

TECHNOLOGY OVERCOMING GEOGRAPHY

A one-semester high-school course on how people overcame the sea, the land and distance itself: the stern rudder and the compass, Harrison's chronometer, the Erie Canal and Stephenson's Rocket, Suez and Panama, the Atlantic cable and the Great Eastern, the Wrights and the polar routes, McLean's container and the GPS satellite, each one studied as a problem geography posed and a solution people built, and ending with what technology has still not overcome.

First edition

"And hath made of one blood all nations of men for to dwell on all the face of the earth, and hath determined the times before appointed, and the bounds of their habitation;" (Acts 17:26, KJV)

COURSE GUIDE

This is a one-semester elective for students in grades 9–12: 25 lessons in five units of five, finished in about 17 weeks. Unit 1 masters the sea (the sail and stern rudder, the compass and chart, longitude, steam and the iron hull). Unit 2 masters the land (Roman roads, canals and locks, the railroad, the transcontinental lines, tunnels and bridges). Unit 3 is the great canals (Suez, the French and American efforts at Panama, Kiel and Corinth). Unit 4 masters distance (the telegraph, the Atlantic cable, the airplane, the jet age and the container). Unit 5 masters location (Sputnik, GPS and the undersea fiber cables) and ends by asking what technology has *not* overcome. Every lesson has a primary source or historic map, worked examples, a practice set with answers and a written response. Each unit ends with a 100-point test and a unit project, there is a midterm after Unit 3, and the course closes with a research paper and a final exam.

Every lesson begins with **the story**: a real person at a real place on a real date. Brunel's *Great Western* steams out of Bristol in 1838; Harrison's fourth watch is tested on the voyage to Jamaica; Ferdinand de Lesseps opens the Suez Canal in 1869, the same year the *Cutty Sark* is launched for a tea trade the canal will soon take from her; William Gorgas fights the mosquito at Panama; Samuel Morse sends "What hath God wrought" from Washington to Baltimore in 1844; Malcom McLean's *Ideal X* sails from Newark to Houston in 1956 with 58 containers on deck. Then comes **the problem geography posed**: the wind, the ocean, the mountain range, the isthmus or simple distance. Then **how the technology solved it**, with the numbers that show it (miles saved, days cut, tons carried, cost per ton), then **what it cost** in money, labor and lives, and finally **what changed in the world**: which ports rose and fell, which empires gained or lost, which routes the world's trade now follows.

Technology overcoming geography is one of the world's great stories, and in this course it is the whole story. Geography is not destiny in the sense of a cage: people have learned to sail against the wind, cut through isthmuses, tunnel under mountains, talk across oceans and find their place on the earth to within a few meters. But geography still sets the terms. The canal that saves 7,000 miles also becomes a choke point; the cable that joins continents can be cut; the airplane still flies around the weather; the mountains are still there. The last unit asks the student to weigh both halves honestly, and the final research paper traces one technology and the geography it overcame from start to finish.

The faith thread runs underneath. God gave mankind the charge to "replenish the earth, and subdue it" (Genesis 1:28), and the inventiveness of the shipwright, the surveyor and the engineer is part of what it means to be made in His image. But the tower of Babel stands as a warning: "let us build us a city and a tower, whose top may reach unto heaven; and let us make us a name" (Genesis 11:4). Great works can serve people or feed pride, and the course looks honestly at both, including the laborers who died at Suez and Panama. Over it all stands the series verse: "And hath made of one blood all nations of men for to dwell on all the face of the earth, and hath determined the times before appointed, and the bounds of their habitation;" (Acts 17:26). Technology has moved the bounds, but it has not moved the One who set them.

WHO IT IS FOR

Written for students in grades 9–12. No earlier geography course is required, though students who have done the School Launch Geography grades will recognize many of the places. The math is high-school arithmetic and a little algebra: rates, distance and time, percentages, map scale and simple ratios, with every new method shown in a worked example first. Students work fairly independently, reading the lesson, studying the primary source and working the examples themselves; a parent or mentor checks the practice sets against the answers, discusses the written responses and helps with the projects. A globe, a good world atlas and household materials are all that is needed; the historic maps used in the lessons are free to view online.

HOW TO USE THIS COURSE

The weekly rhythm. Each lesson takes three sessions of about 50 minutes. Session 1: the warm-up, the story, the primary source and discussion. Session 2: map work in the map notebook and the worked examples. Session 3: the practice set, checked against the answers, and a written response of one or two paragraphs. Each unit ends with a test day and time for the unit project; the midterm after Unit 3 and the final each have a review day. At five sessions a week the 25 lessons, five unit tests, midterm and final fill about 17 weeks, one semester.

The ⚙ thread is the whole course. In the School Launch Geography grades, the ⚙ mark flags the lessons where technology overcomes geography. Here every lesson carries it. Ask the same four questions every time: What problem did geography pose? How did the technology solve it? What did it cost? What changed in the world? By the end of the semester the student should be able to answer them for any invention, including ones not in the course.

The map notebook. Use one bound notebook, ideally with graph paper, for the whole semester. Each unit has a main map: sailing times from London to China across the 1800s, the travel-time maps of the United States from Paullin's 1932 *Atlas of the Historical Geography of the United States*, voyages before and after Suez and Panama, the 1866 Atlantic cable beside today's undersea cables, and the GPS constellation. Draw them by hand, with a title, a scale, a north arrow and a key, and add a short note on what the map shows.

Worked examples and practice. Most lessons have two or three worked examples: how many miles the Suez Canal saves from London to Bombay, how much a lock lifts a ship, how far a clock error of one minute throws off a longitude, how much faster the railroad made the trip west. Cover the solution, try it yourself, then compare line by line. The practice set has answers; check them the same day and rework every miss.

Unit tests and unit projects. Each unit test is worth 100 points and mixes map questions, short calculations, identification and one short essay. Each unit also has a hands-on project: a sail-and-rudder test with a fan in the bathtub, a model canal lock with working gates, a

working lock from bottles and tubing, a great-circle string test on a globe and a flat map, and a floor-sized GPS trilateration with string and tape. Record each project in the map notebook with a sketch, measurements and what you learned. The final project is a research paper on one technology and the geography it overcame.

Where it fits. This is Course C of the School Launch high-school Geography electives. It pairs naturally with Course B, *Geography and Commerce: Sea Lanes, Straits and Trade Routes*, for a full year, and it sets up Course D, *Geopolitics*, where Mahan and Mackinder argue about what these same ships and railroads meant for power. It also sits beside the School Launch Engineering and Business high-school courses: Engineering explains how the lock, the steam engine and the satellite work, Business explains why the container changed the price of everything, and this course shows where on the map it all happened.

SCOPE AND SEQUENCE

Unit 1: Mastering the Sea (Weeks 1-3)

How sailors learned to use the wind, steer a large ship, find their way out of sight of land and finally fix their longitude, and how steam and iron freed the ship from the wind and the size of the tree.

Unit 2: Mastering the Land (Weeks 4-6)

From Roman roads and the state courier service to canals and locks, the railway age, the lines that bound North America and Siberia, and the tunnels and bridges that cut through mountains and across water.

Unit 3: The Great Canals (Weeks 7-10)

Suez, the French failure and the American success at Panama, and Europe's shortcuts at Kiel and Corinth: what each canal cost, how many miles it saved and how it rerouted trade and reshaped strategy. The midterm follows this unit.

Unit 4: Mastering Distance (Weeks 11-13)

The telegraph and the Atlantic cable ended distance for words; the airplane, the jet and the polar routes shrank it for people; and the shipping container made distance cheap for goods.

Unit 5: Mastering Location, and the Limits (Weeks 14-17)

Sputnik, GPS and the fiber-optic cables under the sea, then an honest look at what mountains, weather, distance and choke points still decide, ending with the research paper and the final exam.

MATERIALS

- **A globe:** Any size, as long as it turns freely. Used for great-circle routes, the polar air routes and the satellite lessons.

- **A good world atlas:** A current atlas with physical and political maps. A library copy is fine.
- **Map notebook:** One bound notebook, ideally graph paper, for every map, worked example, project record and written response.
- **Colored pencils, a ruler and a protractor:** For drawing routes, scale bars and bearings neatly.
- **A calculator:** Any scientific or phone calculator, for distance, rate and time and the canal and cable problems.
- **String, painter's tape and a tape measure:** For the great-circle test on the globe and the floor-sized GPS trilateration.
- **Plastic bottles, flexible tubing, a box fan and a cardboard or foam-board scrap:** For the sail-and-rudder test in the bathtub and the two working canal locks.
- **Historic maps online:** Paullin's 1932 Atlas of the Historical Geography of the United States and the other historic maps in the lessons are digitized and free to view online.
- **Optional reading:** Dava Sobel, Longitude (1995); David McCullough, The Path Between the Seas (1977); Marc Levinson, The Box (2006). Good for the research paper; not required.

GRADING

Grades come from the practice sets and written responses, the map notebook, the five unit projects, the five unit tests, the midterm, the final research paper and the final exam. A calculation earns full credit when the setup, the numbers with their units and the answer are all shown. A written response earns full credit when it answers the four questions (the problem, the solution, the cost and what changed) with specific places, dates and evidence.

- Practice sets and written responses (completed and corrected): 15%
- Map notebook (accuracy, neatness, notes): 10%
- Unit projects: 10%
- Unit tests: 30%
- Midterm exam: 10%
- Final research paper: 15%
- Final exam: 10%

A 90–100, B 80–89, C 70–79, D 60–69, F below 60.

- Practice sets are graded for completion and correction, not first-try accuracy: a problem done, checked and correctly reworked earns full credit.
- A map earns full marks when it has a title, a scale, a north arrow, a key and a short note on what it shows, and when the places on it are in the right spots.
- On tests, give partial credit for a correct setup even if the arithmetic slips. An essay earns full credit for a clear claim backed by at least two specific facts from the lessons.
- The research paper (about 1,500 words) should trace one technology from the geographic problem through the solution, the cost and the results, cite at least three

sources including one primary source or historic map, and end with what the technology has not overcome.

- For a high-school transcript this course is one-half credit of social studies (geography). Keep the map notebook, the tests and the research paper as the record of the semester.

A NOTE TO PARENTS

This course is built to make a teenager see the map differently. After a semester of asking why the Suez Canal mattered, why the railroad reached Omaha before it reached the Pacific, why a cable ship had to be the largest ship in the world and why a GPS receiver needs four satellites and not three, most students start noticing geography everywhere: in the price of what they buy, in the news about a blocked strait, in the route their own flight takes over Greenland. You do not need to be an expert. The lessons carry the content and the answers are provided; your part is to ask the four questions, read the written responses and help with the projects.

The course is honest about cost. The great works in these lessons were triumphs of skill and courage, and many of them were also paid for in lives: thousands died at Panama before Gorgas brought the mosquito under control, and the laborers at Suez and on the railroads worked in hard conditions. Students are asked to admire what deserves admiring and to weigh what was wrong by the standard of truth, not by slogans of any kind. Questions of trade and strategy are presented factually and from more than one side.

Above all, we want students to see human inventiveness as a gift. We are made in the image of a Creator, and the urge to build, to measure and to cross the sea is part of that likeness. But Babel reminds us that the same gift can serve pride. A student who finishes this course should be grateful for the engineers and sailors who made the world smaller, humble about how much the mountains and the weather still decide, and mindful that the One who “hath determined the times before appointed, and the bounds of their habitation” still rules over every map.

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- 2.1 Roman Roads
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- 2.5 Tunnels and Bridges

Unit 3: The Great Canals

- 3.1 The Suez Canal
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Unit 4: Mastering Distance

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- 4.3 The Airplane
- 4.4 The Jet Age and the Polar Routes
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Unit 5: Mastering Location, and the Limits

- 5.1 Sputnik and the Satellite Age
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- 5.3 Fiber-Optic Cables: The Internet Under the Sea
- 5.4 What Technology Has Not Overcome
- 5.5 Final Project and Exam: One Technology and the Geography It Overcame

★ quarter path · ⚙ technology overcoming geography

MASTERING THE SEA

For most of history the sea was the greatest barrier on earth, and also the greatest highway. Whoever could cross it safely, carry goods over it cheaply and find the way home again could trade with the world. This unit tells how people mastered the sea, one breakthrough at a time: the sail that harnessed the wind and the stern rudder that steered great hulls; the compass, the chart and the astrolabe that let pilots find their way out of sight of land; the chronometer that finally solved longitude; the steam engine that freed ships from the wind; and the clipper and the iron hull that pushed sail to its limit and then beyond it. In each lesson you will ask four questions: what problem did geography pose, how did the technology solve it, what did it cost, and what changed in the world?

You will meet the shipwrights of the Hanseatic cogs, Columbus watching his compass needle drift, John Harrison at his workbench, Isambard Kingdom Brunel standing before the chains of the Great Eastern, and the tea clippers racing home from China. You will work with real numbers: tacking distances, dead-reckoning plots, latitude from the stars, longitude from the clock, coal ranges and the square-cube law. And you will see that technology never abolished geography; it rewrote it. The winds drew the routes of sail; coal drew the routes of steam.

The Bible teaches that God made the earth and the sea and set the bounds of the nations: “And hath made of one blood all nations of men for to dwell on all the face of the earth, and hath determined the times before appointed, and the bounds of their habitation;” (Acts 17:26). He also gave mankind dominion over the earth and the fish of the sea (Genesis 1:28), and the creativity of shipwrights, navigators and engineers is part of that calling. The story of Babel (Genesis 11) reminds us that great works can also feed pride. Watch for both as you study the people who mastered the sea.

BEFORE YOU BEGIN

- Can read latitude and longitude on a globe or atlas and give compass directions as bearings in degrees (000° to 359°)
- Can work with ratios, percentages, squares and cubes, and convert units with a calculator
- Can use sine, cosine and tangent on a calculator for a right triangle (a short review is given in Lessons 1.1 and 1.2)
- Knows that Earth turns once a day on its axis and orbits the sun once a year

MASTERY CHECKLIST

- I can explain how the sail and the stern rudder let ships cross open oceans, and calculate the cost of tacking upwind.
- I can plot a dead-reckoning position and find latitude from Polaris or the noon sun.
- I can convert between time and longitude and explain how Harrison’s chronometer solved the longitude problem and why Greenwich became the prime meridian in 1884.

- I can use the square-cube law and coal figures to explain why big steamers were economical and why coaling stations mattered.
- I can explain why the clipper gave way to the steamship and how iron hulls let ships grow far beyond wood.
- I can show on a map how the voyage from London to China shrank between 1800 and 1900, and explain what technology did and did not overcome.

OPTIONAL BOOKS AND RESOURCES

- **Royal Museums Greenwich (Royal Observatory, Cutty Sark and National Maritime Museum)** (<https://www.rmg.co.uk/>): Free online collections and articles. The Royal Observatory displays Harrison's H1, H2, H3 and H4 and the Greenwich meridian; the Cutty Sark is nearby. Excellent for Lessons 1.3 and 1.5, and for the picture study in Lesson 1.1.
- **Brunel's SS Great Britain** (<https://www.ssgreatbritain.org/>): The museum ship in Bristol, with articles and images on Brunel, the Great Western, the Great Britain and the Great Eastern (Lessons 1.4 and 1.5).
- **Project Gutenberg (free primary sources)** (<https://www.gutenberg.org/>): Free. Search for Richard Henry Dana Jr., *Two Years Before the Mast* (1840), a sailor's firsthand account of life aboard a sailing ship, and Alfred Thayer Mahan, *The Influence of Sea Power upon History* (1890), for his remarks on coaling stations. A parent may choose the passages.

1.1 THE SAIL AND THE STERN RUDDER

OBJECTIVES

- Explain why sail power let ships carry cargo across open seas that rowed galleys could not cross, and what the wind still controlled.
- Describe how the stern-post rudder replaced the steering oar, and compare the cog and the carrack as ship types.
- Calculate the extra distance and time of tacking upwind for square and fore-and-aft rigs, and convert between knots, km/h and mph.

Warm-up. Hold a sheet of paper by its two top corners just below your lower lip, so it droops away from you. Blow hard straight across the top of it. Which way does the paper move: down, as you might expect, or up into the moving air? Now hold an open book flat on a table and blow across a loose page, then push a toy car across the table with a ruler held at an angle. Write one sentence guessing how a sail might pull a ship partly *toward* the wind instead of only being pushed away from it.

Watch. *How a sailboat sails upwind* (The School of Sailing , 4:05).

<https://www.youtube.com/watch?v=aMXgyCZiLS8>

With The big idea: a sail is a wing. How a sailboat sails upwind.

Backup video. *The Medieval Galleon in Miniature / Maritime Innovation in Miniature Series 2* (Lloyd's Register Foundation Heritage Centre, 6:19).

<https://www.youtube.com/watch?v=C7R5XxZskw8>

With The carrack: a model of a 16th-century ship, its rig, rudder and stern.

KEY TERMS

stern-post rudder

A flat blade hung on hinges (pintles and gudgeons) on the straight post at the back of a ship, on its centerline, and turned by a tiller or wheel.

cog

A sturdy one-masted merchant ship of northern Europe (about 1200–1450) with a flat bottom, overlapping side planks, one square sail and a stern rudder; the workhorse of the Hanseatic League.

carrack

A large three- or four-masted ship of the 1400s and 1500s that combined square sails for power with a triangular lateen sail at the stern for steering, high castles fore and aft, and a deep hold for long voyages.

lateen sail

A triangular sail set on a long slanting yard, used in the Mediterranean and Indian Ocean; a fore-and-aft sail that can point closer to the wind than a square sail.

tacking

Sailing upwind in a zigzag, first with the wind on one side of the bow and then the other, because no sailing ship can sail straight into the wind.

knot

A speed of one nautical mile per hour. One nautical mile is 1,852 m (about 1.15 statute miles), the length of one minute of latitude.

CORE IDEAS

The story. In October 1962, a dredger was deepening the river Weser at Bremen, in northern Germany, to build a new harbor basin. Its buckets struck old oak timbers in the mud. Over the next several years divers and archaeologists lifted out some two thousand pieces of a wooden merchant ship. Tree-ring dating showed that its oaks were felled around the year 1380. The ship seems to have been swept away by a flood while it was still being built, and it sank before it ever carried a cargo. After decades of careful conservation, the **Bremen Cog** now stands reassembled in the German Maritime Museum at Bremerhaven. It is about 23 m (76 ft) long and 7.6 m (25 ft) wide. It has a flat bottom for sitting on tidal mud, overlapping planks along its sides, one tall mast for a single square sail, and at the very back, hung on a straight sternpost, a heavy wooden **rudder**. Those two things, the sail and the stern rudder, are the subject of this lesson, and they were the first great tools by which people overcame the sea.

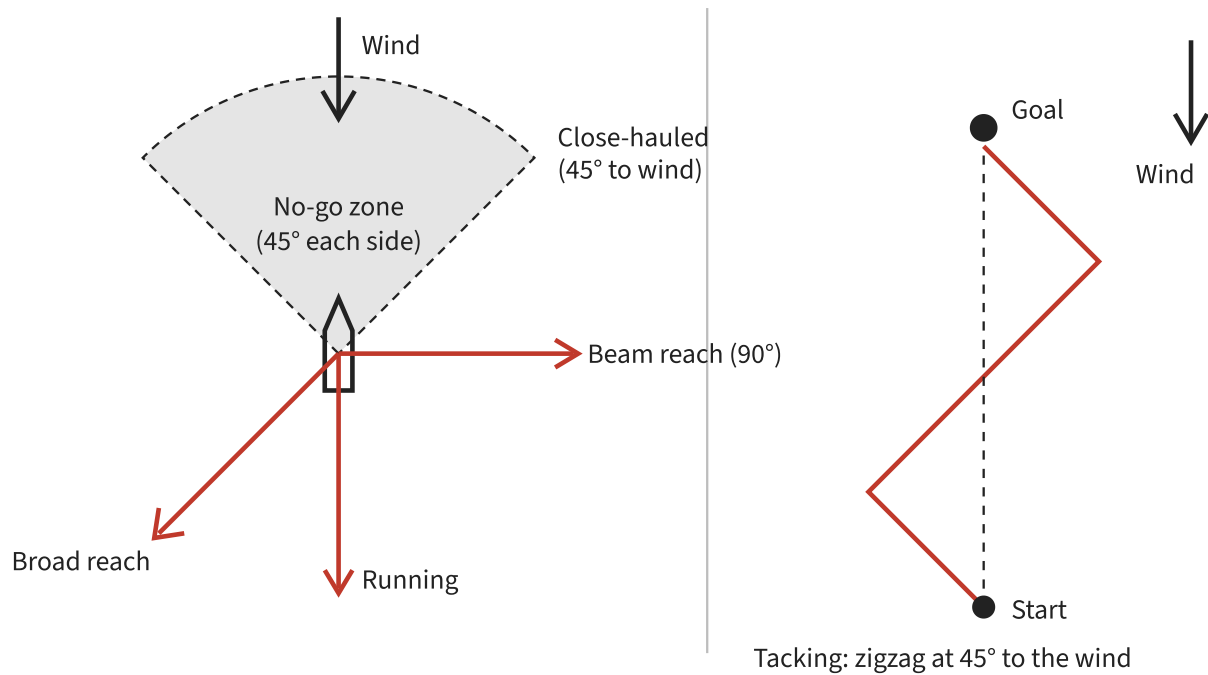
From oars to wind. For thousands of years the fastest ships in the Mediterranean were rowed. An Athenian trireme carried about 170 oarsmen. Oars give speed and control in a calm or a narrow harbor, but a rowing crew is an engine that must eat and drink. Two hundred men working hard in summer heat may drink close to a tonne of water a day, so galleys hugged the coasts, pulled up on beaches at night and stayed close to wells and markets. A sail draws its power from the wind, which costs nothing and never tires. A ship driven by sail needs only enough sailors to handle the ropes, and the space saved can be filled with cargo, food and water for weeks at sea. That trade, men for wind, is what made long voyages across open water possible.

How it worked: steering. Ancient and Viking ships were steered with a large oar hung over the right-hand side near the stern. Sailors called that side the steer-board side, which is where our word **starboard** comes from; the other side, which faced the dock so the steering oar would not be crushed, became the **port** side. A side oar works well on a small ship, but on a big one it is clumsy: when the ship leans away from the wind, the oar can lift out of the water, and the larger the ship, the harder it is to hold. A **stern-post rudder** hangs on hinges along the centerline, stays under water whichever way the ship leans, and can simply be built bigger as ships grow. China had such rudders very early; a pottery model of a river boat with a rudder at its stern, found at Guangzhou, dates from the first century AD. In Europe the earliest clear picture is a ship carved on the black marble font of Winchester Cathedral, made about 1180. Within a hundred years the cogs of the Hanseatic towns, such as Lübeck and Bremen, carried stern rudders across the North Sea and the Baltic.

The big idea: a sail is a wing. When the wind blows from behind, it simply pushes the sail. But when a sail is set at an angle to the wind, the air flowing across its curved surface produces a sideways force, much like the lift on an airplane wing. The hull and keel resist being pushed sideways through the water, so the ship moves forward instead, across the wind or even partly toward it. No sailing ship can sail straight into the wind. A square-rigged ship can point perhaps 60 to 70 degrees from the wind. A **fore-and-aft** sail such as the triangular **lateen** of the Mediterranean and Indian Ocean can point about 45 degrees from it. To reach a harbor dead upwind, a ship must **tack**, zigzagging first on one side of the wind and then the other. The rudder is what lets the helmsman hold each slanting course steady and swing the bow across the wind at each turn.

The carrack. In the 1400s, shipbuilders in Portugal, Spain and Italy combined the best of north and south. They took the square sail and stern rudder of the cog and added the lateen sail of the Mediterranean, built the hull of smooth edge-to-edge planks over a strong frame, and raised castles at bow and stern. The result was the **carrack**: three or four masts, square sails on the front masts for driving power downwind, and a lateen sail on the rear mast to help her steer and work toward the wind. Columbus's flagship *Santa María* in 1492 was a small carrack, and so was the *Victoria*, the first ship to sail around the world (1519-1522). Henry VIII's great warship the *Mary Rose*, launched in 1511, was a carrack; she sank in the Solent in 1545, and her hull was raised in 1982 and now rests in a museum at Portsmouth.

Technology overcoming geography. With a ship that could carry months of supplies and steer across the wind, sailors could use the great wind systems of the ocean itself. The Portuguese learned to swing far out into the Atlantic to find winds that would carry them home, and in a single century carracks reached the Cape of Good Hope, India and China. Yet the sail did not abolish geography; it made sailors students of it. Ships still waited in port for the right season, drifted for days in the calms near the equator, and were wrecked by storms. Every route for the next four hundred years was drawn by the winds, until steam (Lesson 1.4) freed ships from them. The skill of the shipwrights and sailors who made these ships was itself a gift: people made in the image of a Creator who makes, and who set the winds in their circuits.



Points of sail for a fore-and-aft rig. No sailing ship can sail inside the no-go zone, so to reach a goal directly upwind it must tack in a zigzag.

PICTURE STUDY



Portuguese Carracks off a Rocky Coast, Unknown Flemish painter (catalogued by Royal Museums Greenwich as circle of Joachim Patinir; sometimes attributed to Cornelis Anthonisz), about 1540 · Oil on panel · National Maritime Museum, Greenwich, London

This is one of the earliest European paintings made chiefly to show ships, and it shows the carrack at the height of its power. The painter, probably working in the Netherlands, filled the panel with Portuguese carracks in close detail: their rigging, their flags, their stacked

castles and the small boats that served them. Historians of ships study it closely, because few drawings of real carracks from this age survive.

Look at it the way a sailor of 1540 would. These ships were the long-distance trucks and warships of their day. A Portuguese carrack might leave Lisbon in spring and not see home again for a year and a half, sailing to India and back on the seasonal winds.

Look closely

- Count the masts on the nearest ship. Which sails are square, and is there a triangular sail toward the stern?
- Find the tall castles at the front and back of a ship. Why would a ship that might be attacked want high places to fight from?
- Look for the small boats among the big ships. What jobs would they do in a harbor without docks?
- Look for flags and banners. What do they tell an observer about who owns the ships?

Talk about it

1. Compare these ships with the one-masted Bremen Cog. What did the carrack gain by having several masts and two kinds of sail?
2. The painter put the ships beside a rocky shore. What dangers would a coast like this hold for a ship that could not sail straight into the wind?
3. Which part of the ship, the sails or the rudder, do you think was the greater invention? Defend your answer.

Safety first. Keep the fan and every electrical cord completely outside and away from the tub, on a dry floor, and plugged into a GFCI (ground-fault) outlet. Never touch the fan with wet hands. An adult should be present whenever there is water and electricity in the same room. Drain the tub when you finish.

PROJECT: SAIL AND RUDDER TEST IN THE BATHTUB

You will build a small sailing boat with a removable keel, a square sail and a triangular sail, and a stern rudder you can set at different angles. With a fan as your trade wind and a bathtub as your ocean, you will test the two great discoveries of this lesson: that a sail can drive a boat across the wind, and that a rudder on the centerline turns it. Record every trial like a real engineer.

You will need

- A hull: a clean foam meat tray, a half-liter plastic bottle cut in half lengthwise, or a block of light wood about 20–25 cm (8–10 in) long
- A bamboo skewer for a mast and modeling clay to hold it upright
- Two sails cut from an index card or a plastic folder: a square about 8 × 8 cm, and a triangle with sides about 10, 10 and 8 cm

- A rudder and a keel cut from a plastic lid: rudder about 3×4 cm; keel strip about 2×12 cm
- Two paper clips and waterproof tape to hinge the rudder at the stern
- A box fan or desk fan, a protractor, a ruler or tape measure, a stopwatch or phone timer
- Masking tape for marking lines on the tub edge, a notebook for a data table

Steps

1. Fill the tub with about 10 cm (4 in) of water. Set the fan on the dry floor at one end of the tub, aimed down the length of the tub. Mark the wind direction with a strip of tape on the tub rim.
2. Build the hull. Press a lump of clay into the middle and stand the mast in it. Slide the square sail onto the mast through two small holes.
3. Make the rudder. Bend a paper clip into a hinge, tape it to the stern on the centerline, and tape the rudder blade to it so it can swing. Mark 0° , 15° and 30° on the deck beside the tiller with a protractor.
4. Trial 1, running: rudder at 0° , no keel, square sail square to the wind. Release the boat in front of the fan and time it over 1 m. Record the time and whether it held a straight course.
5. Trial 2, beam reach: turn the boat so it points across the tub, 90° to the wind. Angle the sail about 45° to the wind. Release it and record where it goes. Does it move forward, sideways or both? Measure its sideways drift (leeway) over 50 cm of forward travel.
6. Trial 3: tape the keel strip along the bottom centerline and repeat Trial 2. Measure the leeway again. What did the keel change?
7. Trial 4: swap the square sail for the triangular sail, set fore-and-aft (along the boat's length), and repeat Trial 3. Try to find the smallest angle to the wind at which the boat still makes progress forward.
8. Trial 5, the rudder: with the wind behind the boat, set the rudder to 15° and then 30° and measure roughly how wide a circle the boat turns in. Which way does the bow turn when the rudder is pushed to the right?
9. Make a data table with columns: trial, sail, keel, rudder angle, heading to wind, time or distance, observations. Write a short conclusion of four or five sentences.

Tips

- Fans make gusty, uneven wind. Run every trial three times and use the middle result.
- If the boat tips, add clay low in the hull as ballast, as real ships carried stones or sand in the bottom of the hold.
- If the boat will not move across the wind at all, the keel is probably too small; make it deeper, not longer.

Check your work

- I recorded at least five trials in a neat data table.

- I can explain from my results why a keel helps a boat sail across the wind.
- I can say which sail pointed closer to the wind, and which way the bow turned when I moved the rudder.
- I connected my results to the cog and the carrack in my written conclusion.

MAP NOTEBOOK

1. Draw the Bremen Cog from the side and label the mast, square sail, sternpost, rudder, tiller, flat bottom and the overlapping (clinker) planks.
2. Draw a carrack from the side and label the foremast, mainmast, mizzenmast, square sails, lateen sail, forecastle, sterncastle and rudder. Write under it which features came from the north and which from the Mediterranean.
3. Copy the points-of-sail diagram. Add a second, wider no-go wedge in a different color for a square-rigged ship (about 67° each side) and label both.

From history. When the Mary Rose was raised in 1982, divers had already recovered thousands of objects from her: longbows and arrows, navigation tools, a ship's surgeon's chest, musical instruments and the bones of many of the roughly four hundred men aboard, few of whom survived the sinking. Because the mud of the Solent sealed the wreck, she is like a time capsule of one day in July 1545, and the museum built around her hull at Portsmouth lets visitors see how a Tudor carrack was actually built and lived in.

WORKED EXAMPLES

Example 1. A harbor lies 30 nautical miles (nm) directly upwind. Ship A has a fore-and-aft (lateen) rig and can sail 45° from the wind. Ship B is square-rigged and can sail no closer than 67° from the wind. Both sail at 5 knots through the water. Ignoring leeway and current, how far must each sail to reach the harbor, and how long does each take?

(Use the map or drawing “Each 45° tack gains upwind only $\cos 45^\circ$, about 71 percent, of the distance sailed” shown earlier in this lesson.)

1. On any tack, the progress made directly upwind is the distance sailed times the cosine of the angle to the wind. So distance sailed = upwind distance $\div \cos(\text{angle})$. The number of tacks does not change the total.
2. Ship A: $30 \div \cos 45^\circ = 30 \div 0.7071 = 42.4$ nm. Time = $42.4 \div 5 = 8.5$ hours.
3. Ship B: $30 \div \cos 67^\circ = 30 \div 0.3907 = 76.8$ nm. Time = $76.8 \div 5 = 15.4$ hours.
4. Convert: $42.4 \text{ nm} \times 1.852 = 78.5 \text{ km}$ (48.8 miles); $76.8 \text{ nm} \times 1.852 = 142 \text{ km}$ (88.4 miles).

Answer: Ship A sails about 42.4 nm (78.5 km, 49 miles) in about 8.5 hours; Ship B sails about 76.8 nm (142 km, 88 miles) in about 15.4 hours, nearly twice as far. This is why the carrack kept a lateen sail at the stern, and why square-riggers often waited in port for a fair wind.

Example 2. Estimate the drinking water a galley and a cog each need for a 12-day passage. Assume the galley carries 170 rowers and 30 other crew, the cog a crew of 20, and that every man drinks about 4 liters a day. (These are round estimates, not records of real ships.) One liter of water has a mass of 1 kg.

1. Galley: $170 + 30 = 200$ men. Water = $200 \times 4 \text{ L} \times 12 \text{ days} = 9,600 \text{ L}$.
2. Mass: $9,600 \text{ L} \times 1 \text{ kg/L} = 9,600 \text{ kg}$, about 9.6 tonnes (about 10.6 U.S. tons), before any casks or food.
3. Cog: $20 \times 4 \text{ L} \times 12 \text{ days} = 960 \text{ L}$, about 0.96 tonne.
4. Ratio: $9,600 \div 960 = 10$. The galley needs ten times as much water for the same voyage.

Answer: The galley needs about 9,600 liters (9.6 tonnes) and the cog about 960 liters (under 1 tonne). The wind-driven ship can spend that saved space and weight on cargo, which is why sail, not oars, opened the oceans to trade.

Example 3. A Hanseatic cog sails from Bremen (53.1° N) to Bergen in Norway (60.4° N). One minute of latitude is one nautical mile. What is the least possible distance she must sail, and how many days would that take at an average of 4 knots? Give the distance in km and miles too.

1. Difference in latitude: $60.4^\circ - 53.1^\circ = 7.3^\circ$.
2. Each degree is 60 minutes, and each minute is 1 nm: $7.3 \times 60 = 438$ nm.
3. Convert: $438 \times 1.852 = 811$ km; $438 \times 1.151 = 504$ miles.
4. Time at 4 knots: $438 \div 4 = 109.5$ hours; $109.5 \div 24 = 4.6$ days.

Answer: At least 438 nm (811 km, 504 miles), about 4.6 days at 4 knots. The real voyage is longer, because Bergen also lies west of Bremen and the ship must round the coasts of Denmark and Norway, and tack when the wind is foul.

PRACTICE

1. **EASY** Where does the word starboard come from, and which side of a ship is it?
2. **EASY** Give three differences between a cog and a carrack.
3. **EASY** Convert 6 knots to km/h and to mph.
4. **EASY** Give the earliest evidence named in this lesson for the stern-post rudder in China and in Europe.
5. **MEDIUM** A lateen-rigged ship can sail 45° from the wind. Its goal is 20 nm directly upwind. How far must it sail, and how long will it take at 4 knots?
6. **MEDIUM** A square-rigger that can sail no closer than 70° from the wind must reach a point 20 nm directly upwind. How far must it sail? How many times farther is that than the straight-line distance?
7. **MEDIUM** The Mary Rose was launched in 1511, sank in 1545 and was raised in 1982. How many years did she serve, and how many years did she lie on the seabed?
8. **MEDIUM** A trireme with 170 rowers makes a 5-day passage in summer, and each rower drinks about 5 liters a day. How many liters, and how many tonnes, of water must she carry for the rowers alone? What does this suggest about where galleys could go?
9. **HARD** Use the diagram. The wind blows from due north (from 000°). A fore-and-aft-rigged ship cannot sail within 45° of the wind. Which range of compass headings can it not steer? Which heading is a beam reach toward the east?
(Use the map or drawing "Use this diagram for Problem 9. Treat the top of the page as north." shown earlier in this lesson.)
10. **HARD** Portuguese ships sailed south from Lisbon (38.7° N) toward the Cape Verde Islands near Praia (14.9° N). Find the least possible distance in nm, km and miles, and the least number of days at an average of 5 knots.
11. **HARD** Explain in three or four sentences why the stern-post rudder suited large ships better than a steering oar over the side.
12. **CHALLENGE** Write a paragraph answering: In what ways did the sail and rudder overcome geography, and in what ways did geography still rule the sailing ship? Give at least two

examples of each.

COMMON MISTAKES

- Thinking a sail only works by being pushed from behind. Set at an angle, a sail acts like a wing, and with a keel the ship can sail across and partly toward the wind.
- Believing a clever enough sailing ship can sail straight into the wind. None can; every sailing ship must tack to go upwind, and tacking multiplies the distance.
- Mixing up nautical miles and statute miles. A nautical mile (1,852 m) is about 15 percent longer than a land mile (1,609 m), and one knot is one nautical mile per hour, not one mile per hour.

Make it a game · Tack to Harbor. Draw a grid of 10×10 squares on paper with a harbor at the top center and your ship at the bottom center. The wind blows from the top. On each turn a player rolls a die and moves that many squares diagonally (up-left or up-right only), like a ship tacking at 45° ; changing direction costs one turn, as coming about loses speed. A player who rolls a 1 is becalmed and does not move. First into the harbor wins. Then play again with a square-rigger rule: move one square up for every two squares sideways. Discuss why that ship takes so much longer.

Scripture. “Behold also the ships, which though they be so great, and are driven of fierce winds, yet are they turned about with a very small helm, whithersoever the governor listeth.” (James 3:4, KJV)

James wrote these words long before the stern rudder reached Europe, yet every sailor knew the truth of them: a small blade turns a great ship. James uses it to teach that the tongue, though small, steers a whole life. Good tools and good words both have power far beyond their size.

Practice answers

1. From the steer-board, the steering oar that hung over the right-hand side near the stern of early ships. Starboard is the right side when facing forward.
2. Any three: a cog had one mast and a carrack three or four; a cog had one square sail while a carrack had square sails plus a lateen sail; a cog had overlapping (clinker) planks while a carrack had smooth edge-to-edge (carvel) planking over a frame; a carrack had high castles at bow and stern and a larger, deeper hull for long voyages.
3. $6 \times 1.852 = 11.1$ km/h; $6 \times 1.151 = 6.9$ mph.
4. China: a pottery model of a boat with a stern rudder from Guangzhou, first century AD.
Europe: a ship carved on the Winchester Cathedral font, about 1180.
5. $20 \div \cos 45^\circ = 20 \div 0.7071 = 28.3$ nm (52.4 km, 32.6 miles). Time = $28.3 \div 4 = 7.1$ hours.
6. $20 \div \cos 70^\circ = 20 \div 0.342 = 58.5$ nm (108 km, 67 miles), about 2.9 times the straight-line distance.
7. Service: $1545 - 1511 = 34$ years. On the seabed: $1982 - 1545 = 437$ years.
8. $170 \times 5 \times 5 = 4,250$ L, about 4.25 tonnes (1 L $\approx$ 1 kg). Galleys had little room for so much water, so they had to stay near coasts and wells and could not make long ocean passages.

9. It cannot steer any heading from 315° through 000° to 045° (between northwest and northeast). A beam reach toward the east is a heading of 090° .
10. $38.7 - 14.9 = 23.8^\circ \times 60 = 1,428 \text{ nm} = 2,645 \text{ km} (1,644 \text{ miles})$. Time = $1,428 \div 5 = 285.6$ hours ≈ 11.9 days.
11. A side oar is fixed to one side, so when the ship leans away from the wind it can rise out of the water or be buried too deep, and it is hard for one man to hold on a big ship. A stern rudder hangs on the centerline, so it stays in the water whichever way the ship leans. It is hinged to the hull, which takes the strain, and it can be made larger as ships grow. A tiller or later a wheel gives the helmsman leverage to turn it.
12. Answers will vary. A strong answer: sail power freed ships from the food and water needs of rowers, so they could cross open oceans and carry large cargoes; the stern rudder and fore-and-aft sails let ships steer across the wind and work upwind by tacking, so they could use the great wind belts and return home. But geography still ruled: ships could not sail into the wind and had to wait for the right season or monsoon; calms near the equator could stall them for days; storms, reefs and rocky lee shores wrecked them; and every trade route followed the pattern of the winds until steam.

1.2 THE COMPASS AND THE CHART

OBJECTIVES

- Explain how the magnetic compass, the portolan chart and the mariner's astrolabe each answered a different question a navigator must ask.
- Plot a dead-reckoning position from courses, speeds and times, and find latitude from the altitude of Polaris or the noon sun.
- Explain why dead-reckoning errors grow with distance and why latitude could be measured at sea long before longitude.

Warm-up. Stand in a hallway or yard, close your eyes, and try to walk exactly ten paces straight toward a marked target while a partner watches for safety. Open your eyes. How far off were you, and to which side? Now try again, but this time count your paces and carry a phone compass app or a real compass held level. What did knowing your direction and your distance each fix? Write down the two things a sailor out of sight of land must always know.

Watch. *The History of the Magnetic Compass and Its Use in Early Maritime Navigation* (IEEE REACH, 5:25). <https://www.youtube.com/watch?v=LmiJBTZ-LOM>
With The three questions: the history of the magnetic compass at sea.

Backup video. *How did early Sailors navigate the Oceans?* (thecuriousengineer, 6:20). <https://www.youtube.com/watch?v=4DlNhbkPiYY>
With dead reckoning: how early sailors crossed oceans with compass, log and chart.

KEY TERMS

magnetic variation (declination)

The angle between true north (toward the North Pole) and magnetic north (where a compass needle points). It changes from place to place and slowly over the years.

portolan chart

A sea chart drawn on vellum from the late 1200s on, showing coasts and harbors in remarkable detail and covered with a web of compass-direction lines (rhumb lines), but with no latitude or longitude grid.

rhumb line

A line of constant compass bearing. On a portolan chart, rhumb lines radiate from compass roses so a pilot can read the course between two ports.

mariner's astrolabe

A heavy brass ring with a sighting arm (alidade), used at sea from the late 1400s to measure the altitude of the sun or a star above the horizon, from which latitude can be found.

dead reckoning

Finding a ship's present position from its last known position by adding up the courses steered, the speeds and the times sailed.

log line

A line knotted at regular spaces and tied to a wooden float (the chip log), paid out over the stern for a set time measured by a sandglass; the number of knots that run out gives the ship's speed in knots.

CORE IDEAS

The story. On the evening of September 13, 1492, a week out from the Canary Islands, Christopher Columbus's pilots noticed something unsettling. At nightfall their compass needles no longer pointed at the Pole Star, but a little to the west of it, and in the following days the difference grew. When the pilots grew alarmed, Columbus told them the star moved and the needle did not, which was partly true, since Polaris does circle the pole by a small amount each night. In fact the fleet had sailed into a region where **magnetic variation**, the difference between true north and the direction of the needle, was changing, and Columbus became one of the first Europeans to record it. His journal, which survives in a summary made by Bartolomé de las Casas, also tells us that from September 9 he kept two reckonings of distance sailed: a true one for himself and a smaller one to show the crew, so they would not be frightened by how far they had gone from home. Every entry is a record of dead reckoning, the art by which sailors found their way across an ocean with no landmarks.

The three questions. A navigator out of sight of land asks three things: Which way am I going? How fast? And where am I? The **compass** answered the first. Chinese scholars knew that a magnetized needle points north and south; Shen Kuo described one in his *Dream Pool Essays* in 1088 and noted that it points slightly east of true south, and by the early 1100s Chinese writers reported sailors at Guangzhou using the needle in cloudy weather. In Europe, the English scholar Alexander Neckam described sailors using a magnetized needle around 1190, and in 1269 Petrus Peregrinus described a pivoted needle in a box with a scale. Mariners glued the needle to a card marked with 32 points (north, north by east, north-northeast and so on) and called it the compass rose.

The portolan chart. The second great tool was the chart. The oldest that survives is the **Carta Pisana**, drawn on vellum (sheepskin) in the late 1200s and kept today in Paris. Portolan charts of the Mediterranean and Black Sea are so accurate in their coastlines that they still astonish map historians. Port names are written at right angles to the coast, closely packed, with important harbors in red. Over everything lies a web of **rhumb lines**, radiating from compass roses. A pilot laid a straightedge from his port of departure to his destination, found the rhumb line that ran parallel to it, and read the compass course he must steer. A scale bar let him measure the distance. What the portolan did not have was a grid of latitude and longitude; it was built from countless compass courses and distances reported by sailors.

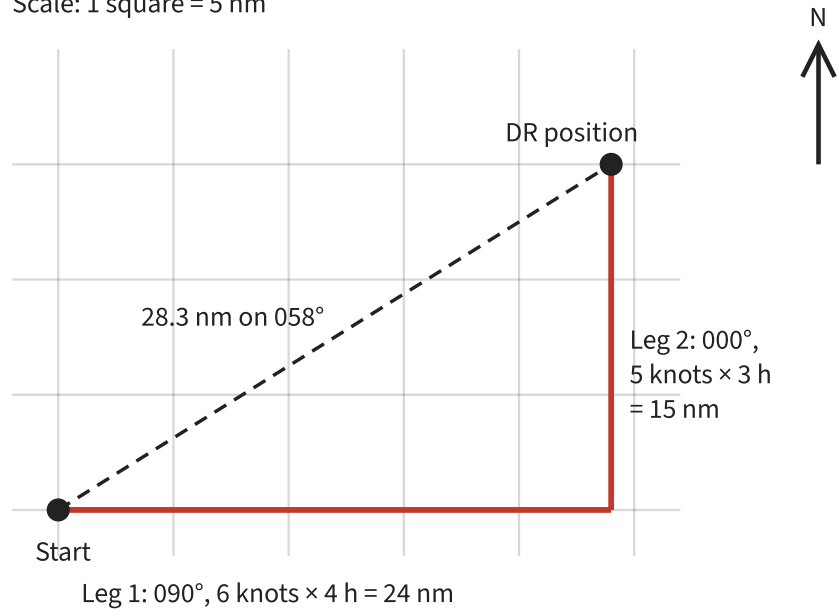
How it worked: dead reckoning. To know how far he had come, a pilot needed the ship's speed. At first he simply judged it by eye, watching foam or a chip of wood pass along the hull. By the late 1500s English seamen used the **log line**: a wooden float on a line marked at

regular spaces, thrown over the stern while a sandglass ran out; in later centuries the line was knotted every 47 feet or so and timed with a 28-second glass. The number of knots that slipped through a sailor's fingers gave the speed in nautical miles per hour, which is why we still measure ships' speed in **knots**. Every half hour or so, the course and speed were pegged on a traverse board or written in the log, and at noon the pilot worked out the ship's new position on the chart. This is **dead reckoning**. Its weakness is that every small error adds to the next: a current, a careless helmsman, an unknown magnetic variation or leeway from the wind pushing the ship sideways all go uncorrected until land is sighted.

The big idea: latitude from the sky. The one coordinate the heavens gave freely was **latitude**. In the Northern Hemisphere, the altitude of Polaris above the horizon is very nearly equal to your latitude. As Portuguese captains pushed south along Africa in the 1400s, Polaris sank lower and finally disappeared below the horizon, so they measured instead the height of the sun at noon and corrected it with printed tables of the sun's **declination**, its distance north or south of the equator on each day of the year. For this they used the quadrant and then the **mariner's astrolabe**, a heavy, open brass ring that the wind could not swing about. Vasco da Gama's men in 1497 went ashore at St. Helena Bay in southern Africa to take the sun's altitude on steady ground, because the rolling deck spoiled the reading. Knowing latitude, a navigator could sail north or south to the latitude of his goal and then run due east or west along it, a method called latitude sailing.

Technology overcoming geography. The compass and chart turned the open sea from a blank fear into a space that could be measured. Pilots could now sail in fog and overcast, cross open water by night and keep a written record that the next voyage could follow. Yet they still could not measure longitude, how far east or west they were, so on every long voyage the east-west position was only an estimate that grew worse each day. Ships sometimes missed islands entirely or ran aground on coasts they thought were days away. Solving that last problem would take three more centuries and is the story of the next lesson.

Scale: 1 square = 5 nm



A dead-reckoning plot. Two legs (east, then north) are added like arrows; the dashed line gives the ship's distance and bearing from where it began.

PICTURE STUDY



The Carta Pisana, Unknown chartmaker, probably of Genoa or Pisa, late 1200s (about 1275-1300) · Ink and color on vellum · Bibliothèque nationale de France, Paris

The Carta Pisana takes its name from the city of Pisa, where it was found in the 1800s. It is the oldest surviving portolan chart, drawn on a single sheepskin. No one knows exactly who made it or how the first chartmakers achieved such accurate coastlines, but they plainly drew on generations of compass bearings and distances gathered by working pilots.

The Carta Pisana was a working tool, not a decoration, and it is worn and faded from use. Later portolan charts became rich works of art, with gold, flags and kings painted in, but the web of lines and the crowded coastal names stayed the same.

Look closely

- Find a point where many straight lines meet. Follow two of them across the sea. What would a pilot use them for?
- Find the boot of Italy and the Black Sea. Which coasts look most accurate to you, and which look least like a modern map?
- Look closely at the place names along a coast. Which way are they written, and why would that help a pilot?
- Portolan charts usually carry a scale of distance. Look for one. What does it tell you the chartmaker could measure, and what could he not?

Talk about it

1. The chart has no lines of latitude or longitude. How then did a pilot find his course from it?
2. Why do you think the Mediterranean is drawn so much better than the lands far from its shores?
3. What kind of person do you think owned this chart, and why did it wear out?

Safety first. Use the needle with care and store it stuck in a cork. Look for Polaris only from a safe, dark place with an adult, never on a road or a roof.

PROJECT: NEEDLE COMPASS AND QUADRANT: FIND YOUR LATITUDE

You will build the two navigator's tools of this lesson: a floating needle compass like the earliest ones at sea, and a quadrant made from a protractor to measure the height of Polaris. With them you will find your own latitude to within a degree or two, as Portuguese pilots did.

You will need

- A steel sewing needle, a strong magnet (a refrigerator magnet will do; a neodymium magnet is better)
- A small cork slice or a 2 cm circle cut from a foam tray, a bowl of water
- A plastic protractor, a drinking straw, tape, about 30 cm of thread and a small weight such as a washer or nut
- A phone or atlas to check your actual latitude, a notebook

Steps

1. Magnetize the needle: stroke it twenty times from eye to point with one end of the magnet, lifting the magnet well away between strokes, always in the same direction.
2. Lay the needle on the cork or foam and float it in the bowl of water, away from metal objects. It will swing and settle. Mark which end points north by checking against the

sun at noon (it is roughly south of you in the Northern Hemisphere) or a phone compass.

3. Build the quadrant: tape the straw along the straight edge of the protractor. Tie the thread through the hole at the center of the straight edge and hang the weight from it so it swings freely across the curved scale.
4. On a clear night, find the Big Dipper and follow the two stars at the end of its cup to Polaris, a moderately bright star standing alone.
5. Sight Polaris through the straw. When it is centered, pinch the thread against the scale. Read the angle where the thread crosses. The altitude of Polaris is 90° minus that reading (if your protractor reads 90° when the straw is level, the altitude is the difference from 90°).
6. Take three readings and average them. Write your result as your latitude in degrees north.
7. Check your answer against a phone or an atlas. Find your error in degrees, and multiply by 60 to find the error in nautical miles.

Tips

- If you live where clouds hide Polaris for weeks, you can measure the sun's noon altitude instead near the March or September equinox: your latitude is 90° minus the sun's noon altitude. Never look at the sun; sight the shadow of the straw instead, turning it until its shadow is a small round dot.
- Polaris is about two-thirds of a degree from the true pole, so a perfect reading can still differ from your latitude by up to about 0.7° .
- Keep the floating compass away from steel spoons, phones and the stove; they pull the needle off true.

Check your work

- My floating needle settles north and south and I marked its north end.
- I measured Polaris (or the noon sun) at least three times and averaged the readings.
- I found my latitude, compared it with the true value and gave my error in degrees and nautical miles.
- I can explain why this method gave me latitude but not longitude.

MAP NOTEBOOK

1. Draw a 32-point compass rose. Label the four cardinal points, the four intercardinal points and at least four of the in-between points (such as north-northeast and north by east), with their bearings in degrees.
2. Copy the dead-reckoning plot from the lesson. Then add a third leg of your own (choose course, speed and time) and find the new position.
3. Sketch a small part of a portolan chart: a coastline with names written at right angles to it and a compass rose with sixteen rhumb lines. Mark one course between two ports.

From history. The Portuguese mariner's astrolabe was built heavy and open on purpose. A solid disk would catch the wind and swing; an open wheel of thick brass, often weighing a few kilograms, hung steady from the navigator's thumb. Dozens have been recovered from shipwrecks. One found off Oman in a wreck from Vasco da Gama's second voyage to India (1502-1503) is among the oldest known, a reminder that these were working instruments carried by real crews into the open ocean.

WORKED EXAMPLES

Example 1. A ship leaves a known position and steers due east (090°) at 6 knots for 4 hours, then due north (000°) at 5 knots for 3 hours. Find her dead-reckoning position relative to the start, her straight-line distance from it and the bearing of that straight line.

(Use the map or drawing "Each leg is a vector; the dead-reckoning position is their sum." shown earlier in this lesson.)

1. Leg 1: $6 \text{ knots} \times 4 \text{ h} = 24 \text{ nm east}$.
2. Leg 2: $5 \text{ knots} \times 3 \text{ h} = 15 \text{ nm north}$.
3. Distance: $\sqrt{(24^2 + 15^2)} = \sqrt{(576 + 225)} = \sqrt{801} = 28.3 \text{ nm (52.4 km, 32.6 miles)}$.
4. Bearing: the angle east of north has tangent $24 \div 15 = 1.6$, so the angle is 58° . The bearing is 058° .

Answer: 24 nm east and 15 nm north of the start; 28.3 nm (52.4 km, 32.6 miles) away on a bearing of 058° .

Example 2. On the day of the March equinox, when the sun's declination is 0° , a Portuguese pilot measures the noon sun 51.3° above the southern horizon. What is his latitude? Which port lies close to this latitude?

1. At the equinox the sun is over the equator. Seen from latitude L north, its noon altitude above the southern horizon is $90^\circ - L$.
2. So $L = 90^\circ - \text{altitude} = 90^\circ - 51.3^\circ = 38.7^\circ$.
3. The sun is south of him, so he is north of the equator: 38.7° N .
4. Lisbon lies at about 38.7° N .

Answer: 38.7° N , the latitude of Lisbon. On other days the pilot adds or subtracts the sun's declination from his tables: $\text{latitude} = 90^\circ - \text{altitude} + \text{declination}$ (declination counted positive when the sun is north of the equator).

Example 3. A log line is used with a 28-second sandglass. How far apart must the knots be tied so that the number of knots run out equals the ship's speed in knots? Give the answer in meters and feet. (1 nm = 1,852 m.)

1. At 1 knot a ship covers 1,852 m in 3,600 seconds.
2. In 28 seconds it covers $1,852 \times 28 \div 3,600 = 14.4$ m.
3. So one knot of line must run out every 14.4 m for each knot of speed.
4. In feet: $14.4 \text{ m} \div 0.3048 = 47.3$ ft, about 47 ft 3 in.

Answer: About 14.4 m (47 ft 3 in) between knots. If 7 knots run out before the glass empties, the ship is making 7 knots.

PRACTICE

1. **EASY** Name the three questions every navigator must answer, and the tool that answered each in 1492.
2. **EASY** What did Columbus's pilots notice on and after September 13, 1492, and what is it called?
3. **EASY** Give two features of a portolan chart and one thing it lacked.
4. **EASY** On a 32-point compass, how many degrees lie between neighboring points? What is the bearing of northeast and of south-southwest?
5. **MEDIUM** A navigator measures Polaris 50.4° above the horizon. About what is his latitude, in degrees and in nautical miles from the equator?
6. **MEDIUM** A ship steers 180° (due south) at 7 knots for 5 hours, then 270° (due west) at 4 knots for 6 hours. How far and in what direction is she from her start?
7. **MEDIUM** Using a 28-second glass and knots spaced 47 ft 3 in, a sailor counts 9 knots run out. What is the ship's speed in knots, km/h and mph?
8. **MEDIUM** On a day when the sun's declination is 23.4° N (the June solstice), a navigator measures the noon sun 75.0° above the southern horizon. What is his latitude?
9. **HARD** A pilot steers by a compass whose variation he does not know, and the needle is actually 5° off true. After sailing 100 nm, about how far is the ship from where he thinks it is? After 600 nm?
10. **HARD** Columbus sailed west from the Canaries at about 28° N. At that latitude, how many nautical miles are in one degree of longitude? If he sailed 10° of longitude due west, how far did he go? (1° of longitude = $60 \text{ nm} \times \cos \text{latitude}$.)
11. **HARD** Use the dead-reckoning plot. If a current has also been setting the ship 1 knot due south for all 7 hours, where is the true position relative to the DR position?
(Use the map or drawing "Use this plot for Problem 11." shown earlier in this lesson.)
12. **CHALLENGE** Explain in a paragraph why Portuguese navigators of the late 1400s could measure their latitude at sea but not their longitude, and how latitude sailing helped them work around the problem.

COMMON MISTAKES

- Assuming a compass points to true north. It points to magnetic north, and the difference (variation) changes from place to place, as Columbus discovered.
- Thinking portolan charts used latitude and longitude. They were built from compass courses and distances; the web of lines shows directions, not a grid.
- Treating dead reckoning as exact. It is an estimate whose errors grow with every hour sailed, until a sighting of land or a star corrects it.

Make it a game · Blind Pilot. In a yard or large room, one player is the pilot and stands at a start mark with a list of three legs written by the navigator (for example: 090° for 8 paces, 000° for 6 paces, 270° for 3 paces). The pilot uses a compass and counts paces, eyes on the compass, and places a coin at the final position. The navigator first computes the expected position on paper and marks it with a second coin. Measure the gap between the coins. That gap is your dead-reckoning error. Swap roles; smallest total error after three rounds wins.

Scripture. “The fowl of the air, and the fish of the sea, and whatsoever passeth through the paths of the seas.” (Psalm 8:8, KJV)

David marveled that God gave mankind dominion over a world that includes the “paths of the seas.” A chart is an attempt to see those paths: the courses, currents and distances God built into the oceans. The navigator does not create the paths; he learns to read them.

Practice answers

1. Which way am I going (the compass)? How fast (judging by eye, later the log line)? Where am I (the chart and dead reckoning, checked by latitude from Polaris or the sun with a quadrant or astrolabe).
2. Their compass needles pointed a little west of the Pole Star, and the difference grew. This is magnetic variation (declination), the angle between true north and magnetic north.
3. Features (any two): accurate coastlines, names written at right angles to the coast, important ports in red, a web of rhumb lines from compass roses, a scale bar. It lacked a grid of latitude and longitude.
4. $360 \div 32 = 11.25^\circ$. Northeast = 045° . South-southwest = 202.5° .
5. About 50.4° N. $50.4 \times 60 = 3,024$ nm (5,600 km, 3,480 miles) north of the equator.
6. South 35 nm, west 24 nm. Distance $\sqrt{(35^2 + 24^2)} = \sqrt{(1,225 + 576)} = \sqrt{1,801} = 42.4$ nm (78.6 km). The angle west of south has tangent $24 \div 35 = 0.686$, so 34.4° ; bearing $180^\circ + 34.4^\circ = 214^\circ$.
7. 9 knots = $9 \times 1.852 = 16.7$ km/h = $9 \times 1.151 = 10.4$ mph.
8. Latitude = $90^\circ - 75.0^\circ + 23.4^\circ = 38.4^\circ$ N.
9. Cross-track error $\approx$ distance $\times \sin 5^\circ = 100 \times 0.0872 \approx 8.7$ nm (16 km). After 600 nm ≈ 52 nm (97 km). The error grows in proportion to the distance sailed.
10. $60 \times \cos 28^\circ = 60 \times 0.883 = 53.0$ nm per degree. $10^\circ \times 53.0 = 530$ nm (981 km, 610 miles).
11. 7 hours $\times$ 1 knot = 7 nm south of the DR position. The true position is 24 nm east and $15 - 7 = 8$ nm north of the start.

12. Latitude is fixed by the sky: Polaris stands at an altitude equal to one's latitude, and the noon sun's altitude, corrected for its declination from tables, gives latitude anywhere. The sky turns east to west once a day, so it looks the same at every longitude at the same local time; to find longitude one must know the time at a reference place, which no instrument of that age could keep at sea. Latitude sailing worked around this: the navigator sailed north or south until he reached the latitude of his destination, then turned and ran due east or west along that parallel, checking his latitude each day, until land appeared.

1.3 LONGITUDE SOLVED

OBJECTIVES

- Explain why longitude is a problem of time, and why the sea clock and the lunar-distance method each solved it.
- Tell the story of John Harrison, the Longitude Act of 1714 and the trial of H4, and explain why the world chose Greenwich as the prime meridian in 1884.
- Convert between time differences and longitude, and between errors of a clock and errors of position, in degrees, nautical miles and kilometers.

Warm-up. Look at a clock and write down the time. Now look up (or ask a parent to look up) the current time in London, in Tokyo and in Honolulu. Write the difference in hours between your time and each one. Earth turns once in 24 hours. How many degrees does it turn in one hour? Use your answer to guess how many degrees of longitude lie between you and London.

Watch. *The longitude problem: history's deadliest riddle* (Map Men, 9:16).

<https://www.youtube.com/watch?v=3mHC-Pf8-dU>

After the story: the longitude problem and John Harrison's clocks, told with humor.

Note: Map Men is comedy history, with songs and silly voices; the actor playing King George says "By God." It ends with a comic sponsor message for a VPN; stop when the history ends.

Backup video. *A Detailed Study of H4 - John Harrison's Longitude Timekeeper*

Reconstruction (Barbara Darby, 2:57). <https://www.youtube.com/watch?v=UeEBa55S7MI>

With How they figured it out: a close look at a reconstruction of Harrison's H4.

KEY TERMS

longitude

Angular distance east or west of a chosen prime meridian, measured from 0° to 180°.

Lines of longitude (meridians) run from pole to pole.

local apparent time

Time told by the sun at a particular place: it is noon when the sun crosses the local meridian and stands highest in the sky.

marine chronometer

A clock built to keep accurate time at sea despite rolling, temperature change and damp, so a ship can carry the time of its home meridian.

lunar distance

A method of finding longitude by measuring the angle between the moon and a star or the sun, then using printed tables (the *Nautical Almanac*) to find the Greenwich time at which that angle occurs.

prime meridian

The meridian chosen as 0° longitude. Since the International Meridian Conference of 1884, the world standard has been the meridian through the Royal Observatory at Greenwich.

rate

The steady amount a clock gains or loses each day. A good chronometer need not be perfect; it must have a known, constant rate that the navigator can correct for.

CORE IDEAS

The story. On the night of October 22, 1707, a British fleet returning from the Mediterranean under Admiral Sir Cloudesley Shovell groped through haze toward the mouth of the English Channel. The navigators misjudged their position, and the ships ran onto the rocks of the Isles of Scilly, off the southwestern tip of England. Four ships were lost, including the flagship *Association*, with some 1,400 to 2,000 men; Shovell himself died. Historians still debate exactly what went wrong, but the disaster became a symbol of a problem every seafaring nation shared: no one could find longitude at sea. In 1714 Parliament passed the **Longitude Act**, offering £20,000, a fortune, for a method that found longitude to within half a degree on a voyage to the West Indies. Smaller prizes were offered for less accuracy, and a Board of Longitude was set up to judge.

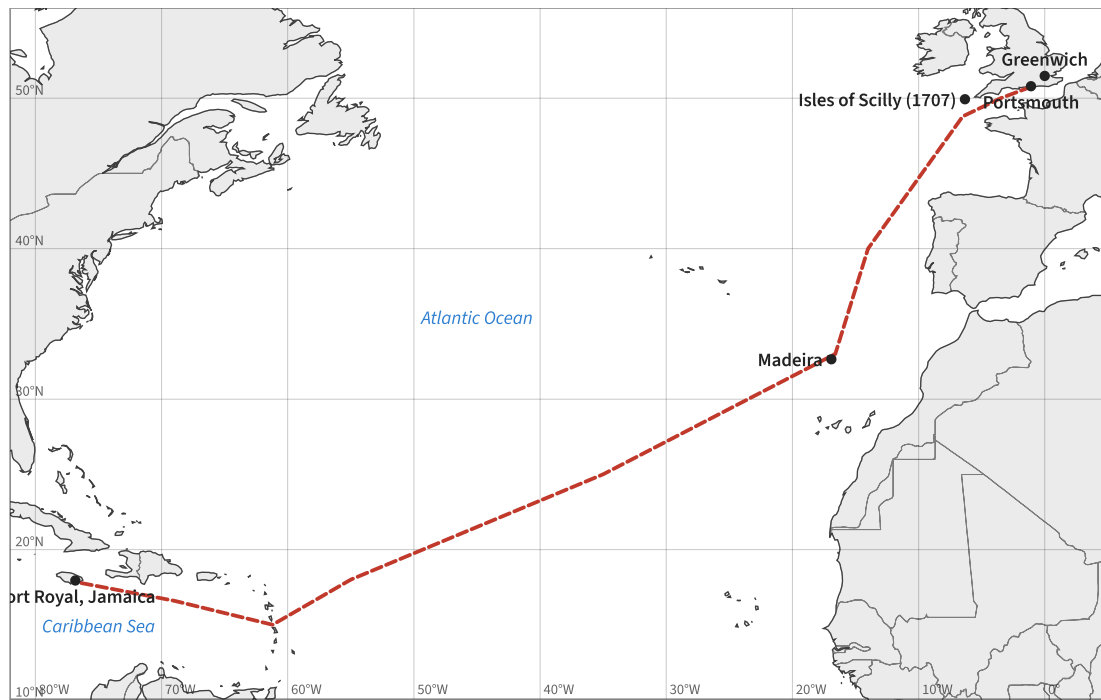
Longitude is time. Earth turns 360° in 24 hours, which is 15° every hour, or 1° every 4 minutes. When the sun stands highest over a ship, it is local noon there. If the navigator also knew, at that moment, what time it was at home, the difference would give his longitude at once. A ship whose local noon comes when it is 3:00 p.m. at Greenwich is $3 \times 15 = 45^\circ$ west of Greenwich. Latitude came from the sky; longitude needed a clock. The trouble was that no clock of 1714 could keep time at sea. Pendulum clocks are thrown off by a ship's rolling; heat and cold change the length of metal parts; oil thickens; damp rusts. And a small error matters greatly: at the equator, each minute of clock error is 15 nautical miles of position error, and half a degree of longitude is only 2 minutes of time over a voyage of six weeks or more.

How they figured it out. John Harrison, born in 1693 in Yorkshire and raised in a Lincolnshire village, was a carpenter who taught himself clockmaking, building early clocks with wooden wheels. He came to London in 1730 with a plan for a sea clock, and in 1735 he finished **H1**, a large brass machine with two linked balances swinging in opposite directions so the ship's motion would cancel out. It did well on a trip to Lisbon in 1736. Harrison then spent most of the next quarter century improving it. **H3** alone took him about nineteen years, and in it he invented the bimetallic strip to cancel the effects of heat and the caged roller bearing, both still used today. Then he turned in a new direction and built **H4**, finished in 1759: a large watch only about 13 cm (5 in) across, with a fast-beating balance that the ship's motion could not easily disturb. In November 1761 his son William carried it aboard HMS *Deptford* from Portsmouth to Jamaica. On the way, William used H4 to predict they would sight Madeira the next morning, and they did. At Jamaica, after allowing for its known rate, H4 was only about 5 seconds slow, a longitude error of little more than a nautical mile.

The prize and its rival. The Board of Longitude did not hand over the prize. Some members, including the astronomer Nevil Maskelyne, favored the **lunar-distance method**: the moon moves against the stars about its own width every hour, so the sky itself is a clock for anyone with good tables. Maskelyne published the first *Nautical Almanac*, for the year 1767, which made the lunar method practical. The Board demanded a second trial (to Barbados in 1764), then that Harrison take H4 apart before experts and that copies be made. Larcum Kendall's copy, K1, sailed with Captain James Cook on his second Pacific voyage (1772-1775), and Cook praised it highly. Harrison received £10,000 from the Board and, after appealing to King George III, a further £8,750 from Parliament in 1773. He died in London on March 24, 1776, his eighty-third birthday. Within a few decades, makers such as John Arnold and Thomas Earnshaw were producing chronometers cheaply enough that most ocean ships carried one.

