? (c) Predict the shadow on September 22.

1. (a) The shortest shadow is 30 cm, on June 21, when the noon Sun is highest (73.5°).
2. (b) Divide: 200 cm ÷ 30 cm ≈ 6.7. The December shadow is between 6 and 7 times as long.
3. (c) September 22 is an equinox, like March 20, so the noon Sun is again 50° high.
4. The same Sun height makes the same shadow, so predict about 84 cm (33 in).

Answer: (a) June 21. (b) About 6.7 times as long. (c) About 84 cm (33 in), the same as on the March equinox.

PRACTICE

1. EASY What do the Latin words in “solstice” and “equinox” mean?
2. EASY Give the approximate dates of the two solstices and the two equinoxes.
3. MEDIUM A town is at 30° north latitude. Find the noon Sun height on the equinoxes, the June solstice and the December solstice.
4. MEDIUM On the December solstice, where on Earth is the noon Sun straight overhead? What is happening north of the Arctic Circle that day?
5. MEDIUM Read the table for a town and find the day length on each date. Which day is longest, and how much longer is it than the shortest?
   March 20: sunrise 7:10 a.m., sunset 7:20 p.m.
   June 21: sunrise 5:30 a.m., sunset 8:30 p.m.
   December 21: sunrise 7:20 a.m., sunset 4:40 p.m.
6. HARD Why is the June solstice the shortest day of the year in Argentina?
7. HARD Experiment design: A student wants to measure how the noon shadow of a stick changes from season to season. Name (a) what changes on purpose, (b) three things to keep the same and (c) what to measure.
8. CHALLENGE Use the noon Sun rule for the December solstice. (a) How high is the noon Sun in Fairbanks, Alaska, at about 65° north? (b) What about Tromsø, Norway, at about 70° north? What does your answer mean?

COMMON MISTAKES

- Thinking the June solstice is the hottest day of the year. The longest day comes first, but land and water take weeks to warm up, so the hottest weather usually comes in

July or August. The coldest weather likewise usually comes after the December solstice.

- Thinking day and night are exactly 12 hours each everywhere on the equinox. They are nearly equal. The air bends sunlight a little and the Sun is a disk, not a point, so the day is a few minutes longer than the night.
- Thinking the Sun is straight overhead at noon on a summer day anywhere. The Sun can be straight overhead only between the Tropic of Cancer and the Tropic of Capricorn. In the lower 48 states it never is.

Make it a game · Walk the Sun. Lay a long strip of tape on the floor. Mark the north end “Tropic of Cancer,” the middle “Equator” and the south end “Tropic of Capricorn.” You are the noon Sun. Your parent calls a date, such as June 21, March 20 or December 21. Walk to the spot where the Sun is straight overhead at noon on that day and tell one fact about the day (longest day in the north, midnight sun, equal night). For dates in between, like early May, stop partway. Score a point for each right spot and fact.

Scripture. “And God said, Let there be lights in the firmament of the heaven to divide the day from the night; and let them be for signs, and for seasons, and for days, and years:” (Genesis 1:14, KJV)

The Sun’s yearly path, with its two turning points and two balance points, is one of the clocks God set in the sky. People in every land have marked the year by it.

Practice answers

1. Solstice: “the sun stands still.” Equinox: “equal night.”
2. June solstice: June 20 or 21. September equinox: September 22 or 23. December solstice: December 21 or 22. March equinox: about March 20.
3. Equinoxes: $90° − 30° = 60°$. June: $60° + 23.5° = 83.5°$. December: $60° − 23.5° = 36.5°$.
4. Straight overhead on the Tropic of Capricorn, 23.5° south of the equator. North of the Arctic Circle the Sun does not rise at all that day.
5. March 20: 12 h 10 min. June 21: 15 h 0 min. December 21: 9 h 20 min. June 21 is longest, 5 h 40 min longer than December 21.
6. Argentina is in the Southern Hemisphere. In June the Southern Hemisphere leans away from the Sun, so the Sun stays low and the days are shortest there. It is the start of winter in Argentina.
7. (a) The date (measure on the solstices and equinoxes, or once a month). (b) The same stick, standing straight up; the same level spot; the same time of day, local noon when the shadow is shortest; the same measuring tape. (c) The length of the noon shadow.
8. (a) $90° − 65° − 23.5° = 1.5°$. The Sun barely peeks over the horizon at noon. (b) $90° − 70° − 23.5° = −3.5°$. A negative height means the Sun stays below the horizon all day. Tromsø is north of the Arctic Circle, so it has no sunrise on the December solstice.

7.3 Julian and Gregorian Calendars (1582)

OBJECTIVES

- Explain why a calendar must keep in step with the solar year of about 365¼ days and how leap days do that.
- Tell the story of the Julian calendar and the Gregorian reform of 1582, including why ten days were dropped.
- Use the Gregorian leap-year rule to decide whether a year is a leap year, and calculate how fast a calendar drifts.

Warm-up. Make two fists side by side and count the months across your knuckles and the dips between them: January on a knuckle, February in a dip, March on a knuckle, and so on. Knuckle months have 31 days; dip months have 30, except February. Add up all twelve months. Why do you think February sometimes gets one extra day?

Video. Coming soon. Why we have leap years: the Julian calendar of Julius Caesar, the Gregorian calendar reform of 1582 and the ten missing days in October (search NASA Space Place, Smithsonian, Royal Museums Greenwich, Homeschool Pop (Alternate), SciShow Kids, Science Max).

KEY TERMS

solar year
The time from one spring equinox to the next, about 365 days, 5 hours and 49 minutes (about 365.2422 days). The seasons repeat on this schedule.

leap year
A year with an extra day, February 29, added to keep the calendar in step with the solar year. A leap year has 366 days.

Julian calendar
The calendar begun by Julius Caesar in 46 B.C., with a leap day every fourth year, making its average year 365¼ days.

Gregorian calendar
The calendar set up by Pope Gregory XIII in 1582 and used for everyday dates around the world today. It skips three leap days every 400 years.

calendar drift
The slow slipping of calendar dates away from the real seasons when a calendar’s average year is a little too long or too short.

CORE IDEAS

The story. On the night of Thursday, October 4, 1582, in the little Spanish town of Alba de Tormes, an old nun named Teresa of Ávila died. She had spent her life founding convents and

writing books on prayer that are still read today. The sisters buried her the next day, and the date on that next day was Friday, *October 15*. No one had slept through ten days. That very night Spain, Portugal, Poland and most of Italy had switched to a new calendar, and in those lands the dates October 5 through October 14, 1582, simply never happened.

How they figured it out. The old calendar came from Julius Caesar, who in 46 B.C. set up a Roman calendar with the help of an astronomer from Alexandria named Sosigenes. Its year had 365 days, with an extra day added every fourth year, so its average year was 365¼ days. But the true **solar year** is about 11 minutes shorter than that. Eleven minutes a year adds up to about one whole day every 128 years. In A.D. 325 the church council at Nicaea knew the spring equinox fell around March 21, and churches used that date to work out Easter. By the 1500s the real equinox was coming around March 11 while the calendar still said March 21. Pope Gregory XIII asked scholars to fix the problem. The plan came from an Italian doctor and astronomer, Aloysius Lilius, and was checked and later explained in long books by Christopher Clavius, a German Jesuit mathematician in Rome. In February 1582 Gregory ordered the change.

The big idea. The reform did two things. First, it dropped ten days to put the spring equinox back near March 21. Second, it changed the leap-year rule so the calendar would not drift again. **A year that can be divided evenly by 4 is a leap year, except century years (ending in 00), which are leap years only if they can be divided evenly by 400.** So 1600 and 2000 were leap years, but 1700, 1800 and 1900 were not, and 2100 will not be. That leaves 97 leap days every 400 years instead of 100. The average **Gregorian** year is 365.2425 days, so close to the solar year that the calendar slips only about one day in 3,000 years.

In the world today. Not every country changed at once. Great Britain and its American colonies waited until 1752. By then the gap had grown to eleven days, so Wednesday, September 2, 1752, was followed by Thursday, September 14. George Washington had been born on February 11, 1731, by the old calendar; on the new calendar that same day is February 22, 1732, which is the birthday Americans remember. (The year changed too, because England had been starting its new year on March 25.) Russia changed in 1918 and Greece in 1923. Some Orthodox churches still keep the Julian calendar for their feast days, so their Christmas, December 25 on the old calendar, falls on January 7 on ours.

God’s handiwork. The Sun keeps its yearly appointment so exactly that an error of 11 minutes a year could be noticed, measured and fixed. Christian scholars like Lilius and Clavius did that careful arithmetic because they wanted to honor God by keeping His feasts at the right time. Moses prayed, “So teach us to number our days, that we may apply our hearts unto wisdom” (Psalm 90:12). Counting days rightly is good science, and it is also a reminder that each day is a gift.

October 1582

Sun	Mon	Tue	Wed	Thu	Fri	Sat
	1	2	3	**4**	**15**	16
17	18	19	20	21	22	23
24	25	26	27	28	29	30
31						

Thursday the 4th was followed by Friday the 15th.

Ten dates were skipped; the week went on without a break.

October 1582 in the lands that changed first. The days of the week went on without a break, but ten dates were skipped.

PICTURE STUDY



The Ambassadors, Hans Holbein the Younger, 1533 · Oil on oak panel · The National Gallery, London

Hans Holbein the Younger was a German painter who worked in London. In 1533 he painted two French friends: Jean de Dinteville, the French ambassador to England, on the left, and Georges de Selve, a bishop, on the right. Between them Holbein painted a whole table of scientific instruments, each one drawn so exactly that experts can tell how it worked.

When this picture was painted, all of Europe still used the Julian calendar, and astronomers already knew it had drifted away from the Sun. The instruments on the top shelf are tools for finding the time of day and the Sun's place in the sky: just the kind of measurements that later showed how to fix the calendar.

Look closely

- On the top shelf, find the tall cylinder-shaped sundial on the left. It is a traveler's sundial that tells the time from the Sun's height, and it must be set for the time of year.
- Find the globe of the stars on the top shelf and the globe of the Earth on the bottom shelf. Why would a gentleman want both?
- Look closely at the lute on the bottom shelf. One of its strings is broken.
- Find the long, stretched shape across the floor. If you look along it from the side, close to the edge of the picture, it turns into a skull, a reminder that our days are numbered.

Talk about it

1. Which instruments in this painting could help someone notice that the calendar and the Sun were out of step?
2. Why do you think Holbein painted the instruments with such care?
3. How does the hidden skull connect with Psalm 90:12, "So teach us to number our days"?

EXPERIMENT: LEAP-YEAR DETECTIVE: TESTING THREE CALENDAR RULES

Which leap-year rule keeps a calendar closest to the Sun? You will test three rules over the same 400 years, from 1601 to 2000, by coloring a chart and counting. Our question: **How far off from the Sun does each rule get in 400 years?** What we change: the leap-year rule. What we keep the same: the 400 years and the true length of the solar year, 365.2422 days. What we measure: how many leap days each rule adds, and how many days the calendar drifts from the Sun.

You will need

- Four sheets of graph paper
- Three colored pencils
- A pencil, a ruler and a calculator (optional)
- Lab notebook

Steps

1. On each sheet of graph paper, draw a 10-by-10 block of squares. Number the squares in the first block 1601 to 1700, the second 1701 to 1800, the third 1801 to 1900 and the fourth 1901 to 2000.
2. Rule A: no leap years at all. Write "0 leap days" in your notebook.
3. Rule B (Julian): every year divisible by 4 is a leap year. Put a small dot of your first color in each of those squares. Count the dots.

4. Rule C (Gregorian): every year divisible by 4, except century years not divisible by 400. Shade those squares with your second color. Look carefully at 1700, 1800, 1900 and 2000. Count the shaded squares.
5. Work out how many leap days the Sun really needs in 400 years: each year is about 0.2422 day longer than 365 days, and 400 × 0.2422 = 96.88, or about 97 days.
6. Make a table: Rule, Leap days added, Days needed (96.88), Days off from the Sun (the difference).
7. Draw a bar graph with one bar for each rule showing the days off from the Sun.
8. Write a conclusion: Which rule is best? Why didn't Gregory simply keep Caesar's rule?

Tips

- You should count 100 leap days under Rule B and 97 under Rule C.
- Rule A drifts almost 97 days in 400 years, more than three months. Under that rule, spring would arrive in what the calendar calls summer!
- Rule B is off by about 3 days (100 − 96.88 = 3.12). Rule C is off by about one-tenth of a day (97 − 96.88 = 0.12).

Check your work

- I tested three rules over the same 400 years and changed only the rule.
- I recorded my counts in a table and drew a bar graph.
- I can explain why the Gregorian rule skips three leap days every 400 years.

FIELD NOTEBOOK

1. Copy the October 1582 calendar page. Under it, write in your own words what happened to the ten missing dates and what did not change (the days of the week).
2. Draw a flow chart for the leap-year rule: Divisible by 4? Ends in 00? Divisible by 400? Test it on your birth year and the year you will turn 21.
3. Draw a timeline with these points: 46 B.C. (Julian calendar), A.D. 325 (Council of Nicaea), 1582 (Gregorian calendar), 1752 (Britain and the colonies change).

> **From history.** In Great Britain, Parliament passed the Calendar Act of 1750 to bring in the new calendar. The act also moved New Year's Day from March 25 to January 1. Because of that, the year 1751 in England and its colonies was a short year: it began on March 25 and ended on December 31. Then 1752 lost eleven days in September. Families in Virginia and Massachusetts had to learn the new calendar along with everyone in London.

WORKED EXAMPLES

Example 1. Use the Gregorian rule to decide whether each year is a leap year: 1900, 2000, 2024, 2100.

1. 2024: 2024 ÷ 4 = 506 with no remainder, and it is not a century year. Leap year.
2. 1900: divisible by 4, but it ends in 00, so test 400. 1900 ÷ 400 = 4.75, not even. Not a leap year.
3. 2000: ends in 00. 2000 ÷ 400 = 5 with no remainder. Leap year.
4. 2100: ends in 00. 2100 ÷ 400 = 5.25, not even. Not a leap year.

Answer: 2000 and 2024 are leap years; 1900 and 2100 are not.

Example 2. The Julian year averages 365.25 days, but the solar year is about 365.2422 days. (a) How much too long is the Julian year, in days and in minutes? (b) How many days did the calendar drift between the Council of Nicaea in 325 and the reform in 1582?

1. (a) Subtract: 365.25 − 365.2422 = 0.0078 day each year.
2. A day has 24 × 60 = 1,440 minutes. 0.0078 × 1,440 ≈ 11.2 minutes.
3. (b) Years from 325 to 1582: 1582 − 325 = 1,257 years.
4. Drift: 1,257 × 0.0078 ≈ 9.8 days, which rounds to 10 days.
5. That is why Gregory dropped exactly ten days: to put the equinox back where it was at the time of the Council of Nicaea.

Answer: (a) About 0.0078 day, or about 11 minutes, too long each year. (b) About 10 days.

PRACTICE

1. EASY Who began the Julian calendar, and how often did it add a leap day?
2. EASY Which pope gave his name to our calendar, and in what year was it introduced? What date came right after Thursday, October 4, that year?
3. MEDIUM Which of these are leap years in the Gregorian calendar: 1600, 1700, 2028, 2200?
4. MEDIUM How many leap years are there in 400 years of the Gregorian calendar? Show how you know.
5. MEDIUM Read the table.
   Spain: changed in 1582, dropped 10 days
   Great Britain and its colonies: 1752, 11 days
   Russia: 1918, 13 days
   Greece: 1923, 13 days
   (a) Which country changed first? (b) Why did countries that changed later have to drop more days?

6. HARD George Washington was born on February 11, 1731, by the old calendar. Today we say February 22, 1732. How many days were added to the date, and why did the year change too?
7. HARD Experiment design: A class wants to test whether Rule B (a leap day every 4 years) or Rule C (the Gregorian rule) keeps a calendar closer to the Sun. Name (a) what they change, (b) what they must keep the same and (c) what they measure.
8. CHALLENGE Right now the Julian calendar is 13 days behind the Gregorian calendar. In the year 2100 the gap will grow to 14 days. Explain why.

COMMON MISTAKES

- Thinking every fourth year is always a leap year. Century years are leap years only if they can be divided by 400, so 1900 and 2100 are not leap years.
- Thinking people in 1582 lost ten days of their lives. No time was lost; only the names of the dates were changed so the calendar matched the Sun again.
- Thinking the days of the week were skipped too. Thursday, October 4, was followed by Friday, October 15. The weeks went on without a break.

Make it a game · Leap or Land. Your parent calls out a year, such as 1996, 1900, 2000 or 2031. If it is a leap year, jump in the air (leap!). If it is not, stand still (land). Then say which part of the rule decided it. Score a point for each right answer. Tricky century years count double. Play to fifteen.

Scripture. “So teach us to number our days, that we may apply our hearts unto wisdom.” (Psalm 90:12, KJV)

Moses asked God to teach His people to count their days wisely. Keeping an honest calendar is careful counting, and it reminds us that every day is given by God and should be used well.

Practice answers

1. Julius Caesar, in 46 B.C. It added a leap day every fourth year.
2. Pope Gregory XIII, in 1582. The next day was Friday, October 15.
3. 1600 (divisible by 400) and 2028 (divisible by 4, not a century year) are leap years. 1700 and 2200 are century years not divisible by 400, so they are not.
4. 97. Every fourth year gives $400 \div 4 = 100$, but three of the four century years are skipped, so $100 - 3 = 97$.
5. (a) Spain. (b) The Julian calendar kept leap days in 1700, 1800 and 1900, but the Gregorian calendar skipped them. Each skipped leap day made the gap one day bigger: 10 days before 1700, 11 after 1700, 12 after 1800 and 13 after 1900.
6. 11 days were added, the size of the gap between the calendars by 1752. The year changed because England used to start the new year on March 25, so a February date belonged to the old year; on the new calendar the year starts January 1, making it 1732.
7. (a) The leap-year rule. (b) The same span of years for both rules (for example 400 years) and the same true solar year length (365.2422 days). (c) The number of leap days each rule adds and how many days each calendar ends up off from the Sun.

8. The year 2100 is divisible by 4, so the Julian calendar will give it a leap day (February 29, 2100). The Gregorian calendar will skip that leap day because 2100 is not divisible by 400. One calendar gains a day the other does not, so the gap grows from 13 to 14 days.

7.4 Passover and Easter Dates

OBJECTIVES

- Explain how the Hebrew calendar uses both the Moon and the Sun to keep Passover in the spring.
- Use the rule most churches follow (the first Sunday after the first full moon on or after March 21) to find the date of Easter.
- Calculate the gap between twelve lunar months and a solar year, and explain why an extra month is sometimes added.

Warm-up. Ask your family, or look at old calendars, to find the date of Easter in the last four years. Write the dates in a list. Christmas is always December 25, so why does Easter jump around? Make a guess about what decides it before you read the lesson.

Video. Coming soon. How the date of Easter is set: Passover in Exodus 12, lunar months, the Hebrew lunisolar calendar, the Council of Nicaea and the full-moon rule (search NASA moon-phase resources, Royal Museums Greenwich, Moody Science classics, Homeschool Pop (Alternate), and Christian history channels for families).

KEY TERMS

lunar month
The time from one new moon (or full moon) to the next, about 29½ days.

lunisolar calendar
A calendar whose months follow the Moon but which adds an extra month in some years so that it stays in step with the Sun and the seasons. The Hebrew calendar is lunisolar.

Passover
The feast God gave Israel in Exodus 12 to remember their rescue from Egypt. The Passover lamb was killed on the evening of the fourteenth day of the first month, in spring.

Nisan
The first month of the Hebrew religious year, called Abib in Exodus. It begins at a new moon in the spring.

paschal full moon
The first full moon on or after the church’s spring equinox date, March 21. Easter is the Sunday after it. *Paschal* comes from *Pascha*, the Greek and Latin word for Passover.

CORE IDEAS

The story. In the year 664, the household of King Oswiu of Northumbria, in the north of England, had a strange problem at Easter. The king had learned his faith from Irish monks, who worked out the date of Easter one way. His wife, Queen Eanflæd, had grown up in Kent, where the churches used the reckoning followed in Rome. The Venerable Bede, the monk

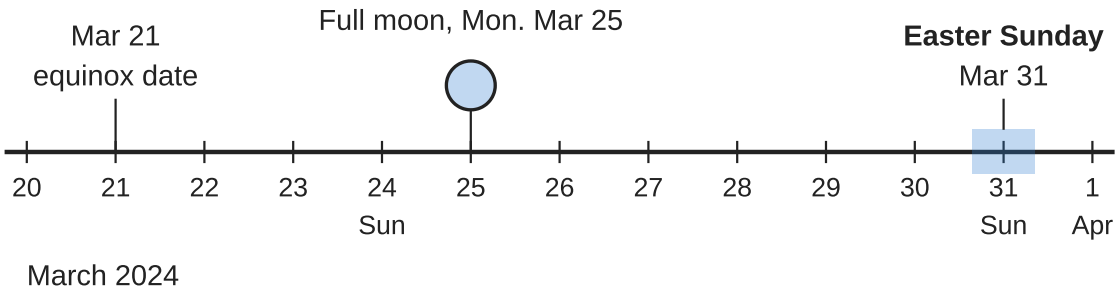
who later wrote the history of the English church, tells us that Easter was sometimes kept twice in one year at court: the king had finished the Lenten fast and was celebrating Easter while the queen and her people were still fasting and keeping Palm Sunday. So the king called a meeting at the abbey of Whitby to settle the question. After hearing both sides, he chose the Roman way.