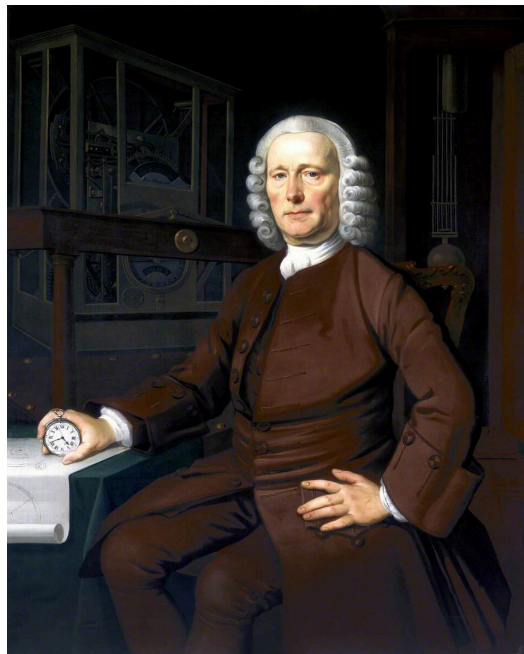
On the map: the prime meridian. Latitude has a natural zero, the equator. Longitude does not, so every nation could pick its own: Paris, Cadiz, Washington, St. Petersburg and others all served as 0°. Because the British *Nautical Almanac* was reckoned from Greenwich, most of the world's sea charts already used Greenwich by the late 1800s. In October 1884, at the invitation of President Chester A. Arthur, delegates from 25 nations met at the **International Meridian Conference** in Washington, D.C. They voted 22 to 1, with 2 abstaining, to adopt the meridian through the transit circle of the Royal Observatory at Greenwich as the world's prime meridian. San Domingo (the Dominican Republic) voted against; France and Brazil abstained. France kept Paris time until 1911, when it adopted Greenwich time under the name "Paris mean time retarded by 9 minutes 21 seconds."

Technology overcoming geography. The chronometer turned the ocean into a grid. For the first time a ship could fix its position anywhere on earth, so charts could be drawn with true longitudes, dangerous reefs could be avoided by reckoning rather than luck, and islands could be found again. It also shows the cost of a breakthrough: Harrison's solution took most of a lifetime, and he had to fight to be believed. And it shows that geography and time are bound together; the world's time zones, its date line and today's satellite navigation (Lesson 5.2) all rest on the idea Harrison made practical: that knowing the exact time is knowing where you are.



The approximate track of HMS Deptford with H4 aboard, Portsmouth to Jamaica, November 1761 to January 1762. The Isles of Scilly, where Shovell's fleet was wrecked in 1707, lie off Land's End.

PICTURE STUDY



John Harrison, Thomas King, about 1767 · Oil on canvas · Science Museum, London

Thomas King painted John Harrison when the clockmaker was in his early seventies, after the trials of H4 and in the middle of his long dispute with the Board of Longitude. The painting was soon copied as a print, which spread Harrison's face across Britain. It shows a respectable gentleman, but the man inside the coat was a village carpenter who had taught himself to build the most accurate machines of his age.

Notice what the painter chose to place beside Harrison. A portrait of the 1700s tells you what the sitter wanted to be remembered for, and Harrison wanted to be remembered for his timekeepers.

Look closely

- Find the large brass timekeeper in the background on the left. It is Harrison's third sea clock, H3. What can you see of its wheels and balances?
- Look at the watch in Harrison's right hand. It was made to his design by John Jefferys in 1753. Why would a small watch matter so much to a man who had spent years on big sea clocks?
- Look at Harrison's face and hands. What do they tell you about his age and his character?
- Look at his clothes and wig. How does the painter show that this carpenter's son had become a man of standing?

Talk about it

1. Harrison spent nearly forty years on his sea clocks. What qualities of character does a task like that require?
2. The painter shows the big H3 behind Harrison and puts a pocket watch, the forerunner of the small H4, in his hand. What story about Harrison's work do those two objects tell together?
3. Is it fair that Harrison was never officially awarded the full Longitude Prize? Weigh the Board's caution against Harrison's achievement.

PROJECT: FIND YOUR LONGITUDE WITH A SHADOW STICK

You will find your own longitude the way a navigator with a chronometer did: by catching the moment of local noon and comparing it with the time at Greenwich. Your phone or a radio time signal will be your chronometer, and a stick in the sun will be your sky. With care you can come within a degree or two.

You will need

- A straight stick or dowel about 1 m (3 ft) long, or a pencil in clay on a sunny windowsill
- Flat, level, sunny ground or a large board, chalk or small stones to mark points
- A string about 1.5 m long tied loosely to the base of the stick, a tape measure
- An accurate clock: a phone set to network time
- The equation of time for your date (from the NOAA Solar Calculator online, or a printed almanac)

Steps

1. Choose a clear day. Push the stick upright into level ground (check it with a plumb line made of string and a nut).

2. Starting about an hour before your local clock noon (or before 1:00 p.m. during daylight saving time), mark the tip of the shadow every 5 minutes with a stone or chalk dot. Write the exact time beside each mark.
3. Keep marking until about an hour after the shortest shadow. The shadow shortens, reaches its shortest, then lengthens again.
4. Find local noon by the equal-shadow method: pick a morning mark, and with the string tied to the stick, swing an arc to find the afternoon mark at exactly the same distance. Local apparent noon is halfway between those two times. Repeat with two more pairs and average.
5. Convert your noon time to UTC (Greenwich time). For example, U.S. Eastern Standard Time is UTC – 5 hours; Eastern Daylight Time is UTC – 4.
6. Correct for the equation of time, E, the amount the sun runs fast or slow of an even clock on your date. If the sun is fast by E minutes, add E to your UTC noon time; if slow, subtract it.
7. $\text{Longitude (degrees west)} = (\text{corrected UTC of noon} - 12:00, \text{ in minutes}) \div 4$. For example, 17:42 UTC corrected $\rightarrow 342 \text{ minutes} \div 4 = 85.5^\circ \text{ W}$.
8. Compare with your true longitude from a map or phone. Find your error in degrees and in kilometers at your latitude ($111 \text{ km} \times \cos \text{ latitude per degree}$).

Tips

- Shadows change slowly near noon, which is why the equal-shadow method, using times well before and after noon, is more accurate than looking for the shortest shadow.
- Every minute of time error is a quarter of a degree of longitude. Record times to the nearest 15 seconds if you can.
- Harrison's H4 was off by about 5 seconds after crossing an ocean. Compare that with how hard it was for you to time noon to within a minute.

Check your work

- I recorded at least twelve shadow marks with times.
- I found local noon by the equal-shadow method and converted it to UTC.
- I applied the equation of time and computed my longitude.
- I found my error in degrees and kilometers and explained one cause of it.

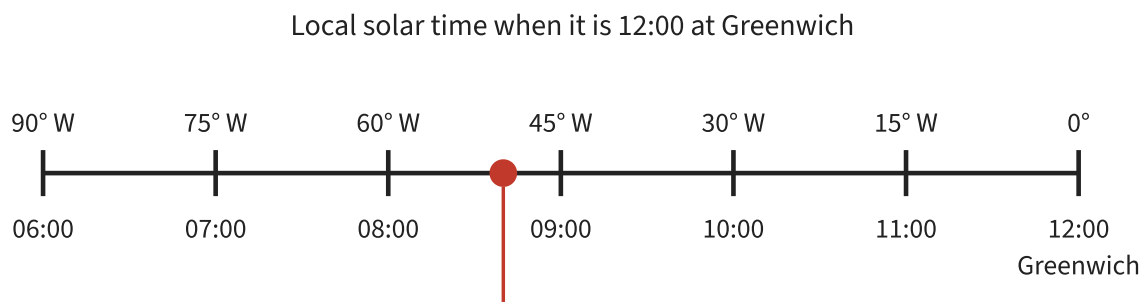
MAP NOTEBOOK

1. Draw a 24-hour clock face around a globe seen from above the North Pole. Mark every 15° meridian and label 0° (Greenwich), 90° W , 180° and 90° E .
2. Make a timeline from 1707 to 1884 with at least eight events from this lesson (Scilly, the Longitude Act, H1, H4, the Deptford trial, the first Nautical Almanac, Cook's second voyage, the Meridian Conference).
3. Copy the map of the Deptford voyage. Add the latitude and longitude of Portsmouth, Madeira and Port Royal beside each place.

From history. The 1884 conference also recommended a “universal day” beginning at midnight at Greenwich, but most nations kept local or national time for years. Railroads had already forced the issue: on November 18, 1883, the railroads of the United States and Canada adopted standard time zones based on meridians 75°, 90°, 105° and 120° west of Greenwich, each one hour apart, and many towns set their clocks back or forward that day. Congress did not make the time zones law until the Standard Time Act of 1918.

WORKED EXAMPLES

Example 1. A navigator observes local noon (the sun at its highest) when his chronometer, set to Greenwich time, reads 15:20. What is his longitude? If his latitude is 40° N, how many nautical miles is one degree of longitude there?



15° of longitude = 1 hour; 1° = 4 minutes

When it is 12:00 at Greenwich it is 08:40 at 50° W. So when it is noon at the ship, it is 15:20 at Greenwich.

1. Local noon came 3 h 20 min after Greenwich noon, so the ship is west of Greenwich (the sun reaches it later).
2. 3 h 20 min = 3.333 h. Longitude = $3.333 \times 15^\circ = 50.0^\circ$ W.
3. One degree of longitude = $60 \text{ nm} \times \cos(\text{latitude}) = 60 \times \cos 40^\circ = 60 \times 0.766 = 46.0 \text{ nm}$ (85.1 km, 52.9 miles).

Answer: 50.0° W. At 40° N one degree of longitude is about 46 nm (85 km, 53 miles).

Example 2. When HMS Deptford reached Jamaica (latitude about 18° N) in January 1762, H4 was about 5.1 seconds slow after correcting for its rate. Convert this time error into an error in longitude (in minutes of arc) and into nautical miles and kilometers at Jamaica. How does it compare with the half-degree required for the £20,000 prize?

1. Earth turns 15° per hour = $15'$ (minutes of arc) per minute of time = $15''$ (seconds of arc) per second of time.
2. $5.1 \text{ s} \times 15'' = 76.5'' = 1.275'$ of longitude.
3. At the equator $1'$ of longitude = 1 nm; at 18° N it is $\cos 18^\circ = 0.951$ nm. So $1.275 \times 0.951 = 1.21 \text{ nm} = 2.2 \text{ km}$ (1.4 miles).
4. Half a degree = $30'$. H4's error of $1.275'$ is about $1/24$ of the allowed error.

Answer: About $1.3'$ of longitude, or about 1.2 nm (2.2 km, 1.4 miles) at Jamaica, roughly one twenty-fourth of the half-degree the Longitude Act allowed.

Example 3. The Paris meridian lies $2^\circ 20' 14''$ east of Greenwich. Why did France's 1911 law define legal time as "Paris mean time retarded by 9 minutes 21 seconds"? Show the calculation.

1. Convert to decimal degrees: $2 + 20/60 + 14/3,600 = 2 + 0.3333 + 0.0039 = 2.3372^\circ$.
2. Each degree is 4 minutes of time: $2.3372 \times 4 = 9.349$ minutes.
3. $0.349 \text{ minutes} \times 60 = 20.9 \text{ seconds}$, so about 9 min 21 s.
4. Paris is east, so its mean time is ahead of Greenwich. Setting clocks back (retarding them) 9 min 21 s made them show Greenwich time.

Answer: Paris is 2.337° east of Greenwich, which is 9 min 21 s of time. Retarding Paris time by that amount gave Greenwich time without using the word "Greenwich."

PRACTICE

1. **EASY** How many degrees does Earth turn in 1 hour? In 4 minutes? In 1 minute?
2. **EASY** What did the Longitude Act of 1714 offer, and for what accuracy?
3. **EASY** Name the two methods that finally solved the longitude problem and the man most connected with each.
4. **EASY** In what year and city did the International Meridian Conference meet, how many nations attended, and what was the vote?
5. **MEDIUM** A ship observes local noon when Greenwich time is 08:12. What is her longitude?
6. **MEDIUM** What time is it at Greenwich when it is local noon at 75° W? At 120° E?
7. **MEDIUM** A chronometer gains 2 seconds a day, and the navigator forgets to correct for it. After a 40-day voyage, what is the error in longitude, and how many nautical miles is

that at the equator?

8. **MEDIUM** To win the full prize, a method had to find longitude within half a degree. If a voyage took 42 days, what was the largest allowable average clock error per day in seconds?
9. **HARD** Use the map. Port Royal, Jamaica, is at about 76.8° W, and Portsmouth at about 1.1° W. What is the difference in local time between them? When it is noon at Portsmouth, what is the local time at Port Royal?
(Use the map or drawing "Use this map for Problem 9." shown earlier in this lesson.)
10. **HARD** A navigator at 51.5° N (the latitude of London) has a chronometer error of 1 minute. How large is his position error in nautical miles and kilometers? Why is it smaller than the same error at the equator?
11. **HARD** Harrison was born on March 24, 1693, and died on March 24, 1776. H4 was finished in 1759, and he received £8,750 from Parliament in 1773. How old was he at each of those three events?
12. **CHALLENGE** Write a paragraph comparing the chronometer and the lunar-distance method as solutions to the longitude problem. Which would you have backed in 1765 if you sat on the Board of Longitude, and why?

COMMON MISTAKES

- Reversing east and west. If local noon comes *later* than Greenwich noon (the chronometer reads after 12:00), the ship is *west* of Greenwich.
- Using 60 nm per degree of longitude everywhere. That is true only at the equator; elsewhere multiply by the cosine of the latitude.
- Thinking Harrison's clock had to be perfect. It needed a steady, known rate; navigators corrected for a steady gain or loss each day.

Make it a game · Noon Around the World. One player is Greenwich and calls out a time (for example, "It is 15:00 at Greenwich!"). The others draw cards naming a city and its longitude (New York 74° W, Rio de Janeiro 43° W, Cairo 31° E, Mumbai 73° E, Beijing 116° E, Honolulu 158° W). Each player must give the local solar time in their city, to the nearest 10 minutes, within 20 seconds. Correct answers score a point; the first to 10 points becomes Greenwich.

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, moon and stars were made to mark time, and time, Harrison showed, marks place. The navigator who measures the noon sun and checks his chronometer is reading a clock God set in the heavens, with a regularity faithful enough to steer by.

Practice answers

1. 15° in 1 hour; 1° in 4 minutes; $15'$ (a quarter of a degree) in 1 minute.

2. A prize of £20,000 for a practical method of finding longitude at sea to within half a degree, tested on a voyage to the West Indies (with smaller prizes for less accuracy).
3. The marine chronometer (John Harrison) and the lunar-distance method with the Nautical Almanac (Nevil Maskelyne).
4. 1884, Washington, D.C.; 25 nations; 22 for Greenwich, 1 against (San Domingo), 2 abstaining (France and Brazil).
5. Local noon came 3 h 48 min before Greenwich noon, so she is east. $3.8 \text{ h} \times 15^\circ = 57.0^\circ \text{ E}$.
6. 75° W : $75 \div 15 = 5 \text{ h}$, so 17:00 at Greenwich. 120° E : $120 \div 15 = 8 \text{ h}$, so 04:00 at Greenwich.
7. $40 \times 2 = 80 \text{ s of time} \times 15'' = 1,200'' = 20'$ of longitude = 20 nm (37 km, 23 miles) at the equator. A known, steady rate is easy to correct; that is why rate matters more than perfection.
8. Half a degree = 2 minutes of time = 120 s. $120 \div 42 = \text{about } 2.9 \text{ seconds per day}$.
9. Difference = $76.8 - 1.1 = 75.7^\circ \div 15 = 5.05 \text{ h} \approx 5 \text{ h } 3 \text{ min}$. At Portsmouth noon it is about 06:57 at Port Royal.
10. 1 minute of time = $15'$ of longitude. At 51.5° N , $1'$ of longitude = $\cos 51.5^\circ = 0.623 \text{ nm}$, so $15 \times 0.623 = 9.3 \text{ nm}$ (17.3 km). Meridians converge toward the poles, so each degree of longitude covers less ground at high latitudes.
11. Finished H4 at about 66 (1759 – 1693; 65 if it was finished before his March birthday); received the 1773 award at about 80 (1773 – 1693); died on his 83rd birthday (1776 – 1693 = 83).
12. Answers will vary. A strong answer notes that the chronometer was simple and quick to use (compare local noon with the clock), but in 1765 only one or two existed, they were very expensive and a single failure could leave a ship lost. The lunar method needed only a sextant and the Nautical Almanac, which any ship could buy, but it required clear skies, a visible moon, skill and hours of calculation. A careful board member might fairly back the lunar method for the short term while encouraging cheaper chronometers; in practice ships used both until chronometers became cheap in the 1800s.

1.4 STEAM AT SEA

OBJECTIVES

- Explain how the steamship freed ships from the winds, and why Brunel's *Great Western* (1838) proved that a steamer could cross the Atlantic on its own coal.
- Use the square-cube law and coal-consumption figures to calculate a steamer's range, and explain why bigger steamers were more economical.
- Locate the coaling stations of the 1800s on a world map and explain how steam created a new strategic geography of coal, harbors and islands.

Warm-up. Take two boxes, one small (such as a matchbox or a tea box) and one with every side twice as long (if you have none, draw them on graph paper). For each, find the volume (length $\times$ width $\times$ height) and the area of the bottom. How many times bigger is the volume of the large box? How many times bigger is its bottom? A ship's cargo space grows like the volume, and the water dragging on its hull grows like the surface. Guess: which ship burns less coal for each ton it carries, the small one or the large one?

Watch. *Steam Engine - How Does It Work* (Real Engineering, 4:50).

<https://www.youtube.com/watch?v=fsXpaPSVasQ>

With How it worked: how a steam engine works, from the early pumping engine to the separate condenser, crank and flywheel.

Backup video. *8th April 1838: The steamship Great Western begins her maiden voyage to New York* (HistoryPod, 2:39). <https://www.youtube.com/watch?v=hu0uX8JevLo>

With the story: the Great Western begins her first voyage to New York in 1838.

KEY TERMS

paddle steamer

A steamship driven by large paddle wheels on its sides (or stern), turned by a steam engine. Most early ocean steamers were paddle steamers that also carried sails.

screw propeller

A turning set of twisted blades under the stern that drives a ship forward. It replaced paddle wheels on ocean ships from the 1840s on because it works whether the ship rolls or not.

bunker

A compartment in a ship where its fuel (coal, later oil) is stored. "Bunkering" means taking on fuel.

coaling station

A harbor where steamships could take on coal, kept stocked by shipping companies or navies along the main sea routes.

square-cube law

When a shape is scaled up, its surface area grows with the square of its size and its volume with the cube. A ship twice as long (in every dimension) has about four times the hull surface but eight times the volume.

range

The greatest distance a ship can travel on the fuel it carries, usually with a safety reserve.

CORE IDEAS

The story. In April 1838 two steamships raced across the North Atlantic. The little *Sirius*, a coastal packet of about 700 tons chartered for the occasion, left Cork in Ireland on April 4. Four days later, on April 8, the much larger *Great Western* left Bristol. *Sirius* reached New York on April 22 after about eighteen days, so short of coal that her arrival was a near thing. *Great Western* steamed in the next day, April 23, after only fifteen days, with about 200 tons of coal still in her bunkers. Crowds lined the waterfront to see them. *Sirius* won the race, but *Great Western* proved the point: a properly designed steamship could cross the ocean on its own fuel, on a schedule, and do it again.

How they figured it out. The *Great Western* was the idea of Isambard Kingdom Brunel, the engineer of the Great Western Railway from London to Bristol. The story goes that in 1835, when a director complained about how long the railway was, Brunel suggested making it longer still, by building a steamboat to carry passengers on from Bristol to New York. Experts doubted it. The scientific writer Dionysius Lardner argued in public lectures that no steamer could carry enough coal for so long a crossing. Brunel answered with geometry: the coal a ship needs depends on the resistance of the water against its hull, which grows roughly with the hull's surface, but the coal and cargo it can carry grows with its volume. Double every dimension of a ship and its surface grows about four times, but its volume about eight. So a large ship can carry far more coal in proportion to what it burns. Brunel designed the *Great Western*, a wooden paddle steamer 236 ft (72 m) long, then the largest passenger ship in the world. Before her first voyage, a fire broke out in her engine room on the Thames, and Brunel was badly hurt when he fell through a hatch fighting it; but the ship sailed, and in eight years she made dozens of Atlantic crossings.

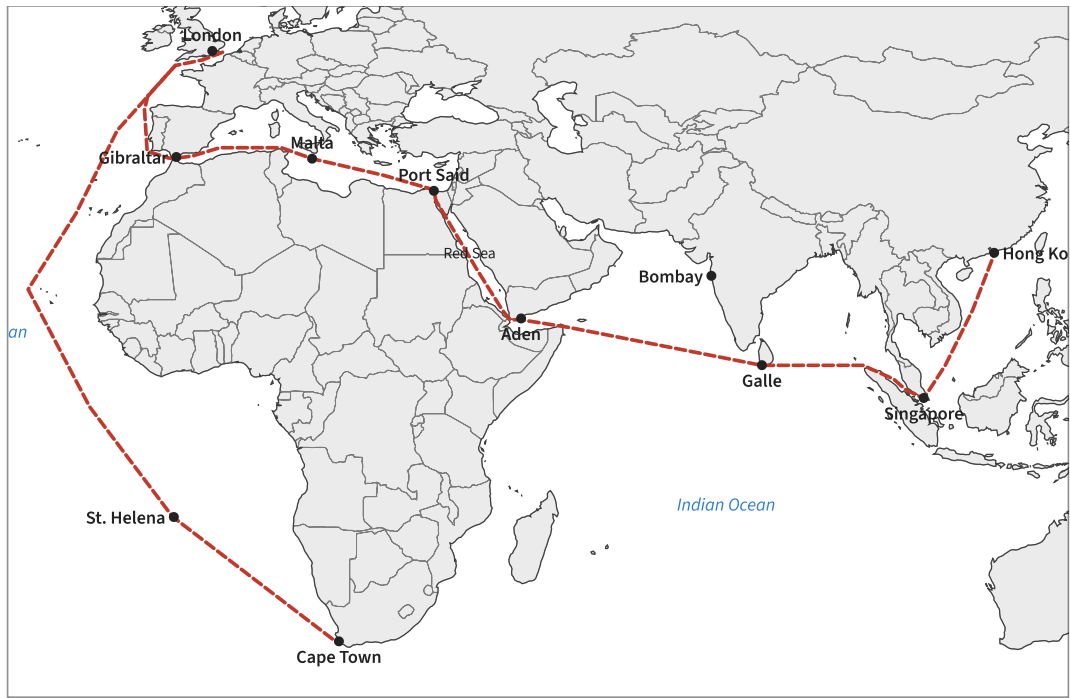
How it worked. Early marine engines burned coal under boilers, often fed with sea water, to make low-pressure steam that pushed great pistons up and down. Levers and cranks turned paddle wheels on each side of the hull. The ships still carried masts and sails to save coal and to get home if the engine failed. Steam's first great gift was regularity. In 1840 Samuel Cunard's *Britannia* began a mail service from Liverpool to Halifax and Boston on fixed dates, wind or no wind. Then came the **screw propeller**. In April 1845 the Royal Navy tied two nearly equal sloops stern to stern, the screw-driven HMS *Rattler* and the paddle-driven HMS *Alecto*, and let them pull against each other. *Rattler* dragged *Alecto* backward, and the navy adopted the screw. Later engines used steam two or three times over (the compound and triple-expansion engines), and by the 1880s a steamer burned only a fraction of the coal per ton-mile that the *Great Western* had.

The big idea: steam freed ships from the wind and chained them to coal. A sailing ship could go anywhere the wind allowed and never needed fuel. A steamship could go

against the wind, through calms and up rivers, on a timetable, but only as far as its bunkers would carry it. Coal is heavy and bulky; every ton in the bunkers is a ton of cargo not carried. So the steamship created a new map: a chain of **coaling stations** along the great sea routes. Britain, with the best steam coal in the world in the valleys of South Wales, shipped coal through Cardiff to depots around the globe. In January 1839 the East India Company seized the port of Aden, at the entrance to the Red Sea, chiefly to serve as a coaling station for steamers running between Suez and Bombay. Gibraltar, Malta, Cape Town, Ceylon, Singapore (founded 1819) and Hong Kong (ceded 1842) all became coaling ports, and after the Suez Canal opened in 1869, Port Said became one of the busiest in the world.

On the map. A coaling station needed a sheltered harbor, a position on a main route roughly every few days' steaming, and a navy to protect it. Rocky islands no one had wanted for farming suddenly mattered: Ascension, St. Helena, the Falklands. Other nations followed. The United States gained the right to a naval coaling station at Pago Pago in Samoa by treaty in 1878 and exclusive use of Pearl Harbor in Hawaii by treaty in 1887, and took Guam in 1898. In 1890 the American naval officer Alfred Thayer Mahan argued that a navy without coaling stations abroad was like a land bird unable to fly far from its own shore, an idea you will weigh in other courses. Coaling itself was brutal work. In most ports, gangs of laborers carried the coal aboard in baskets on their heads or backs, up plank after plank, for hours in heat and dust, often for very low pay.

Technology overcoming geography. Steam conquered the wind, the calm and the current. Passages that had depended on the season became fixed schedules; the Atlantic crossing fell from four to six weeks under sail westward to about two weeks under steam. But steam did not abolish geography; it rewrote it. Ports and islands rose or fell in value according to where coal could be stored. Ships' routes followed the coaling stations, and the nations that held them held the sea lanes. The old order passed slowly. In September 1838, five months after the *Great Western's* triumph, a steam tug towed the old sailing warship *Temeraire*, a veteran of Trafalgar, up the Thames to be broken up. J. M. W. Turner painted the scene, and it became the most famous picture of an age ending.



Coaling stations of the steam age. Before 1869, steamers for India and China went round the Cape or landed passengers in Egypt to cross overland to Suez; after 1869 they steamed through the Suez Canal.

PICTURE STUDY



The Fighting Temeraire, tugged to her last berth to be broken up, 1838, Joseph Mallord William Turner, 1839 · Oil on canvas · National Gallery, London

HMS *Temeraire* was a 98-gun ship of the line launched in 1798. At the Battle of Trafalgar in 1805 she sailed into action directly behind Nelson's flagship *Victory* and fought so hard that the nation called her "the Fighting Temeraire." By 1838 she was old and rotten, and she was

sold for scrap. In September of that year two steam tugs towed her from Sheerness to a breaker's yard at Rotherhithe on the Thames.

Turner exhibited this painting at the Royal Academy the next year and never sold it; he left it to the nation at his death. He took liberties with the facts: by the time of the tow, the *Temeraire's* masts and sails had been removed, but Turner painted them back, pale and ghostly. In 2005 listeners to a BBC radio poll voted it the greatest painting in Britain, and since 2020 it has appeared on the Bank of England's £20 note.

Look closely

- Compare the old warship and the tug. How do their colors, sizes and outlines differ? Which one looks alive and which looks like a ghost?
- Find the tug's funnel and the fire and smoke pouring from it. What is Turner saying about the new power that has replaced sail?
- Find the setting sun and the rising moon. Why might Turner have put a sunset in a picture about the end of an old ship?
- Look at the other sailing ships on the river. Are they gone yet?

Talk about it

1. Is this painting a celebration of steam or a lament for sail? Can it be both? Give evidence from the picture.
2. Turner painted masts that were not really there. When is it right for an artist to change the facts, and when is it wrong for a historian?
3. The Great Western crossed the Atlantic in April 1838 and the *Temeraire* went to the breakers in September 1838. What does this year tell you about how quickly technology was changing?

Safety first. This project uses an open flame and makes copper tubing hot enough to burn. Work only with an adult present, on a stable surface or in a basin of water away from curtains and paper, with long hair tied back. Let the boat cool for several minutes before touching the coil. Never leave a lit candle unattended.

PROJECT: BUILD A POP-POP STEAMBOAT

The pop-pop boat is a toy steam engine with no moving parts, first patented in the 1890s and still sold today. A candle boils water in a small copper coil; the steam pushes water out of the tubes, then condenses and lets water flow back in. Because the water leaves as a narrow jet but returns from all directions, the boat is pushed forward with each pop. Building one will show you the basic trade of every steamship: fire and water turned into motion, with fuel always being burned.

You will need

- About 60 cm (2 ft) of soft copper tubing, 3 mm (1/8 in) outside diameter (sold at hardware and hobby shops)

- A pencil or round dowel about 8 mm across to bend the coil around
- A hull of light wood or thick foam board about 15 cm × 8 cm (6 × 3 in); cover any foam near the flame with aluminum foil
- A tea-light candle in its metal cup, a small piece of foil to make a candle shelf
- A syringe or eyedropper, waterproof putty or epoxy, a ruler and marker
- A basin, sink or bathtub with a few centimeters of water, a stopwatch

Steps

1. Find the middle of the tubing. Carefully wind three tight turns around the pencil at the middle, leaving two straight ends about 20 cm long side by side. Bend slowly so the tube does not kink.
2. Make two small holes near the back of the hull, close together. Push both tube ends through from the top so they run under the hull and stick out about 2 cm behind the stern, pointing straight back, just below the waterline.
3. Seal the holes with putty or epoxy. Bend the coil so it sits about 1 cm above where the candle will stand. Make a foil shelf so the candle sits under the coil without touching the hull.
4. Fill the tubes with water: with the boat floating, push water through one tube end with the syringe until it flows out of the other. Both ends must stay under water.
5. With an adult, light the candle and set it under the coil. Wait 20 to 60 seconds. When the water boils, you will hear popping and the boat will move forward.
6. Time the boat over 1 m (3 ft) three times and record its speed. Record how long the candle lasts. Calculate the distance the boat could travel on one candle.
7. Try two changes, one at a time: one coil instead of three, and two candles instead of one (only if the hull is protected). Record the effect of each.

Tips

- If the boat does not pop, there is air in the tubes. Refill them completely with the syringe.
- Do not make the coil too long or the tubes too wide; small volumes boil and condense faster.
- The boat cannot run without its candle, just as the Great Western could not run without coal. Your 'coaling station' is a fresh tea light.

Check your work

- My boat moves forward under steam power.
- I recorded speed, fuel time and the range on one candle.
- I can explain in my own words why the boat moves forward even though water goes in and out of the same tubes.
- I compared my boat's need for fuel with a real steamship's need for coaling stations.

MAP NOTEBOOK

1. Draw a cross-section of the Great Western showing the boilers, engine, paddle wheels, coal bunkers, cargo hold, cabins and masts. Shade the space taken by coal.
2. Copy the coaling-stations map. Beside each station, write the year Britain (or the United States) gained it and one reason its location mattered.
3. Sketch the Temeraire and the tug from Turner's painting as simple outlines. Under them write two sentences: what steam gained and what was lost.

From history. Brunel's next ship, the SS Great Britain (launched 1843), combined an iron hull with a screw propeller and was the first such ship to cross the Atlantic, in 1845. After a long career carrying emigrants to Australia, she ended up abandoned in the Falkland Islands, one of the old coaling and repair ports of the South Atlantic. In 1970 she was floated on a pontoon and towed back to Bristol, to the very dry dock where she was built. She is now a museum ship there.

WORKED EXAMPLES

Example 1. A steamer carries 600 tonnes of coal in her bunkers and burns 30 tonnes a day while steaming at 9 knots. Her captain keeps 20 percent of the coal as a safety reserve. What is her range in nautical miles, kilometers and statute miles? (These are round figures for practice, typical of a mid-1800s steamer.)

1. Usable coal = $600 \times 0.80 = 480$ tonnes.
2. Days of steaming = $480 \div 30 = 16$ days.
3. Distance per day = $9 \text{ knots} \times 24 \text{ h} = 216 \text{ nm}$.
4. Range = $16 \times 216 = 3,456 \text{ nm} = 3,456 \times 1.852 = 6,400 \text{ km} = 3,456 \times 1.151 = 3,978 \text{ miles}$.

Answer: About 3,460 nm (6,400 km, 3,980 miles). That would carry her across the North Atlantic, but not from Britain to the Cape of Good Hope (well over 5,000 nm) without coaling on the way.

Example 2. Brunel's argument: a ship B is built with every dimension twice that of ship A. Assume the coal burned per day grows with the wetted surface of the hull and the coal (or cargo) carried grows with the volume. Compare the coal capacity, the daily coal use and the days of steaming of B with those of A.

1. Scale factor = 2. Surface grows by $2^2 = 4$; volume by $2^3 = 8$.
2. B carries 8 times A's coal and burns about 4 times A's coal per day.
3. Days of steaming = capacity $\div$ daily use: B can steam $8 \div 4 = 2$ times as many days as A.
4. If both steam at the same speed, B has about twice A's range, or can carry the same voyage's coal and use the rest of her space for cargo.

Answer: B carries 8 times the coal but burns only about 4 times as much per day, so she can steam about twice as long. Bigger steamers were more economical, which is why Brunel built big, and why Lardner's calculation, based on smaller ships, was wrong. (Real resistance also depends on speed and hull shape, so this is a first approximation.)

Example 3. Using round figures, treat Great Western's 1838 passage as about 3,000 nm in 15 days and Sirius's as about 2,900 nm in 18 days. Find each ship's average speed in knots, km/h and mph. How many days would a sailing packet take on the westbound crossing at an average of 3 knots against the prevailing westerlies?

1. Great Western: $3,000 \div (15 \times 24) = 3,000 \div 360 = 8.3$ knots = 15.4 km/h = 9.6 mph.
2. Sirius: $2,900 \div (18 \times 24) = 2,900 \div 432 = 6.7$ knots = 12.4 km/h = 7.7 mph.
3. Sailing packet: $3,000 \div 3 = 1,000$ hours $\div 24 = 41.7$ days.

Answer: Great Western averaged about 8.3 knots (15.4 km/h, 9.6 mph) and Sirius about 6.7 knots (12.4 km/h, 7.7 mph). A sailing packet at 3 knots would take about 42 days, nearly three times as long, and could not promise an arrival date.

PRACTICE

1. **EASY** Give the departure ports, departure dates and arrival dates in New York of Sirius and Great Western in 1838.
2. **EASY** What did the 1845 tug-of-war between HMS Rattler and HMS Alecto show?
3. **EASY** Name four British coaling stations on the route from Britain to China via Suez, in order.
4. **EASY** Why did the East India Company seize Aden in 1839?
5. **MEDIUM** A ship is scaled up so that every dimension is 3 times larger. By what factor do its hull surface and its volume grow? Using Brunel's reasoning, how much longer can it steam on a full load of coal?

6. **MEDIUM** A steamer burns 35 tonnes of coal a day at 10 knots. The run from Aden to Galle in Ceylon is about 2,100 nm. How many days does it take, and how much coal does it burn?
7. **MEDIUM** Great Western was 236 ft long. Convert this to meters. How many times longer was she than the Bremen Cog (about 23 m)?
8. **MEDIUM** Great Western arrived with about 200 tonnes of coal left. If she burned about 30 tonnes a day, how many more days could she have steamed? What did that prove against Lardner's claim?
9. **HARD** Use the map. Which coaling station guards the southern entrance to the Red Sea? Which guards the meeting of the Mediterranean and the Atlantic? Which lies halfway along the old route round Africa, in the South Atlantic?
(Use the map or drawing "Use this map for Problem 9." shown earlier in this lesson.)
10. **HARD** A steamer can carry 1,000 tonnes of coal and burns 40 tonnes a day at 10 knots. The route from Britain to Cape Town is about 6,000 nm. Can she make it without coaling, keeping a 15 percent reserve? If not, where on the map might she coal?
11. **HARD** Explain in three or four sentences why steam "freed ships from the wind but chained them to coal."
12. **CHALLENGE** Turner painted the Temeraire's masts though they had been removed before the tow. Write a paragraph on what Turner meant by the painting and whether his change of the facts helps or harms its value as a historical source.

COMMON MISTAKES

- Thinking early steamships gave up sails. Nearly all ocean steamers into the 1870s carried masts and sails to save coal and as a backup.
- Assuming twice as big means twice as much fuel. Because of the square-cube law, a ship twice as big in every dimension burns roughly four times the coal but carries eight times as much.
- Seeing coaling stations as only a matter of trade. They were also strategic: navies needed them, and whoever held them could deny them to others in war.

Make it a game • Coal to Hong Kong. Draw the steamer route from London to Hong Kong as a board of 20 spaces, with coaling stations at Gibraltar, Malta, Port Said, Aden, Galle and Singapore. Each player's ship starts with 6 coal tokens and may hold no more than 6. Each turn, roll a die and move that many spaces, paying 1 coal token per space. Landing on or passing a coaling station lets you stop and refill to 6 (passing it without stopping means no coal). A ship that runs out of coal drifts back 3 spaces and loses a turn. First to Hong Kong wins. Play a second round with only 4 tokens to feel why ship designers built bigger bunkers.

Scripture. "They that go down to the sea in ships, that do business in great waters; These see the works of the LORD, and his wonders in the deep." (Psalm 107:23-24, KJV)

Steam changed how men went down to the sea, but not what they found there. Engineers like Brunel used the laws God built into heat, water and iron; sailors still saw storms and

waves that no engine could command.

Practice answers

1. Sirius left Cork on April 4 and arrived April 22. Great Western left Bristol on April 8 and arrived April 23.
2. That the screw propeller (Rattler) was more powerful than paddle wheels (Alecto) for ships of similar power; Rattler towed Alecto backward, and the Royal Navy adopted the screw.
3. Any four in order, for example: Gibraltar, Malta, Aden, Galle (Ceylon), Singapore, Hong Kong. (Port Said, after 1869, was a major coaling port but lay in Egypt, not in a British colony.)
4. Chiefly as a coaling station for steamers running between Suez and Bombay, at the entrance to the Red Sea.
5. Surface $\times 3^2 = 9$; volume $\times 3^3 = 27$. It can steam about $27 \div 9 = 3$ times as long.
6. $2,100 \div 10 = 210$ h $\div 24 = 8.75$ days. Coal = $8.75 \times 35 = 306$ tonnes (about 310 tonnes).
7. $236 \times 0.3048 = 71.9$ m (about 72 m). $72 \div 23 =$ about 3.1 times as long.
8. $200 \div 30 =$ about 6.7 days more. She carried a comfortable margin, proving that a large, well-designed steamer could cross the Atlantic on its own coal.
9. Aden guards the southern entrance to the Red Sea; Gibraltar guards the strait between the Mediterranean and the Atlantic; St. Helena lies in the South Atlantic on the route to the Cape.
10. Usable coal = $850 \text{ t} \div 40 = 21.25$ days $\times 240 \text{ nm/day} = 5,100 \text{ nm}$. She cannot make 6,000 nm without coaling; she might coal at Madeira, the Canaries, Cape Verde or St. Helena (St. Helena is the station shown on the map).
11. Steamers could move against the wind, through calms and on a fixed schedule, so the winds no longer decided when and where ships went. But coal is heavy and bulky, and a steamer can go only as far as its bunkers allow. That meant ships had to stop at coaling stations along their route, and nations needed harbors in the right places, guarded by navies. Geography still ruled, but now it was the geography of coal and harbors rather than of winds.
12. Answers will vary. A strong answer explains that Turner contrasted the pale, noble sailing warship of Trafalgar with the small, dark, fiery steam tug, under a setting sun, to show the passing of the age of sail and the coming of steam, with both admiration and sadness. Painting the masts made the old ship recognizable and beautiful, which serves the painting's meaning. As a historical source, it is reliable for the mood and opinions of 1839 but not for the details of the tow, which must be checked against records; a historian must ask what an artist intended before trusting a picture as evidence.

1.5 THE CLIPPER AND THE IRON HULL

OBJECTIVES

- Explain how the tea clippers pushed sail to its limit, and why the steamship, the iron hull and the Suez Canal still ended their trade.
- Describe how iron (and later steel) hulls let ships grow far beyond the limits of wood, using the SS Great Britain and the Great Eastern as examples, and name the problems iron created.
- Compute average speeds, scale ratios and percentage changes to map how the voyage from London to China shrank between 1800 and 1900.

Warm-up. Take a long, thin strip of cardboard (about 60 cm by 4 cm) and a strip of the same size cut from a metal baking sheet or a metal ruler. Support each strip at both ends on two books and place a small weight, such as a full can, in the middle. Which one sags more? Now imagine a wooden ship 100 m long riding over waves, supported at its two ends by one wave and then in its middle by the next. Write one sentence on why shipbuilders wanted iron.

Watch. *1951: CUTTY SARK - Last of the TEA CLIPPERS* / Newsreel / Retro Transport / BBC Archive (BBC Archive, 2:32). https://www.youtube.com/watch?v=a0fbz_1zRig.
With The clipper: a 1951 BBC newsreel on the Cutty Sark, last of the tea clippers.

Backup video. *Isambard Kingdom Brunel's 'Great Eastern'* (Royal Museums Greenwich, 2:05). <https://www.youtube.com/watch?v=maAbHKjErL4>
With The giant: Brunel's Great Eastern, from Royal Museums Greenwich.

KEY TERMS

clipper

A fast sailing ship of the mid-1800s with a long, narrow hull, sharp bow and huge spread of sail, built for speed rather than cargo capacity.

composite hull

A hull with an iron frame and wooden planking. The wood could be sheathed in copper alloy to keep off weed and shipworm, which could not be done on iron without corrosion.

hogging and sagging

The bending of a long hull when it is supported by a wave in the middle (hogging, the ends droop) or at the two ends (sagging, the middle droops). Wooden hulls could not grow much longer than about 90 m (300 ft) because of it.

compass deviation

The error in a ship's compass caused by the ship's own iron. It must be measured and corrected with magnets or iron balls placed near the compass.

fouling

The growth of weed, barnacles and other sea life on a ship's bottom, which slows it down.
Iron hulls fouled badly in warm seas.

day's run

The distance a ship covers from one noon to the next, the standard measure of a ship's progress.

CORE IDEAS

The story. On May 30, 1866, a fleet of sailing ships loaded with the first tea of the season left the anchorage below Fuzhou, on the coast of southern China, within a day or two of each other. The first tea to reach London would earn its ship a premium and its captain glory, and newspapers followed the race. The clippers crossed the South China Sea, threaded the straits into the Indian Ocean, rounded the Cape of Good Hope, sailed the length of the Atlantic, and on September 6, 1866, after 99 days and some 14,000 nautical miles, *Ariel* and *Taeping* came up the English Channel almost side by side. *Taeping* docked in London only minutes ahead, and the owners agreed to share the premium. *Serica* docked the same night. After more than three months at sea, three ships arrived on the same tide.

The clipper. The **clipper** was the last and finest form of the sailing ship. Its hull was long and narrow, with a sharp bow that cut the water; its masts carried a vast cloud of canvas. On the night of November 22, 1869, a new clipper slid into the river Leven at Dumbarton in Scotland: the *Cutty Sark*, built for the London shipowner John Willis to beat the fastest ship in the tea trade, the *Thermopylae*. She is about 65 m (212 ft) long and could reach about 17 knots. Her hull is **composite**: an iron frame for strength, covered with teak and elm planks, which were sheathed in a copper alloy called Muntz metal to keep the bottom clean in tropical seas. Her name comes from Robert Burns's poem "Tam o' Shanter" (1791), in which a witch named Nannie dances in a short shirt, a *cutty sark*, and the hero shouts, "Weel done, Cutty-sark!" Her figurehead is Nannie.

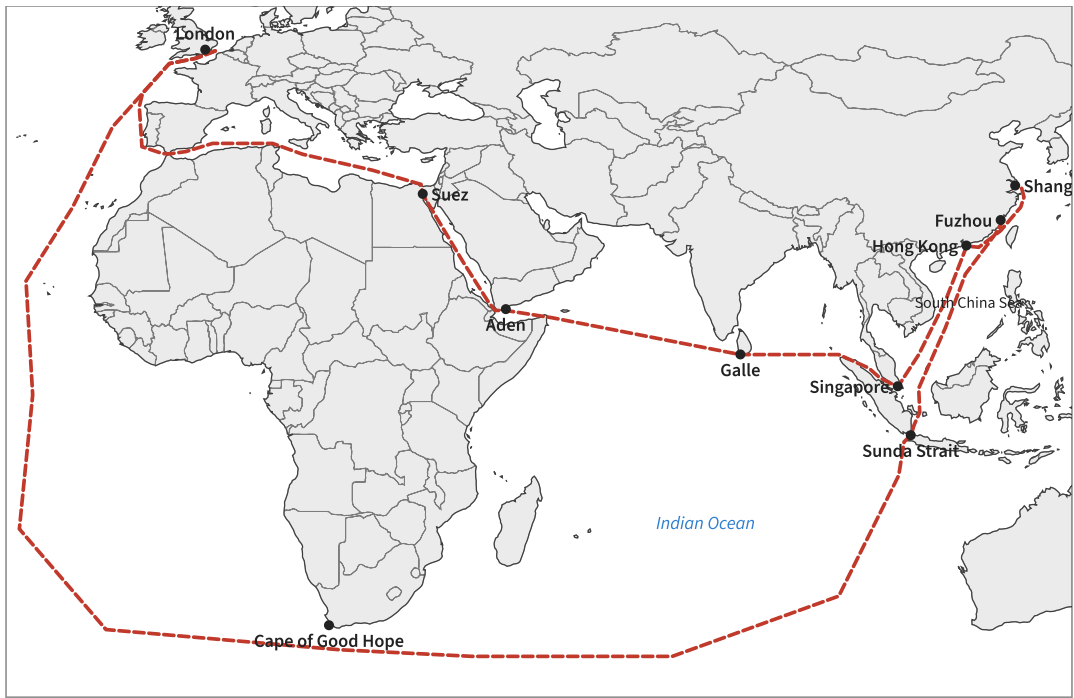
But the world had just changed. Five days before the *Cutty Sark* was launched, the Suez Canal opened, on November 17, 1869 (Unit 3). Steamers could now run from London to China through the Mediterranean and the Red Sea, thousands of miles shorter than the route around Africa. Sailing ships could not use the canal well: the Red Sea's winds blow the wrong way for much of the year, and towing was costly. Within a few years steamers carried most of the tea. The *Cutty Sark* made eight tea voyages, then turned to carrying wool from Australia, where under Captain Richard Woodget she made some of the fastest passages of her day. She was sold to Portuguese owners in 1895, bought back by a British captain in 1922, and has stood in a dry dock at Greenwich since 1954. After a fire in 2007 she was restored and reopened in 2012.

How it worked: the iron hull. Wood had reached its limit. A wooden hull much longer than about 90 m (300 ft) bends as waves lift its middle and then its ends (**hogging and sagging**), working its seams open until it leaks. Iron plates riveted to iron frames are far stronger for their weight, take up less room inside, and can be built to almost any size. Brunel's SS *Great Britain* (launched 1843), 98 m (322 ft) long, joined an iron hull to a screw propeller and crossed the Atlantic in 1845. Iron brought new problems. The ship's own iron pulled the

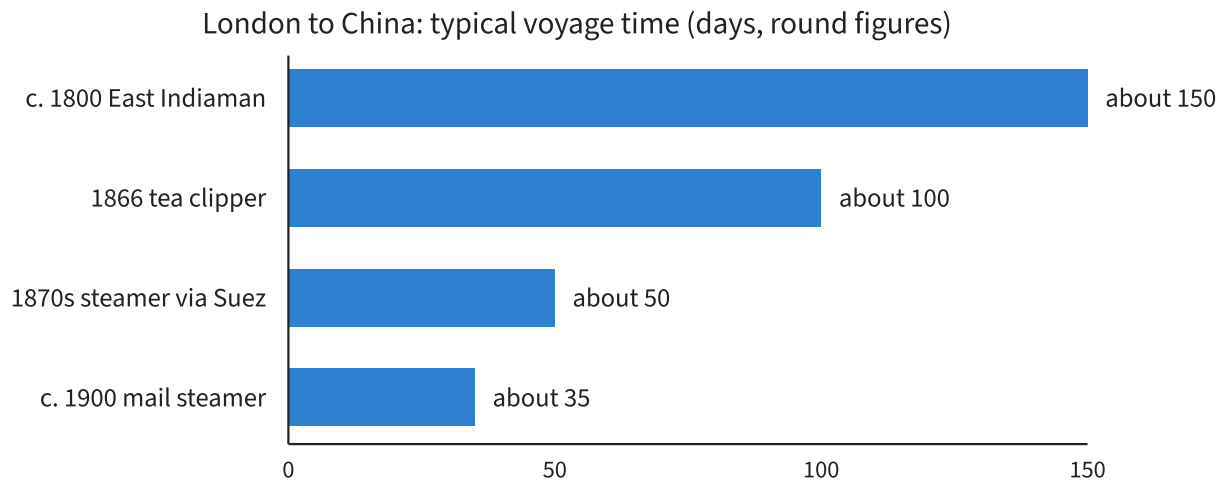
compass needle off true until the Astronomer Royal, George Airy, showed in 1838 how to correct it with magnets placed near the compass. Iron hulls also fouled quickly with weed and barnacles in warm seas, which is one reason tea clippers stayed composite. From the 1880s, cheaper and stronger steel replaced iron, and triple-expansion engines made steamers economical on even the longest routes.

The giant. Brunel's last ship showed both the power of iron and the cost of ambition. The *Great Eastern* was 211 m (692 ft) long, about six times the tonnage of any ship then afloat, with a double iron hull, two paddle wheels 17 m (56 ft) across, a screw propeller 7.3 m (24 ft) across and six masts. She was designed to carry some 4,000 passengers all the way to Australia without stopping for coal. She was so long that she had to be built and launched sideways into the Thames at Millwall. The launch began on November 3, 1857, but she stuck on the slipway and was not afloat until January 31, 1858, after months of struggle and great expense. Brunel suffered a stroke aboard her in September 1859, and died on September 15, days after an explosion on her first trials. As a passenger ship she was a commercial failure; her real fame came later, when she laid the Atlantic telegraph cable of 1866 (Unit 4). No ship surpassed her length until the last years of the century.

Technology overcoming geography. In 1800 a ship of the East India Company might take five months or more to sail from London to China, timed to the monsoons. By 1866 the best clippers made it in about 100 days. By 1900 a mail steamer through Suez could do it in about five weeks, on a schedule printed in advance. The voyage shrank by three-quarters in a single century. Yet the triumph had costs: the beauty and skill of the sailing ship passed away, iron ships demanded coal, coaling stations and new industries, and the greatest ship of the age nearly ruined its makers. The sea had been mastered, but not tamed. The same oceans still sank ships, and the next century's engineers would turn to an even greater task: cutting through the land itself.



Two roads to China. Clippers sailed round the Cape of Good Hope, following the winds; after 1869 steamers took the shorter route through the Suez Canal.



London to China, 1800–1900 (typical voyages, round figures).

PICTURE STUDY



Isambard Kingdom Brunel Standing before the Launching Chains of the Great Eastern, Robert Howlett, November 1857 · Albumen print from a wet collodion glass negative · National Portrait Gallery, London (prints are also held in other collections)

Robert Howlett was one of the first photographers to record a great engineering project as it happened. He photographed the building of the Great Eastern at Millwall for the *Illustrated Times*, and in November 1857, during the long struggle to launch her, he posed Brunel in front of the giant chains of the launching gear. The exposure took several seconds, so Brunel had to stand still.

This photograph has become one of the most famous portraits of an engineer ever made. It shows a man at the height of his ambition, in the middle of the hardest weeks of his life.

Look closely

- Look at the chain links behind Brunel. Compare one link with his hat or his body. What does their size tell you about the ship they held back?
- Look at his clothes, especially his trousers and boots. What do they tell you about where he had been working?
- Look at his face, his hat, his cigar and his hands. What kind of man does the photograph suggest?
- Notice what is not in the picture: the ship itself. Why might the photographer have chosen chains instead?

Talk about it

1. The launch of the Great Eastern took nearly three months and cost a fortune. How does knowing that change the way you see Brunel's pose?

2. Is this a photograph of confidence, of pride or of strain? Defend your answer.
3. Compare this photograph with Turner's *Fighting Temeraire*. Each shows a turning point in ships. How do the painter and the photographer tell their stories differently?

PROJECT: UNIT MAP: SAILING TIMES FROM LONDON TO CHINA, 1800–1900

You will make the unit's great map: a hand-drawn map of the sea routes from London to China, with the clipper route around the Cape and the steamer route through Suez, the coaling stations, and a timeline chart showing how the voyage shrank from about five months to about five weeks. This map will anchor your unit portfolio.

You will need

- A large sheet of paper (at least 45 × 60 cm, 18 × 24 in) or poster board
- A world atlas or printed outline map to trace the coastlines from Western Europe to East Asia
- Colored pencils or fine markers in at least three colors, a ruler, a string for measuring routes
- Your notes and figures from Lessons 1.1–1.5

Steps

1. Trace or sketch the coastlines from Britain to China and Japan, including Africa, Arabia, India and the East Indies. Add lines of latitude every 20° (the equator, 20° N and S, 40° N and S).
2. In one color, draw the clipper route: London, down the Atlantic, round the Cape of Good Hope, east across the Indian Ocean in the westerly winds, north through the Sunda Strait and up the South China Sea to Fuzhou.
3. In a second color, draw the steamer route: London, Gibraltar, Malta, Port Said, the Suez Canal, the Red Sea, Aden, Galle, Singapore, Hong Kong, Shanghai. Mark each coaling station with a small black square.
4. Use string and your map's scale (or an atlas) to estimate the length of each route. Label each route with its length in nautical miles and kilometers.
5. In a corner, draw a bar chart titled "London to China" with four bars: about 1800 (East Indiaman, about 150 days), 1866 (tea clipper, about 100 days), the 1870s (steamer via Suez, about 50 days) and about 1900 (mail steamer, about 35 days).
6. Add small drawings of an East Indiaman, the *Cutty Sark* and a steamer beside their routes, and the date of the Suez Canal's opening, November 17, 1869.
7. Below the map, write a paragraph of six to eight sentences explaining the three reasons the voyage shrank: faster ships, steam freed from the winds, and a shorter route.

Tips

- Clippers did not take the shortest line; they swung far west in the Atlantic and far south in the Indian Ocean to find the trade winds and westerlies. Show this on your

map.

- Keep the map uncluttered: label the main stations and seas, and put extra information in the margin.
- Use the same scale bar for both routes so a reader can compare them.

Check your work

- My map shows both routes clearly in different colors, with at least six coaling stations.
- Both routes are labeled with estimated lengths in nautical miles and kilometers.
- My bar chart shows the four voyage times correctly.
- My paragraph explains how faster ships, steam and the Suez route each shortened the voyage.

MAP NOTEBOOK

1. Draw the Cutty Sark from the side with her three masts and label the bowsprit, foremast, mainmast, mizzenmast, figurehead and the Muntz-metal sheathing on her bottom.
2. Draw two simple diagrams of a long hull on waves: one hogging (wave in the middle, ends drooping) and one sagging (waves at the ends, middle drooping). Label each.
3. Draw the Great Eastern, the Great Western and the Cutty Sark to the same scale as three simple side outlines (692 ft, 236 ft and 212 ft). Use 1 cm for every 50 ft.

From history. The Great Tea Race of 1866 was followed by telegraph as well as newspapers: as the leading ships were sighted off the English coast, the news was telegraphed ahead to London. Fast ships, slow news and fast news met in that one summer. Within five years, a telegraph cable reached China itself, and a merchant in London could order tea by wire in a few hours and have it shipped by steamer through Suez, which made the tea race, and the clipper, a thing of the past.

WORKED EXAMPLES

Example 1. In 1866 Ariel and Taeping took 99 days from Fuzhou to London. Taking the track they sailed as about 14,000 nm (a round figure; the actual track varied), find their average speed in knots, km/h and mph. A clipper in a strong wind might run 13 knots. What does the difference tell you?

(Use the map or drawing “The clipper route was long because it followed the winds.” shown earlier in this lesson.)

1. Hours = $99 \times 24 = 2,376$ h.
2. Average speed = $14,000 \div 2,376 = 5.9$ knots.
3. Convert: $5.9 \times 1.852 = 10.9$ km/h; $5.9 \times 1.151 = 6.8$ mph.
4. A day at 13 knots covers $13 \times 24 = 312$ nm, more than twice the average day’s run of $14,000 \div 99 = 141$ nm.

Answer: About 5.9 knots (10.9 km/h, 6.8 mph), or about 141 nm a day on average. The best days were more than twice as fast; the rest of the time was lost in calms, light winds and tacking against headwinds, which is the weakness steam removed.

Example 2. The Great Eastern was 692 ft long and the Great Western 236 ft. Find the ratio of their lengths. If every dimension were scaled up by that ratio, by what factors would the hull surface and the volume grow? By Brunel’s square-cube reasoning, how much farther could the larger ship steam on full bunkers?

1. Length ratio: $692 \div 236 = 2.93$.
2. Surface factor: $2.93^2 = 8.6$.
3. Volume factor: $2.93^3 = 25.2$.
4. Range factor $\approx$ volume $\div$ surface = $25.2 \div 8.6 = 2.93$.

Answer: The Great Eastern was about 2.93 times as long; scaled evenly she would have about 8.6 times the hull surface and 25 times the volume, and so could steam about 2.9 times as far on full bunkers. That was Brunel’s plan: a ship big enough to reach Australia without coaling. (The real ships were not exact scale copies, so this is an estimate.)

Example 3. Using the round figures on the bar chart, find the percentage by which the London-China voyage time fell from about 1800 (150 days) to about 1900 (35 days), and how many times faster the 1900 voyage was. Which single change between 1866 and the 1870s saved the most days?

(Use the map or drawing “Typical voyage times, round figures.” shown earlier in this lesson.)

1. Reduction = $150 - 35 = 115$ days. Percentage = $115 \div 150 \times 100 = 76.7$ percent.
2. Speed-up = $150 \div 35 = 4.3$ times as fast.
3. Changes: 1800 to 1866 saved $150 - 100 = 50$ days; 1866 to the 1870s saved $100 - 50 = 50$ days; the 1870s to 1900 saved $50 - 35 = 15$ days.
4. The 1866-to-1870s change, steam plus the Suez Canal, saved 50 days in less than a decade, as much as the previous 66 years of sail improvements.

Answer: The voyage fell by about 77 percent and became about 4.3 times as fast. The switch to steamers through Suez saved as many days in a few years as better sailing ships had saved in two-thirds of a century.

PRACTICE

1. **EASY** When and where was the Cutty Sark launched, and why was her timing unlucky?
2. **EASY** What is a composite hull, and why were tea clippers built that way instead of all iron?
3. **EASY** Give two advantages of iron hulls over wood and two problems they created.
4. **EASY** Where does the Cutty Sark’s name come from?
5. **MEDIUM** Convert the Cutty Sark’s top speed of about 17 knots to km/h and mph. How far would she run in 24 hours at that speed?
6. **MEDIUM** Convert the Great Eastern’s length of 692 ft to meters. How many Cutty Sarks (212 ft) laid end to end would equal her length?
7. **MEDIUM** The Great Eastern’s launch began on November 3, 1857, and she was afloat on January 31, 1858. How many days did the launch take?
8. **MEDIUM** A steamer through Suez covers about 10,500 nm from London to Shanghai at an average of 10 knots and spends 5 days in port coaling along the way. How many days does the voyage take?
9. **HARD** Use the map. Through which strait did the clippers pass between the Indian Ocean and the Java Sea, and through which strait did the steamers pass between the Indian Ocean and Singapore? Which cape did only the clippers round?
(Use the map or drawing “Use this map for Problem 9.” shown earlier in this lesson.)
10. **HARD** A wooden ship 90 m long is replaced by an iron ship 135 m long of the same shape. By what factor does the length increase? By what factors would the hull surface and the cargo volume grow?
11. **HARD** Explain why the best tea clippers were faster than early steamers on a good day, yet steamers took over the tea trade within a few years of 1869.

12. **CHALLENGE** Write a paragraph assessing the Great Eastern: was she a success or a failure? Consider her design goals, her cost, her career and what she made possible.

COMMON MISTAKES

- Thinking the Cutty Sark was an iron ship. She is composite: iron frames with wooden planking sheathed in Muntz metal.
- Believing clippers were simply slower than steamers. On a good day the best clippers were faster; steamers won through reliability, schedules and the shorter Suez route.
- Assuming the biggest ship must be the most profitable. The Great Eastern was a triumph of engineering and a commercial failure; size helps only when there is cargo and a market to fill it.

Make it a game • Tea Race. Each player is a clipper captain racing from Fuzhou to London on a board of 30 spaces drawn along the clipper route (South China Sea, Sunda Strait, Indian Ocean, Cape of Good Hope, South Atlantic, Doldrums, North Atlantic, English Channel). Each turn, draw a wind card or roll a die: 1 = calm (no move), 2-3 = light wind (move 1), 4-5 = fair wind (move 3), 6 = gale (move 4 but lose your next turn repairing sails). In the Doldrums every roll below 4 is a calm. Then play a second round with one player as a steamer through Suez on a board of 15 spaces, moving 2 spaces every turn no matter what. Who wins, and why?

Scripture. “And God blessed them, and God said unto them, Be fruitful, and multiply, and replenish the earth, and subdue it: and have dominion over the fish of the sea, and over the fowl of the air, and over every living thing that moveth upon the earth.” (Genesis 1:28, KJV)

The skill that built the Cutty Sark and the Great Eastern is part of the dominion God gave mankind: to understand His creation and put it to good use. The Bible also warns, at Babel (Genesis 11), against building to make a name for ourselves. The best engineers have held both together: bold work done in humility, for the good of others.

Practice answers

1. November 22, 1869, at Dumbarton, Scotland. The Suez Canal had opened five days earlier (November 17, 1869), giving steamers a much shorter route to China that sailing ships could not use well.
2. An iron frame with wooden planking. The wood could be sheathed in copper alloy (Muntz metal) to prevent fouling and shipworm; copper on an iron hull would cause corrosion, and bare iron fouled badly in tropical seas.
3. Advantages (any two): stronger for their weight, could be built much longer without hogging and leaking, thinner sides leaving more cargo space, less fire and rot risk. Problems: the iron disturbed the compass (deviation), and iron fouled quickly with weed and barnacles in warm seas.
4. From Robert Burns’s poem “Tam o’ Shanter” (1791), in which the witch Nannie dances in a short shirt, a “cutty sark.” Her figurehead shows Nannie.

5. $17 \times 1.852 = 31.5$ km/h; $17 \times 1.151 = 19.6$ mph. In 24 h: $17 \times 24 = 408$ nm (756 km, 470 miles).
6. $692 \times 0.3048 = 210.9$ m (about 211 m). $692 \div 212 = 3.3$ Cutty Sark.
7. November 3 to 30 = 27 days; all of December = 31; January 1 to 31 = 31. Total $27 + 31 + 31 = 89$ days.
8. $10,500 \div 10 = 1,050$ h $\div 24 = 43.75$ days, plus 5 days = about 49 days (roughly 7 weeks).
9. Clippers: the Sunda Strait (between Sumatra and Java). Steamers: the Strait of Malacca (between Sumatra and the Malay Peninsula). Only the clippers rounded the Cape of Good Hope.
10. $135 \div 90 = 1.5$. Surface $\times 1.5^2 = 2.25$; volume $\times 1.5^3 = 3.375$ (about 3.4 times the cargo space).
11. A clipper in a strong fair wind could make 15 knots or more, faster than most steamers, but over a whole voyage she lost many days in calms and headwinds and had to follow the long route round the Cape. A steamer moved steadily whatever the wind, could promise an arrival date, and after 1869 could take the much shorter route through the Suez Canal, which sailing ships could not use well because of the Red Sea winds. Reliable, scheduled delivery of fresh tea was worth more to merchants than the clipper's best days.
12. Answers will vary. A strong answer notes that as a commercial passenger ship she was a failure: her launch took nearly three months and huge sums, she never served the Australia route she was built for, she lost money on the Atlantic, and the strain may have contributed to Brunel's death. But as a feat of engineering she proved that iron ships could be built on a vast scale, her double hull and size pointed the way to later liners, and her great capacity made her the only ship able to carry and lay the 1866 Atlantic telegraph cable in one piece. A fair verdict weighs both: ahead of her time, wrong for her market, and vital for a purpose her designer did not plan.

UNIT 1 TEST

Answer each question. Show your work for every calculation, give units, and give distances in both nautical miles or kilometers and statute miles where asked. Use complete sentences for explanations. A calculator is allowed. The test is worth 100 points.

1. (6 pts) Explain where the word starboard comes from, and give two reasons the stern-post rudder was better than a steering oar for large ships.
2. (6 pts) A lateen-rigged ship can sail 45° from the wind. Its destination is 24 nm directly upwind. How far must it sail, and how long will it take at 6 knots?
3. (6 pts) A ship steers 090° at 8 knots for 3 hours, then 180° at 6 knots for 3 hours. Find her distance and bearing from the start.
4. (6 pts) A navigator measures Polaris 41.0° above the horizon. What is his approximate latitude, and how far is he from the equator in nautical miles and kilometers?
5. (6 pts) Describe a portolan chart and explain how a pilot used it to choose his course. What important information did it lack?
6. (6 pts) A navigator observes local noon when his chronometer, set to Greenwich time, reads 16:36. What is his longitude?
7. (8 pts) A chronometer gains 3 seconds a day, but the navigator forgets to correct it. After 30 days, what is the error in longitude in minutes of arc, and in nautical miles and kilometers at latitude 30° N?
8. (8 pts) Tell the story of H4's trial on HMS Deptford in 1761–1762 and explain why the International Meridian Conference of 1884 chose Greenwich as the prime meridian.
9. (8 pts) A steamer carries 800 tonnes of coal and burns 40 tonnes a day at 10 knots. Keeping a 10 percent reserve, what is her range in nautical miles, kilometers and statute miles?
10. (8 pts) Using Brunel's square-cube reasoning, a ship is scaled up so every dimension is 1.5 times larger. By what factors do its hull surface, its volume and its range on full bunkers change? Why did this answer Lardner's doubts?
11. (8 pts) Name four coaling stations on the route from Britain to China via Suez, in order. Why did Britain take Aden in 1839, and what did Mahan argue about coaling stations in 1890?
12. (8 pts) A tea clipper sails about 14,400 nm from Fuzhou to London in 100 days. Find her average speed in knots and km/h. If a steamer via Suez covered about 10,500 nm at an average of 9 knots, how many days would it take at sea?
13. (8 pts) Explain why the Cutty Sark was built with a composite hull, why iron hulls let ships grow larger than wooden ones, and why the opening of the Suez Canal in 1869 doomed the tea clippers.
14. (8 pts) Write a paragraph (6–8 sentences) answering: How did technology overcome the geography of the sea between 1400 and 1900, and what did it not overcome? Use at least three examples from the unit, including Turner's Fighting Temeraire.

UNIT PROJECT: MASTERING THE SEA: A NAVIGATOR'S DOSSIER

Assemble a dossier that shows how people mastered the sea, built from your own experiments and maps. Include: your bathtub sail-and-rudder test report with its data table (Lesson 1.1); your latitude measurement with your homemade quadrant (Lesson 1.2); your shadow-stick longitude result (Lesson 1.3); your pop-pop steamboat log of speed and fuel (Lesson 1.4); and your large map of sailing times from London to China, 1800 to 1900, with its bar chart (Lesson 1.5).

Finish with a two-page essay titled "Technology Overcoming the Sea," using at least two primary sources or historic images from the unit (such as Columbus's journal, the Longitude Act, Turner's Fighting Temeraire or Howlett's photograph of Brunel), and ending with what the sea still demands of those who cross it.

- **Experiments and data:** All four hands-on records are complete, with measurements, units, repeated trials and a clear conclusion for each.
- **Map accuracy:** The London–China map shows both routes, at least six coaling stations, correct straits and capes, route lengths in two units and a correct bar chart of voyage times.
- **Reasoning and calculation:** Latitude, longitude, speed and scale calculations are shown step by step, correct, and checked against real values with errors explained.
- **Essay:** The essay explains what each technology overcame and what it cost, uses primary sources accurately, and weighs both achievements and limits in clear, well-organized prose.

Answer key

1. Early ships were steered by an oar (the steer-board) over the right-hand side near the stern, so the right side became starboard. The stern rudder hangs on the centerline, so it stays in the water whichever way the ship leans; it is hinged to the hull, which takes the strain; and it can be built larger as ships grow (any two reasons).
2. $24 \div \cos 45^\circ = 24 \div 0.7071 = 33.9$ nm (62.8 km, 39.0 miles). Time = $33.9 \div 6 = 5.7$ hours.
3. 24 nm east and 18 nm south. Distance = $\sqrt{(24^2 + 18^2)} = \sqrt{900} = 30$ nm (55.6 km, 34.5 miles). The angle east of south has tangent $24 \div 18 = 1.333$, so 53.1° ; bearing = $180^\circ - 53.1^\circ = 126.9^\circ$, about 127° .
4. About 41.0° N. $41 \times 60 = 2,460$ nm = 4,556 km (2,831 miles) from the equator.
5. A sea chart on vellum (from the late 1200s) with accurate coastlines, port names written at right angles to the coast and a web of rhumb lines radiating from compass roses. The pilot laid a straightedge between two ports, found the parallel rhumb line and read the compass course; he measured the distance with the scale. It lacked a grid of latitude and longitude.
6. $16:36 - 12:00 = 4$ h 36 min = 4.6 h. $4.6 \times 15^\circ = 69.0^\circ$ W (west, because local noon comes after Greenwich noon).
7. $30 \times 3 = 90$ s of time. $90 \times 15'' = 1,350'' = 22.5'$ of longitude. At 30° N, 1' of longitude = $\cos 30^\circ = 0.866$ nm, so $22.5 \times 0.866 = 19.5$ nm = 36.1 km (22.4 miles).
8. In November 1761 William Harrison carried H4 aboard HMS Deptford from Portsmouth to Jamaica; on the way he predicted the sighting of Madeira, and at Jamaica, after correcting for its known rate, H4 was only about 5 seconds slow, a longitude error of little more than a

nautical mile. In 1884, delegates of 25 nations met in Washington and voted 22-1-2 for Greenwich, largely because the British Nautical Almanac and most of the world's sea charts were already reckoned from Greenwich.

9. Usable coal = $720 \text{ t} \div 40 = 18 \text{ days}$. $18 \times 24 \times 10 = 4,320 \text{ nm} = 8,000 \text{ km}$ (4,972 miles).
10. Surface $\times 1.5^2 = 2.25$; volume $\times 1.5^3 = 3.375$; range $\times 3.375 \div 2.25 = 1.5$. Lardner reasoned from small ships, but a larger ship carries coal in proportion to its volume and burns it roughly in proportion to its surface, so big steamers could carry enough coal to cross the Atlantic, as the Great Western proved in 1838.
11. For example: Gibraltar, Malta, Port Said, Aden, Galle, Singapore, Hong Kong (any four in order). The East India Company took Aden chiefly as a coaling station for steamers between Suez and Bombay, at the entrance to the Red Sea. Mahan argued that a navy without coaling stations abroad could not operate far from home (he compared such warships to land birds unable to fly far from their own shores).
12. Clipper: $14,400 \div 2,400 \text{ h} = 6.0 \text{ knots} = 11.1 \text{ km/h}$ (6.9 mph). Steamer: $10,500 \div 9 = 1,167 \text{ h} \div 24 = 48.6 \text{ days}$, about 49 days at sea.
13. Composite (iron frames, wooden planks) let her bottom be sheathed in Muntz metal against fouling and shipworm, which could not be done on iron without corrosion. Iron is stronger for its weight, so iron hulls could be built far longer than about 90 m (300 ft) without hogging and leaking, and had more room inside. The Suez Canal opened a much shorter route that steamers could use on a schedule; sailing ships could not use it well because of the Red Sea's winds, so steamers took the tea trade within a few years.
14. Answers will vary. A strong answer explains that the sail and stern rudder let ships carry cargo across oceans and steer across the wind; the compass, chart and astrolabe let pilots find their way and their latitude; the chronometer solved longitude and turned the ocean into a grid; steam freed ships from the winds and gave them schedules; and iron hulls allowed far bigger ships, so the London-China voyage fell from about five months to about five weeks. It should use the Temeraire, towed by a steam tug to the breakers in 1838, as an image of sail giving way to steam. It should also name limits: storms and wrecks still happened, steamers were tied to coal and coaling stations, routes still followed straits and capes, and new technology had costs in money, labor and lives.

MASTERING THE LAND

For most of history the sea was the easy road and the land was the hard one. A ship could carry a cargo across an ocean more cheaply than a wagon could haul it over a range of hills, because on land every mile meant mud, slopes, rivers to ford and animals to feed. Isaiah spoke of a day when “every valley shall be exalted, and every mountain and hill shall be made low” (Isaiah 40:4). In this unit you will watch engineers do something like that in stone, water and iron: lowering the cost of hills, valleys and distance until a continent could be crossed in days.

You will walk the Via Appia with Roman couriers, climb the locks of the Canal du Midi and the Erie Canal, ride behind Stephenson’s *Rocket* at Rainhill, stand at Promontory Summit on May 10, 1869, follow the Trans-Siberian to the Pacific, and pass through the Gotthard, across the Forth Bridge and under the Strait of Dover. For each breakthrough you will ask the four questions of this course: **What problem did geography pose? How did the technology solve it? What did it cost? What changed in the world?** You will read Claude Monet’s painting of the Gare Saint-Lazare and Charles O. Paullin’s travel-time maps of the United States, and you will build a model canal lock with gates that really work.

The costs will be named honestly: the dangerous labor of Irish canal diggers, Chinese and Irish railroad crews and Italian tunnel miners; the lands of Native nations crossed and lost; the debts, scandals and disasters. And the limits will appear too. Railways must still find gentle grades, tunnels must follow the rock, and a bridge must still answer to the wind.

BEFORE YOU BEGIN

- Can compute speed, distance and time and convert between kilometers and miles
- Can read latitude and longitude and explain how sun time changes with longitude (Unit 1)
- Can compute a percent and the volume of a rectangular box
- Can locate Italy, France, Britain, Russia and the regions of the United States on a world map

MASTERY CHECKLIST

- I can explain how Roman roads were built and how the *cursus publicus* carried news, and why “All roads lead to Rome” is a medieval proverb.
- I can explain step by step how a pound lock works and calculate the lift and the water used per lockage.
- I can explain why *Rocket* won at Rainhill, why railways need gentle grades, and how railways created standard time.
- I can trace the first transcontinental railroad and the Trans-Siberian on a map and describe the geography, the workers and the peoples affected.

- I can explain how cantilever bridges, spiral tunnels and base tunnels overcome mountains and water, and what the Tay Bridge disaster teaches.
- I can read an isochrone map and explain how new technology shrank travel time unevenly.

OPTIONAL BOOKS AND RESOURCES

- **Charles O. Paullin, *Atlas of the Historical Geography of the United States* (1932), digital edition** (<https://dsl.richmond.edu/historicalatlas/>): Free. The University of Richmond's Digital Scholarship Lab has put Paullin's whole atlas online. Use its "Rates of Travel" maps for 1800, 1857 and 1930 in Lessons 2.3 and 2.4 and in the portfolio.
- **Golden Spike National Historical Park (National Park Service)** (<https://www.nps.gov/gosp/>): Free. Photographs, maps and background on Promontory Summit and the building of the first transcontinental railroad (Lesson 2.4).
- **Erie Canalway National Heritage Corridor** (<https://eriecanalway.org/>): Free. Maps, history and pictures of the Erie Canal and its locks, useful for Lesson 2.2 and the model lock project.

2.1 ROMAN ROADS

OBJECTIVES

- Explain how Roman engineers built roads that crossed marshes, hills and rivers, and why the best roads were built in layers with a crown and side ditches.
- Describe the *cursus publicus*, the state courier and transport service begun by Augustus, and calculate how fast news, officials and armies moved along the roads.
- Trace the Via Appia on a modern map, convert Roman miles to kilometers and miles, and explain why “All roads lead to Rome” is a medieval proverb rather than a Roman saying.

Warm-up. Lay a dinner plate upside down beside a flat cutting board. Drip a spoonful of water onto the middle of each. Where does the water go on each surface, and where does it stay? Now imagine a road that must carry carts through two thousand winters of rain and frost. Which shape would you build, and where would you send the water? Write two sentences, then compare your answer with the Roman one in this lesson.

Watch. *How the Romans Built Straight Roads.* (Paul Whitewick, 11:49).

https://www.youtube.com/watch?v=37tajoy_gW4

With How it worked: how Roman surveyors laid out such straight roads.

Note: Paul Whitewick includes a short sponsor message; skip it.

Backup video. *The Roman Road System at the Time of Jesus* (Drive Thru History with Dave Stotts, 2:43). <https://www.youtube.com/watch?v=MI1LFFmFG1U>

With The network and the couriers: the Roman road system Paul traveled on.

KEY TERMS

Via Appia

The Appian Way, begun in 312 BC by the censor Appius Claudius Caecus from Rome to Capua and later extended to the port of Brundisium (Brindisi). The poet Statius called it the queen of the long roads.

crown (camber)

A gentle arch across the width of a road, higher in the middle than at the edges, so that rain runs off into side ditches instead of soaking the roadbed.

Roman mile (mille passus)

A thousand paces, each pace (a double step) being 5 Roman feet. It is about 1,480 m, or about 0.92 of a modern mile.

milestone (miliarium)

A stone column set beside a Roman road at each Roman mile, often carved with the distance and the name of the official or emperor who built or repaired the road.

cursus publicus

The state courier and transport service founded by Augustus. It carried official messages, officials and government goods, using animals and vehicles kept at stations along the main roads.

mansio and mutatio

Stations of the *cursus publicus*. A *mutatio* was a changing station for fresh animals; a *mansio* was a larger stopping place with lodging for the night.

CORE IDEAS

The story. In 312 BC a Roman official named Appius Claudius Caecus held the office of censor, which put public works under his care. Rome was at war with the Samnites, a hard mountain people of the southern Apennines, and its armies needed to reach the rich plain of Campania quickly. Appius ordered a road built south from Rome to the city of Capua, a distance of roughly 210 km (130 miles). It ran across the Alban Hills, straight across the Pontine Marshes and down the coast to Terracina, and for long stretches it is almost ruler-straight. In the same year he also built Rome's first aqueduct, the Aqua Appia. Later generations carried the road on across the Apennines to Beneventum and Tarentum and finally to Brundisium on the heel of Italy, the harbor for ships to Greece and the East. About 370 years later a prisoner named Paul walked its last miles to Rome, and Christians from the city came out along it to meet him at Appii Forum and the Three Taverns (Acts 28:15).

How it worked. A Roman highway was not just a cleared path. Surveyors laid out the line with a *groma*, a cross-shaped instrument with hanging plumb lines, and sighted from one point to the next to keep the route straight wherever the ground allowed. Workers, often soldiers, dug a trench down to firm ground and filled it in layers: large stones at the bottom, then rubble and gravel, sometimes bound with lime, then finer gravel or sand. On the great roads near cities the top was paved with tightly fitted, many-sided blocks of hard volcanic stone. The surface was given a **crown** so rain ran to the sides, curbs held the edges, and ditches carried the water away. Where a hill or cliff stood in the way, the Romans cut through it: at Terracina, under the emperor Trajan, workers cut away the foot of the Pisco Montano cliff so the road could pass along the sea, and they marked the height of the cut in tens of Roman feet down to about 120 feet (about 36 m). Where rivers crossed the line they built stone bridges, many of which still carry traffic today.

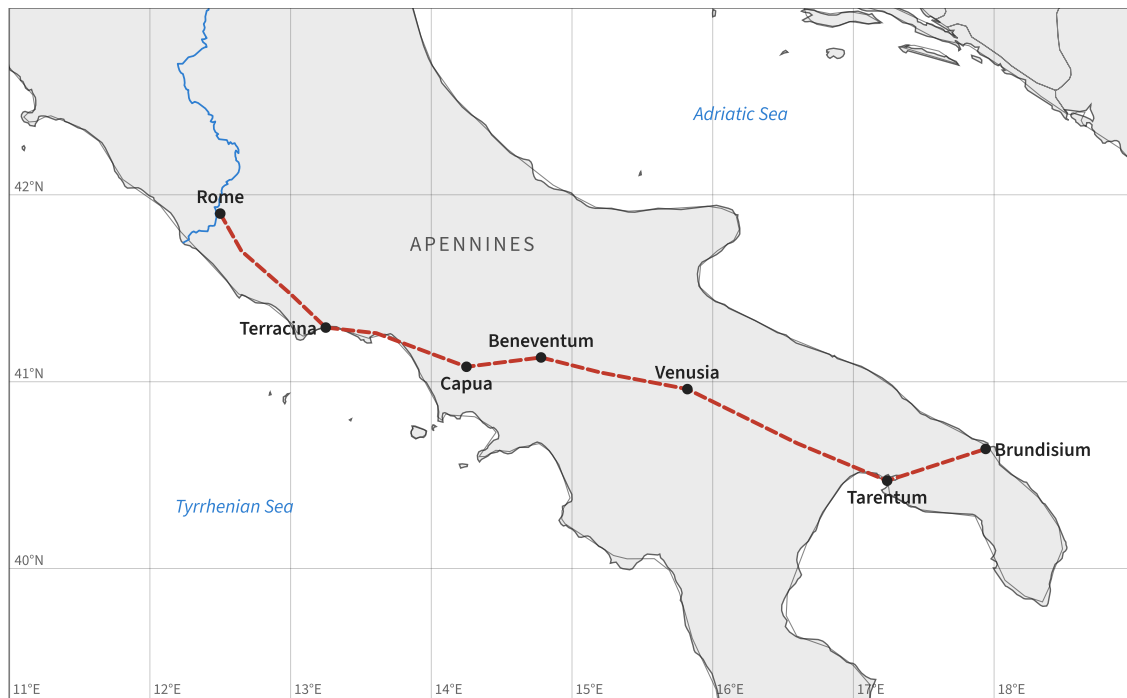
The network and the couriers. By the second century AD the empire had something like 80,000 km (50,000 miles) of major paved roads, from Hadrian's Wall in Britain to the Euphrates, and many times that length of lesser roads. A stone column set up by Augustus in the Forum in 20 BC, the Golden Milestone, symbolized Rome as the center of it all. Augustus also founded the **cursus publicus**. The historian Suetonius tells that he first placed young runners at short intervals along the military roads to pass dispatches from hand to hand, and later kept vehicles instead, so that the same man could carry a message the whole way and be questioned about it on arrival. Along the main routes stood changing stations (*mutationes*) with fresh animals and larger overnight stations (*mansiones*). Only travelers with an official permit could use the service, and the towns along the road had to supply the animals and fodder, a heavy burden that emperors complained of again and again. A normal

official journey might cover about 50 Roman miles (about 75 km) a day. In an emergency much more was possible: Pliny the Elder records that Tiberius, racing to his dying brother Drusus in Germany in 9 BC, covered about 200 Roman miles in a day and a night by changing vehicles. A marching legion, by contrast, was expected to cover about 20 Roman miles in five hours at the ordinary military pace, according to the late Roman writer Vegetius.

The big idea. Geography sets a price on every journey: hills to climb, marshes to cross, rivers to ford, mud in winter. A good road lowers that price for everyone who uses it, all year, for centuries. Rome's roads turned Italy, and then the Mediterranean world, into one connected space in which legions, tax collectors, merchants, letters and missionaries could move at a predictable speed. That is why the network became the skeleton of the empire. Yet the famous saying "All roads lead to Rome" is not Roman at all. It is a medieval proverb; a twelfth-century Latin form, often credited to the French poet Alain de Lille, says that a thousand roads lead men forever to Rome. By then the city was the center of the Western Church and pilgrims, not legions, filled the roads. In Roman times many roads in the provinces actually ran between frontier forts, ports and provincial capitals and never pointed toward Rome at all.

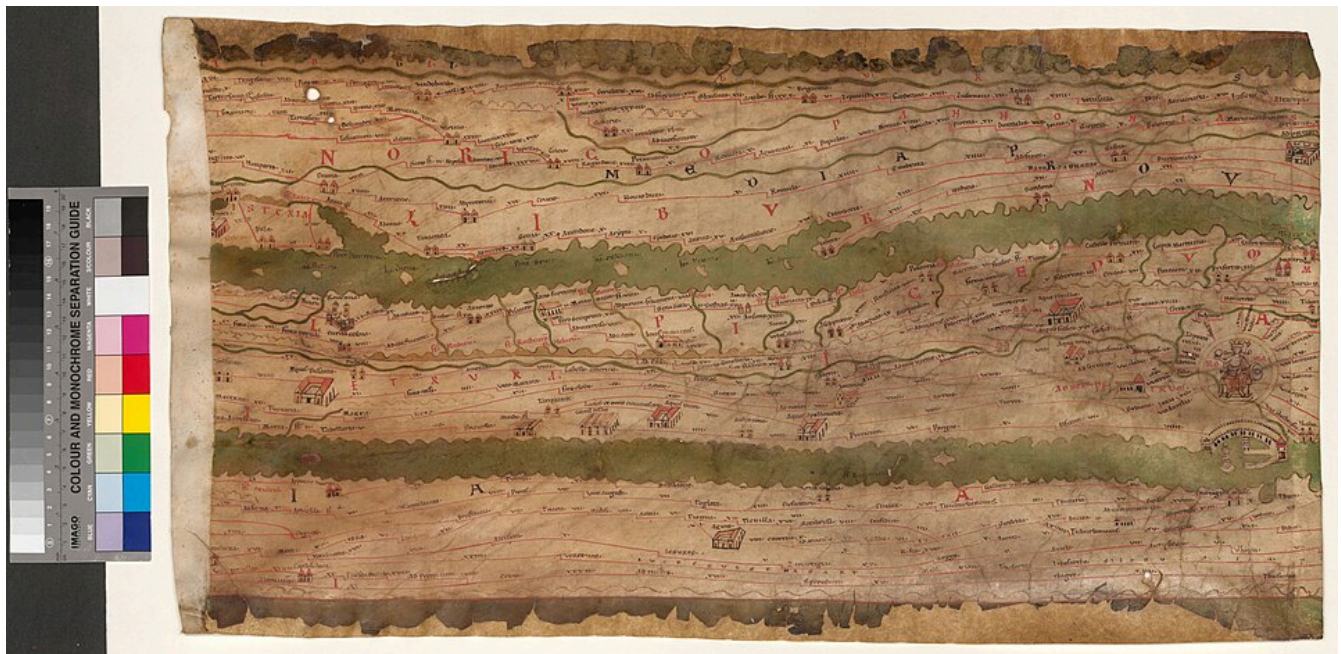
On the map. The Romans kept written route lists such as the *Antonine Itinerary*, which gives stations and distances in Roman miles along hundreds of routes. One painted road map survives in a medieval copy, the *Tabula Peutingeriana*, studied in this lesson. On a modern map you can still trace many Roman roads, because later builders reused good lines: the Via Aemilia, built in 187 BC from Rimini to Piacenza, still gives its name to the Emilia region and its road, and much of the modern A5 road in England follows the Roman road the Anglo-Saxons called Watling Street. On the map of the Via Appia (Figure hc-via-appia), notice how the road first follows the coast and then turns inland through the mountains toward Beneventum, choosing passes and valleys rather than the shortest straight line to the heel of Italy.

Technology overcoming geography. Roman roads did not move mountains, but they made mountains and marshes cost less. The price was enormous: soldiers' labor, taxes, forced service by local towns, and constant repair. Roads also cut both ways. The same highways that let Rome's armies reach a frontier quickly later let invaders reach the heart of Italy. And they carried something the builders never planned: the gospel. The apostles and the early missionaries walked and sailed along Roman routes, and Paul wrote of the "fulness of the time" (Galatians 4:4) in which Christ came into a world unusually well connected. As you study each later breakthrough in this unit, ask the same four questions: What problem did geography pose? How did the technology solve it? What did it cost? What changed in the world?



The Via Appia, begun 312 BC, from Rome to Brundisium.

PICTURE STUDY



Tabula Peutingeriana (the Peutinger Map), Unknown medieval copyist, after a late Roman original, copy made about 1200; the Roman original probably dates from the 4th century AD · Ink and color on parchment, a scroll of 11 sheets, about 6.75 m (22 ft) long and 34 cm (13 in) tall · Austrian National Library, Vienna

This is the only surviving map of the Roman road network. It is a medieval copy of a late Roman original, named after Konrad Peutinger, a scholar of Augsburg who received it in the early 1500s. The map stretches from Britain (whose westernmost part is lost) to India, but it

squeezes the whole world into a strip a little over a foot tall, so seas become thin ribbons and Italy becomes a long sausage of land.

It is not a map in our sense of true shapes and directions. It is a traveler's diagram, like a subway map: it shows which places are connected, in what order, and how far apart. Small kinks in the red road lines mark the stages, and numbers give the distances between them.

Look closely

- Find Rome, shown as a crowned figure seated in a circle with roads spreading out from it like spokes.
- Follow one red road line. Find the little kinks or hooks that mark each stage, and the numbers that give the distance.
- Find the small pictures of buildings. Some mark towns; some with courtyards mark places to stay or bathe.
- Look at the seas and the shapes of the lands. What did the mapmaker sacrifice to fit the world onto a scroll?

Talk about it

1. Why would a courier or an official care more about the order of stations and the distances between them than about the true shape of Italy?
2. Name a modern map that, like this one, distorts shapes on purpose to show connections clearly.
3. What does a map like this tell you about how the Romans thought of their world?

PROJECT: BUILD AND TEST A ROMAN ROAD

You will build two model roads side by side in clear containers: an ordinary dirt track and a Roman-style layered road with a crown and ditches. Then you will rain on them and load them with weight, measuring what happens. By the end you will know from your own hands why the Romans dug so deep.

You will need

- Two clear plastic containers or shoeboxes, at least 25 cm (10 in) long
- Garden soil
- Large pebbles or aquarium rocks, small gravel and coarse sand
- Flat stones, slate chips or broken tile pieces for the paving
- A watering can or a cup with holes punched in the bottom
- A ruler, a brick or heavy book wrapped in a plastic bag, and a notebook

Steps

1. In container A, pack 8 cm (3 in) of damp soil and smooth it flat. This is a dirt track.
2. In container B, build a Roman road in layers: 3 cm (1¼ in) of large pebbles, 2 cm (¾ in) of small gravel, 2 cm of sand, then fit the flat stones tightly on top.

3. Shape the top of road B so the middle is about 1 cm higher than the edges, and scrape a small ditch along each side.
4. Measure the height of each road surface at the center and write it down.
5. Rain on each road with the same amount of water, about two cups, poured slowly from the same height. Watch where the water goes. Note puddles and wash-outs.
6. Lay a ruler across each road and press the wrapped brick on it as a cart axle, rolling it back and forth ten times.
7. Measure the center height again and the depth of any ruts. Record your results in a table.
8. Repeat the rain and the load once more. Write a paragraph explaining which road a Roman engineer would choose for a road meant to last a century, and why.

Tips

- Do the test outdoors or in a sink, because the dirt road will turn to mud.
- The Romans did not use the same layers everywhere. On firm, dry ground they built more simply; in marshes they dug deeper or built on causeways. Your model shows the idea, not a single recipe.

Check your work

- I measured the ruts and the puddles on both roads and recorded them in a table.
- I can explain what the crown and the ditches do.
- I can explain why a layered road spreads the weight of a cart and why that matters on soft ground.

MAP NOTEBOOK

1. Draw a labeled cross-section of a Roman highway: trench, foundation stones, rubble, gravel, paving, crown, curbs and ditches. Add arrows showing where rain goes.
2. Trace the Via Appia from Rome to Brundisium on an outline map of Italy. Mark Capua, Beneventum, Tarentum and Brundisium, and shade the Apennines.
3. Make a two-column chart titled “Who Used the Road?” with travelers on the left (legion, courier, merchant, pilgrim, missionary) and what each one needed from the road on the right.

From history. In 20 BC Augustus set up the Golden Milestone (Milliarium Aureum), a gilded bronze-covered column near the Temple of Saturn in the Roman Forum, as the symbolic starting point of the empire’s great roads. Only part of its marble base is thought to survive today. The idea lived on: many modern countries have a “kilometer zero” marker in their capitals, such as the plaque in front of Notre-Dame Cathedral in Paris and the Zero Milestone near the White House in Washington, D.C.

WORKED EXAMPLES

Example 1. Pliny the Elder records that Tiberius traveled about 200 Roman miles in a day and a night (24 hours). Using 1 Roman mile $\approx$ 1.48 km, express this distance in kilometers and in modern miles, and find his average speed.

1. Distance in kilometers: $200 \times 1.48 \text{ km} = 296 \text{ km}$.
2. Convert to miles: $296 \text{ km} \div 1.609 \text{ km per mile} \approx 184 \text{ miles}$.
3. Average speed: $296 \text{ km} \div 24 \text{ h} \approx 12.3 \text{ km/h}$, or $184 \text{ mi} \div 24 \text{ h} \approx 7.7 \text{ mph}$.
4. Check: this is about the speed of a horse at a steady trot kept up all day and all night, which is why he needed many changes of vehicle and animals.

Answer: About 296 km (184 miles), an average of about 12 km/h (about 7.7 mph) for a full day and night.

Example 2. The road from Rome to Capua is roughly 210 km (130 miles). How long would the trip take (a) for a courier making 50 Roman miles a day, (b) for a legion marching 20 Roman miles a day, and (c) at Tiberius's emergency pace of 200 Roman miles a day?

1. Convert each daily rate to kilometers: $50 \times 1.48 = 74 \text{ km}$; $20 \times 1.48 = 29.6 \text{ km}$; $200 \times 1.48 = 296 \text{ km}$.
2. Courier: $210 \div 74 \approx 2.8 \text{ days}$.
3. Legion: $210 \div 29.6 \approx 7.1 \text{ days}$.
4. Emergency pace: $210 \div 296 \approx 0.71 \text{ day}$, or about 17 hours.

Answer: About 3 days for an ordinary courier, about 7 days for a marching legion, and about 17 hours at emergency pace.

Example 3. A stretch of the Via Appia is about 4.2 m (about 14 ft) wide. If the center of the paving stands 10 cm (about 4 in) higher than each edge, what is the cross slope from the crown to the edge, as a percent?

1. The water runs from the center to one edge, a horizontal distance of half the width: $4.2 \text{ m} \div 2 = 2.1 \text{ m}$.
2. The drop over that distance is $10 \text{ cm} = 0.10 \text{ m}$.
3. Slope = drop $\div$ run = $0.10 \div 2.1 \approx 0.048$.
4. As a percent: $0.048 \times 100 \approx 4.8\%$.

Answer: About 4.8%, a gentle slope a cart hardly notices but enough to shed rain into the ditches.

PRACTICE

1. **EASY** Who began the Via Appia, in what year, and between which two cities did it first run?
2. **EASY** What is a Roman mile based on, and how long is it in meters and in modern miles?
3. **EASY** What was the *cursus publicus*, and who founded it?
4. **EASY** Is “All roads lead to Rome” a saying of the ancient Romans? Explain.
5. **MEDIUM** Convert 50 Roman miles, a normal day’s travel for an official courier, into kilometers and modern miles.
6. **MEDIUM** A road 6.0 m (about 20 ft) wide is built with a 4% slope from the crown to each edge. How much higher is the center than the edges?
7. **MEDIUM** Use the map. In what general compass direction does a traveler go from Rome to Brundisium?
(Use the map or drawing “The Via Appia.” shown earlier in this lesson.)
8. **MEDIUM** A legion marches 20 Roman miles a day. About how many days would it need to march 300 km (about 186 miles)?
9. **HARD** Rome is at about 41.9° N, 12.5° E and Brundisium at about 40.6° N, 17.9° E. Using 111 km per degree of latitude and about 84 km per degree of longitude at this latitude, estimate the straight-line distance. Why is the road longer?
10. **HARD** A courier rides 200 Roman miles, starting with a fresh horse. If changing stations stand every 10 Roman miles, how many times does he change horses before arriving?
11. **HARD** A governor’s dispatch must travel 1,500 km (about 930 miles) to Rome, and an answer must come back. How long does the round trip take at an ordinary 74 km a day, and at an urgent 250 km a day (ignoring time to write the reply)?
12. **CHALLENGE** In a paragraph, explain how the Roman road network both strengthened the empire and created new dangers, and in what sense the medieval proverb “All roads lead to Rome” was true and in what sense it was not.

COMMON MISTAKES

- Treating the Roman mile as a modern mile. A Roman mile is about 1.48 km, a little shorter than a modern mile of 1.609 km.
- Quoting “All roads lead to Rome” as something Romans said. It is a medieval proverb.
- Imagining every Roman road as a paved stone highway. Only the most important roads near cities were paved with fitted stone blocks; many were gravel, and construction varied with the ground.

Make it a game • Cursus Publicus Relay. Write a short “imperial dispatch” on a card and seal it in an envelope. Mark a course around the yard or a park with stations every 20 paces. Round 1: one runner carries the dispatch the whole course while someone times it. Round 2: post runners at each station to pass it hand to hand. Round 3: one runner carries it, but must stop at each station and answer one question from the station keeper about Roman roads before going on. Compare the times and discuss Suetonius’s point: why might an emperor prefer one messenger who can be questioned over a faster relay?

Scripture. “And from thence, when the brethren heard of us, they came to meet us as far as Appii forum, and The three taverns: whom when Paul saw, he thanked God, and took courage.” (Acts 28:15, KJV)

Appii Forum and the Three Taverns were stations on the Via Appia south of Rome. The road Appius built for war became, in God’s providence, the road on which the apostle came to the capital and on which believers walked out to welcome him.

Practice answers

1. Appius Claudius Caecus, as censor, in 312 BC, from Rome to Capua.
2. A thousand paces (mille passus), each pace being 5 Roman feet. It is about 1,480 m, or about 0.92 of a modern mile.
3. The state courier and transport service of the Roman Empire, founded by Augustus. It carried official messages, officials and government goods using animals and vehicles kept at stations along the main roads.
4. No. It is a medieval proverb. A twelfth-century Latin form is often credited to Alain de Lille, written when Rome was the center of the Western Church and drew pilgrims.
5. $50 \times 1.48 = 74$ km; $74 \div 1.609 \approx 46$ miles.
6. Half the width is 3.0 m. Rise = $3.0 \text{ m} \times 0.04 = 0.12 \text{ m}$, so 12 cm (about 4.7 in).
7. East-southeast (Brundisium is far to the east and a little to the south of Rome).
8. 20 Roman miles ≈ 29.6 km a day. $300 \div 29.6 \approx 10.1$, so about 10 days.
9. North-south: $1.3^\circ \times 111 \approx 144$ km. East-west: $5.4^\circ \times 84 \approx 454$ km. Distance $\approx \sqrt{(144^2 + 454^2)} \approx 476$ km (about 296 miles). The road is longer because it follows the coast and then winds through Apennine valleys and passes to keep grades gentle, and it links cities along the way.
10. Stations at miles 10, 20, ... 190 are passed before the end: 19 changes. (The station at mile 200 is the destination.)
11. Ordinary: $3,000 \div 74 \approx 41$ days. Urgent: $3,000 \div 250 = 12$ days. Even with the best roads, governing a large empire meant waiting weeks for answers, so governors had to be trusted to act on their own.
12. Model answer: Roads made armies, couriers, tax officials and trade fast and predictable, binding distant provinces to the center and letting Rome answer threats quickly. The cursus publicus gave the emperor news within days instead of weeks. But roads were costly to build and repair, the courier service burdened local towns, and the same highways let invaders move quickly toward Italy in later centuries. The proverb was true in Italy, where the great roads radiated from the city and the Golden Milestone marked Rome as the center, and true in the Middle Ages, when pilgrims came to Rome from everywhere. It was not literally true across the empire, where many roads linked frontier forts, ports and provincial capitals to each other.

2.2 CANALS AND LOCKS

OBJECTIVES

- Explain step by step how a pound lock with miter gates lifts and lowers a boat, and calculate lifts, water used and transit times.
- Tell the stories of Pierre-Paul Riquet's Canal du Midi (1681) and DeWitt Clinton's Erie Canal (1825), naming the geographic problem each one solved.
- Compare freight costs before and after the Erie Canal and explain why the Mohawk Valley route made New York City the leading port of the United States.

Warm-up. Float a bottle cap “boat” in a baking dish with a little water. Set a cake pan with an inch of water on top of a stack of books beside it. Your boat must get from the low dish to the high pan without being lifted by hand. You may use cups of water, a plastic box, and your imagination. Spend five minutes sketching a plan. Keep your sketch; you will compare it with the real answer the Chinese and Europeans found.

Watch. *The Surprising Efficiency of Canal Locks* (Practical Engineering, 10:37).

<https://www.youtube.com/watch?v=SBvclVcesEE>

With How it worked: the physics of a pound lock and why it uses so little water.

Note: Practical Engineering includes a short Patreon thank-you at the end.

KEY TERMS

pound lock

A chamber with gates at both ends in which the water level is raised or lowered so a boat can move between two stretches of canal (pounds) at different heights.

miter gates

A pair of lock gates that meet at an angle pointing upstream, like a shallow V. The higher water pushes them together, so the pressure seals them shut.

lift

The difference in water level between the upper and lower pounds of a lock, which is how far a boat is raised or lowered.

summit level

The highest stretch of a canal that crosses a divide between two river basins. It must be kept full by feeders, because every lockage lets water run down from it.

staircase (flight) of locks

Several locks built one right after another, so that the upper gates of one lock are the lower gates of the next, used to climb a steep slope.

towpath

A path along the bank of a canal on which horses or mules walked as they pulled boats by a rope.

CORE IDEAS

The story. For centuries French kings dreamed of a waterway joining the Atlantic to the Mediterranean, so that ships would not have to sail more than 3,000 km (1,900 miles) around Spain past Gibraltar. The Garonne River already ran from Bordeaux up to Toulouse; the problem was the ridge between Toulouse and the Mediterranean. Any canal over that divide would lose water at every lock, and the summit had no river to refill it. The man who solved it was not a trained engineer but a tax official, Pierre-Paul Riquet, who collected the salt tax in Languedoc and knew the hills of the Montagne Noire from boyhood. He worked out how to gather the streams of those hills into a long feeder channel and lead them to the Seuil de Naurouze, the low saddle where the canal would cross the divide, with a great earthen dam at Saint-Ferréol to store water for the dry summer. Backed by Louis XIV's minister Colbert, he received royal approval in 1666. Some 12,000 workers, men and women, dug for fifteen years. Riquet poured his own fortune into the work and died in October 1680, a few months before the canal opened in May 1681.

How it worked. The Canal du Midi runs about 240 km (150 miles) from Toulouse to the Étang de Thau near the sea, with about 63 locks. Its locks are oval, with curved walls that resist the push of the earth behind them better than straight ones. At Béziers a staircase of eight locks at Fonsérannes lifts boats about 21.5 m (70 ft). Near the same town the builders bored the Malpas tunnel, the first tunnel ever made for a canal. Every one of these locks works the same way. A boat going up enters the lower gates, which are closed behind it. Then the keeper opens small sluices (paddles) in the upper gates, and water from the upper pound flows in until the chamber level matches the upper level. The upper gates open and the boat sails out, perhaps 2 to 4 m (7 to 13 ft) higher. Going down reverses the steps. The **miter gates** meet in a V pointing upstream, so the higher water presses them tighter together; Leonardo da Vinci drew gates of this kind for the canals of Milan around 1500. The pound lock itself is older still: a Chinese official, Qiao Weiyue, built one on the Grand Canal in 984.

The Erie Canal. In the young United States the barrier was the Appalachian chain, which runs from New England almost to Alabama and cut the farms of the Ohio country off from Atlantic ports. Freight from the interior went down the Mississippi to New Orleans or over the mountains by wagon at great cost. But in New York one river breaks through the barrier: the Mohawk, flowing east from the center of the state to the Hudson, offers a low, water-level gap. Governor DeWitt Clinton pushed for a canal from Albany on the Hudson to Buffalo on Lake Erie. Critics mocked "Clinton's Ditch," and Thomas Jefferson, when asked about the plan in 1809, thought it little short of madness for that day. New York paid for it alone after President Madison vetoed federal funds for internal improvements in 1817. Work began at Rome, New York, on July 4, 1817. Self-taught surveyors such as Benjamin Wright and James Geddes laid it out, and Canvass White found a local rock that made cement that hardens under water. Local farmers, contractors and many Irish immigrants dug it with picks, shovels, horses and stump-pullers; in the Montezuma Marshes in 1819 hundreds fell sick with fever. When it opened on October 26, 1825, it was about 363 miles (584 km) long, 40 ft (12 m) wide and 4 ft (1.2 m) deep, with 83 locks raising boats a net 568 ft (173 m) from the

Hudson to Lake Erie, including a famous flight of five double locks up the Niagara Escarpment at Lockport. It cost about \$7 million. On November 4, 1825, Clinton poured a keg of Lake Erie water into the Atlantic off Sandy Hook, the “Wedding of the Waters.”

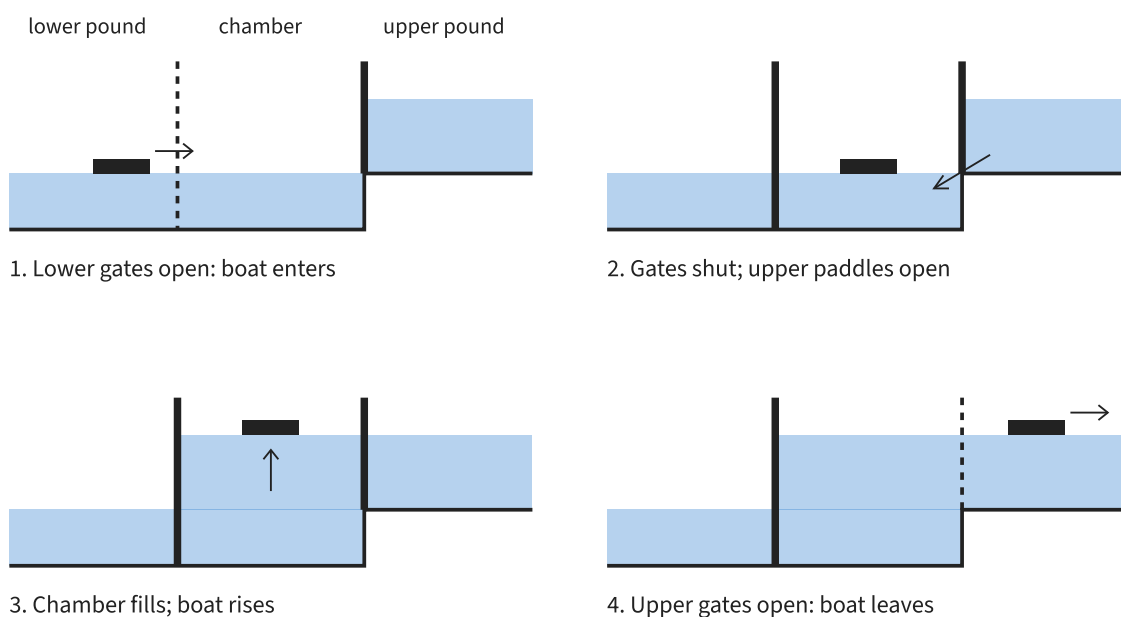
The big idea. Before the canal, moving a ton of goods from Buffalo to New York City cost about \$100. After it opened the cost fell to about \$10 and later less. Flour, grain and lumber poured east; settlers and manufactured goods went west. Towns such as Syracuse, Rochester and Buffalo grew along the line, and New York City, already a good harbor, became the gateway to the whole interior. Its population rose from about 124,000 in 1820 to about 516,000 in 1850. The tolls repaid the state’s debt within about a decade. The geography of the Mohawk gap, turned into an engineered waterway, made New York the “Empire State.” The canal also carried a less happy story: it ran through the old homeland of the Haudenosaunee (Iroquois) nations, much of which had already passed out of their hands through treaties and sales after the Revolution, and the flood of settlers it brought sealed that change.

On the map. Look at the map of the Erie Canal (Figure hc-erie-canal). Notice how the canal follows the Mohawk west from Albany and Schenectady through Utica and Rome, then runs across the lowlands south of Lake Ontario through Syracuse and Rochester to Lockport and Buffalo. Notice what it avoids: the Adirondacks to the north and the Catskills and Allegheny Plateau to the south. The diagram of a lock (Figure hc-lock-steps) shows the four steps of raising a boat. Compare the two canals: Riquet crossed a divide and had to feed the summit; Clinton’s builders climbed mostly in one direction, from the Hudson up to Lake Erie, which itself fed the western end of the canal.

Technology overcoming geography. A lock turns a slope into a staircase of flat water, and flat water is the cheapest road ever made: one horse on a towpath could pull a boat carrying many tons, far more than it could draw in a wagon. But canals have limits that geography still sets. They need a steady water supply, especially at a summit. They freeze in winter (the Erie closed from about December to April). They need gentle ground, and every lock costs time. Within a generation the railroad, which you will study next, could go where water could not and run all winter. Yet canals did not vanish: the Canal du Midi still carries boats, and the enlarged New York State Canal System still links the Hudson to the Great Lakes.



The Erie Canal, 1825: Albany to Buffalo, about 363 miles (584 km).



Solid thick line = gate closed; dashed line = gate open. Schematic, not to scale.

How a pound lock raises a boat in four steps.

PICTURE STUDY



The Erie Canal at Lockport, Unknown engraver; published by Herrmann J. Meyer, New York, about 1855 · Engraving on paper · Print in a private collection; image on Wikimedia Commons

When the builders of the Erie Canal reached Lockport, about twenty miles from Lake Erie, they met a wall of rock: the Niagara Escarpment, a cliff roughly sixty feet high. They climbed it with a staircase of five locks, built side by side in pairs so boats could go up and down at the same time, and beyond the top they blasted a deep channel through solid rock. The town of Lockport grew up around the locks and took its name from them.

This engraving was sold to the public about thirty years after the canal opened in 1825. Look at it the way a geographer would. It shows a technology fitted to its landscape: the rock had to be cut, the water had to be held level, and the lock let boats step up or down from one level to the next.

Look closely

- Find the lock gates in the foreground. How are the men opening them? Notice the long beams they push against.
- Look at the walls of the lock chamber. What are they made of, and why must they be so strong?
- Find the deep gorge beyond the gates. What do you think the builders had to cut through to make it?
- Look for signs that the canal made a town: the hotel, the houses, the crates and barrels, the people waiting. What business might they be about?

Talk about it

1. A canal must be flat between locks, but the land is not. Using this picture, explain how a lock lets a boat climb a hill.
2. Why would a town grow up around a flight of locks, where every boat had to stop?
3. How does this busy scene compare with the hard digging and blasting of the men who built the locks and the deep cut?

Safety first. An adult should do all cutting of plastic with a utility knife or saw and all hot-glue work. Work outdoors or in a bathtub, and wipe up spills at once so no one slips.

PROJECT: A MODEL CANAL LOCK WITH WORKING GATES

This is the main project of the unit. You will build a lock chamber between an upper and a lower pound, fit it with gates that open and close and paddles that let water through, and then work a boat up and down. You will measure the lift and the water used per lockage, the same numbers a real canal engineer must know.

You will need

- A long clear plastic storage box, at least 60 cm (24 in) long, or a 1 m (3 ft) length of vinyl rain gutter with two end caps
- A thin plastic cutting mat or sheet of acrylic or corrugated plastic for walls and gates
- Duct tape (for hinges) and waterproof tape or silicone sealant
- Hot-glue gun (adult use) and craft sticks
- Four wine corks or rubber stoppers and a drill or awl to make paddle holes
- A small foam block or bar of soap for the boat
- A ruler, a measuring cup and a permanent marker

Steps

1. Divide the box into three sections with two cross walls about one third of the way from each end: lower pound, lock chamber, upper pound. The cross walls hold the gates.
2. Make the upper pound's floor higher: glue a sealed plastic shelf or a waterproofed block into the upper third, about 5 cm (2 in) above the box floor, so the upper pound holds water at a higher level.
3. Cut each cross wall with a doorway in the middle. Make two gate leaves for each doorway and hinge them to the wall with duct tape so they swing, meeting in a shallow V that points toward the upper pound.
4. Drill one hole near the bottom of each gate leaf for a paddle and plug it with a cork.
5. Seal the edges with tape or silicone and let it cure. Test for leaks with plain water and fix them.
6. Fill the upper pound to a level 5 cm above the lower pound. Mark both water levels on the outside of the box with the marker.
7. Work the lock upward: open the lower gates and float the boat in; close them; pull the corks in the upper gates and watch the chamber fill; when the levels match, open the upper gates and float the boat out. Then work it downward.

8. Measure the chamber's length and width and the lift. Calculate the volume of water used per lockage (length $\times$ width $\times$ lift) and check it with your measuring cup by catching or adding water.
9. Push on the closed gates from the high side with a finger. Then try to push them from the low side. Write down what you notice about why miter gates point upstream.

Tips

- Petroleum jelly along the gate edges makes a better seal.
- If the gates will not open, the water levels on the two sides are not yet equal. That is exactly what happens on a real canal: the pressure of a few centimeters of water holds the gates shut.
- A large chamber uses a lot of water. If your upper pound runs low, you have discovered the summit-level problem Riquet solved.

Check your work

- My gates swing, meet in a V pointing upstream, and hold back water.
- I can work a boat up and down in the right order.
- I measured the lift and calculated the water used per lockage.
- I can explain why water pressure keeps miter gates closed.

MAP NOTEBOOK

1. Draw the four steps of a lock raising a boat as a comic strip, labeling the upper pound, lower pound, chamber, gates and paddles.
2. On an outline map of New York, draw the Erie Canal and the Hudson. Shade the Adirondacks and the Allegheny Plateau and write one sentence explaining why the canal follows the Mohawk.
3. Sketch a map of southern France showing the Garonne, the Canal du Midi from Toulouse to the Étang de Thau, and the long sea route around Spain it replaced.

From history. The pound lock was invented in China long before Europe. In 984, during the Song dynasty, an official named Qiao Weiyue built a lock with two gates on a section of the Grand Canal, replacing the dangerous double slipways on which boats had been dragged up and down and often damaged or robbed. The idea reached Europe centuries later, where it was improved with Leonardo's miter gates and spread through the canals of Italy, the Low Countries, France and Britain.

WORKED EXAMPLES

Example 1. An original Erie Canal lock chamber was about 90 ft long and 15 ft wide. How much water flows down from the upper pound each time a boat is raised 8 ft? Give the answer in cubic feet, gallons and cubic meters ($1 \text{ ft}^3 \approx 7.48 \text{ gallons} \approx 0.0283 \text{ m}^3$).

(Use the map or drawing “The water in the filled chamber comes from the upper pound.” shown earlier in this lesson.)

1. Volume = length $\times$ width $\times$ lift = $90 \text{ ft} \times 15 \text{ ft} \times 8 \text{ ft} = 10,800 \text{ ft}^3$.
2. Gallons: $10,800 \times 7.48 \approx 80,800$ gallons.
3. Cubic meters: $10,800 \times 0.0283 \approx 306 \text{ m}^3$.
4. This water leaves the upper pound and ends up in the lower pound every time the lock is used, whichever way the boat is going.

Answer: $10,800 \text{ ft}^3$, about 80,800 gallons or about 306 m^3 per lockage.

Example 2. Erie Canal boats were held to about 4 mph to keep their wash from damaging the banks. Suppose a packet boat travels the 363 miles from Albany to Buffalo at 4 mph and spends an average of 15 minutes at each of the 83 locks. About how long is the trip, in hours and days, if it runs day and night?

1. Moving time: $363 \text{ mi} \div 4 \text{ mph} \approx 90.8 \text{ h}$.
2. Lock time: $83 \times 15 \text{ min} = 1,245 \text{ min} \approx 20.8 \text{ h}$.
3. Total: $90.8 + 20.8 \approx 111.6 \text{ h}$.
4. In days: $111.6 \div 24 \approx 4.6$ days.

Answer: About 112 hours, a little over $4\frac{1}{2}$ days.

Example 3. Shipping a ton of goods from Buffalo to New York City cost about \$100 before the canal and about \$10 after. The route is about 363 miles by canal plus about 150 miles down the Hudson. Find the cost per ton-mile before and after, and the percent saved.

1. Total distance: $363 + 150 = 513$ miles (about 826 km).
2. Before: $\$100 \div 513 \approx \0.195 , about $19\frac{1}{2}$ cents per ton-mile.
3. After: $\$10 \div 513 \approx \0.019 , about 2 cents per ton-mile.
4. Percent saved: $(100 - 10) \div 100 = 90\%$.

Answer: About $19\frac{1}{2}$ cents per ton-mile before and about 2 cents after, a saving of 90%.

PRACTICE

1. **EASY** Match each canal with its year of opening and its chief promoter: Canal du Midi, Erie Canal.
2. **EASY** Which way do miter gates point, and why?
3. **EASY** Why does a canal that crosses a divide need a feeder supplying its summit level?
4. **EASY** Put these in order for raising a boat: (a) open upper paddles, (b) boat enters chamber, (c) open upper gates, (d) close lower gates, (e) levels become equal.
5. **MEDIUM** The Fonsérannes staircase has eight locks that together lift boats about 21.5 m. What is the average lift per lock in meters and feet?
6. **MEDIUM** The Erie Canal's 83 locks overcame a net rise of 568 ft. What is the average net rise per lock? Why is this smaller than the lift of a typical lock?
7. **MEDIUM** A lock chamber is 30 m long and 6 m wide with a lift of 2.5 m. How much water does one lockage use, in cubic meters and cubic feet ($1 \text{ m}^3 \approx 35.3 \text{ ft}^3$)?
8. **MEDIUM** Use the map. Which river valley does the Erie Canal follow west from Albany, and which large mountain region lies to the north of that valley?
(Use the map or drawing "The Erie Canal, 1825." shown earlier in this lesson.)
9. **MEDIUM** New York City had about 124,000 people in 1820 and about 516,000 in 1850. By what factor did it grow?
10. **HARD** A feeder brings 0.5 m^3 of water per second (about $17.7 \text{ ft}^3/\text{s}$) to a summit pound. If each lockage uses 450 m^3 , how many lockages a day can the feeder support, ignoring leaks and evaporation?
11. **HARD** Bordeaux to the Mediterranean coast near Sète is about 500 km (310 miles) by the Garonne and the Canal du Midi, compared with more than 3,000 km (1,900 miles) by sea around Spain. About how many times longer is the sea route? Name one reason a merchant in 1690 might still choose the sea.
12. **CHALLENGE** Pennsylvania also tried to link Philadelphia to Pittsburgh with canals, but its route had to cross the Allegheny ridge on a series of inclined-plane railways. In a paragraph, use geography to explain why the Erie Canal was more successful.

COMMON MISTAKES

- Thinking a lock pumps water. A lock uses only gravity: water flows from the upper pound into the chamber, and from the chamber into the lower pound.
- Saying the Erie Canal's locks each lifted 568 ft divided by 83. The net rise was 568 ft, but some locks lowered boats, so individual lifts varied.
- Forgetting that every lockage, up or down, uses a full chamber of water from above. That is why summit water supply decides whether a canal can work.

Make it a game • Lock Keeper's Orders. Write each step of locking a boat up and locking a boat down on separate index cards (enter, close gates, open paddles, levels equal, open gates, leave). Shuffle both sets. Players race to lay out the correct order for "up" and then "down." Then the leader calls out a mistake, such as "open the upper gates

while the chamber is low!", and the first player to explain what would happen (the gates will not open, or a flood rushes in) wins the round.

Scripture. "Behold, I will do a new thing; now it shall spring forth; shall ye not know it? I will even make a way in the wilderness, and rivers in the desert." (Isaiah 43:19, KJV)

Isaiah speaks of God's own saving work, not of canal building. Still, made in His image, people delight to make ways where there were none. A canal builder who leads water to a dry summit is imitating, in a small way, the Creator who gives rivers in the desert.

Practice answers

1. Canal du Midi: 1681, Pierre-Paul Riquet. Erie Canal: 1825, Governor DeWitt Clinton.
2. They meet in a V pointing upstream, toward the higher water. The higher water pushes the two leaves together, so the pressure seals them shut.
3. Every lockage in either direction lets a chamberful of water run down from the summit. Without a feeder, the summit pound would drain and boats could not float.
4. b, d, a, e, c.
5. $21.5 \div 8 \approx 2.7$ m, about 8.8 ft.
6. $568 \div 83 \approx 6.8$ ft (about 2.1 m). Some locks lowered boats where the canal dipped between the Mohawk summit and the climb to Lake Erie, so the total of all lifts was greater than the net rise.
7. $30 \times 6 \times 2.5 = 450$ m³, about 15,900 ft³.
8. The Mohawk Valley; the Adirondack Mountains lie to the north.
9. $516,000 \div 124,000 \approx 4.2$, so it grew more than fourfold.
10. Water per day: $0.5 \times 86,400 \text{ s} = 43,200$ m³. Lockages: $43,200 \div 450 = 96$ a day.
11. $3,000 \div 500 = 6$, so at least six times longer. Reasons for choosing the sea: a seagoing ship can carry much larger cargoes than canal barges; goods would not have to be transferred between river boats and canal boats; the canal charged tolls and closed for repairs or low water.
12. Model answer: The Erie Canal followed the Mohawk Valley, a low gap that breaks through the Appalachian barrier, so it could climb gently with ordinary locks and carry boats all the way from Lake Erie to the Hudson without unloading. Pennsylvania had no such gap. Its route had to climb over the high Allegheny ridge, where canal boats or their cargoes had to be hauled up and down inclined planes, adding cost, time and transfers. Lower costs and an unbroken water route drew the trade of the Great Lakes to New York rather than Philadelphia.

2.3 THE RAILROAD

OBJECTIVES

- Explain why Stephenson's Rocket won the Rainhill Trials of 1829 and why iron wheels on iron rails cut the cost of moving goods over land.
- Calculate speeds, travel times and gradients, and explain why railways need gentle grades and therefore cuttings, embankments, viaducts and tunnels.
- Explain how the railway reshaped geography: standard time, the growth of cities around stations, and the shrinking of travel time shown on isochrone maps.

Warm-up. Tie a rubber band to a heavy book and drag it slowly across a carpet or table, noticing how far the band stretches. Now lay four round pencils under the book like rollers and drag it again. Then set the book on a toy car or skateboard. Compare the stretch each time. The difference you feel is the whole reason for the railway: less friction means one engine, or one horse, can pull far more.

Watch. *Sans Pareil: Rocket's Rainhill Rival | Curator with a Camera* (National Railway Museum, 11:03). <https://www.youtube.com/watch?v=ACPqym3islw>
With the story: Sans Pareil, Rocket's rival at Rainhill, with a curator at the National Railway Museum.

Backup video. *How Stephenson's Rocket Changed The World* (Science Museum, 1:17). <https://www.youtube.com/watch?v=XR4OVtjE3JU>
As review: what made Rocket so important.

KEY TERMS

locomotive

A self-propelled engine that pulls a train. Early locomotives burned coal or wood to boil water and used the steam to push pistons that turned the wheels.

multi-tubular boiler

A boiler in which many small tubes carry hot gases from the fire through the water. More tube surface means more heat reaches the water, so the engine makes steam faster.
Rocket had 25 copper tubes.

blastpipe

A pipe that sends used steam up the chimney in strong puffs, drawing air through the fire and making it burn hotter the harder the engine works.

gauge

The distance between the inner edges of the two rails. Stephenson's gauge of 4 ft 8½ in (1,435 mm) became the standard gauge of Britain, North America and much of the world.

gradient (grade)

The steepness of a track, given as rise over run (1 in 100) or as a percent (1%). The steepest grade on a line, which limits how heavy a train can be, is the ruling grade.

standard time

One agreed clock time for a whole region instead of each town's own sun time. British railways adopted London time in the 1840s; American and Canadian railroads adopted time zones on November 18, 1883.

CORE IDEAS

The story. In October 1829, crowds gathered at Rainhill, a village on the new Liverpool and Manchester Railway, to watch a contest. The railway's directors had not yet decided whether to haul their trains with horses, with fixed steam engines pulling cables, or with moving locomotives, and they offered a prize of £500 for the best locomotive that met their conditions. Several engines ran back and forth over a level test track. Timothy Hackworth's *Sans Pareil* cracked a cylinder. The light, fast *Novelty* of Braithwaite and Ericsson was the crowd's favorite but broke down. Only one engine completed the trials: *Rocket*, built by George Stephenson and his son Robert, with Robert doing much of the design. It hauled its load at an average of about 12 mph and ran alone at nearly 30 mph, an astonishing speed for a machine. The company bought it and ordered more.

How it worked. *Rocket* combined three ideas. Its **multi-tubular boiler** sent the fire's hot gases through 25 copper tubes inside the water, instead of one big flue, so steam came much faster. Its **blastpipe** sent the used steam up the chimney in puffs that drew air through the fire, so the harder the engine worked, the hotter it burned. And its two cylinders drove the wheels directly through rods, with no gears. Just as important was the track. An iron wheel rolling on an iron rail meets very little resistance compared with a cart wheel on a muddy road. Engineers of the day liked to compare loads: a horse that could draw only a ton or two in a wagon on a good road could draw several times as much in a wagon on rails, and far more in a canal boat. But the railway, unlike the canal, could be fast, could run all winter and did not need a water supply at a summit.

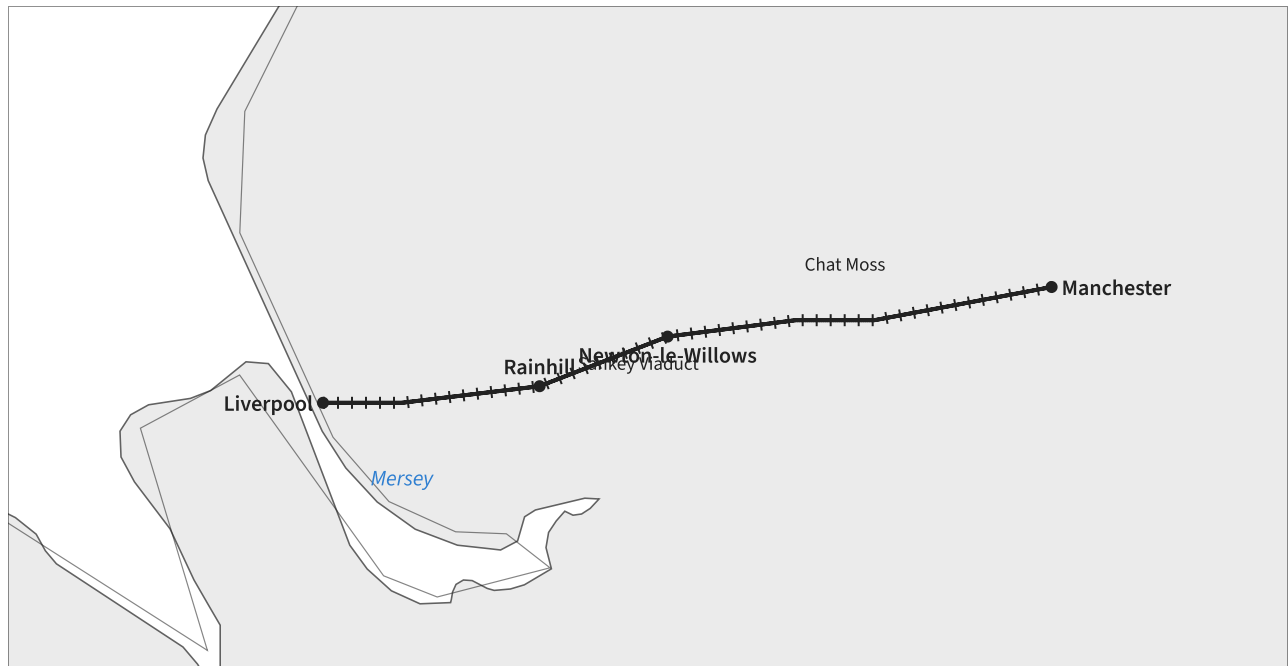
The line and its works. The Liverpool and Manchester Railway linked a great port and a great manufacturing town about 30 miles (50 km) apart. It was the first intercity railway on which all trains, passenger and freight, ran by steam locomotive on a timetable. Building it meant fighting geography. Stephenson floated the line across Chat Moss, a deep peat bog, on mats of brushwood and heather. At Olive Mount near Liverpool, workers cut a narrow trench through solid sandstone, and over the Sankey valley they built a viaduct of nine arches so canal boats could pass beneath. The line opened on September 15, 1830, with the Duke of Wellington aboard, and on that same day William Huskisson, a member of Parliament, was struck and fatally injured by *Rocket*, the first widely reported railway death. Within weeks the line was carrying far more passengers than anyone expected.

The big idea. Railways need gentle grades. A locomotive can pull only as hard as the grip of its driving wheels on the rails allows, and on a steep climb that grip runs out. Main lines were usually built with ruling grades of about 1 percent or less, so engineers spent fortunes on cuttings, embankments, viaducts and tunnels to keep the line nearly level. Once built, the

railway changed everything about distance. Britain built thousands of miles of line in the “railway mania” of the 1840s. In the United States track grew from about 30,000 miles (49,000 km) in 1860 to a peak of about 254,000 miles (409,000 km) in 1916. Cities grew outward along the lines; stations became the new city gates. Speed also changed **time**. Each town had kept its own sun time, and Bristol’s clocks ran about 10 minutes behind London’s. A timetable cannot work that way, so the Great Western Railway adopted London time in 1840, most British railways followed by 1848, and Parliament made Greenwich time the legal time of Great Britain in 1880. In North America the railroads adopted standard time zones on November 18, 1883, a year before the Prime Meridian Conference you studied in Unit 1.

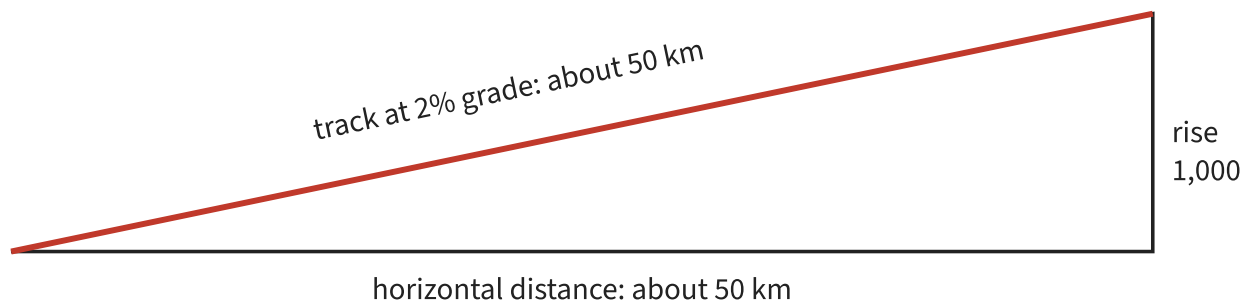
On the map. The best way to see what railways did is an **isochrone map**, a map with lines joining places that can be reached in the same travel time. Charles O. Paullin’s *Atlas of the Historical Geography of the United States* (1932) contains a famous set of such maps, showing how long it took to travel from New York City in 1800, 1830, 1857 and 1930. In 1800 a week’s travel carried a traveler only about as far as the Appalachians; the Ohio country and the Great Lakes were weeks away. By 1857, with railroads across the East, Chicago could be reached in about two days. By 1930 a passenger could cross the whole country by train in about four days. Compare these maps with the map of the Liverpool and Manchester Railway (Figure hc-lmr) and the grade diagram (Figure hc-grade), and notice that the railway shrinks travel time most along the lines themselves: places off the line stay far away.

Technology overcoming geography. Claude Monet’s painting of the Gare Saint-Lazare in Paris shows the railway age at its height, with smoke and steam filling the iron-and-glass shed of the station where trains left for Normandy. Before the railway, a river or a coast decided where a great city could thrive; afterward, a junction on dry land could become a city, as Chicago and Atlanta did. The costs were real: rough and dangerous work for the navvies who dug the cuttings, smoke and noise in the cities, accidents, and the ruin of coaching inns and some canal companies. Some railways were built in speculative booms that ruined investors. But the railway gave ordinary people what only couriers and kings had known before: the power to cross a country in a day or two. It is one of the clearest examples of the creativity God gave people when He told them to fill the earth and subdue it (Genesis 1:28).



The Liverpool and Manchester Railway, opened 1830.

Grade = rise ÷ distance = 1,000 m ÷ 50,000 m = 0.02 = 2%. Height greatly exaggerated.



A 1% grade: 1 m of rise for every 100 m of run (vertical exaggerated).

PICTURE STUDY



Arrival of the Normandy Train, Gare Saint-Lazare, Claude Monet, 1877 · Oil on canvas · Art Institute of Chicago

In early 1877 Claude Monet, one of the founders of Impressionism, rented a small studio near the Gare Saint-Lazare in Paris and obtained permission to paint inside the station. Over a few months he painted about a dozen views of it, and he showed several of them at the third Impressionist exhibition that spring. This one shows a train arriving from Normandy.

Saint-Lazare was the station for the lines to Rouen and Le Havre on the coast of Normandy, and it was the terminus of the first passenger railway in France, the line to Saint-Germain-en-Laye opened in 1837. Monet painted not the engine's machinery but the atmosphere it made: light, smoke, steam and movement under a great roof.

Look closely

- Find the locomotive. How much detail did Monet give it? What did he care about more?
- Look at the roof of the shed. What materials do you think it is made of, and why would a station need such a roof?
- Find the people on the platform. How large are they compared with the train and the station?
- Look at the colors of the steam and smoke. How many colors can you count in what we usually call "gray"?

Talk about it

1. Why might an artist in 1877 find a railway station as worthy a subject as a cathedral or a landscape?
2. What does this painting tell you about how the railway changed the feeling of a city?

3. Compare this scene with John William Hill's quiet Erie Canal from Lesson 2.2. What changed in fifty years?

PROJECT: THE SECRET OF THE RAILWAY WHEEL

Railway wheels are not flat cylinders. Their treads are slightly cone-shaped, wider near the flange on the inside. This lets a fixed axle steer itself around curves and back to the center of the track. You will build two "wheelsets" from cups and test them on a track of rulers, then test how steep a grade a rolling load can climb or hold.

You will need

- Four identical paper or plastic cups with sloping sides
- Tape
- Two yardsticks or meter sticks and a few books
- A toy car or small wheeled toy
- A protractor or a ruler for measuring heights

Steps

1. Tape two cups together rim to rim. This wheelset is fat in the middle and thin at the ends, like two railway wheels joined by an axle (the cone slopes the same way as a real wheel tread).
2. Tape the other two cups together bottom to bottom. This wheelset is thin in the middle and fat at the ends.
3. Lay the two yardsticks side by side on a slight slope (raise one end on a book), as rails about half a cup-length apart.
4. Roll the rim-to-rim wheelset down the rails ten times, starting it a little off center each time. Count how many times it stays on the track.
5. Repeat with the bottom-to-bottom wheelset. Count how many times it stays on.
6. Explain what happens: when the good wheelset drifts to one side, that side rolls on a larger diameter, travels farther per turn and steers it back to the middle.
7. Grade test: set up a smooth board as a ramp. Raise one end until the toy car just begins to roll by itself. Measure the height and length and compute the grade as a percent ($\text{rise} \div \text{run} \times 100$).
8. Write a paragraph on why real railways keep grades low and why the coned wheel matters on curves.