How they figured it out. Easter's date comes from Passover, and Passover's date comes from the Moon. God told Moses, "This month shall be unto you the beginning of months" (Exodus 12:2). That month, Abib, later called **Nisan**, comes in the spring, and the Passover lamb was killed on "the fourteenth day of the same month" (Exodus 12:6). Hebrew months begin at the new moon, so the fourteenth day falls near the full moon. But a **lunar month** lasts only about 29½ days, and twelve of them make about 354 days, about 11 days short of a solar year. If nothing were done, Passover would come 11 days earlier every year and drift back into winter. So in some years a thirteenth month is added. In Bible times this was done by watching the season; later the Jewish calendar fixed the pattern at seven extra months in every 19 years. A calendar that follows both the Moon and the Sun is called a **lunisolar calendar**.

The big idea. Jesus was crucified at Passover time and rose from the dead on the first day of the week (Matthew 28:1). From the beginning, Christians remembered His resurrection every year. Some early churches kept it on the fourteenth day of the month, whatever day of the week that was; most kept it on a Sunday. In A.D. 325 the bishops who met at the Council of Nicaea, in what is now Turkey, agreed that all Christians should keep Easter together on a Sunday. The rule most churches came to use is this: **Easter is the first Sunday after the first full moon on or after March 21.** The church counts March 21 as the spring equinox and uses printed tables of full moons that usually match the real Moon within a day or so. So Easter always falls between March 22 and April 25.

In the world today. Look at the diagram for 2024. The first full moon after March 21 came on Monday, March 25, so Easter was the next Sunday, March 31. Western churches, Catholic and Protestant, work out Easter with the Gregorian calendar. Many Orthodox churches still use the Julian calendar's March 21 and older moon tables, so their Easter often comes one or more weeks later. In 2024 Orthodox Easter fell on May 5. In some years the two dates match: in 2025 both fell on April 20. Passover still follows the Hebrew calendar, so it usually comes near Easter, though not always in the same week.

God's handiwork. "He appointed the moon for seasons" (Psalm 104:19). The Moon's steady phases are a calendar hung in the sky for every nation to read. The apostle Paul wrote, "For even Christ our passover is sacrificed for us" (1 Corinthians 5:7). The lamb of Exodus pointed forward to Christ, and the full moon of spring still points us each year toward the cross and the empty tomb. Monks like Bede studied the Sun and Moon with great care so that the whole church could rejoice together.



Equinox date, then the first full moon, then the next Sunday

Finding Easter in 2024: start at March 21, find the first full moon (Monday, March 25), then go to the next Sunday (March 31).

PICTURE STUDY



The Feast of the Passover (from the Altarpiece of the Holy Sacrament), Dieric Bouts, 1464–1468 · Oil on oak panel · St. Peter's Church, Leuven, Belgium

Dieric Bouts was a painter in the Flemish town of Leuven. A brotherhood of the town's church asked him to paint an altarpiece about the Lord's Supper. In the middle he painted Jesus with His disciples at the Last Supper. On the wings beside it he painted four scenes from the Old Testament that point toward that supper. One of them is the first Passover in Egypt.

God told Israel to eat the Passover lamb "with your loins girded, your shoes on your feet, and your staff in your hand" (Exodus 12:11), ready to leave Egypt that very night. Bouts painted the Israelites in clothes of his own day, standing around the table exactly as Exodus describes.

Look closely

- Find the roasted lamb on the table. What else is on the table?
- Count the people standing around the table. Why are they standing instead of sitting?
- Find the walking staffs. What does a staff tell you about where these people are about to go?
- Look at the room, the windows and the clothes. Does it look like ancient Egypt or like a town in Bouts's own time?

Talk about it

1. Why did Bouts place the Passover beside the Last Supper in the same altarpiece?
2. Passover came in the month of Abib, near a full moon in spring. Why would a bright full moon be helpful on a night of travel?
3. How does this painting help explain why Christians call Easter by the name *Pascha* in many languages?

EXPERIMENT: MOON YEAR VERSUS SUN YEAR

How fast does a calendar of twelve moon-months slip away from the seasons? You will build a paper model at a scale of 1 millimeter for each day. Our question: **How many years does it take for twelve-month moon years to fall a whole month behind the Sun?** What we change: the number of years. What we keep the same: the scale (1 mm = 1 day), the length of a sun year (365 days) and the length of a moon year (12 months of about 29½ days, or 354 days). What we measure: the gap between the end of the sun strips and the end of the moon strips. Then you will use the full-moon rule to find this year's Easter.

You will need

- A roll of adding-machine tape or long strips of paper
- A meter stick or metric ruler, a pencil and scissors
- Two colors of markers
- A calendar for this year with the dates of full moons (many wall calendars show them, or use the U.S. Naval Observatory moon phase tables)
- Lab notebook

Steps

1. Write your prediction: after how many years will the moon calendar be a whole lunar month (about 29½ days) behind the Sun?
2. Cut three sun-year strips, each 365 mm (36.5 cm, about 14⅜ in) long. Color them yellow and label them Year 1, 2 and 3.
3. Cut three moon-year strips, each 354 mm (35.4 cm, about 14 in) long. Color them blue.
4. Lay one sun strip and one moon strip side by side with their left ends even. Measure the gap at the right end and record it.

5. Add a second strip to each row, end to end, and measure the gap again. Then add the third and measure again.
6. Make a table: Years, Sun days, Moon days, Gap in days.
7. When the gap is bigger than 29½ days, cut a short blue strip 30 mm long for an extra month and add it to the moon row. Is the moon row now back in step?
8. Calculate without strips: how big would the gap be after 19 years (19 × 11 days)? How many extra months of about 29½ days fit into that gap?
9. Now find Easter for this year: start at March 21 on the calendar, find the first full moon on or after that date, then find the next Sunday. Check your answer against a church calendar.

Tips

- You should find gaps of 11, 22 and 33 days. After 3 years the moon calendar is more than a month behind, so it needs a thirteenth month.
- After 19 years the gap is about 19 × 11 = 209 days, and 7 × 29½ = 206½, so about 7 extra months are needed. That is why the Hebrew calendar adds 7 months in every 19 years.
- If the full moon falls on a Sunday, Easter is the following Sunday, not the same day.

Check your work

- I changed only the number of years and kept the scale and strip lengths the same.
- I recorded the gap in a table and explained when an extra month is needed.
- I found this year's Easter date using the full-moon rule.

FIELD NOTEBOOK

1. Draw the Moon's phases in a circle: new moon, first quarter, full moon, last quarter. Label the new moon "Day 1 of a Hebrew month" and the full moon "about Day 14 or 15."
2. Copy the 2024 Easter timeline and make a new one for this year, marking March 21, the full moon and Easter Sunday.
3. Write Exodus 12:2 in your best handwriting and draw a spring scene beneath it: barley in the field and a full moon rising.

> **From history.** In 725 the Venerable Bede finished *The Reckoning of Time* at his monastery in Jarrow, in northern England. It taught monks how to count days, months and years, how the Moon's phases work and how to find the date of Easter. Bede also helped spread the habit of counting years from the birth of Christ, *Anno Domini* ("in the year of our Lord"), a system begun by a monk named Dionysius Exiguus while he was making Easter tables. Every time you write A.D., you use a dating system that came from working out the date of Easter.

WORKED EXAMPLES

Example 1. In 2024 the first full moon after March 21 came on Monday, March 25. On what date was Easter?

(Use the map or drawing "Equinox date, full moon, then the next Sunday." shown earlier in this lesson.)

1. Start at the church's equinox date, March 21.
2. Find the first full moon on or after March 21: Monday, March 25.
3. Find the next Sunday after the full moon. Monday is the 25th, so Tuesday is the 26th, Wednesday 27th, Thursday 28th, Friday 29th, Saturday 30th and Sunday 31st.
4. Easter is the first Sunday after that full moon: March 31.

Answer: Easter 2024 was Sunday, March 31.

Example 2. A lunar month is about 29½ days. (a) How many days are in 12 lunar months? (b) How many days short of a 365-day year is that? (c) After 3 years, how far behind the Sun is a twelve-month moon calendar, and what must be done?

1. (a) $12 \times 29\frac{1}{2} = 12 \times 29 + 12 \times \frac{1}{2} = 348 + 6 = 354$ days.
2. (b) $365 - 354 = 11$ days short each year.
3. (c) After 3 years: $3 \times 11 = 33$ days behind.
4. 33 days is more than one lunar month of 29½ days, so a thirteenth month must be added to bring the calendar back near the seasons.

Answer: (a) 354 days. (b) 11 days. (c) 33 days behind, so an extra (thirteenth) month must be added.

PRACTICE

1. EASY About how many days pass from one full moon to the next?
2. EASY According to Exodus 12, in which month and on which day was the Passover lamb killed? In which season does that month come?
3. MEDIUM In a certain year the first full moon on or after March 21 falls on Wednesday, April 2. When is Easter?
4. MEDIUM In a certain year the first full moon after March 21 falls on Sunday, April 13. Is Easter on April 13? Explain.
5. MEDIUM Read the table of Easter dates.
   2024: Western Easter March 31; Orthodox Easter May 5
   2025: Western April 20; Orthodox April 20
   2026: Western April 5; Orthodox April 12
   (a) In which year did both fall on the same day? (b) How many days apart were they in 2024? (c) In 2026?

6. HARD What is the earliest possible date for Easter under the full-moon rule? Explain how it could happen.
7. HARD Experiment design: A student models a twelve-month moon calendar with paper strips to see how fast it drifts from the seasons. Name (a) what the student changes, (b) two things that must stay the same, (c) what is measured and (d) which strip is the standard everything is compared to.
8. CHALLENGE The Greek astronomer Meton noticed that 19 solar years almost exactly equal 235 lunar months. Check him: use 365.24 days for a solar year and 29.53 days for a lunar month. How close are they?

COMMON MISTAKES

- Thinking Easter is simply the first Sunday after the first spring full moon, and forgetting the word “after.” If that full moon falls on a Sunday, Easter is the next Sunday.
- Thinking our calendar months follow the Moon. Our months (30 or 31 days, February 28 or 29) are set by the Sun-based calendar and do not match the Moon’s 29½-day cycle, so full moons fall on different dates each month.
- Thinking Passover and Easter always fall on the same day. Passover follows the Hebrew lunisolar calendar and begins on different days of the week in different years; Easter is always a Sunday, and the two calendars’ rules for the spring moon are different.

> **Make it a game · Easter Hunt on the Calendar.** Your parent draws a two-month calendar page for March and April and secretly puts a full-moon circle on two or three dates, some before March 21 and some after. You find the first full moon on or after March 21 and then the next Sunday, and circle Easter. Score a point for each correct Easter. For a bonus point, say what happens if the full moon falls on a Sunday. Take turns being the one who hides the moons.

> **Scripture.** “He appointed the moon for seasons: the sun knoweth his going down.” (Psalm 104:19, KJV)

The Moon marks months and feasts, and the Sun marks days and years. Passover and Easter are set by both together, a sign that God made the lights in the sky to serve His people.

Practice answers

1. About 29½ days.
2. In the first month, Abib (later called Nisan), on the evening of the fourteenth day. It comes in the spring.
3. The next Sunday after Wednesday, April 2: Sunday, April 6.
4. No. Easter is the first Sunday *after* the full moon, so when the full moon falls on a Sunday, Easter is the following Sunday, April 20.
5. (a) 2025. (b) March 31 to April 30 is 30 days, plus 5 more to May 5, so 35 days (5 weeks). (c) April 5 to April 12 is 7 days (1 week).

6. March 22. If the full moon falls on Saturday, March 21 (the church’s equinox date), the next day, Sunday, March 22, is Easter.
7. (a) The number of years laid end to end. (b) The scale (1 mm per day) and the lengths of the strips (365 mm for a sun year, 354 mm for a moon year). (c) The gap between the ends of the two rows, in days. (d) The sun-year strips, because the seasons follow the Sun.
8. 19 × 365.24 = 6,939.56 days. 235 × 29.53 = 6,939.55 days. They differ by only about 0.01 day, a few minutes. That is why a 19-year pattern (12 × 19 = 228 regular months plus 7 extra = 235 months) keeps a lunisolar calendar in step.

Unit 7 review

Answer each question. Show your work for calculations and use complete sentences for explanations. The quiz is worth 50 points.

1. (5 pts) Explain what causes the seasons. Name the two ways the tilt makes summer warmer than winter.
2. (5 pts) Earth is closest to the Sun in early January. Use this fact to show that distance does not cause the seasons.
3. (5 pts) A flashlight held straight down lights 10 squares of graph paper. Tipped at a slant from the same distance, it lights 20 squares. Compare the light on each square and connect your answer to winter.
4. (5 pts) Name the two solstices and two equinoxes and give the approximate date of each.
5. (5 pts) A town is at 35° north latitude. Find the noon Sun height on the equinoxes, the June solstice and the December solstice.
6. (5 pts) On the June solstice, where is the noon Sun straight overhead? What happens north of the Arctic Circle that day? What season begins in the Southern Hemisphere?
7. (5 pts) The Julian year was about 0.0078 day (about 11 minutes) too long. Explain why Pope Gregory XIII dropped ten days in 1582. Show the calculation from 325 to 1582.
8. (5 pts) Use the Gregorian rule to decide whether each is a leap year: 1800, 2000, 2032, 2300. Give a reason for each.
9. (5 pts) In a certain year the first full moon on or after March 21 falls on Saturday, April 5. When is Easter? What would Easter be if that full moon had fallen on Sunday, April 6 instead?
10. (5 pts) Why does the Hebrew calendar sometimes add a thirteenth month? Use numbers in your answer.

Unit project: my wheel of the year

Make a large round poster, a Wheel of the Year, that shows how the Sun and Moon set our seasons and calendar. Divide it into four parts at the two solstices and two equinoxes. At each one, draw Earth with its tilted axis in the right place around the Sun, write the date, and give the noon Sun height and day length for your own town (use your latitude and the NOAA Solar Calculator). Around the rim, mark the months and February 29 with the leap-year rule written beside it. In one corner, show this year’s Easter: March 21, the first full moon and the Sunday after it.

Beside the wheel, include your flashlight-angle data table, your day-length globe results and your leap-year bar graph, and write a paragraph explaining what causes the seasons and why our calendar needs leap days.

- **Accuracy**: The tilt is drawn pointing the same way all year, the solstices, equinoxes and seasons are correctly placed, and the noon Sun heights and Easter date are calculated correctly.

- **Records**: The flashlight table, day-length results and leap-year graph are complete, labeled with units and include what was changed, kept the same and measured.
- **Explanation**: The paragraph explains sun angle and day length, rejects the distance idea, and tells why leap days and the 1582 reform were needed.
- **Care**: The wheel is neat, colorful and easy to read, with clear labels and careful drawings.

Answer key

1. Earth’s axis is tilted about 23.5° and keeps pointing the same way as Earth travels around the Sun, so each hemisphere leans toward the Sun for part of the year and away for part. When a hemisphere leans toward the Sun it has summer because (1) the Sun is higher and its rays strike more directly, and (2) the days are longer.
2. If being closer caused summer, the Northern Hemisphere would have summer in January. Instead it has winter then. Also, the two hemispheres have opposite seasons at the same time, though they are the same distance from the Sun.
3. At the slant the same light is spread over twice as many squares, so each square gets half as much light (1/20 instead of 1/10). Low winter sunlight is spread out the same way, so it warms the ground less.
4. March equinox, about March 20; June solstice, June 20 or 21; September equinox, September 22 or 23; December solstice, December 21 or 22.
5. Equinoxes: 90° − 35° = 55°. June solstice: 55° + 23.5° = 78.5°. December solstice: 55° − 23.5° = 31.5°.
6. Straight overhead on the Tropic of Cancer, 23.5° north. North of the Arctic Circle the Sun does not set (the midnight sun). Winter begins in the Southern Hemisphere.
7. 1582 − 325 = 1,257 years. 1,257 × 0.0078 ≈ 9.8, about 10 days. The calendar had drifted about ten days from the Sun since the Council of Nicaea, so the spring equinox was coming around March 11 instead of March 21. Dropping ten days put it back.
8. 1800: no (century year not divisible by 400). 2000: yes (divisible by 400). 2032: yes (divisible by 4, not a century year). 2300: no (century year not divisible by 400).
9. Easter is Sunday, April 6, the first Sunday after the full moon. If the full moon fell on Sunday, April 6, Easter would be the next Sunday, April 13.
10. Its months follow the Moon. Twelve lunar months of about 29½ days make about 354 days, about 11 days shorter than the 365-day solar year. Without an extra month, Passover would come 11 days earlier each year and drift out of spring. After about 3 years the gap is more than a month (33 days), so a thirteenth month is added, seven times in every 19 years.

UNIT 8

Navigation by the Sky

Long before satellites and phone maps, travelers found their way by the sky. God made the lights in the heavens “for signs, and for seasons, and for days, and years” (Genesis 1:14), and for thousands of years sailors, caravan leaders and people walking to freedom read those signs to know where they were and which way to go. In this unit you will learn to do the same: to find north and south from the stars, to measure the sky in degrees, and to turn a star’s height into your own latitude.

You will follow Harriet Tubman north by the light of Polaris, learn the astrolabe alongside ten-year-old Lewis, for whom Geoffrey Chaucer wrote a book, and sail south of the equator with the Portuguese until the North Star disappears and the Southern Cross rises in its place. You will build and test your own straw astrolabe. Last, you will read Matthew 2 carefully and think like both a scientist and a Bible reader about the star that led the wise men to the young child Jesus.

BEFORE YOU BEGIN

- Knows that the earth rotates once a day and that this makes the sky seem to turn (Unit 1)
- Can read a protractor and measure angles in degrees
- Can find north, south, east and west with a compass
- Can multiply and divide whole numbers and simple decimals

MASTERY CHECKLIST

- I can find Polaris using the pointer stars of the Big Dipper and explain why it seems to stay still.
- I can measure a star’s altitude with my fists or a straw astrolabe and use Polaris to find my latitude.
- I can name the parts of an astrolabe and explain how sailors measured the sun safely.
- I can find the south celestial pole using the Southern Cross and the Pointers.
- I can retell Matthew 2 accurately and compare the Magi’s star with the way ordinary stars move.

OPTIONAL BOOKS AND RESOURCES

- **Stellarium (free planetarium software)** (https://stellarium.org/): Free for computers, with a web version. Set your location to see tonight’s sky, find Polaris and the Big Dipper, then “travel” to Sydney, Australia, to see the Southern Cross (Lessons 8.1 and 8.3). You can also set the date back to 7 B.C. to watch Jupiter and Saturn meet (Lesson 8.4).
- **NASA Skywatching** (https://science.nasa.gov/skywatching/): Free. Monthly guides to what is visible in the night sky, including bright planets and conjunctions, written for

families.

- **NASA Night Sky Network** (https://nightsky.jpl.nasa.gov/): Free. Find a local astronomy club and its public star parties, where volunteers will help you find Polaris and let you look through their telescopes.

8.1 Polaris, the North Star ★

OBJECTIVES

- Find Polaris in the night sky by following the pointer stars of the Big Dipper.
- Explain why Polaris seems to stay still while the other stars circle around it.
- Measure the height of Polaris above the horizon in degrees and use it to find your latitude.

Warm-up. Sit on a spinning office chair (or stand and turn slowly in place) and look straight up at the ceiling. Pick one spot right above your head and one spot near the wall. As you turn, which spot seems to stay in the same place, and which one swings around you? Write one sentence about what you noticed.

Video. Coming soon. Finding Polaris with the Big Dipper pointer stars, star-trail time-lapse around the North Star, and how latitude equals Polaris's height; search NASA, NASA Night Sky Network, planetarium channels, SciShow Kids and Homeschool Pop (Alternate).

KEY TERMS

Polaris
The North Star: a star that sits almost exactly above the earth's North Pole, so it stays nearly still in the sky all night and all year.

pointer stars
The two stars at the end of the Big Dipper's bowl, Merak and Dubhe. A line through them points to Polaris.

altitude
How high something is above the horizon, measured as an angle in degrees, from 0° at the horizon to 90° straight overhead.

latitude
How far north or south of the equator a place is, measured in degrees from 0° at the equator to 90° at a pole.

celestial pole
The point in the sky right above the earth's North or South Pole. The stars seem to circle around it as the earth turns.

circumpolar star
A star close enough to the celestial pole that it circles around it without ever setting below the horizon.