Tips

- If the cups are very light, put a little modeling clay inside each one to make the wheelset steadier.
- Keep the slope gentle at first. The self-centering works best when the wheelset rolls slowly.

Check your work

- I recorded results for both wheelsets and can explain why one stayed on the rails.
- I computed the grade of my ramp as a percent.
- I can explain how a coned wheel helps a train take curves without sliding its wheels.

MAP NOTEBOOK

1. Draw a labeled cutaway of Rocket showing the firebox, the tubes, the water space, the blastpipe and chimney, and the cylinder driving the wheel.
2. Draw an isochrone map of your own town: mark your house, then sketch lines joining places you can reach in 10, 20 and 30 minutes by car or bike. Notice how the lines stretch along main roads.
3. Sketch a railway line crossing a valley in profile: show a cutting through a hill, an embankment, and a viaduct, and label each.

From history. On November 18, 1883, often called “the day of two noons,” railroads across the United States and Canada reset their clocks to standard time zones (four across the United States). In cities in the eastern part of a zone, clocks were set back a few minutes at noon, so the bells struck noon twice. The railroads made the change on their own; Congress did not make standard time zones federal law until the Standard Time Act of 1918.

WORKED EXAMPLES

Example 1. Running alone at Rainhill, Rocket reached about 29 mph. How long would it take to cover a 1.5-mile test section at that speed? Give the speed in km/h too.

1. Time = distance $\div$ speed = $1.5 \text{ mi} \div 29 \text{ mph} \approx 0.0517 \text{ h}$.
2. In minutes: $0.0517 \times 60 \approx 3.1 \text{ minutes}$.
3. Speed in km/h: $29 \times 1.609 \approx 46.7 \text{ km/h}$. The section is $1.5 \times 1.609 \approx 2.4 \text{ km}$.

Answer: About 3.1 minutes; 29 mph is about 47 km/h.

Example 2. A railway must climb 150 m (about 490 ft) to cross a ridge. How many kilometers of track does it need at a ruling grade of 1%? How long would a road at 6% need to be? What does this tell you about railway routes?

(Use the map or drawing “A 1% grade climbs 1 m in 100 m.” shown earlier in this lesson.)

1. Grade = rise $\div$ run, so run = rise $\div$ grade.
2. Railway: $150 \text{ m} \div 0.01 = 15,000 \text{ m} = 15 \text{ km}$ (about 9.3 miles).
3. Road: $150 \text{ m} \div 0.06 = 2,500 \text{ m} = 2.5 \text{ km}$ (about 1.6 miles).
4. The railway needs six times as much distance to make the same climb, so it must wind along valleys, loop around hills or tunnel through them.

Answer: 15 km (9.3 mi) of track at 1%, versus 2.5 km (1.6 mi) of road at 6%. Railways must find long, gentle routes or build cuttings and tunnels.

Example 3. Local sun time changes by 4 minutes for every degree of longitude. Bristol is at about 2.6° W and London at about 0.1° W. Before railway time, how far apart were their clocks, and which was behind?

1. Difference in longitude: $2.6^\circ - 0.1^\circ = 2.5^\circ$.
2. Time difference: $2.5^\circ \times 4 \text{ min per degree} = 10 \text{ minutes}$.
3. The sun rises and crosses the meridian later the farther west a place is, so Bristol, to the west, was behind London.

Answer: About 10 minutes, with Bristol behind London. That is why the Great Western Railway had to choose one time for its timetables.

PRACTICE

1. **EASY** Where and when were the Rainhill Trials held, and which engine won?
2. **EASY** Name two features of Rocket that made it more powerful than earlier engines, and say what each did.
3. **EASY** What is standard gauge in feet and inches and in millimeters?
4. **EASY** Why did railways force towns to adopt a common standard time?
5. **MEDIUM** A trip of 30 miles (48 km) takes a stagecoach averaging 8 mph and a train averaging 20 mph. How much time does the train save?
6. **MEDIUM** A line rises 30 ft in one mile (5,280 ft). What is the grade as a percent? Express the same rise in meters per kilometer.
7. **MEDIUM** New York is at about 74.0° W and Chicago at about 87.6° W. Before standard time, about how many minutes behind New York were Chicago's sun-time clocks?
8. **MEDIUM** U.S. railroad mileage was about 30,600 miles in 1860 and about 254,000 miles in its peak year, 1916. By what factor did it grow? Give both figures in kilometers.

9. **MEDIUM** Use the map. Which end of the Liverpool and Manchester Railway is the port, and in what direction does a train travel from there to Manchester?
(Use the map or drawing “The Liverpool and Manchester Railway.” shown earlier in this lesson.)
10. **HARD** Suppose that in 1857 a rail journey of about 900 miles (1,450 km) from New York to Chicago took 2 days (48 hours), including stops and changes of train. What was the average speed? Why is it much lower than the top speed of the engines?
11. **HARD** The 1883 U.S. time zones were based on meridians 15° apart: 75° W (Eastern), 90° W (Central), 105° W (Mountain), 120° W (Pacific). When standard Eastern time reads 12:00 noon, what is local sun time in Boston (about 71.1° W)?
12. **CHALLENGE** Paullin’s travel-time maps of 1800, 1857 and 1930 show the United States “shrinking.” In a paragraph, explain what that means, why the shrinking was uneven, and one way it changed where people lived and worked.

COMMON MISTAKES

- Saying Stephenson invented the steam locomotive. Richard Trevithick ran a locomotive in Wales in 1804, and others followed; Rocket’s achievement was combining the best ideas into a fast, reliable engine.
- Confusing the Stockton and Darlington Railway (1825, the first public railway to use steam locomotives, though horses also worked it) with the Liverpool and Manchester (1830, the first intercity line run wholly by steam locomotives on a timetable).
- Forgetting that railways need gentle grades. A line cannot simply go “straight over” a hill the way a road can.

Make it a game · Beat the Clock: Railway Time. Give each player a card naming a 19th-century city and its longitude (for example London 0.1° W, Bristol 2.6° W, New York 74.0° W, Chicago 87.6° W, St. Louis 90.2° W, Denver 105.0° W, San Francisco 122.4° W). The leader announces, “It is noon by the sun in London” or “It is noon standard Eastern time.” Each player computes their own sun time or standard zone time and calls it out. The first correct answer scores a point; a wrong answer means you missed your train and sit out one round.

Scripture. “And God blessed them, and God said unto them, Be fruitful, and multiply, and replenish the earth, and subdue it: and have dominion over the fish of the sea, and over the fowl of the air, and over every living thing that moveth upon the earth.” (Genesis 1:28, KJV)

The command to fill and subdue the earth is the root of the whole story of this course. The railway is a striking example of human dominion over distance, given by God, to be used for the good of neighbors and not for pride.

Practice answers

1. At Rainhill on the Liverpool and Manchester Railway, in October 1829. Rocket, built by George and Robert Stephenson, won.

2. The multi-tubular boiler (25 copper tubes carried hot gases through the water, making steam faster) and the blastpipe (exhaust steam up the chimney drew air through the fire). Direct drive from the cylinders to the wheels is also correct.
3. 4 ft 8½ in, or 1,435 mm.
4. Trains ran on timetables across many towns, each with its own sun time. One shared time was needed to avoid confusion, missed connections and accidents.
5. Coach: $30 \div 8 = 3.75$ h. Train: $30 \div 20 = 1.5$ h. Saving: 2.25 h, or 2 hours 15 minutes.
6. $30 \div 5,280 \approx 0.0057$, so about 0.57%. That is about 5.7 m of rise per km.
7. $87.6 - 74.0 = 13.6$; $13.6 \times 4 = 54.4$ minutes, so about 54 minutes behind.
8. $254,000 \div 30,600 \approx 8.3$ times. About 49,200 km in 1860 and about 408,700 km in 1916.
9. Liverpool, on the Mersey estuary near the Irish Sea, is the port. The train travels east to Manchester.
10. $900 \div 48 \approx 18.8$ mph (about 30 km/h). The average includes stops at stations, changes between separate railroad companies, slow running on curves and grades, and waiting for connections.
11. Boston is $75 - 71.1 = 3.9^\circ$ east of the zone meridian, so its sun time is $3.9 \times 4 \approx 15.6$ minutes ahead: about 12:16 p.m.
12. Model answer: The maps draw lines of equal travel time from New York. In 1800 a week's travel reached only about as far as the Appalachians; by 1857 railroads had pulled Chicago within about two days; by 1930 the whole country was within a few days. The country did not get smaller in miles, but in hours, which is what matters for trade, news and settlement. The shrinking was uneven because it followed the rail lines: towns on a main line drew close to New York while places a day's wagon ride off the line stayed remote. As a result, farms, factories and new towns crowded along railroads, junctions like Chicago grew into great cities, and older river and canal towns that the railroad bypassed often declined.

2.4 THE TRANSCONTINENTAL RAILROAD AND THE TRANS-SIBERIAN

OBJECTIVES

- Trace the first transcontinental railroad from Omaha to Sacramento and the Trans-Siberian Railway from Moscow to Vladivostok, naming the main geographic barriers each crossed.
- Explain how each line was paid for and built, and describe honestly the work of Chinese, Irish and other crews and the effect on the peoples whose lands the lines crossed.
- Calculate travel times, speeds, land grants and time-zone differences, and read a historic travel-time (isochrone) map.

Warm-up. With a piece of string and a globe (or a world map), measure the sea route from New York to San Francisco around the tip of South America, then measure the straight overland distance. Compare the two lengths of string. In 1849, gold seekers bound for California had to choose between those two routes, or a shortcut across Panama with its fevers. Which would you have chosen, and why?

Watch. *10th May 1869: ‘Golden Spike’ completes the first transcontinental railroad in the United States* (HistoryPod, 2:38). <https://www.youtube.com/watch?v=RHQMqS54PZc>
With the story: the golden spike at Promontory Summit on May 10, 1869.

Backup video. *Trans-Siberian Railway: The Queen of Railways* (Railways Explained, 14:57). <https://www.youtube.com/watch?v=VazUuBxeb74>
With The Trans-Siberian: how Russia built the longest railway in the world. Note: Runs about 15 minutes. It covers prison labor, Lake Baikal and the war with Japan, and ends with a plug for a travel website.

KEY TERMS

Pacific Railway Act

The law signed by President Lincoln on July 1, 1862, that chartered the Union Pacific and authorized the Central Pacific to build a railroad and telegraph to the Pacific, with government bonds and land grants as aid.

land grant

Public land given to a railroad company along its line, in alternate square-mile sections, which the company could sell to settlers to raise money and fill the country with customers.

Promontory Summit

The place in Utah Territory, north of the Great Salt Lake, where the Central Pacific and Union Pacific tracks were joined on May 10, 1869.

Trans-Siberian Railway

The railway across Russia from Moscow to Vladivostok on the Pacific, begun in 1891. At about 9,289 km (5,772 miles) it is the longest railway line in the world.

isochrone

A line on a map joining places that can be reached in the same amount of travel time from a starting point.

break of gauge

A place where two railways of different track widths meet, so that passengers and freight must change trains. Russia chose a broad gauge of 5 ft (1,524 mm, today 1,520 mm), wider than the standard 4 ft 8½ in.

CORE IDEAS

The story. On May 10, 1869, two locomotives stood face to face on a bare plateau at Promontory Summit, Utah Territory. From the west had come the Central Pacific's *Jupiter*; from the east, the Union Pacific's No. 119. Between them a last tie of polished laurel was laid, and ceremonial spikes, including a golden one, were tapped into place. Then an ordinary iron spike, wired to the telegraph, was struck, and the operator sent one word to a waiting nation: DONE. Cannons fired in San Francisco and bells rang in Philadelphia. The photographer Andrew J. Russell recorded the chief engineers of the two companies shaking hands between the engines. A trip from the Missouri River to California that had taken a wagon train four to six months could now be made in less than a week.

How they built it. The idea was old; the route came from a young engineer, Theodore Judah, who found a way over the Sierra Nevada near Donner Pass and persuaded four Sacramento merchants, Leland Stanford, Collis Huntington, Mark Hopkins and Charles Crocker, to back the Central Pacific. In the middle of the Civil War, Congress passed the Pacific Railway Act, signed by Lincoln on July 1, 1862. The government lent each company bonds for every mile finished, \$16,000 a mile on level ground, \$32,000 in the foothills and \$48,000 in the mountains, and granted it alternate sections of public land along the line (doubled in 1864 to ten sections per mile on each side). The Central Pacific started east from Sacramento in 1863 and faced the hardest geography first: granite ridges, snowdrifts many feet deep, and avalanches. Its Summit Tunnel near Donner Pass, about 1,659 ft (506 m) long, was bored through solid granite with hand drills, black powder and, later, nitroglycerin, from both ends and from a shaft sunk in the middle, sometimes advancing only about a foot a day at each face. The Union Pacific started west from Omaha, raced across the Great Plains, climbed to its high point at Sherman Summit in Wyoming, about 8,200 ft (2,500 m), and descended into Utah.

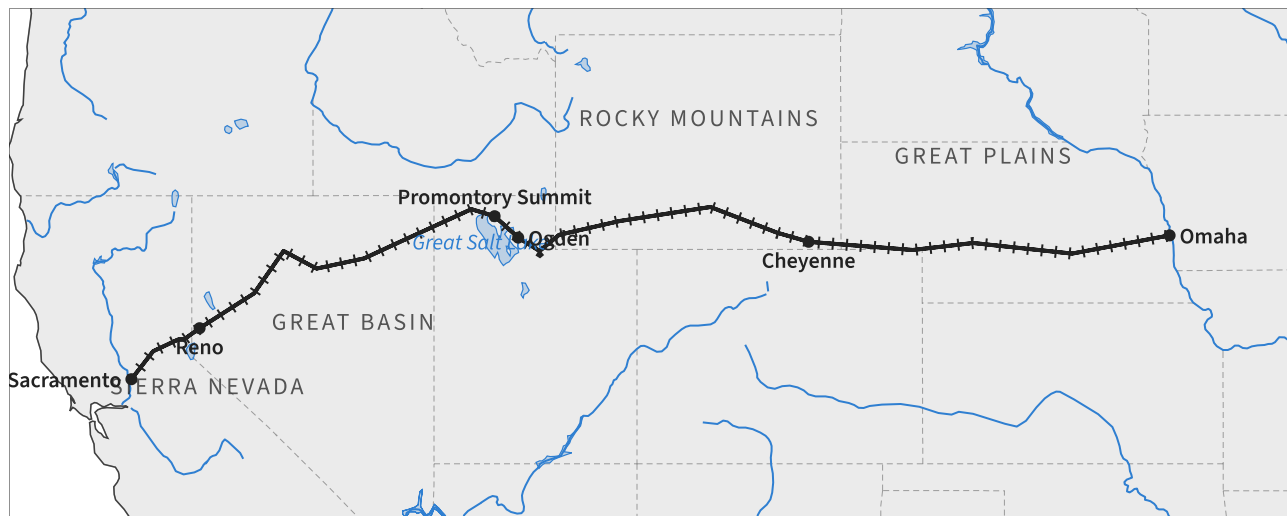
The workers and the land. Labor was scarce in California, and in 1865 the Central Pacific began hiring Chinese immigrants. They proved so capable that by 1867 they made up most of its workforce, perhaps 10,000 or more men. They were paid less than white workers and had to buy their own food; in June 1867 thousands of them struck for equal pay and shorter hours in the tunnels, and the company broke the strike by cutting off their supplies. Many died in blasting accidents and avalanches, and no one kept an exact count. On the Union

Pacific, crews of Irish immigrants and Civil War veterans of both armies laid track at astonishing speed under the brothers Jack and Dan Casement, and Mormon crews graded much of the line in Utah. On April 28, 1869, a Central Pacific crew laid a record 10 miles 56 feet of track in a single day. The line also crossed the hunting lands of the Lakota, Cheyenne, Arapaho and other Plains nations. Some, like Pawnee scouts, worked with the Union Pacific; others fought its advance. Within two decades the railroads had carried hunters and settlers onto the Plains, the great bison herds had been nearly destroyed, and the Plains nations had been confined to reservations, often in violation of treaties. These wrongs belong in the story alongside the achievement.

The Trans-Siberian. Russia faced a far greater distance. Its empire reached the Pacific, but Vladivostok was months away from Moscow by road and river. In May 1891 the heir to the throne, the future Nicholas II, turned the first earth at Vladivostok, and the finance minister Sergei Witte made the line a state project. Builders, including soldiers, convicts and hired laborers, crossed the West Siberian Plain, bridged the Ob, Yenisei and other great rivers, and ran into the mountains around Lake Baikal, where for a time trains crossed the lake by ferry, including the icebreaker *Baikal*, built in England and assembled on the shore. To save distance, the first through route to Vladivostok ran across Manchuria in China on the Chinese Eastern Railway; the line around the southern end of Lake Baikal was finished in 1904, during the Russo-Japanese War, and an all-Russian route along the Amur River was completed in 1916. The main line from Moscow to Vladivostok is about 9,289 km (5,772 miles) long and crosses seven time zones. A railway bridge over the Ob gave birth to a new town, Novonikolayevsk, today Novosibirsk, the largest city in Siberia.

On the map. Compare the two routes on the maps (Figures hc-pacific-railroad and hc-trans-siberian). The American line crossed plains, two mountain systems and the deserts of the Great Basin, but it was only about 1,775 miles (2,860 km) of new track because it joined existing eastern railroads at Omaha. The Russian line was more than three times as long and crossed a frozen, thinly peopled land where in places the ground stays frozen year round. Then turn to Paullin's travel-time maps of 1800, 1857 and 1930. In 1857 the railroads of the East had put the Mississippi within a few days of New York, but California was still weeks away by stagecoach or by sea through Panama. By 1930 the whole country lay within a few days by train.

Technology overcoming geography. Both railroads were built as much to bind a nation together as to make money. The American line tied California, which some feared might drift away during the Civil War, to the Union; the Russian line tied the Pacific coast and the resources of Siberia to Moscow and drew millions of settlers east. Both came at great cost: debt, corruption (the Crédit Mobilier scandal of 1872 exposed how Union Pacific insiders had enriched themselves), and lives. And both changed how thinkers saw the world. In 1904 the British geographer Halford Mackinder argued that railways might give a great land power in the heart of Eurasia a new mobility to rival sea power, an idea you can weigh in the Geopolitics course. Acts 17:26 reminds us that God "hath made of one blood all nations of men": railways brought peoples together, for good and ill, as never before.



The first transcontinental railroad, joined at Promontory Summit on May 10, 1869.



The Trans-Siberian Railway, Moscow to Vladivostok, about 9,289 km (5,772 miles).

PICTURE STUDY



East and West Shaking Hands at Laying of Last Rail, Andrew J. Russell, May 10, 1869 · Photograph, albumen print from a glass-plate negative · Prints survive in several collections; the image is in the public domain

Andrew J. Russell had photographed railroads for the Union army during the Civil War and was hired by the Union Pacific to record its construction. At Promontory Summit he posed the crowd between the two locomotives: the Central Pacific's Jupiter on the left and the Union Pacific's No. 119 on the right. In the center the chief engineers, Samuel S. Montague of the Central Pacific and Grenville M. Dodge of the Union Pacific, shake hands.

The photograph became one of the most famous images of the century. It is also worth noticing who is hard to find in it: the Chinese workers who had built most of the Central Pacific line are scarcely visible, though they had done so much of the work.

Look closely

- Find the two locomotives. How can you tell they came from opposite directions on the same track?
- Find the two men shaking hands in the center. Why do you think the photographer placed them there?
- Look at the men standing on the engines holding up bottles. What mood does the photograph capture?
- Look at the landscape behind the crowd. What does it tell you about the country the railroad crossed?

Talk about it

1. A photograph is a record, but it is also a choice of who stands where. What story did this picture tell the nation in 1869?

2. What story would a photograph of the Central Pacific's Chinese crews in the Sierra snows have told?
3. How does this photograph show "technology overcoming geography"?

PROJECT: REDRAWING PAULLIN'S TRAVEL-TIME MAPS

Charles O. Paullin's 1932 atlas mapped how long it took to travel from New York City at different dates. You will study the 1800, 1857 and 1930 maps in the free digital edition, redraw their isochrone lines on one outline map of the United States in three colors, and measure how the country "shrank."

You will need

- Access to Paullin's atlas online (the University of Richmond's digital edition) or a library copy
- Three printed outline maps of the United States, or one map and two sheets of tracing paper
- Colored pencils in three colors
- A ruler and the map's scale, and a calculator

Steps

1. Find Paullin's "Rates of Travel" maps for 1800, 1857 and 1930. Read the key: what does each band of color or line mean?
2. On your first map (or tracing sheet), redraw the 1800 isochrones from New York in one color, labeling each line with its travel time.
3. On the second, redraw the 1857 isochrones in a second color. On the third, redraw 1930 in a third color.
4. Stack the tracings over one base map, or copy all three sets onto one map, so you can compare them.
5. Choose four cities: for example Pittsburgh, Chicago, New Orleans and San Francisco. Make a table of the travel time to each in 1800, 1857 and 1930.
6. For each city, measure the straight-line distance from New York with the map scale, and compute the average speed of travel in each year (distance ÷ time).
7. Mark the transcontinental railroad of 1869 on your map. Write a paragraph explaining which technologies (roads, canals, steamboats, railroads) moved each set of lines outward, and which places were left behind.

Tips

- Paullin's maps give travel time in days or weeks. Convert everything to days before you compute speeds.
- Straight-line distance is always shorter than the real route, so your average speeds are lower limits of the true travel speeds.

Check your work

- My three sets of isochrones are drawn accurately and labeled with their travel times.
- My table gives the travel times and average speeds for four cities in three years.
- My paragraph names the technologies that shrank travel time and explains why the shrinking was uneven.

MAP NOTEBOOK

1. On an outline map of the United States, draw the Union Pacific and Central Pacific lines, mark Omaha, Cheyenne, Ogden, Promontory Summit, Reno and Sacramento, and shade the Rockies, the Great Basin and the Sierra Nevada.
2. On an outline map of Russia, draw the Trans-Siberian, mark the Urals, the Ob and Yenisei rivers and Lake Baikal, and draw the Chinese Eastern shortcut as a dashed line.
3. Make a T-chart titled “Who Paid the Price?” listing the gains of the transcontinental railroad on one side and its human costs on the other.

From history. The famous golden spike, the “Last Spike,” was made for the ceremony from about \$350 worth of gold and was provided by David Hewes, a San Francisco businessman. It was tapped into a pre-drilled hole in the laurel tie and removed right after the ceremony; it is now kept by Stanford University’s Cantor Arts Center. The spike that actually completed the line was an ordinary iron one.

WORKED EXAMPLES

Example 1. Under the Pacific Railway Act, the government lent \$16,000 per mile on level ground, \$32,000 per mile in the foothills and \$48,000 per mile in the mountains. In a simplified example, a company builds 500 miles of level line, 100 miles of foothills and 150 miles of mountain line. How much would it receive in bonds?

1. Level: $500 \times \$16,000 = \$8,000,000$.
2. Foothills: $100 \times \$32,000 = \$3,200,000$.
3. Mountains: $150 \times \$48,000 = \$7,200,000$.
4. Total: $\$8,000,000 + \$3,200,000 + \$7,200,000 = \$18,400,000$.

Answer: \$18.4 million. The higher mountain rate shows how much more it cost to build where geography was hardest.

Example 2. In 1851 the clipper ship Flying Cloud sailed from New York to San Francisco around Cape Horn in about 89 days, a famous record. After 1869 the trip by rail took about 7 days. By what factor was the trip shortened, and by what percent?

1. Factor: $89 \div 7 \approx 12.7$.
2. Time saved: $89 - 7 = 82$ days.
3. Percent saved: $82 \div 89 \approx 0.92$, or 92%.

Answer: About 13 times faster, a reduction of about 92%, compared with the very best clipper voyage. Ordinary ships took far longer.

Example 3. Moscow keeps UTC+3 and Vladivostok keeps UTC+10. A train leaves Moscow on Monday at 12:00 noon Moscow time and runs 160 hours to Vladivostok, a distance of about 9,289 km. What is the local time and day of arrival, and the average speed?

(Use the map or drawing “Moscow to Vladivostok crosses seven time zones.” shown earlier in this lesson.)

1. 160 hours = 6 days 16 hours.
2. Monday 12:00 + 6 days = Sunday 12:00; + 16 hours = Monday 04:00, Moscow time.
3. Vladivostok is $10 - 3 = 7$ hours ahead: Monday 04:00 + 7 h = Monday 11:00 local time.
4. Average speed: $9,289 \text{ km} \div 160 \text{ h} \approx 58 \text{ km/h}$, about 36 mph.

Answer: It arrives Monday at 11:00 a.m. Vladivostok time, one week later by the calendar, averaging about 58 km/h (36 mph).

PRACTICE

1. **EASY** On what date and at what place were the Central Pacific and Union Pacific joined?
2. **EASY** Which company built east from Sacramento, and which built west from Omaha?
3. **EASY** Name the mountain range the Central Pacific had to cross first and the dry region it crossed afterward.
4. **EASY** Give the two ends of the Trans-Siberian main line, the year construction began, and its length in kilometers and miles.
5. **MEDIUM** On April 28, 1869, a Central Pacific crew laid 10 miles 56 feet of track. Convert this to feet and to kilometers. If rails were 30 ft long, about how many rails were laid (two per length of track)?
6. **MEDIUM** The Summit Tunnel was about 1,659 ft long. If crews worked four faces at once (two ends and both directions from a central shaft), each advancing about 1 ft a day, about how many days of digging would it take? Why did the real job take longer?

7. **MEDIUM** After 1864 a railroad received 20 square-mile sections (10 on each side) per mile of line. A section is 640 acres. How many acres per mile is that, and how many acres for 1,000 miles? Give the second answer in hectares (1 acre $\approx$ 0.405 ha).
8. **MEDIUM** When it is 12:00 noon in Moscow (UTC+3), what time is it in Vladivostok (UTC+10)?
9. **MEDIUM** Use the map. Is Promontory Summit north or south of the Great Salt Lake? In which present-day state is the Sierra Nevada crossing near Donner Pass?
(Use the map or drawing “The first transcontinental railroad.” shown earlier in this lesson.)
10. **HARD** The Union Pacific built about 1,086 miles and the Central Pacific about 690 miles. What fraction of the total did each build? Convert the total to kilometers.
11. **HARD** Suppose a passenger train in 1870 took 4 days (96 hours) from Omaha to Sacramento, about 1,776 miles. What was its average speed in mph and km/h? A wagon train averaged about 15 miles a day. How many days would the wagon need?
12. **CHALLENGE** In a paragraph, compare the American transcontinental railroad and the Trans-Siberian: who built and paid for each, what geography each overcame, and why each government wanted it. Include at least one human cost of each.

COMMON MISTAKES

- Saying the transcontinental railroad ran from coast to coast in 1869. It linked Omaha, already joined to eastern railroads, with Sacramento; a link onward to San Francisco Bay followed later that year.
- Telling the Golden Spike story without the workers who built the line, or telling the workers’ story without the engineering achievement. Both are true.
- Assuming the Trans-Siberian was finished in one piece. The first through route ran across Manchuria, Lake Baikal was crossed by ferry until 1904, and the all-Russian Amur route was finished only in 1916.

Make it a game • Race to Promontory. Lay a long strip of paper on the floor as the route from Sacramento to Omaha, with Promontory marked about 690 squares from the west end and 1,086 from the east (scale it down, for example one square per 50 miles). Two teams, Central Pacific and Union Pacific, take turns answering questions from this lesson. A correct answer lets a team roll a die and lay that many squares of track toward Promontory; the Central Pacific team must answer two questions before moving through the Sierra squares. The first team to reach Promontory sends the telegraph word “DONE” and wins.

Scripture. “And hath made of one blood all nations of men for to dwell on all the face of the earth, and hath determined the times before appointed, and the bounds of their habitation;” (Acts 17:26, KJV)

The series verse speaks to this lesson twice. Railways crossed the bounds of whole continents and brought peoples together; and because all nations are of one blood, the Chinese tunnel worker, the Irish track layer and the Lakota hunter each bore the same dignity before God as the men who posed for the photograph.

Practice answers

1. May 10, 1869, at Promontory Summit, Utah Territory.
2. The Central Pacific built east from Sacramento; the Union Pacific built west from Omaha.
3. The Sierra Nevada, then the Great Basin of Nevada and Utah.
4. Moscow and Vladivostok; begun in 1891; about 9,289 km (5,772 miles).
5. $10 \times 5,280 + 56 = 52,856$ ft, about 16.1 km. $52,856 \div 30 \approx 1,762$ lengths of track, so about 3,524 rails.
6. $1,659 \div 4 \approx 415$ days. The real job took longer because the central shaft first had to be sunk, the shaft faces could not start until it was finished, progress varied with the rock, and winter storms buried the camps.
7. $20 \times 640 = 12,800$ acres per mile. For 1,000 miles: 12,800,000 acres, about 5.2 million hectares.
8. 7 hours later: 7:00 p.m. (19:00).
9. Promontory Summit is north of the Great Salt Lake. Donner Pass is in California.
10. Total 1,776 miles. Union Pacific: $1,086 \div 1,776 \approx 61\%$. Central Pacific: $690 \div 1,776 \approx 39\%$. Total $\approx 2,858$ km.
11. $1,776 \div 96 \approx 18.5$ mph (about 29.8 km/h). Wagon: $1,776 \div 15 \approx 118$ days, about four months.
12. Model answer: The American line was built by two private companies, the Central Pacific and Union Pacific, with large government aid in bonds and land grants; the Trans-Siberian was a state project of the Russian government under Witte. The American builders crossed the Great Plains, the Rockies, the Great Basin and the Sierra Nevada, with the Sierra's granite and snow the hardest obstacle; the Russian builders crossed a far longer distance of plains, great rivers, permafrost and the mountains around Lake Baikal, and at first took a shortcut through Manchuria. Both governments wanted to bind distant Pacific lands to the capital, move troops and settlers, and develop resources. Human costs included the dangerous, underpaid work of Chinese crews in the Sierra and the loss of land and the bison for the Plains nations in America, and in Russia the hard labor of soldiers and convicts and enormous public expense.

2.5 TUNNELS AND BRIDGES

OBJECTIVES

- Explain how engineers carried railways through the Alps at the Gotthard, across the Firth of Forth on a cantilever bridge, and under the Strait of Dover in the Channel Tunnel.
- Use grades, lengths, rates of advance, thermal expansion and travel times to reason quantitatively about tunnels and bridges.
- Weigh the costs of these works in money and lives, and explain what the Tay Bridge disaster teaches about humility in engineering.

Warm-up. Take five identical books (or decks of cards). Stack them at the edge of a table so the top one sticks out as far as possible past the edge without the stack falling. Measure the overhang. Then try to beat it. You have just built a cantilever: a structure that reaches out over empty space because its weight is balanced back over a support. Keep your best overhang measurement for the end of the lesson.

Watch. *Forth Bridges: Spanning Three Centuries of Engineering Innovation* (The B1M, 7:37). <https://www.youtube.com/watch?v=tgeFKVX2C-o>
With How it worked: the Forth Bridge and its two newer neighbors.

Backup video. *History of The Spiral Tunnels* (History of British Columbia, 11:31). <https://www.youtube.com/watch?v=Wci2LRZyqSk>
With The Gotthard: how spiral tunnels let trains climb, shown on Canada's Kicking Horse Pass. Note: The spiral tunnels in this video are in Canada; they work the same way as the spirals on the Gotthard line.

KEY TERMS

cantilever

A beam or framework fixed and balanced at one end or over a support, reaching out over empty space without a support at its far end. A cantilever bridge joins arms reaching out from piers, often with a short suspended span between their tips.

compression and tension

Compression is a pushing force that squeezes a member; tension is a pulling force that stretches it. In the Forth Bridge, great steel tubes carry compression and lattice girders carry tension.

spiral (helical) tunnel

A tunnel that turns in a loop inside a mountain so a railway can gain height while keeping a gentle grade. The Gotthard line uses several.

base tunnel

A long tunnel bored near the level of the valley floors on each side of a mountain range, so trains cross it nearly flat instead of climbing to a high summit tunnel.

tunnel boring machine (TBM)

A huge machine with a rotating cutting head that grinds through rock or soil, removes the spoil and lines the tunnel behind it as it advances.

chalk marl

A soft layer of chalky clay beneath the Strait of Dover. It is easy to cut and holds back water fairly well, so the Channel Tunnel was bored within it.

CORE IDEAS

The story. On the stormy night of December 28, 1879, a train crossing the new Tay Bridge at Dundee in Scotland plunged into the river when the central girders collapsed in a gale. Everyone aboard died; the count given at the time was 75, though later research has identified 59 victims. The inquiry found that the bridge had been badly designed, badly built and badly maintained, and that its designer, Sir Thomas Bouch, had made too little allowance for the force of the wind. Bouch had also been chosen to bridge the much wider Firth of Forth, near Edinburgh, with a suspension bridge. That plan was dropped. The new design came from Sir John Fowler and Benjamin Baker, and it was built by William Arrol's company to be, above all, unmistakably strong. When the Prince of Wales drove the last rivet on March 4, 1890, the Forth Bridge was the longest-spanning bridge in the world.

How it worked. The Forth Bridge is a **cantilever** bridge. Three great double cantilevers stand on piers, one on each shore and one on the island of Inchgarvie in the middle. From each, steel arms reach outward over the water, balanced against each other, and short suspended spans join the tips of neighboring arms. The two main spans are each about 521 m (1,710 ft), and the whole structure is about 2.5 km (1.5 miles) long, carrying the tracks about 46 m (150 ft) above high water so tall ships can pass beneath. The bottom members are huge steel tubes about 3.7 m (12 ft) across, which carry **compression**; the upper members are open lattice girders, which carry **tension**. After the Tay disaster, Baker designed the bridge to resist a wind pressure of 56 pounds per square foot, far more than earlier bridges. To explain the idea to the public, he staged a famous demonstration: two men sat on chairs with their arms holding out wooden poles, a third man sat on a short board slung between the poles' tips, and weights at the outer ends balanced the load. The man in the middle was Kaichi Watanabe, a young Japanese engineer who had studied at Glasgow.

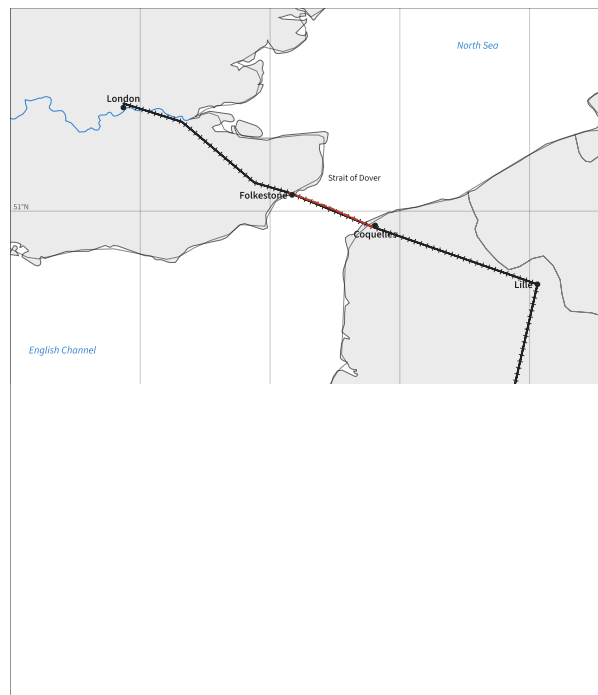
The Gotthard. The Alps are the great wall between northern Europe and Italy. The Gotthard Pass had been a key mule and carriage route for centuries, but no railway could climb it. Between 1872 and 1882 the Gotthard Railway was built from Lucerne to the Ticino valley, with a summit tunnel about 15 km (9.3 miles) long between Göschenen and Airolo, then the longest in the world. Its engineer, Louis Favre of Geneva, used Alfred Nobel's new dynamite and drills driven by compressed air from water turbines. The work was brutally hard: heat, water bursting from the rock, bad air, and an outbreak of hookworm disease among the miners that alerted doctors across Europe. In July 1875 striking workers at Göschenen were fired on by a local militia and four were killed. Officially 199 workers died in building the

tunnel, most of them Italians, and Favre himself died of a heart attack inside it in 1879, months before the two headings met in February 1880. To reach the tunnel at a gentle grade, the line climbs the steep valleys on each side through spiral tunnels, so that near the village of Wassen a traveler sees the same church three times from three levels of track. In 2016 Switzerland opened the Gotthard Base Tunnel, about 57 km (35.4 miles) long, the longest railway tunnel in the world, which passes beneath the mountains almost flat.

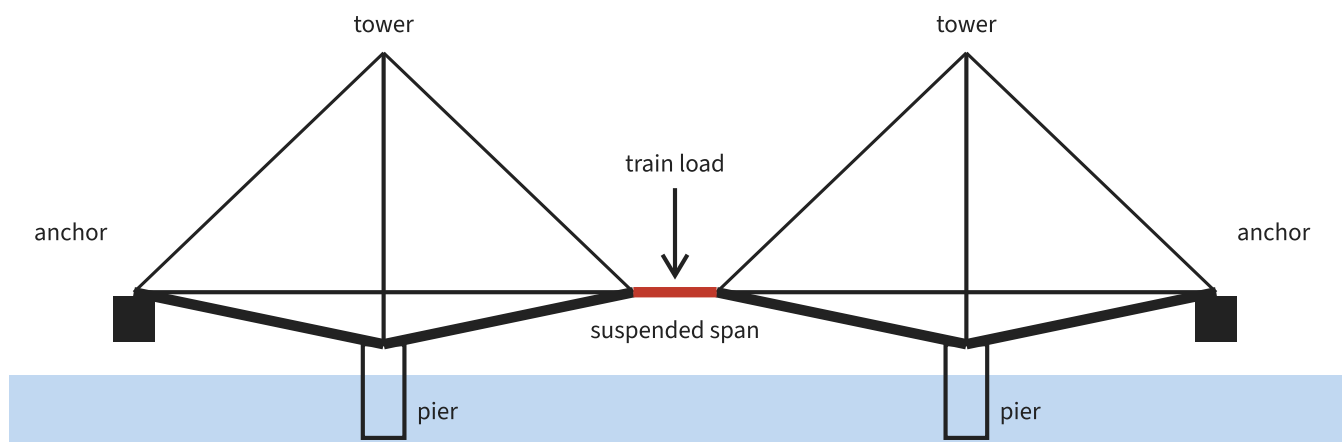
The Channel Tunnel. Britain is an island, and for centuries the Strait of Dover, only about 33 km (21 miles) wide at its narrowest, was both its moat and its barrier to trade. Plans for a tunnel were drawn up as early as 1802, and digging actually began in the 1880s before the British government stopped it, partly from fear that an enemy army could use it. The project was finally built by private companies between 1988 and 1994. Geologists found a layer of chalk marl running beneath the strait, soft enough to cut and tight enough to keep the sea out, and tunnel boring machines followed it from both sides. Two railway tunnels and a central service tunnel run about 50.5 km (31.4 miles) from near Folkestone in Kent to Coquelles near Calais, about 38 km (23.6 miles) of it under the sea, at depths up to about 75 m (250 ft) below sea level. On December 1, 1990, English and French workers met in the service tunnel and shook hands through the opening. Queen Elizabeth II and President François Mitterrand opened the tunnel on May 6, 1994. It cost far more than planned, but today trains run from London to Paris in a little over two hours.

On the map. Find the Channel Tunnel on the map (Figure hc-channel-tunnel) and notice how short the gap is compared with the length of the coast. Then study the cantilever diagram (Figure hc-cantilever) and trace how the train's weight passes from the suspended span into the arms, down the tubes to the piers, and into the ground. On a map of Switzerland, find Lucerne, the Gotthard Pass and Lugano; on a map of Scotland, find Edinburgh, the Firth of Forth and the Tay at Dundee. Before the Forth Bridge, trains between Edinburgh and the north had to go far inland around the firth or cross by train ferry.

Technology overcoming geography. Tunnels and bridges are the most permanent answers people have given to mountains and water: the Forth Bridge still carries trains well over a century after it opened. But they show the limits too. Each one cost lives, and each one had to be built where geology allowed, through chalk marl, granite or solid rock, not wherever a straight line would be shortest. The Tay disaster is a warning that runs through this whole course. At Babel men said "let us make us a name" (Genesis 11:4), and their tower failed. Good engineering is not timid, but it is humble: it respects the wind, the water and the weight of what it carries, and it tests its pride against the facts of the world God made.



The Channel Tunnel, opened 1994, and the London-Paris rail route.



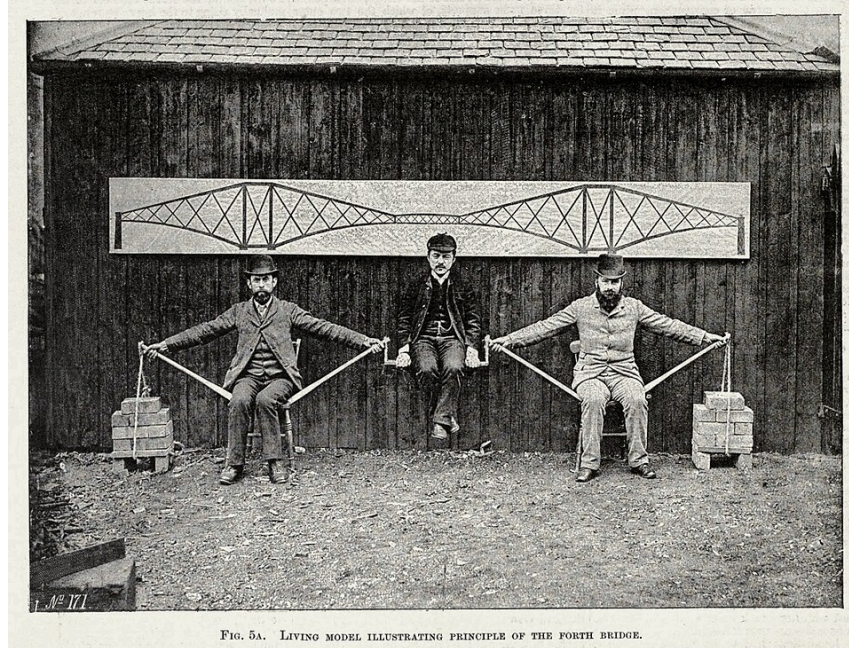
— compression (steel tubes)

— tension (lattice ties)

Schematic, not to scale. The Forth Bridge has three such double cantilevers and two suspended spans.

How a cantilever bridge carries a load (schematic, not to scale).

PICTURE STUDY



The “human cantilever” demonstration of the Forth Bridge principle, Photographer unknown, for the engineers Sir John Fowler and Benjamin Baker, 1887 · Photograph · Reproduced in many books and archives; public domain

Benjamin Baker wanted ordinary people to understand how his strange-looking bridge could stand. In this photograph two men sit on chairs, which stand for the piers. Their arms are in tension, pulling like the lattice ties, and the sticks pressing against the chairs are in compression, pushing like the great steel tubes. The board between the stick tips is the suspended span, and the man sitting on it is the load. Weights at the outer ends are the anchors that keep the arms from tipping inward.

The man in the middle is Kaichi Watanabe, one of the first Japanese engineers trained in Britain. He later returned to Japan, where the country was building its own railways and bridges.

Look closely

- Find the two “piers.” What are they made of in the photograph?
- Find the parts in compression and the parts in tension. How can you tell which is which?
- Find the anchor weights. What would happen if someone took them away?
- Look at the faces of the men. Does the demonstration look comfortable? Why might that help an audience remember it?

Talk about it

1. Why do you think Baker used people instead of a model for this demonstration?

2. After the Tay disaster, why would it matter so much to convince the public that the new bridge was safe?
3. Where else in daily life do you see a cantilever (a diving board, a balcony, a shelf, a crane)?

Safety first. Do the tabletop model only, not a human version with someone sitting on the span. Keep the anchor weights low and away from toes, and have an adult help with any cutting.

PROJECT: BUILD AND LOAD A CANTILEVER BRIDGE

You will build a small model of the Forth Bridge principle with books, rulers, string and pencils, then load the suspended span with coins until something gives way. You will see compression and tension at work and discover why anchors matter.

You will need

- Two equal stacks of heavy books to serve as piers
- Four 30 cm (12 in) rulers or paint stirrers for the cantilever arms
- Strong string and tape
- Two pencils for compression struts
- A strip of stiff cardboard about 10 cm (4 in) long for the suspended span
- A paper cup and a supply of coins or washers
- Two small bags of rice or sand as anchor weights
- A ruler and a notebook

Steps

1. Set the two book piers about 50 cm (20 in) apart on a table or floor.
2. On top of each pier, tape two rulers end to end so that one reaches inward toward the other pier and one reaches outward. These are the cantilever arms.
3. Tie a string from the tip of each inward arm up over a pencil standing on the pier (like a tower) and down to the tip of the outward arm. Hang an anchor bag from each outward tip.
4. Lay the cardboard strip across the gap between the two inward tips as the suspended span. Tape it lightly so it rests on the tips.
5. Hang or set the paper cup in the middle of the span. Add coins one at a time and record the number of coins when the arms begin to droop and when the bridge fails.
6. Remove the anchor bags and test again. Record what happens.
7. Draw your bridge and mark each string in tension (T) and each pencil or ruler in compression (C).
8. Write a paragraph comparing your model with the Forth Bridge and with Baker's human cantilever.

Tips

- Measure the droop of the span with a ruler held upright beside it after every five coins; a graph of coins against droop makes a fine record.
- If your bridge fails at once, shorten the inward arms. Longer arms put more turning force on the piers, which is why the Forth Bridge's arms are so deep where they meet the towers.

Check your work

- My cantilever bridge stands and carries a measured load.
- I recorded the load at first droop and at failure, with and without anchors.
- I can point to the members in tension and in compression and explain what the anchors do.

MAP NOTEBOOK

1. Draw the Forth Bridge in side view: three double cantilevers, two suspended spans and the piers. Label the Fife and Queensferry shores and Inchgarvie.
2. Draw a cross-section of the Strait of Dover showing the sea, the seabed, the chalk marl layer and the three tunnels within it.
3. Sketch a mountain with a railway climbing it through a spiral tunnel, and beside it the same mountain with a base tunnel. Label the summit tunnel, the spiral and the base tunnel.

From history. Before the Forth Bridge, railway passengers and goods crossed the Firth of Forth on ferries. In 1850 a line between Granton, near Edinburgh, and Burntisland in Fife began carrying loaded freight wagons across on a specially built ferry, the Leviathan, one of the first train ferries in the world. The young engineer in charge of the line and its loading arrangements was Thomas Bouch, whose Tay Bridge later failed; his ferry was in the end made unnecessary by the bridge that replaced his own Forth design.

WORKED EXAMPLES

Example 1. On the north side of the Gotthard, the line climbs from Erstfeld (about 470 m above sea level) to the summit tunnel portal at Göschenen (about 1,100 m). At an average grade of 2.6%, how much track is needed for the climb? The two towns are only about 17 km (11 miles) apart in a straight line. What does this tell you?

1. Rise: $1,100 - 470 = 630$ m (about 2,070 ft).
2. Track needed: $630 \text{ m} \div 0.026 \approx 24,200 \text{ m} \approx 24 \text{ km}$ (about 15 miles).
3. Compare: 24 km of track must fit between towns only about 17 km apart.
4. The extra length is gained by curving along the valley sides and looping through spiral tunnels.

Answer: About 24 km (15 miles) of track, roughly 7 km more than the straight-line distance, which is why the line winds and uses spiral tunnels.

Example 2. Steel expands by about 12 millionths of its length for each degree Celsius it warms. The Forth Bridge is about 2,500 m long. How much longer does the steel become between a cold winter night and a warm summer afternoon 30 °C warmer? Give the answer in meters and feet.

1. Change in length = original length $\times$ expansion rate $\times$ temperature change.
2. $= 2,500 \text{ m} \times 0.000012 \times 30 = 0.9 \text{ m}$.
3. In feet: $0.9 \times 3.281 \approx 3.0 \text{ ft}$.
4. Engineers allow for this with sliding bearings and expansion joints, so the steel can move without cracking the piers.

Answer: About 0.9 m, or about 3 ft, spread across the bridge's joints and bearings.

Example 3. Eurostar trains run through the Channel Tunnel at about 160 km/h (about 100 mph). How long does a train take to pass through the whole tunnel (about 50.5 km) and through the undersea part (about 38 km)?

(Use the map or drawing "The Channel Tunnel from Folkestone to Coquelles." shown earlier in this lesson.)

1. Whole tunnel: $50.5 \text{ km} \div 160 \text{ km/h} \approx 0.316 \text{ h}$.
2. In minutes: $0.316 \times 60 \approx 19$ minutes.
3. Undersea part: $38 \div 160 \approx 0.2375 \text{ h} \approx 14$ minutes.
4. Check in miles: $31.4 \text{ mi} \div 100 \text{ mph} \approx 0.31 \text{ h} \approx 19$ minutes.

Answer: About 19 minutes for the whole tunnel, about 14 of them under the sea.

PRACTICE

1. **EASY** Give the opening year of the Gotthard Railway, the Forth Bridge and the Channel Tunnel.
2. **EASY** What is a cantilever? Give one everyday example.
3. **EASY** How did the Tay Bridge disaster of 1879 shape the design of the Forth Bridge?
4. **EASY** Why was the Channel Tunnel bored through the chalk marl layer?
5. **MEDIUM** The Gotthard Base Tunnel is about 57 km long and the old summit tunnel about 15 km. Give both in miles, and say how many times longer the base tunnel is.
6. **MEDIUM** The old Gotthard summit tunnel reaches about 1,150 m above sea level, and the base tunnel's highest point is about 550 m. How much less must a train climb using the base tunnel, in meters and feet?
7. **MEDIUM** Each main span of the Forth Bridge is about 521 m. Convert to feet. The railway runs about 46 m above high water: how many feet is that?
8. **MEDIUM** The Channel Tunnel is about 50.5 km long, with about 38 km under the sea. What percent is under the sea? Give both lengths in miles.
9. **MEDIUM** Use the map. In what general direction does a train travel from Folkestone to Coquelles? Which body of water does it pass beneath?
(Use the map or drawing "The Channel Tunnel." shown earlier in this lesson.)
10. **HARD** A spiral tunnel 1,500 m long is built at a grade of 2.6%. How much height does a train gain inside it? If the line needs 630 m of climbing in all, what fraction of the climb does one spiral provide?
11. **HARD** Using the expansion rate of steel (12 millionths per °C), how much does one 521 m main span of the Forth Bridge lengthen when it warms by 40 °C? Give the answer in centimeters and inches.
12. **CHALLENGE** Write a paragraph comparing the Tay Bridge and the Forth Bridge with the story of Babel (Genesis 11). What is the difference between bold confidence and pride in engineering?

COMMON MISTAKES

- Confusing the Forth Bridge (the railway cantilever bridge of 1890) with the Forth Road Bridge (a suspension bridge of 1964) or the Queensferry Crossing (2017) beside it.
- Thinking a longer tunnel is always worse. A long base tunnel lets trains run almost flat, saving the climb, the spirals and much time.
- Mixing up compression and tension. Ask whether the member is being squeezed (compression) or stretched (tension).

Make it a game • Tension or Compression? One player acts out a structure with their body or with household things (pushing palms together, pulling a rope, holding a broom out level, leaning on a wall). The others call "Tension!" or "Compression!" and point to where the force is. Then take turns naming a real bridge or tunnel from this unit and one geographic barrier it overcame: the first to name a correct pair scores. Finish with the

warm-up book stack: whoever achieves the longest measured overhang wins a bonus point.

Scripture. “And they said, Go to, let us build us a city and a tower, whose top may reach unto heaven; and let us make us a name, lest we be scattered abroad upon the face of the whole earth.” (Genesis 11:4, KJV)

The sin of Babel was not building but the pride that wanted a name apart from God. The Forth Bridge and the Gotthard are wonders of the creativity God gave people; the Tay Bridge reminds us that our works must answer to the wind, the water and the truth.

Practice answers

1. Gotthard Railway: 1882. Forth Bridge: 1890. Channel Tunnel: 1994.
2. A structure fixed or balanced at one end or over a support that reaches out over empty space with no support at its far end. Examples: a diving board, a balcony, a wall shelf.
3. The Tay Bridge fell in a gale partly because too little allowance was made for wind. Bouch's Forth design was dropped, and Fowler and Baker designed the Forth Bridge to resist a far greater wind pressure and to look and be unmistakably strong.
4. Chalk marl is soft enough for tunnel boring machines to cut easily but tight enough to hold back much of the seawater.
5. $57 \text{ km} \approx 35.4 \text{ miles}$; $15 \text{ km} \approx 9.3 \text{ miles}$. $57 \div 15 = 3.8$ times longer.
6. $1,150 - 550 = 600 \text{ m}$, about 1,970 ft.
7. $521 \times 3.281 \approx 1,709 \text{ ft}$ (usually given as 1,710 ft). $46 \times 3.281 \approx 151 \text{ ft}$ (about 150 ft).
8. $38 \div 50.5 \approx 75\%$. $50.5 \text{ km} \approx 31.4 \text{ miles}$; $38 \text{ km} \approx 23.6 \text{ miles}$.
9. East-southeast (roughly southeast). It passes beneath the Strait of Dover, where the English Channel meets the North Sea.
10. $1,500 \times 0.026 = 39 \text{ m}$ (about 128 ft). $39 \div 630 \approx 0.062$, about 6% of the climb.
11. $521 \times 0.000012 \times 40 \approx 0.25 \text{ m} = 25 \text{ cm}$, about 9.8 in (roughly 10 in).
12. Model answer: The builders of Babel wanted to “make us a name,” trusting their own power and ignoring God, and their project failed. The Tay Bridge was built quickly and cheaply, with too little respect for the wind and careless workmanship, and it fell. The Forth Bridge was just as bold, the longest span in the world, but its designers studied the failure, tested their assumptions, allowed generously for wind and weight, and explained their reasoning openly to the public. Bold confidence attempts great things while respecting the facts of creation and the limits of human knowledge; pride attempts great things to exalt the builder and refuses to be corrected by those facts.

UNIT 2 TEST

Answer each question. Show your work for every calculation, give units, and give both metric and U.S. customary units where asked. Use complete sentences for explanations. The test is worth 100 points.

1. (5 pts) A Roman route list gives a distance of 120 Roman miles between two towns. Using 1 Roman mile $\approx$ 1.48 km, give the distance in kilometers and in modern miles.
2. (7 pts) What was the *cursus publicus*? Name its founder, describe how it moved messages, and explain why “All roads lead to Rome” should not be quoted as a Roman saying.
3. (7 pts) A Roman road is 5.0 m (about 16 ft) wide, and its crown is 10 cm (about 4 in) higher than its edges. Find the cross slope from the crown to an edge as a percent, and explain what the crown and side ditches are for.
4. (7 pts) List in order the steps for lowering a boat through a pound lock, starting with the boat waiting in the upper pound and the chamber full.
5. (8 pts) A lock chamber is 100 ft long and 18 ft wide, with a lift of 10 ft. How much water does one lockage use in cubic feet, gallons (1 ft³ $\approx$ 7.48 gal) and cubic meters (1 ft³ $\approx$ 0.0283 m³)? Why must a summit level have a feeder?
6. (7 pts) Explain why the Erie Canal could be built across New York when no similar canal crossed the Appalachians farther south, and name two results of its opening in 1825.
7. (7 pts) Why did Rocket win the Rainhill Trials of 1829? Name two features of its design and explain what each did.
8. (7 pts) A railway must climb 200 m (about 660 ft) with a ruling grade of 0.8%. How many kilometers and miles of track are needed for the climb? Name two kinds of engineering work builders use to keep grades this low.
9. (8 pts) Philadelphia is at about 75.2° W and Pittsburgh at about 80.0° W. Before standard time, how many minutes apart were their sun-time clocks, and which was behind? Why did railroads adopt standard time zones in 1883?
10. (7 pts) Give the date and place where the first transcontinental railroad was joined, the two companies and their starting cities, and the hardest geographic barrier the Central Pacific faced.
11. (7 pts) Moscow keeps UTC+3, Irkutsk UTC+8 and Vladivostok UTC+10. When it is 8:00 a.m. in Moscow, what time is it in Irkutsk and in Vladivostok? About how long is the Trans-Siberian main line in kilometers and miles?
12. (8 pts) Before the railroad, the Butterfield Overland Mail stagecoaches of 1858 carried mail and passengers about 2,800 miles (about 4,500 km) from Missouri to San Francisco in about 24 days. Find the average distance per day and the average speed in mph if the coaches ran day and night. Then explain what an isochrone map is and what Paullin’s maps of 1800, 1857 and 1930 show.
13. (7 pts) Explain how the Forth Bridge carries a train across the firth. Use the words cantilever, compression, tension and suspended span, and explain how the Tay Bridge disaster of 1879 influenced its design.

14. (8 pts) A train passes through the whole Channel Tunnel, about 50.5 km (31.4 miles), in 20 minutes. What is its average speed in km/h and mph? Give one reason the tunnel was bored through the chalk marl layer and one reason Britain long hesitated to build it.

UNIT PROJECT: MASTERING THE LAND: A WORKING LOCK AND A TRAVEL-TIME ATLAS

Present your model canal lock with working gates (Lesson 2.2). Demonstrate it raising and lowering a boat, and attach a data sheet giving the chamber's length, width and lift, the water used per lockage, and how long one lockage takes. Beside it, present your travel-time atlas: Paullin's 1800, 1857 and 1930 isochrones from New York redrawn in three colors on one map of the United States, with the Erie Canal and the first transcontinental railroad drawn in and a table of travel times and average speeds to four cities.

Finish with a one-page essay answering the four questions of this course for one breakthrough from the unit (a road, canal, railway, tunnel or bridge): What problem did geography pose? How did the technology solve it? What did it cost, including in human lives? What changed in the world?

- **Working model:** The lock's gates swing, seal and are worked in the correct order; the boat rises and falls; the measurements and water calculations are correct and clearly recorded.
- **Accurate maps:** The three sets of isochrones are faithfully redrawn and labeled; the canal and railroad are placed correctly; the table of times and speeds is complete and correctly computed.
- **Geographic reasoning:** The essay explains clearly how the technology changed the cost of crossing a real landform, and why its benefits fell unevenly across places.
- **Honesty and care:** The essay names real costs and real people fairly and without exaggeration, and the whole portfolio is neat, accurate and easy to follow.

Answer key

1. $120 \times 1.48 = 177.6$ km, about 178 km; $177.6 \div 1.609 \approx 110$ miles.
2. It was the state courier and transport service of the Roman Empire, founded by Augustus. Official couriers with permits used animals and vehicles kept at changing stations (mutationes) and overnight stations (mansiones) along the main roads; Suetonius says Augustus first used relays of young runners and then vehicles so one messenger could carry a dispatch the whole way and be questioned. The proverb is medieval; a twelfth-century Latin form is credited to Alain de Lille, so it does not come from the Romans.
3. Run = 2.5 m; slope = $0.10 \div 2.5 = 0.04 = 4\%$. The crown sheds rain to the sides and the ditches carry it away, so water does not soak and weaken the roadbed.
4. Open the upper gates; the boat enters the chamber; close the upper gates; open the paddles in the lower gates; water drains until the chamber level equals the lower pound; open the lower gates; the boat leaves.
5. $100 \times 18 \times 10 = 18,000$ ft³ $\approx 134,600$ gallons ≈ 509 m³. Each lockage in either direction drains a chamberful from the summit pound, so without a feeder the summit would run dry.

6. The Mohawk Valley offers a low, water-level gap through the Appalachian barrier, so the canal could climb gently with ordinary locks from the Hudson to Lake Erie. Results: freight costs from Buffalo to New York City fell from about \$100 a ton to about \$10; New York City became the leading U.S. port and grew rapidly; towns such as Syracuse, Rochester and Buffalo grew; settlement of the Great Lakes region sped up.
7. It was the only engine to complete the trials, hauling its load reliably at an average of about 12 mph and running alone at nearly 30 mph. Features: the multi-tubular boiler (25 copper tubes carried hot gases through the water, raising steam faster); the blastpipe (exhaust steam up the chimney drew air through the fire); direct drive from the cylinders to the wheels.
8. $200 \div 0.008 = 25,000 \text{ m} = 25 \text{ km}$, about 15.5 miles. Works: cuttings, embankments, viaducts, tunnels, and long curving or spiral routes.
9. $80.0 - 75.2 = 4.8^\circ$; $4.8 \times 4 \approx 19$ minutes, with Pittsburgh (farther west) behind. Railroads needed one agreed time across many towns to make timetables work and to prevent confusion, missed connections and collisions.
10. May 10, 1869, at Promontory Summit, Utah Territory. The Central Pacific built east from Sacramento; the Union Pacific built west from Omaha. The hardest barrier was the Sierra Nevada, with granite, deep snow and avalanches (for example the Summit Tunnel near Donner Pass).
11. Irkutsk: $8:00 + 5 \text{ h} = 1:00 \text{ p.m.}$ Vladivostok: $8:00 + 7 \text{ h} = 3:00 \text{ p.m.}$ The line is about 9,289 km (5,772 miles) long.
12. $2,800 \div 24 \approx 117$ miles (about 188 km) a day; $117 \div 24 \approx 4.9$ mph (about 7.8 km/h). An isochrone map joins places that can be reached in equal travel time from a starting point. Paullin's maps from New York show the United States "shrinking" in travel time: in 1800 a week reached only about to the Appalachians, by 1857 railroads had brought the Mississippi within a few days, and by 1930 the whole country was within a few days by train, with the greatest gains along the rail lines.
13. The bridge has three double cantilevers on piers whose arms reach out over the water, balanced against each other; short suspended spans join the tips of neighboring arms. The train's weight passes from the suspended span into the arms, along the steel tubes (in compression) and lattice ties (in tension) to the piers and the ground. After the Tay Bridge fell in a gale because too little allowance was made for wind, Bouch's Forth design was dropped and Fowler and Baker designed the Forth Bridge for a much greater wind pressure.
14. $50.5 \div (20/60) \approx 152 \text{ km/h}$; $31.4 \div (1/3) \approx 94 \text{ mph}$. Chalk marl is soft enough to cut easily and tight enough to hold back much of the sea. Britain hesitated partly from fear that an enemy army could use a tunnel to invade an island that had relied on the sea for defense.

THE GREAT CANALS

For most of history, two narrow strips of land forced the world's ships on enormous detours: the Isthmus of Suez, which made Africa a wall between Europe and Asia, and the Isthmus of Panama, which made South America a wall between the Atlantic and the Pacific. In this unit you will watch people cut through both. You will follow Ferdinand de Lesseps from his triumph at Suez in 1869 to his failure at Panama in 1889, where rock, rain, a flooding river and two unseen mosquitoes defeated the plan that had worked in the desert. Then you will see how William Gorgas, John Stevens, George Goethals and tens of thousands of West Indian workers built a canal of lakes and locks that opened in 1914, and why the Kiel and Corinth canals succeeded in such different ways.

Each lesson asks the same four questions: what problem did geography pose, how did the technology solve it, what did it cost, and what changed in the world? You will compute lock lifts and water budgets, measure routes before and after the canals, and build a working lock from bottles and tubing that runs, like Panama's, on gravity alone. You will also read primary sources from Herodotus to Josephus and meet the ideas of Alfred Thayer Mahan. Through it all, remember that the land is God's making: the wisest builders learned to work with it rather than simply against it. The Course C midterm, covering Units 1-3, follows this unit.

BEFORE YOU BEGIN

- Understands how a canal lock raises and lowers a boat (Unit 2, Lesson 2.2)
- Can convert between kilometers, statute miles and nautical miles, and use knots for speed
- Can read latitude and longitude and estimate distance from degrees
- Can find the area of a rectangle and a trapezoid and the volume of a box

MASTERY CHECKLIST

- I can tell the stories of the Suez Canal, the French failure at Panama and the American Panama Canal with correct names and dates.
- I can explain why Suez and Corinth need no locks, why Kiel has tide locks and why Panama climbs to a lake 26 m (85 ft) above the sea.
- I can calculate a lock's lift, the water used in a lockage and the distance and time a canal saves.
- I can explain how Gorgas defeated yellow fever and why the miasma theory had made the French hospitals dangerous.
- I can describe how canals rerouted trade, set the size of ships and created choke points that shaped strategy.
- I can name the workers who built the canals and describe both their achievement and the wrongs they suffered.

OPTIONAL BOOKS AND RESOURCES

- **Library of Congress, Prints and Photographs Online Catalog** (<https://www.loc.gov/pictures/>): Free. Search “Culebra Cut,” “Panama Canal construction,” “Suez Canal” and “Corinth Canal” for historic photographs and photochrom prints to use in the picture studies and the portfolio map.
- **Panama Canal Authority** (<https://pancanal.com/>): Free. The canal’s official site, with current facts on the locks, Gatun Lake, transits and ship sizes. Useful for checking numbers and seeing today’s operations.
- **Project Gutenberg** (<https://www.gutenberg.org/>): Free. Search for Herodotus (Book 2, on Necho’s canal), Josephus’s *The Wars of the Jews* (Book 3, on Nero and the Isthmus of Corinth) and Mahan’s *The Influence of Sea Power upon History* for primary-source readings.

3.1 THE SUEZ CANAL

OBJECTIVES

- Tell the story of Ferdinand de Lesseps and the Suez Canal from the concession of 1854 to the opening on November 17, 1869, including who dug it and at what cost.
- Explain why the geography of the Isthmus of Suez (low, flat, dry, with no great river and two seas at nearly the same level) allowed a canal without locks.
- Compute the distance and time saved between London and Bombay by the canal, in nautical miles, kilometers and statute miles, and estimate the earth moved.

Warm-up. Fill two shallow baking pans with water to the same depth and set them side by side with a gap of about two inches between them. Lay a short piece of drinking straw or a strip of foil folded into a trough across the gap so it touches both pans. Does water flow from one pan to the other? Now lift one pan on a book and try again. What would happen if two seas joined by a canal were at different heights? Write one sentence of prediction before you read.

Watch. *The History of the Suez Canal Explained* (FactSpark, 8:40).

<https://www.youtube.com/watch?v=bGdKAUhBctM>

With How it worked: the history of the Suez Canal.

Backup video. *25th April 1859: Construction begins on the Suez Canal at the Egyptian port town of Port Said* (HistoryPod, 2:35). <https://www.youtube.com/watch?v=weT17D0whC4>

<https://www.youtube.com/watch?v=weT17D0whC4>

As review: the canal opens on November 17, 1869.

KEY TERMS

isthmus

A narrow strip of land joining two larger land masses and separating two bodies of water, such as the Isthmus of Suez between Africa and Asia.

sea-level canal

A canal dug down below the level of the sea at both ends, so the water lies level all the way through and no locks are needed.

concession

A grant from a government giving a person or company the right to build and run something, such as a canal, for a set number of years.

corvée

Forced, unpaid or poorly paid labor owed to a ruler; in Egypt, peasants (fellahin) were called up in rotation to dig canals.

dredge

A machine that scoops or sucks earth from under water to deepen a channel.

nautical mile

The sailor's mile: one minute of latitude, about 1.852 km or 1.151 statute miles. A knot is one nautical mile per hour.

CORE IDEAS

The story. On the morning of November 17, 1869, a line of ships dressed in flags steamed out of Port Said, a brand-new town built on a sandbar where the desert meets the Mediterranean. At the head of the procession was the French imperial yacht *L'Aigle*, carrying Empress Eugénie of France. Behind her came ships bearing the Emperor of Austria, Franz Joseph, the Crown Prince of Prussia and envoys from across Europe, all guests of Egypt's ruler, the Khedive Ismail. On board *L'Aigle* stood a man about to turn sixty-four: **Ferdinand de Lesseps**, a former French diplomat who was not an engineer at all. For fifteen years he had raised money, argued with governments and driven the work forward. That evening the ships anchored in Lake Timsah, halfway across the isthmus, at the new town of Ismailia. Three days later they steamed into the Red Sea at Suez. For the first time, a ship could sail from Europe to Asia without going around Africa.

The problem geography posed. Africa is a wall more than 8,000 km (5,000 mi) long. A ship bound from London to Bombay had to sail south past the Canary Islands, cross the equator, round the Cape of Good Hope and climb north again through the Indian Ocean: about 10,700 nautical miles. Yet at Suez, Africa is joined to Asia only by an isthmus of low sand and salt marsh roughly 120 km (75 mi) across. People had seen the opportunity for thousands of years. The Greek historian **Herodotus** wrote (Book 2) that the pharaoh Necho began a canal from the Nile to the Red Sea, that 120,000 Egyptians died digging it, and that the Persian king Darius finished it. That ancient canal was restored and lost again many times as the sand filled it. When Napoleon invaded Egypt in 1798, his engineer Jacques-Marie Le Père surveyed the isthmus and reported that the Red Sea stood about 10 m (about 30 ft) higher than the Mediterranean. If that were true, a direct canal would need locks, or might even flood the low lands of the Nile Delta. It was not true. A survey in 1847 showed that the two seas stand at nearly the same level, and the way was open for a canal with no locks at all.

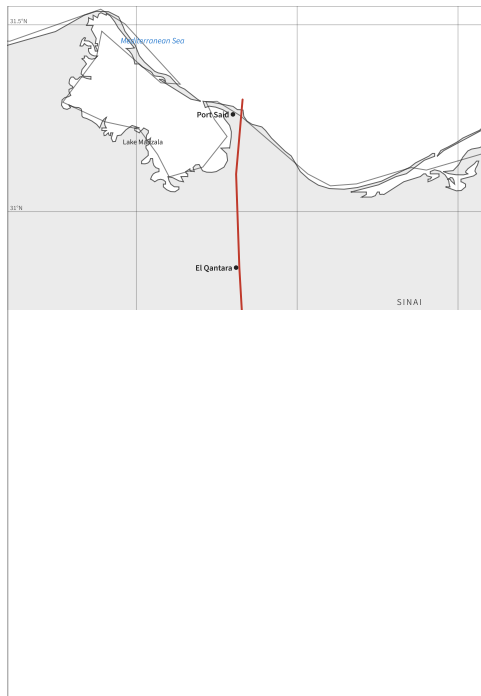
How it worked. De Lesseps had known Said, a son of Egypt's ruler Muhammad Ali, since Said was a boy. When Said became ruler in 1854, de Lesseps hurried to Egypt, and on November 30, 1854, Said granted him a concession to cut a canal. The Universal Company of the Suez Maritime Canal was formed in 1858, with most shares sold to French investors and a large block taken by Said himself. Work began at Port Said on April 25, 1859. The route followed the low ground: across the shallow Lake Manzala, through the sandy ridge of El Guisr, into Lake Timsah, then through the dry salt basins of the Bitter Lakes, which were flooded with seawater in 1869, and on to Suez. Because the desert had no fresh water, the company also dug the Sweet Water Canal from the Nile to Ismailia and Suez to supply the workers. In the early years the digging was done mostly by hand by Egyptian peasants called up under the **corvée**, tens of thousands at a time, carrying the sand out in baskets. This forced labor was a real wrong, and it drew protest, partly from Britain, which opposed the canal for its own reasons. In 1864 an arbitration by Napoleon III ended the *corvée*, and

Egypt was required to pay the company compensation. The contractors Borel and Lavalley then brought in steam dredges and long chutes that dumped spoil far from the banks. In all, roughly 75 million cubic meters of earth were moved. How many workers died, many of them in a cholera epidemic in 1865, is disputed, and estimates vary widely.

The big idea. The Suez Canal could be a sea-level canal because *the geography cooperated*. The isthmus is low and nearly flat. It is dry, so there was no great river to flood the works. It had natural basins, Lake Timsah and the Bitter Lakes, that saved digging. Sand is easy to excavate. And the two seas lie at nearly the same level, so no locks were needed. De Lesseps learned to trust that formula. Twelve years later he would try to repeat it in a very different place, and the result is the story of the next lesson. Technology never works in a vacuum: the same tool that succeeds on one piece of ground can fail on another.

Technology overcoming geography. The canal cut the voyage from London to Bombay from about 10,700 to about 6,300 nautical miles, a saving of roughly 40 percent. It favored the steamship. Sailing ships had trouble in the narrow canal and in the Red Sea, where in its northern part the wind blows from the north most of the year, so most kept to the Cape route. Five days after the canal opened, the clipper *Cutty Sark* was launched at Dumbarton in Scotland, built for a sailing trade that the canal would soon take from her. The canal also had costs beyond money. Egypt borrowed heavily, and in 1875 Khedive Ismail, deep in debt, sold his 176,602 shares to the British government of Benjamin Disraeli for £4 million. Britain occupied Egypt in 1882, and the Convention of Constantinople in 1888 declared the canal open to ships of all nations in war and peace.

On the map. Find Port Said at about 31.26° N, 32.30° E and Suez at about 29.97° N, 32.55° E. The canal of 1869 was about 164 km (102 mi) long, about 8 m (26 ft) deep. It has been widened and lengthened many times and today is about 193 km (120 mi) long, deep enough for nearly all of the world's ships. Notice on the second map how the canal turns the long loop around Africa into a short line through the Mediterranean and the Red Sea, and how it creates new choke points at Port Said, Suez and Bab-el-Mandeb.



The Suez Canal follows the low ground and natural basins of the isthmus from Port Said to Suez.



London to Bombay: about 10,700 nautical miles by the Cape and about 6,300 by Suez.

PICTURE STUDY



Inauguration Ceremony of the Suez Canal at Port Said, November 1869, Édouard Riou, 1896 (showing the ceremony of 16–17 November 1869) · Oil on canvas · Musée national du château de Compiègne, France

Édouard Riou (1833–1900) was a French illustrator best known for his drawings in the adventure novels of Jules Verne. He traveled to Egypt for the opening of the canal in November 1869 and made a series of watercolors of the ceremonies. Many years later he painted this large canvas of the opening day at Port Said, the new town built where the canal meets the Mediterranean.

On 16 November 1869 the Khedive of Egypt, the Empress Eugénie of France and other royal guests gathered on the beach at Port Said. Three pavilions were built: one for the royal guests, one for Muslim religious leaders and one for a Christian altar, and both faiths blessed the canal. The next morning a procession of ships led by the French imperial yacht *L'Aigle* set off down the canal toward the Red Sea. Riou painted a celebration, as the canal company wished it to be seen. As you look, ask what the picture shows clearly and what it leaves out.

Look closely

- Find the three pavilions. How are they decorated? Which do you think was for the royal guests?
- Look at the land around Port Said. Can you see any hills, trees or rivers? What is the ground like?
- Find the line of ships and the lighthouse in the distance. Why would a new port need a lighthouse?
- Look at the crowds in the foreground. Who seems to be watching, and who seems to be working or trading?

Talk about it

1. What does the flat, sandy shore tell you about why a canal without locks was possible here?
2. The picture celebrates the opening. Whose labor built the canal, and does the picture show them?
3. If you were a merchant in London or Bombay in 1869, what would the ships lined up at Port Said mean to you?

PROJECT: A SAND CANAL AND THE SLOPE OF THE BANKS

A sea-level canal in sand looks simple: dig a ditch and let the sea in. But loose sand will not stand in a steep wall, and the banks of the Suez Canal had to be sloped and later protected with stone. In this project you dig a model sea-level canal between two “seas” and discover the steepest bank that sand will hold.

You will need

- A long shallow plastic storage bin or a large baking pan
- Play sand or garden sand, slightly damp
- Water in a pitcher, with a little blue food coloring if you like
- A ruler and a protractor
- A spoon and a craft stick for digging
- Two small toy boats or bottle caps

Steps

1. Fill the bin with damp sand about 8 cm (3 in) deep. Scoop out a “sea” about 10 cm (4 in) long at each end, down to the bottom of the bin.
2. Pour water into both seas to the same depth, about 3 cm (1 in). These are the Mediterranean and the Red Sea.
3. With the craft stick, cut a narrow channel with vertical walls straight across the isthmus, deeper than the water, and watch what happens when the water enters.
4. Measure the slope at which the sand comes to rest after it slumps. Hold the protractor against the bank and record the angle. This is the sand’s angle of repose.
5. Now dig a second channel beside the first with banks cut gently, at a slope less than the angle you measured. Let the water in and see whether the banks hold.
6. Float a boat through each channel. Push a wave along with your hand and see what the wash does to the banks.
7. Measure the width of each channel at the water surface and at the bottom. Sketch the cross-section of each in your notebook, labeled with the measurements.

Tips

- Dry sand slumps to a lower angle than damp sand. Try both and compare.
- Line part of one bank with small pebbles to model the stone facing used on the real canal, and test whether the boat’s wake still erodes it.

Check your work

- I measured the angle of repose of my sand.
- I can explain why a canal in sand must be much wider at the top than at the bottom.
- I can explain why the water stood still in my canal when both seas were at the same level.

MAP NOTEBOOK

1. Trace or sketch the Isthmus of Suez. Label the Mediterranean, the Gulf of Suez, Lake Manzala, Lake Timsah, the Great Bitter Lake, Port Said, Ismailia and Suez, and draw the canal in blue.
2. On an outline map of the Old World, draw the London to Bombay route around the Cape in one color and through Suez in another. Write the distance of each beside it.
3. Draw a cross-section of a sea-level canal in sand, with sloping banks and the water level marked. Beside it, write one sentence explaining why it needs no locks.

From history. Ferdinand de Lesseps was fond of saying that he had been inspired as a young diplomat in Egypt in the 1830s by reading the report of Napoleon's engineers. He was also friends with the engineer Alois Negrelli, an Austrian who had studied a route across the isthmus in the 1840s, and the canal's final line drew heavily on Negrelli's plans. The British engineer Robert Stephenson, son of George Stephenson of the *Rocket*, took part in the 1847 survey, but he later told Parliament he believed a canal at Suez would not succeed. He favored a railway instead, and his own railway from Alexandria to Cairo carried mail and passengers to the Red Sea for years before the canal opened.

WORKED EXAMPLES

Example 1. A steamship sails from London to Bombay. By the Cape of Good Hope the voyage is about 10,700 nautical miles; by the Suez Canal it is about 6,300. How far does the canal save, in nautical miles, kilometers and statute miles, and by what percent?

(Use the map or drawing "The Cape route and the Suez route compared." shown earlier in this lesson.)

1. Saving in nautical miles: $10,700 - 6,300 = 4,400$ nmi.
2. Kilometers: $4,400 \times 1.852 = 8,149$, about 8,150 km.
3. Statute miles: $4,400 \times 1.151 = 5,064$, about 5,060 mi.
4. Percent saved: $4,400 \div 10,700 = 0.411$, about 41 percent.

Answer: About 4,400 nautical miles (about 8,150 km or 5,060 mi), roughly 41 percent of the Cape route.

Example 2. A steamer of the 1870s averages 10 knots and burns about 40 tons of coal a day. How many days does each route take, and about how much coal does the Suez route save?

1. A knot is one nautical mile per hour. Cape route: $10,700 \div 10 = 1,070$ hours; $1,070 \div 24 = 44.6$ days.
2. Suez route: $6,300 \div 10 = 630$ hours; $630 \div 24 = 26.3$ days.
3. Days saved: $44.6 - 26.3 = 18.3$ days.
4. Coal saved: $18.3 \times 40 = 732$, about 730 tons (before counting delays in the canal).

Answer: About 45 days by the Cape and 26 days by Suez; the canal saves about 18 days and roughly 730 tons of coal.

Example 3. Model the 1869 channel as a trapezoid about 8 m deep, 22 m wide at the bottom and 58 m wide at the surface, running 164 km. What volume of water does the channel hold? Compare it with the roughly 75 million cubic meters of earth that was actually moved.

1. Area of a trapezoid: $(\text{bottom} + \text{top}) \div 2 \times \text{depth} = (22 + 58) \div 2 \times 8 = 40 \times 8 = 320$ m².
2. Length in meters: 164 km = 164,000 m.
3. Volume: $320 \times 164,000 = 52,480,000$ m³, about 52 million m³.
4. The real excavation, about 75 million m³, was larger because much of the route ran through ground above sea level (such as the ridge of El Guisr), and that earth above the water line had to be removed too.

Answer: About 52 million m³ of channel below water; the extra 22 million or so cubic meters came mostly from ground standing above sea level.

PRACTICE

1. **EASY** Give the dates when work on the Suez Canal began and when it opened, and name the man who led the project.
2. **EASY** Why could the Suez Canal be built with no locks?
3. **EASY** Using the map of the isthmus, list from north to south the lakes the canal passes along or through.
(Use the map or drawing “The Isthmus of Suez.” shown earlier in this lesson.)
4. **EASY** What error did Napoleon’s engineer Le Père make in 1799, and why did it matter?
5. **MEDIUM** Port Said is at about 31.26° N and Suez at about 29.97° N. One degree of latitude is about 111 km. How far apart are they north to south? The canal of 1869 was about 164 km long. Give two reasons it is longer than the north-south distance.

6. **MEDIUM** Convert the canal's length in 1869 (164 km) and today (193 km) to statute miles. By how many kilometers has it grown?
7. **MEDIUM** A slower steamer averages 9 knots. How many days does the canal's 4,400 nautical mile saving represent?
8. **MEDIUM** Name two features of Egypt's geography that made a sea-level canal possible, and one that made the work hard.
9. **HARD** About 75 million cubic meters of earth were moved over roughly ten and a half years. On average, how many cubic meters is that per day? If a worker's basket held about 0.02 m³ (20 liters), how many basket-loads a day would that equal?
10. **HARD** Why did the Suez Canal favor steamships over sailing ships? Use the geography of the Red Sea in your answer.
11. **CHALLENGE** In 1875 Britain bought Khedive Ismail's 176,602 Suez Canal shares for £4 million. What was the price per share? Why would a nation, not just merchants, want to own a canal?
12. **CHALLENGE** Write a paragraph: Was the Suez Canal a triumph of technology or of geography? Use at least three facts from the lesson.

COMMON MISTAKES

- Thinking the Suez Canal has locks like the Panama Canal. It is a sea-level canal with no locks at all.
- Mixing up nautical and statute miles. A nautical mile (1.852 km) is about 15 percent longer than a statute mile (1.609 km).
- Assuming de Lesseps was an engineer. He was a diplomat and promoter; engineers, contractors and tens of thousands of workers built the canal.

Make it a game • Cape or Canal?. One player names a voyage, such as London to Bombay, Marseille to Saigon, Liverpool to Melbourne, New York to Cape Town, or Hamburg to Shanghai. The others race to say "Cape" or "Canal" for the shorter route after 1869 and name one choke point the ship would pass. Check with a globe and string. A correct route scores 1 point and a correct choke point scores 1 more. Watch out: some voyages, like New York to Cape Town, never needed Suez at all.

Scripture. "Every valley shall be exalted, and every mountain and hill shall be made low: and the crooked shall be made straight, and the rough places plain:" (Isaiah 40:4, KJV)

Isaiah speaks of preparing a way for the Lord. Engineers love the image of a straight and level road, but the prophet's point is the coming of God Himself. Even the greatest canal is a small picture of the way God makes for His people.

Practice answers

1. Work began April 25, 1859, at Port Said; the canal opened November 17, 1869. Ferdinand de Lesseps led it.

2. The isthmus is low and nearly flat, and the Mediterranean and the Red Sea stand at nearly the same level, so a channel dug below sea level holds level water from end to end.
3. Lake Manzala (along its eastern edge), Lake Timsah and the Great Bitter Lake, as labeled on the map. In fact the canal also passes the small Lake Ballah (between Lake Manzala and Lake Timsah) and the Little Bitter Lake (just south of the Great Bitter Lake).
4. He reported that the Red Sea was about 10 m (30 ft) higher than the Mediterranean. If true, a canal would have needed locks and might have flooded the low land of the Nile Delta; the error discouraged a direct canal until surveys in the 1840s showed the seas were nearly level.
5. $31.26 - 29.97 = 1.29^\circ$; $1.29 \times 111 = 143$ km (about 89 mi). The canal is longer because Suez also lies about 0.25° east of Port Said, and because the route bends to follow low ground and pass through Lake Timsah and the Bitter Lakes.
6. $164 \text{ km} \div 1.609 = 102$ mi; $193 \text{ km} \div 1.609 = 120$ mi. It has grown by 29 km (about 18 mi), mainly from extended approach channels.
7. $4,400 \div 9 = 489$ hours; $489 \div 24 = 20.4$ days, about 20 days.
8. Possible: low, flat sandy ground; two seas at nearly the same level; natural basins (Lake Timsah, Bitter Lakes); no great river to flood the works. Hard: the desert had no fresh water (a Sweet Water Canal from the Nile was needed), heat, and blowing sand that fills channels.
9. $10.5 \times 365 = 3,833$ days; $75,000,000 \div 3,833 =$ about 19,600 m³ per day. $19,600 \div 0.02 =$ about 980,000 basket-loads a day, which shows why steam dredges replaced hand labor.
10. The canal is narrow, so ships could not tack and sailing ships had to be towed. In the northern Red Sea the wind blows from the north most of the year, against a ship bound south, and the sea is long and lined with reefs. Steamers could go straight through, so the canal gave them the short route while most sailing ships kept to the Cape.
11. $\text{£}4,000,000 \div 176,602 =$ about £22.65 per share. A government wanted a say over the route to its empire in India, the safe passage of its warships and trade, and the canal's income; owning shares gave Britain influence over a strategic choke point.
12. Answers vary. A strong answer notes that the technology (steam dredges, planning, finance) mattered, but the geography made the plan possible: a low, dry, sandy isthmus with natural basins and two seas at nearly the same level, so no locks were needed. It names costs (forced corvée labor until 1864, disputed deaths, Egypt's debt and the sale of its shares) and the result (London to Bombay cut by about 4,400 nmi). It may observe that de Lesseps's faith in the formula led him astray at Panama.

3.2 THE FRENCH AT PANAMA

OBJECTIVES

- Tell the story of the French attempt to cut a sea-level canal at Panama (1881–1889) and explain why it failed.
- Compare the geography of Panama with that of Suez: relief, rock, rainfall, rivers and disease.
- Use coordinates, cross-sections and rainfall volumes to show in numbers why a sea-level canal at Panama was so much harder than at Suez.

Warm-up. Take a plate of damp sand or soil and cut a deep, straight-sided trench through a mound of it with a butter knife. Then pour a cup of water slowly over the mound like a tropical rainstorm. What happens to the walls of your trench? Now imagine that the trench is 100 m (330 ft) deep and the rain falls for eight months of the year.

Watch. *Panama Canal: The Mountain That Would Not Stay Cut* (The Photographed Past, 6:24). https://www.youtube.com/watch?v=c_w7zGARdEA
With The cost: the slides of the Culebra Cut and why the mountain would not stay cut.

KEY TERMS

continental divide

The high ground separating rivers that drain to one ocean from those that drain to another; at Panama it crosses the canal route at Culebra.

yellow fever

A deadly viral disease of the tropics, spread by the bite of the *Aedes aegypti* mosquito, which breeds in clean standing water near houses.

malaria

A disease caused by a parasite in the blood, spread by *Anopheles* mosquitoes; it brings repeated chills and fevers and weakened many canal workers.

miasma

The old theory that diseases came from “bad air” rising from swamps and rotting matter; it led doctors to fight the wrong enemy.

watershed (drainage basin)

All the land whose rain drains into one river; the Chagres watershed sends its floods straight across the canal route.

slide

A mass of earth and rock that slips down the side of a cut, burying track and filling the channel.

CORE IDEAS

The story. In 1883 a capable French engineer named **Jules Dingler** arrived at Panama as director general of the canal works, bringing his wife, his son, his daughter and his daughter's fiancé. He was a confident man. Yellow fever, he believed, struck only people who drank and lived carelessly. In January 1884 his daughter died of yellow fever. Within weeks his son was dead of the same disease, and then the young fiancé. The next year, after Dingler had spent months at his work, his wife died too. Dingler went home to France a broken man. His story was not unusual. On the French works, clerks, engineers, nuns and laborers died by the thousands, and no one knew why.

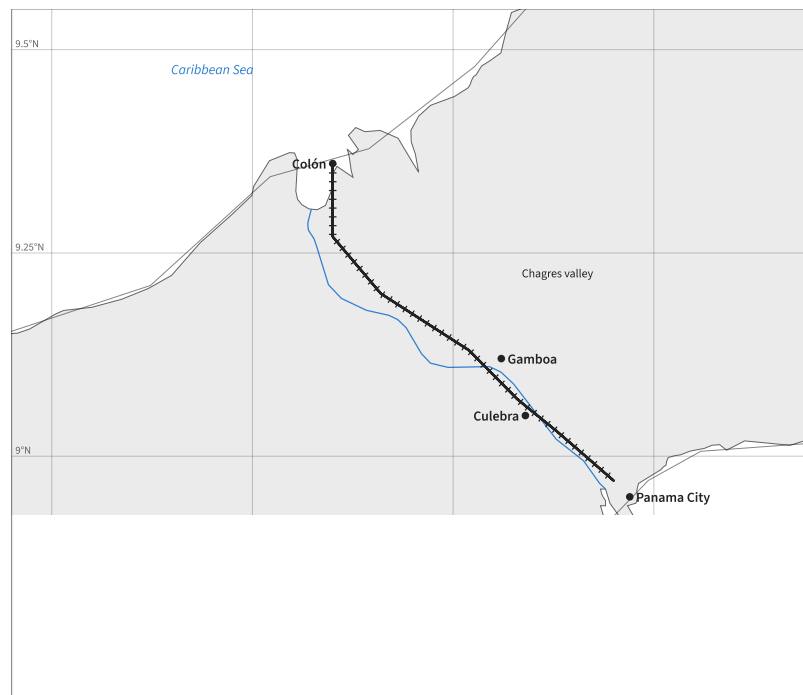
The problem geography posed. At first glance Panama looked like an easier Suez. The crossing from sea to sea is only about 80 km (50 mi), and since 1855 the Panama Railroad had carried passengers between Colón on the Caribbean and Panama City on the Pacific in a few hours. But almost everything else was different. Suez is a flat desert; Panama is a spine of hills and rock that rises at the **continental divide** at Culebra to roughly 100 m (330 ft). Suez had no river; Panama had the **Chagres**, a river fed by tropical rains that could rise many meters in a day, and the canal route ran down its valley. Suez gets almost no rain; the Caribbean side of Panama gets well over 3 m (about 120 in) in a year, most of it in a rainy season from about May to December. Suez had sand that stayed put once sloped; Panama's Culebra hills were made of soft clays and shales that grew slick when wet and slid into every cut. And Panama's lowland forests and swamps bred two deadly mosquitoes.

How they tried. In May 1879 Ferdinand de Lesseps, now the hero of Suez, gathered an international congress in Paris that voted for a canal at Panama, at sea level, like Suez. One French engineer, **Adolphe Godin de Lépinay**, stood up with a different plan: dam the rivers to make lakes high above the sea and lift ships to them with locks. He was outvoted. De Lesseps formed a company, sold shares to hundreds of thousands of French families, bought the Panama Railroad and began excavating in 1881. Machines poured in: steam excavators, dredges, locomotives and dump cars. But every rainy season the Chagres flooded the works, and at Culebra the walls of the cut kept sliding back in. The deeper the French dug, the more the hills moved. In 1887, too late, the company gave up the sea-level plan and hired Gustave Eiffel, builder of the Eiffel Tower, to design locks. In December 1888 the company could no longer pay its bills, and in February 1889 it was put into liquidation. Investigations in 1892 and 1893 revealed that money had been paid to newspapers and members of the French parliament; de Lesseps, his son Charles and Eiffel were convicted, though the convictions were overturned on appeal. De Lesseps died in 1894.

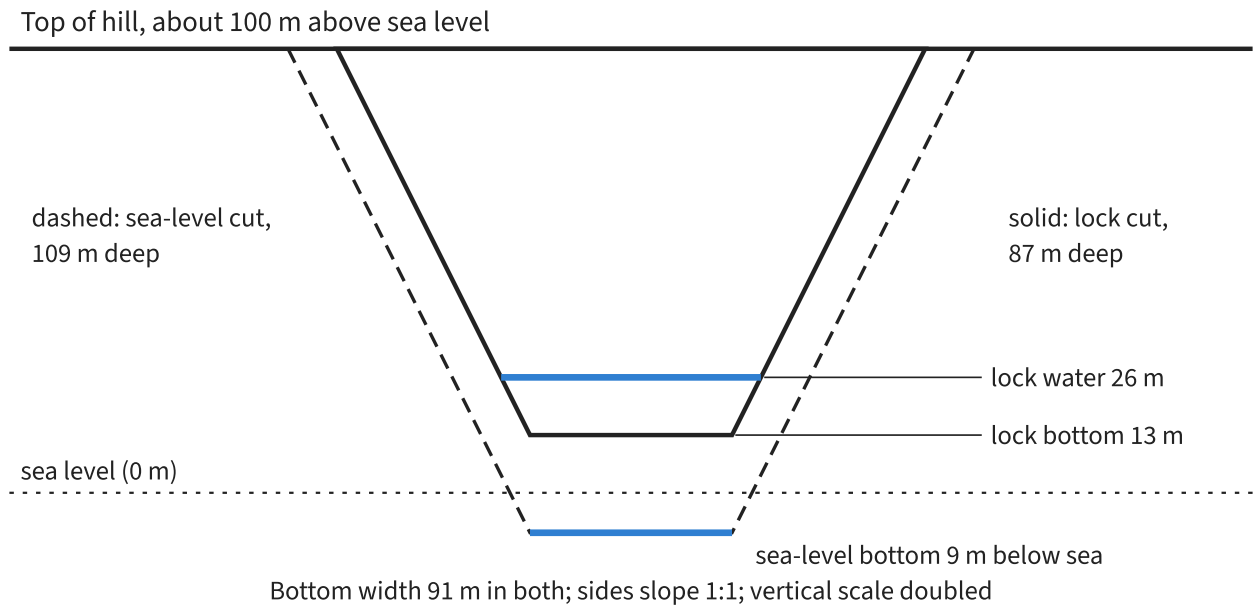
The hidden enemy. The doctors of the 1880s believed in **miasma**, bad air from swamps. They did not know that mosquitoes carried yellow fever and malaria. In the French hospital at Ancón, run by devoted Sisters of Charity, the legs of the beds stood in pans of water to keep ants from climbing up, and the pans bred mosquitoes beside the patients. In 1881 a Cuban doctor, **Carlos Finlay**, proposed that a mosquito spread yellow fever, but few listened. The French death toll is uncertain; the most widely cited estimate is about 22,000, and most of the dead were laborers from Jamaica and other West Indian islands, who did most of the digging.

The big idea. De Lesseps tried to carry a solution from one place to another without studying how the places differed. At Suez the geography cooperated; at Panama it fought back. Relief, rock, rain, rivers and disease each added cost, and together they broke the company. Jesus warned that a builder should sit down first and count the cost. De Lesseps had counted the cost of Suez, not of Panama. His failure is also a warning about pride, the kind of pride the builders of Babel showed when they said, “let us make us a name.” Yet the French did not fail completely. They dug tens of millions of cubic meters at Culebra and elsewhere, mapped the land, measured the Chagres for years and left behind machines, buildings and a railroad, all of which the Americans would later use.

On the map. Find Colón at about 9.36° N, 79.90° W and Panama City at about 8.95° N, 79.53° W. Surprise: the Pacific end of the route lies *east* of the Caribbean end. The isthmus curves, so a ship going from the Atlantic to the Pacific through Panama travels from northwest to southeast.

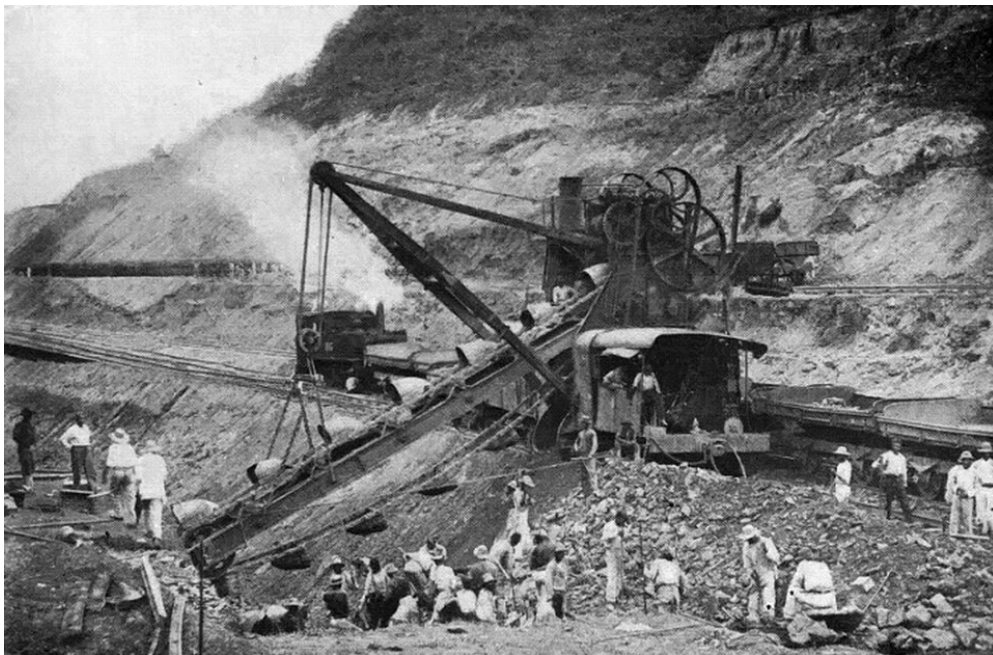


The isthmus the French tried to cut. The railroad of 1855 runs from Colón to Panama City, northwest to southeast.



Why the sea-level plan was so costly at Culebra (schematic, vertical scale doubled).

PICTURE STUDY



French Method of Excavation in the Culebra Cut, Photographer not recorded, about 1896 · Photograph, reproduced as a halftone · Published in Farnham Bishop, Panama Past and Present (1913); image on Wikimedia Commons

After de Lesseps's company went bankrupt in 1889, a new French company kept a small force digging at Culebra through the 1890s, mostly to protect the value of the work already done. This photograph shows the kind of machine the French relied on: a bucket-chain excavator, which scraped earth up a long slanting arm in a line of small buckets and tipped it into cars waiting on the track.

When the Americans published this photograph in 1913, they used it to show how much smaller the French effort had been. Study it now and remember it. In the next lesson you will compare it with the Culebra Cut as the Americans photographed it in 1913.

Look closely

- Find the long arm with the chain of buckets. Follow it from the bottom to the top. Where does the earth go?
- Find the rails and the dump cars. Where do you think the earth was being taken?
- Look at the hillside behind. Can you see where it has been cut into steps? Does the ground look like hard rock or like something that could slide?
- Look for people. How large are they compared with the machine and the hill?

Talk about it

1. The French company wanted investors to believe in the work. What does this picture not show that an investor ought to have known?
2. From what you see, would this cut be easier or harder to dig in the rainy season? Why?

PROJECT: SEA LEVEL OR LOCKS? A CROSS-SECTION TO SCALE

The French spent years arguing whether to cut Panama down to sea level or lift ships over the hills with locks. You will settle the question with graph paper. By drawing the hill and both kinds of cut to scale, and counting squares, you will measure how much more earth the sea-level plan required.

You will need

- Graph paper (1 cm or 1/4 inch squares)
- Pencil, ruler and two colored pencils
- Calculator
- Optional: a lump of modeling clay and a plastic knife

Steps

1. Choose a scale: 1 square = 5 m. Draw a horizontal line near the bottom of the page for sea level.
2. Draw a simplified hill: a flat top 20 squares (100 m) above sea level, wide enough to fill the page.
3. Draw the sea-level cut in one color: a bottom 9 m below sea level and 91 m wide (about 1.8 and 18 squares), with sides sloping 1 square across for each 1 square up until they meet the top of the hill.
4. Draw the lock-canal cut in the second color: water at 26 m above sea level and a bottom 13 m above sea level, with the same bottom width and the same side slope.
5. Count the squares (estimating half squares) inside each cut. Multiply by 25 m² per square to find each cross-section area.
6. Find what fraction of the sea-level excavation the lock plan saves at this hill.

7. Optional: shape the hill from clay, slice both cuts, and weigh or compare the removed clay.

Tips

- The area of a trapezoid with 1:1 side slopes is $\text{bottom} \times \text{depth} + \text{depth} \times \text{depth}$. Use it to check your square count.
- Remember that at Culebra the sides had to be cut much flatter than 1:1 because of slides, which made both cuts far bigger in real life.

Check your work

- My two cuts are drawn to the same scale and labeled.
- I found both areas by counting squares and checked them with the formula.
- I can explain why raising the water level shrinks the cut.

MAP NOTEBOOK

1. Draw a sketch map of the Isthmus of Panama with Colón, Panama City, the Chagres River, Culebra and the railroad. Add a north arrow and note that the route runs northwest to southeast.
2. Make a two-column chart, "Suez" and "Panama," comparing relief, rock, rainfall, rivers and disease.
3. Draw the life cycle of a mosquito (egg, larva, pupa, adult) and circle the stage that needs standing water.

From history. In 1887 the painter Paul Gauguin, who had given up a career as a stockbroker in Paris, traveled to Panama with a fellow painter, Charles Laval, hoping to find work. Gauguin took a job digging on the canal for a short time before he was laid off, and he wrote home of the hard labor and the heat. He soon left for the French island of Martinique, where he painted some of his first tropical pictures.

WORKED EXAMPLES

Example 1. Colón is at about 9.36° N, 79.90° W and Panama City at about 8.95° N, 79.53° W. In which direction does a ship travel from the Caribbean end to the Pacific end, and what is the straight-line distance? (One degree of latitude is about 111 km; one degree of longitude at 9° N is about 110 km.)

(Use the map or drawing “The Pacific end lies east of the Caribbean end.” shown earlier in this lesson.)

1. Latitude change: $9.36 - 8.95 = 0.41^\circ$ south. Distance: $0.41 \times 111 = 45.5$ km.
2. Longitude change: $79.90 - 79.53 = 0.37^\circ$. West longitude is getting smaller, so the movement is east. Distance: $0.37 \times 110 = 40.7$ km.
3. Straight line: $\sqrt{(45.5^2 + 40.7^2)} = \sqrt{(2,070 + 1,656)} = \sqrt{3,726} = 61$ km, about 38 mi.
4. South and east by similar amounts means the direction is roughly southeast.

Answer: Roughly southeast, about 61 km (38 mi) in a straight line. The canal route itself is longer, about 80 km (50 mi), because it follows the valleys.

Example 2. Model the hill at Culebra as flat-topped, 100 m above sea level. The cut is 91 m wide at the bottom, with sides sloping 1 m out for each 1 m up. Compare the cross-section of a sea-level cut (bottom 9 m below sea level) with a lock-canal cut whose bottom is 13 m above sea level.

(Use the map or drawing “Raising the water 26 m above the sea makes the cut smaller.” shown earlier in this lesson.)

1. Sea-level cut depth: $100 - (-9) = 109$ m. Area = bottom $\times$ depth + depth² = $91 \times 109 + 109^2 = 9,919 + 11,881 = 21,800$ m².
2. Lock-canal cut depth: $100 - 13 = 87$ m. Area = $91 \times 87 + 87^2 = 7,917 + 7,569 = 15,486$ m².
3. Ratio: $15,486 \div 21,800 = 0.71$.
4. So the lock plan removes about 29 percent less earth for every meter of cut through the hill, and its shallower walls are less likely to slide.

Answer: About 21,800 m² versus about 15,500 m²: the lock plan saves roughly 29 percent of the excavation through the hill.

Example 3. Suppose a tropical storm drops 10 cm (about 4 in) of rain in one day on 1,000 km² of the Chagres watershed. What volume of water is that? Compare it with the roughly 52 million m³ held by the whole Suez Canal channel of 1869.

1. Convert the area: $1,000 \text{ km}^2 = 1,000 \times 1,000,000 \text{ m}^2 = 1,000,000,000 \text{ m}^2$.
2. Convert the rain: $10 \text{ cm} = 0.1 \text{ m}$.
3. Volume = area $\times$ depth = $1,000,000,000 \times 0.1 = 100,000,000 \text{ m}^3$.
4. $100 \text{ million} \div 52 \text{ million} = \text{about } 1.9$.

Answer: About 100 million m³ of water in a single day, nearly twice the volume of the entire Suez channel, much of it rushing down the Chagres valley across the canal route.

PRACTICE

1. **EASY** In what years did the French company dig at Panama, and when did it collapse?
2. **EASY** What plan did Adolphe Godin de Lépinay propose at the 1879 Paris congress, and what happened to it?
3. **EASY** Name the two mosquito-borne diseases that killed so many canal workers, and the mosquito that carries each.
4. **EASY** What was the miasma theory, and why did it make the French hospitals more dangerous?
5. **MEDIUM** Give five ways the geography of Panama differed from the geography of Suez.
6. **MEDIUM** Using the map, which ocean end of the Panama route is farther east? A sailor says, "Going through Panama from the Atlantic to the Pacific, you sail west." Correct him.
(Use the map or drawing "The Isthmus of Panama." shown earlier in this lesson.)
7. **MEDIUM** The Caribbean side of the isthmus gets about 3.2 m of rain a year. Convert this to inches. If two-thirds of it falls in the eight-month rainy season, how much falls per rainy month on average?
8. **MEDIUM** Using the cross-section formula $\text{area} = \text{bottom} \times \text{depth} + \text{depth}^2$, find the area of a cut 91 m wide at the bottom and 50 m deep with 1:1 side slopes.
9. **HARD** At Culebra the slides forced engineers to cut the walls much flatter, say 3 m out for each 1 m up instead of 1 m. For a cut 87 m deep and 91 m wide at the bottom, the area becomes $\text{bottom} \times \text{depth} + 3 \times \text{depth}^2$. How much larger is this than the 1:1 cut of 15,486 m²?
10. **HARD** Why would a sea-level canal at Panama have had to deal with the Chagres River in a way the lock canal did not? Explain using the profile of the land.
11. **CHALLENGE** If about 22,000 people died during the roughly 8 years of the French effort (1881 to 1889), how many deaths is that per year on average and per day? What does this suggest about the workforce the company had to keep recruiting?
12. **CHALLENGE** Write a paragraph: Was the French failure at Panama mainly a failure of technology, of knowledge or of judgment? Support your answer.

COMMON MISTAKES

- Thinking the French failed because they were lazy or unskilled. They were brilliant engineers who faced unknown diseases and chose the wrong plan for the ground.
- Assuming the Panama route runs east to west. The isthmus curves, and the Pacific end is southeast of the Atlantic end.
- Forgetting that the French work was not wasted. The Americans used their excavation, surveys, river records, railroad and equipment.

Make it a game · Suez or Panama? A leader reads a clue, such as “a flooding river crosses the route,” “the seas are at nearly the same level,” “rain falls over 3 m a year,” “dug through sand,” “the walls kept sliding,” “opened in 1869” or “the company went bankrupt in 1889.” Players hold up an S card or a P card. Score 1 point for each right card and 1 more for explaining why the clue made the work easier or harder.

Scripture. “For which of you, intending to build a tower, sitteth not down first, and counteth the cost, whether he have sufficient to finish it?” (Luke 14:28, KJV)

Jesus uses a builder’s common sense to teach about following Him wholeheartedly. Counting the cost means honestly studying the ground, the danger and the price before beginning, something de Lesseps did at Suez but not at Panama.

Practice answers

1. Excavation began in 1881; the company stopped payments in December 1888 and was put into liquidation in February 1889.
2. He proposed damming the rivers to form lakes above sea level and lifting ships to them with locks. He was outvoted in favor of de Lesseps’s sea-level plan; the Americans later built essentially his kind of canal.
3. Yellow fever, carried by *Aedes aegypti*; malaria, carried by *Anopheles* mosquitoes.
4. The belief that disease came from bad air from swamps. Because doctors did not suspect mosquitoes, they left standing water about, such as the pans under bed legs to stop ants, where mosquitoes bred beside the patients.
5. Relief: hills rising to about 100 m at Culebra versus flat desert. Rock: slippery clays and shales versus sand. Rain: over 3 m a year on the Caribbean side versus almost none. Rivers: the flooding Chagres versus no river. Disease: yellow fever and malaria in tropical forest and swamp versus a dry desert. (Also: the Pacific has large tides, the Mediterranean small ones.)
6. The Pacific end (Panama City, about 79.5° W) is east of the Caribbean end (Colón, about 79.9° W). A ship going from the Atlantic to the Pacific through the isthmus actually moves southeast.
7. $3.2 \text{ m} = 320 \text{ cm}$; $320 \div 2.54 = 126 \text{ in}$. Two-thirds is about 2.13 m (84 in); $\div 8 =$ about 0.27 m (about 10.5 in) per rainy month.
8. $91 \times 50 + 50^2 = 4,550 + 2,500 = 7,050 \text{ m}^2$.
9. $91 \times 87 + 3 \times 87^2 = 7,917 + 22,707 = 30,624 \text{ m}^2$. That is 15,138 m² more, about twice the 1:1 area ($30,624 \div 15,486 = 1.98$). Slides doubled the work even before counting the earth that slid back in.

10. The canal route follows the Chagres valley. At sea level, the canal would be the lowest ground in the valley, so the river and its floods would pour straight into the channel, carrying silt and fast currents; it would need huge diversion channels and dams. A lock canal could dam the Chagres and turn it into a lake that is part of the canal, so the river's water becomes the canal's supply instead of its enemy.
11. Over about 8 years: $22,000 \div 8 = 2,750$ a year; $2,750 \div 365 =$ about 7.5 a day. The company had to keep replacing workers constantly, mostly by recruiting laborers from Jamaica and other islands, which raised cost, slowed work and destroyed experience.
12. Answers vary. A strong answer weighs all three: the steam excavators of the 1880s were small for the job (technology); no one yet knew mosquitoes carried yellow fever and malaria (knowledge); and de Lesseps chose a sea-level plan against good advice and kept to it until 1887 because it had worked at Suez (judgment). It uses facts such as the Culebra slides, the Chagres floods, about 22,000 deaths and the collapse in 1888-1889, and may connect to Luke 14:28 and counting the cost.

3.3 THE AMERICAN PANAMA CANAL

OBJECTIVES

- Tell how the United States built the Panama Canal (1904–1914), and explain the work of William Gorgas against disease, John Stevens and George Goethals in planning and engineering, and the West Indian workers who did most of the labor.
- Explain how a lake-and-lock canal works: the Gatun Dam, Gatun Lake, the three sets of locks and the gravity-fed culverts, and why the plan turned the Chagres River from an enemy into the canal's water supply.
- Calculate lock lifts, the water used in each lockage and the effect of traffic on the level of Gatun Lake.

Warm-up. Fill a clear glass halfway with water and mark the level with tape. Lower a toy boat or bottle cap onto the water: does the level change? Now pour water from a higher cup into the glass through a straw or tube held as a siphon (fill the tube, pinch both ends, place one end in each cup and let go). When does the water stop flowing? Predict what this has to do with the locks at Panama, which have no pumps.

Watch. *Panama Canal Construction in 1912* / *American Vintage Documentary* (The Best Film Archives, 7:28). <https://www.youtube.com/watch?v=YKj42vXeFus>
With How it worked: a 1912 film of the canal under construction, with the locks and the dam.

Note: An old documentary film with narration; some terms are dated.

Backup video. *How Does the Panama Canal Work?* (The Panama Canal, 1:03).
<https://www.youtube.com/watch?v=hoQ7RHyG-EA>
As review: the Panama Canal Authority shows how the locks work.

KEY TERMS

lock

A chamber with gates at both ends in which water is raised or lowered to lift or lower a ship from one water level to another.

lockage

One complete passage of a ship (or group of ships) through a lock chamber, using one chamber-full of water.

culvert

A large tunnel inside the lock walls and floor that carries water into or out of a lock chamber; at Panama the water flows by gravity alone.

miter gate

A pair of gate leaves that close at an angle, pointing upstream, so that the higher water presses them tightly shut.

earthen dam

A dam built mostly of compacted earth and rock fill; the Gatun Dam across the Chagres created Gatun Lake.

vector control

Stopping a disease by attacking the animal that carries it, here the mosquito, by draining, screening, oiling and fumigating.

CORE IDEAS

The story. In November 1906 President Theodore Roosevelt sailed to Panama to see the canal works for himself, the first time a sitting American president had traveled outside the country. He came in the rainy season on purpose, to see the work at its worst. Photographers caught him in a white suit and hat sitting at the controls of a giant Bucyrus steam shovel in the Culebra Cut, grinning. He tramped through the mud, walked into workers' quarters unannounced and asked the men what they ate and how they were treated. He told the workers that they were doing something as great as any work in history and that he wanted every one of them to feel that he was part of it.

How the Americans got there. In 1902 Congress chose Panama over a rival route through Nicaragua and authorized buying the French company's rights and property for \$40 million. Panama was then part of Colombia, and in 1903 the Colombian senate rejected the treaty the United States offered. On November 3, 1903, Panama declared its independence; Colombian troops who landed at Colón were kept from crossing the isthmus, and American warships blocked more from arriving to stop it, and the United States quickly recognized the new nation. Two weeks later the Hay-Bunau-Varilla Treaty gave the United States control of a Canal Zone about 10 miles (16 km) wide for \$10 million and a yearly payment. These events were controversial then and remain so; in 1921 the United States paid Colombia \$25 million. The Americans took over the works on May 4, 1904.

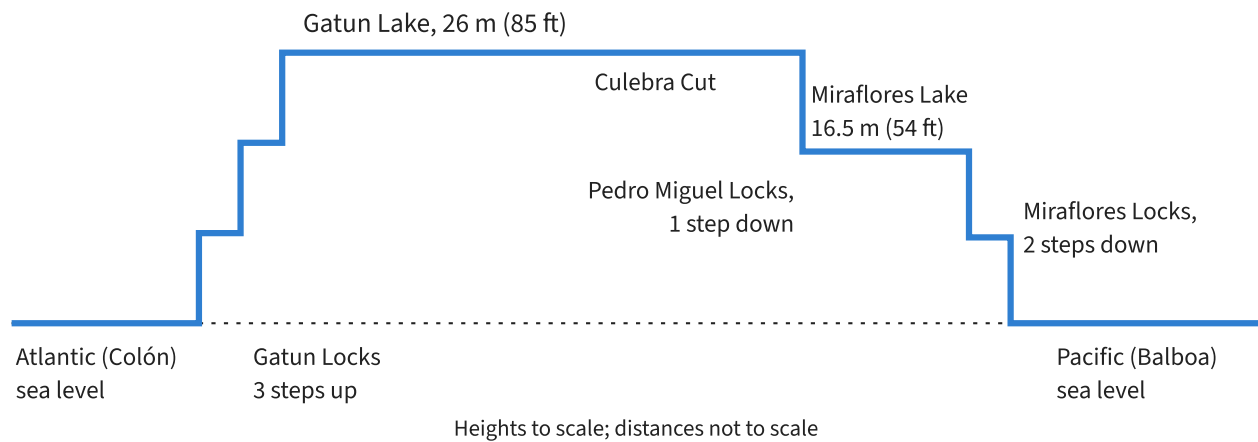
Gorgas and the mosquito. The first enemy was disease. In 1900 an Army commission in Cuba led by Major Walter Reed confirmed what Carlos Finlay had proposed: the *Aedes aegypti* mosquito carries yellow fever. The British doctor Ronald Ross had already shown in 1897 that mosquitoes carry malaria. Colonel **William C. Gorgas**, who had cleared yellow fever from Havana, became chief sanitary officer at Panama. His teams put screens on windows, fumigated houses building by building, drained swamps, spread oil on standing water to kill larvae, and gave Panama City and Colón piped water so families no longer needed open water barrels where mosquitoes bred. Many officials doubted him at first, but Roosevelt backed him. By 1906 yellow fever was gone from the Canal Zone, and malaria was sharply reduced.

How it worked. John F. Stevens, a railroad builder, took charge as chief engineer in 1905. He saw that the job was really a railroad problem: moving earth out of the cut by the trainload. He rebuilt the Panama Railroad, built housing and kitchens, and persuaded Roosevelt and then Congress (in June 1906) to build a lock canal. When Stevens resigned in 1907, Roosevelt gave the job to an Army engineer, **Lt. Col. George W. Goethals**, who led it to the end. The plan: build the **Gatun Dam**, an earthen dam about 2.4 km (1.5 mi) long,

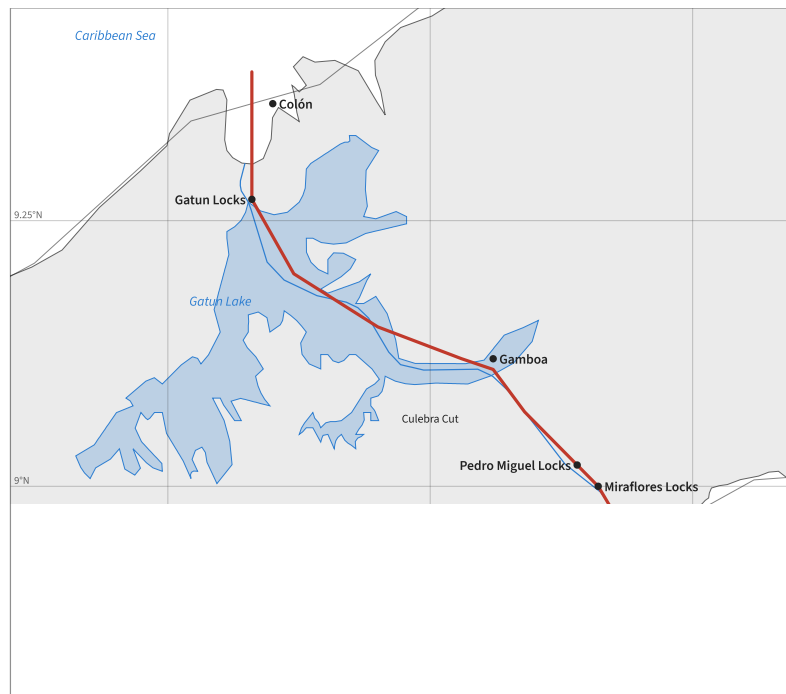
across the Chagres near the Caribbean coast. Behind it rose **Gatun Lake**, its surface about 26 m (85 ft) above sea level, at the time the largest artificial lake in the world. Ships climb to the lake through three steps of the **Gatun Locks**, cross the lake, pass through the nine-mile **Culebra Cut** through the divide, then go down one step at **Pedro Miguel** to little Miraflores Lake (about 16.5 m, 54 ft) and two more at **Miraflores** to the Pacific. Every lock chamber is 1,000 ft long and 110 ft wide (about 305 m by 33.5 m). Huge culverts, about 18 ft (5.5 m) across, run through the walls and floor; open the valves and water flows from the higher level into the chamber by gravity alone. There are no pumps. Electric locomotives called mules guide ships through. Each ship that crosses releases about 52 million gallons (about 200,000 m³) of fresh lake water to the sea.

The cost. The Culebra Cut was the hardest part. Steam shovels loaded spoil trains around the clock, and dynamite broke the rock, but slides like the great Cucaracha slide kept refilling the cut, so far more earth was removed than first planned. The cut was later named for David Gaillard, the engineer in charge there, who died in 1913. At the peak more than 40,000 people worked on the canal. Most were Black laborers from the West Indies, above all from Barbados, alongside Europeans, Panamanians and Americans. Pay and housing were divided into the “gold roll,” mostly white Americans paid in gold dollars, and the “silver roll,” mostly West Indian and other workers paid less in silver; this was a real injustice. The canal’s official records count 5,609 deaths from disease and accidents between 1904 and 1914, most of them West Indian workers. The total cost to the United States was about \$375 million.

Technology overcoming geography. On October 10, 1913, President Woodrow Wilson pressed a telegraph key in the White House, and the signal set off the charge that blew up the Gamboa dike and let the water into the cut. On August 15, 1914, the steamship *Ancon* made the first official transit, in the same month the First World War began in Europe. The deepest lesson is in the design. The French fought the Chagres; the Americans dammed it and made it the canal’s water supply. The rain that drowned the French works now fills the lake that lifts the ships. Instead of cutting the mountain all the way down, the engineers raised the ship most of the way up. The best engineering does not simply overpower geography; it works with the land God made.



The water staircase of the Panama Canal (not to scale).



The Panama Canal, about 80 km (50 mi) from deep water to deep water.

PICTURE STUDY



Man-Made Canyon at Culebra, Ernest Hallen, official photographer of the Isthmian Canal Commission (as credited on Wikimedia Commons), about 1912–1913 (published 1913) · Photograph · Published in Frederic J. Haskin, *The Panama Canal* (1913); image on Wikimedia Commons (University of Washington Freshwater and Marine Image Bank)

In 1913, the last full year of digging, photographers of the Isthmian Canal Commission recorded the Culebra Cut from its rim and floor. The commission's official photographer, Ernest Hallen, made thousands of pictures of the work from 1907 onward, and these photographs were sent to newspapers and magazines around the world.

Compare this photograph with the French photograph of Culebra from the last lesson. The place is the same, but the scale of the work, the machines and the organization are very different.

Look closely

- Count the railroad tracks you can see on the floor and the benches of the cut. What does this tell you about how the earth was moved?
- Find the steam shovels. How do they compare in size with the French machines and with the people?
- Look at the walls of the cut. Can you find places where the earth has slid or where the slope has been cut back?
- Look for a person or a railroad car you can use as a scale. About how deep and wide does the cut look?

Talk about it

1. What has changed since the French photograph, and what has stayed the same about the ground itself?

2. The workers in this photograph are hard to see. Who were most of them, and how should we remember them?
3. Why might Americans in 1913 have found photographs like this so stirring?

Safety first. An adult should cut the bottles and make any holes (a heated nail melts clean holes in plastic but is hot). Work outdoors, in a bathtub or on a towel; water on the floor is slippery.

PROJECT: A WORKING LOCK FROM BOTTLES AND TUBING

The locks at Panama have no pumps. Water simply runs downhill through culverts from the higher level into the chamber, and out of the chamber to the lower level. In this project you build a lock from bottles and plastic tubing that works exactly the same way, then measure how much water each lockage uses. This is the main project of the unit.

You will need

- Three clear 2-liter bottles (or two bottles and one clear plastic food container about the size of a shoebox for the chamber)
- About 1.5 m (5 ft) of clear plastic tubing, about 6–10 mm (1/4 to 3/8 in) across (aquarium or hardware-store tubing)
- Two binder clips or tubing clamps to use as valves
- Books or boxes to set up three different heights
- A baking pan or basin for the lower sea
- A cork, bottle cap or small foam boat
- Masking tape, a ruler and a waterproof marker
- A measuring cup marked in milliliters
- Scissors or a craft knife (adult)

Steps

1. Have an adult cut the top third off two bottles to make open tanks: one is the upper lake, the other is the lock chamber. (Or use the clear food container as the chamber.) The basin is the lower sea.
2. Stack books so the upper lake stands highest, the chamber stands next to it a little lower, and the basin sits on the table. The bottom of the chamber should be below the water level of the lake and its top above it.
3. Tape a ruler or a strip of masking tape marked in centimeters on the side of the chamber.
4. Make the filling culvert: fill one piece of tubing completely with water, pinch both ends, put one end deep in the lake and the other deep in the chamber, and clamp it with a binder clip. Make the emptying culvert the same way between the chamber and the basin. (Or have an adult melt holes near the bottoms of the containers, push the tubing through and seal it with hot glue or putty.)

5. Fill the lake. Put the boat in the chamber. Open the filling valve and time how long it takes for the chamber to fill. Mark where the water stops. Is it level with the lake?
6. Close the filling valve and open the emptying valve. Watch the boat sink with the water. Where does the level stop now?
7. Measure the water used in one lockage: measure the inside of the chamber (or find its area by pouring in 500 mL and measuring how much the level rises), then multiply the area by the height the water rose.
8. Try a staircase: add a second chamber between the first chamber and the basin and lift the boat in two steps, as at Miraflores. Compare the water used with a single big lift.

Tips

- If a siphon stops, it has an air bubble; refill the tube and try again.
- Wider or shorter tubing fills the chamber faster. Real Panama culverts are about 18 ft (5.5 m) across so a chamber fills in about ten minutes.
- Keep the clamps on the tubing when you rearrange things, or your lake will drain into the chamber.

Check your work

- My lock filled and emptied without pumps, using only gravity.
- I showed that the chamber can rise only to the level of the upper lake and fall only to the level of the lower sea.
- I measured the water used in one lockage and recorded it.
- I can explain why the Panama Canal needs a large lake of fresh water to keep running.

MAP NOTEBOOK

1. Draw the water staircase of the Panama Canal from the profile figure, labeling the Atlantic, Gatun Locks, Gatun Lake (26 m, 85 ft), Culebra Cut, Pedro Miguel, Miraflores Lake (16.5 m, 54 ft), Miraflores Locks and the Pacific.
2. Draw a lock chamber from above with its miter gates closed, and add an arrow showing which way the higher water pushes. Explain in one sentence why the gates point upstream.
3. Make a map of the canal and label the six places you would stop on a ship's transit, from Colón to Balboa.

From history. When John Stevens arrived in 1905, many workers were leaving in fear of yellow fever and the work had nearly stopped. He famously halted most digging for months while he built housing, kitchens, water and sewer systems and rebuilt the railroad. Critics complained that the dirt was not flying. Stevens believed that preparation was the work, and when digging resumed, his railroad system carried the spoil out of the Culebra Cut on trains that ran in a steady loop, so that the shovels never had to wait.

WORKED EXAMPLES

Example 1. The Gatun Locks lift ships from the sea to Gatun Lake, about 26 m (85 ft) above sea level, in three equal steps. How much does each step lift? The Miraflores Locks lower ships from Miraflores Lake, about 16.5 m (54 ft), to the sea in two steps. How much does each of those steps lower?

(Use the map or drawing “Up three steps at Gatun; down one at Pedro Miguel and two at Miraflores.” shown earlier in this lesson.)

1. Gatun: $26 \text{ m} \div 3 = 8.7 \text{ m}$ per step; $85 \text{ ft} \div 3 = 28.3 \text{ ft}$.
2. Pedro Miguel, one step: $26 - 16.5 = 9.5 \text{ m}$ ($85 - 54 = 31 \text{ ft}$).
3. Miraflores: $16.5 \text{ m} \div 2 = 8.25 \text{ m}$ per step; $54 \text{ ft} \div 2 = 27 \text{ ft}$.
4. Check: going down, $9.5 + 8.25 + 8.25 = 26 \text{ m}$, the same height the ship climbed at Gatun.

Answer: About 8.7 m (28 ft) per step at Gatun, 9.5 m (31 ft) at Pedro Miguel and about 8.25 m (27 ft) per step at Miraflores (at mean sea level; Pacific tides change the lowest step).

Example 2. A lock chamber is 305 m long and 33.5 m wide. How much water does it take to raise the level 8.7 m? Give the answer in cubic meters and in U.S. gallons ($1 \text{ m}^3 = 264.2 \text{ gal}$).

1. Area of the chamber floor: $305 \times 33.5 = 10,218 \text{ m}^2$.
2. Volume: $10,218 \times 8.7 = 88,900 \text{ m}^3$ (rounded).
3. Gallons: $88,900 \times 264.2 = 23,490,000 \text{ gal}$, about 23.5 million gallons.
4. A ship crossing from sea to sea drains one top chamber at Gatun and one at Pedro Miguel into lower levels, and the water used at each top step comes from the lakes. Roughly $89,000 + 97,000$ (at Pedro Miguel, $10,218 \times 9.5$) $= 186,000 \text{ m}^3$, close to the 52 million gallons (about $197,000 \text{ m}^3$) usually quoted.

Answer: About $89,000 \text{ m}^3$ (about 23.5 million gallons) for one 8.7 m lift; a full transit uses roughly $200,000 \text{ m}^3$ (about 52 million gallons) of lake water.

Example 3. Gatun Lake covers about 425 km². Suppose 40 ships a day cross, each using about 200,000 m³ of lake water, and no rain falls. How much does the lake fall each day? How much over a 120-day dry season?

1. Water used per day: $40 \times 200,000 = 8,000,000 \text{ m}^3$.
2. Lake area in m²: $425 \text{ km}^2 \times 1,000,000 = 425,000,000 \text{ m}^2$.
3. Daily drop = volume $\div$ area = $8,000,000 \div 425,000,000 = 0.0188 \text{ m}$, about 1.9 cm (3/4 in).
4. Over 120 days: $0.0188 \times 120 = 2.26 \text{ m}$, about 2.3 m (7.4 ft), before counting evaporation and water for the cities.

Answer: About 1.9 cm a day and about 2.3 m (7 ft) over a dry season. This is why the canal depends on the rainy season to refill Gatun Lake, and why a dry year forces limits on ship drafts and transits.

PRACTICE

1. **EASY** Match each man to his work: Gorgas, Stevens, Goethals, Gaillard.
2. **EASY** List the three sets of locks in order from the Atlantic to the Pacific, with the number of steps in each.
3. **EASY** Name three things Gorgas's teams did to fight mosquitoes.
4. **EASY** When and by what ship was the first official transit of the Panama Canal made?
5. **MEDIUM** Convert the lock chamber dimensions, 1,000 ft by 110 ft, to meters (1 ft = 0.3048 m). What is the floor area in square meters and in square feet?
6. **MEDIUM** Using the profile figure, a ship enters at Balboa and leaves at Colón. List every change in water level it experiences, with heights.
(Use the map or drawing "Read the profile from right to left for a Pacific-to-Atlantic transit." shown earlier in this lesson.)
7. **MEDIUM** Why do the miter gates of a lock point upstream, toward the higher water?
8. **MEDIUM** Explain why the Panama Canal needs no pumps to fill or empty its locks.
9. **HARD** The tide range at the Pacific end is up to about 6 m (20 ft), while at the Atlantic end it is only about 0.5 m (under 2 ft). At extreme low tide in the Pacific, the sea stands about 3 m below mean sea level. How much does the bottom Miraflores step have to lower a ship then? Why did this matter for a sea-level canal plan?
10. **HARD** The French fought the Chagres River; the Americans used it. Explain this sentence in four to six sentences.
11. **CHALLENGE** In a dry year Gatun Lake stands 1.5 m below normal. A ship normally allowed a draft of 12 m must now leave enough room under her keel. If the channel depth falls by the same 1.5 m and the keel clearance must stay the same, what is her new maximum draft? How much cargo must a ship that carries about 6,000 tonnes per meter of draft leave behind?
12. **CHALLENGE** Write a paragraph: Who built the Panama Canal? Weigh the roles of leaders, doctors, engineers and laborers, and include the gold roll and silver roll.

COMMON MISTAKES

- Thinking ships are pumped up and down. The locks work by gravity; all the water comes from Gatun Lake and Miraflores Lake.
- Saying the canal runs east to west. A ship from the Atlantic to the Pacific travels southeast.
- Forgetting the workers. Engineers designed the canal, but most of the digging, and most of the dying, was done by West Indian laborers.

Make it a game · Transit Race. Make a board of eleven squares: Colón, Gatun step 1, Gatun step 2, Gatun step 3, Gatun Lake, Culebra Cut, Pedro Miguel, Miraflores Lake, Miraflores step 1, Miraflores step 2, Balboa. Players roll a die to move, but at each lock square they must answer a question card (a lift height, a name, a date, a conversion) before they may pass. A wrong answer means waiting a turn for the chamber to fill. The first ship to reach the Pacific wins.

Scripture. “And God blessed them, and God said unto them, Be fruitful, and multiply, and replenish the earth, and subdue it: and have dominion over the fish of the sea, and over the fowl of the air, and over every living thing that moveth upon the earth.” (Genesis 1:28, KJV)

God made people to work with His creation, not to worship it or merely to fear it. The canal shows both sides of that calling: wise dominion that turned a deadly river into a lake that serves the world, and the duty to treat the workers who build such things as fellow bearers of God’s image.

Practice answers

1. Gorgas: chief sanitary officer who defeated yellow fever and reduced malaria. Stevens: chief engineer 1905–1907 who rebuilt the railroad system and won the lock plan. Goethals: Army engineer who led the work from 1907 to completion in 1914. Gaillard: engineer in charge of the Culebra Cut, later named for him.
2. Gatun (3 steps up), Pedro Miguel (1 step down), Miraflores (2 steps down).
3. Any three: screened windows and doors; fumigated houses; drained swamps and puddles; spread oil on standing water to kill larvae; gave Panama City and Colón piped water so open water barrels were no longer needed.
4. August 15, 1914, by the SS *Ancon*.
5. $1,000 \times 0.3048 = 304.8$ m; $110 \times 0.3048 = 33.5$ m. Area: $110,000 \text{ ft}^2$, or $304.8 \times 33.5 = 10,211 \text{ m}^2$ (about $10,200 \text{ m}^2$).
6. Up two steps at Miraflores from sea level to Miraflores Lake (16.5 m, 54 ft); up one step at Pedro Miguel to the level of Gatun Lake (26 m, 85 ft); through the Culebra Cut and across Gatun Lake; down three steps at Gatun to sea level.
7. So the higher water pushes the two leaves together and presses them tightly shut, like an arch; the greater the difference in level, the tighter the seal. Gates pointing the other way would be pushed open.

8. Water flows by gravity from a higher level to a lower one. To fill a chamber, valves open culverts from the higher lake or chamber; to empty it, culverts drain it to the next lower level. The lakes are kept full by rain on the Chagres watershed, so the rain is the canal's power.
9. $8.25 + 3 =$ about 11.25 m (about 37 ft). For a sea-level canal, the large Pacific tide against the small Atlantic tide would have driven strong currents back and forth through the channel, so even sea-level plans needed a tidal lock at the Pacific end.
10. A sea-level canal would have been the lowest ground in the Chagres valley, so the river's floods would have poured into it with silt and strong currents. The French had no good answer. The Americans built the Gatun Dam across the Chagres and let it fill Gatun Lake, 26 m above the sea. The lake became the canal's main highway and the water source for every lockage. The heavy rains that ruined the French works now refill the lake each rainy season. An obstacle became the power supply.
11. $12 - 1.5 = 10.5$ m. Cargo left behind: $1.5 \times 6,000 =$ about 9,000 tonnes. This is why droughts at Panama reduce trade even though no machinery breaks.
12. Answers vary. A strong answer credits Roosevelt's determination, Gorgas's defeat of yellow fever, Stevens's railroad system and lock plan, Goethals's leadership and the engineers like Gaillard; but it stresses that tens of thousands of workers, most of them West Indian, especially Barbadian, did most of the labor and most of the dying (5,609 recorded deaths, mostly West Indian). It names the gold roll and silver roll as a system that paid and housed workers unequally, largely by race and nationality, and calls it a wrong without denying the achievement.

3.4 KIEL AND CORINTH

OBJECTIVES

- Tell the stories of the Kiel Canal (1887–1895) across the base of Jutland and the Corinth Canal (1882–1893) across the Isthmus of Corinth, including the ancient Diolkos and Nero's failed canal.
- Explain why the Kiel Canal has locks even though it is nearly at sea level, and why the Corinth Canal, though a marvel, carries little trade today.
- Measure and compare the routes each canal shortens, and judge a canal's value by distance saved, traffic, ship size and cost.

Warm-up. Put a toy boat or a small box with a few coins in it on a smooth table and drag it 50 cm (20 in) with a rubber band hooked to it. Watch how far the rubber band stretches. Now lay three pencils under the boat as rollers and drag it again. Finally float it in a pan of water and pull it with the same rubber band. Which way needs the least force? You have just compared a slipway, a rolling road and a canal.