CORE IDEAS

The story. In 1849 a young woman named Harriet Tubman slipped away from a farm in Maryland where she had been held in slavery. Pennsylvania, a free state, lay about 145 kilometers (90 miles) to the north. She had no map and no compass. She traveled mostly at night and hid by day, and on clear nights she looked for one quiet star that never seemed to move. She kept that star in front of her, and it led her north to freedom in Philadelphia. In the years that followed, she went back again and again to lead others out, guided by the same star. It was **Polaris**, the North Star.

How they figured it out. Anyone who watches the sky for a few hours sees that the stars move. Like the sun, they rise in the east and set in the west. But people long ago noticed that the stars in the northern sky do not rise or set at all. They wheel in slow circles around one point, and Polaris sits almost exactly at the center, less than 1° away. To find it, start with the Big Dipper. The two stars at the outer end of its bowl, Merak and Dubhe, are the **pointer stars**. Draw a line from Merak through Dubhe and keep going about five times the space between them. The first fairly bright star you reach is Polaris, the end of the handle of the Little Dipper. Polaris is not the brightest star in the sky. Dozens of stars outshine it. It is special because of *where* it is.

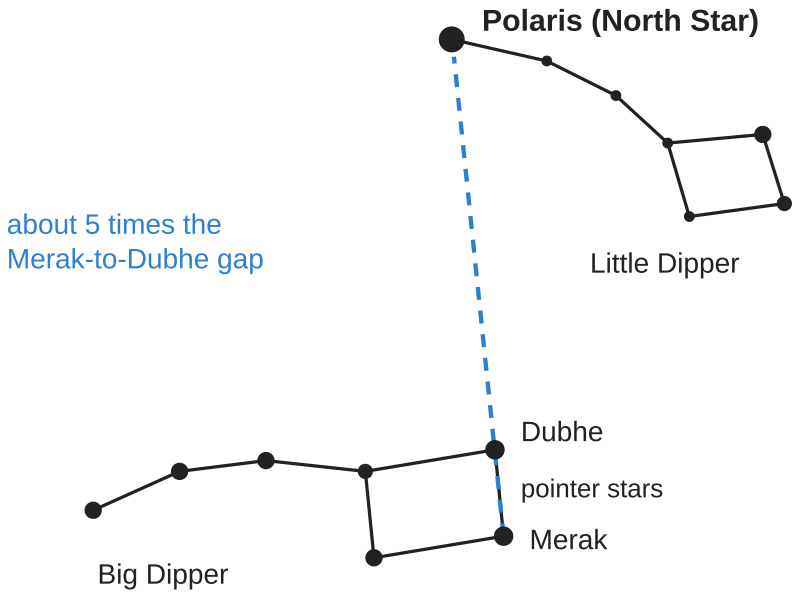
The big idea. Polaris stays still because the earth spins. Picture the earth's axis, the line it turns around once a day, poking out of the North Pole and running far out into space. It points almost straight at Polaris. A spot at the center of a merry-go-round barely moves while the edges swing around, and Polaris is like that center spot. The sky seems to turn a full 360° in about 24 hours, which is 15° every hour. Stars near Polaris, like the Big Dipper as seen from the northern United States, never set. They are **circumpolar stars**.

A second gift. Polaris also tells you how far north you are. Its **altitude**, its height above the horizon in degrees, is the same as your **latitude**. At the North Pole (90° N), Polaris is straight overhead. At the equator (0°), it sits right on the horizon. In the middle of the United States, around 40° N, it is a little less than halfway up the sky. South of the equator you cannot see it at all. Sailors used this for centuries. To reach a port, a captain sailed north or south until Polaris stood at the port's height, then turned east or west and kept Polaris at that same height until land appeared.

Try it and see. You do not need a tool to measure the sky roughly. Hold your arm straight out and make a fist. For most people, a fist at arm's length covers about 10° of sky. Rest the bottom of your fist on the horizon below Polaris and stack fist over fist until you reach the star. Four fists means about 40°, so you live near latitude 40° N. Check it with a map later. You will usually be within a few degrees.

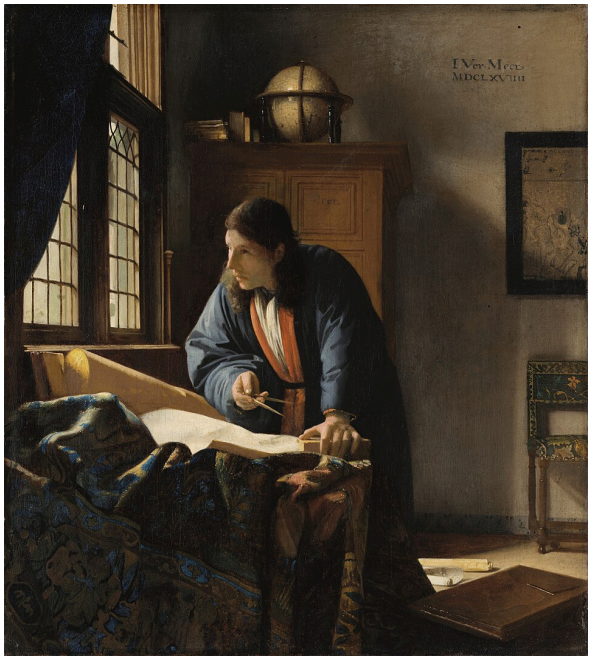
God's handiwork. God said the lights in the sky would be "for signs, and for seasons, and for days, and years" (Genesis 1:14). He made the earth spin steadily and placed a star near the point its axis aims at, so that travelers in every century could find their way. In Job 38:32 God asks Job, "canst thou guide Arcturus with his sons?" Many Bible scholars think the star

group named there is the Great Bear, the group that holds the Big Dipper. The same stars that pointed Harriet Tubman north were known to God long before anyone named them.



Follow the pointer stars, Merak and Dubhe, about five times the gap between them to reach Polaris.

PICTURE STUDY



The Geographer, Johannes Vermeer, 1669 · Oil on canvas · Städel Museum, Frankfurt, Germany

Johannes Vermeer lived and painted in the Dutch city of Delft. In his day the Dutch were among the greatest sailors in the world, and their ships crossed every ocean. Map makers

and geographers were busy drawing coastlines, measuring latitudes and printing globes and sea charts for captains.

In this painting a geographer has paused in his work and looks up toward the window, as if a thought has just come to him. Vermeer painted a companion picture, *The Astronomer*, around the same time, and many think the same man posed for both.

Look closely

- Find the pair of dividers in the man’s hand. Map makers used dividers to measure distances on a chart.
- Find the globe on top of the cabinet. Is it a globe of the earth or of the stars?
- Look at where the light comes from. What is the man looking at?
- Look for rolled-up charts and papers. What does the room tell you about his work?

Talk about it

1. Why would a sea captain need the work of a geographer before a long voyage?
2. A chart shows lines of latitude. How could a sailor use Polaris to find which latitude line his ship was on?
3. What do you think the geographer has just figured out?

> **Safety first.** Observe the night sky only with an adult, in a safe place away from roads, water and steep drop-offs. Bring a flashlight covered with red cellophane so you can see your notebook without losing your night vision.

EXPERIMENT: THE STILL STAR AND THE TURNING DIPPER

Is Polaris really still while the other stars move? You will test it like a scientist. On one clear night you will measure and sketch the sky twice, three hours apart, and compare.

You will need

- A clear night and an adult partner
- Notebook, pencil and a clipboard
- Flashlight covered with red cellophane or a red balloon stretched over the end
- A watch or clock
- A chair or a piece of tape on the ground to mark your exact spot
- A map or globe that shows your latitude (or an adult can look it up)

Steps

1. Question: Does Polaris stay in the same place while the Big Dipper moves? Write your prediction in your notebook.
2. What we keep the same: the exact spot where you stand, the direction you face (north), and the person whose fist measures the sky. Mark your spot with tape or a chair.

3. About an hour after dark, face north and find the Big Dipper. Follow the pointer stars to Polaris.
4. Sketch the horizon first: rooftops, trees or poles. Then sketch Polaris and the Big Dipper in their true places above those landmarks. Write the time.
5. Measure Polaris's altitude with fists at arm's length, starting with your bottom fist on the horizon. Record the number of fists and multiply by 10 to get degrees.
6. Measure the altitude of Dubhe the same way and record it.
7. Wait about 3 hours (or as long as your parent allows). Stand on the same spot, sketch again on the same page in a different color, and measure both stars again.
8. Compare: Which star changed position against the landmarks? Which stayed put? How many degrees did Dubhe's altitude change?
9. Look up your latitude. How close was your Polaris measurement?

Tips

- Let your eyes adjust to the dark for 10 to 15 minutes before you look for faint stars.
- In autumn evenings the Big Dipper sits low in the north, and in spring evenings it rides high. If it is hidden behind trees, find Cassiopeia, the bright W shape on the other side of Polaris.
- If 3 hours is too long, even 1 hour shows the Dipper turn about 15°.

Check your work

- I can find Polaris using the pointer stars.
- I measured Polaris's altitude and compared it with my real latitude.
- I can explain from my own sketches why Polaris seems to stand still.

FIELD NOTEBOOK

1. Draw the Big Dipper and the Little Dipper with the pointer line between them. Label Merak, Dubhe and Polaris.
2. Draw the earth with its axis sticking out of the North Pole and a long arrow running to a star labeled Polaris. Add a note: "The sky turns 15° each hour."
3. Draw yourself on a hill with your fists stacked up to Polaris. Write your latitude beside it.

> **From history.** Songs and stories passed along the Underground Railroad told people escaping slavery to keep the North Star ahead of them, and the antislavery newspaper Frederick Douglass started in Rochester, New York, in 1847 was named *The North Star*. On cloudy nights, travelers were also taught that moss tends to grow thickest on the shady north side of trees, though Polaris was far more reliable.

WORKED EXAMPLES

Example 1. On a clear night in Kansas, Grace measures Polaris with her fists at arm's length. It takes 3½ fists to reach Polaris from the horizon. About how high is Polaris, and about what is Grace's latitude?

1. One fist at arm's length covers about 10°.
2. 3½ fists × 10° per fist = 35°.
3. The altitude of Polaris equals the observer's latitude.
4. So Grace is at about latitude 35° N. (Kansas lies between about 37° N and 40° N, so her estimate is close for a fist measurement.)

Answer: Polaris is about 35° high, so Grace is near latitude 35° N.

Example 2. A photographer points a camera at Polaris and leaves the shutter open. When she looks at the picture, each star has drawn a curved trail around Polaris that covers 60° of a full circle. How long was the shutter open?

1. The sky seems to turn 360° in about 24 hours.
2. 360° ÷ 24 hours = 15° per hour.
3. 60° ÷ 15° per hour = 4 hours.

Answer: About 4 hours.

PRACTICE

1. EASY Name the two pointer stars of the Big Dipper. Which constellation is Polaris part of?
2. EASY True or false: Polaris is the brightest star in the night sky. Explain.
3. MEDIUM You stack 4½ fists at arm's length to reach Polaris. About what is your latitude?
4. MEDIUM Data table. The altitude of Polaris seen from four cities is: Miami, Florida 26°; Nashville, Tennessee 36°; Minneapolis, Minnesota 45°; Anchorage, Alaska 61°. (a) Which city is farthest north? (b) How many degrees higher is Polaris in Anchorage than in Miami? (c) A fifth city sees Polaris at 40°. Between which two cities does its latitude fall?
5. MEDIUM How many degrees does the sky seem to turn around Polaris in 3 hours? In 12 hours?
6. HARD Experiment design. Sam wants to test whether Polaris's altitude changes between 8 p.m. and 11 p.m. (a) What is the one thing he changes? (b) Name three things he must keep the same. (c) What does he measure? (d) Why is it a good idea to measure Dubhe at the same times too?
7. HARD Quito, Ecuador, is almost exactly on the equator. Sydney, Australia, is at about 34° S. Where would Polaris appear from each city?

8. CHALLENGE A ship leaves a port at 40° N, where Polaris is 40° high. Days later the navigator measures Polaris at 30°. Did the ship sail north or south? Each degree of latitude is about 111 km (69 miles). About how far north or south did it go?

COMMON MISTAKES

- Thinking Polaris is the brightest star. It is only medium-bright; its value is its position near the celestial pole.
- Thinking Polaris is straight overhead everywhere. It is overhead only at the North Pole; its height equals your latitude, and it cannot be seen south of the equator.
- Thinking the stars really move around the earth each night. The stars seem to circle because the earth rotates on its axis.

Make it a game · Point to the North Star. One player stands in the middle of the room as the "earth" and slowly turns. Another player holds a paper star high on the "north" wall (Polaris), while others hold paper stars on the side walls. The turning player calls out which stars seem to move past and which stays in the same place overhead. Then switch: the parent calls out a latitude such as 30°, 45° or 90°, and players race to hold an arm up at that angle toward Polaris. Closest arm wins a point.

Scripture. "Canst thou bring forth Mazzaroth in his season? or canst thou guide Arcturus with his sons?" (Job 38:32, KJV)

God asks Job whether he can lead the stars along their paths. Job cannot, and neither can we, but God does it every night. The steady circling of the northern stars around Polaris is a picture of His faithful order.

Practice answers

1. Merak and Dubhe. Polaris is the end of the handle of the Little Dipper (Ursa Minor, the Little Bear).
2. False. Dozens of stars are brighter (Sirius is the brightest). Polaris is important because it sits almost exactly above the North Pole, so it stays nearly still.
3. 4½ × 10° = 45°, so about latitude 45° N.
4. (a) Anchorage, because Polaris is highest there. (b) 61° − 26° = 35°. (c) Between Nashville (36°) and Minneapolis (45°).
5. 15° per hour × 3 = 45°. 15° × 12 = 180°, half a circle.
6. (a) The time of night. (b) Any three: the spot he stands on, the person and arm doing the measuring (or the same measuring tool), facing north, the same horizon point. (c) The altitude of Polaris in degrees (or fists). (d) Dubhe is a comparison: it should change while Polaris stays the same, which shows the measuring method can detect a change.
7. From Quito, Polaris sits right on the northern horizon (altitude about 0°), so it is very hard to see. From Sydney, Polaris is 34° below the horizon and can never be seen.
8. South, because Polaris got lower. It moved 40° − 30° = 10° of latitude, about 10 × 111 = 1,110 km (10 × 69 = 690 miles).

8.2 An Astrolabe

OBJECTIVES

- Name the main parts of an astrolabe and tell what each part does.
- Build a straw astrolabe and use it to measure the altitude of a star or a tall object.
- Use a measured altitude of Polaris, or of the noon sun on an equinox, to find latitude.

Warm-up. Lay a protractor flat on the table. Hold a pencil along its straight edge, then tilt the pencil up until it points at the top corner of a door or window. Ask a helper to guess the angle. How could you measure that angle exactly, without anyone touching the window?

Video. Coming soon. How a medieval brass astrolabe works and how to make a simple protractor-and-straw astrolabe; search museum channels (history of science museums, Smithsonian), NASA educator videos, Science Max and Homeschool Pop (Alternate).

KEY TERMS

astrolabe
An old instrument, usually made of brass, used to measure the altitude of the sun or a star and to work out the time, latitude and other sky facts.

alidade
The sighting bar on the back of an astrolabe. It has two small holes or slits that you line up with a star.

rete
The lacy, cut-out star map on the front of an astrolabe, with pointers for bright stars. It turns to show the sky at any hour.

zenith
The point in the sky straight above your head, at an altitude of 90°.

equinox
One of the two days each year, in March and September, when the sun is straight over the equator at noon and day and night are about equal everywhere.

CORE IDEAS

The story. Around the year 1391, in London, the poet Geoffrey Chaucer sat down to write a book for a ten-year-old boy. Chaucer is famous for *The Canterbury Tales*, but this book was for his son, Lewis. Lewis had asked to learn how to use an astrolabe, and Chaucer had given him one made for the latitude of Oxford. Most science books of that time were written in Latin. Chaucer wrote this one in plain English so that his boy could understand it. We call it *A Treatise on the Astrolabe*, and it is one of the oldest instruction books for a scientific

instrument written in English. A ten-year-old was learning to measure the sky, just as you will.

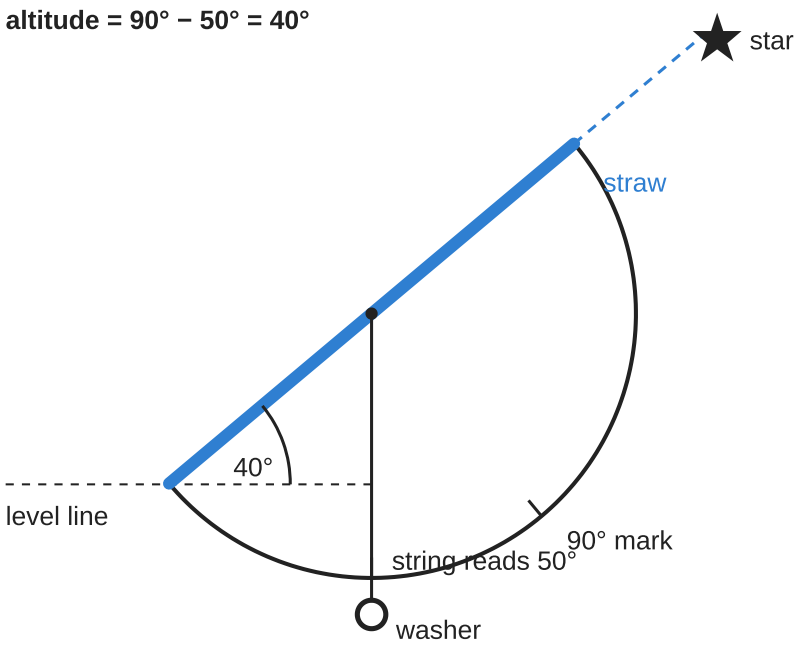
How they figured it out. The astrolabe was worked out by Greek astronomers long ago, improved by astronomers in the Islamic world, and carried into Europe in the Middle Ages. A fine astrolabe is a brass disk that fits in your hand. It hangs from a ring so it falls straight down. The body is called the *mater* (Latin for "mother"). Inside it rest thin plates engraved with lines for one latitude. On top lies the **rete**, a lacy cut-out map of the brightest stars that can turn around a center pin. On the back is the **alidade**, a sighting bar with a tiny hole at each end, turning over a ring marked in degrees. You hang the astrolabe, turn the alidade until a star shines through both holes, and read its altitude on the scale. Then, by turning the rete, you can find the time of night, the hour of sunrise and much more. It was a star map, a measuring tool and a calculator in one.

The big idea. Every use of the astrolabe begins with **altitude**, the angle of something above the horizon, from 0° at the horizon to 90° at the **zenith**. You already know one use from Lesson 8.1: the altitude of Polaris equals your latitude. The sun can tell you too. On the two **equinox** days in March and September, the noon sun stands straight over the equator, so your latitude is 90° minus the sun's noon altitude. On other days sailors used printed tables to correct for where the sun was that day.

Sailors take it to sea. In the late 1400s, Portuguese navigators sailing down the coast of Africa stripped the astrolabe down to what they needed. The mariner's astrolabe was a heavy brass wheel with open spokes, so the wind could blow through it without swinging it, plus an alidade and a degree scale. Sailors did not look at the sun through it, because that would hurt their eyes. Instead they turned the alidade until a spot of sunlight passing through the upper hole fell exactly on the lower hole, and then read the angle. On a rolling deck this was hard, but a careful navigator could find his latitude within a degree or so.

Try it and see. You can build a simple astrolabe with a protractor, a drinking straw, string and a washer. Tape the straw along the protractor's straight edge and hang the washer on a string from the center hole. When the straw is level, the string hangs across the 90° mark. Tilt the straw up toward a star, and the string swings away from 90°. The altitude is 90° minus the reading. If the string reads 50°, the star is 40° high.

In the world today. Ships and airplanes now use satellites to find their place, but navigators still learn to measure the sky in case the electronics fail. In 2015 the U.S. Naval Academy brought celestial navigation back into its classes for that very reason. The sky is a map that cannot be switched off. When David considered the heavens, "the work of thy fingers, the moon and the stars, which thou hast ordained" (Psalm 8:3), he saw order that people could trust and measure.



The string always hangs straight down. Altitude = 90° − the string reading.

PICTURE STUDY



Three Astronomers, from the Psalter of Blanche of Castile, Unknown French illuminator, about 1230 · Paint and gold leaf on parchment (manuscript illumination) · Bibliothèque de l’Arsenal, Paris

This tiny painting comes from a psalter, a hand-copied book of the Psalms, made in France for Queen Blanche of Castile, the mother of King Louis IX. Monks and craftsmen painted pictures like this with brushes as fine as a few hairs and laid real gold leaf behind the figures.

It is one of the oldest pictures in Europe of an astrolabe in use. The three scholars show the three jobs of an astronomer: observing, reading what others have found, and writing down the results.

Look closely

- Find the astrolabe. How is the man in the middle holding it? Why would he hold it up by a ring?
- Look at the man with the book. What might he be checking?
- Look at the man who is writing. What numbers might he be recording?
- Notice the gold background. Why do you think the painter used gold in a book of Psalms?

Talk about it

1. Why does a scientist need to observe, to read and to record? Which of those jobs do you do in your sketchbook?
2. This picture is in a book of Psalms. How do the Psalms and the study of the sky belong together?

> **Safety first.** Never look at the sun through your straw or any other instrument, even for a moment. Measure the sun only by its shadow, as in the tips below. Have an adult help with scissors, and observe at night only with an adult nearby.

EXPERIMENT: BUILD AND TEST A STRAW ASTROLABE

You will build a working astrolabe and test how trustworthy it is. A good scientist does not just trust a new instrument. He or she measures the same thing several times and sees how close the readings are.

You will need

- A plastic protractor with a hole at the center of its straight edge
- A drinking straw (a stiff, straight one works best)
- About 25 cm (10 inches) of thread or thin string
- A metal washer, nut or paper clip for a weight
- Clear tape and scissors
- Notebook and pencil
- A tall object outdoors, such as a flagpole, tree or roof corner, and a clear night for Polaris

Steps

1. Tape the straw along the straight edge of the protractor so you can sight through it.
2. Tie the string through the center hole and tie the washer to the other end so it hangs below the curved edge.

3. Test it: hold the straw level, using a book on a table to check. The string should hang across 90°. If it does not, retie the string at the exact center.
4. Question: How close together are three readings of the same target? Write a prediction, such as “within 2°.”
5. What we keep the same: the spot where you stand (mark it), the target, and the instrument. What we change: the trial number, and then the person measuring.
6. Sight the top of the tall object through the straw. Let the string stop swinging, pinch it against the protractor and read the number. Record it, then subtract from 90° to get the altitude.
7. Repeat two more times, then have a family member take three readings too. Make a table: Person, Trial, String reading, Altitude.
8. Find each person’s average altitude. How far apart were the highest and lowest readings?
9. On a clear night, with an adult, sight Polaris three times and average the altitudes. Compare with your latitude on a map.

Tips

- Hold the astrolabe gently by its edges and let the washer hang freely. Pressing on the string spoils the reading.
- To measure the sun safely, do not sight through the straw. Instead, tilt the protractor until the straw’s shadow is as small as possible (just a round spot on your hand or paper below). Then read the string.
- Readings within 1° to 2° of each other mean you have a steady hand and a good instrument.

Check your work

- I built an astrolabe that reads 90° when level.
- I took repeated readings and found the average.
- I used my astrolabe to estimate my latitude from Polaris.

FIELD NOTEBOOK

1. Draw a medieval astrolabe and label the mater, the rete and the alidade.
2. Draw your straw astrolabe pointed at a star, with the string hanging down. Write the string reading and the altitude.
3. Draw a sailor on a ship deck letting a spot of sunlight fall through the mariner’s astrolabe. Write: “Never look at the sun.”

> **From history.** Chaucer planned his astrolabe book in five parts but finished only the first two. Even so, it was copied by hand many times, and dozens of old manuscript copies still survive. Some of them include little diagrams of the astrolabe’s parts, drawn so that young Lewis could follow along.

WORKED EXAMPLES

Example 1. Lewis sights a star through his straw astrolabe. The string crosses the protractor at 55°. What is the star's altitude?

(Use the map or drawing "Altitude = 90° − string reading." shown earlier in this lesson.)

1. When the straw is level, the string reads 90°.
2. Tilting the straw up moves the string away from 90° by the same angle as the tilt.
3. Altitude = 90° − 55° = 35°.

Answer: The star is 35° above the horizon.

Example 2. On the September equinox, a navigator measures the sun at noon (safely, with the shadow method). Its altitude is 52°. What is the ship's latitude?

1. On an equinox, the noon sun is straight over the equator.
2. So latitude = 90° − the noon altitude of the sun.
3. Latitude = 90° − 52° = 38°.
4. The sun was in the southern part of the sky, so the ship is north of the equator.

Answer: The ship is at about latitude 38° N.

PRACTICE

1. EASY Match each part to its job: (a) alidade, (b) rete, (c) mater. Jobs: the main body that holds the plates; a sighting bar with two holes; a turning star map.
2. EASY What is the altitude of a star on the horizon? Of a star at the zenith?
3. MEDIUM Your straw astrolabe string reads 72° when you sight a bird's nest at the top of a tree. What is the nest's altitude?
4. MEDIUM Data table. Ruth sights Polaris four times. Her string readings are 49°, 51°, 50° and 50°. (a) Find the altitude for each reading. (b) Find the average altitude. (c) What is her latitude?
5. MEDIUM Why did Portuguese sailors make the mariner's astrolabe heavy, with open spokes?
6. HARD On the March equinox, the noon sun is 65° high where you live. What is your latitude?
7. HARD Experiment design. Ben wonders whether using a heavier weight on the string changes his astrolabe readings. (a) What is the variable he changes? (b) Name two things he keeps the same. (c) What does he measure? (d) How many trials should he do with each weight, and why?
8. CHALLENGE Explain in two or three sentences why sailors never looked straight at the sun through an astrolabe, and how they measured it instead.

COMMON MISTAKES

- Reading the string number as the altitude. On a protractor astrolabe the altitude is 90° minus the string reading.
- Thinking the noon sun's altitude equals your latitude. The rule is latitude = 90° − noon altitude, and only on the equinoxes without a correction.
- Thinking it is safe to look at the sun for a moment through a straw or tube. It never is; measure the sun only with shadows or a spot of light.

Make it a game · Altitude Guess and Check. Players take turns naming an object in the room or yard: the top of a door, a ceiling light, a treetop. Everyone writes a guess of its altitude in degrees from a marked spot. Then one player measures it with the straw astrolabe. The closest guess scores a point, and an exact guess scores three. After a few rounds, see whether everyone's guesses get better.

Scripture. "When I consider thy heavens, the work of thy fingers, the moon and the stars, which thou hast ordained; What is man, that thou art mindful of him? and the son of man, that thou visitest him?" (Psalm 8:3–4, KJV)

David measured nothing with brass, but he "considered" the heavens carefully. Every careful measurement of the sky is a kind of considering. The more exactly we see how God ordained the stars, the more amazing it is that He is mindful of us.

Practice answers

1. (a) alidade: the sighting bar with two holes. (b) rete: the turning star map. (c) mater: the main body that holds the plates.
2. 0° on the horizon; 90° at the zenith.
3. 90° − 72° = 18°.
4. (a) 41°, 39°, 40°, 40°. (b) (41 + 39 + 40 + 40) ÷ 4 = 160 ÷ 4 = 40°. (c) About 40° N.
5. The weight helped it hang straight down on a rolling ship, and the open spokes let the wind pass through so it would not swing.
6. 90° − 65° = 25°. You are at about latitude 25° N (about the latitude of Miami).
7. (a) The weight on the string (for example a paper clip, a washer, a large nut). (b) Any two: the same target, the same spot, the same person, the same protractor and string. (c) The string reading (or altitude) for the target. (d) At least three trials for each weight, so he can average them and see whether a difference is bigger than his normal hand wobble.
8. Looking at the sun can badly and permanently damage the eyes. Sailors held the astrolabe so sunlight passed through the hole in the upper vane of the alidade and turned it until the bright spot fell exactly on the lower hole. Then they read the sun's altitude from the scale without ever looking at the sun.

8.3 The Southern Cross

OBJECTIVES

- Explain why Polaris cannot guide travelers south of the equator and why the southern sky has no bright pole star.
- Find the south celestial pole using the Southern Cross and the Pointer stars.
- Use the altitude of the south celestial pole to find latitude in the Southern Hemisphere.

Warm-up. Hold a globe (or a ball with a dot drawn at the top for the North Pole). Stick a small piece of tape on the United States and another on Australia. Point a pencil straight up from each piece of tape. Which way does each pencil point into space? Could a person in Australia ever see a star that sits straight above the North Pole?

Video. Coming soon. Finding south with the Southern Cross and the Pointers (Alpha and Beta Centauri), the southern night sky and the False Cross; search NASA, planetarium and observatory channels from Australia and New Zealand, Stellarium tutorials and Homeschool Pop (Alternate).

KEY TERMS

Southern Cross
Crux, a small, bright constellation of four main stars shaped like a cross. It is used to find south in the Southern Hemisphere.

south celestial pole
The point in the sky right above the earth’s South Pole. Southern stars circle around it, but no bright star marks it.

the Pointers
Alpha Centauri and Beta Centauri, two bright stars beside the Southern Cross that help locate the south celestial pole.

Southern Hemisphere
The half of the earth south of the equator.

False Cross
A larger, dimmer cross-shaped group of stars near the Southern Cross that can fool beginners. It has no Pointers beside it.

CORE IDEAS

The story. In 1515 an Italian traveler named Andrea Corsali was sailing on a Portuguese ship around the bottom of Africa toward India. Far south of the equator, he looked up and saw a group of stars no one in Europe had ever seen from home. He wrote a letter back to Florence and described it as a marvelous cross of stars, so beautiful that he thought no other sign in the heavens could compare with it. He even drew it. His letter, printed in Florence in

1516, is one of the earliest European descriptions of the constellation we call the **Southern Cross**. The people of the Pacific islands and of Australia had known these stars for a very long time, but for Europeans it was a brand-new sight.

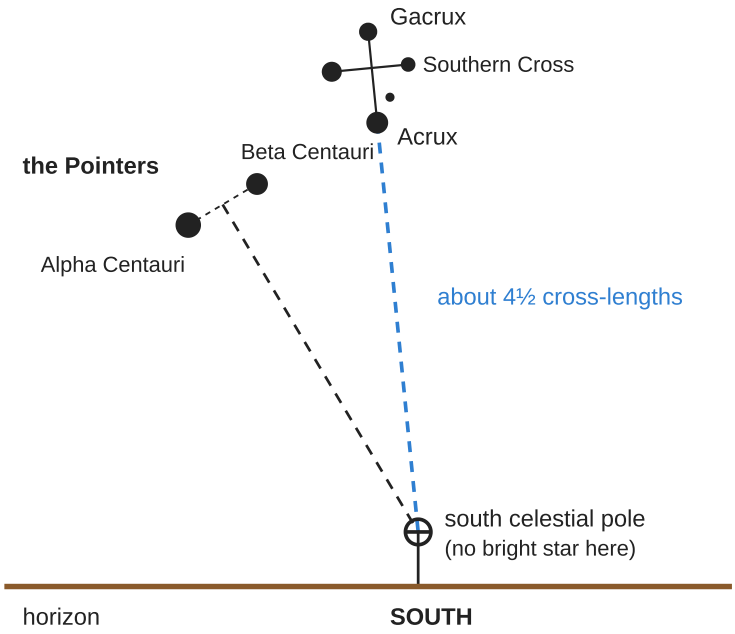
How they figured it out. When Portuguese ships first worked their way down the coast of Africa in the 1400s, sailors watched Polaris sink lower every night. Near the equator it touched the horizon, and then it was gone. Navigators needed a new guide, and the southern sky did not make it easy. There is a **south celestial pole**, a point the southern stars circle around, but no bright star sits on it. The nearest one, Sigma Octantis, is so faint it can barely be seen on a dark night. So sailors learned to find the empty pole point from stars nearby.

The big idea. Here is the method. Find the Southern Cross: four bright stars in a kite-like cross, with a fainter fifth star tucked between two of them. The long bar runs from Gacrux at the top to Acrux at the foot. Measure that long bar, and go about 4½ times its length beyond Acrux, in the same direction. That spot in the sky is close to the south celestial pole. Now check it with **the Pointers**, Alpha Centauri and Beta Centauri, two bright stars beside the Cross. Draw an imaginary line halfway between them, crossing at a right angle, and follow it. It runs to the same spot. Drop straight down from that spot to the horizon, and you are looking due south.

A mirror sky. Everything you learned about Polaris works the same way in the south, only upside down. The altitude of the south celestial pole equals your latitude south of the equator. In Sydney, Australia, at about 34° S, the pole point is 34° above the southern horizon. The southern stars circle around it once a day as the earth turns, so the Cross is seen upright, lying on its side, or even upside down depending on the hour and season. The Southern Cross is the smallest of all 88 constellations, but it is one of the brightest. Beginners sometimes mistake the **False Cross** for it. The False Cross is bigger and dimmer and has no Pointers beside it.

In the world today. The Southern Cross is so loved that it appears on the flags of Australia, New Zealand, Brazil, Samoa and Papua New Guinea. From most of the United States it never rises, but from Hawaii and the southernmost tips of Florida and Texas it peeks just above the southern horizon on spring evenings. Alpha Centauri, one of the Pointers, is the nearest bright star to our sun. With free planetarium software you can “travel” to Sydney tonight and see the Cross for yourself.

God’s handiwork. God did not leave half of the world without lights. He set guides in the southern sky as surely as in the northern. When sailors crossed the equator into unknown seas, the psalm was true for them: “If I take the wings of the morning, and dwell in the uttermost parts of the sea; Even there shall thy hand lead me” (Psalm 139:9–10).



Two ways to the south celestial pole: extend the Cross's long bar about 4½ times, or bisect the Pointers. Drop straight down to find due south.

PICTURE STUDY



Astrolabium (Amerigo Vespucci and the Southern Cross), from Nova Reperta, Designed by Jan van der Straet (Stradanus); engraved in Antwerp, about 1590s, published about 1600 · Engraving on paper · Copies in several collections, including the Metropolitan Museum of Art, New York

Jan van der Straet, called Stradanus, was a Flemish artist who worked in Florence. He designed a set of prints called *Nova Reperta*, which means "New Discoveries," to celebrate

the inventions and discoveries of his age: the compass, the printing press, eyeglasses, the clock and the New World.

In this print he imagines the Florentine explorer Amerigo Vespucci on a southern shore at night, measuring the stars with an astrolabe. Overhead shines the Southern Cross. Vespucci lived about a century before the print was made, so this is a picture of how people remembered him, not a portrait drawn on the spot.

Look closely

- Find the astrolabe. Compare it with the astrolabes you learned about in Lesson 8.2.
- Find the cross of stars in the sky. How many stars make it?
- Look around Vespucci. Who is awake, and who is not? What does that tell you about the hour?
- Find the ship. Why would sailors need to know their latitude to find their way home?

Talk about it

1. Why would the Southern Cross have seemed so wonderful to European sailors who had never seen it?
2. The artist put Vespucci's discovery of new stars in a series with the compass and the printing press. Why might he think finding new stars was as important as an invention?

> **Safety first.** Use scissors and a pushpin carefully, with an adult nearby. If you darken the room for the flashlight activity, clear the floor first so no one trips.

EXPERIMENT: DOES THE CROSS ALWAYS POINT SOUTH?

The Southern Cross turns around the pole all night, so sometimes it stands upright and sometimes it lies on its side. Does the "4½ lengths" rule still find the pole no matter how the Cross is turned? You will test it on a star chart you make yourself.

You will need

- A printout of the southern sky around the Southern Cross (from free planetarium software such as Stellarium, set to Sydney, Australia), or a careful copy of this lesson's figure
- A sheet of poster board or a large piece of paper
- Ruler marked in centimeters, pencil and a protractor
- A brass fastener or pushpin and a scrap of cardboard
- A small sticky note to hide the pole mark
- Notebook

Steps

1. Glue or tape your star chart to the poster board. Mark the south celestial pole with a dot (it is labeled in the software, or use the dot in the figure). Cover the dot with a

small sticky note so you cannot see it.
2. Push a fastener or pin through the hidden pole dot into cardboard underneath so the whole chart can spin around that point, the way the real sky turns.
3. Question: Does the 4½-lengths rule find the pole whether the Cross is upright, sideways or upside down? Write your prediction.
4. What we change: how far the chart is turned (0°, 90°, 180° and 270°). What we keep the same: the chart, the ruler, the rule (4½ lengths) and the person measuring. What we measure: how far, in centimeters, your guess lands from the real pole.
5. Turn the chart to 0°. Measure the Cross from Gacrux to Acrux in centimeters, multiply by 4.5, and mark that distance beyond Acrux along the same line. Lift the sticky note and measure how far your mark is from the pole. Record it.
6. Repeat at 90°, 180° and 270°.
7. Now try the Pointers method: find the midpoint between Alpha and Beta Centauri, draw a line from it at a right angle, and see whether it passes near the pole.
8. Make a table: Turn, Distance from pole (cm). Write a conclusion: Does the rule work at every hour of the night? Why?

Tips

- Your mark will not land exactly on the pole. The “4½ times” rule is a navigator’s shortcut, so a small miss is normal.
- If your chart is small, your measurements will be small too. Measure to the nearest millimeter.
- The rule works at every turn because the Cross, the Pointers and the pole all turn together around the same point.

Check your work

- I can find the Southern Cross, the Pointers and the south celestial pole on a chart.
- I tested the rule at four different turns and recorded my results.
- I can explain why the rule works at any hour.

FIELD NOTEBOOK

1. Draw the Southern Cross with its four main stars and the faint fifth star. Label Gacrux and Acrux, and add the Pointers.
2. Draw two globes side by side. On one, draw a person in the United States pointing to Polaris; on the other, a person in Australia pointing to the south celestial pole.
3. Sketch one of the flags that shows the Southern Cross, and count how many stars it uses for the Cross.

> **From history.** In 1520 Ferdinand Magellan’s ships, the first to sail all the way around the world, crossed into the far southern seas. Antonio Pigafetta, who kept a journal of the voyage, wrote about the southern stars and described two cloudy patches of light near

the south pole of the sky. Today those patches are called the Magellanic Clouds, after the captain of that voyage.

WORKED EXAMPLES

Example 1. A sailor measures the long bar of the Southern Cross, from Gacrux to Acrux, and finds it covers about 6° of sky. About how far beyond Acrux should she look for the south celestial pole?

(Use the map or drawing "Extend Gacrux to Acrux about 4½ times to reach the pole point." shown earlier in this lesson.)

1. The rule: go about 4½ times the length of the long bar beyond Acrux.
2. 4.5 × 6° = 27°.
3. She should look about 27° beyond Acrux, along the line from Gacrux through Acrux. That is a little under 3 fists at arm's length.

Answer: About 27° beyond Acrux.

Example 2. A family on holiday in Sydney, Australia (latitude about 34° S), finds the south celestial pole. How high above the horizon is it, and about how many fists is that?

1. In the Southern Hemisphere, the altitude of the south celestial pole equals your latitude south.
2. Sydney is at about 34° S, so the pole point is about 34° above the southern horizon.
3. One fist at arm's length is about 10°, so 34° ÷ 10° = 3.4 fists, a little more than 3 fists.

Answer: About 34° high, a bit more than 3 fists above the southern horizon.

PRACTICE

1. EASY Why can't a sailor in the Southern Hemisphere use Polaris?
2. EASY Name the two stars that form the long bar of the Southern Cross and the two Pointer stars.
3. MEDIUM Data table. The altitude of the south celestial pole from four cities is: Darwin, Australia 12°; Rio de Janeiro, Brazil 23°; Sydney, Australia 34°; Hobart, Australia 43°. (a) Which city is farthest south? (b) What is Rio's latitude? (c) How many degrees of latitude separate Darwin and Hobart?
4. MEDIUM On a chart, the Southern Cross's long bar measures 3 cm. How far beyond Acrux, in centimeters, should you mark the south celestial pole?
5. MEDIUM Give two ways to tell the real Southern Cross from the False Cross.

6. HARD Experiment design. Mia wants to know whether the “4½ lengths” rule works as well with the Cross upside down as upright. (a) What variable does she change? (b) What does she keep the same? (c) What does she measure? (d) What result would show the rule works at every turn?
7. HARD A ship sails south from the equator. On the first night the south celestial pole is on the horizon. Some nights later it is 20° high. About how far has the ship sailed? (Each degree of latitude is about 111 km, or 69 miles.)
8. CHALLENGE In two or three sentences, explain why the Southern Cross is sometimes seen upright and sometimes upside down, even though the stars in it never change their shape.

COMMON MISTAKES

- Thinking there is a bright “South Star” like Polaris. The south celestial pole has no bright star; it must be found from the Southern Cross and the Pointers.
- Thinking the Southern Cross itself marks south. It points toward the pole; you must extend its long bar about 4½ times and then drop to the horizon.
- Thinking you can see the same stars from everywhere on earth. Which stars you can see depends on your latitude.

> **Make it a game · Find South in the Dark.** Tape five glow-in-the-dark stars (or paper stars) on a wall or ceiling in the shape of the Southern Cross, and two more for the Pointers. A parent secretly puts a small mark where the south celestial pole should be. Turn out the lights. Each player uses a flashlight to trace from Gacrux through Acrux and on about 4½ lengths, then stops the beam where they think the pole is. The closest beam wins. Then the parent rotates the stars to a new position for the next round.