Watch. *The World's Deepest Canal | Europe From Above S2 | National Geographic UK* (National Geographic UK, 3:17). https://www.youtube.com/watch?v=iK-BujpY_uY
With the problem geography posed at Corinth: the world's deepest canal from the air.

Backup video. *What is the Story of Ancient Corinth?* (Drive Thru History with Dave Stotts, 5:16). https://www.youtube.com/watch?v=jiRM_FEqJmI
With the history note: the story of ancient Corinth and the Diolkos.

KEY TERMS

Diolkos

A paved trackway across the Isthmus of Corinth, used from about the 6th century BC, over which ships and cargo were hauled between the two gulfs.

tide lock

A lock at the mouth of a canal whose main purpose is not to climb a hill but to keep rising and falling sea tides from running into the canal.

Jutland

The peninsula of Denmark and northern Germany that separates the North Sea from the Baltic; its northern tip is the Skaw (Skagen).

Sound Dues

Tolls that Denmark charged ships passing the Øresund strait into and out of the Baltic for about four centuries, until 1857.

submersible bridge

A bridge that sinks below the water to let ships pass over it, then rises again for traffic; there is one at each end of the Corinth Canal.

dreadnought

A type of large, heavily armed battleship named for HMS *Dreadnought* (1906); the Kiel Canal was widened so Germany's dreadnoughts could use it.

CORE IDEAS

The story. In June 1895 Kaiser Wilhelm II of Germany stood aboard his yacht *Hohenzollern* as it led a procession of ships from the mouth of the Elbe across Holstein to the Baltic port of Kiel. Warships from many nations, including Britain and the United States, had come for the opening of the canal his grandfather Wilhelm I had begun in 1887. It was named the Kaiser-Wilhelm-Kanal, and it ran about 98 km (61 mi) through farmland and marsh. Two years earlier, in 1893, far to the south in Greece, a much shorter canal had opened: a narrow, straight slot cut through solid rock across the Isthmus of Corinth, finishing a project that the Greeks and Romans had dreamed of for more than two thousand years.

The problem geography posed at Kiel. The peninsula of Jutland sticks up between the North Sea and the Baltic like a thumb. A ship from Hamburg or London bound for Kiel, Danzig, Stockholm or St. Petersburg had to sail north around the Skaw (Skagen), where the shallow, stormy waters of the Skagerrak and Kattegat claimed many wrecks, and then pass through the narrow Danish straits. For about four centuries Denmark had charged the **Sound Dues** on ships passing the Øresund, until they were abolished in 1857. A small canal, the Eider Canal, had crossed Holstein since 1784, but it was far too small for steamships. After Prussia and Austria took Schleswig and Holstein from Denmark in 1864, a large canal could be dug entirely on German soil. The new German Empire also had a strategic reason: its navy was split between two seas. A canal would let the fleet move from the Baltic to the North Sea without passing through Danish waters.

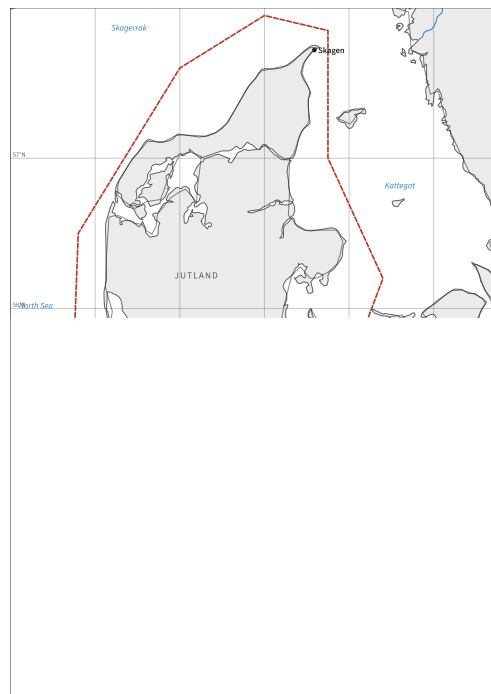
How it worked. Unlike Panama, the Kiel Canal crosses low country, and its water lies close to sea level. Yet it has locks at both ends, at Brunsbüttel on the Elbe and at Kiel-Holtenau on the Baltic. They are **tide locks**. The North Sea tide in the mouth of the Elbe rises and falls about 3 m (10 ft) twice a day, while the nearly tideless Baltic changes level with wind and weather. Without locks, the canal would become a river running first one way and then the other. Thousands of workers dug the canal in eight years. Soon after it opened, Britain launched HMS *Dreadnought* (1906), and battleships suddenly grew too big for the canal. From 1907 to 1914 Germany widened and deepened it and built new, larger locks. The work was finished in June 1914, weeks before the First World War. After the war, the Treaty of Versailles opened the canal to the ships of all nations at peace with Germany, and in 1923, in the case of the steamship *Wimbledon*, the Permanent Court of International Justice ruled that Germany had to honor that promise. Today the Kiel Canal is the busiest artificial waterway in the world by number of ships, and it saves an average of about 250 nautical miles (460 km) compared with the route around Jutland.

The problem geography posed at Corinth. The Peloponnese is nearly an island, joined to mainland Greece by an isthmus only about 6 km (4 mi) wide. A ship from Athens to Italy had to sail around the southern capes, such as Cape Malea, feared by sailors for its sudden winds. Ancient Corinth grew rich on this isthmus, with two harbors: Lechaëum on the Gulf of

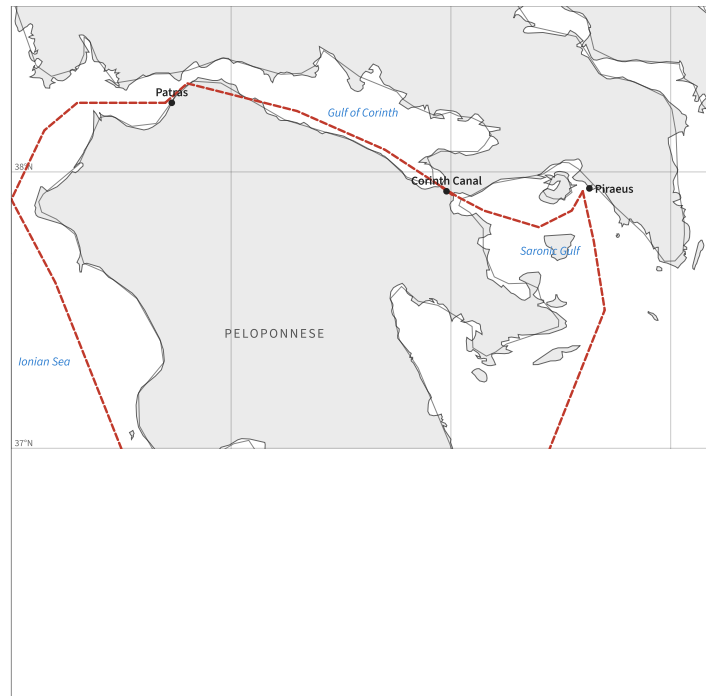
Corinth to the west and Cenchreae on the Saronic Gulf to the east. From about the 6th century BC, goods, and sometimes whole ships, were dragged across on the **Diolkos**, a paved road whose grooved stones can still be seen. In AD 67 the emperor Nero began a canal himself, striking the ground with a golden tool. The Jewish historian **Josephus** records that the Roman general Vespasian sent six thousand of the strongest young prisoners from the war in Judea to Nero to dig through the isthmus. After Nero's death the next year, the work was abandoned. The apostle Paul knew this isthmus well: he lived in Corinth for a year and a half, and a church met at Cenchreae.

How it worked at Corinth. The modern canal was begun in 1882 by a company led by the Hungarian general István Türr, ran into money trouble, and was finished by a Greek company in 1893. It is a sea-level canal with no locks: about 6.4 km (4 mi) long, roughly 21 to 25 m (70 to 80 ft) wide and about 8 m (26 ft) deep, cut straight down through rock walls that in places rise more than 60 m (200 ft). It was a marvel, but it came too late and too small. Ships were growing fast, the narrow channel had strong currents, and its walls shed rock slides that have closed it many times. Today it carries mostly yachts and small cruise ships, and at each end a **submersible bridge** sinks to let them pass.

The big idea. A shortcut is worth building only if enough ships need it and can fit through it. Kiel sits across one of the busiest trade lanes in Europe, between the North Sea and the Baltic, and it was built, then rebuilt, big enough for the ships of its day. Corinth saves a voyage of a few hundred kilometers around the Peloponnese, but most large ships cannot fit, so they still go around. When you judge a canal, multiply the distance it saves by the traffic that can use it, and weigh that against the cost of building and keeping it open.



The Kiel Canal saves ships the long voyage around Jutland and through the Danish straits.



The Corinth Canal cuts the isthmus that joins the Peloponnese to mainland Greece.

PICTURE STUDY



Vue du Canal de Corinthe (View of the Corinth Canal), Unknown photographer, about 1893–1910 · Collotype print from a photograph · Boston Public Library, Arts Department (Nicholas Catsimpooulas Collection), via Digital Commonwealth; image on Wikimedia Commons

This photograph was printed as a souvenir for travelers not long after the Corinth Canal opened in 1893. The number 18 and the French title *Vue du Canal de Corinthe* are written in the lower corner, so it was probably one of a numbered set of views of Greece. We do not know who took it. The print is now in the Boston Public Library.

Compare it with the wide, terraced Culebra Cut. At Corinth the engineers did not cut slopes and steps. They cut almost straight down through the rock of the isthmus, nearly 80 meters at the deepest point, and left a channel only about 25 meters wide at the water.

Look closely

- Follow the canal into the distance. How straight is it, and why could the builders make it so straight?
- Look at the two walls. Is one side steeper than the other? How do they compare with the slopes of the Suez Canal or the Culebra Cut, and what does this tell you about the rock?
- Find the steamship. Compare its width with the width of the water, and its height with the height of the walls.
- Find the small boat and the narrow ledge at the foot of each wall. What might they be for?

Talk about it

1. Would you want to steer a large ship through this channel in a strong wind? Why or why not?
2. What does the picture suggest about why the Corinth Canal never carried as much trade as Kiel?

PROJECT: HAUL IT OR FLOAT IT? THE DIOLKOS TEST AND THE SHORTCUT LEDGER

Before there was a canal at Corinth, people dragged cargo and ships across the isthmus. In the first part of this project you measure how much force it takes to move a load by dragging, by rolling and by floating, as the Corinthians and Nero would have understood it. In the second part you measure the routes around Jutland and the Peloponnese with string and build a ledger of what each canal saves.

You will need

- A small plastic box or toy boat that floats
- Coins or washers for cargo
- A rubber band and a ruler (or a small spring scale)
- Six round pencils or dowels for rollers
- A long pan or bathtub with water
- A printed map or atlas page of Denmark and northern Germany, and one of Greece
- Thin string and a fine marker

Steps

1. Load the box with 20 coins. Hook the rubber band to it and drag it across a table at a steady pace. Measure how long the rubber band stretches.
2. Lay the pencils under the box as rollers, like a slipway, and drag it again. Measure the stretch.

3. Float the box in the water and pull it at a slow, steady pace. Measure the stretch. Record all three in a table.
4. Repeat with 40 coins. How does doubling the load change each method?
5. On the map of Jutland, lay the string along a ship's route from the mouth of the Elbe around Skagen and down to Kiel, keeping offshore. Mark it, straighten it on the map's scale bar and convert to kilometers and nautical miles. Then measure the route through the canal.
6. Do the same on the map of Greece, from Piraeus to Patras, around the capes and through the canal.
7. Make a shortcut ledger with columns: Canal, Route around, Route through, Distance saved, Hours saved at 12 knots. Fill in a row for each canal.

Tips

- Pull slowly and steadily; jerking the rubber band gives false readings.
- Sailing ships could not sail close to the shore, so keep your string well out from the coast when you measure around the capes.

Check your work

- I measured the force to drag, roll and float the same load and found that floating needs the least.
- I measured the long and short routes for both canals with string and a scale bar.
- My ledger shows distance and time saved, and I can explain why Kiel carries far more ships than Corinth.

MAP NOTEBOOK

1. Draw a sketch map of Jutland with the North Sea, the Baltic, the Elbe, Brunsbüttel, Rendsburg, Kiel, Skagen and the Øresund, and draw both routes.
2. Draw a sketch map of the Isthmus of Corinth showing ancient Corinth, Lechaëum, Cenchreæ, the line of the Diolkos and the modern canal. Note where Paul lived and where the church at Cenchreæ met.
3. Midterm review: make a one-page timeline of every technology in Units 1–3, from the stern rudder to the Panama Canal, with a date and the geographic problem each one solved.

From history. When the Kiel Canal's widened locks were reopened in June 1914, Britain sent a squadron of battleships to Kiel for the celebrations of Kiel Week as a gesture of friendship. On June 28, while the British and German officers were still enjoying the festivities, news arrived that Archduke Franz Ferdinand of Austria had been assassinated at Sarajevo. Within weeks the two navies whose sailors had dined together were at war.

WORKED EXAMPLES

Example 1. On average the Kiel Canal saves about 250 nautical miles compared with the route around Jutland. A cargo ship cruises at 12 knots at sea, but inside the 98 km canal she must slow to about 8 knots. About how many hours does she save?

1. Time to sail the 250 extra nautical miles at sea: $250 \div 12 = 20.8$ hours.
2. Canal length in nautical miles: $98 \div 1.852 = 52.9$ nmi.
3. Extra time for going slowly in the canal: at 8 knots, $52.9 \div 8 = 6.6$ h; at 12 knots it would be $52.9 \div 12 = 4.4$ h; the difference is 2.2 h.
4. Net saving: $20.8 - 2.2 = 18.6$ hours (not counting time spent in the locks).

Answer: About 18 to 19 hours, nearly a full day, plus the safety of avoiding the stormy waters off Skagen.

Example 2. Model the Corinth Canal as about 21 m wide at the bottom. If a pilot requires at least 2 m of clearance on each side of a ship, what is the widest ship that can pass? Can a Panamax ship, 32.3 m wide, use the canal?

1. Clearance on both sides: $2 \times 2 = 4$ m.
2. Widest ship: $21 - 4 = 17$ m (about 56 ft).
3. A Panamax ship is 32.3 m wide, nearly twice that.

Answer: About 17 m (56 ft). A Panamax ship cannot fit, which is why most cargo ships still sail around the Peloponnese.

Example 3. Brunsbüttel is at about 53.90° N, 9.14° E and Kiel-Holtenau at about 54.37° N, 10.14° E. Find the straight-line distance and the general direction from Brunsbüttel to Kiel. (One degree of latitude is about 111 km; one degree of longitude at 54° N is about 65 km.) Compare with the canal's 98 km.

(Use the map or drawing "Brunsbüttel to Kiel." shown earlier in this lesson.)

1. North: $54.37 - 53.90 = 0.47^\circ$; $0.47 \times 111 = 52$ km.
2. East: $10.14 - 9.14 = 1.00^\circ$; $1.00 \times 65 = 65$ km.
3. Straight line: $\sqrt{(52^2 + 65^2)} = \sqrt{(2,704 + 4,225)} = \sqrt{6,929} = 83$ km (about 52 mi).
4. More east than north, so the direction is east-northeast to northeast. The canal is 98 km, about 15 km longer, because it bends to follow low ground and old waterways.

Answer: About 83 km (52 mi), roughly northeast; the canal adds about 15 km by following the lowlands.

PRACTICE

1. **EASY** Give the opening year, length and the two end points of the Kiel Canal.
2. **EASY** What was the Diolkos, and about when was it used?
3. **EASY** Who began a canal at Corinth in AD 67, and what does Josephus say about the workers?
4. **EASY** Name Corinth's two ancient harbors and the gulf each faced.
5. **MEDIUM** The Kiel Canal is nearly at sea level. Why does it have locks?
6. **MEDIUM** Convert: Kiel Canal 98 km and Corinth Canal 6.4 km into statute miles and nautical miles.
7. **MEDIUM** Why did Germany widen the Kiel Canal from 1907 to 1914?
8. **MEDIUM** Using the Corinth map, a route measured on a chart from Piraeus to Patras is roughly 115 nautical miles through the canal and roughly 300 nautical miles around the southern capes. How much does the canal save, in nautical miles and kilometers, and how many hours at 10 knots?
(Use the map or drawing "Through the isthmus or around the capes." shown earlier in this lesson.)
9. **HARD** In your warm-up and project, why did floating need the least force? Explain why that made the Diolkos a costly second-best and a canal worth dreaming of for two thousand years.
10. **HARD** What was the *Wimbledon* case (1923), and what does it show about canals and nations?
11. **CHALLENGE** Kiel carries tens of thousands of ships a year; Corinth only a small fraction of that. Use the rule "value $\approx$ distance saved $\times$ traffic that can fit" to explain the difference, naming at least three geographic or engineering factors.
12. **CHALLENGE** Write a paragraph comparing Kiel and Corinth with Suez and Panama. Which canal is most like Suez, and which most like Panama? Defend your choice.

COMMON MISTAKES

- Thinking every canal with locks climbs over a hill. The Kiel Canal's locks mainly keep out the tides.
- Placing the Corinth Canal on an island. The Peloponnese is a peninsula joined to the mainland by the isthmus; the canal is what makes it act like an island.
- Assuming any canal is valuable. A shortcut that big ships cannot use, or that few ships need, may save little.

Make it a game • Which Way Around? Set out a map of Europe. One player names a voyage, such as Hamburg to Stockholm, London to Riga, Piraeus to Brindisi, Rotterdam to Kiel or Athens to Venice. Others decide: through Kiel, through Corinth, or around? Then they must give one reason, such as ship size, tides, distance or weather. One point for the right route and one for a good reason. Bonus point for naming the cape or strait the long route would pass.

Scripture. “After these things Paul departed from Athens, and came to Corinth;” (Acts 18:1, KJV)

Paul chose great crossroads for his work. Corinth sat on the isthmus between two seas, with harbors facing east and west, so sailors, merchants and travelers passed through constantly. A church planted at a crossroads could send the gospel in every direction.

Practice answers

1. 1895; about 98 km (61 mi); Brunsbüttel on the Elbe and Kiel-Holtenau on the Baltic.
2. A paved trackway across the Isthmus of Corinth on which cargo and sometimes ships were hauled between the Gulf of Corinth and the Saronic Gulf, from about the 6th century BC.
3. The emperor Nero. Josephus says Vespasian sent six thousand of the strongest young Jewish prisoners from the war in Judea to Nero to dig through the isthmus.
4. Lechaëum on the Gulf of Corinth (west) and Cenchreae on the Saronic Gulf (east).
5. They are tide locks. The Elbe at Brunsbüttel has a tide of about 3 m twice a day, and the Baltic level changes with wind and weather. The locks keep these changes out so the canal does not become a current flowing back and forth.
6. Kiel: $98 \div 1.609 = 61$ mi; $98 \div 1.852 = 53$ nmi. Corinth: $6.4 \div 1.609 = 4.0$ mi; $6.4 \div 1.852 = 3.5$ nmi.
7. After HMS *Dreadnought* (1906), battleships grew much larger. The German navy needed its new big ships to move between the Baltic and the North Sea, so the canal was widened, deepened and given larger locks; the work was finished in June 1914.
8. About 185 nmi; $185 \times 1.852 =$ about 340 km (about 210 mi); $185 \div 10 = 18.5$ hours.
9. Water holds up the weight of a floating load (buoyancy), so the only force needed is to overcome the water’s drag, which is small at slow speed. Dragging or rolling has to fight friction on the whole weight. On the Diolkos, gangs of men or animals had to haul heavy loads and ships uphill and down, slowly; a canal would let ships float across with little effort and no unloading.
10. Germany refused passage through the Kiel Canal to the British steamship *Wimbledon* carrying munitions to Poland during the Polish–Soviet War. The Permanent Court of International Justice ruled that under the Treaty of Versailles Germany had to let the ship through. It shows that once a canal becomes a major international route, other nations seek treaty rights over it, even when it lies wholly within one country.
11. Kiel lies across one of Europe’s busiest trade lanes (North Sea to Baltic) and saves about 250 nmi around stormy Skagen and through the Danish straits; it is wide and deep enough for most ships of its region. Corinth saves a voyage around the Peloponnese of a similar order, but it is only about 21–25 m wide and 8 m deep, too small for most modern cargo ships; it has strong currents and rock slides that close it; and the trade it would serve (Aegean to Adriatic) can also use large ports elsewhere. So far less traffic can use it.
12. Answers vary. A good answer might say Corinth is most like Suez: a short sea-level cut with no locks across an isthmus between two seas at the same level, but in rock instead of sand. Kiel shares something with Panama: it has locks and was shaped by national strategy and the need to move warships, though its locks are for tides, not for climbing a hill. Strong answers use dimensions, dates and the reason each has or lacks locks.

3.5 WHAT CANALS CHANGED

OBJECTIVES

- Measure how Suez and Panama shortened the world's great sea routes, and compute distances and voyage times before and after each canal.
- Explain how canals rerouted trade, set the size of ships (Panamax and Neopanamax) and created new choke points.
- Describe how canals reshaped strategy, from the voyage of USS *Oregon* (1898) and Mahan's ideas to the Suez Crisis (1956), the closure of 1967–1975 and the return of the Panama Canal to Panama (1999), presenting each factually.

Warm-up. Take a globe (or a world map) and a piece of string. Stretch the string from New York to San Francisco along the sea, around the tip of South America, keeping offshore. Mark it. Now stretch it again through Panama. Lay the two pieces side by side. Without measuring, guess what fraction of the voyage the canal saves.

Watch. *The 1956 Suez Crisis: History Matters (Short Animated Documentary)* (History Matters, 3:42). <https://www.youtube.com/watch?v=xICnObSHU0M>
With Strategy reshaped: the Suez Crisis of 1956 in under four minutes.

Backup video. *Why did the US side against Britain and France during the Suez Crisis? (Short Animated Documentary)* (History Matters, 3:21). <https://www.youtube.com/watch?v=4358hILcYgM>
As follow-up: why the United States sided against Britain and France in 1956.

KEY TERMS

choke point

A narrow passage on a major route, such as a strait or canal, where traffic is concentrated and can be blocked or controlled.

Panamax

The largest ship that fits the original Panama locks: about 294 m (965 ft) long, 32.3 m (106 ft) wide and 12 m (39.5 ft) of draft.

Neopanamax

The largest ship that fits the new Panama locks opened in 2016: about 366 m (1,200 ft) long and 49 m (161 ft) wide, with about 15.2 m (50 ft) of draft.

sea power

A nation's strength at sea: its navy, merchant ships, ports and bases. Alfred Thayer Mahan argued in 1890 that it was the key to national greatness.

transit

One passage of a ship through a canal from one end to the other.

nationalization

A government taking ownership of a private company or property, as Egypt did with the Suez Canal Company in 1956.

CORE IDEAS

The story. On March 19, 1898, as war with Spain loomed, the new battleship USS *Oregon* steamed out of San Francisco Bay under orders to join the fleet in the Atlantic. There was no canal. The *Oregon* raced south along two continents, through the Strait of Magellan in a gale, and north again up the coast of South America, coaling where she could. She reached the coast of Florida on May 24, after a voyage of about 14,000 nautical miles in some 67 days, in time to fight at the Battle of Santiago de Cuba in July. Americans followed her progress in the newspapers with pride and alarm. Her voyage proved that a battleship could make such a trip, but it also showed that in a war on two oceans, an American fleet on one coast was two months from the other. The demand for a canal at the isthmus became almost irresistible.

Distance saved. The great canals changed the shape of the world map for sailors. Suez cut London to Bombay from about 10,700 to about 6,300 nautical miles. Panama cut New York to San Francisco from about 13,000 nautical miles around Cape Horn to about 5,200, a saving of nearly 8,000. On the map, the curving loops around Africa and South America collapse into short lines through the isthmuses. Ports changed too. Places on the old routes, like Cape Town and the coaling ports of the Strait of Magellan, lost through traffic, while Port Said, Aden, Colón and Balboa became busy junctions. Countries gained new neighbors by sea: the west coast of the United States moved closer to Europe and the east coast closer to Asia.

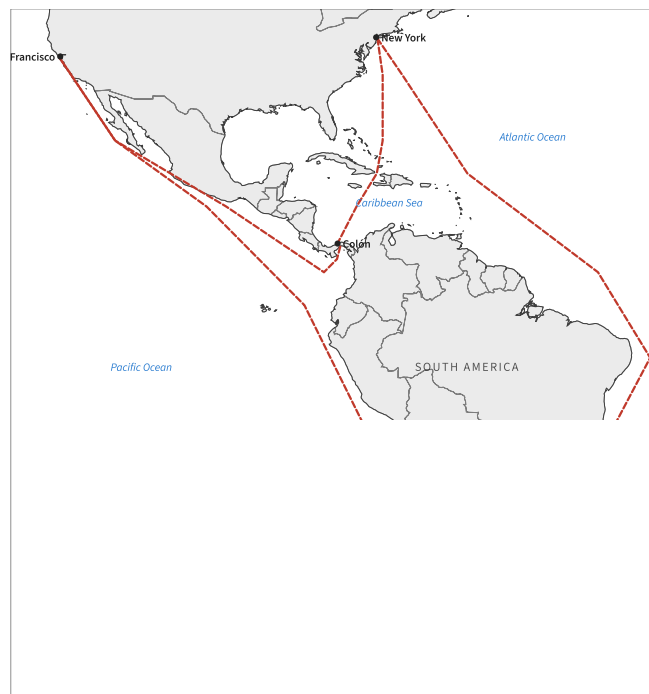
Trade rerouted and ships reshaped. Canals do not merely shorten trips; they set rules. A ship that wants to use Panama must fit its locks. For nearly a century naval architects designed ships to the **Panamax** limit: 32.3 m (106 ft) wide, in chambers 33.5 m (110 ft) wide. Some ships, especially big oil tankers and the largest container ships, grew too big and went around the capes instead. In 2016 Panama opened new, larger locks, the Agua Clara locks on the Atlantic side and the Cocolí locks on the Pacific, for **Neopanamax** ships up to 49 m (161 ft) wide. Suez has no locks, so its limits are depth and width, and it has been deepened and widened many times. Today the two canals together carry a large share of the world's seaborne trade; Suez is often estimated at about 12 percent of world trade and Panama at about 5 percent.

Strategy reshaped. In 1890 the American naval officer **Alfred Thayer Mahan** published *The Influence of Sea Power upon History, 1660–1783*. He argued that great nations rose on sea power: navies, merchant fleets, bases and control of the sea lanes. He urged an isthmian canal and American strength in the Caribbean, its approaches. Leaders such as Theodore Roosevelt read him closely. Canals became prizes and liabilities at once. Britain called Suez the route to India and occupied Egypt in 1882 in part to protect it. When Russia's Baltic Fleet sailed to the Far East in 1904–1905, its largest battleships went the long way around Africa rather than through the British-dominated canal, and after a voyage of seven months they were destroyed at Tsushima in May 1905. In 1956 Egypt's president Gamal Abdel Nasser nationalized the Suez Canal Company; Britain, France and Israel attacked, then

withdrew under pressure from the United States and the Soviet Union. After the war of 1967 the canal was closed for eight years, trapping fifteen merchant ships in the Great Bitter Lake, known as the Yellow Fleet from the desert dust that covered them. Oil companies responded by building supertankers too big for the canal, to carry oil the long way around Africa more cheaply. At Panama, the Torrijos-Carter Treaties of 1977 arranged the transfer of the canal, and on December 31, 1999, Panama took full control. People have judged these events differently, and students should weigh the arguments made on each side.

The big idea. A canal overcomes one geographic barrier by creating another: a narrow point where traffic concentrates. In March 2021 the giant container ship *Ever Given* ran aground across the Suez Canal in a sandstorm and blocked it for six days; hundreds of ships waited at each end. In 2023 a long dry season left Gatun Lake so low that Panama limited transits and ship drafts. Physical geography still rules the shortcut: wind, rain, sand and water supply. Canals shrink the world, but they also make the whole world depend on a few narrow places.

On the map. On your map of voyages before and after, look at how the canals pulled the world's sea lanes toward the middle of the map. The Mediterranean, once a dead end for Asian trade, became a highway. The Caribbean became the crossroads of the Americas. And notice the choke points that came with them: Gibraltar and Bab-el-Mandeb on the Suez route, the Windward and Mona Passages and the Yucatán Channel on the approaches to Panama.



New York to San Francisco: about 13,000 nautical miles by Cape Horn and about 5,200 by Panama.

PICTURE STUDY



The SS Ancon entering Pedro Miguel Locks on opening day, August 15, 1914, Photographer of the Panama Canal (official canal photographs of this period were made under Ernest "Doc" Hallen), August 15, 1914 · Photograph · U.S. National Archives, Records of the Panama Canal (Record Group 185), photograph 185-G-0889; image on Wikimedia Commons

The *Ancon* was a cargo and passenger steamer owned by the Panama Railroad. On August 15, 1914, she made the first official transit of the Panama Canal from the Atlantic to the Pacific, carrying canal officials and guests. Because the First World War had begun in Europe less than three weeks earlier, the grand opening the United States had planned was cancelled, and the event made smaller headlines than it deserved.

Photographs of the *Ancon* show the moment the long work of the French and the Americans began to pay off: an ordinary working ship, crossing a continent in a day.

Look closely

- Find the people on deck. What do you think they were feeling?
- Look at the lock walls or the banks. How close is the ship to the sides?
- Compare the size of the *Ancon* with the size of the lock chambers you studied. Would a modern container ship fit?
- Look for the towing locomotives, ropes or the canal's workers.

Talk about it

1. Why might a quiet opening, overshadowed by a world war, be a fitting picture of what canals do: change the world without much ceremony?
2. If you had been on board, what would you have written home about?

PROJECT: VOYAGES BEFORE AND AFTER: THE CANAL MAP

This is the map for the whole unit. You will draw the world's great sea routes before and after Suez and Panama, measure them with string, and build a table of voyage times for a sailing ship, an 1870s steamer and a modern container ship.

You will need

- A large outline world map (an equal-area or Robinson map is best) or a sheet of poster paper and an atlas to trace from
- A globe and thin string
- Colored pencils or markers in two colors
- Ruler and calculator
- The voyage table below, copied into your notebook

Steps

1. Mark these ports: London, New York, San Francisco, Bombay (Mumbai), Shanghai, Yokohama, Cape Town, Port Said, Colón and Balboa.
2. Draw four routes in the before color: London to Bombay by the Cape of Good Hope; New York to San Francisco by Cape Horn; London to Shanghai by the Cape; New York to Yokohama by Cape Horn or the Cape.
3. Draw the same four routes in the after color through Suez or Panama.
4. On the globe, measure each route with string, keeping offshore and following the sea lanes. Convert with the globe's scale (or by comparing the string with the length of the equator, 21,600 nautical miles) and record the distance.
5. Make a table with columns: Voyage, Before (nmi), After (nmi), Saved (nmi), Saved (percent), Days at 6 knots (sailing ship average), Days at 10 knots (1870s steamer), Days at 18 knots (container ship).
6. Mark the choke points each new route passes with a small red triangle and label them.
7. Write a caption at the bottom: three sentences on what the canals changed.

Tips

- A globe gives honest distances; a flat map stretches the high latitudes. Measure on the globe and draw on the map.
- Compare your string measurements with the figures in the lesson. Within 10 percent is good work.

Check your work

- My map shows four routes before and after, in two colors, with ports and choke points labeled.
- My table gives distances, savings and times for three kinds of ships.
- My caption explains distance saved, trade rerouted and strategy reshaped.

MAP NOTEBOOK

1. Draw two small world sketches side by side, “1860” and “1920,” showing the main routes from Europe to Asia and from the U.S. East Coast to the West Coast.
2. Draw the outlines of a Panamax ship and a Neopanamax ship to the same scale (1 cm = 20 m) from above, inside outlines of the old and new lock chambers.
3. List six choke points created or made more important by the canals and draw a symbol for each on a world map.

From history. In 1928 the American adventurer and writer Richard Halliburton swam the length of the Panama Canal over about ten days, under the watch of a rowboat crew. Like every vessel, he had to pay a toll based on tonnage. He weighed 140 pounds, and his toll was 36 cents, still the lowest toll ever paid in the canal’s history.

WORKED EXAMPLES

Example 1. New York to San Francisco is about 13,000 nautical miles by Cape Horn and about 5,200 by Panama. Find the distance saved in nautical miles, kilometers and statute miles, the percent saved, and the days saved for a ship at 15 knots.

(Use the map or drawing “Cape Horn versus Panama.” shown earlier in this lesson.)

1. Saved: $13,000 - 5,200 = 7,800$ nmi.
2. Kilometers: $7,800 \times 1.852 = 14,446$, about 14,400 km. Statute miles: $7,800 \times 1.151 = 8,978$, about 9,000 mi.
3. Percent: $7,800 \div 13,000 = 0.60$, so 60 percent.
4. Time saved at 15 knots: $7,800 \div 15 = 520$ hours; $520 \div 24 = 21.7$ days.

Answer: About 7,800 nmi (about 14,400 km or 9,000 mi), 60 percent of the voyage, or nearly 22 days at 15 knots.

Example 2. USS *Oregon* steamed about 14,000 nautical miles in about 67 days. What was her average distance per day and average speed? Through a canal, the voyage from San Francisco to Key West would have been roughly 4,300 nautical miles. At the same average pace, how many days would it have taken, and how many would have been saved?

1. Distance per day: $14,000 \div 67 = 209$ nmi per day.
2. Average speed: $209 \div 24 = 8.7$ knots (including stops for coal).
3. Through a canal: $4,300 \div 209 = 20.6$ days, about 21 days.
4. Saved: $67 - 21 = 46$ days.

Answer: About 209 nmi a day (an average of 8.7 knots); about 21 days through a canal, saving roughly 46 days, more than six weeks.

Example 3. The original Panama lock chambers are 33.5 m wide; a Panamax ship is 32.3 m wide. The new chambers are 55 m wide; a Neopanamax ship is 49 m wide. How much space is left on each side of each ship when centered? Why does it matter?

1. Old locks: $33.5 - 32.3 = 1.2$ m of spare width; on each side $1.2 \div 2 = 0.6$ m (about 2 ft).
2. New locks: $55 - 49 = 6$ m of spare width; on each side $6 \div 2 = 3$ m (about 10 ft).
3. With only 0.6 m on each side, ships in the old locks must be held exactly in place by towing locomotives; in the new locks tugboats guide them instead.

Answer: About 0.6 m (2 ft) on each side in the old locks and 3 m (10 ft) in the new ones. The lock size sets the largest ship, so ship designers build to it.

PRACTICE

1. **EASY** What did the voyage of USS *Oregon* in 1898 show, and why did it matter for the canal?
2. **EASY** Who was Alfred Thayer Mahan, and what was his main idea?
3. **EASY** Give the date Panama took full control of the Panama Canal and the treaties that arranged it.
4. **EASY** What was the Yellow Fleet?
5. **MEDIUM** Using the figure, list three choke points or narrow passages on the route from New York to San Francisco through Panama, and two on the route by Cape Horn. (Use the map or drawing “Find the narrow places on each route.” shown earlier in this lesson.)
6. **MEDIUM** A clipper averaging 6 knots sails 13,000 nautical miles from New York to San Francisco by the Horn. How many days? A steamer at 10 knots goes 5,200 nautical miles through Panama. How many days?

7. **MEDIUM** Why did the closure of the Suez Canal from 1967 to 1975 encourage oil companies to build supertankers?
8. **MEDIUM** Convert the Neopanamax limits (366 m long, 49 m wide, 15.2 m draft) to feet (1 m = 3.281 ft).
9. **HARD** The Russian Baltic Fleet sailed from the Baltic to the Far East in 1904–1905. Its largest ships went around Africa. Using the London–Bombay figures from Lesson 3.1 as a guide, estimate how much farther the African route was, and explain why the fleet chose it.
10. **HARD** In March 2021 the *Ever Given* blocked the Suez Canal for six days. If about 50 ships a day normally transit, how many ships' voyages were delayed? What geographic features made the blockage possible?
11. **CHALLENGE** Gatun Lake depends on rain. Explain how a dry year at Panama can raise the price of goods in a city on another continent, tracing at least four links in the chain.
12. **CHALLENGE** Write a short essay (two paragraphs): "Canals shrink the world, but they also make it fragile." Agree or disagree, using at least four events from this unit.

COMMON MISTAKES

- Assuming every ship uses the canals. The largest tankers and bulk carriers have long been too big for them, and they still sail around the capes.
- Treating the political history as simple heroes and villains. Present events such as 1903, 1956 and 1977 factually and weigh the arguments made by each side.
- Measuring routes on a flat map. Map projections distort distance; measure on a globe.

Make it a game • Shortcut Auction. Each player is a shipping company with 100 points. A leader reads a voyage card (for example, Shanghai to Rotterdam, New York to Yokohama, Hamburg to Saint Petersburg, Piraeus to Patras) and a ship card (Panamax tanker, Neopanamax container ship, small coaster, supertanker). Players bid points for the fastest legal route: they must name the canal or cape and show the ship fits. The leader checks with a globe and the lesson's limits. A correct route that fits earns double its bid back; a route the ship cannot fit loses the bid.

Scripture. "And hath made of one blood all nations of men for to dwell on all the face of the earth, and hath determined the times before appointed, and the bounds of their habitation;" (Acts 17:26, KJV)

God set the nations in their places and appointed their times. Canals did not erase those bounds, but they drew the nations into closer contact than ever before. Paul spoke these words in Athens, not far from the isthmus where men had dreamed of a canal for centuries.

Practice answers

1. It took about 67 days and about 14,000 nautical miles to bring a battleship from San Francisco to the Atlantic around South America. It showed that without a canal the U.S. fleet

could not quickly be brought together in a war on two oceans, and it built public support for a canal at the isthmus.

2. An American naval officer and historian who in 1890 published *The Influence of Sea Power upon History, 1660-1783*. He argued that sea power (navies, merchant fleets, bases and control of sea lanes) was the key to national strength, and he supported an isthmian canal.
3. December 31, 1999, under the Torrijos-Carter Treaties of 1977.
4. Fifteen merchant ships trapped in the Great Bitter Lake when the Suez Canal was closed after the 1967 war; they stayed there until the canal reopened in 1975 and were named for the yellow desert dust that covered them.
5. Through Panama: a Caribbean passage such as the Windward Passage, the Panama Canal itself (Gatun Locks, Culebra Cut, Pedro Miguel and Miraflores) and the approaches at Colón and Balboa. By the Horn: Cape Horn (or the Drake Passage) and the Strait of Magellan if used.
6. Clipper: $13,000 \div 6 = 2,167$ h $\div 24 = 90$ days. Steamer: $5,200 \div 10 = 520$ h $\div 24 = 21.7$ days, about 22 days.
7. With the canal shut, oil from the Persian Gulf had to go around Africa anyway. On the long route the cost per barrel falls as ships get bigger, so companies built very large tankers that could never have fit the canal of that time. Once built, those ships kept using the Cape route even after the canal reopened.
8. $366 \times 3.281 = 1,201$ ft (about 1,200 ft); $49 \times 3.281 = 161$ ft; $15.2 \times 3.281 = 49.9$ ft (about 50 ft).
9. Roughly 4,000 to 5,000 nautical miles farther (London to Bombay is about 4,400 nmi longer by the Cape). The fleet avoided Suez because the canal ran through British-controlled Egypt, and Britain was allied with Japan; the deepest-drafted battleships also risked grounding in the canal. The long voyage wore down ships and crews before Tsushima in May 1905.
10. $6 \times 50 =$ about 300 ships, plus those that had already been waiting or chose to divert around Africa. The canal is a single narrow channel through sand in many stretches, without room to pass a stuck ship; a sandstorm with strong wind pushed the tall, boxy ship against the bank.
11. Less rain $\rightarrow$ Gatun Lake falls $\rightarrow$ the canal limits ship drafts and the number of daily transits to save water $\rightarrow$ ships carry less cargo or wait longer, or shippers send goods by longer routes (around the capes, through Suez or overland by rail) $\rightarrow$ shipping costs and delivery times rise $\rightarrow$ those costs show up in the prices of goods, such as grain or manufactured goods, wherever the ships were headed.
12. Answers vary. A strong essay uses figures for distance saved (London-Bombay about 4,400 nmi; New York-San Francisco about 7,800 nmi) and events that show fragility or strategic risk: the British occupation of Egypt in 1882, the Russian fleet's long voyage in 1904-1905, the Suez Crisis of 1956, the closure of 1967-1975 and the Yellow Fleet, the *Ever Given* in 2021, the Panama drought of 2023. It weighs both sides fairly and reaches a reasoned conclusion.

UNIT 3 TEST

Answer each question. Show your work for every calculation, including units, and use complete sentences for explanations. Use 1 nautical mile = 1.852 km = 1.151 statute miles and 1 m = 3.281 ft. The test is worth 100 points.

1. (6 pts) Give the dates when work on the Suez Canal began and when it opened, and explain in two sentences why it could be built without locks.
2. (8 pts) London to Bombay is about 10,700 nautical miles by the Cape and about 6,300 by Suez. Find the distance saved in nautical miles and kilometers, and the days saved for a steamer at 10 knots.
3. (6 pts) Describe the *corvée* at Suez. When and how did it end, and what replaced it?
4. (8 pts) Name four ways the geography of Panama differed from that of Suez and explain how each made the French sea-level plan harder.
5. (6 pts) What was the miasma theory, and how did it make the French hospital at Ancón dangerous?
6. (8 pts) A hill is 100 m high. A cut through it is 91 m wide at the bottom with 1:1 side slopes (area = bottom $\times$ depth + depth²). Find the cross-section area for a sea-level cut with its bottom 9 m below sea level, and for a lock-canal cut with its bottom 13 m above sea level. What percent does the lock plan save?
7. (6 pts) Who was William Gorgas, and name three methods he used to defeat yellow fever at Panama.
8. (8 pts) Gatun Lake stands about 26 m (85 ft) above sea level, reached by three equal lock steps. Find the lift of each step in meters and feet. Then find the water needed to raise a 305 m by 33.5 m chamber by that lift, in cubic meters.
9. (8 pts) Explain how the American plan turned the Chagres River from the canal's enemy into its water supply. Include the Gatun Dam, Gatun Lake and why the locks need no pumps.
10. (6 pts) Describe the people who did most of the labor on the American canal and explain the gold roll and silver roll.
11. (6 pts) The Kiel Canal is nearly at sea level. Why does it have locks? Name the two end points.
12. (6 pts) What was the Diolkos, who began a canal at Corinth in AD 67, and why does the modern Corinth Canal carry little cargo today?
13. (6 pts) The Kiel Canal saves about 250 nautical miles. How many kilometers is that, and how many hours at 12 knots?
14. (8 pts) New York to San Francisco is about 13,000 nautical miles by Cape Horn and 5,200 by Panama. Find the percent saved. Then explain how the voyage of USS *Oregon* in 1898 showed the strategic value of a canal.
15. (4 pts) Define Panamax, and give one reason ships are designed to a canal's limits.

UNIT PROJECT: THE CANAL ENGINEER'S REPORT

Put together a report on the great canals in three parts. First, your working bottle-and-tubing lock, demonstrated to your family or class, with a data sheet showing the chamber's area, the lift, the water used in one lockage and the time to fill. Second, your large map of voyages before and after Suez and Panama, with four routes in two colors, choke points marked and your table of distances and voyage times. Third, a two-page written report on one of the four canals in this unit: the problem geography posed, how the technology solved it, what it cost (in money, labor and lives), and what it changed in the world, citing at least one primary source (Herodotus, Josephus, Mahan or a photograph from the Library of Congress).

- **Working model:** The lock fills and empties by gravity alone, and the data sheet's measurements and calculations are complete and correct.
- **Map accuracy:** Ports, routes and choke points are correctly placed and labeled, and the distance table is within about 10 percent of the lesson figures.
- **Analysis:** The written report answers all four questions (problem, solution, cost, change) with accurate names, dates and numbers, uses a primary source, and treats workers and contested events fairly.
- **Craft and clarity:** The model, map and report are neat, clearly labeled and easy for a reader to follow.

Answer key

1. Begun April 25, 1859; opened November 17, 1869. The isthmus is low and nearly flat, and the Mediterranean and Red Sea stand at nearly the same level, so a channel dug below sea level holds level water from end to end.
2. 4,400 nmi; $4,400 \times 1.852 =$ about 8,150 km. $4,400 \div 10 = 440$ h $\div 24 =$ about 18.3 days.
3. Egyptian peasants were called up in rotation for forced labor, tens of thousands at a time, digging largely by hand and carrying sand in baskets. It was ended in 1864 after an arbitration by Napoleon III, with Egypt paying the company compensation; the contractors Borel and Lavalley then used steam dredges and other machines.
4. Any four: hills rising to about 100 m at Culebra (a far deeper cut); soft clays and shales (slides refilled the cut); heavy rain, over 3 m a year on the Caribbean side (floods and mud); the Chagres River (its floods crossed the route); tropical disease, yellow fever and malaria (killed and drove away workers); large Pacific tides (currents in a sea-level channel).
5. The belief that disease came from bad air from swamps. Not suspecting mosquitoes, the hospital stood bed legs in pans of water to keep ants away, and the pans bred the mosquitoes that carried yellow fever and malaria to patients.
6. Sea level: depth 109 m; $91 \times 109 + 109^2 = 9,919 + 11,881 = 21,800$ m². Lock: depth 87 m; $91 \times 87 + 87^2 = 7,917 + 7,569 = 15,486$ m². Saving: $1 - 15,486 \div 21,800 = 0.29$, about 29 percent.
7. The chief sanitary officer of the American canal effort, who had cleared yellow fever from Havana. Methods: screening windows and doors, fumigating houses, draining standing water, oiling pools to kill larvae, piping water to Panama City and Colón so open barrels were not needed.

8. $26 \div 3 = 8.7$ m; $85 \div 3 = 28.3$ ft. Area $305 \times 33.5 = 10,218$ m²; volume $10,218 \times 8.7 =$ about 88,900 m³ (using the unrounded lift of 8.67 m gives about 88,600 m³; either is acceptable).
9. The Gatun Dam across the Chagres created Gatun Lake, about 26 m above the sea, which forms a large part of the canal route. Ships climb to it and descend from it by locks. Rain on the Chagres watershed keeps the lake full, and because the lake is higher than the lock chambers below it, water flows into and out of the chambers by gravity through culverts, with no pumps.
10. More than 40,000 at the peak, most of them Black workers from the West Indies, especially Barbados, alongside Europeans, Panamanians and Americans. The gold roll, mostly white Americans, was paid in gold dollars with better housing; the silver roll, mostly West Indian and other workers, was paid less in silver and housed worse. It was a system of unequal treatment largely by race and nationality; most of the 5,609 recorded deaths were West Indian workers.
11. They are tide locks that keep out the roughly 3 m tide of the Elbe and the changing level of the Baltic, so the canal does not become a current flowing back and forth. Ends: Brunsbüttel on the Elbe and Kiel-Holtenau on the Baltic.
12. The Diolkos was a paved trackway, from about the 6th century BC, for hauling cargo and ships across the isthmus. Nero began a canal in AD 67. The modern canal is only about 21-25 m wide and 8 m deep, too small for most modern cargo ships, and it suffers currents and rock slides, so it carries mostly yachts and small cruise ships.
13. $250 \times 1.852 = 463$ km (about 460 km). $250 \div 12 = 20.8$ hours.
14. $7,800 \div 13,000 = 60$ percent. The *Oregon* took about 67 days and about 14,000 nmi to go from San Francisco around South America to the Atlantic before the war with Spain. It showed that without a canal the U.S. Navy's two coasts were two months apart, and public support for a canal grew.
15. The largest ship that fits the original Panama locks: about 294 m long, 32.3 m wide and 12 m draft. Ships are built to the limit so they can use the shortest route while carrying as much cargo as possible.

MASTERING DISTANCE

For most of history, distance was the master of every message, traveler and cargo. A letter, a merchant and a bale of cotton all moved at the speed of the horse or the ship, and an ocean meant weeks of waiting. In this unit you will watch five breakthroughs break that rule one at a time. Samuel Morse's telegraph (1844) freed words from the speed of travel. Cyrus Field's Atlantic cable, finally laid by the *Great Eastern* in 1866, carried those words beneath an ocean. The Wright brothers (1903) and the Douglas DC-3 (1935) carried people above mountains and seas, and the propeller and jet airliners of the 1950s flew over the top of the world on the great-circle routes. Finally, Malcom McLean's *Ideal X* (1956) and the humble steel container made it cheap to move goods across the globe.

Each lesson asks the same questions as the rest of this course: what problem did geography pose, how did the technology solve it, what did it cost, and what changed in the world? You will compute great-circle distances with the spherical law of cosines, work out headwinds and tailwinds, convert nautical miles, read time from longitude and count ships in TEU. You will stretch string across a globe to see why the shortest route looks curved on a flat map, and you will discover that every new technology, even as it overcame old barriers, created a new geography of its own: cable stations at the nearest points of continents, island stepping stones across the Pacific, a refueling crossroads in Alaska and new ports with deep water and flat land.

Scripture tells us that God “hath made of one blood all nations of men for to dwell on all the face of the earth, and hath determined the times before appointed, and the bounds of their habitation” (Acts 17:26). The inventions of this unit drew those nations closer than ever before. Human creativity is part of what it means to be made in God's image, and the first telegraph message, “What hath God wrought!”, gave Him the credit. The builders of Babel wanted to make a name for themselves; the right response to a great invention is gratitude, humility and good use in the service of our neighbors.

BEFORE YOU BEGIN

- Can read latitude and longitude and knows that 1° of longitude equals 4 minutes of time (Lesson 1.3)
- Can use a scientific calculator for sine, cosine and inverse cosine, and can rearrange $\text{distance} = \text{speed} \times \text{time}$
- Can convert between miles, kilometers and nautical miles
- Knows the story of the steamship and the *Great Eastern* from Unit 1

MASTERY CHECKLIST

- I can explain how the telegraph works and how it separated the movement of words from the movement of people and goods.

- I can tell the story of the Atlantic cable from 1857 to 1866 and explain why it failed and then succeeded.
- I can compute a great-circle distance with the spherical law of cosines and compare it with a rhumb-line distance.
- I can calculate ground speed and flight time with headwinds and tailwinds, and explain how range shaped early air routes.
- I can explain why the shortest routes between Europe, North America and Asia cross the Arctic.
- I can explain how the container made distance cheap and how it moved ports and reshaped trade, including its costs.

OPTIONAL BOOKS AND RESOURCES

- **History of the Atlantic Cable & Undersea Communications** (<https://atlantic-cable.com/>): Free. A large, carefully researched site with original documents, photographs, cable samples and Robert Dudley's pictures of the 1865 and 1866 expeditions (Lesson 4.2).
- **Robert Charles Dudley, *Deck of the Great Eastern, the Cable Trough, etc., 1866* (The Metropolitan Museum of Art)** (<https://www.metmuseum.org/art/collection/search/383835>): Free, open access. The picture study for Lesson 4.2; from this page you can browse the other Dudley works Cyrus Field gave to the museum in 1892.
- **Submarine Cable Map (TeleGeography)** (<https://www.submarinecablemap.com/>): Free interactive map of today's undersea cables and their landing points. Use it for the unit map comparing the 1866 cable with today's network.

4.1 THE TELEGRAPH

OBJECTIVES

- Explain how Samuel Morse’s electric telegraph worked (battery, key, line wire, electromagnet, earth return and code) and why it separated the movement of words from the movement of people and goods.
- Compare the speed of news before and after the telegraph using real journeys (the Battle of New Orleans, the Pony Express, the 1861 transcontinental line) and compute travel speeds and local-time differences from longitude.
- Weigh what the telegraph changed and what it did not change in the geography of commerce, government and war.

Warm-up. Work with a partner on opposite sides of the room. Without speaking or writing words, send the message “meet at noon” using only two signals: a short tap and a long tap on the table. Agree on a code first if you like, and time yourselves. Then discuss: what did you need besides the taps to make the message work? (A shared code, someone listening, and a way to mark where one letter ends and the next begins.) That is the whole problem Samuel Morse had to solve, except his table was forty miles long.

Watch. *How a Telegraph Worked* (Inside The Machine, 6:56).

<https://www.youtube.com/watch?v=mEdefcE2epM>

With How it worked: how the electric telegraph and Morse code worked.

Backup video. *Claude Chappe and the Napoleon Telegraph* (The History Guy: History Deserves to Be Remembered, 14:45). <https://www.youtube.com/watch?v=sv7bhfVRzLY>

With the history note: Claude Chappe’s optical telegraph, the system the electric telegraph replaced. Note: Runs about 15 minutes. It mentions that Chappe took his own life in 1805.

KEY TERMS

telegraph

From Greek words meaning “far writing”: a system that sends messages over a distance as coded signals. Morse’s electric telegraph sent pulses of current along a wire.

electromagnet

A coil of wire around an iron core that becomes a magnet only while current flows. It turned an invisible current at the far end of the line into a click a person could hear.

Morse code

A code of short and long signals (dots and dashes) standing for letters and numbers; the commonest letters, such as E and T, got the shortest codes.

relay

A device in which a weak current at the end of a long line works a switch that starts a fresh, strong current on the next section, so a message can travel hundreds of miles.

earth return (ground)

Using the earth itself as the return half of the circuit, so a telegraph line needs only one wire instead of two.

local solar time

Time set by the sun at a particular place, so that noon is when the sun is highest there. It changes by 4 minutes for every degree of longitude.

CORE IDEAS

The story. On Friday, May 24, 1844, a crowd gathered in the Supreme Court chamber of the United States Capitol in Washington. Samuel F. B. Morse sat at a small instrument wired to a line that ran on poles along the Baltimore and Ohio Railroad, about 40 miles (64 km) to the Mount Clare depot in Baltimore. There his partner Alfred Vail waited at a receiving machine. Morse tapped out a message chosen by young Annie Ellsworth, daughter of the U.S. Commissioner of Patents. She took it from Numbers 23:23: “What hath God wrought!” In Baltimore the receiver’s pen embossed the dots and dashes on a moving paper strip, and Vail sent the words back. A sentence had crossed forty miles faster than anyone in the room could blink. For all of human history before that afternoon, a message could travel no faster than the horse, the ship, the runner or the signal fire that carried it. Words now traveled by themselves.

The man behind it. Morse was not trained as an engineer. He was a painter, a son of the Congregational minister Jedidiah Morse, whose *Geography Made Easy* (1784) made him known as the father of American geography. In 1825, while Samuel was in Washington painting a portrait of Lafayette, his young wife Lucretia died suddenly at home in New Haven. The letter telling him she was ill reached him too late; by the time he got home she had been buried. Seven years later, sailing home from Europe on the packet ship *Sully* in 1832, he heard fellow passengers talk about electromagnets and seized on an idea: if current could be sent along a wire and detected at the other end, it could carry news. It took him twelve years, help from the scientist Leonard Gale, the mechanical skill and money of Alfred Vail, the published work of Joseph Henry on powerful electromagnets, and finally \$30,000 voted by Congress in 1843 to build the test line. (In Britain, William Cooke and Charles Wheatstone had built a working needle telegraph in 1837; the idea was in the air on both sides of the Atlantic.) Morse was also a man of his time in less admirable ways: in the 1830s he wrote fierce pamphlets against Catholic immigrants, and during the Civil War he defended slavery in print. Honest history records both his genius and those wrongs.

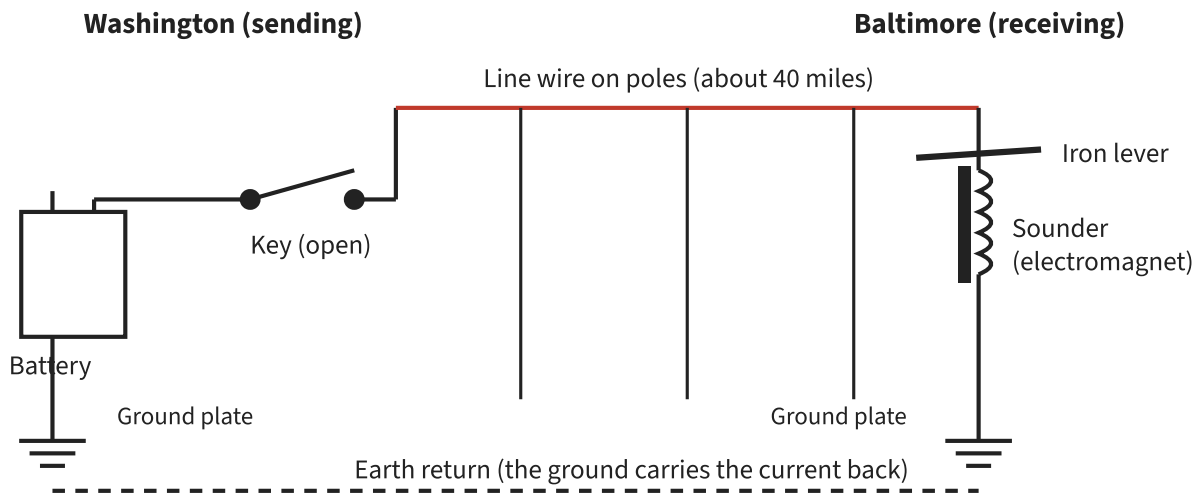
How it worked. The telegraph is a loop of electricity that someone can open and close. At the sending station a battery pushes current through a **key**, a spring-loaded switch. Press the key and current flows out along a single iron or copper wire strung on poles, through an **electromagnet** at the far station, and down into the ground; the earth itself carries the current back, so the line needs only one wire (see the diagram). Each time the key closes, the far electromagnet pulls down an iron lever with a click; when it opens, a spring lifts the

lever. A short press makes a dot, a longer press a dash, and spaces mark the breaks between letters and words. Morse and Vail gave the shortest signals to the commonest letters (E is a single dot) so that messages were quick to send. Morse's first try, burying wire in lead pipe beside the railroad, failed when the insulation leaked, so the crew switched to wire on poles with glass insulators. Over long distances the current grows weak, so **relays** let a faint signal trip a switch that starts a fresh current on the next stretch. Before long, skilled operators stopped reading the paper tape and simply listened to the clicks of a **sounder**.

Technology overcoming geography. Distance had always been a tax on information. When American and British diplomats signed the Treaty of Ghent ending the War of 1812 on December 24, 1814, no one in Louisiana knew. On January 8, 1815, Andrew Jackson's army fought the Battle of New Orleans, and news of the peace did not reach Washington until February. In 1860 the Pony Express cut the time for a letter from St. Joseph, Missouri, to Sacramento, California, to about ten days by relays of riders over roughly 1,900 miles (3,060 km). Then on October 24, 1861, the lines of the transcontinental telegraph were joined at Salt Lake City, and California's chief justice, Stephen J. Field (brother of Cyrus Field, whom you meet in the next lesson), sent a message to President Lincoln pledging California's loyalty to the Union. Within days the Pony Express announced it would close. Ten days had become a few minutes.

The big idea. For the first time, *communication* was separated from *transportation*. Cotton, coal and people still moved at the speed of the train and the ship, but prices, orders, weather reports and news now moved almost instantly. Railroads used the telegraph to dispatch trains safely on single tracks. Merchants in New York knew Chicago grain prices the same day. Newspapers in New York formed the Associated Press in 1846 to share the cost of telegraphed news. During the Civil War, President Lincoln spent long hours in the War Department telegraph office reading dispatches from his generals. Government, war and markets all began to run on telegraph time. Notice the words Morse chose to send, or rather the words he accepted: "What hath God wrought!" The builders of Babel said, "let us make us a name" (Genesis 11:4). The first telegraph message gave the credit elsewhere. Human creativity is part of what it means to be made in God's image (Genesis 1:27-28), and the right response to a great invention is wonder and thanks, not pride.

On the map. Telegraph lines followed the easiest geography: railroad grades, river valleys and wagon roads, because poles had to be set, inspected and repaired. The 1861 line followed the overland trails across the plains, through South Pass and past Salt Lake City, the same corridor the Pony Express had used. But the wire did not care about mountains the way a wagon did. Once it was strung, a range like the Sierra Nevada cost a message nothing in time. The telegraph also changed how people thought about **time and longitude**. Every town kept its own local solar time, four minutes different for each degree of longitude. When a message could cross 48 degrees of longitude from New York to San Francisco in minutes, the clocks at the two ends disagreed by more than three hours. Telegraphed time signals helped the railroads adopt standard time zones in 1883, and the 1884 prime meridian conference you studied in Unit 1 finished the job for the world.



Morse's telegraph is a loop: battery, key, line wire, electromagnet (sounder) and the earth itself as the return path. Pressing the key closes the loop and makes the far sounder click.

PICTURE STUDY



Gallery of the Louvre, Samuel F. B. Morse, 1831-1833 · Oil on canvas · Terra Foundation for American Art, Chicago

Before he changed the world with a wire, Samuel Morse hoped to be remembered as a painter. In Paris in 1831 to 1833 he worked for months inside the Louvre, painting tiny copies of the old masters he loved (works by Leonardo, Titian, Raphael, Rubens and others) and arranging them together on the walls of one imaginary gallery, the Salon Carré. He meant to carry the painting home and show Americans, who could not cross the ocean, the treasures of Europe in a single picture.

Think about that goal. Morse was already trying to overcome distance: to bring the Louvre to people an ocean away. When he exhibited the painting in New York it drew little interest and earned little money. Within a few years he had nearly given up painting for the telegraph, a far more powerful way to bring distant things near.

Look closely

- Count how many paintings you can see on the walls. Which ones do you recognize?
- Find the man in the center leaning over a young woman who is drawing. Many historians think Morse painted himself here as a teacher.
- Look at the people copying paintings and studying them. What does the picture say about how artists learned in Morse's day?
- Look at the light coming from above. How does Morse make one room feel enormous?

Talk about it

1. How is this painting itself an attempt to overcome geography?
2. Morse once had to wait days for a letter that came too late. How might that experience connect to the picture and to the telegraph?
3. Why do you think a gifted artist turned to invention? What skills might painting and invention share?

Safety first. Use only a 6-volt lantern battery or a holder of four AA cells. Never connect anything to a wall outlet. The nail and wire can get warm if the key is held down; tap it, do not hold it.

PROJECT: BUILD A ONE-WIRE TELEGRAPH

You will build a working telegraph from a battery, a nail electromagnet and a homemade key, send Morse code across the room, and measure how your sending speed compares with a written note carried by hand.

You will need

- A 6-volt lantern battery or a holder of four AA batteries
- About 30 feet (9 m) of insulated copper wire (22 gauge bell or hookup wire), plus a small roll of thinner enameled magnet wire if available
- A large iron or steel nail (3 to 4 inches long)
- A strip of thin steel from a tin can lid with edges taped, or a steel paper clip, for the armature
- A small block of wood, two thumbtacks or brass paper fasteners, a few rubber bands and tape
- Wire strippers or sandpaper (to clean wire ends) and a stopwatch
- A printed Morse code chart (International Morse)

Steps

1. Make the electromagnet: wrap the magnet wire (or the hookup wire) tightly around the nail 80 to 100 times, leaving 6 inches free at each end. Strip or sand the ends.
2. Make the sounder: tape the nail upright to one end of a wooden block. Bend the steel strip so it is fixed at one end and its free end hovers about 1/8 inch above the nail head. When the nail is magnetized the strip should snap down with a click.
3. Make the key: push two thumbtacks or brass fasteners into a second block about an inch apart. Bend a stiff strip of wire or a paper clip so it is fixed under one tack and springs up just above the other. Pressing it down closes the circuit.
4. Wire the loop: battery terminal to the key, key to the long line wire, line wire across the room to one end of the electromagnet coil, other end of the coil back to the other battery terminal by a second wire. (Our one-wire earth return does not work at this scale, so use two wires; explain in your notebook why Morse could use the ground and we cannot.)
5. Test: tap the key and listen for the click. Adjust the gap until short and long taps are clear.
6. Send: the sender chooses a 10-letter message from a list of geography words and sends it in Morse. The receiver writes dots and dashes, then decodes. Time it.
7. Compare: time a runner carrying the same message written on paper across the room. Then calculate how long each method would take over 40 miles if the runner averaged 6 mph and the telegraph signal arrived instantly but the operator sent 5 words a minute.
8. Record your times, error count and calculations in your notebook.

Tips

- If nothing clicks, check that every wire end is bare metal and the battery is fresh. More turns of wire make a stronger magnet.
- Agree on spacing before you start: a dash is three dots long, a pause between letters three dots long, and between words seven.
- Disconnect the battery when you are finished so it does not drain.

Check your work

- My telegraph clicks reliably for both dots and dashes.
- I sent and decoded a message and recorded the time and errors.
- I can explain what each part of the circuit does and why Morse's real line used the earth as a return path.

MAP NOTEBOOK

1. Draw the telegraph circuit from the diagram from memory and label the battery, key, line wire, electromagnet, sounder and earth return.
2. On an outline map of the United States, draw the Washington-Baltimore line of 1844 and the transcontinental line of 1861 through Omaha, Salt Lake City and Sacramento. Mark where the two halves met on October 24, 1861.

3. Make a timeline strip from 1815 to 1861 showing how long news took: the Treaty of Ghent and New Orleans (weeks), the Pony Express (about 10 days), the transcontinental telegraph (minutes).

From history. Morse's original receiver did not make sounds people listened to; it embossed dots and dashes onto a moving paper tape, and the strip of tape from May 24, 1844, survives in the Library of Congress. Within a few years operators found they could read messages faster by ear from the clicking of the armature, and the "sounder" replaced the tape register on most American lines. A good operator could send and receive more than 25 words a minute by ear.

WORKED EXAMPLES

Example 1. The Pony Express carried mail about 1,900 miles (3,060 km) from St. Joseph, Missouri, to Sacramento, California, in about 10 days. Find its average speed in miles per day and in miles per hour, and in km/h.

1. Miles per day: $1,900 \text{ mi} \div 10 \text{ days} = 190 \text{ miles per day}$.
2. Ten days is $10 \times 24 = 240$ hours, riding day and night with fresh horses and riders.
3. Miles per hour: $1,900 \text{ mi} \div 240 \text{ h} \approx 7.9 \text{ mph}$.
4. Kilometers per hour: $3,060 \text{ km} \div 240 \text{ h} \approx 12.8 \text{ km/h}$.

Answer: About 190 miles a day, or about 7.9 mph (12.8 km/h) around the clock. That was astonishingly fast for horses, yet the telegraph that replaced it in October 1861 carried a message the same distance in minutes.

Example 2. In 1861 each city kept local solar time. New York is at about 74.0° W and San Francisco at about 122.4° W . A telegram leaves New York at exactly noon New York time and arrives within minutes. What time is it in San Francisco by local solar time?

1. The earth turns 360° in 24 hours, so 1° of longitude equals $24 \times 60 \div 360 = 4$ minutes of time.
2. Difference in longitude: $122.4^\circ - 74.0^\circ = 48.4^\circ$.
3. Time difference: $48.4 \times 4 \text{ min} = 193.6 \text{ min} \approx 3 \text{ hours } 14 \text{ minutes}$.
4. San Francisco is farther west, so the sun reaches its highest point there later; its clocks are behind New York's: $12:00 - 3:14 = 8:46 \text{ a.m.}$

Answer: About 8:46 a.m. in San Francisco. A message sent at noon "arrived" before 9 in the morning, one of the puzzles that pushed the railroads toward standard time zones in 1883.

Example 3. Morse's 1844 line ran about 40 miles along the railroad from Washington to Baltimore. Washington is at about 38.9° N, 77.0° W and Baltimore at about 39.3° N, 76.6° W. (a) Estimate the straight-line distance using a flat-map approximation. (b) How much longer was the line than the straight distance? (c) Congress gave \$30,000. What was the cost per mile of line?