> **Scripture.** “If I take the wings of the morning, and dwell in the uttermost parts of the sea; Even there shall thy hand lead me, and thy right hand shall hold me.” (Psalm 139:9–10, KJV)

Sailors who crossed the equator lost sight of the star that had guided them all their lives. But they were not lost to God. He had placed new guides in the southern sky, and His hand reaches to the uttermost parts of the sea.

Practice answers

1. Polaris is above the North Pole, so south of the equator it is below the horizon and cannot be seen.
2. Long bar: Gacrux (top) and Acrux (foot). Pointers: Alpha Centauri and Beta Centauri.
3. (a) Hobart, because the pole is highest there. (b) About 23° S. (c) 43° − 12° = 31°.
4. 4.5 × 3 cm = 13.5 cm.
5. The real Cross is smaller and brighter, and it has the two bright Pointers (Alpha and Beta Centauri) beside it. The False Cross is larger, dimmer and has no Pointers.
6. (a) How far the star chart is turned (for example 0°, 90°, 180°, 270°). (b) The same chart, ruler, rule and person measuring. (c) The distance from her marked spot to the real pole. (d)

The distances are small and about the same at every turn.

7. 20° × 111 km = 2,220 km (20 × 69 = 1,380 miles) south of the equator.
8. The earth rotates once a day, so all the southern stars seem to circle around the south celestial pole. The Cross is close to the pole, so as it goes around, it is upright when above the pole, sideways to the left or right, and upside down when below the pole. Its shape stays the same; only its tilt changes.

8.4 The Magi's Star (Matthew 2)

OBJECTIVES

- Retell what Matthew 2 says about the wise men and the star, and tell which details come from the Bible and which come from later tradition.
- Describe how ordinary stars and planets move across the sky and compare that with what the Magi's star did.
- Explain the main ideas people have offered about the star, including Kepler's, and why a careful reader tests each idea against the text.

Warm-up. On a night when the Moon is up, or in daytime with a faraway hill or water tower in view, walk 20 steps along a straight sidewalk or path while watching the Moon (or the faraway object) and also a nearby mailbox or tree. Which one seemed to stay in the same direction as you walked? Which one slid past? (Never do this with the sun.)

Video. Coming soon. The Star of Bethlehem, Kepler and the conjunction of Jupiter and Saturn, and how stars and planets move across the night sky; search planetarium shows, NASA skywatching videos on planetary conjunctions, Moody Science classics and Christian homeschool science channels.

KEY TERMS

Magi
The "wise men from the east" in Matthew 2: learned men, probably from Persia or Babylon, who studied the stars and old writings.

conjunction
A time when two planets, or a planet and a star, appear very close together in our sky, even though they are really far apart in space.

planet
A large body that travels around the sun. To the eye, planets look like bright stars that slowly wander among the other stars.

comet
A ball of ice and dust that travels around the sun. Near the sun it can grow a glowing tail that may stretch across the sky.

nova
From the Latin word for "new": a star that suddenly grows much brighter, so that it looks like a new star where none was seen before.

CORE IDEAS

The story. Matthew tells it simply: "Now when Jesus was born in Bethlehem of Judaea in the days of Herod the king, behold, there came wise men from the east to Jerusalem, Saying,

Where is he that is born King of the Jews? for we have seen his star in the east, and are come to worship him" (Matthew 2:1–2). These **Magi** were probably scholars from Persia or Babylon who watched the sky and read old writings. King Herod called his priests and scribes, who searched the Scriptures and found that the Christ would be born in Bethlehem (Matthew 2:5–6, quoting Micah 5:2). Then, as the wise men went, "the star, which they saw in the east, went before them, till it came and stood over where the young child was" (Matthew 2:9).

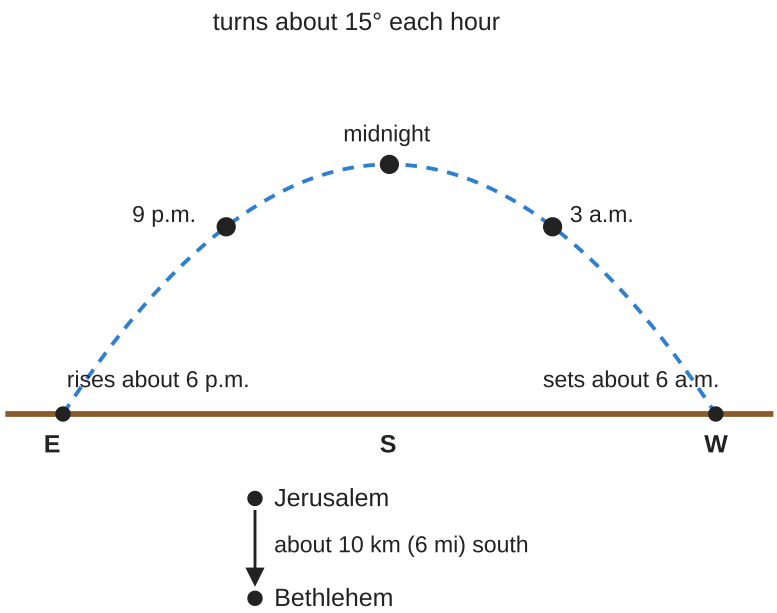
How they figured it out. Christians have wondered about this star for centuries. In December 1603, in Prague, the astronomer Johannes Kepler watched the planets Jupiter and Saturn draw close together in the sky, a **conjunction**. The next autumn a brilliant new star blazed out near them. Kepler worked his planet tables backward and found that Jupiter and Saturn had met three times in the year 7 B.C., in the constellation Pisces. He wondered whether a meeting like that, perhaps with a new star, had first caught the Magi's attention. Others have suggested a **comet**, a **nova**, or the dazzling close meeting of Jupiter and Venus in 2 B.C. Many Christians believe the star was a special light that God made for this one purpose.

The big idea. A good scientist and a good Bible reader both test ideas carefully. Science tells us how stars and **planets** ordinarily move. Because the earth turns, they all wheel across the sky about 15° every hour. Except for stars near the celestial poles, they rise in the east, cross the sky and set in the west. They are so far away that they stay in the same direction while you walk, just as the Moon seems to "follow" your car. An ordinary star could guide a traveler in a general direction, as Polaris guided Harriet Tubman. Bethlehem lies about 10 kilometers (6 miles) south of Jerusalem, so a star in the southern sky could have been "before them" on the road. But no ordinary star or planet can stop and stand over one house. The text describes something unusual.

Reading carefully. Matthew also corrects some things we picture from Christmas cards. The Bible does not say there were three wise men; it names three gifts, gold, frankincense and myrrh. It does not call them kings. And by the time they arrived, Mary and the young child were in a "house" (Matthew 2:11), not a stable. Herod had asked the wise men exactly when the star appeared (Matthew 2:7), which suggests some time had passed since the birth. Careful observers read Scripture as carefully as they read the sky.

Try it and see. Walk along a straight path at night, watching the Moon or a bright planet and a nearby lamppost. The lamppost slides past quickly, but the faraway Moon stays in the same direction. That is why ordinary stars point a direction but cannot lead you to one doorstep. Record what you see, and then read Matthew 2:9 again.

God's handiwork. Notice that the Magi needed both the sky and Scripture. The star brought them to Jerusalem, but it was God's Word that told where the Christ would be born. "The heavens declare the glory of God" (Psalm 19:1), and the One who made every star chose to announce His Son's birth with one. When the wise men saw the star again, "they rejoiced with exceeding great joy" (Matthew 2:10).



An ordinary star never stands still: it rises in the east, crosses the south and sets in the west, turning about 15° each hour. Bethlehem lay south of Jerusalem.

PICTURE STUDY



Adoration of the Magi, Giotto di Bondone, about 1305 · Fresco (paint on wet plaster) · Scrovegni Chapel (Arena Chapel), Padua, Italy

Giotto was a painter from Florence who covered the walls of a small chapel in Padua with scenes from the lives of Mary and Jesus. Instead of the flat gold backgrounds of older paintings, he painted a deep blue sky and real-looking people with weight and feeling.

Look at his star. It is not a small twinkling point but a blazing ball with a long tail, like a comet. Halley's Comet had appeared in the sky in 1301, a few years before Giotto painted this, and many think he had seen it. In 1986 a European spacecraft that flew close to Halley's Comet was named *Giotto* in his honor.

Look closely

- Find the star. What makes it look like a comet?
- Find the wise man who is kneeling. What has he done with his crown?
- Look at the camels. Do you think Giotto had ever seen a real camel? What makes you think so?
- Find the shelter. Does it match the "house" of Matthew 2:11, or a Christmas-card stable?

Talk about it

1. Giotto painted the star as a comet. What other ideas about the star have people had?
2. The kneeling wise man has taken off his crown. What is Giotto teaching about how even great men should come to Christ?
3. Which details in the painting come from Matthew 2, and which come from later tradition?

> **Safety first.** Do the night walk only with an adult, on a safe sidewalk or path away from traffic, and carry a flashlight. Never use the sun for the walking test.

EXPERIMENT: DOES A STAR LEAD THE WAY? THE NIGHT WALK TEST

Matthew says the star "went before them." How do ordinary faraway lights behave when you walk? You will test it by walking a measured distance while tracking a faraway light and a near one with a compass.

You will need

- A compass (a phone compass app works)
- A tape measure, or count steps (about 2 steps per meter for most children)
- A safe, straight path or sidewalk at least 100 meters (about 330 feet) long
- The Moon, a bright planet or a bright star low in the sky, and a nearby lamppost, mailbox or tree
- Notebook, pencil and a red-covered flashlight
- An adult partner

Steps

1. Question: As I walk, does the direction to a faraway light change less than the direction to a near object? Write your prediction.

2. What we change: how far you have walked (0, 25, 50 and 100 meters). What we keep the same: the path, the compass, the two objects and the way you hold the compass. What we measure: the compass direction (in degrees) to each object.
3. Choose a near object about 20 to 30 meters (65 to 100 feet) off to one side of the path, and a faraway light such as the Moon.
4. At the start, hold the compass flat, point it at the Moon and read the direction in degrees. Then point it at the near object and read it. Record both.
5. Walk 25 meters along the path and measure both again. Repeat at 50 and 100 meters.
6. Make a table: Distance walked, Direction to Moon, Direction to near object. Then figure out how much each direction changed from the start.
7. Conclusion: Write two sentences. Which object changed direction? What does that tell you about whether an ordinary star could lead travelers to one house?

Tips

- Compass readings can jump a few degrees, so hold still and wait for the needle to settle.
- Stay away from cars and metal fences when reading the compass; metal can pull the needle.
- If the Moon is not up, a bright planet such as Jupiter or Venus works well. Ask an adult which one is visible this month.

Check your work

- I measured directions to a near object and a faraway light at four distances.
- My table shows which direction changed and which stayed nearly the same.
- I can explain why an ordinary star points a direction but cannot stop over one house.

FIELD NOTEBOOK

1. Draw the sky above Jerusalem with a curved star path from east to west. Mark Bethlehem to the south and the road between them.
2. Make a T-chart titled “The Magi’s Star”: on one side, what Matthew 2 says; on the other, what Christmas cards often add.
3. Draw Giotto’s comet-star and, beside it, Jupiter and Saturn close together as Kepler saw them in 1603. Label each idea.

> **From history.** Kepler first wrote about the Star of Bethlehem in his 1606 book about the new star of 1604, and he returned to it in later writings about the date of Christ’s birth. He was one of the first to use careful planet tables to work backward and ask what the sky looked like in the days of Herod, a method planetarium shows still use every Christmas season.

WORKED EXAMPLES

Example 1. Bethlehem is about 10 km (6 miles) south of Jerusalem. If the wise men walked at about 4 km per hour (2.5 miles per hour), about how long did the trip take?

(Use the map or drawing "The road from Jerusalem ran south to Bethlehem." shown earlier in this lesson.)

1. Time = distance ÷ speed.
2. 10 km ÷ 4 km per hour = 2.5 hours.
3. Check with miles: 6 miles ÷ 2.5 miles per hour = 2.4 hours, about the same.

Answer: About 2½ hours.

Example 2. Suppose the Magi came from Babylon. The usual travel route from Babylon to Jerusalem, following the rivers around the desert, was about 1,400 km (about 900 miles). If a caravan traveled 25 km (about 15 miles) a day, how many days would the journey take? About how many weeks?

1. Days = distance ÷ distance per day.
2. 1,400 km ÷ 25 km per day = 56 days.
3. 56 days ÷ 7 days per week = 8 weeks.
4. Ezra's large company made the same journey in about four months (Ezra 7:9), so a smaller group moving faster could take about two months.

Answer: About 56 days, or 8 weeks.

PRACTICE

1. EASY According to Matthew 2, where did the wise men first go, and who told them where the Christ was to be born?
2. EASY True or false: The Bible says there were three wise men and that they were kings. Explain.
3. MEDIUM How many degrees does an ordinary star move across the sky in 4 hours?
4. MEDIUM Data table. On a night walk, Hannah recorded these compass directions. At 0 m: Moon 135°, lamppost 90°. At 50 m: Moon 135°, lamppost 60°. At 100 m: Moon 136°, lamppost 40°. (a) How much did the direction to the lamppost change from 0 m to 100 m? (b) How much did the direction to the Moon change? (c) What does this show?
5. MEDIUM What is a conjunction? Which conjunction did Kepler calculate for the time of Christ's birth?
6. HARD Experiment design. Caleb wants to test whether the Moon really "follows" his family's car. (a) What variable does he change? (b) What must he keep the same? (c)

What does he measure? (d) What near object could he measure at the same time for comparison?

7. HARD Name three natural explanations people have offered for the Magi's star, and one detail from Matthew 2 that any explanation must account for.
8. CHALLENGE In three or four sentences, explain why an ordinary star cannot stop over one house, and what this tells us about how to read Matthew 2:9.

COMMON MISTAKES

- Thinking the Bible says there were three kings. Matthew says "wise men" and lists three gifts; the number and the crowns came from later tradition.
- Picturing the wise men at the stable on the night Jesus was born. Matthew says they found the young child in a house, probably some time later.
- Thinking stars stay in one place all night. As the earth turns, every star moves across the sky; only a star almost exactly at a celestial pole, like Polaris, seems to stay put.

Make it a game · Bible or Christmas Card?. A parent reads a statement aloud, such as "The wise men followed a star," "There were three wise men," "They brought gold, frankincense and myrrh," "They found Jesus in a house," "They rode camels," or "The star stood over where the young child was." Players shout "Bible!" if Matthew 2 says it, or "Card!" if it comes from later tradition. Give one point for each right answer and a bonus point for naming the verse. (Hint: the Bible never mentions camels in Matthew 2.)

Scripture. "When they had heard the king, they departed; and, lo, the star, which they saw in the east, went before them, till it came and stood over where the young child was. When they saw the star, they rejoiced with exceeding great joy." (Matthew 2:9–10, KJV)

The wise men studied the sky, listened to the Scriptures, and then obeyed by traveling on. Their careful watching ended in worship. All our study of the stars should lead to the same place: joy in the One who made them.

Practice answers

1. They first went to Jerusalem. King Herod gathered the chief priests and scribes, who found in Scripture (Micah 5:2) that He would be born in Bethlehem.
2. False. Matthew does not give their number or call them kings. He lists three gifts (gold, frankincense and myrrh), which is probably why people later pictured three.
3. 15° per hour × 4 = 60°.
4. (a) 90° − 40° = 50°. (b) Only about 1°, which is within normal compass wobble. (c) Faraway objects like the Moon and stars stay in the same direction as you walk, while near objects shift. An ordinary star points a direction but does not lead to one spot.
5. A conjunction is when two planets (or a planet and a star) appear very close together in our sky. Kepler found that Jupiter and Saturn met three times in 7 B.C., in the constellation Pisces.
6. (a) How far the car (or he) has traveled. (b) The road direction (a straight road), the compass and how he holds it, and the same Moon. (c) The compass direction to the Moon at each

distance. (d) A roadside tree, sign or barn, whose direction should change a lot while the Moon’s stays the same.

7. Any three: a conjunction of Jupiter and Saturn (Kepler’s idea), the close meeting of Jupiter and Venus, a comet, a nova (new star). Details: the star “went before them” and “stood over where the young child was” (Matthew 2:9), or the wise men saw it “in the east” and saw it again on the way to Bethlehem.
8. Because the earth rotates, every ordinary star and planet keeps moving across the sky from east to west, about 15° each hour. Stars are also so far away that they appear in the same direction from every house in a town, so none can mark one particular house. Matthew 2:9 says the star went before the wise men and stood over where the young child was, which is unlike any ordinary star. This tells us the star behaved in an unusual way, and many Christians believe God guided it or made it specially for that purpose.

Unit 8 review

Answer each question. Show your work for calculations and use complete sentences for explanations. The review is worth 50 points.

1. (5 pts) Explain how to find Polaris using the Big Dipper.
2. (5 pts) Why does Polaris seem to stay still while the other stars move?
3. (5 pts) A girl stacks 3 fists at arm’s length to reach Polaris. About what is her latitude? How high would Polaris be at the North Pole?
4. (5 pts) Name three parts of an astrolabe and tell what each does.
5. (5 pts) The string on your straw astrolabe reads 58° when you sight a star. What is the star’s altitude?
6. (5 pts) On the March equinox the noon sun is 50° high. What is your latitude? How did sailors measure the sun without looking at it?
7. (5 pts) Why did southern sailors need the Southern Cross instead of Polaris, and why is there no “South Star” to use?
8. (5 pts) The long bar of the Southern Cross covers about 6°. About how far beyond Acrux is the south celestial pole? If the pole point is 30° above the horizon, what is your latitude?
9. (5 pts) Name two details people often add to the story of the wise men that Matthew 2 does not say, and one thing Matthew does say about where they found the child.
10. (5 pts) Describe how an ordinary star moves across the sky in one night, and explain why that is different from what Matthew 2:9 says the Magi’s star did.

Unit project: my navigator’s log

Make a navigator’s log book that shows you can find your way by the sky. Include your Big Dipper sketches from the turning-sky night, your straw astrolabe (or a careful drawing of it) with a table of repeated Polaris readings and your latitude worked out from them, a star chart of the Southern Cross showing how you found the south celestial pole, and your night-walk table from Lesson 8.4. End with a one-page letter to a younger child explaining how a traveler could find north at night and what Matthew 2 really says about the wise men’s star.

- **Accuracy**: Star names, pointer lines, altitudes and latitudes are correct, and the Southern Cross method is drawn correctly.
- **Records**: Observation pages are dated and timed, tables are complete, and averages and calculations are shown and correct.
- **Explanation**: The letter clearly explains why Polaris stays still, how altitude gives latitude, and what Matthew 2 says, separating Scripture from later tradition.
- **Care**: The log is neat, labeled and illustrated, and the astrolabe is built so it reads 90° when level.

Answer key

1. Find the two pointer stars at the outer end of the Big Dipper’s bowl, Merak and Dubhe. Draw a line from Merak through Dubhe and go about five times the distance between them. The fairly bright star there is Polaris, the end of the Little Dipper’s handle.
2. The earth spins on its axis, and the axis points almost straight at Polaris. So as the earth turns, the other stars seem to circle around Polaris, while Polaris, near the center of the circles, barely moves.
3. 3 × 10° = 30°, so about latitude 30° N. At the North Pole, Polaris is straight overhead, at 90°.
4. Mater: the main body that holds the plates. Rete: the turning cut-out star map. Alidade: the sighting bar with two holes used to measure altitude. (Plates engraved for one latitude are also acceptable.)
5. 90° − 58° = 32°.
6. 90° − 50° = 40°, so about 40° N. They let sunlight pass through the hole in the upper vane of the alidade and turned it until the spot of light fell on the lower hole, then read the angle.
7. South of the equator Polaris is below the horizon. The south celestial pole has no bright star on it (the nearest, Sigma Octantis, is very faint), so sailors found the pole from the Southern Cross and the Pointers.
8. 4.5 × 6° = 27° beyond Acrux. The pole’s altitude equals your latitude, so about 30° S.
9. Matthew does not say there were three of them, does not call them kings, and does not mention camels or a stable. He says they found the young child with Mary in a house (Matthew 2:11).
10. An ordinary star moves about 15° each hour as the earth turns, rising in the east and setting in the west (unless it is near a celestial pole), and it appears in the same direction from every house in a town. Matthew says the star went before the wise men and stood over where the young child was, which no ordinary star can do, so the star behaved in an unusual way.

Bonus: Field Lab

This bonus unit takes everything you have learned about the sky outdoors. You will not read about the heavens so much as work under them, the way Kepler, Herschel and every good astronomer did: watching, measuring, sketching and writing it all down. “The heavens declare the glory of God” (Psalm 19:1), and in this unit you will listen to what they say with a stick, a paper plate, your own two hands and a notebook.

You will build a sundial that is aimed at Polaris and tilted to your own latitude, and find true north from the shortest shadow of the day. On a dark night you will map the stars around Polaris, as Johann Bayer did in 1603, and watch the whole sky turn. For one month you will sketch the Moon and discover its cycle from your own data. Last, you will shrink the solar system until the Sun is a big exercise ball and the planets stretch across your whole neighborhood.

Each lab is short and playful, and each one is a real experiment with a question, a prediction, careful measurements and a record. Keep all four labs in one Field Lab notebook. By the end it will hold a month of the sky in your own hand.

BEFORE YOU BEGIN

- Knows that Earth rotates once a day and revolves around the Sun once a year (Unit 1)
- Can name the phases of the Moon and explain that the Moon shines by reflected sunlight (Unit 2)
- Can multiply and divide decimals and measure angles with a protractor
- Can find north, south, east and west outdoors

MASTERY CHECKLIST

- I can build an equatorial sundial, aim it at true north and explain why its hour lines are 15° apart.
- I can find Polaris from the Big Dipper, measure the sky with my hand and explain why the stars circle Polaris.
- I can keep a Moon journal and use it to name the phases and predict when the next ones will come.
- I can build a scale model of the solar system with one scale for sizes and distances and plot it on a map.
- I can plan a fair test, naming what I change, what I keep the same and what I measure.

OPTIONAL BOOKS AND RESOURCES

- **NASA Moon** (https://moon.nasa.gov/): Free. NASA’s Moon site has pictures, phase explanations and observing ideas to go with the Moon journal in Lesson 9.3.

- **Globe at Night** (https://globeatnight.org/): Free. A citizen-science project from NSF NOIRLab in which families compare the stars they see with simple charts and report how dark their sky is. A good next step after the star map in Lesson 9.2.
- **NASA Space Place** (https://spaceplace.nasa.gov/): Free. Short, kid-friendly articles and make-and-do projects about the Sun, Moon, planets and stars, useful for all four labs.

9.1 Sundial in the Yard

OBJECTIVES

- Build an equatorial sundial whose pointer is aimed at true north and tilted at the angle of your latitude.
- Find true north from the shortest shadow of the day and explain why the hour lines on this dial are 15° apart.
- Compare sundial time with clock time and explain why they are different.

Warm-up. Stand a pencil upright in a lump of clay on a sunny windowsill or table. Mark the tip of its shadow with a dot, wait 15 minutes, and mark it again. Which way did the shadow move? Draw an arrow, then predict where the tip will be in one more hour and mark your guess with an X. Check it later.

Video. Coming soon. How to build an equatorial sundial and find true north with a shadow stick; search NASA Space Place, NOAA SciJinks, Science Max, Homeschool Pop (Alternate), and museum or university planetarium channels.

KEY TERMS

gnomon
The part of a sundial that casts the shadow. On our dial it is a pencil.

equatorial sundial
A sundial whose face is tilted to lie parallel to Earth's equator, with its gnomon pointing along Earth's axis toward Polaris. Its hour lines are evenly spaced, 15° apart.

latitude
How far north or south of the equator a place is, measured in degrees. The equator is 0° and the North Pole is 90° N.

true north
The direction toward the North Pole along Earth's surface. A compass points to magnetic north, which in many places is a few degrees away from true north.

solar noon
The moment each day when the Sun is highest in the sky and shadows are shortest. It is seldom exactly 12:00 on the clock.

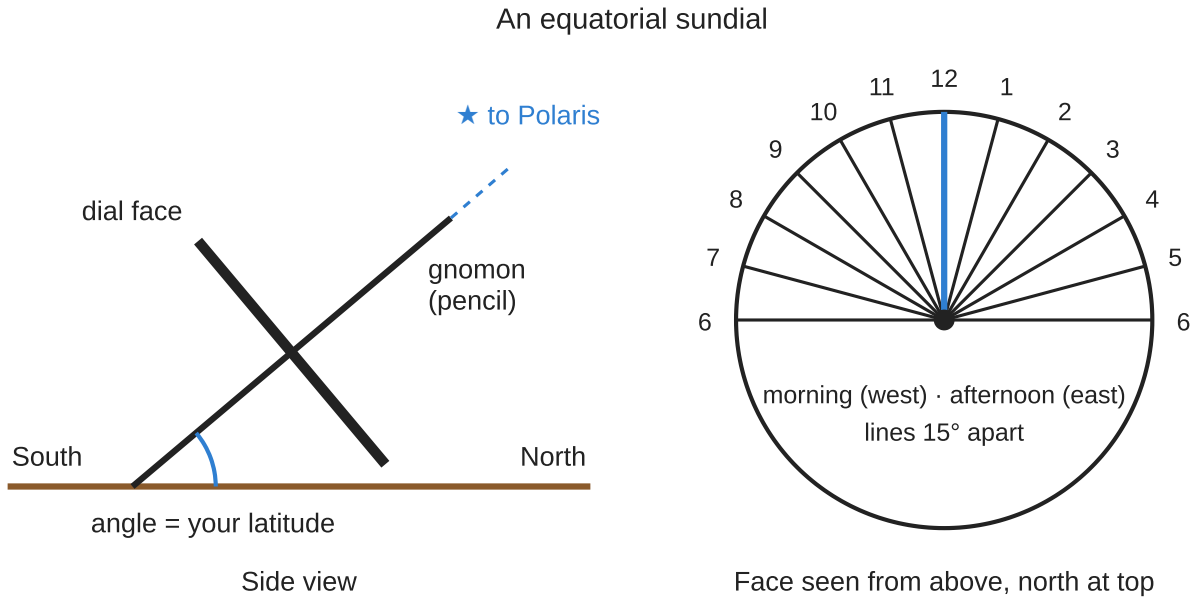
CORE IDEAS

The story. In January 2004 two NASA rovers named *Spirit* and *Opportunity* bounced down onto Mars inside giant air bags. Each one carried a small sundial on its deck called the MarsDial. Colored patches at its corners let scientists check the colors in the rover's camera pictures, and the shadow of its little post showed where the Sun was in the Martian sky. Bill Nye "the Science Guy" helped plan it. Around its face were the words "Two Worlds, One

Sun” and the word *Mars* in seventeen languages. The same Sun that lit the rovers lights your yard, and its shadow can tell you the time.

The big idea. A shadow clock works because Earth turns at a steady pace: one full turn of 360° in a day, so 360 ÷ 24 = **15° every hour**. If the **gnomon** points along Earth’s own axis, toward Polaris, and the dial face is tilted to match the equator, the shadow sweeps around the face at exactly 15° an hour. That is an **equatorial sundial**. To aim it, tilt the gnomon so its angle with level ground equals your **latitude**, and point its high end toward **true north**. You can find true north without a compass. Anywhere in the 48 connected states, the Sun at **solar noon** stands due south, so the shortest shadow of the day points due north.

Try it and see. Your finished dial will not agree with the clock exactly, and the reasons are good science. A sundial tells sun time for your own spot. A clock tells time for a whole time zone, so towns west of the zone’s middle see noon a little later. In summer, daylight saving time moves the clock ahead one hour, so solar noon often comes near 1 p.m. And because Earth’s orbit is an oval and its axis is tilted, sun time runs up to about a quarter of an hour fast or slow during the year. One more surprise: from the March equinox to the September equinox the Sun shines on the top of an equatorial dial, but for the rest of the year it shines underneath, so you will mark hours on both sides. **God’s handiwork.** On the fourth day God set lights in the heaven “for signs, and for seasons, and for days, and years” (Genesis 1:14). Every sundial is a small way of reading that clock He set in the sky.



An equatorial sundial. The pencil points at Polaris and is tilted at your latitude; the hour lines are 15° apart.

PICTURE STUDY



The Harvesters, Pieter Bruegel the Elder, 1565 · Oil on wood panel · The Metropolitan Museum of Art, New York

Pieter Bruegel the Elder painted this picture in 1565 as part of the same set of paintings about the times of the year as *The Hunters in the Snow* (Lesson 7.1), made for a merchant in Antwerp. This panel shows late summer, the wheat harvest of July and August. The Metropolitan Museum bought it in 1919, and it is one of the best-loved paintings in New York.

Bruegel has chosen the middle of the day. The Sun stands high, the shadows under the tree are short, and the harvesters have stopped work to eat their midday meal. People in 1565 had few clocks in the fields. They told the time of day the way a sundial does, by the height of the Sun and the length of the shadows.

Look closely

- Look at the shadows under the pear tree and beside the standing wheat. Are they long or short? What does that tell you about how high the Sun is?
- Find the men cutting with scythes and the women binding the sheaves. Find the man carrying jugs up the path through the wheat.
- Look at the group eating under the tree. One man is fast asleep. Why would harvesters rest in the middle of the day instead of in the evening?
- Look far into the distance. How does Bruegel make the hazy summer air feel hot?

Talk about it

1. If you set your equatorial sundial in this field at the moment Bruegel painted, about where would the pencil’s shadow fall?

2. The harvesters had no clock. Name two things in the picture that could tell them it was about noon.
3. Compare this painting with *The Hunters in the Snow*. How are the light and the shadows different between a summer noon and a winter afternoon?

> **Safety first.** Never look at the Sun, even for a moment; look only at the shadows. Wear a hat and sunscreen if you will be outside for hours. Ask an adult before poking holes with a sharp pencil or pin, and push stakes into the ground only where there are no buried pipes or wires.

EXPERIMENT: A PAPER-PLATE EQUATORIAL SUNDIAL

Question: If a sundial points at true north and is tilted to our latitude, will it keep pace with the clock all day? **Prediction:** write down whether you think the difference between dial time and clock time will stay the same, grow or shrink through the day.

What we change: the time of day. **What we keep the same:** the dial's place, its tilt and its aim. **What we measure:** the time the shadow shows and the clock time, once an hour. **Record:** a table with columns for clock time, dial time and the difference in minutes.

You will need

- A sturdy paper plate about 23 cm (9 inches) across
- An unsharpened pencil or a straight stick about 20 cm (8 inches) long
- A protractor, a ruler and a fine marker
- Modeling clay or a cardboard wedge, and a square of stiff cardboard for a base
- A straight stick about 1 meter (3 feet) long, a few small stones and a string, for finding north
- The latitude of your town (from an atlas, a globe or a parent's map app)
- Notebook, pencil and a clock or watch

Steps

1. Find true north first. On a sunny day, push the long stick straight up into level ground. From about 11 a.m. to 2 p.m. (12 to 3 p.m. during daylight saving time), set a small stone on the tip of the shadow every 15 minutes. The stone closest to the stick marks the shortest shadow. Stretch the string from the stick through that stone: it points due north. This is your noon line.
2. Make the dial face. Find the center of the plate and draw a straight line from the center to the edge. Label it 12. With the protractor, draw lines every 15° on each side: 11, 10, 9, 8, 7 and 6 on the left and 1, 2, 3, 4, 5 and 6 on the right, as if you were looking down on a clock.
3. Push a pin through the rim at the end of each line. Turn the plate over and draw the same lines on the back, from the center to each pin hole, and number them so each hour sits right behind the same hour on the front. From the September equinox to the March equinox, you will read the back.

4. Push the pencil through the center so it sticks out the same on both sides, at a right angle to the plate.
5. Set the dial on its cardboard base on level ground beside your noon line. Tilt the pencil until its angle with the ground equals your latitude (check with the protractor), and prop it with clay or the cardboard wedge. The pencil's high end must point north along the noon line, and the 12 line must run from the pencil down to the low, north edge of the plate.
6. Every hour, write the clock time and the hour the pencil's shadow is pointing to. Estimate between lines: halfway between 10 and 11 is 10:30.
7. Find the difference between dial time and clock time for each reading. Compare it with your prediction and write two sentences about why the dial and the clock disagree.

Tips

- Each 15° on the dial is one hour, so each 5° is 20 minutes and each 1° is 4 minutes.
- If the difference between dial and clock stays nearly the same all day, your dial is aimed well. If it grows or shrinks a lot, check the tilt and the aim toward north.
- Leave the base in place or mark its corners with chalk so you can set the dial back in exactly the same spot tomorrow.

Check your work

- I found true north from the shortest shadow.
- My pencil is tilted at my latitude and aimed north.
- I can explain why the dial and the clock do not read the same time.

FIELD NOTEBOOK

1. Draw your stones and stick from the north-finding step as seen from above. Mark the shortest shadow and label north, south, east and west.
2. Draw a side view of your finished dial and label the gnomon, the dial face, the ground and the angle that equals your latitude.
3. Make a table of your hourly readings (clock time, dial time, difference) and write one sentence about what the numbers show.

> **From history.** On the south walls of many old English churches you can still find small "scratch dials" or "mass dials," carved into the stone during the Middle Ages. Each is a half circle of lines cut around a hole where a stick once stood. They were not meant to tell every hour. They showed the village priest and people when it was time for the daily services.

WORKED EXAMPLES

Example 1. A family lives in a town at 38° north latitude. At what angle should they tilt the pencil on their equatorial sundial? How far from the 12 line should they draw the 3 p.m. line, and on which side?

(Use the map or drawing "Count three 15° steps from 12 to reach 3 p.m." shown earlier in this lesson.)

1. The pencil must point along Earth's axis, so its angle with level ground equals the latitude: 38°.
2. Earth turns 360° in 24 hours, so the shadow moves 360 ÷ 24 = 15° each hour.
3. 3 p.m. is 3 hours after noon: 3 × 15° = 45°.
4. In the afternoon the Sun is in the west, so the shadow points toward the east side of the dial, the right side when you look down at the face with north at the top.

Answer: Tilt the pencil to 38°. Draw the 3 p.m. line 45° from the 12 line, on the right-hand (east) side.

PRACTICE

1. EASY Why are the hour lines on an equatorial sundial exactly 15° apart?
2. EASY In the United States, which way does the shortest shadow of the day point, and when does it happen?
3. MEDIUM A student at 40° north latitude measured the noon shadow of a stick 1 meter (about 3.3 feet) tall on four dates.
   Date | Noon shadow length
   March 20 | 0.84 m
   June 21 | 0.30 m
   September 22 | 0.84 m
   December 21 | 2.00 m
   (a) On which date was the shadow longest? (b) Why? (c) About how many times longer was the December shadow than the June shadow?
4. HARD Does the tilt of the pencil really matter? Design a fair test. What will you change? Name two things you will keep the same. What will you measure?
5. CHALLENGE On a July afternoon, a well-aimed sundial shows 12:00 when the clock says 1:04 p.m. Explain where the extra hour and the extra 4 minutes come from.

COMMON MISTAKES

- Thinking the Sun is highest at exactly 12:00 on the clock. Solar noon can come well before or after 12:00, and near 1 p.m. during daylight saving time.
- Thinking a compass needle points to true north. It points to magnetic north, which can be several degrees away. The noon shadow shows true north.

- Thinking the Sun is straight overhead at noon. In the 48 connected states it never is; at noon it stands in the south, so noon shadows point north.

Make it a game · Where Will the Shadow Be?. A parent calls out a clock time, such as 10:30 or 2:00. The player stands beside the sundial and points to the hour line where the shadow will fall then, remembering any daylight saving hour. Check at the real time if you can, or check with the 15° rule. A point for each answer within half an hour line; first to five points wins.

Scripture. “And God said, Let there be lights in the firmament of the heaven to divide the day from the night; and let them be for signs, and for seasons, and for days, and years:” (Genesis 1:14, KJV)

God made the Sun to mark out our days and hours. A sundial simply reads the steady clock He set in the heavens.

Practice answers

1. Earth turns 360° in 24 hours, and 360 ÷ 24 = 15, so the Sun’s shadow moves 15° each hour.
2. It points due north (true north), and it happens at solar noon, when the Sun is highest in the sky.
3. (a) December 21. (b) In winter the noon Sun is lowest in the sky, so it casts the longest shadow; in June it is highest. (c) 2.00 ÷ 0.30 ≈ 6.7, so almost 7 times longer.
4. Change: the tilt of the pencil (one dial tilted to our latitude, an identical dial with its pencil straight up). Keep the same (any two): the same kind of plate and hour lines, the same place, the same aim toward north, the same reading times. Measure: the dial time and clock time every hour on both dials, then the difference. The tilted dial’s difference should stay nearly steady all day; the upright dial with evenly spaced lines will drift and read some hours wrong.
5. The hour comes from daylight saving time, which sets clocks one hour ahead in summer. The extra minutes come from the dial telling sun time for its own spot (a town west of the middle of its time zone sees noon later) and from sun time running a little fast or slow at different times of the year because of Earth’s oval orbit and tilted axis.

9.2 Star Map Night

OBJECTIVES

- Draw a star map of the northern sky, using fists and fingers held at arm's length to measure angles.
- Find Polaris with the pointer stars of the Big Dipper and label stars with Johann Bayer's Greek-letter system.
- Observe and explain how the stars circle Polaris during the night at about 15° each hour.

Warm-up. Make your hand ruler. Stretch your arm out straight and hold up your little finger: its width covers about 1° of sky. Three fingers together cover about 5°, a fist about 10°, and a hand spread wide from thumb tip to little-finger tip about 20°. Stand across a room and measure a doorway in fists. Then guess: how many little fingers wide is the full Moon? (Answer at the end of the lesson.)

Video. Coming soon. How to find Polaris from the Big Dipper, measure the sky with your hand, and watch the stars circle the pole; search NASA Night Sky Network, NASA Space Place, Sky and Telescope, university planetarium channels and Homeschool Pop (Alternate).

KEY TERMS

star map
A drawing of the stars as they appear in the sky, showing their patterns and the angles between them.

angular distance
How far apart two things look in the sky, measured in degrees. A fist at arm's length covers about 10°.

Bayer letter
A Greek letter given to a star in a constellation, usually starting with α (alpha) for the brightest. Polaris is Alpha Ursae Minoris, "alpha of the Little Bear."

pointer stars
Dubhe and Merak, the two stars at the end of the Big Dipper's bowl. A line through them points to Polaris.

circumpolar star
A star close enough to Polaris that, from your latitude, it circles the pole all night and never sets.

CORE IDEAS

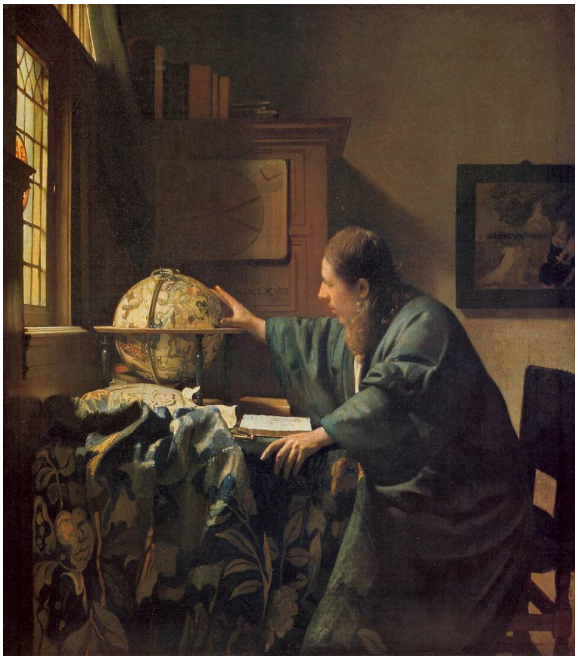
The story. In 1603, in the German city of Augsburg, a lawyer named Johann Bayer published a book of star maps called *Uranometria*. It was the first atlas to show the whole sky, north and south, with each constellation engraved on copper by Alexander Mair. Bayer added something astronomers still use every night. In each constellation he gave the stars Greek letters, usually naming the brightest α (alpha), the next β (beta), then γ (gamma) and on down the alphabet. That is why Polaris is called Alpha Ursae Minoris. Bayer did not always follow brightness exactly: in Orion, Betelgeuse is alpha, yet Rigel, the beta star, usually shines brighter.

The big idea. A star map measures **angles**, not meters, and your hand is the ruler. Face north and find the Big Dipper, seven bright stars shaped like a long-handled pan. The two stars at the end of its bowl, Dubhe and Merak, are the **pointer stars**. Follow the line from Merak through Dubhe about five times the gap between them, and you reach Polaris, the North Star. Polaris hardly moves all night, because Earth's axis points almost straight at it. The other stars near it are **circumpolar**: they wheel around Polaris like the hands of a clock running backward, counterclockwise as you face north. Earth turns 15° an hour, so the Big Dipper swings 15° around Polaris every hour, a full circle in about a day.

Try it and see. Go out with an adult on a clear, moonless night and let your eyes adjust in the dark for 15 to 20 minutes. More and fainter stars will appear as your pupils open wide. Use a flashlight covered with red cellophane, because red light spoils night vision much less than white light. Map the Big Dipper, Polaris and Cassiopeia, then map them again two hours later and measure how far they turned. **God's handiwork.** The Lord asked Job, "Canst thou guide Arcturus with his sons?" (Job 38:32). On spring and summer evenings you can find Arcturus yourself: follow the curve of the Dipper's handle away from the bowl, and "arc to Arcturus," a bright orange star. No one but God keeps the stars on their paths, yet He lets us learn those paths well enough to draw them.