1. One degree of latitude is about 111.2 km. North-south distance: $(39.3 - 38.9) \times 111.2 = 0.4 \times 111.2 \approx 44.5$ km.
2. One degree of longitude shrinks by the cosine of the latitude. At the average latitude of 39.1° , $\cos 39.1^\circ \approx 0.776$, so 1° of longitude $\approx 111.2 \times 0.776 \approx 86.3$ km. East-west distance: $(77.0 - 76.6) \times 86.3 = 0.4 \times 86.3 \approx 34.5$ km.
3. Straight-line distance by the Pythagorean theorem: $\sqrt{(44.5^2 + 34.5^2)} = \sqrt{(1,980 + 1,190)} = \sqrt{3,170} \approx 56$ km ≈ 35 miles.
4. The line followed the railroad, about 40 miles (64 km): roughly 5 miles, or about 14 percent, longer than the straight line.
5. Cost: $\$30,000 \div 40$ miles = \$750 per mile (about \$470 per km).

Answer: (a) About 56 km (35 miles). (b) About 5 miles (14 percent) longer, because it followed the railroad right-of-way where poles were easy to set and inspect. (c) About \$750 per mile.

PRACTICE

1. **EASY** Give the date, the two cities and the words of the first public message on Morse's 1844 line. Where do the words come from?
2. **EASY** Name the five parts of a one-wire telegraph circuit and say what each does.
3. **EASY** Convert the 40-mile Washington-Baltimore line to kilometers. (1 mile = 1.609 km)
4. **MEDIUM** Boston is at about 71.1° W and Chicago at about 87.6° W. If it is noon by local solar time in Boston, what is the local solar time in Chicago?
5. **MEDIUM** Explain how the Battle of New Orleans (January 8, 1815) shows what the world was like before the telegraph.
6. **MEDIUM** Washington, D.C., is at about 77.0° W and London at about 0.1° W. When it is noon by local solar time in London, what is the local solar time in Washington?
7. **MEDIUM** Suppose telegraph poles were set every 200 feet. About how many poles were needed per mile, and for a 40-mile line? (1 mile = 5,280 feet)
8. **HARD** Use the flat-map method from Worked Example 3 to estimate the straight-line distance from Baltimore (39.3° N, 76.6° W) to Philadelphia (40.0° N, 75.2° W). Give km and miles.
9. **HARD** Convert the Pony Express average speed of about 7.9 mph to km/h, and find how many hours it would take at that speed to carry a letter the 40 miles from Washington to Baltimore.
10. **HARD** In two or three sentences, explain why railroads were among the first and biggest users of the telegraph.

11. **CHALLENGE** Before standard time, a railroad timetable between New York (74.0° W) and Chicago (87.6° W) had to choose whose noon to use. How many minutes apart were the two cities' local times? If a train left New York at 8:00 a.m. New York time and took 24 hours, at what Chicago local time did it arrive?
12. **CHALLENGE** Written response (one paragraph): Historians say the telegraph brought "the end of distance for words." What did it change in the geography of trade and government, and what did it leave unchanged?

COMMON MISTAKES

- Thinking Morse invented electricity or the electromagnet. He built on the work of others, especially Joseph Henry, and his achievement was a practical system: circuit, code and relays.
- Forgetting that the telegraph moved only words. Freight and passengers still traveled at the speed of the train and the ship; the telegraph changed what people knew, not how fast cargo moved.
- Adding instead of subtracting time when going west. Places west of you have earlier local times, 4 minutes for every degree of longitude.

Make it a game · Relay Station. Line up four or more players across a large room or yard, each a "station" about 20 feet apart. The first station receives a short geography message (such as "ERIE CANAL 1825") on paper and must pass it to the next station using only flashlight blinks or taps in Morse code; the next station decodes, re-encodes and passes it on. Time the message from first to last station and count errors. Then play again with a runner carrying the paper. Discuss: where did the errors come in, and why did real telegraph lines need skilled operators and relays?

Scripture. "Canst thou send lightnings, that they may go, and say unto thee, Here we are?" (Job 38:35, KJV)

God asked Job whether he could command the lightning to carry a message. Three thousand years later, people learned to send electric current along a wire to say, in effect, "Here we are." The question still humbles us: we harness the forces God made, but we did not make them. Morse's first message gave the glory to God.

Practice answers

1. May 24, 1844, from the Supreme Court chamber of the Capitol in Washington to the Mount Clare depot in Baltimore: "What hath God wrought!" The words come from Numbers 23:23.
2. Battery (supplies current); key (a switch the sender presses to open and close the circuit); line wire on poles (carries current to the far station); electromagnet or sounder (becomes a magnet when current flows and pulls a lever down with a click); earth return or ground (carries the current back so only one wire is needed).
3. $40 \times 1.609 \approx 64.4$ km.
4. Difference $87.6 - 71.1 = 16.5^\circ$; $16.5 \times 4 = 66$ minutes. Chicago is west, so its clock is behind: about 10:54 a.m.

5. The Treaty of Ghent ending the War of 1812 had been signed on December 24, 1814, but the news traveled by sailing ship and did not reach America in time. The battle was fought two weeks after the peace was signed, and Washington did not learn of the treaty until February 1815. News could move only as fast as a ship or a horse.
6. Difference 76.9° ; $76.9 \times 4 = 307.6 \text{ min} \approx 5 \text{ h } 8 \text{ min}$. Washington is west, so it is about 6:52 a.m.
7. $5,280 \div 200 = 26.4$, so about 26 poles per mile; $26.4 \times 40 \approx 1,056$, about 1,060 poles for 40 miles.
8. North-south: $0.7 \times 111.2 \approx 77.8 \text{ km}$. Average latitude 39.65° , $\cos \approx 0.770$, so 1° of longitude $\approx 85.6 \text{ km}$; east-west $1.4 \times 85.6 \approx 119.8 \text{ km}$. Distance $\approx \sqrt{(77.8^2 + 119.8^2)} = \sqrt{(6,053 + 14,352)} = \sqrt{20,405} \approx 143 \text{ km} \approx 89 \text{ miles}$.
9. $7.9 \times 1.609 \approx 12.7 \text{ km/h}$. $40 \div 7.9 \approx 5.1$ hours, compared with seconds by telegraph.
10. Most early American railroads were single-track, so trains going opposite ways had to meet at sidings. With the telegraph, a dispatcher could know where every train was and order one to wait, preventing head-on collisions and keeping trains moving. The lines also ran conveniently along the railroad right-of-way, so the two systems grew together.
11. $13.6 \times 4 = 54.4 \text{ min}$, about 54 minutes. It arrives at 8:00 a.m. New York time the next day, which is about 7:06 a.m. Chicago local time (8:00 – 0:54).
12. A strong answer explains that the telegraph separated communication from transportation: prices, orders, news, military dispatches and train orders now moved in minutes, so markets in distant cities were linked, railroads ran more safely, governments and generals could direct events far away, and news agencies like the Associated Press formed. It should also note what did not change: goods and people still moved at the speed of horses, trains and ships; lines had to follow easy routes for poles and repair crews; oceans still blocked the wire until the undersea cable (next lesson); and a message was only as good as the operators and the code.

4.2 THE ATLANTIC CABLE

OBJECTIVES

- Tell the story of the Atlantic cable from Cyrus Field's first attempt through the brief success of 1858 to the lasting cables of 1866 laid by the *Great Eastern*, and explain why each failure happened.
- Compute the great-circle distance from Valentia, Ireland, to Heart's Content, Newfoundland, using the spherical law of cosines, and convert between degrees, nautical miles, statute miles and kilometers.
- Explain how the ocean floor, the size of ships and the physics of long cables shaped the route and the outcome, and how the 1866 cable began the network of undersea cables that carries the world's internet today.

Warm-up. Tie a heavy metal washer or a large nut to the end of a long piece of string. Stand on a chair and lower it slowly into a bucket of water while a partner walks slowly away from you holding the bucket. Watch the angle of the string. Now have your partner walk faster. What happens to the string? Imagine doing this with a cable two and a half miles long from a ship rolling in a storm. That is the problem the cable layers faced.

Watch. *The Transatlantic Telegraph Cable* (Newfoundland and Labrador Heritage Website, 14:52). https://www.youtube.com/watch?v=IAaTGMm4X_I
With Twelve years of failure: the Atlantic cables of 1858 and 1866 and the landing at Heart's Content, Newfoundland.

Note: Runs about 15 minutes.

KEY TERMS

submarine cable

A cable laid on the sea floor to carry signals between continents or islands; the first carried telegraph signals, and today's carry internet data on optical fibers.

gutta-percha

A natural latex from trees of Malaya that hardens into a tough, waterproof insulator; it made undersea cables possible in the 1850s.

Telegraph Plateau

The name the American naval officer Matthew Fontaine Maury gave to the broad, fairly even stretch of North Atlantic floor between Ireland and Newfoundland, about two miles deep, which his soundings suggested was suitable for a cable.

great circle

The largest circle that can be drawn on a sphere, whose center is the center of the earth. The shortest route between two points on a globe follows a great circle.

nautical mile

One minute of arc (1/60 of a degree) along a great circle on the earth, 1,852 meters or about 1.15 statute miles. Sea and air navigators use it because it ties distance directly to latitude and angle.

grapnel

A hooked iron grappling tool dragged along the sea floor on a long rope to catch and lift a lost cable.

CORE IDEAS

The story. On Friday, July 27, 1866, the largest ship in the world steamed slowly into Trinity Bay, Newfoundland, and anchored off the fishing village of Heart's Content. Behind her, running back across the floor of the North Atlantic to Valentia Island off the southwest coast of Ireland, lay a single continuous cable. The *Great Eastern* had left Ireland on July 13. For fourteen days she had paid out cable over her stern day and night while electricians at both ends tested it every minute. When the shore end was hauled through the surf and connected, Europe and North America were joined by a wire that worked, and would keep working. Among the first messages to cross was news that Prussia and Austria had made peace after their short war that summer. A businessman named Cyrus West Field had spent twelve years and much of his fortune to reach that day.

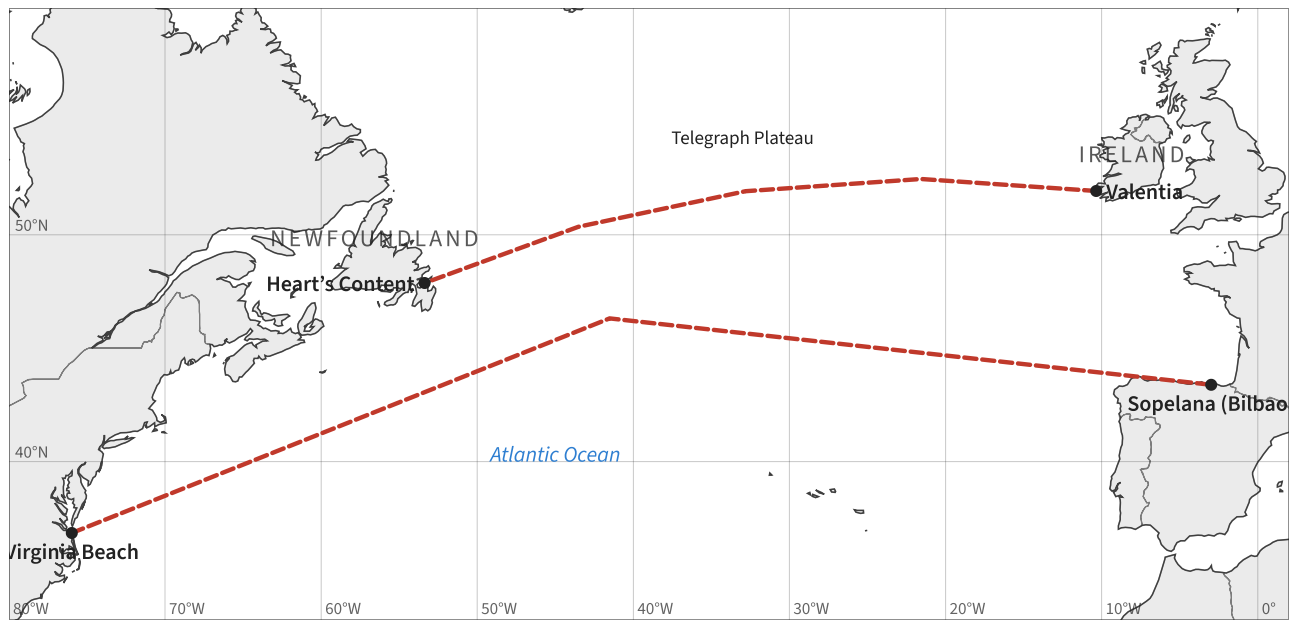
Twelve years of failure. Field was a New York paper merchant who had retired wealthy in his thirties. In 1854 he was drawn into a plan to run a telegraph line across Newfoundland so that news from Europe could be landed there and telegraphed on to New York. Looking at a globe, he asked a bigger question: why not cross the ocean itself? Maury's soundings told him the North Atlantic floor between Ireland and Newfoundland was deep but fairly even, and Samuel Morse told him a long cable could carry signals. Field raised money in New York and London and formed the Atlantic Telegraph Company in 1856. The first attempt, in 1857, began from Valentia with two warships, HMS *Agamemnon* and USS *Niagara*, each too small to carry the whole cable alone; the cable snapped a few hundred miles out and was lost. In the summer of 1858 the two ships tried a new plan: meet in mid-ocean, splice the two halves together, and steam in opposite directions. After more breaks and a terrible storm, the cable was completed on August 5, 1858. Queen Victoria sent a message of 98 words to President James Buchanan; it took about sixteen hours to get through. New York celebrated with parades, and fireworks set the cupola of City Hall on fire. But the signals grew weaker. The company's electrician, Wildman Whitehouse, tried to force messages through with very high voltage, which likely damaged the insulation, and within about three weeks the cable went silent. Many people decided the whole thing had been a hoax.

How they figured it out. Two kinds of progress made 1866 possible. The first was science. The young Scottish physicist William Thomson (later Lord Kelvin) showed that a long cable acts like a vast storage jar for electric charge, so each pulse smears out as it travels; the delay grows roughly with the *square* of the cable's length, his "law of squares." The answer was not higher voltage but a thicker copper core, better insulation of gutta-percha, careful testing, and very sensitive receivers such as Thomson's mirror galvanometer, which reflected a spot of light that moved with even a faint current. The second was a ship. Isambard

Kingdom Brunel's *Great Eastern*, launched in 1858, was 692 feet (211 m) long, far larger than any other ship afloat. She had been a financial failure as a passenger liner, but she was the only ship in the world that could carry an entire Atlantic cable, thousands of tons of it coiled in huge water-filled tanks, so no mid-ocean splice was needed. In 1865 she laid about 1,200 miles of cable before it broke and sank in water more than two miles deep. Her crew grappled for it for days, hooked it three times, and lost it each time when the rope parted. In 1866 they returned with a new cable, finished it on July 27, and then sailed back to the spot where the 1865 cable lay. Dragging a grapnel across the bottom in about two and a half miles of water, they found it, raised it, spliced on new cable and completed a second line to Newfoundland in early September 1866.

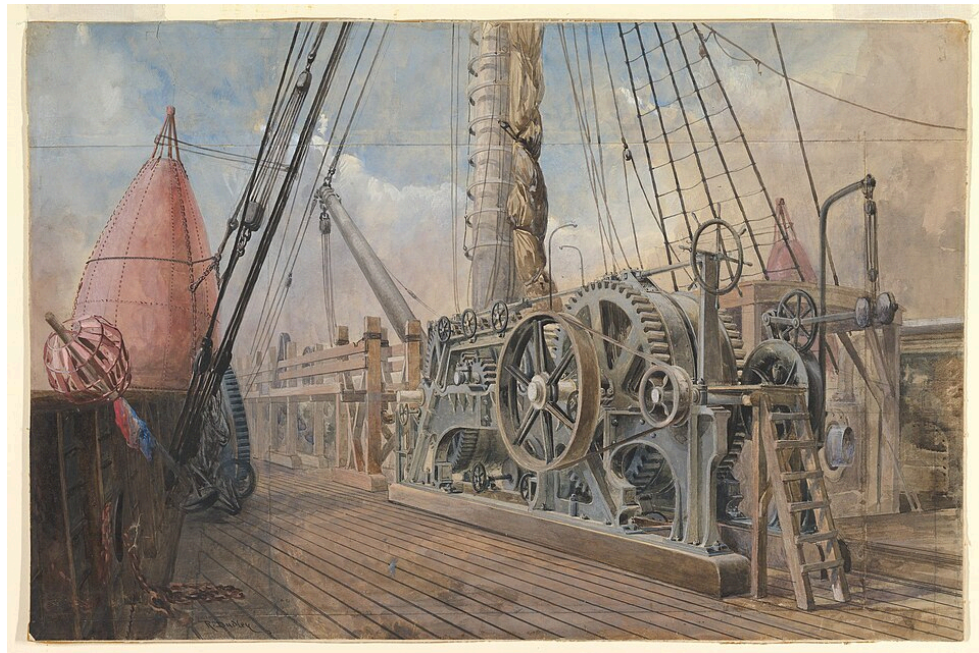
Technology overcoming geography. Before the cable, the fastest way to send news across the Atlantic was a steamship, about ten days in the 1860s. The 1858 cable carried barely a tenth of a word per minute; the 1866 cables carried about eight words a minute, and later improvements carried far more. At first a message was very expensive, a luxury for governments, newspapers and merchants, but prices fell as more cables were laid. Cotton and grain traders in Liverpool and New York could now see each other's prices the same day. Governments could instruct their ambassadors overnight instead of by letter weeks later. Within a few decades cables linked Britain to India, Australia and the Far East, and London became the center of a world telegraph network. A single cable laid along the ocean floor had shrunk an ocean that once took ten days to cross into a gap of minutes.

On the map. Why Valentia and Heart's Content? Look at the map. Ireland is the westernmost large piece of Europe, and Newfoundland juts far east from North America. Together they make the shortest crossing of open ocean between the two continents, roughly 1,650 nautical miles (about 3,070 km). The route also crossed Maury's "Telegraph Plateau," where his soundings showed a deep but fairly even floor. (Later surveys showed that the Mid-Atlantic Ridge runs down the middle of the whole ocean, so every crossing passes over it; Maury's few soundings could not reveal it.) Heart's Content had a deep, sheltered harbor on the eastern shore of Trinity Bay where a ship could come close to shore. The route on the map curves northward. That is not because the ships wandered: the shortest path across a globe, a **great circle**, appears as a curve bending toward the pole on most flat maps. Today more than four hundred undersea cables crisscross the oceans, most of them carrying internet traffic on hair-thin glass fibers (Lesson 5.3). Many still land where geography makes the crossing shortest or the harbor safest, such as Cornwall in England, Ireland, Nova Scotia, New Jersey and Virginia Beach. The 1866 line was the first strand of the web that carries your words today.



The 1866 Atlantic cable followed nearly a great circle across Maury's Telegraph Plateau. For comparison, the MAREA fiber-optic cable (2017) links Virginia Beach and Spain; its line here is drawn approximately.

PICTURE STUDY



Deck of the Great Eastern, the Cable Trough, etc., 1866, Robert Charles Dudley, 1865–66 · Watercolor over graphite with touches of gouache · The Metropolitan Museum of Art, New York (gift of Cyrus W. Field, 1892)

Robert Dudley was an English artist who sailed with the *Great Eastern* on both the 1865 and 1866 cable expeditions. His sketches, watercolors and oil paintings are the only full pictorial record of the voyages: the cable coiled in its tanks, the machines that paid it out, the anxious men on deck, the grappling for the lost cable and the landing at Heart's Content. Many of his 1865 scenes were printed as color lithographs in William Howard Russell's book *The Atlantic Telegraph* (1866).

In 1892 Cyrus Field gave a large group of Dudley's pictures, along with medals and pieces of cable, to the Metropolitan Museum of Art. This scene shows the working heart of the ship in 1866: the trough along which the cable ran from the great tanks below decks toward the paying-out machinery at the stern.

Look closely

- Trace the path the cable would take across the deck. Where does it start and where is it going?
- Find the people. What jobs are they doing, and how can you tell?
- Look at the scale of the ship compared with the people. What does this tell you about why only the *Great Eastern* could carry the whole cable?
- Notice the details Dudley recorded. Why would a careful, accurate drawing matter more here than a dramatic one?

Talk about it

1. Dudley was hired to make a record, a bit like a photographer. What can a painting of an event show that a written report cannot?
2. Why do you think Cyrus Field kept these pictures for more than twenty-five years and then gave them to a museum?
3. If something went wrong on this deck, the whole cable could be lost in the deep sea. How does the picture show the care the work required?

PROJECT: GREAT-CIRCLE TEST: STRING ON A GLOBE VERSUS A FLAT MAP

Is the straight line on a map the shortest route? You will find out by stretching string between real cities on a globe and on a flat map, then transferring the globe route to the map. This is the unit project; you will add air routes to it in Lessons 4.3 and 4.4.

You will need

- A classroom or desk globe (at least 12 inches across if possible)
- A flat world map, ideally Mercator, and a second map of another projection if available
- Thin string or embroidery thread, a fine-tip marker, masking tape and small sticky dots
- A flexible tape measure and a ruler
- Notebook and calculator

Steps

1. On the globe, put a sticky dot on Valentia, Ireland (about 51.9° N, 10.4° W) and one on Heart's Content, Newfoundland (about 47.9° N, 53.4° W).
2. Tape one end of the string on Valentia and pull it tight to Heart's Content. A tight string on a globe lies along a great circle, the shortest path.
3. Without moving the string, read the latitude and longitude of four or five points under it (for example where it crosses 20° W, 30° W, 40° W). Record them.

4. Measure the string's length on the globe and the globe's circumference at the equator. Distance on earth = (string length ÷ globe circumference) × 40,075 km. Record your answer.
5. On the flat map, draw a ruler-straight line between the two places. Then plot the points you read from the globe and join them with a smooth curve. Which bends toward the pole?
6. Repeat with two longer routes: New York to London, and Seattle to Tokyo (or Chicago to Tokyo). Record which way the great circle bends each time.
7. Compare your measured Valentia distance with the calculated value in Worked Example 1. Find your percentage error.
8. Write a paragraph explaining why the cable route and airline routes look curved on flat maps.

Tips

- Keep the string tight; a slack string does not follow the great circle.
- Routes that run north and south along one meridian, or along the equator, are already great circles. The difference shows up most on long east-west routes far from the equator.
- Save your map: you will add the 1858 and 1866 cable routes, a modern cable and the polar air routes to it for the unit portfolio.

Check your work

- I stretched great-circle routes on the globe and transferred at least three of them point by point to a flat map.
- I measured the Valentia-Heart's Content distance and compared it with the calculated value.
- I can explain why the shortest route looks curved on a Mercator map.

MAP NOTEBOOK

1. Draw a cross-section of the 1866 cable from your reading: a copper core, layers of gutta-percha insulation, a padding layer and an outer armor of iron wires. Label each layer and its job.
2. On your North Atlantic map, draw the 1866 route from Valentia to Heart's Content, label the Telegraph Plateau, and mark where the 1865 cable was lost and later recovered (about two-thirds of the way across).
3. Visit the free online Submarine Cable Map (TeleGeography) with a parent and sketch five modern Atlantic cables. Note at least three landing places that are near the 1866 terminals or on other short crossings.

From history. The *Great Eastern* was the work of Isambard Kingdom Brunel, who had also designed the steamship *Great Western* you met in Unit 1. He meant her to carry 4,000 passengers all the way to Australia without stopping for coal. Her launch in 1858 was so difficult that she stuck on the slipway for months, and Brunel died in 1859, just

after her first trials. As a passenger ship she lost money, but as a cable layer she found her calling: after 1866 she went on to lay further Atlantic cables and a cable from Aden to Bombay.

WORKED EXAMPLES

Example 1. Find the great-circle distance from Valentia, Ireland (51.9° N, 10.4° W) to Heart's Content, Newfoundland (47.9° N, 53.4° W). Use the spherical law of cosines: $\cos d = \sin \varphi_1 \sin \varphi_2 + \cos \varphi_1 \cos \varphi_2 \cos \Delta\lambda$, where φ is latitude, $\Delta\lambda$ is the difference in longitude and d is the central angle. Give the answer in degrees, nautical miles, kilometers and statute miles.

(Use the map or drawing "The 1866 route is close to the great circle between Valentia and Heart's Content" shown earlier in this lesson.)

1. $\Delta\lambda = 53.4^\circ - 10.4^\circ = 43.0^\circ$.
2. $\sin 51.9^\circ \approx 0.7869$, $\sin 47.9^\circ \approx 0.7419$, so $\sin \varphi_1 \sin \varphi_2 \approx 0.5838$.
3. $\cos 51.9^\circ \approx 0.6171$, $\cos 47.9^\circ \approx 0.6704$, $\cos 43.0^\circ \approx 0.7314$, so $\cos \varphi_1 \cos \varphi_2 \cos \Delta\lambda \approx 0.6171 \times 0.6704 \times 0.7314 \approx 0.3026$.
4. $\cos d \approx 0.5838 + 0.3026 = 0.8864$, so $d = \arccos 0.8864 \approx 27.6^\circ$.
5. Nautical miles: each degree is 60 nautical miles, so $27.6 \times 60 \approx 1,655$ nautical miles.
6. Kilometers: one degree of a great circle is about 111.2 km, so $27.6 \times 111.2 \approx 3,070$ km. Statute miles: $3,070 \div 1.609 \approx 1,908$ miles.

Answer: About 27.6° , or about 1,655 nautical miles, 3,070 km or 1,908 statute miles. The cable itself had to be longer than this, because it was laid with slack so it could settle onto the uneven bottom without being stretched.

Example 2. Queen Victoria's 98-word message in August 1858 took about 16 hours to send. The 1866 cable carried about 8 words per minute. (a) Find the 1858 speed in words per minute. (b) How long would Victoria's message have taken in 1866? (c) How many times faster was the 1866 cable?

1. 16 hours = $16 \times 60 = 960$ minutes.
2. (a) $98 \text{ words} \div 960 \text{ min} \approx 0.10$ words per minute, about one word every ten minutes.
3. (b) $98 \text{ words} \div 8 \text{ words per minute} \approx 12.3$ minutes.
4. (c) $8 \div 0.10 \approx 80$ (or $960 \text{ min} \div 12.3 \text{ min} \approx 78$).

Answer: (a) About 0.1 word per minute. (b) About 12 minutes. (c) Roughly 80 times faster.

Example 3. Thomson's law of squares says that the delay that smears out each signal on a long cable grows with the square of its length. A cable 300 miles long works well. How much worse is the smearing on a cable about 1,900 miles long? What did this tell engineers about how to build the Atlantic cable?

1. Ratio of lengths: $1,900 \div 300 \approx 6.3$.
2. By the law of squares, the delay ratio is $6.3^2 \approx 40$.
3. So each signal on the long cable spreads out about 40 times as much as on the short one. Pushing harder with high voltage cannot fix this and may burn the insulation.
4. Instead, the core must carry current more easily (more copper), the insulation must store less charge (more and better gutta-percha), signals must be sent more slowly and carefully, and receivers must detect very faint currents.

Answer: About 40 times more smearing. Engineers learned to build a heavier cable with a thicker copper core and better insulation and to use sensitive receivers such as Thomson's mirror galvanometer, rather than forcing signals with high voltage as Whitehouse did in 1858.

PRACTICE

1. **EASY** Name the two places where the 1866 cable landed and the ship that laid it. Who designed the ship?
2. **EASY** Why did the 1858 expedition use a mid-ocean splice?
3. **EASY** Give two reasons the 1858 cable failed after about three weeks.
4. **MEDIUM** Convert 1,655 nautical miles to kilometers and to statute miles. (1 nmi = 1.852 km; 1 nmi $\approx$ 1.151 statute miles)
5. **MEDIUM** At the 1858 speed of about 98 words in 16 hours, how long would it take to send a 500-word newspaper report? Was that still faster than a steamship of about 10 days?
6. **MEDIUM** At about 8 words per minute (1866), how long would the same 500-word report take?
7. **MEDIUM** The *Great Eastern* recovered the lost 1865 cable from water about 2.5 miles deep. Convert this depth to feet and to kilometers.
8. **HARD** The *Great Eastern* left Valentia on July 13, 1866, and arrived at Heart's Content on July 27, a route of about 1,905 statute miles (3,070 km). Find her average speed in miles per day, mph and km/h.
9. **HARD** Explain why one nautical mile equals one minute of arc, and why that makes the nautical mile useful to navigators.
10. **HARD** Use the spherical law of cosines to find the great-circle distance from London (51.5° N, 0.1° W) to New York (40.7° N, 74.0° W) in km and statute miles.
11. **CHALLENGE** By Thomson's law of squares, if a 100-mile cable has a signal delay of 1 unit, what is the delay for cables of 500 miles and 2,000 miles? Why did this make some experts doubt an Atlantic cable could ever work?

12. **CHALLENGE** Written response (one paragraph): Using the map, explain why the Atlantic cable ran from Valentia to Heart's Content rather than from London to New York. Include at least three geographic reasons.

COMMON MISTAKES

- Thinking the 1858 cable was the lasting success. It worked for only about three weeks; the lasting cables came in 1866.
- Assuming a straight line on a Mercator map is the shortest route. Long routes far from the equator follow great circles, which look curved on most flat maps.
- Mixing nautical and statute miles. A nautical mile (1,852 m) is about 15 percent longer than a statute mile (1,609 m).

Make it a game · Grapple for the Cable. Lay a length of rope (the “lost cable”) across the floor of a room and cover it with a blanket or sheet (the sea). Players take turns standing at one wall and dragging a “grapnel” (a hook made from a coat hanger tied to a string) across the floor beneath the blanket, trying to catch the rope and lift it clear without it slipping off. Each catch that is lifted all the way scores a point. Then discuss: how did the *Great Eastern*’s crew do this through two and a half miles of water, and why did they fail three times in 1865 before succeeding in 1866?

Scripture. “As cold waters to a thirsty soul, so is good news from a far country.” (Proverbs 25:25, KJV)

For families with sons and daughters across the ocean, for merchants waiting on prices and for governments waiting on word of war or peace, news from a far country once took weeks. The first messages over the 1866 cable carried news of peace in Europe. Solomon knew how precious such news is; the cable made it come in minutes.

Practice answers

1. Valentia Island, Ireland, and Heart's Content, Trinity Bay, Newfoundland. The *Great Eastern*, designed by Isambard Kingdom Brunel.
2. No ship then in service (the *Great Eastern*, launched only in January 1858, was not yet fitted out) could carry the whole cable, so HMS *Agamemnon* and USS *Niagara* each carried half, met in mid-ocean, spliced the ends together, and steamed in opposite directions toward Ireland and Newfoundland.
3. The cable and its insulation were weak and imperfectly made (and had been handled roughly over two summers of attempts), and the electrician Wildman Whitehouse applied very high voltages to force signals through, which likely damaged the insulation. Signals were also very slow because of the effects Thomson explained.
4. $1,655 \times 1.852 \approx 3,065$ km; $1,655 \times 1.151 \approx 1,905$ statute miles.
5. Rate $\approx 98 \div 16 \approx 6.1$ words per hour; $500 \div 6.1 \approx 82$ hours, about 3.4 days. Yes, still faster than 10 days, but far too slow and costly for ordinary business.
6. $500 \div 8 = 62.5$ minutes, a little over an hour.
7. $2.5 \times 5,280 = 13,200$ feet; $2.5 \times 1.609 \approx 4.0$ km.

8. 14 days: $1,905 \div 14 \approx 136$ miles per day; $14 \times 24 = 336$ hours, so $1,905 \div 336 \approx 5.7$ mph, and $3,070 \div 336 \approx 9.1$ km/h. Cable ships moved slowly so the cable could be paid out safely.
9. The nautical mile was defined as the length of one minute ($1/60$ of a degree) of arc along a great circle on the earth (now fixed at 1,852 m). So a central angle in degrees converts straight to distance (multiply by 60), and one minute of latitude on a chart equals one nautical mile, letting navigators measure distance with the latitude scale on the chart's side.
10. $\Delta\lambda = 73.9^\circ$. $\sin 51.5 \times \sin 40.7 \approx 0.7826 \times 0.6521 \approx 0.5103$; $\cos 51.5 \times \cos 40.7 \times \cos 73.9 \approx 0.6225 \times 0.7581 \times 0.2773 \approx 0.1309$. $\cos d \approx 0.6412$, $d \approx 50.1^\circ$. Distance $\approx 50.1 \times 111.2 \approx 5,570$ km $\approx 3,460$ miles.
11. 500 miles: $(5)^2 = 25$ units. 2,000 miles: $(20)^2 = 400$ units. Because the delay grows so fast with length, signals on a 2,000-mile cable would blur into each other unless sent very slowly; doubters thought a cable that long could never carry messages fast enough to pay for itself. Thicker conductors, better insulation and very sensitive receivers proved them wrong.
12. A strong answer names several of these: Ireland and Newfoundland are the nearest points of the two continents, so the open-ocean crossing (about 1,650 nautical miles) is as short as possible; the route crosses the Telegraph Plateau, which Maury's soundings showed as a fairly even stretch of deep floor; Heart's Content and Valentia offered sheltered water where a ship could approach and the shore end could be landed; existing land lines connected Ireland to London and Newfoundland (by a short cable) to the mainland and New York, so the expensive and risky undersea part was kept short.

4.3 THE AIRPLANE

OBJECTIVES

- Explain how the Wright brothers solved the problems of lift, control and power, and why they chose the dunes at Kill Devil Hills near Kitty Hawk, North Carolina.
- Trace how airplanes grew from 120-foot hops to scheduled air routes (the air mail beacons, Lindbergh, the China Clipper and the Douglas DC-3), and explain how aircraft range made islands, coasts and refueling stops into new strategic geography.
- Calculate ground speed, flight time and the effect of headwinds and tailwinds on real and model air routes.

Warm-up. Fold a simple paper airplane and fly it three times with a small fan or hair dryer (on cool) blowing toward you, then three times with the air blowing from behind you, then three times in still air. Measure each distance. Which went farthest and which went shortest? Pilots have argued with the wind since the first day of flight; today you will learn how to calculate it.

Watch. *The Brilliant Engineering of FIRST FLIGHT !* (Sabin Civil Engineering, 8:36).

<https://www.youtube.com/watch?v=LigpsX1KoQE>

With How they figured it out: the engineering of the Wright Flyer.

Backup video. *Douglas DC-3: Most Successful Airliner* (Smithsonian National Air and Space Museum, 1:29). https://www.youtube.com/watch?v=e_zskQVsD9w

With The DC-3: why the DC-3 was the most successful early airliner, from the National Air and Space Museum.

KEY TERMS

lift

The upward force on a wing produced as air flows over and under it; it must equal the airplane's weight for level flight.

wing warping

The Wrights' method of control: twisting the wingtips in opposite directions so one wing gains lift and the other loses it, banking the airplane into a turn. Later airplanes do the same job with hinged ailerons.

airspeed and ground speed

Airspeed is the airplane's speed through the air; ground speed is its speed over the ground. Ground speed = airspeed – headwind, or airspeed + tailwind.

range

The greatest distance an airplane can fly on a full load of fuel, with a safe reserve. Range decided where early air routes could go.

prevailing westerlies

The winds that blow mostly from west to east across the middle latitudes (about 30° to 60° N and S), including most of the United States and Europe.

air route

A regular path flown by aircraft between airports, shaped by distance, range, winds, weather, terrain and the places where planes can land and refuel.

CORE IDEAS

The story. On the cold, windy morning of Thursday, December 17, 1903, two bicycle makers from Dayton, Ohio, laid a 60-foot wooden starting rail on the flat sand below the Kill Devil Hills, about four miles south of Kitty Hawk, North Carolina. At about 10:35 a.m. Orville Wright lay down on the lower wing of their Flyer, opened the throttle of a small gasoline engine, and slid along the rail into a headwind of more than 20 miles an hour, with his brother Wilbur running alongside. The Flyer rose and flew 120 feet in about 12 seconds. A man from the nearby lifesaving station, John T. Daniels, squeezed the bulb of the camera Orville had set up, and took one of the most famous photographs ever made. The brothers took turns and flew three more times that morning; on the fourth flight Wilbur covered 852 feet in 59 seconds. Then a gust overturned the machine and wrecked it. That afternoon they walked to the weather station at Kitty Hawk and telegraphed their father: “Success four flights thursday morning,” the message began, ending “inform Press home Christmas.” (The operator garbled it to say the longest flight was 57 seconds and misspelled Orville’s name.) The telegraph of Lesson 4.1 carried the news of the airplane.

How they figured it out. The Wrights solved flight as engineers, one problem at a time. Others had built wings that could lift and engines that could push; the missing piece was **control**. Watching buzzards twist the tips of their wings to keep their balance, Wilbur realized in 1899, while idly twisting a long cardboard box, that a flexible wing could be twisted the same way. This **wing warping** let a pilot bank and steer. When their 1900 and 1901 gliders lifted less than the published tables said they should, the brothers built a small wind tunnel in their bicycle shop in the autumn of 1901 and tested about two hundred little wing shapes, producing their own, far better, data. With their mechanic Charlie Taylor they built a light engine of about 12 horsepower and carved their own propellers, which they understood as rotating wings. They chose Kitty Hawk after writing to the U.S. Weather Bureau for places with steady strong winds; the Outer Banks offered wind, soft sand for landings and privacy. Faith shaped them too: their father, Milton Wright, was a bishop of the Church of the United Brethren in Christ, and the brothers would not fly on Sundays.

From hops to routes. Progress came fast. In 1908 Wilbur astonished crowds in France with long, controlled flights. On July 25, 1909, Louis Blériot flew across the English Channel, and British newspapers warned that Britain was no longer safely an island. On January 1, 1914, the St. Petersburg-Tampa Airboat Line began the world’s first scheduled airline service with a flying boat across Tampa Bay, about 21 miles (34 km) that took hours around by land. The U.S. Post Office began air mail on May 15, 1918, and by 1924 mail planes were flying coast to coast day and night, following a chain of rotating beacons on towers, often built beside huge concrete arrows on the ground, that marked the airway across plains and mountains.

On May 20–21, 1927, Charles Lindbergh flew the *Spirit of St. Louis* alone from Roosevelt Field, New York, to Le Bourget, Paris, about 3,600 miles (5,800 km) in about 33½ hours.

The DC-3. The airplane that turned flying into a business first flew on December 17, 1935, the 32nd anniversary of the Wrights' first flight. C. R. Smith of American Airlines asked Donald Douglas for a larger, more comfortable version of the DC-2; the result, the Douglas DC-3, carried 21 passengers in its day version at about 180 mph (290 km/h), with two reliable engines, a strong metal wing and a range of roughly 1,500 miles. With a few refueling stops it crossed the United States in about 15 to 17 hours, compared with about three days by train. It was the first airliner that could earn a profit carrying passengers alone, without depending on mail contracts, and by the end of the 1930s DC-3s carried most of America's airline passengers. Thousands more were built as the C-47 military transport in the Second World War, and some still fly today.

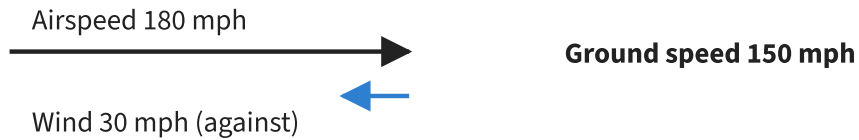
Technology overcoming geography. The airplane ignored the barriers that had shaped every earlier lesson in this course: mountains, rivers, swamps, deserts, even oceans. But it created a geography of its own. Range was everything. On November 22, 1935, Pan American Airways' Martin M-130 *China Clipper* left Alameda, on San Francisco Bay, carrying air mail across the Pacific; it reached Manila about a week later after stops at Honolulu, Midway, Wake and Guam. The longest leg, San Francisco to Honolulu, was about 2,400 miles (3,860 km) of open ocean. Pan Am had to build bases, hotels and radio stations on tiny Midway and Wake islands, because a flying boat could not cross the Pacific in one hop. Specks of coral that sailors had barely noticed became stepping stones of a world air route. In the same way, places like Gander in Newfoundland and Shannon in Ireland became famous refueling stops for transatlantic flights in the 1940s, because they sat at the two ends of the shortest ocean crossing, the same geography that put the 1866 cable at Heart's Content and Valentia.

On the map: the wind. The ocean of air has its own currents. Across the middle latitudes the prevailing westerlies blow from west to east, so flights from Los Angeles to New York usually take less time than flights from New York to Los Angeles. A headwind subtracts from airspeed and a tailwind adds to it (see the diagram). Pilots and dispatchers plan routes to use tailwinds and avoid headwinds, and early airmail pilots also had to cross the Rockies and the Sierra Nevada, where weather and altitude, not distance, were the greatest dangers. A map of air routes is therefore not just a map of distances; it is a map of range, wind, weather and places to land.

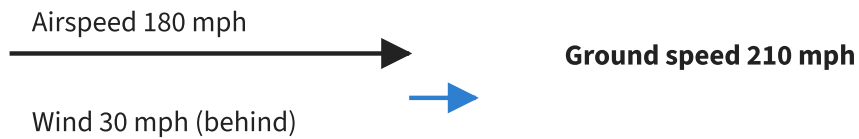
Calm air



Headwind



Tailwind



Ground speed = airspeed – headwind, or airspeed + tailwind. The same airplane covers the ground faster with the wind behind it.

PICTURE STUDY



First Flight, December 17, 1903, Photograph taken by John T. Daniels with Orville Wright's camera, December 17, 1903 · Glass-plate negative (photograph) · Library of Congress, Prints and Photographs Division, Washington, D.C.

Orville Wright set up his big box camera on a tripod, aimed it at the end of the starting rail, and asked John T. Daniels of the Kill Devil Hills lifesaving station to squeeze the rubber bulb if the machine left the ground. Daniels, by the usual account, had never taken a photograph before. He caught the Flyer about two feet in the air, just after leaving the rail, with Wilbur standing on the sand beside it.

The brothers did not publish the photograph for years; they were cautious about protecting their invention. Today the glass negative is kept by the Library of Congress, and the Flyer itself hangs in the Smithsonian's National Air and Space Museum in Washington.

Look closely

- Find Orville at the controls. What position is he in, and why might the Wrights have designed the Flyer to be flown lying down?
- Find Wilbur. What has he just been doing, and what does his posture tell you?
- Find the starting rail and the marks on the sand. What do they tell you about the ground the Wrights chose?
- Look at the empty horizon. What does it tell you about why the Wrights came to this place?

Talk about it

1. This photograph shows the first powered, controlled, sustained flight of an airplane carrying a pilot. Why does each of those four words matter?
2. How does the landscape in the photo explain the Wrights' choice of Kitty Hawk?
3. A twelve-second flight of 120 feet changed the world within a generation. What other small beginnings in this course led to great changes?

PROJECT: AIR ROUTE PLANNING: RANGE CIRCLES AND STEPPING STONES

Early airliners could not fly far without refueling, so planners drew range circles around airports to see which routes were possible. You will draw range circles on a world map and plan a 1930s-style air route across the Pacific and the Atlantic, then add the routes to your great-circle map from Lesson 4.2.

You will need

- A world map or a Pacific Ocean map with a scale bar (or printouts of two maps)
- A drawing compass, a ruler and colored pencils
- The great-circle map and globe from Lesson 4.2
- Notebook and calculator

Steps

1. Using the map's scale bar, set your compass to a range of 2,400 miles (3,860 km), about the distance from San Francisco to Honolulu. Draw a circle around San Francisco. Does Honolulu fall inside?
2. Now give your airplane a range of 1,500 miles (2,400 km), like a DC-3. Draw circles around San Francisco and Honolulu. Can the DC-3 make the Pacific crossing? Explain.
3. Plan the 1935 China Clipper route from San Francisco to Manila through Honolulu, Midway, Wake and Guam. Mark each stop and draw a circle of about 2,500 miles around each to show that every next stop lies within range.

4. On the Atlantic side, mark Gander (Newfoundland) and Shannon (Ireland). Measure the distance between them with the scale bar and compare it with the Valentia-Heart's Content cable distance.
5. On the globe, stretch a string from San Francisco to Manila. Does the great-circle route pass near the island stops? Explain why the airline used islands south of the great circle anyway.
6. Add the routes to your unit map in a new color and write a key.

Tips

- Map scales on Mercator maps change with latitude; use the scale for the latitude you are measuring, or measure on the globe.
- Real flight plans kept a reserve of fuel for headwinds and bad weather, so a 2,400-mile leg needed an airplane with a range well beyond 2,400 miles.

Check your work

- I drew range circles and showed which legs a DC-3 could and could not fly.
- I plotted the 1935 Pacific route and explained why each island was needed.
- I compared the Gander-Shannon air gap with the Atlantic cable route.

MAP NOTEBOOK

1. Sketch the 1903 Wright Flyer from the picture study and label the wings, the front elevator, the rudder, the propellers and the engine.
2. Draw a cross-section of a curved wing with arrows showing air flowing over and under it and the direction of lift.
3. On your map, draw the 1920s transcontinental air mail route from New York to San Francisco, mark where it crosses the Appalachians, the Rockies and the Sierra Nevada, and write one sentence on why those crossings were the most dangerous.

From history. The original 1903 Wright Flyer spent many years in the Science Museum in London because of a long dispute between Orville Wright and the Smithsonian Institution over credit for the first airplane. After the Smithsonian corrected its account, the Flyer came home and was placed on display in Washington in December 1948, shortly after Orville's death that January. A small piece of its wing fabric and a piece of wood from its propeller were carried to the moon by Neil Armstrong on Apollo 11 in 1969.

WORKED EXAMPLES

Example 1. On the first flight, the Wright Flyer covered 120 feet over the ground in 12 seconds while flying into a headwind of about 21 mph. Find its ground speed in feet per second and mph, then estimate its airspeed.

(Use the map or drawing “Airspeed and ground speed differ by the speed of the wind.” shown earlier in this lesson.)

1. Ground speed: $120 \text{ ft} \div 12 \text{ s} = 10 \text{ ft/s}$.
2. Convert to mph: $10 \text{ ft/s} \times 3,600 \text{ s/h} = 36,000 \text{ ft/h}$; $36,000 \div 5,280 \approx 6.8 \text{ mph}$.
3. Airspeed = ground speed + headwind $\approx 6.8 + 21 \approx 28 \text{ mph}$.
4. Check: the Wrights’ telegram reported an average speed through the air of 31 mph for the day’s flights, close to our estimate.

Answer: About 10 ft/s, or 6.8 mph over the ground; about 28 mph through the air. Flying into a strong wind let the Flyer reach flying speed while moving slowly over the sand, which made takeoff and landing safer.

Example 2. Lindbergh flew about 3,600 miles (5,800 km) from New York to Paris in about $33\frac{1}{2}$ hours in May 1927. Find his average ground speed in mph and km/h. A 1927 ocean liner averaged about 22 knots. How many days would it take to cover the same 3,600 miles (3,130 nautical miles)?

1. Lindbergh: $3,600 \text{ mi} \div 33.5 \text{ h} \approx 107 \text{ mph}$; $5,800 \text{ km} \div 33.5 \text{ h} \approx 173 \text{ km/h}$.
2. Liner: 22 knots means 22 nautical miles per hour. $3,130 \text{ nmi} \div 22 \approx 142 \text{ hours}$.
3. $142 \text{ h} \div 24 \approx 5.9 \text{ days}$.

Answer: About 107 mph (173 km/h) for Lindbergh, versus nearly 6 days for a fast liner. One man in a small airplane crossed in a day and a half, though it took twelve more years, until Pan American’s flying boats of 1939, before passengers crossed the Atlantic by air on regular schedules.

Example 3. Suppose a DC-3 cruises at an airspeed of 180 mph on a 2,500-mile route across the United States. The prevailing westerlies give a 30 mph headwind westbound and a 30 mph tailwind eastbound. Find the flying time each way and for the round trip, and compare with a calm day.

1. Westbound ground speed = $180 - 30 = 150$ mph. Time = $2,500 \div 150 \approx 16.7$ h.
2. Eastbound ground speed = $180 + 30 = 210$ mph. Time = $2,500 \div 210 \approx 11.9$ h.
3. Round trip with wind $\approx 16.7 + 11.9 = 28.6$ h.
4. Calm round trip = $5,000 \div 180 \approx 27.8$ h.

Answer: About 16.7 hours westbound and 11.9 hours eastbound, 28.6 hours for the round trip, almost an hour longer than on a calm day. A wind helps less on the way with it than it hurts on the way against it, because you spend more time flying into it.

PRACTICE

1. **EASY** Give the date and place of the Wrights' first flight, who flew first, and the distance and time of the first and longest flights that day.
2. **EASY** Give three reasons the Wrights chose the Outer Banks of North Carolina for their experiments.
3. **EASY** What problem did wing warping solve, and how did Wilbur get the idea?
4. **MEDIUM** Wilbur's fourth flight covered 852 feet in 59 seconds. Find the ground speed in ft/s, mph and km/h.
5. **MEDIUM** Convert Lindbergh's distance of 3,600 statute miles to kilometers and to nautical miles.
6. **MEDIUM** A DC-3 flies 2,500 miles at 180 mph and makes 3 refueling stops of 30 minutes each. What is the total trip time? A train took about 72 hours. How many times faster was the DC-3?
7. **MEDIUM** Name the four island stops on the 1935 China Clipper route from San Francisco to Manila, in order, and explain why each was needed.
8. **HARD** Suppose a flying boat with a cruising airspeed of 130 mph flies the 2,400 miles from San Francisco to Honolulu against a 20 mph headwind and returns with a 20 mph tailwind. Find each flight time and the round-trip time, and compare with calm air.
9. **HARD** If the flying boat in problem 8 could stay in the air for at most 24 hours with its fuel, what was its reserve on the outbound leg in hours and in miles of still-air flying? Why did planners insist on a reserve?
10. **HARD** Explain why Gander, Newfoundland, and Shannon, Ireland, became important airports in the 1940s, and connect your answer to the Atlantic cable.
11. **CHALLENGE** Show algebraically that an out-and-back trip of distance d each way, with airspeed v and a wind of speed w (headwind one way, tailwind the other, $w < v$), always takes longer than the same trip in calm air.
12. **CHALLENGE** Written response (one paragraph): The airplane flew over mountains, deserts and oceans that had stopped travelers for thousands of years. Explain how it

nevertheless created a new geography of its own. Use at least two examples from the lesson.

COMMON MISTAKES

- Confusing airspeed with ground speed. The airplane flies through the air; the air itself may be moving over the ground.
- Thinking a tailwind on the return trip cancels a headwind on the way out. It does not: the round trip with wind always takes longer.
- Thinking the Wrights' great breakthrough was the engine. Their key contribution was control (wing warping, elevator and rudder) together with accurate wing data from their wind tunnel.

Make it a game • Headwind Dash. Mark a 30-foot course with a start and a turnaround. The “airplane” walks at a steady pace of one step per beat while a caller claps a steady beat (the airspeed). First time a calm round trip with normal steps. Then add wind: on the outbound leg (headwind) the walker may only take half-length steps, heel to toe; on the return leg (tailwind) the walker takes one and a half normal steps per beat. Time both legs and compare the windy total with the calm round trip. Then use the formula from practice problem 11 to explain why the windy round trip lost time.

Scripture. “Doth the hawk fly by thy wisdom, and stretch her wings toward the south?” (Job 39:26, KJV)

God asked Job whether he understood the flight of birds. The Wrights learned to fly in part by watching soaring birds and copying how they balance by twisting their wings. Human flight is a fruit of careful attention to the wisdom God built into creation.

Practice answers

1. December 17, 1903, at the Kill Devil Hills near Kitty Hawk, North Carolina. Orville flew first: 120 feet in about 12 seconds. Wilbur made the longest flight: 852 feet in 59 seconds.
2. Steady strong winds (they asked the Weather Bureau for windy sites), soft sand for safer landings, open ground with tall dunes for gliding, and privacy away from crowds and reporters.
3. Control in the air, especially balance and turning (roll). He watched birds twist their wingtips to keep balance and realized, while twisting a long cardboard box, that a flexible wing could be twisted the same way.
4. $852 \div 59 \approx 14.4$ ft/s; $14.4 \times 3,600 \div 5,280 \approx 9.8$ mph; $852 \text{ ft} \approx 260 \text{ m}$, and $260 \div 59 \approx 4.4$ m/s ≈ 15.9 km/h.
5. $3,600 \times 1.609 \approx 5,790$ km (about 5,800); $5,790 \div 1.852 \approx 3,130$ nautical miles.
6. Flying time $2,500 \div 180 \approx 13.9$ h; stops 1.5 h; total ≈ 15.4 h. $72 \div 15.4 \approx 4.7$ times faster.
7. Honolulu, Midway, Wake and Guam. No airplane of the time could cross the Pacific in one hop, so the route was broken into legs short enough to fly with a safe fuel reserve; each island was a place to land, refuel, rest crews and carry weather and radio stations.

8. Out: $2,400 \div 110 \approx 21.8$ h. Back: $2,400 \div 150 = 16.0$ h. Round trip ≈ 37.8 h. Calm: $4,800 \div 130 \approx 36.9$ h. The wind adds about an hour to the round trip.
9. Reserve = $24 - 21.8 = 2.2$ hours, about $2.2 \times 130 \approx 290$ miles at cruising airspeed. Planners required a reserve because winds could be stronger than forecast, weather could force a detour and there was no other place to land between California and Hawaii.
10. Propeller airliners had limited range, so transatlantic flights needed to fuel at the two ends of the shortest ocean crossing between North America and Europe. Newfoundland and western Ireland are the nearest points of the two continents, the same geography that put the 1866 cable at Heart's Content and Valentia.
11. With wind: $T = d/(v - w) + d/(v + w) = d(v + w + v - w)/(v^2 - w^2) = 2dv/(v^2 - w^2)$. Calm: $T_0 = 2d/v = 2dv/v^2$. Since $v^2 - w^2 < v^2$ whenever $w > 0$, $T > T_0$. You lose more time flying into the wind than you gain flying with it.
12. A strong answer explains that range, fuel, winds, weather and landing places shaped air routes: the Pacific crossing depended on tiny islands such as Midway and Wake, which became valuable bases; transatlantic flights refueled at Gander and Shannon at the ends of the shortest crossing; prevailing westerlies made eastbound flights faster; and mountains like the Rockies and Sierra Nevada still mattered because of weather and altitude, which is why the air mail route needed beacons. The airplane changed which places mattered rather than making place unimportant.

4.4 THE JET AGE AND THE POLAR ROUTES

OBJECTIVES

- Explain how the jet engine (the de Havilland Comet, 1952, and the Boeing 707, 1958) changed the speed, altitude and reach of air travel, and how the jet stream affects flight times.
- Explain why the shortest routes between Europe, North America and Asia cross the Arctic, and compute great-circle and rhumb-line distances to compare them.
- Describe how SAS pioneered the commercial polar route in 1954, how navigators solved the problem of steering near the poles, and why Anchorage became a crossroads of world air routes.

Warm-up. Take an orange or a ball and mark two dots on it at the same “latitude,” about two-thirds of the way up from the equator to the top and a quarter of the way around from each other. Hold a rubber band tight between the dots. Does it follow the line of latitude, or does it bend up toward the top? Now draw the same two dots on a flat sheet of paper on a horizontal line and connect them with a ruler. Which drawing tells the truth about the shortest path?

Watch. *How Jet Engines Work* (Animagraffs, 5:01). <https://www.youtube.com/watch?v=L24Wf0VITEQ>

With How it worked: an animation of how a jet engine works.

Backup video. *Why You Wouldn't Want to Fly The First Jet Airliner: De Havilland Comet Story* (Mustard, 10:00). <https://www.youtube.com/watch?v=v0Cg2ZeYa5E>

With The jet age: the de Havilland Comet, the first jet airliner, and why it failed. Note: Mustard includes a sponsor message; skip it.

KEY TERMS

jet engine

An engine that draws in air, compresses it, burns fuel in it and blasts the hot gas out the back, pushing the airplane forward; it works best at high speed and high altitude.

jet stream

A narrow band of very strong west-to-east winds high in the atmosphere, near the altitudes where jets cruise; it often blows 100 to 200 mph (160 to 320 km/h).

rhumb line

A line on the globe that crosses every meridian at the same angle; it is a straight line on a Mercator map but usually longer than the great circle.

gnomonic projection

A map projection on which every great circle appears as a straight line, used to plan the shortest routes, especially near the poles.

grid navigation

A method used near the poles in which navigators steer by a grid of parallel lines laid over the chart and a gyroscope, instead of by meridians and a magnetic compass, which become useless there.

polar route

An air route that crosses the Arctic to follow the great circle between distant cities, such as Copenhagen to Los Angeles or Europe to Tokyo.

CORE IDEAS

The story. On November 15, 1954, two Douglas DC-6B airliners of Scandinavian Airlines System (SAS) took off at the same time from opposite ends of the world. The *Helge Viking* left Copenhagen for Los Angeles, and the *Leif Viking* left Los Angeles for Copenhagen. Instead of flying west across the Atlantic to New York and then across the continent, they flew northwest over the top of the world: to Søndre Strømfjord on the west coast of Greenland, across the ice and the Canadian Arctic to Winnipeg, and on to their destinations. Passengers were handed warm clothing and the crews carried Arctic survival manuals, because there were very few places to land below. It was the world's first regularly scheduled passenger route across the polar regions. To understand why an airline would fly over Greenland to get from Denmark to California, you must look not at a flat map but at a globe.

The geometry of the globe. The shortest route between two points on a sphere lies along a **great circle**, a circle whose center is the center of the earth. On a Mercator map, a ruler-straight line is a **rhumb line**, which keeps a constant compass heading. Rhumb lines were wonderful for sailors steering by compass, but between distant places far from the equator they are not the shortest path. Because the meridians crowd together toward the poles, the great circle between two places in the northern hemisphere always bends poleward of the rhumb line, and the farther apart the places are in longitude, the farther north it climbs. The great circle from New York to Tokyo reaches about 70° N, crossing northern Canada and Alaska. From Copenhagen to Los Angeles it passes over Greenland and the Canadian Arctic. Look at the arctic from above, as on a polar map or a globe, and Europe, North America and Asia appear as a ring of lands around a small ocean. The North Pole is not the edge of the world; for air travel, it is the center.

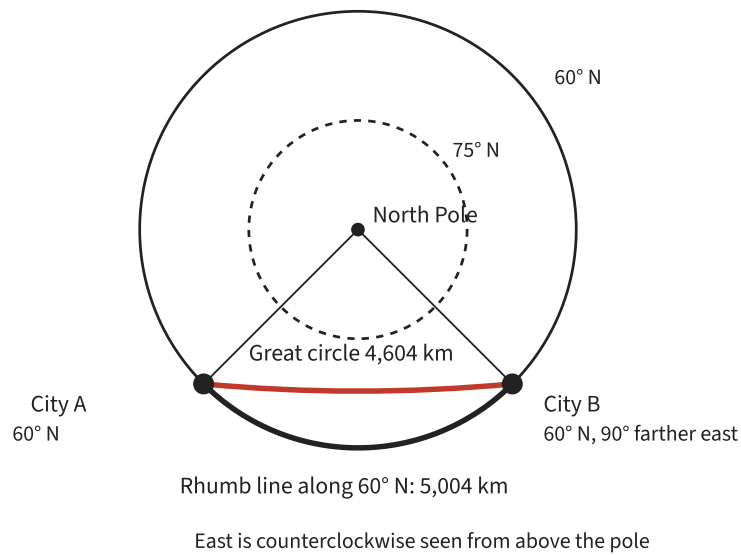
How it worked. Two problems had kept airlines out of the Arctic: range and navigation. Range improved with each new airliner of the 1940s and 1950s, and Greenland and northern Canada had airfields left from the Second World War, such as the American base at Søndre Strømfjord. Navigation was harder. Near the north magnetic pole, which in the 1950s lay among the islands of the Canadian Arctic, a magnetic compass swings wildly or points the wrong way. Near the geographic pole the meridians all converge, so “true north” changes direction very quickly as you fly; a straight course might cross dozens of meridians in an hour. SAS navigators used **grid navigation**: they laid a square grid over polar charts aligned with one reference meridian and steered by a gyroscope set to that grid. A sky compass, which found direction from the position of the sun even when it was below the horizon in the

polar twilight, checked the gyro. Careful planning, the gnomonic chart and celestial navigation turned the Arctic from a barrier into a shortcut. In February 1957 SAS opened a polar route from Copenhagen to Tokyo by way of Anchorage, Alaska, cutting a long journey across southern Asia by many hours.

The jet age. At the same time, the jet engine was changing what an airliner could do. On May 2, 1952, British Overseas Airways Corporation (BOAC) flew the world's first jet airliner service, a de Havilland Comet from London to Johannesburg. The Comet cruised at about 480 mph (770 km/h), far above most weather, in a pressurized cabin. Then, in 1954, two Comets broke apart in the air. British investigators tested a whole Comet fuselage in a giant water tank, pressurizing and depressurizing it again and again, and found **metal fatigue**: cracks that started at the corners of openings in the cabin and grew with each flight. The lessons learned helped make every later airliner safer. On October 4, 1958, a redesigned Comet 4 of BOAC flew the first transatlantic jet passenger service, and on October 26, 1958, Pan American began Boeing 707 service from New York to Paris. The 707 cruised at around 550 to 600 mph (about 900 to 970 km/h), nearly twice as fast as the propeller airliners, and carried well over a hundred passengers. A trip that had taken a week by ship and half a day by propeller airliner now took about seven hours.

Technology overcoming geography. Jets flew in the region of the **jet stream**, the river of fast wind that circles the globe from west to east in the middle latitudes. The Japanese meteorologist Wasaburo Ooishi measured it with weather balloons in the 1920s, and American B-29 crews flying over Japan in 1944 and 1945 met headwinds so strong they could barely move over the ground. Today flight planners route jets to ride the jet stream eastbound and avoid it westbound, which is why a flight from New York to London is usually about an hour shorter than the flight back. Geography also showed up in politics. During the Cold War, the Soviet Union generally did not allow Western airlines to cross Siberia, so flights between Europe and Japan used the polar route through Anchorage, Alaska, which became one of the busiest refueling stops in the world. After the Cold War ended and longer-range jets arrived, most passenger flights began flying nonstop across Russia or the pole, and Anchorage became instead one of the world's great cargo airports, because it sits within a short flight of both Asia and North America along the great circles between them.

On the map. A Mercator map makes the Arctic look enormous and the polar routes look like strange detours. A globe, a polar map or a gnomonic chart shows the truth: the great circles between the great cities of the Northern Hemisphere bend toward the pole, and the shortest air routes between Europe, North America and East Asia run over Greenland, Canada, Alaska and the Arctic Ocean. The places that matter changed: Gander and Shannon faded as jets crossed the Atlantic nonstop, while Anchorage, Søndre Strømfjord and Fairbanks gained. The farther technology reached, the more the true shape of the earth, God's round world, decided the routes.



Seen from above the pole, the great circle between two cities on the same parallel bends toward the pole and is shorter than the rhumb line along the parallel.



The first SAS polar route, November 15, 1954. On a flat map it looks like a detour; on a globe it is close to the great circle.

PICTURE STUDY



Septentrionalium Terrarum descriptio (Description of the Northern Lands), Gerardus Mercator, Published 1595 · Copper engraving, often hand-colored · Published in Mercator's *Atlas* (Duisburg, 1595); copies are held in many map libraries

Gerardus Mercator, whose 1569 world map gave sailors the projection that makes rhumb lines straight, knew his famous projection could not show the poles at all: they stretch away to infinity. So he drew the Arctic separately, as seen from above. A small version appeared as an inset on his 1569 map, and this larger map was published by his son Rumold in 1595, the year after Mercator died, in the first book to be called an *Atlas*.

Much of it is imagination. With almost no real reports, Mercator relied on a lost medieval account and showed four islands around the pole, divided by rivers that pour into a great whirlpool around a black rock. But the coasts of Scandinavia, Iceland and northern Russia are drawn from the best knowledge of his day, and the view from above the pole is exactly the way airline planners looked at the world when they opened the polar routes three and a half centuries later.

Look closely

- Find the North Pole at the center. What did Mercator imagine was there?
- Find Scandinavia, Iceland and Greenland. How close do they look to North America in this view?
- Find where Mercator separated Asia from America. He could not have known for certain that a strait existed there; Europeans did not confirm it until Vitus Bering sailed through it in 1728.
- Lay a ruler from Scandinavia to the western side of North America across the pole. What do you notice about the shortest path?

Talk about it

1. Why couldn't Mercator show the Arctic on his famous world map?
2. What parts of the map are based on knowledge, and what parts on imagination? How can you tell?
3. Why is a map centered on the pole a better tool than a Mercator map for planning a flight from Copenhagen to Los Angeles?

PROJECT: MAKE A POLAR MAP AND FLY THE POLAR ROUTE

You will draw a polar map (an azimuthal equidistant projection centered on the North Pole) by hand, plot real cities on it, and compare the polar routes with your great-circle strings on the globe and with the flat map from Lesson 4.2.

You will need

- A large sheet of paper (at least 18 by 18 inches), a drawing compass or a string and pencil, a protractor and a ruler
- Your globe, string and flat map from Lessons 4.2 and 4.3
- Colored pencils and a list of city coordinates (below)

Steps

1. Mark the North Pole at the center of the paper. Draw circles for 80°, 70°, 60°, 50°, 40°, 30° and 20° N, with radii of 1, 2, 3, 4, 5, 6 and 7 inches (each 10° of latitude is 1 inch from the pole).
2. With the protractor, draw straight meridians from the pole every 30°. Label 0° (Greenwich) pointing straight down, then 30° E, 60° E and so on counterclockwise, and 30° W, 60° W and so on clockwise.
3. Plot these cities: Copenhagen (55.7° N, 12.6° E), London (51.5° N, 0.1° W), Søndre Strømfjord (67.0° N, 50.7° W), Winnipeg (49.9° N, 97.1° W), Los Angeles (34.1° N, 118.2° W), New York (40.7° N, 74.0° W), Anchorage (61.2° N, 149.9° W) and Tokyo (35.7° N, 139.7° E).
4. Connect Copenhagen-Søndre Strømfjord-Winnipeg-Los Angeles in one color (SAS, 1954) and Copenhagen-Anchorage-Tokyo in another (SAS, 1957). Draw a straight line from New York to Tokyo across your map.
5. On the globe, stretch strings for the same three routes and check whether they match your polar map.
6. Draw the same routes on the Mercator map from Lesson 4.2. Write down which map makes the routes look shortest and why.
7. Use the scale on your polar map (1 inch = 10° = about 1,112 km along any meridian) to measure the distance from the North Pole to Anchorage and to London. Check each against the formula $(90^\circ - \text{latitude}) \times 111.2 \text{ km}$. Distances measured from the center of this map are true.

Tips

- Distances measured straight out from the pole are true on this projection; other distances are only approximate, especially far from the pole.
- Remember that east longitudes go counterclockwise when you look down on the North Pole.

Check your work

- My polar map has correct latitude circles and meridians, and all eight cities are plotted correctly.
- I drew both SAS routes and the New York-Tokyo line and compared them with the globe.
- I can explain why the polar routes look like detours on a Mercator map but are really shortcuts.

MAP NOTEBOOK

1. Draw a simple cutaway of a jet engine and label the intake, compressor, combustion chamber, turbine and exhaust nozzle, with arrows for the air.
2. Copy the polar diagram from memory and label the rhumb line, the great circle and their lengths.
3. On your polar map, shade the band of the jet stream across North America, the Atlantic and Europe, and draw arrows showing which way it blows. Mark which direction of the New York-London flight is faster.

From history. During the Second World War, Japanese scientists put the jet stream to use in a strange way. From November 1944 to April 1945, Japan launched more than nine thousand hydrogen balloons carrying small bombs, called Fu-Go, into the jet stream, which carried them across the Pacific to North America in about three days. Most fell harmlessly or were never found, but in May 1945 a balloon bomb found in the woods near Bly, Oregon, exploded and killed a pregnant woman and five children on a church picnic, the only deaths from enemy action on the U.S. mainland in the war.