Facing north, the Big Dipper circles Polaris counterclockwise, about 15° each hour. In two hours it turns about 30°.

PICTURE STUDY



The Astronomer, Johannes Vermeer, 1668 · Oil on canvas · Musée du Louvre, Paris

Johannes Vermeer lived in the Dutch city of Delft and painted quiet rooms filled with soft window light. He painted fewer than forty pictures that we know of, and this is one of only two that show a man of science. Here a scholar reaches toward a globe of the heavens. Instead of countries, it shows the constellations as figures, the way star atlases like Bayer's drew them.

Vermeer signed and dated this painting 1668. The astronomer is studying the sky in the daytime, from books and a globe, and making ready for the night when he can see the real thing.

Look closely

- Find the globe. How is it different from a globe of the earth?
- Look at the astronomer's hand on the globe. What do you think he is doing: measuring, turning it or finding a star?
- Find the window. How does Vermeer use its light to lead your eye to the globe?
- Look at the open book. What might be in a book an astronomer would study?

Talk about it

1. Why is a globe of the stars useful even though the stars are not really painted on a ball?
2. How is your star map tonight like the globe in this painting? How is it different?

> **Safety first.** Observe only with an adult. Choose a safe, open spot such as your own yard or a park you know, away from roads. Walk carefully in the dark and use a red flashlight to watch your footing. Dress warmer than you think you need, because nights cool quickly.

EXPERIMENT: MY NORTHERN SKY MAP: WATCHING THE SKY TURN

Question: How do the stars around Polaris move in two hours? **Prediction:** draw an arrow showing which way you think the Big Dipper will move, and guess how many fists it will turn.

What we change: the time (a first map, then a second map two hours later). **What we keep the same:** the observing spot, facing north and Polaris at the center of both maps. **What we measure:** the angle the pointer stars turn around Polaris, in fists and degrees. **Record:** two dated, timed maps on the same sheet.

You will need

- A sheet of paper on a clipboard, with a circle about 20 cm (8 inches) across drawn on it and a dot in the middle for Polaris
- A pencil and a blue colored pencil
- A flashlight with red cellophane or red tissue held on with a rubber band
- Your noon line from Lesson 9.1, or a compass, to find north
- A lawn chair or blanket
- A printed star chart for this month from a library book or a planetarium (optional, for checking)

Steps

1. Choose a clear, moonless evening. Go outside with an adult about an hour after dark, face north, and sit still for 15 to 20 minutes while your eyes adjust. Use only the red flashlight.
2. Find the Big Dipper. Measure the gap between the pointer stars with your fingers, then follow the line about five gaps to Polaris. Check: Polaris is about as bright as the Dipper’s stars and sits alone.
3. Draw Polaris at the center dot. Draw the seven Dipper stars in pencil, using fists and fingers to place each one the right angle from Polaris. Make brighter stars bigger dots.
4. Find Cassiopeia, a W or M shape on the other side of Polaris from the Dipper, and draw it too. Write the date and time beside your map.
5. Measure how high Polaris is above the horizon in fists. Write it down; it should be close to your latitude in degrees.
6. Two hours later, come back to the same spot. Draw the Dipper and Cassiopeia again in blue on the same circle.
7. Draw a line from Polaris to Dubhe on each map and measure the angle between the lines with a protractor. Compare it with your prediction and with the 15° per hour rule.

Tips

- Hold your arm fully straight every time you measure; a bent arm makes your fist cover more sky.
- If the Dipper is low and hidden by trees, use Cassiopeia instead. It turns around Polaris just as the Dipper does.
- City lights hide faint stars, but the Big Dipper and Polaris are bright enough to see from most towns.

Check your work

- I found Polaris using the pointer stars.
- I drew two maps two hours apart and measured how far the stars turned.
- I can explain that the stars appear to circle Polaris because Earth turns.

FIELD NOTEBOOK

1. Copy your two-time star map neatly. Label Polaris, Dubhe, Merak and Cassiopeia, and draw an arrow showing which way the stars turned.
2. Draw your hand ruler: a little finger (1°), three fingers (5°), a fist (10°) and a spread hand (20°) held at arm’s length.
3. Pick three stars in the Big Dipper and give them Bayer letters in the order of how bright they looked to you. Then look up their real letters and compare.

> **From history.** Bayer drew the 48 constellations listed by the ancient astronomer Ptolemy, and he added 12 new ones in the far southern sky, taken from the records of Dutch sailors such as Pieter Dirkszoon Keyser and Frederick de Houtman, who mapped stars that cannot be seen from Europe. In 1922 astronomers from many nations agreed on an

> official list of 88 constellations, and by 1930 they had drawn exact borders between them, so every star in the sky now belongs to one constellation.

WORKED EXAMPLES

Example 1. At 8 p.m. a student draws the Big Dipper below Polaris. Later she finds that the line from Polaris to Dubhe has turned 30° counterclockwise. About what time is it now?

(Use the map or drawing "Two hours of turning moves the Dipper about 30° around Polaris." shown earlier in this lesson.)

1. Earth turns 360° in about 24 hours, so the stars turn 360 ÷ 24 = 15° each hour.
2. Divide the angle turned by 15° per hour: 30 ÷ 15 = 2 hours.
3. Add 2 hours to 8 p.m.

Answer: About 10 p.m. The Dipper turned 30° in about 2 hours.

PRACTICE

1. EASY In Bayer's system, what does the Greek letter α (alpha) usually tell you about a star?
2. EASY About how many fists at arm's length cover 30° of sky? How many cover 45°?
3. MEDIUM A student measured how far the line from Polaris to Dubhe had turned, starting at 8 p.m.
   Time | Angle turned
   8 p.m. | 0°
   9 p.m. | 15°
   10 p.m. | 30°
   11 p.m. | 45°
   (a) How many degrees does the line turn each hour? (b) Predict the angle at midnight. (c) About how long would it take to turn all the way around?
4. HARD Does using a white flashlight instead of a red one change how many stars you can see? Design a fair test. Name the variable you change, two things you keep the same and what you measure.
5. CHALLENGE Explain in two or three sentences why Polaris stays nearly still while the other stars circle it, and why a child in Australia cannot see Polaris at all.

COMMON MISTAKES

- Thinking Polaris is the brightest star in the sky. It is only of medium brightness, and dozens of stars are brighter; Sirius is the brightest star of the night sky. Polaris is special because it stays put.
- Thinking the Big Dipper is a constellation. It is a star pattern inside the larger constellation Ursa Major, the Great Bear.

- Thinking the stars circle Polaris because they are moving. The circling we see in one night comes from Earth turning on its axis.

Make it a game · Star Hop Relay. Draw the Big Dipper, Polaris, Cassiopeia and Arcturus on a big sheet of paper, or use your star map. One player names a start and a finish, such as “Dipper to Arcturus.” The other must trace the path with a finger and say how to get there: “follow the pointers,” “arc to Arcturus,” “across Polaris to the W.” A correct hop earns a point. Take turns until each player has made five hops. (Warm-up answer: the full Moon is only about half a little finger wide.)

Scripture. “Canst thou bind the sweet influences of Pleiades, or loose the bands of Orion? Canst thou bring forth Mazzaroth in his season? or canst thou guide Arcturus with his sons? Knowest thou the ordinances of heaven? canst thou set the dominion thereof in the earth?” (Job 38:31–33, KJV)

God set the stars on their paths and keeps them there. We cannot guide Arcturus, but we can learn the “ordinances of heaven” well enough to map them and find our way by them.

Practice answers

1. That it is usually the brightest star in its constellation.
2. A fist is about 10°, so 30° is about 3 fists and 45° is about 4½ fists.
3. (a) 15° each hour. (b) 45° + 15° = 60°. (c) 360 ÷ 15 = 24 hours, about one day (really about 4 minutes less, which is why stars rise a little earlier each night).
4. Change: the color of the flashlight used to look at your map (red one night, white the next, or red then white on the same night). Keep the same (any two): the same observer, the same spot, the same patch of sky such as the inside of the Dipper’s bowl, the same time after dark, the same 20 minutes of waiting first, a clear moonless sky. Measure: the number of stars you can count in that patch one minute after looking at the map with each light. Prediction: fewer stars after the white light.
5. Earth’s axis points almost straight at Polaris, so as Earth turns, Polaris stays near the center of the turning while other stars swing around it. Australia is in the Southern Hemisphere, where the north end of the axis points below the horizon, so Polaris never rises there.

9.3 A Month of Moon Sketches

OBJECTIVES

- Keep a Moon journal for one month, recording the date, time, direction, height and shape of the Moon.
- Use your own records to name each phase, find the length of the Moon's cycle and predict coming phases.
- Explain from your observations that the lit side of the Moon always faces the Sun and that the Moon rises about 50 minutes later each day.

Warm-up. Without looking anything up, draw what you think the Moon will look like tonight and where in the sky it will be at bedtime. Write one sentence explaining your guess. Seal the drawing in an envelope labeled "Open in one month." At the end of this lab you will compare it with a whole month of real sketches.

Video. Coming soon. Keeping a Moon journal and watching the Moon's phases and moonrise change over a month; search NASA Moon (moon.nasa.gov), NASA Space Place, NOAA SciJinks, Sky and Telescope, and Homeschool Pop (Alternate).

KEY TERMS

lunar month
The time from one new Moon to the next, about 29½ days.

waxing
Growing. A waxing Moon shows more of its lit side each night, from new Moon to full.

waning
Shrinking. A waning Moon shows less of its lit side each night, from full Moon back to new.

earthshine
A faint glow on the dark part of a crescent Moon, made by sunlight bouncing off Earth onto the Moon.

Moon illusion
The trick of the eye that makes the Moon look bigger near the horizon than high in the sky, though it is really the same size.

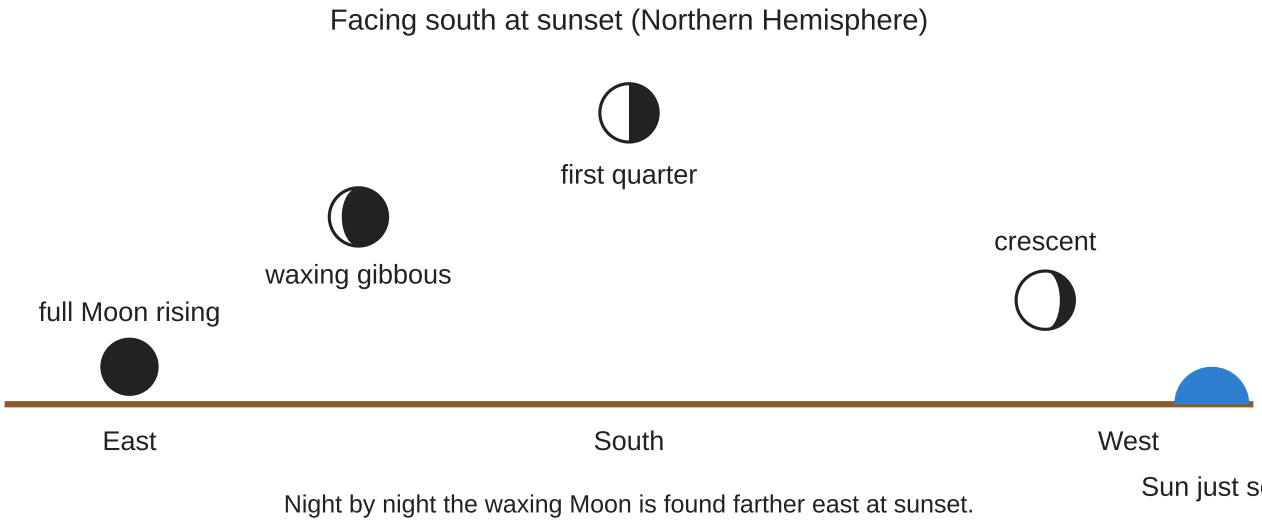
CORE IDEAS

The story. In March 1840, in New York City, a chemistry professor named John William Draper aimed a camera through a telescope and made one of the first clear photographs of the Moon. It was a daguerreotype, a picture on a silver-coated copper plate, and the plate had to soak up moonlight for about twenty minutes. Before cameras, every picture of the Moon was drawn by hand, and even today careful sketching is one of the best ways to learn

the sky. A sketch makes you *look*: at the shape of the lit part, at where the Moon sits, at what time it rises. Kept for a month, those sketches become real scientific data.

The big idea. Your journal will show a pattern that repeats about every **29½ days**. After new Moon, a thin crescent appears low in the west just after sunset. Night by night it is **waxing**, lit on the right side (as seen from the Northern Hemisphere), and it moves farther east. About a week later the first quarter, a half Moon, stands high in the south at sunset. About two weeks after new Moon, the full Moon rises in the east as the Sun sets in the west. Then the Moon is **waning**, rising later and later until it is seen mostly in the morning sky, lit on the left. In every sketch the lit side faces the Sun. The Moon also rises about **50 minutes later** each day on average, because while Earth turns, the Moon moves a little farther east along its orbit, and Earth must turn a bit extra to catch up.

Try it and see. Look at a thin crescent with binoculars or just your eyes. You may see the rest of the Moon glowing faintly: that is **earthshine**, sunlight bounced off Earth. When a full Moon rises huge and orange over the trees, test the **Moon illusion**: hold a pencil eraser at arm's length and see how much of it the Moon covers, then measure again when the Moon is high. **God's handiwork.** David wrote, "When I consider thy heavens, the work of thy fingers, the moon and the stars, which thou hast ordained" (Psalm 8:3). Considering means looking carefully and thinking, and that is exactly what a month of sketches trains you to do.



Where the waxing Moon is at sunset, seen from the Northern Hemisphere facing south. The lit side always faces the Sun.

PICTURE STUDY



Two Men Contemplating the Moon, Caspar David Friedrich, about 1819–1820 · Oil on canvas · Galerie Neue Meister, Staatliche Kunstsammlungen Dresden, Germany

Caspar David Friedrich was a German painter who loved mountains, forests, seashores and the sky at dawn and dusk. He often painted people from behind, so that we stand with them and look at what they see. Here two men have stopped on a forest path in the evening to watch the Moon.

Friedrich painted the twilight sky with great care, glowing near the horizon and darkening above. Paintings like this one remind us that looking at the sky slowly, in silence, is a kind of study and a kind of wonder.

Look closely

- Find the Moon. What shape is it? Use your journal to name the phase.
- Look at the color of the sky from the horizon upward. How does it change?
- Look at the men. Why do you think Friedrich painted them from behind?
- Find the big tree. How does it frame the Moon?

Talk about it

1. If this is an evening sky, in which direction are the men probably looking? Use what you know about where a crescent Moon is seen after sunset.
2. How is quietly watching the Moon, like these two men, the first step of science?

> **Safety first.** When you look for the Moon in the daytime, never look at the Sun; turn so the Sun is behind you or blocked by a building. Observe at night only with an adult, in a safe spot away from roads, and use a red flashlight to see your journal.

EXPERIMENT: MY MOON JOURNAL

Question: How do the Moon's shape, place in the sky and rising time change over one month? **Prediction:** write how many days you think it will take for the Moon to go from one full Moon to the next.

What we change: the date (one observation each clear day or night). **What we keep the same:** the observing spot, the way we measure height (fists at arm's length) and the way we name directions. **What we measure:** the phase, the direction, the height in fists and the time. **Record:** one journal box for each observation.

You will need

- A notebook with 30 circles traced around a coin or bottle cap, one per box, with lines below each for notes
- A pencil, an eraser and a soft pencil or charcoal for shading
- Your noon line from Lesson 9.1 or a compass, so you know north, south, east and west
- A red flashlight
- A calendar, and a newspaper or almanac table of moonrise times if you can find one
- A pencil with an eraser, or a paper hole-punch dot, for measuring the Moon's size

Steps

1. Start soon after a new Moon, when the first thin crescent appears in the west after sunset. (A calendar or almanac shows the date of each new Moon.)
2. Each clear evening, go to the same spot. Shade the dark part of the Moon in your circle so the lit part shows its true shape. Lit side on the correct side!
3. Under each sketch write the date, the time, the direction you faced (E, SE, S, SW, W) and the Moon's height in fists above the horizon.
4. On cloudy nights, write "cloudy" and leave the circle blank. Missing data is still honest data.
5. After full Moon, the Moon rises later each night. Look for it in the late evening, or in the morning sky in the west and south before school. Note any daytime Moon too.
6. On a night near full Moon, measure the Moon illusion: when the Moon is just rising, see how much of an arm's-length eraser it covers. Measure again two or three hours later, when it is high. Record both.
7. At the end of the month, label each sketch with its phase name, count the days from full Moon to full Moon (or new to new), and open your warm-up envelope.

Tips

- Look at the same clock time each evening when you can. Then you will see the Moon shift east and grow night by night.
- If moonrise times are printed in your newspaper or almanac, copy them into your journal and find how much later the Moon rises each day.

- A daytime Moon is easiest to find in the afternoon about a week after new Moon, or in the morning about a week after full Moon.

Check your work

- I kept at least 15 dated observations with sketch, time, direction and height.
- I labeled the phases and found the length of the cycle from my own data.
- I can explain why the lit side always faces the Sun.

FIELD NOTEBOOK

1. Choose your eight best sketches and arrange them in a circle in phase order, from new Moon around to the last crescent. Label each phase.
2. Draw a crescent Moon with earthshine, shading the dark part a soft gray. Write one sentence explaining where that glow comes from.
3. Make a small table of five moonrise times from your journal or an almanac and write the number of minutes later each one is than the day before.

> **From history.** About five hundred years ago, Leonardo da Vinci wondered why the dark part of a crescent Moon glows faintly. In one of his notebooks, now called the Codex Leicester, he wrote that the glow is sunlight reflected from Earth onto the Moon. He was right. Today we call it earthshine, and it is brightest when the Moon is a thin crescent, because then a nearly “full Earth” is shining in the Moon’s sky.

WORKED EXAMPLES

Example 1. Your journal shows a full Moon on the evening of March 3. About when should you expect the last-quarter Moon, and about when will the next full Moon come?

(Use the map or drawing “The full Moon rises in the east as the Sun sets in the west.” shown earlier in this lesson.)

1. The lunar month is about 29½ days. A quarter of it is about $29.5 \div 4 \approx 7.4$ days.
2. Last quarter comes about a quarter of a month after full: March 3 + 7.4 days ≈ March 10 or 11.
3. The next full Moon comes about 29½ days after this one: $3 + 29.5 = 32.5$.
4. March has 31 days, so day 32.5 of March is $32.5 - 31 = 1.5$, which is April 1 or 2.

Answer: Last quarter around March 10 or 11, and the next full Moon around April 1 or 2.

PRACTICE

1. EASY Seen from the United States, which side of a waxing crescent Moon is lit: the left or the right?
2. EASY At sunset, where should you look to see the full Moon?

3. MEDIUM A student copied these moonrise times into her journal.
   Day | Moonrise
   Monday | 6:10 p.m.
   Tuesday | 6:58 p.m.
   Wednesday | 7:49 p.m.
   Thursday | 8:41 p.m.
   (a) How many minutes later did the Moon rise each day? (b) What is the average delay? (c) Predict Friday's moonrise.
4. HARD Is the rising full Moon really bigger than the high Moon? Design a fair test. Name what you change, two things you keep the same and what you measure.
5. CHALLENGE Explain why you will never see a thin crescent Moon high in the south at midnight.

COMMON MISTAKES

- Thinking Earth's shadow makes the phases. Phases come from how much of the Moon's sunlit half we can see; Earth's shadow falls on the Moon only during a lunar eclipse.
- Thinking the Moon is only out at night. For about half of each month you can find it in the daytime sky.
- Thinking the Moon really grows larger near the horizon. Measuring with an eraser at arm's length shows it stays the same size.

> **Make it a game · Phase Calendar Challenge.** Lay out eight cards showing the phases in a mixed-up pile. A parent calls out a day of the cycle, such as "day 7" or "day 22," counting from new Moon. The player picks the matching phase card and says where it would be at sunset or when it would rise. A point for the right card and another for the right place. After eight rounds, line up all the cards in order to finish.

> **Scripture.** "When I consider thy heavens, the work of thy fingers, the moon and the stars, which thou hast ordained; What is man, that thou art mindful of him? and the son of man, that thou visitest him?" (Psalm 8:3–4, KJV)

David had kept sheep under the open night sky, and he was amazed that the God who made the Moon and stars cared for him. A month of Moon sketches is a month of considering His works.

Practice answers

1. The right side.
2. Low in the east, where it is rising, opposite the setting Sun in the west.
3. (a) 48 minutes, 51 minutes and 52 minutes. (b) (48 + 51 + 52) ÷ 3 = 151 ÷ 3 ≈ 50 minutes. (c) 8:41 p.m. + 50 minutes ≈ 9:31 p.m.
4. Change: the Moon's height in the sky (just after it rises, then a few hours later when it is high). Keep the same (any two): the same night, the same observer, the same arm stretched fully straight, the same eraser or hole-punch dot. Measure: how much of the eraser or dot the

Moon covers each time (or snap a photo with the same camera zoom). Result: it covers the same amount, so the bigger look near the horizon is a trick of the eye.

5. A thin crescent is only a little way from the Sun in the sky, so it is lit mostly from behind and shows just a sliver. At midnight the Sun is far below the horizon, on the opposite side of Earth from the midnight sky overhead, so a crescent that stays near the Sun has already set or has not yet risen. High in the south at midnight you can only see a Moon that is opposite the Sun, near full.

9.4 Scale Solar-System Walk

OBJECTIVES

- Build a neighborhood-sized model of the solar system in which the Sun is a 65-centimeter ball and every size and distance uses the same scale.
- Change distances in astronomical units into model meters (1 AU = 70 meters) and plot the farthest planets on a town map using its map scale.
- Compare an orrery with a true scale model and explain what each one can and cannot show.

Warm-up. Draw a chalk circle 65 centimeters (about 26 inches) across on a driveway or sidewalk, or set out a big exercise ball. That is the Sun. Now hold up a tennis ball: it is Jupiter at the same scale. Guess how far from the Sun this Jupiter belongs: across the yard, down the block or farther? Write your guess and keep it until the end of the walk.

Video. Coming soon. Building a scale model of the solar system in a neighborhood, and how an orrery works; search NASA Space Place, NASA Jet Propulsion Laboratory education, Smithsonian National Air and Space Museum, Science Max, museum orrery demonstrations and Homeschool Pop (Alternate).

KEY TERMS

orrery
A machine with gears that shows the planets and moons moving around the Sun. It shows the motions well but squeezes the sizes and distances far out of scale.

scale
The rule linking a model to the real thing. In this walk the rule is 1 AU = 70 meters, used for every size and every distance.

astronomical unit (AU)
The average distance from Earth to the Sun, about 150 million kilometers (93 million miles).

map scale
The rule linking distances on a map to distances on the ground, such as 1 centimeter on the map = 100 meters on the ground.

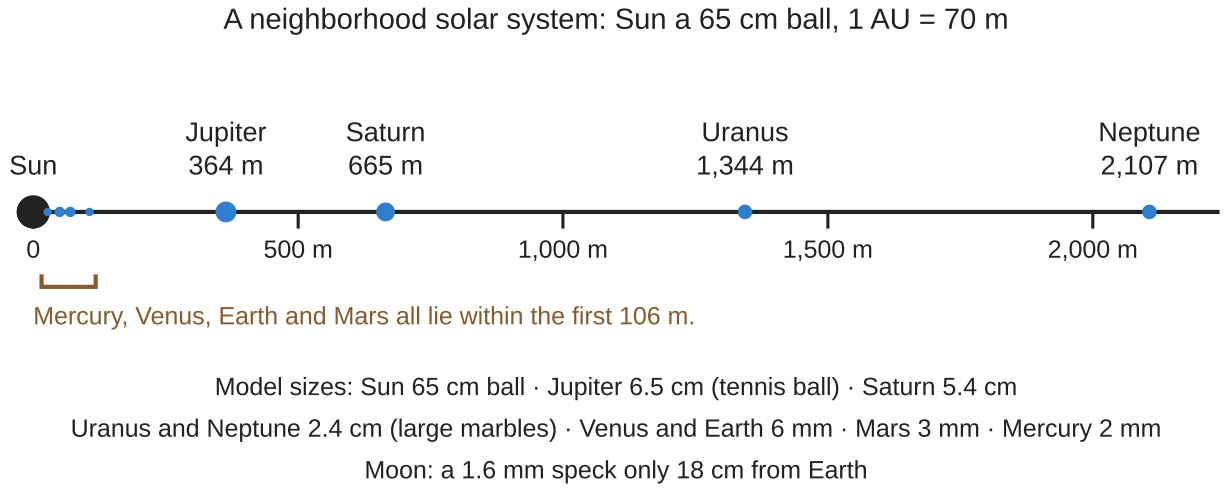
CORE IDEAS

The story. Around 1704, in London, George Graham, working with his master, the famous clockmaker Thomas Tompion, built a little machine of brass gears. Turn its handle and a ball for Earth circled a ball for the Sun while a tiny Moon circled Earth. A few years later the instrument maker John Rowley made one for a nobleman, Charles Boyle, the Earl of Orrery, and such machines have been called **orreries** ever since. Orreries are wonderful for showing

motion: why there are months and years, and why the inner planets lap the outer ones. But no orrery can show true *size* and *distance*, because on a tabletop the planets would be too small to see.

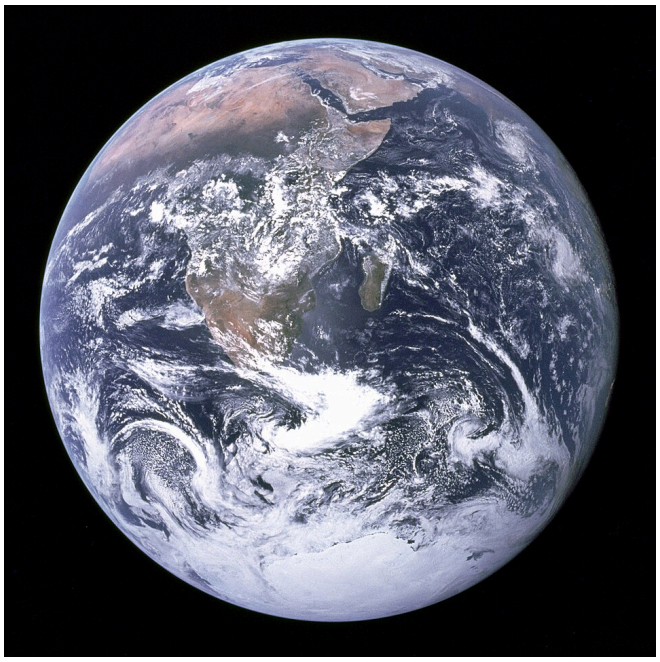
The big idea. To feel the real solar system you have to go outside. Make the Sun a ball 65 centimeters (about 26 inches) across, the size of a big exercise ball. Then the **scale** is 1 AU = 70 meters (about 230 feet), and everything else follows. Earth is a 6-millimeter bead 70 meters away, and the Moon is a speck 1.6 millimeters across only 18 centimeters (7 inches) from Earth. Mercury, Venus and Mars are beads of 2, 6 and 3 millimeters at 27, 50 and 106 meters. Jupiter is a tennis ball 364 meters from the Sun, and Saturn a ball about 5.4 centimeters across at 665 meters. Uranus and Neptune, each the size of a large marble, sit at 1,344 and 2,107 meters, about 0.8 and 1.3 miles. Your solar system fills a whole neighborhood, and the last two planets are best found on a **map** or with a car's odometer.

Try it and see. Stand at model Earth and look back at the 65-centimeter Sun, 70 meters away. It looks just as wide as the real Sun looks from the real Earth, about half a little finger at arm's length, because every part of the model uses the same scale. (Check the model, never the real Sun.) At this scale the nearest star beyond the Sun would be another ball nearly 19,000 kilometers away, almost halfway around the world. **God's handiwork.** "The heavens declare the glory of God; and the firmament sheweth his handywork" (Psalm 19:1). A model that stretches across your town still holds only our Sun's small family, and the stars God made lie far beyond it.



The neighborhood solar system, with the Sun a 65 cm ball and 1 AU = 70 meters. Neptune is about 2.1 kilometers (1.3 miles) away.

PICTURE STUDY



The Blue Marble: Earth Seen from Apollo 17, The crew of Apollo 17 (Eugene Cernan, Ronald Evans and Harrison Schmitt), NASA, December 7, 1972 · Photograph on 70 mm film, taken with a Hasselblad camera · NASA (photograph AS17-148-22727)

About five hours after Apollo 17 lifted off for the Moon, one of the three astronauts turned a hand-held camera back toward home. The spacecraft was about 29,000 kilometers (18,000 miles) from Earth, and the Sun was behind it, so the whole face of the planet was lit. The picture shows Africa, Arabia and, for the first time in a photograph taken by people, the great ice cap of Antarctica. It became one of the most reproduced photographs in history.

Hold this picture up beside your model. This entire ball, with all its oceans, deserts and clouds, is the 6-millimeter bead on your Earth card. At the same scale the camera that took this picture was only about 1.4 centimeters from the bead, and the Moon the astronauts were heading for was 18 centimeters away. No one has traveled far enough to take a picture like this since 1972.

Look closely

- Find the shapes of Africa and the Arabian Peninsula. Which parts look brown and dry, and which look green?
- Find Antarctica at the bottom. Why does it look white, and why can we see so much of it in this picture?
- Look at the clouds. Do they look like the swirls on a weather map? Find one big storm.
- Look at the edge of the Earth against the black sky. Is there anything between the planet and space?

Talk about it

1. On your neighborhood walk, the Sun ball was 65 centimeters across and Earth was a 6-millimeter bead. How does this photograph help you picture that difference?
2. The astronauts were on their way to the Moon, 18 centimeters from the bead in your model. Why do you think no one has yet traveled to the next bead, Mars?
3. Psalm 19:1 says the heavens declare the glory of God. What does seeing the whole Earth in one picture say about its Maker?

> **Safety first.** Walk only with an adult, on sidewalks or park paths, and stay well away from traffic. Use the map or a car ride with a parent for the farthest planets instead of crossing busy roads. Keep the small beads away from little brothers and sisters who might put them in their mouths. Never look at the real Sun.

EXPERIMENT: A NEIGHBORHOOD SOLAR SYSTEM

Question: If the Sun were a 65-centimeter ball in our yard, where in our neighborhood would each planet be? **Prediction:** mark on the map where you think Jupiter and Neptune will land.

What we change: the planet we are placing. **What we keep the same:** one scale for every size and distance (Sun 65 cm, 1 AU = 70 m) and the same starting point. **What we measure:** the model distance to each planet, by paces, tape measure, map or odometer. **Record:** a table of planet, real distance in AU, model distance, model size and the landmark where it lands.

You will need

- A 65 cm exercise ball, or chalk and a 33 cm string to draw a 65 cm circle
- Beads or clay balls: 2 mm (Mercury), two of 6 mm (Venus and Earth), 3 mm (Mars) and a 1.6 mm seed bead or clay speck (the Moon)
- A tennis ball (Jupiter), a ball about 5.5 cm across such as a clementine with a paper ring (Saturn), and two large marbles about 2.4 cm across (Uranus and Neptune)
- Index cards, tape and a fine marker for planet signs
- A tape measure or a string exactly 10 meters long
- A printed map of your neighborhood with a scale bar, a ruler and a compass for drawing circles (a string and pin work too)
- Notebook, pencil and calculator

Steps

1. Copy this table: Mercury 0.39 AU, Venus 0.72 AU, Earth 1.00 AU, Mars 1.52 AU, Jupiter 5.2 AU, Saturn 9.5 AU, Uranus 19.2 AU, Neptune 30.1 AU. Multiply each by 70 to get model meters (Mercury is $0.39 \times 70 \approx 27$ m).
2. Tape each bead or ball to an index card labeled with the planet’s name, model size and model distance.
3. Measure your pace: walk the 10-meter string with normal steps, count, and divide 10 by your count.

4. Set the Sun at your starting point. Pace off Mercury, Venus, Earth and Mars and set each card down. Put the Moon’s speck 18 cm from Earth.
5. With an adult, walk on to Jupiter (364 m) and, if you can, Saturn (665 m). Note the landmark at each stop.
6. For Uranus and Neptune, use the map. Change 1,344 m and 2,107 m into map distance with the map scale, then draw circles that far from your Sun. Find a landmark on each circle. If a parent drives you, check the distance on the odometer: about 0.8 mile and 1.3 miles.
7. From Earth’s card, look back at the Sun ball and hold up your little finger at arm’s length. Then compare your warm-up guess for Jupiter with the real model distance and write two sentences about what surprised you.

Tips

- The planets do not need to be in a straight line. Each one only needs to be the right distance from the Sun, and in the real sky they are spread all around it.
- If the walk is too long, do the inner planets and Jupiter on foot and put the rest on the map.
- Ask permission before taping a planet sign to anything that is not yours, and pick up every card at the end.

Check your work

- I used one scale for every size and distance.
- I changed AU into model meters by multiplying by 70 and used a map scale for the farthest planets.
- I can explain what an orrery shows well and what it cannot show.

FIELD NOTEBOOK

1. Tape a copy of your neighborhood map into your notebook. Mark the Sun and every planet, with the landmark beside each.
2. Draw the Sun ball and Jupiter’s tennis ball side by side, then Earth’s 6 mm bead with the Moon 18 cm away, all at true model size. Label each.
3. Draw a simple orrery with its arms and gears, and beside it write two things it shows well and one thing it cannot show.

> **From history.** In 1771 David Rittenhouse, a Pennsylvania clockmaker and astronomer, finished a large orrery that was bought by the College of New Jersey, now Princeton University. He then built a second one for the College of Philadelphia, now the University of Pennsylvania. Rittenhouse’s orreries showed the planets and their moons turning in their true positions for any date he chose, and Americans of his day counted them among the finest scientific instruments in the colonies. Both survive today.

WORKED EXAMPLES

Example 1. Neptune is 30.1 AU from the Sun. Using 1 AU = 70 meters, how far from the Sun ball does Neptune go? How far is that on a map whose scale is 1 cm = 100 m? About how many miles is it? (1 mile ≈ 1,609 meters.)

(Use the map or drawing "Find Neptune at the far end of the line, 2,107 meters from the Sun." shown earlier in this lesson.)

1. Model distance: 30.1 × 70 = 2,107 meters.
2. Map distance: each centimeter on the map stands for 100 meters, so 2,107 ÷ 100 ≈ 21.1 cm on the map.
3. Miles: 2,107 ÷ 1,609 ≈ 1.3 miles.

Answer: Neptune goes 2,107 meters from the Sun ball: about 21 centimeters on the map, or about 1.3 miles.

PRACTICE

1. EASY What can an orrery show well, and what can it not show?
2. EASY Mars is 1.52 AU from the Sun. Using 1 AU = 70 meters, how far is model Mars from the Sun ball? About how many feet is that? (1 meter ≈ 3.28 feet.)
3. MEDIUM Use the table of model distances.
   Planet | Model distance from Sun
   Mercury | 27 m
   Venus | 50 m
   Earth | 70 m
   Mars | 106 m
   Jupiter | 364 m
   Saturn | 665 m
   Uranus | 1,344 m
   Neptune | 2,107 m
   (a) How far apart are Saturn and Uranus? (b) About how many times farther from the Sun is Neptune than Earth? (c) Which planets would fit in a park 120 meters long with the Sun at one end?
4. HARD Could you see model Earth, a 6 mm bead, from the Sun ball 70 meters away? Design a fair test. Name what you change, two things you keep the same and what you measure.
5. CHALLENGE In the model the Moon is 18 cm from Earth, the farthest any person has ever traveled. How many of those Earth-to-Moon trips would it take to cover the 2,107 meters from the Sun to Neptune? (1 meter = 100 cm.)

COMMON MISTAKES

- Thinking orreries and book pictures show the true spacing of the planets. They squeeze the distances so everything fits.
- Thinking the planets stand in a straight line from the Sun. Each one is at its own place on its orbit, all around the Sun.
- Thinking a small model Sun would look tiny from model Earth. Because the model keeps one scale, the 65 cm ball at 70 meters looks exactly as wide as the real Sun does from Earth.

Make it a game · Planet Lineup. Lay the Sun ball, the tennis ball, the marbles and the bead cards in a mixed-up pile. Round one: line them up from biggest to smallest. Round two: a parent names a planet, and the player must give its model distance from memory within 10 percent to earn a point (Jupiter, 364 m, scores for anything from about 330 to 400 m). Round three: name a landmark in your town for each outer planet. Most points after three rounds wins.

Scripture. “The heavens declare the glory of God; and the firmament sheweth his handywork.” (Psalm 19:1, KJV)

A model as big as a town is still tiny next to the real heavens. Every step of the walk is a small sermon on how great their Maker is.

Practice answers

1. It shows the motions well: planets and moons going around in the right order and at the right relative speeds. It cannot show the true sizes and distances, which would be far too big or too small for a tabletop.
2. 1.52 × 70 = 106.4 meters, about 106 meters. 106.4 × 3.28 ≈ 349 feet, about 350 feet.
3. (a) 1,344 − 665 = 679 meters. (b) 2,107 ÷ 70 ≈ 30 times. (c) Mercury, Venus, Earth and Mars.
4. Change: the distance between the observer and the bead. Keep the same (any two): the same bead, the same background (such as a white card), the same daylight, the same observer and eyes (glasses on or off each time). Measure: the distance, stepped back a few meters at a time, at which the observer can no longer find the bead. Most people lose sight of it long before 70 meters, which shows how tiny Earth is compared with the space around it.
5. 2,107 meters = 210,700 cm. 210,700 ÷ 18 ≈ 11,706, so about 11,700 Moon trips.

Unit 9 review

Answer each question. Show your work for calculations and use complete sentences for explanations. The review has 6 questions and is worth 50 points.

1. (8 pts) A family at 42° north latitude builds an equatorial sundial. (a) At what angle to the ground should they tilt the pencil, and which way should its high end point? (b) How many degrees from the 12 line is the 4 p.m. line?
2. (8 pts) (a) How can you find true north with a stick and the Sun? (b) In July, a well-aimed sundial reads 12:00 when the clock reads about 1:00 p.m. Give the main reason.
3. (8 pts) At 9 p.m. you map the Big Dipper. Later you find it has turned 45° around Polaris. (a) About what time is it? (b) As you face north, which way did it turn? (c) Why does it turn at all?
4. (8 pts) (a) Explain how to find Polaris using the Big Dipper. (b) In Johann Bayer’s star atlas of 1603, what did the letter α (alpha) usually mean? (c) Why should you use a red flashlight when making a star map?
5. (9 pts) Your Moon journal shows a first-quarter Moon on June 10. (a) About when will the Moon be full? (b) About when will the next first quarter come? (June has 30 days.) (c) If the Moon rises at 7:20 p.m. tonight, about when will it rise tomorrow?
6. (9 pts) In the neighborhood model the Sun is a 65 cm ball and 1 AU = 70 meters. (a) Jupiter is 5.2 AU and Saturn 9.5 AU from the Sun. Find each model distance. (b) How far apart are model Jupiter and model Saturn? (c) Explain why a tabletop orrery cannot show the planets at this scale.

Unit project: my field lab notebook of the sky

Gather your four labs into one Field Lab notebook. Include your sundial readings table and a drawing of your dial, your two-time star map with the angle the Dipper turned, at least fifteen dated Moon sketches with times, directions and heights, and your neighborhood map with every planet and landmark marked. Finish with a one-page “What the Sky Taught Me” summary that names one thing you predicted correctly, one thing that surprised you, and one way these labs showed you the order God set in the heavens (Genesis 1:14).

- **Observations**: Every lab has dated, timed observations recorded honestly, including cloudy nights and missed days.
- **Measurements**: Angles, times, distances and scale calculations are correct and show units, with metric and U.S. customary where asked.
- **Fair tests**: Each lab names its question, prediction, what was changed, what was kept the same and what was measured.
- **Explanation and care**: The summary explains the patterns clearly, and the drawings and maps are neat, labeled and easy to read.

Answer key

1. (a) 42°, the same as the latitude, with the high end pointing true north (toward Polaris). (b) 4 hours × 15° = 60° from the 12 line, on the afternoon (east) side of the dial.
2. (a) Stand a stick upright and mark the tip of its shadow every 15 minutes around midday. The shortest shadow, at solar noon, points due north. (b) Daylight saving time sets clocks one hour ahead in summer, so solar noon comes near 1 p.m. on the clock.
3. (a) 45 ÷ 15 = 3 hours later, about midnight. (b) Counterclockwise. (c) Earth turns on its axis, which points almost at Polaris, so the stars appear to circle Polaris about 15° each hour.
4. (a) Find the two pointer stars at the end of the Dipper’s bowl, Merak and Dubhe, and follow the line from Merak through Dubhe about five times their gap to Polaris. (b) The brightest star in a constellation. (c) Red light spoils night vision much less than white light, so you can still see faint stars after reading your map.
5. (a) About a quarter of a month (7.4 days) later: around June 17 or 18. (b) 10 + 29.5 = 39.5, and 39.5 − 30 = 9.5, so around July 9 or 10. (c) About 50 minutes later, near 8:10 p.m.
6. (a) Jupiter: 5.2 × 70 = 364 m. Saturn: 9.5 × 70 = 665 m. (b) 665 − 364 = 301 m. (c) The distances between the planets are enormous compared with their sizes. If an orrery used true scale, the planets on a tabletop would be too tiny to see, or the machine would have to stretch for kilometers, so orreries squeeze the distances and enlarge the planets.