WORKED EXAMPLES

Example 1. Two cities lie on latitude 60° N, 90° of longitude apart. Compare the distance along the parallel (the rhumb line) with the great-circle distance. Use 1° of a great circle = 111.2 km.

(Use the map or drawing “The great circle bends toward the pole and saves about 400 km.” shown earlier in this lesson.)

1. Along a parallel, 1° of longitude = $111.2 \times \cos(\text{latitude})$. At 60° N, $\cos 60^\circ = 0.5$, so $1^\circ = 55.6$ km.
2. Rhumb line: $90 \times 55.6 \approx 5,004$ km.
3. Great circle (law of cosines): $\cos d = \sin 60^\circ \sin 60^\circ + \cos 60^\circ \cos 60^\circ \cos 90^\circ = 0.75 + 0 = 0.75$.
4. $d = \arccos 0.75 \approx 41.4^\circ$, so the distance $\approx 41.4 \times 111.2 \approx 4,604$ km.
5. Saving: $5,004 - 4,604 = 400$ km, about 8 percent.

Answer: Rhumb line about 5,004 km (3,110 miles); great circle about 4,604 km (2,861 miles), a saving of about 400 km (250 miles), or 8 percent.

Example 2. Find the great-circle distance from New York (40.7° N, 74.0° W) to Tokyo (35.7° N, 139.7° E). Hint: the difference in longitude, measured the short way, is $360^\circ - (74.0^\circ + 139.7^\circ)$.

1. $\Delta\lambda = 360^\circ - 213.7^\circ = 146.3^\circ$, so $\cos \Delta\lambda = \cos 146.3^\circ \approx -0.8320$.
2. $\sin 40.7^\circ \times \sin 35.7^\circ \approx 0.6521 \times 0.5835 \approx 0.3805$.
3. $\cos 40.7^\circ \times \cos 35.7^\circ \times \cos \Delta\lambda \approx 0.7581 \times 0.8121 \times (-0.8320) \approx -0.5122$.
4. $\cos d \approx 0.3805 - 0.5122 = -0.1317$. A negative cosine means the angle is more than 90° : $d \approx 97.6^\circ$.
5. Distance $\approx 97.6 \times 111.2 \approx 10,850$ km $\approx 6,740$ miles.

Answer: About 10,850 km (6,740 miles). This great circle climbs to about 70° N over northern Canada and Alaska, which is why nonstop flights from New York to Tokyo fly north, not west.

Example 3. Suppose a jet cruises at an airspeed of 900 km/h on the 5,570 km route between New York and London, and the jet stream gives a 150 km/h tailwind eastbound and a 150 km/h headwind westbound. Find both flight times.

1. Eastbound ground speed = $900 + 150 = 1,050$ km/h. Time = $5,570 \div 1,050 \approx 5.3$ h (about 5 h 18 min).
2. Westbound ground speed = $900 - 150 = 750$ km/h. Time = $5,570 \div 750 \approx 7.4$ h (about 7 h 26 min).
3. Difference ≈ 2.1 hours.

Answer: About 5.3 hours eastbound and 7.4 hours westbound. Real flight planners avoid the strongest headwinds westbound by flying north or south of the jet stream core, so the real difference is usually smaller, about an hour.

PRACTICE

1. **EASY** Give the date and airline of the first jet airliner service and of the first Boeing 707 service across the Atlantic.
2. **EASY** Is the equator a great circle? Is the 60th parallel? Is the meridian of Greenwich together with its opposite meridian (180°)? Explain.
3. **EASY** On which kind of map projection does every great circle appear as a straight line, and why is it useful?
4. **MEDIUM** How long is one degree of longitude at 60° N and at 80° N? What is it at the North Pole?
5. **MEDIUM** Two cities lie on 40° N, 90° of longitude apart. Find the rhumb-line distance along the parallel and the great-circle distance, and the saving.
6. **MEDIUM** The great-circle distance from Copenhagen to Los Angeles is about 9,000 km. Before 1954, a traveler flew Copenhagen–New York (about 6,190 km) and then New York–Los Angeles (about 3,940 km). How much shorter was the polar route? At a DC-6B speed of about 500 km/h, about how much flying time did it save?
7. **MEDIUM** Convert 5,570 km to statute miles and to nautical miles.
8. **HARD** Suppose a jet with an airspeed of 900 km/h flies the 5,570 km between New York and London with a 100 km/h jet-stream wind. Find the eastbound and westbound times.
9. **HARD** Two cities lie on 45° N on exactly opposite meridians (180° apart). Find the rhumb-line distance along the parallel and the great-circle distance. Which way does the great circle go?
10. **HARD** Explain in two or three sentences why a magnetic compass is unreliable on a polar flight and how SAS navigators solved the problem.
11. **CHALLENGE** Two cities lie on 60° N, 90° of longitude apart. At its midpoint the great circle reaches its highest latitude ϕ , where $\tan \phi = \tan 60^\circ \div \cos 45^\circ$. Find ϕ and explain in words why the route bends toward the pole.

12. **CHALLENGE** Written response (one paragraph): Explain why Anchorage, Alaska, became a major stop for flights between Europe and Asia from the late 1950s until the early 1990s, and why it is now mostly a cargo hub. Keep your answer factual.

COMMON MISTAKES

- Thinking a straight line on a Mercator map is the shortest route. It is a rhumb line; the great circle is shorter and bends toward the pole.
- Using 111.2 km for every degree of longitude. That is true only at the equator; at other latitudes multiply by the cosine of the latitude.
- Confusing the geographic North Pole (where the meridians meet) with the north magnetic pole (where a compass needle points down), which lies hundreds of miles away and moves over time.

Make it a game • Globe Shortcut Challenge. One player names two cities far apart in the Northern Hemisphere (for example Chicago and Beijing, or London and Seattle). Every other player must predict, without touching the globe, which countries or seas the shortest route will cross, and write them down. Then stretch a string tight on the globe to check. Score one point for each correct country or sea, and two points for anyone who correctly predicted that the route crosses the Arctic Circle. Play five rounds.

Scripture. “He stretcheth out the north over the empty place, and hangeth the earth upon nothing.” (Job 26:7, KJV)

Job speaks of God stretching out the north and hanging the earth on nothing. When airline navigators finally looked at the world from above the pole, they saw a round earth suspended in space, its continents gathered around the north. Every great-circle route is a reminder that the shape of the world is God’s design, not ours.

Practice answers

1. May 2, 1952, BOAC (de Havilland Comet, London to Johannesburg). October 26, 1958, Pan American (Boeing 707, New York to Paris). (BOAC’s Comet 4 had begun transatlantic jet service on October 4, 1958.)
2. The equator is a great circle (its center is the earth’s center). The 60th parallel is not; it is a smaller circle whose center lies on the earth’s axis above the equator. A meridian together with its opposite meridian forms a great circle through both poles.
3. The gnomonic projection. A navigator can draw a straight line between two places to find the shortest route, then transfer points on it to a Mercator chart to steer.
4. 60° N: $111.2 \times \cos 60^\circ = 111.2 \times 0.5 = 55.6$ km (34.6 miles). 80° N: $111.2 \times 0.1736 \approx 19.3$ km (12.0 miles). At the pole: 0, because all the meridians meet.
5. Rhumb: $90 \times 111.2 \times \cos 40^\circ = 90 \times 111.2 \times 0.7660 \approx 7,666$ km. Great circle: $\cos d = \sin^2 40^\circ = 0.4132$, $d \approx 65.6^\circ$, distance $\approx 7,295$ km. Saving ≈ 370 km (230 miles), about 5 percent.
6. Via New York: $6,190 + 3,940 = 10,130$ km. Saving $\approx 1,130$ km (about 700 miles). Time saved $\approx 1,130 \div 500 \approx 2.3$ hours of flying.
7. $5,570 \div 1.609 \approx 3,460$ statute miles; $5,570 \div 1.852 \approx 3,010$ nautical miles.

8. East: $5,570 \div 1,000 \approx 5.6$ h. West: $5,570 \div 800 \approx 7.0$ h.
9. Rhumb: $180 \times 111.2 \times \cos 45^\circ \approx 180 \times 111.2 \times 0.7071 \approx 14,150$ km. Great circle: $\cos d = \sin^2 45^\circ + \cos^2 45^\circ \times \cos 180^\circ = 0.5 - 0.5 = 0$, so $d = 90^\circ$, about 10,010 km. It goes straight over the North Pole: 45° up to the pole and 45° down the other side. Saving about 4,140 km.
10. Near the north magnetic pole (in the Canadian Arctic in the 1950s) the compass needle points steeply down and swings or points the wrong way, and near the geographic pole the meridians converge so true north changes direction rapidly. SAS used grid navigation, steering by a gyroscope against a square grid laid over the chart, and checked it with a sky compass and celestial observations.
11. $\tan \phi = 1.732 \div 0.7071 \approx 2.449$, so $\phi \approx 67.8^\circ$ N, nearly 8° north of the cities. Because meridians converge toward the pole, the east-west distance is shorter farther north; the shortest path trades a little northward travel for a large saving in east-west distance.
12. A strong answer explains that the great circle between Europe and Japan crosses the Arctic near Alaska; that propeller and early jet airliners could not fly the whole distance nonstop and needed a fuel stop; that the Soviet Union generally did not allow Western airlines to cross Siberia during the Cold War, so the polar route through Anchorage was the best available; and that after the Cold War ended, routes across Russia opened and longer-range jets could fly nonstop, so passenger stops faded. Cargo flights still use Anchorage because it lies near the great circles between Asia and North America and heavy freighters gain by refueling there.

4.5 THE CONTAINER

OBJECTIVES

- Tell the story of Malcom McLean and the *Ideal X* (April 26, 1956) and explain how the standardized shipping container replaced break-bulk cargo handling.
- Calculate with real container measures (TEU and FEU), loading costs per ton, crane rates and ship turnaround times to show why the container made distance cheap.
- Explain how containerization reshaped the map of ports, cities and trade, and weigh its costs honestly, including the loss of dock work in older ports.

Warm-up. Empty a small box of mixed household items onto a table: a few cans, a box of pasta, a bag of rice, some socks and a book. Time how long it takes a partner to load them one by one into a backpack so they fit tightly. Now put the same items into a shoebox first, close the lid, and time how long it takes to put the shoebox in the backpack. Which was faster? Now imagine a ship with a million items.

Watch. *Shipping Containers: The Box that Changed the World* (The History Guy: History Deserves to Be Remembered, 18:33). <https://www.youtube.com/watch?v=WyNkcsQGaV4>
With the story: Malcom McLean and the container.

Note: Near the end there is one sentence on recent supply-chain trouble during COVID-19.

Backup video. *How A Container Ship Secures Containers - Design, Safety, Container Locating* (3D Living Studio, 7:37). https://www.youtube.com/watch?v=JebcH4_LVEU
With How it worked: how containers are locked down and stacked on a ship.

KEY TERMS

break-bulk cargo

Goods loaded and unloaded piece by piece (sacks, barrels, bales, crates) by gangs of dockworkers; the way most cargo moved before containers.

shipping container

A standard steel box with fittings at each corner, made to be lifted by crane and carried by ship, truck and train without the goods inside being touched.

TEU

Twenty-foot equivalent unit: the capacity of one 20-foot container, used to measure ships and ports. A 40-foot container (FEU) counts as 2 TEU.

intermodal

Moving the same container by more than one mode of transport (ship, rail, truck) with no unpacking in between.

twist lock

A locking device that fits into a container's corner fittings and turns to fasten it to a crane, a truck chassis, a railcar or another container.

longshoreman

A dockworker who loads and unloads ships (in Britain, a docker or stevedore).

CORE IDEAS

The story. On April 26, 1956, a crowd of about a hundred invited guests watched a crane at Port Newark, New Jersey, lift aluminum truck bodies, without their wheels, off their trailers and set them one after another on a special deck built above the pipes of an old tanker. The ship was the *Ideal X*, a T2 tanker left over from the Second World War. In less than eight hours she was loaded with 58 trailer vans, each 35 feet long, and that evening she sailed for Houston, Texas. When she arrived, cranes lifted the boxes onto waiting truck chassis, and trucks drove them straight to their customers. The man behind the voyage was Malcom McLean, a trucking businessman from North Carolina. The real news was in the accounts: loading cargo the old way cost about \$5.86 a ton; loading the *Ideal X* cost about 16 cents a ton.

The problem. McLean was born in 1913 in Maxton, North Carolina, and started with one secondhand truck in the 1930s. He later told of a day in 1937 when he drove a load of cotton bales to a pier in Hoboken, New Jersey, and waited for hours while longshoremen unloaded truck after truck by hand, carried each item into a sling, hoisted it into the ship's hold and stowed it piece by piece. That was **break-bulk** shipping, the way cargo had been handled since the Phoenicians. A typical freighter carried hundreds of thousands of separate items. Loading and unloading took days, sometimes more than a week, and a ship often spent as much time tied up in port as it did at sea. Goods were damaged, lost and stolen. On many routes, handling cargo at the two ports cost more than carrying it across the ocean. For all the engines, canals and railroads of this course, the last few hundred feet between the dock and the ship remained the most expensive part of the journey.

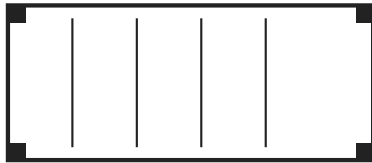
How it worked. McLean's idea was simple: do not handle the cargo at all; handle the box. By 1955 his trucking company was one of the largest in the country. Because the law did not allow him to run both a trucking line and a shipping line, he sold his trucking business and bought a small steamship company, Pan-Atlantic, which he later renamed Sea-Land. His engineer, Keith Tantlinger, designed strong steel corner fittings and the **twist lock** that fastened a box to a crane, a truck or another box in seconds. In October 1957 Sea-Land's *Gateway City* sailed as the first ship fitted with cells, vertical guide rails in the holds into which containers dropped and stacked. Other companies built boxes of different sizes, which meant one firm's box would not fit another's ship or crane. In the 1960s American and international standards bodies agreed on standard sizes, chiefly 20 and 40 feet long and 8 feet wide, and McLean made Tantlinger's corner-fitting and twist-lock patents available free so that every box could fit every ship, crane, truck and train. From then on a container could travel from a factory in one country to a store in another, by truck, rail and ship, without anyone opening it.

Technology overcoming geography. The container did not make ships much faster. It made distance *cheap*. Ships that once spent a week in port now unloaded and reloaded in a day or two, so the same ship could make many more voyages a year. Loading costs collapsed, theft and damage nearly vanished, and insurance became cheaper. In 1966 Sea-Land began container service across the Atlantic to Europe. During the Vietnam War, Sea-Land ships carried military supplies to Cam Ranh Bay, and rather than sail home empty, they stopped in Japan to pick up export cargo, helping open the container trade across the Pacific. Today the largest container ships are about 400 meters (1,300 feet) long and carry more than 24,000 TEU. Shanghai, the world's busiest container port, handles more than 40 million TEU a year. When the cost of moving a box from Asia to America became a tiny part of the price of the goods inside it, factories could be built wherever labor, skill and materials were best, and parts could cross oceans several times before becoming a finished product. Geography still matters, but much less as a wall and much more as a set of routes and gateways.

On the map. Containers moved the ports themselves. The old finger piers of Manhattan and Brooklyn sat on crowded streets with no room to stack thousands of boxes or to bring in trucks and trains. In 1962 the Port Authority opened a container terminal at Elizabeth, New Jersey, next to Port Newark, with acres of flat land, highway and rail connections and a dredged channel. Within a few decades almost all of New York's cargo moved through the New Jersey side, and the Manhattan and Brooklyn waterfronts emptied. Thousands of longshoremen, many of them Irish, Italian and Black American workers whose families had worked the docks for generations, lost their jobs, a real cost that honest history should not hide. The same shift happened elsewhere: Oakland grew while the old San Francisco piers declined; Felixstowe rose in England while London's old docks closed; and Rotterdam, Singapore, Hong Kong, Busan and the new ports of China became giants. The new ports needed deep water for huge ships, flat land for stacking, and fast rail and highway links inland. The sea lanes themselves, through straits like Malacca and canals like Suez and Panama, became more crowded and more important than ever.

The big idea. The container is a humble steel box, yet it may have done more to tie the world together than any machine in this unit. It shows that overcoming geography is not only about speed. The telegraph conquered distance for words; the airplane for people; the container for goods, by making the cost of distance small. Each step brought neighbors across the world closer. Each also made the world more dependent on a few routes and a few ports, which is why a blocked canal or a closed strait can still empty store shelves on the other side of the globe. Wise stewardship of these gifts means thanking God for them while remembering that the world He made still has its narrow places.

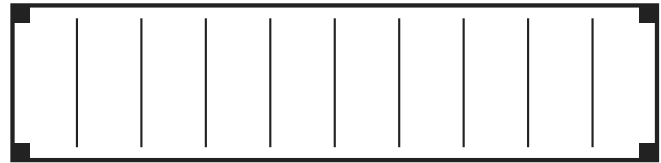
20-foot container = 1 TEU



20 ft (6.1 m) long

Width of both sizes: 8 ft (2.44 m)

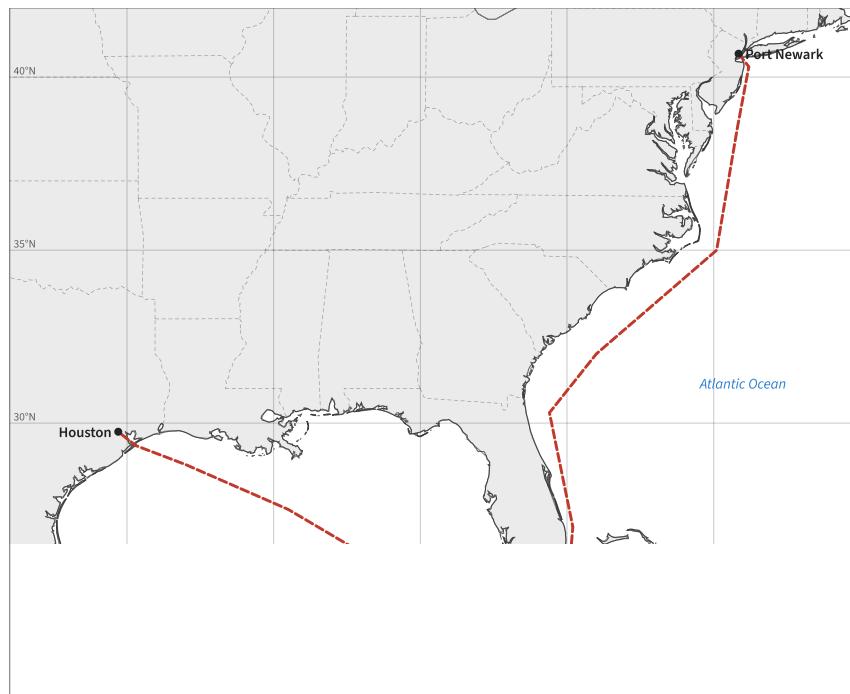
40-foot container = 1 FEU = 2 TEU



40 ft (12.2 m) long

Black squares: corner fittings, where twist locks
fasten the box to cranes, trucks, railcars and other boxes

The two standard container sizes. Ships and ports are measured in TEU; a 40-foot box counts as two.



The first voyage of the Ideal X, April 1956, from Port Newark to Houston (route drawn approximately).

PICTURE STUDY



Men Unloading Coal (Les Déchargeurs de charbon), Claude Monet, 1875 · Oil on canvas · Musée d'Orsay, Paris

Claude Monet is famous for sunlit gardens and water lilies, but here he painted something very different: men unloading coal from barges on the Seine at Asnières, just outside Paris. Each man carries a heavy basket on his shoulder up a narrow plank, empties it, and walks back down for another. Monet painted them as dark shapes moving in a rhythm, almost like a machine made of people.

This is break-bulk cargo handling as it was done for thousands of years, from the harbors of ancient Tyre to the piers of Hoboken where Malcom McLean waited in 1937. Every sack, basket and barrel was moved by human muscle. Look at it as an economist would: how many trips, how many men, how many hours for one barge?

Look closely

- Count the planks and the men walking on them. Which way is each man walking, and what is he carrying?
- Find the bridge in the background. What does it suggest about the city around this river?
- Look at the colors Monet chose. What feeling do the grays and browns give the scene?
- Notice that the faces are not painted in detail. Why might Monet have painted the workers this way?

Talk about it

1. How many hours do you think it took to unload one barge this way? What would change if the coal arrived in large boxes a crane could lift?

2. Monet painted honest, hard labor. What was gained and what was lost when the container replaced this kind of work?
3. Compare this painting with Turner's *The Fighting Temeraire* from Unit 1. Both show an old way of working giving way to a new one. How?

PROJECT: BREAK-BULK VERSUS CONTAINER: A LOADING RACE AND CARGO PUZZLE

You will load a model "ship" two ways, piece by piece and by container, time both, and then solve a stacking puzzle like the ones real ship planners solve every day.

You will need

- A large cardboard box or plastic tub as the ship's hold (about 24 × 12 inches)
- About 60 small mixed items (blocks, toy cars, spools, small boxes, socks)
- Six to ten identical small boxes (tea boxes or shoeboxes cut down) to serve as containers, with two half-length boxes if you can make them
- A stopwatch, a ruler, tape and markers
- Notebook and calculator

Steps

1. Break-bulk round: one person is the crane and may carry only one item at a time from a table 10 feet away into the hold. Time how long it takes to load all 60 items so the hold is packed tightly and nothing rolls. Count any items dropped or left out.
2. Unload the hold the same way and time it.
3. Container round: first pack the items into the small identical boxes at the "factory" table (this is done before the ship arrives). Then time how long it takes the crane, still carrying one thing at a time, to load and unload the boxes.
4. Calculate the ship's time in port each way and the percentage of time saved.
5. Label your boxes: mark the long ones FEU (2 TEU) and the short ones TEU. Count the total TEU your ship carries.
6. Stacking puzzle: label each box with a destination port (Rotterdam, New York, Santos) in the order the ship will call. Load the hold so that the boxes for the first port are on top and can be unloaded without moving the others. Heavier boxes must go on the bottom.
7. Write a paragraph comparing the two methods and explaining why ports needed more land, bigger cranes and better rail and highway connections after containers arrived.

Tips

- Count the packing of the containers at the factory as time spent before the ship arrives, not as port time; that is the whole point of the container.
- Real ship planners use computers to plan stacking by weight, port order and balance; try to keep your ship balanced from side to side.

Check your work

- I timed both loading methods and calculated the time saved.
- I counted my ship's capacity in TEU.
- My stack let each port's boxes come off without moving boxes for later ports, with heavy boxes low.

MAP NOTEBOOK

1. Draw the two standard container sizes to scale (1 inch = 4 feet) and label their length, width and height in feet and meters.
2. Draw a map of the Port of New York and New Jersey showing Manhattan, Brooklyn, Port Newark and Port Elizabeth, and write two sentences on why cargo moved to the New Jersey side.
3. Trace the journey of one container of sneakers from a factory in Asia to a store near you: name the factory port, the strait or canal it passes, the port where it lands, and the rail or highway route inland.

From history. Before the container, cargo that went to sea was so often pilfered on the docks that shippers joked about it, and insurers charged accordingly. A sealed container, locked at the factory and opened only by the customer, cut theft dramatically and made insurance cheaper, a saving almost as important as the faster loading. When Malcom McLean died in May 2001, container ships around the world sounded their horns in his honor on the morning of his funeral.

WORKED EXAMPLES

Example 1. Loading break-bulk cargo cost about \$5.86 a ton in 1956, while loading the *Ideal X* cost about 16 cents a ton. For a cargo of 2,000 tons, find each loading cost, the saving, and how many times cheaper the container was.

1. Break-bulk: $2,000 \times \$5.86 = \$11,720$.
2. Container: $2,000 \times \$0.16 = \320 .
3. Saving: $\$11,720 - \$320 = \$11,400$.
4. Ratio: $\$5.86 \div \$0.16 \approx 37$.

Answer: \$11,720 by break-bulk versus \$320 by container, a saving of \$11,400; the container was about 37 times cheaper to load.

Example 2. A container ship carries 1,800 forty-foot containers and 2,400 twenty-foot containers. (a) What is its load in TEU? (b) A 20-foot container measures about $6.06\text{ m} \times 2.44\text{ m} \times 2.59\text{ m}$ on the outside. What is its outside volume in cubic meters and cubic feet?

(Use the map or drawing “A 40-foot box counts as 2 TEU.” shown earlier in this lesson.)

1. (a) Each 40-foot box = 2 TEU: $1,800 \times 2 = 3,600$ TEU. Add the 20-foot boxes: $3,600 + 2,400 = 6,000$ TEU.
2. (b) Volume = $6.06 \times 2.44 \times 2.59 \approx 14.79 \times 2.59 \approx 38.3\text{ m}^3$.
3. In feet: $20\text{ ft} \times 8\text{ ft} \times 8.5\text{ ft} = 1,360\text{ ft}^3$ (check: $38.3\text{ m}^3 \times 35.31 \approx 1,352\text{ ft}^3$, the same within rounding).

Answer: (a) 6,000 TEU. (b) About 38.3 m^3 , or about 1,360 cubic feet, on the outside (the inside is a little smaller because of the steel walls).

Example 3. A ship must unload and load a total of 4,800 container moves at a terminal. The terminal assigns 5 cranes, each making 30 moves an hour. How long is the ship at the berth? Compare with an older break-bulk freighter that needed 6 days in port.

1. Moves per hour for all cranes: $5 \times 30 = 150$ moves per hour.
2. Time: $4,800 \div 150 = 32$ hours.
3. 6 days = 144 hours; $144 \div 32 = 4.5$.

Answer: About 32 hours, roughly a day and a third. The container ship handles far more cargo in less than a quarter of the break-bulk freighter’s time in port.

PRACTICE

1. **EASY** Give the date, the ports of departure and arrival, and the number of containers on the first voyage of the *Ideal X*.
2. **EASY** What does TEU stand for, and how many TEU is a 40-foot container?
3. **EASY** Who designed the corner fittings and twist lock for McLean’s containers, and why did it matter that the patents were made available free?
4. **MEDIUM** A ship carries 1,500 forty-foot containers and 3,000 twenty-foot containers. What is its load in TEU?
5. **MEDIUM** Using the 1956 figures (\$5.86 a ton break-bulk; \$0.16 a ton by container), find the loading cost of 5,000 tons each way, and the saving.
6. **MEDIUM** A terminal works a ship with 6 cranes at 30 moves an hour each. How long does it take to make 4,800 moves?
7. **MEDIUM** Convert the length of a 40-foot container to meters and a 400-meter ship to feet. ($1\text{ ft} = 0.3048\text{ m}$)

8. **HARD** If the 24,000 twenty-foot boxes of a 24,000-TEU ship were placed end to end, how long would the line be in miles and in kilometers? (Use 20 ft and 6.06 m per box.)
9. **HARD** Suppose it costs \$3,000 to ship one 40-foot container from Asia to the U.S. West Coast, and the box holds 10,000 shirts. What is the shipping cost per shirt? What does this show about the effect of containers on where factories can be located?
10. **HARD** Give three geographic reasons cargo shifted from the Manhattan and Brooklyn piers to Port Newark and Port Elizabeth after 1960.
11. **CHALLENGE** A ship's sea voyage between two ports takes 12 days each way. A break-bulk ship spends 6 days in port at each end; a container ship spends 1 day. How many days is each round trip, and how many round trips can each make in a year (365 days)? How many container ships would do the work of 10 break-bulk ships?
12. **CHALLENGE** Written response (one paragraph): The container has been called "the box that changed the world." Explain how it changed the geography of ports and trade, and name at least one real cost that came with it. Keep your answer factual.

COMMON MISTAKES

- Thinking the container made ships faster. Its great saving was time and cost in port, not speed at sea.
- Counting containers instead of TEU. A 40-foot container is 2 TEU; ship and port capacities are given in TEU.
- Forgetting the land side. Containers succeeded only because trucks, trains, cranes and standard fittings were all designed to fit the same box.

Make it a game • Stack and Ship. Cut 20 cards into small rectangles (containers), and mark each with a weight from 1 to 5 and one of three ports: A, B or C. Shuffle and deal them face down. Players take turns drawing a card and adding it to a stack in a shoebox "ship" with up to four stacks. At the end, the ship calls at Port A, then B, then C. Each box that can be lifted off at its port without moving another scores 2 points; each heavier box sitting on a lighter one costs 1 point. The best-planned ship wins.

Scripture. "She is like the merchants' ships; she bringeth her food from afar." (Proverbs 31:14, KJV)

Solomon's picture of the virtuous woman borrows the image of merchant ships bringing good things from far away. Trade between distant peoples is an old and honorable part of human life. The container made it possible for ordinary families to enjoy goods from the far side of the world, a reason for gratitude and for wise, fair dealing.

Practice answers

1. April 26, 1956, from Port Newark, New Jersey, to Houston, Texas, carrying 58 thirty-five-foot trailer vans (containers).
2. Twenty-foot equivalent unit. A 40-foot container is 2 TEU.

3. Keith Tantlinger. Making the designs free let every company adopt the same fittings, so any standard box could be lifted by any crane and carried on any ship, truck or railcar.
4. $1,500 \times 2 + 3,000 = 3,000 + 3,000 = 6,000$ TEU.
5. Break-bulk: $5,000 \times 5.86 = \$29,300$. Container: $5,000 \times 0.16 = \$800$. Saving: \$28,500.
6. $6 \times 30 = 180$ moves an hour; $4,800 \div 180 \approx 26.7$ hours (about 26 hours 40 minutes).
7. $40 \times 0.3048 \approx 12.2$ m. $400 \div 0.3048 \approx 1,312$ ft.
8. $24,000 \times 20$ ft = 480,000 ft; $480,000 \div 5,280 \approx 90.9$ miles. $24,000 \times 6.06$ m = 145,440 m $\approx$ 145 km.
9. $\$3,000 \div 10,000 = \0.30 per shirt. Ocean shipping becomes a very small part of the price, so factories can be located wherever labor, skills, materials and costs are best, even an ocean away from customers.
10. Any three: Port Elizabeth had large areas of flat land for stacking containers and parking trucks; it had direct connections to highways (such as the New Jersey Turnpike) and to railroads leading inland, while Manhattan's piers sat on congested streets; its channels could be dredged deep for larger ships; the old finger piers were narrow and built for break-bulk handling, not for giant cranes.
11. Break-bulk: $12 + 6 + 12 + 6 = 36$ days; $365 \div 36 \approx 10.1$, about 10 round trips. Container: $12 + 1 + 12 + 1 = 26$ days; $365 \div 26 \approx 14.0$, about 14 round trips. Ten break-bulk ships make about 101 trips a year; $101 \div 14 \approx 7.2$, so about 7 container ships of the same size could do the same work (and each container ship is usually much larger).
12. A strong answer explains that the container cut loading costs and port time dramatically, so shipping across oceans became cheap; trade grew and factories could locate far from their customers; ports moved to places with deep water, flat land and rail and highway links (Port Elizabeth, Oakland, Felixstowe, Rotterdam, Singapore, Shanghai); and old waterfronts declined. Costs include the loss of thousands of longshoremen's jobs in older ports, the decline of old harbor neighborhoods, and greater dependence on a few routes, straits and canals, so a blockage can disrupt supplies worldwide.

UNIT 4 TEST

Answer every question. Show your work for all calculations, give units, and use complete sentences for explanations. Use 1° of a great circle = 111.2 km = 60 nautical miles, 1 mile = 1.609 km, and 1° of longitude = 4 minutes of time. A calculator is allowed. The test is worth 100 points.

1. (6 pts) Give the date, the two cities and the words of the first public message on Morse's telegraph line. Explain in one sentence why this message marked "the end of distance for words."
2. (6 pts) Philadelphia is at about 75.2° W and St. Louis at about 90.2° W. When it is noon by local solar time in Philadelphia, what is the local solar time in St. Louis? Show your work.
3. (8 pts) The Pony Express carried mail about 1,900 miles in about 10 days. (a) Find its average speed in mph. (b) Explain why it closed in October 1861.
4. (6 pts) The 1858 Atlantic cable worked for about three weeks; the 1866 cables lasted. Give two reasons the 1858 cable failed and two things that were different in 1866.
5. (8 pts) The great circle from Valentia, Ireland, to Heart's Content, Newfoundland, spans a central angle of about 27.6° . Find the distance in nautical miles, kilometers and statute miles.
6. (6 pts) Give three geographic reasons the Atlantic cable was laid between Valentia and Heart's Content.
7. (8 pts) An airliner with an airspeed of 200 mph flies a 1,200-mile route. Find the flight time with a 40 mph headwind and with a 40 mph tailwind. Is the round trip longer or shorter than in calm air, and by how much?
8. (6 pts) Explain how limited range turned Midway and Wake islands, and Gander and Shannon, into important places in the history of flight.
9. (8 pts) Two cities lie on latitude 50° N, 60° of longitude apart. (a) How long is 1° of longitude at 50° N? (b) Find the rhumb-line distance along the parallel. (c) Find the great-circle distance using $\cos d = \sin \varphi_1 \sin \varphi_2 + \cos \varphi_1 \cos \varphi_2 \cos \Delta\lambda$.
10. (6 pts) Why did SAS fly from Copenhagen to Los Angeles by way of Greenland in 1954? Name the stops and explain the navigation problem the crews had to solve.
11. (8 pts) Suppose a jet with an airspeed of 850 km/h flies a 6,000 km route with a 120 km/h jet-stream wind. Find the eastbound (tailwind) and westbound (headwind) times to the nearest tenth of an hour.
12. (6 pts) Describe the first voyage of the *Ideal X* (date, ports and cargo). Loading cost about \$5.86 a ton by break-bulk and about \$0.16 a ton by container. How many times cheaper was the container?
13. (8 pts) (a) A ship carries 2,000 forty-foot and 1,500 twenty-foot containers. What is its load in TEU? (b) Four cranes each make 25 moves an hour. How long will 3,000 moves take?
14. (10 pts) Essay (two paragraphs): Choose two of the technologies in this unit (telegraph, Atlantic cable, airplane, jet and polar routes, container). For each, explain what

geographic barrier it overcame and what new geography it created (new places that mattered, new routes, new dependencies). End with one sentence on how a Christian should think about such inventions.

UNIT PROJECT: MASTERING DISTANCE: A GREAT-CIRCLE ATLAS

Assemble a small atlas of the routes that mastered distance. Include: (1) your flat map from Lesson 4.2 showing the great-circle string test, with the 1866 Atlantic cable route from Valentia to Heart's Content and at least five of today's undersea cables traced from the Submarine Cable Map, each labeled with its landing points; (2) your polar map from Lesson 4.4 with the SAS routes of 1954 and 1957 and the New York-Tokyo great circle; (3) the 1935 Pacific air route with range circles from Lesson 4.3; and (4) a map of the *Ideal X* voyage and one modern container route from Asia to a port near you.

Add a one-page written report on your great-circle string test: three routes you measured on the globe, your measured distances compared with calculated great-circle distances (with percentage error), and a clear explanation of why the shortest routes look curved on a flat map but straight on a gnomonic chart or a tight string on a globe.

- **Accuracy:** Places, routes and cables are plotted at the correct latitudes and longitudes; the 1866 cable, the polar routes and the island stops are correct and labeled.
- **Calculation:** Great-circle and rhumb-line distances, measured distances and percentage errors are computed correctly with units and shown work.
- **Explanation:** The report explains great circles, map projections and how each technology created new important places, using evidence from the maps.
- **Craft:** Maps are neat, have a title, key, scale or grid and north arrow (or pole), and use clear colors for each era of technology.

Answer key

1. May 24, 1844, Washington to Baltimore: "What hath God wrought!" For the first time a message traveled faster than any person, horse or ship could carry it; words were separated from transportation.
2. Difference 15.0° ; $15 \times 4 = 60$ minutes. St. Louis is west, so it is 11:00 a.m.
3. (a) 10 days = 240 h; $1,900 \div 240 \approx 7.9$ mph. (b) The transcontinental telegraph was completed on October 24, 1861, carrying messages coast to coast in minutes, so the Pony Express could no longer compete for urgent news.
4. 1858 failure: weak cable and insulation; very slow signals; high voltages applied by Wildman Whitehouse likely damaged the insulation. 1866: a heavier cable with a thicker copper core and better gutta-percha insulation; William Thomson's science and sensitive receivers (mirror galvanometer); the *Great Eastern* could carry the entire cable, so no mid-ocean splice was needed; better testing and paying-out machinery. (Any two of each.)
5. $27.6 \times 60 \approx 1,656$ nautical miles; $27.6 \times 111.2 \approx 3,069$ km (about 3,070); $3,069 \div 1.609 \approx 1,907$ statute miles (about 1,910).
6. They are near the closest points of Europe and North America, giving the shortest open-ocean crossing; the route crossed the fairly even Telegraph Plateau charted by Maury; both ends

had sheltered water where a ship could land the shore end; both connected by land lines (and a short cable from Newfoundland) to London and New York. (Any three.)

7. Headwind: $1,200 \div 160 = 7.5$ h. Tailwind: $1,200 \div 240 = 5.0$ h. Round trip 12.5 h; calm $2,400 \div 200 = 12.0$ h. Longer by 0.5 h.
8. Early airliners could not cross oceans in one hop. Pan Am's 1935 Pacific route needed island stops (Honolulu, Midway, Wake, Guam) to refuel, so tiny islands got airfields or seaplane bases, hotels and radio stations. Transatlantic propeller airliners refueled at Gander and Shannon, which lie at the two ends of the shortest crossing between North America and Europe.
9. (a) $111.2 \times \cos 50^\circ = 111.2 \times 0.6428 \approx 71.5$ km. (b) $60 \times 71.5 \approx 4,290$ km. (c) $\cos d = 0.5868 + 0.4132 \times 0.5 = 0.7934$, $d \approx 37.5^\circ$, distance $\approx 37.5 \times 111.2 \approx 4,170$ km. The great circle is about 120 km shorter.
10. The great circle between Copenhagen and Los Angeles crosses Greenland and the Canadian Arctic, so the polar route was much shorter than going by way of New York. The stops were Søndre Strømfjord (Greenland) and Winnipeg. Near the poles a magnetic compass is unreliable and meridians converge, so navigators used grid navigation with gyroscopes, checked by a sky compass and celestial observations.
11. Eastbound: $6,000 \div 970 \approx 6.2$ h. Westbound: $6,000 \div 730 \approx 8.2$ h.
12. April 26, 1956, from Port Newark, New Jersey, to Houston, Texas, carrying 58 thirty-five-foot trailer vans. $5.86 \div 0.16 \approx 37$ times cheaper.
13. (a) $2,000 \times 2 + 1,500 = 5,500$ TEU. (b) $4 \times 25 = 100$ moves an hour; $3,000 \div 100 = 30$ hours.
14. A strong essay accurately names the barrier each technology overcame (for example, the telegraph and cable overcame distance and the ocean for words; the airplane overcame mountains, deserts and oceans for people; polar routes used the true shape of the globe; the container made distance cheap for goods) and the new geography each created (cable landings at Valentia and Heart's Content; island stepping stones like Midway and Wake; Gander, Shannon and Anchorage as refueling stops; new container ports like Port Elizabeth with deep water, flat land and rail links; dependence on straits and canals). It uses at least one number or date from the unit for each technology. The final sentence reflects gratitude for creativity as part of the image of God and humility rather than Babel-like pride, or a similar thoughtful point. Grade 4 points per technology paragraph and 2 for the closing reflection.

MASTERING LOCATION, AND THE LIMITS

On October 4, 1957, a polished metal ball called Sputnik began circling the earth every 96 minutes, and the lookout from which people study the world moved off the planet. In this last unit you will follow the satellite age from Sputnik's beep to the GPS receiver in your pocket. You will learn how a satellite stays up, how two young physicists turned Sputnik's radio signal into a way to find ships at sea, and how GPS turns time into distance and distance into position. Then you will follow the hair-thin glass fibers that carry the world's internet along the floor of the oceans, through the same straits the telegraph cables used a century before.

Then the course turns to its last and most important question: what has technology **not** overcome? A container ship wedged in the Suez Canal in 2021, an ash cloud from Iceland in 2010 and a road that has never crossed the Darién Gap all show that mountains, weather, distance and choke points still govern the world. The course ends with Apollo 8 and *Earthrise*, the view of the whole earth from the moon, and with your own research paper on one technology and the geography it overcame. As the series verse puts it, God "hath made of one blood all nations of men for to dwell on all the face of the earth, and hath determined the times before appointed, and the bounds of their habitation;" (Acts 17:26). Human creativity has crossed many of those bounds; wisdom remembers that the earth is still the Lord's.

BEFORE YOU BEGIN

- Can compute speed, distance and time, and convert between kilometers, miles and nautical miles
- Can find the circumference of a circle and use a square root on a calculator
- Knows the history of the telegraph, the Atlantic cable, the airplane and the container from Unit 4
- Can read latitude and longitude on a world map

MASTERY CHECKLIST

- I can tell the story of Sputnik and Explorer 1 and explain how an orbit works.
- I can calculate a satellite's speed, its orbits per day and the delay of a signal through space or fiber.
- I can explain how GPS uses timing and trilateration, and why it needs four satellites.
- I can read a world cable map and name the choke points where cables and ships crowd together.
- I can give a real example of how mountains, weather, distance and choke points still limit technology.
- I can write a research paper with a thesis, primary sources, a map and a before-and-after comparison.

OPTIONAL BOOKS AND RESOURCES

- **GPS.gov (official U.S. government information about GPS)** (<https://www.gps.gov/>): Free. Clear explanations of how GPS works, the satellites, the control stations and GPS accuracy, with diagrams students can use in Lesson 5.2.
- **Submarine Cable Map, from TeleGeography** (<https://www.submarinecablemap.com/>): Free interactive world map of undersea cables and their landing stations. Use it for the cable map in Lesson 5.3 and to compare with the 1901 telegraph map.
- **Smithsonian National Air and Space Museum** (<https://airandspace.si.edu/>): Free online collections and articles on Sputnik, Explorer 1 and Apollo 8. Useful for primary sources for the final paper.

5.1 SPUTNIK AND THE SATELLITE AGE

OBJECTIVES

- Narrate the launch of Sputnik 1 on October 4, 1957, and explain why a 184-pound metal ball changed how nations thought about distance and oceans.
- Explain what an orbit is and calculate a satellite's speed, its number of orbits per day and the westward shift of its ground track.
- Describe the four great jobs of satellites (weather, communication, mapping and navigation) and how the Transit navigation system grew out of tracking Sputnik.

Warm-up. Stand at one end of a hallway and gently toss a soft ball or rolled-up pair of socks straight ahead. Mark where it lands with a piece of tape. Toss it harder, and harder again, marking each landing. Now imagine the floor curving downward the way the earth does. Write one sentence: if you could throw the ball fast enough, what would happen when the ground curved away as fast as the ball fell?

Watch. *Sputnik - 60 years on from the Start of the Space Race* (Curious Droid, 9:44).

<https://www.youtube.com/watch?v=5M-QinwmdKc>

With the story: Sputnik and the start of the space race.

Backup video. *Why Don't Satellites Fall Out of the Sky?* (NOAA SciJinks, 2:37).

https://www.youtube.com/watch?v=YSh_S2bHrHE

With How it worked: why satellites do not fall out of the sky, from NOAA.

KEY TERMS

satellite

Any object that orbits a larger body. The moon is a natural satellite of the earth; Sputnik 1 (1957) was the first artificial one.

orbit

The curved path of an object that is falling toward a body but moving sideways so fast that it keeps missing it.

low Earth orbit

An orbit roughly 160 to 2,000 km (100 to 1,200 miles) above the earth, where a satellite circles the globe in about 90 minutes to two hours.

geostationary orbit

A circular orbit 35,786 km (22,236 miles) above the equator, where a satellite circles once a day and so seems to hang still over one spot.

Doppler effect

The change in pitch (frequency) of a wave when its source is moving toward or away from the listener. A satellite's radio tone rises as it approaches and falls as it leaves.

ground track

The path on the earth's surface directly beneath a satellite. Because the earth turns, each orbit's ground track lands farther west.

CORE IDEAS

The story. On the evening of October 4, 1957, on the flat steppe of Kazakhstan near a railroad stop called Tyuratam, a Soviet R-7 rocket rose into the dark. The R-7 had been built to carry a nuclear warhead across the world, but that night it carried something small: a polished metal ball 58 centimeters (23 inches) across and weighing 83.6 kilograms (184 pounds), with four long antennas swept back like whiskers. The Soviets called it *Sputnik*, “fellow traveler.” Within minutes it was circling the earth about once every 96 minutes, sending a steady *beep, beep* on two radio frequencies that anyone with a good shortwave receiver could hear. Radio amateurs on every continent tuned in. Its chief designer, Sergei Korolev, had once been a prisoner in Stalin's labor camps; the Soviet government kept his name secret until his death in 1966. In the United States the news landed like a thunderclap. A nation that could put a ball into orbit could send a warhead anywhere on earth. The two oceans that had sheltered America since its founding suddenly counted for much less. A race followed. On November 3, 1957, Sputnik 2 carried a dog named Laika, the first animal to orbit the earth (she did not survive the flight). On December 6 America's first attempt, the Navy's Vanguard rocket, rose about four feet off its pad at Cape Canaveral and exploded on live television. Then on January 31, 1958, an Army team using a Jupiter-C rocket launched *Explorer 1*. A small Geiger counter built by physicist James Van Allen of the University of Iowa found belts of trapped radiation circling the earth, the first great discovery of the space age. That summer Congress created NASA, and the National Defense Education Act of 1958 poured money into science, mathematics and language teaching. Sputnik itself sank into thicker air and burned up on January 4, 1958, after about 1,440 trips around the world.

How it worked. Isaac Newton had explained the idea long before: a cannonball fired from a high mountain falls to earth, but the faster it is fired, the farther it lands, until at last it falls all the way around the world and never lands at all. The numbers make it clear. The earth's surface curves downward about 5 meters (16 feet) for every 8 kilometers (5 miles) you travel along it. Any object, dropped, falls about 4.9 meters in its first second. So an object moving sideways at about 8 kilometers per second (nearly 18,000 miles per hour) falls exactly as fast as the ground curves away beneath it. That is an orbit: endless falling, endlessly missing. The rocket's whole job is to lift the satellite above the air, where drag will not slow it, and then push it sideways fast enough. Sputnik's orbit was an ellipse, dipping to about 215 km (134 miles) and rising to about 939 km (583 miles); the thin air at its lowest point slowly robbed it of speed.

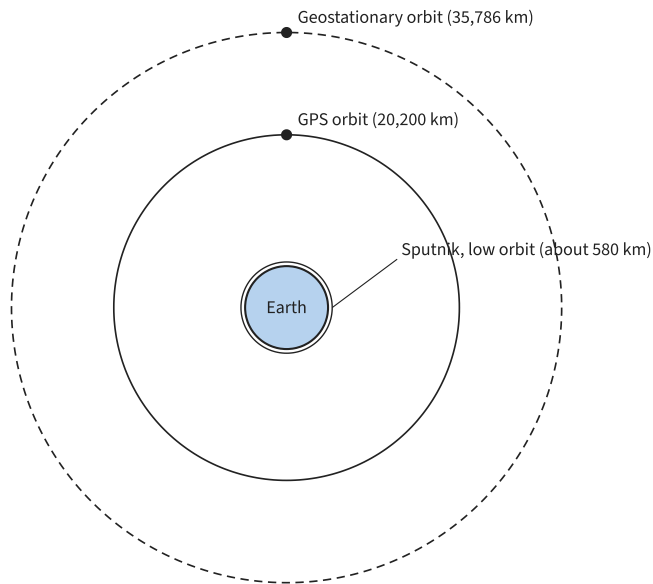
How a beep became a map. At the Johns Hopkins Applied Physics Laboratory in Maryland, two young physicists, William Guier and George Weiffenbach, listened to Sputnik's signal for fun. They noticed that its tone rose as the satellite came toward them and fell as it went away: the **Doppler effect**. By measuring exactly how the pitch changed, they could calculate Sputnik's whole orbit from a single pass. Their colleague Frank McClure then asked the reverse question: if you already know where the satellite is, can a listener on the ground use the same Doppler curve to find *his own* position? He could. The Navy built that idea into

Transit, the first satellite navigation system, to let its Polaris missile submarines fix their positions at sea. The first successful Transit satellite flew in 1960, the system went into service in 1964, and from 1967 merchant ships could use it too. A tool built to track a rival's satellite became the grandfather of GPS.

The big idea. Within a few years satellites had four great jobs, and each one overcame a piece of geography. **Weather:** TIROS-1 (April 1, 1960) sent back the first television pictures of clouds from orbit, so storms over empty oceans could be seen before they reached land. **Communication:** in 1945 the writer Arthur C. Clarke had proposed that three relay stations in a 24-hour orbit above the equator could link nearly the whole world; Telstar carried the first live television across the Atlantic in 1962, and *Early Bird* (1965) became the first commercial satellite in geostationary orbit. **Mapping:** Landsat 1 (1972) began photographing the whole land surface in repeated passes. **Navigation:** Transit led to GPS, the subject of our next lesson. Mountains, deserts and oceans that had hidden places from mapmakers for thousands of years were now seen from above.

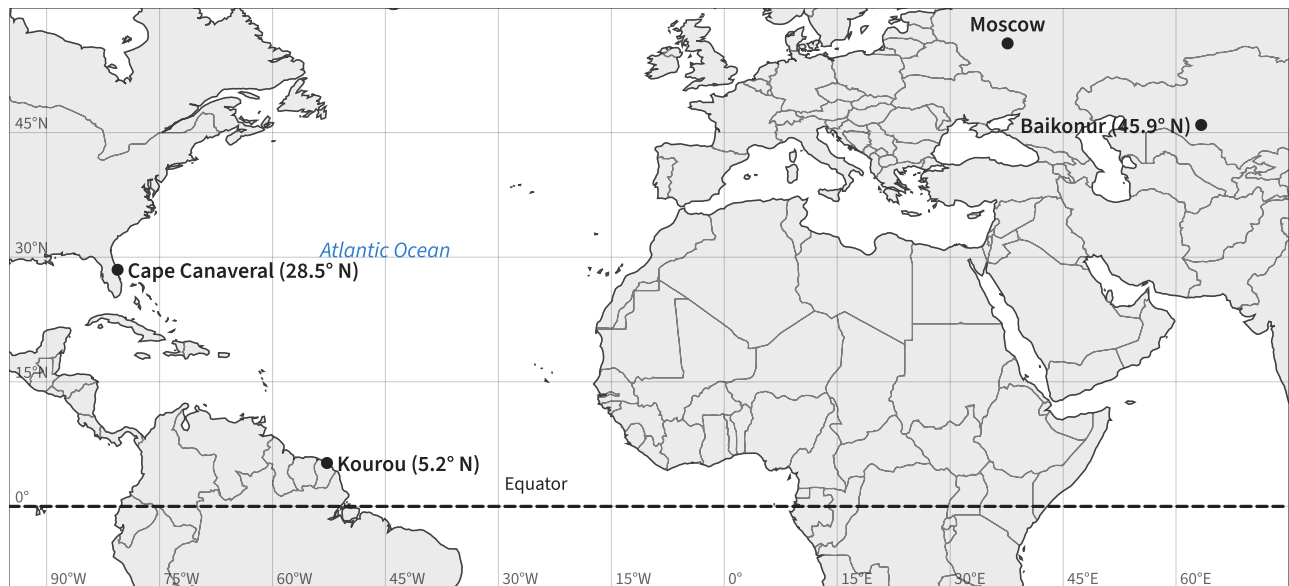
On the map. Geography shapes space travel too. Because the earth spins eastward, a rocket launched toward the east gets a free push: about 465 meters per second at the equator, less at higher latitudes. That is why the United States launched from Cape Canaveral at 28.5° N, where rockets fly east over the open Atlantic, and why Europe launches from Kourou in French Guiana, only about 5° north of the equator. The Soviets, with no southern coast, used Baikonur at about 46° N. Once in orbit, a satellite's path is fixed in space while the earth turns beneath it, so each lap's **ground track** falls farther west. Sputnik's orbit was tilted 65° to the equator, so over a few days it passed above every place between 65° N and 65° S. A geostationary satellite does the opposite: it sits over the equator and sees the same face of the earth forever, though it sinks below the horizon for anyone near the poles. See the figure of orbits drawn to scale.

Technology overcoming geography. For thousands of years people found their place on earth by looking at landmarks, stars or a clock. After 1957 the lookout moved off the earth altogether. In a single lifetime the world went from Harrison's chronometer to satellites that see every ocean at once. Yet notice what did not change: rockets still had to launch from the right latitude, satellites still needed ground stations on real islands and coasts, and the laws of motion that God set in the heavens decided every orbit.



Earth radius 6,371 km = 30 units. The moon would be about 1,800 units away.

Orbits drawn to scale around the earth. Sputnik skimmed just above the air; GPS satellites fly about 3 earth radii up; geostationary satellites about 5.6 earth radii up.



Three great launch sites. The closer to the equator, the bigger the push from the earth's spin.

PICTURE STUDY



The Explorer 1 Team Holds Up a Model of America's First Satellite, Photographer for NASA / Jet Propulsion Laboratory (U.S. government photograph), February 1, 1958 · Black-and-white photograph · NASA / Jet Propulsion Laboratory; image on Wikimedia Commons

In the early hours of February 1, 1958, a few hours after *Explorer 1* reached orbit, three men held a full-size model of it over their heads for the cameras at a news conference in Washington, D.C. On the left is William Pickering, director of the Jet Propulsion Laboratory, which built the satellite. In the middle is James Van Allen, the University of Iowa physicist whose instrument rode inside it. On the right is Wernher von Braun, whose Army rocket team built the launcher.

The photograph is a picture of relief and triumph after the shock of Sputnik. It also deserves an honest look. Von Braun had built the V-2 missile for Nazi Germany, where prisoners from concentration camps were worked to death in its underground factory, and he had been a member of the Nazi party and the SS. After the war the United States brought him and his team to America. History asks us to see both the achievement and the wrong.

Look closely

- Find the satellite itself: the long, thin cylinder on top. Explorer 1 weighed only about 14 kilograms (31 pounds), far less than Sputnik.
- Look at the men's faces and arms. What feeling does the photographer capture?
- Compare this slim tube with Sputnik's polished ball and four antennas. Why might the two nations' first satellites look so different?
- Notice that the picture shows men and a model, not the rocket or the launch. What story was this photograph meant to tell the public?

Talk about it

1. Why did Americans feel such relief when Explorer 1 reached orbit, less than four months after Sputnik?
2. How should we judge a man like von Braun, whose work helped open space but who also served an evil regime?
3. Van Allen's small instrument made a real discovery. Why do small scientific instruments sometimes matter more than the size of the rocket?

PROJECT: ORBITS TO SCALE IN YOUR HOUSE

Most pictures of satellites draw them far too close to the earth or far too far away. You will build a true scale model, using a ball for the earth and string for the orbits, so you can see where Sputnik, GPS satellites, geostationary satellites and the moon really are.

You will need

- A basketball or other ball about 24 cm (9.5 in) across, to stand for the earth
- A ball of string or yarn at least 8 meters (26 feet) long
- Masking tape and a marker
- A metric tape measure or meter stick
- Four small sticky notes or paper flags
- A calculator

Steps

1. Measure your ball. If it is 24 cm across, its radius is 12 cm, and your scale is 12 cm for 6,371 km, the earth's radius. Write your scale in your notebook.
2. Compute the scaled height above the surface for each object: height in km $\times$ (12 $\div$ 6,371) gives centimeters. Do it for Sputnik (about 580 km average), GPS (20,200 km), geostationary orbit (35,786 km) and the moon (about 378,000 km above the surface; 384,400 km center to center).
3. Check your answers: Sputnik about 1.1 cm, GPS about 38 cm, geostationary about 67 cm, moon about 712 cm (7.1 m) from the surface.
4. Set the ball on the floor of a long hallway. Tape a sticky note flag 1.1 cm above its surface for Sputnik. Lay string straight out from the ball and tape flags at 38 cm (GPS), 67 cm (geostationary) and about 7.1 m (moon).
5. Stand at the GPS flag and look back at the ball. Then stand at the moon flag and look back. In your notebook, sketch what the earth would look like from each place.
6. Use the ball and a short string loop to show a geostationary orbit: hold the loop level with the ball's "equator" and turn the loop once as you turn the ball once.
7. Write a paragraph: what surprised you most about the true distances?

Tips

- If you use a smaller ball, recompute your scale. A 7.5 cm (3 in) tennis ball puts the moon about 2.2 m away.

- Sputnik's 1.1 cm is not a mistake. Low Earth orbit really is that close, which is why its satellites can see only a small part of the globe at once.

Check your work

- I can set up a scale from a ball's radius and the earth's radius.
- I can place low Earth orbit, GPS orbit, geostationary orbit and the moon at the correct scaled distances.
- I can explain why a geostationary satellite must orbit above the equator.

MAP NOTEBOOK

1. Draw Newton's cannon on a mountain with three cannonball paths: one that lands nearby, one that lands far away and one that circles the earth. Label the orbit.
2. Sketch a world map and draw three lines of Sputnik's ground track, each one about 24° of longitude west of the one before. Label the 65° N and 65° S limits.
3. Make a four-box chart titled "What Satellites Do": weather, communication, mapping and navigation. In each box, write the first satellite or system named in this lesson and the year.

From history. Satellites also opened the earth to mapmakers in secret. Under a program called Corona, the United States launched camera satellites whose film was dropped back to earth in capsules. In August 1960 a capsule from Discoverer 14 was caught in midair over the Pacific by an Air Force plane, and its single load of film showed more of the Soviet Union than all the earlier U-2 spy flights put together. Corona's photographs were kept secret until 1995; today historians and geographers use them to study how cities, farms and coastlines looked in the 1960s.

WORKED EXAMPLES

Example 1. Sputnik's average height was about 577 km, and it went around the earth once every 96.2 minutes. Treating its orbit as a circle, find its speed in km/s, km/h and mph. (Earth's radius: 6,371 km.)

(Use the map or drawing "Sputnik flew in the thin ring just outside the earth." shown earlier in this lesson.)

1. Radius of the orbit = earth's radius + height = $6,371 \text{ km} + 577 \text{ km} = 6,948 \text{ km}$.
2. Distance around one orbit = $2 \times \pi \times 6,948 \text{ km} \approx 43,650 \text{ km}$.
3. Time for one orbit = $96.2 \text{ min} \times 60 \text{ s/min} = 5,772 \text{ s}$.
4. Speed = $43,650 \text{ km} \div 5,772 \text{ s} \approx 7.56 \text{ km/s}$.
5. In km/h: $7.56 \times 3,600 \approx 27,200 \text{ km/h}$. In mph: $27,200 \div 1.609 \approx 16,900 \text{ mph}$.

Answer: About 7.56 km/s, or about 27,200 km/h (16,900 mph): New York to London in about 12 minutes.

Example 2. While Sputnik made one orbit (96.2 minutes), the earth turned beneath it. How many degrees of longitude did the ground track shift west on each lap, and about how far is that at the equator? (Use 15° of turning per hour, and 111 km per degree at the equator.)

1. Convert the period to hours: $96.2 \text{ min} \div 60 = 1.603 \text{ h}$.
2. Turning of the earth in that time: $1.603 \text{ h} \times 15^\circ/\text{h} \approx 24.0^\circ$.
3. Distance at the equator: $24.0^\circ \times 111 \text{ km}/^\circ \approx 2,670 \text{ km}$.
4. In miles: $2,670 \div 1.609 \approx 1,660 \text{ miles}$.

Answer: About 24° of longitude west per orbit, roughly 2,670 km (1,660 miles) at the equator. That is why about 15 laps a day carried Sputnik over most of the inhabited world.

Example 3. The earth's surface at the equator moves east at about 0.465 km/s. At latitude ϕ , the speed is $0.465 \times \cos \phi$. Find the free eastward push at Kourou (5.2° N), Cape Canaveral (28.5° N) and Baikonur (45.9° N).

(Use the map or drawing "Kourou lies closest to the equator." shown earlier in this lesson.)

1. Kourou: $\cos 5.2^\circ = 0.996$, so $0.465 \times 0.996 \approx 0.463 \text{ km/s}$ (463 m/s).
2. Cape Canaveral: $\cos 28.5^\circ = 0.879$, so $0.465 \times 0.879 \approx 0.409 \text{ km/s}$ (409 m/s).
3. Baikonur: $\cos 45.9^\circ = 0.696$, so $0.465 \times 0.696 \approx 0.324 \text{ km/s}$ (324 m/s).
4. Compare: Kourou gets about 139 m/s more than Baikonur, roughly 2 percent of the 7.8 km/s needed to reach low orbit.

Answer: Kourou about 463 m/s, Cape Canaveral about 409 m/s, Baikonur about 324 m/s. Latitude is a real advantage, which is why launch sites are chosen with a map.

PRACTICE

1. **EASY** Give the date of Sputnik 1's launch, the country that launched it and the place it was launched from.
2. **EASY** Sputnik weighed 83.6 kg. Convert this to pounds ($1 \text{ kg} = 2.205 \text{ lb}$).
3. **EASY** Sputnik's period was 96.2 minutes. About how many orbits did it make each day?
4. **MEDIUM** Sputnik's radio worked for about 21 days. About how many orbits did it make while it was still beeping?
5. **MEDIUM** A telephone signal goes from the ground up to a geostationary satellite 35,786 km high and straight back down. Radio travels at 299,792 km/s. How long does the trip take?
6. **MEDIUM** The distance to the horizon from height h is about $\sqrt{2Rh}$, where $R = 6,371 \text{ km}$. How far could Sputnik "see" from 580 km up? Give km and miles.
7. **MEDIUM** The drop of the earth's surface below a straight line over a distance d is about $d^2 \div 2R$. Find the drop over 8 km, in meters, and explain what it has to do with orbits.

8. **MEDIUM** A geostationary satellite circles at 42,164 km from the earth's center once every 86,164 seconds. Find its speed in km/s.
9. **HARD** Arthur C. Clarke proposed three geostationary relay stations spaced 120° apart. Find the straight-line distance between two of them (chord = $2r \sin 60^\circ$, $r = 42,164$ km).
10. **HARD** Use the worked example. How many more meters per second of free eastward speed does a rocket at Kourou get than one at Baikonur? Why does this matter more for a heavy satellite?
11. **CHALLENGE** Explain why a ship near the North Pole cannot use a geostationary satellite, and name one kind of orbit that serves the far north better.
12. **MEDIUM** In a short paragraph, explain how the scientists at Johns Hopkins turned the tracking of Sputnik into a way to navigate ships.

COMMON MISTAKES

- Thinking satellites stay up because there is “no gravity” in space. Gravity at Sputnik's height was still about 84 percent as strong as on the ground; satellites stay up because they move sideways fast enough to keep missing the earth.
- Placing all satellites at the same height. Low orbit (a few hundred km), GPS (about 20,200 km) and geostationary orbit (35,786 km) are very different, with very different jobs.
- Assuming a geostationary satellite can be parked over any city. It can only stay fixed above a point on the equator.

Make it a game • Satellite Says. One player is the earth and slowly turns in place. Another is a satellite and walks a circle around the earth. The caller names an orbit: “low orbit” (walk fast and close), “GPS” (walk farther out, a bit slower), or “geostationary” (walk far out, matching the earth's turn so you always face the same side). If the satellite matches the right distance and speed, score a point. Bonus point for naming the satellite's job: weather, communication, mapping or navigation.

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 looked up at a sky no one could reach. Since 1957 people have placed their own small moons in it, but every orbit still follows laws God ordained. Human creativity is a gift of being made in His image, and the vastness of the heavens is a call to humility, not pride.

Practice answers

1. October 4, 1957, by the Soviet Union, from Tyuratam (later called the Baikonur Cosmodrome) in Kazakhstan, then part of the USSR.
2. $83.6 \times 2.205 \approx 184$ lb.
3. $1,440 \text{ min} \div 96.2 \text{ min} \approx 15$ orbits per day.

4. $21 \text{ days} \times \text{about } 15 \text{ orbits per day} \approx 315 \text{ orbits}$ ($21 \times 14.97 \approx 314$).
5. Distance $2 \times 35,786 = 71,572 \text{ km}$. Time $= 71,572 \div 299,792 \approx 0.239 \text{ s}$, about a quarter of a second (and longer if the stations are far from the point directly under the satellite).
6. $\sqrt{2 \times 6,371 \times 580} = \sqrt{7,390,000} \approx 2,720 \text{ km}$, about 1,690 miles.
7. $8^2 \div (2 \times 6,371) = 64 \div 12,742 \approx 0.00502 \text{ km} \approx 5.0 \text{ m}$. A falling object drops about 4.9 m in its first second, so an object moving sideways at about 8 km/s falls just as fast as the ground curves away: it is in orbit.
8. Circumference $2\pi \times 42,164 \approx 264,900 \text{ km}$. Speed $= 264,900 \div 86,164 \approx 3.07 \text{ km/s}$, much slower than a low orbit.
9. $2 \times 42,164 \times 0.866 \approx 73,000 \text{ km}$ (about 45,400 miles).
10. $463 - 324 \approx 139 \text{ m/s}$. Every bit of speed the rocket does not have to make itself saves fuel, and for a heavy payload the savings in fuel and rocket size are large.
11. A geostationary satellite sits over the equator. From latitudes above about 81° , it lies below the horizon, so no straight radio path reaches it (and it is very low in the sky even farther south). Satellites in tilted or polar orbits, such as low polar orbits or the Soviet Molniya orbits first used in 1965, pass high over the far north.
12. Guier and Weiffenbach used the Doppler shift in Sputnik's radio tone to calculate its orbit from the ground. Frank McClure reversed the problem: if a satellite's orbit is already known, a receiver can measure the same Doppler shift and calculate its own position. The Navy built this into the Transit system (first successful satellite 1960, in service 1964), the first satellite navigation system and a forerunner of GPS.

5.2 GPS: TIMING, SATELLITES AND TRILATERATION

OBJECTIVES

- Tell the story of GPS from the Pentagon planning meeting of 1973 and the first satellite of 1978 to its opening for everyone after 1983 and 2000.
- Explain how a receiver turns time into distance and distance into position by trilateration, and why it needs signals from four satellites.
- Calculate signal travel times, distance errors from clock errors, and a position from three distances on a grid.

Warm-up. Stand in a room with a partner. Close your eyes while your partner stands somewhere and tells you only, “I am 8 feet from the door.” Where could they be? Now add, “And I am 5 feet from the window.” Now how many places could they be? Write down how many clues you needed to be sure, and why one clue was not enough.

Watch. *Everyday Einstein: Demonstrating GPS Trilateration* (Perimeter Institute for Theoretical Physics, 3:59). <https://www.youtube.com/watch?v=e80AzFW9Q0s>
With How it works: a hands-on demonstration of trilateration.

Backup video. *GPS, How does it work? / ICT #12* (Sabin Civil Engineering, 7:18).
https://www.youtube.com/watch?v=8eTlI19_57g
As review: how GPS satellites and receivers work together.

KEY TERMS

GPS (Global Positioning System)

The U.S. satellite navigation system: a constellation of about 31 working satellites, ground control stations and the receivers in phones, ships, cars and aircraft.

trilateration

Finding a position from *distances* to known points. Each distance puts you somewhere on a circle (on a map) or a sphere (in space); where they meet is your position.

triangulation

Finding a position from *angles* measured from the ends of a known baseline. Old surveys used it; GPS does not.

atomic clock

A clock that keeps time by the steady vibrations of atoms such as cesium or rubidium, accurate to billionths of a second.

constellation

A planned group of satellites working together. GPS has six orbital planes tilted 55° to the equator, about 20,200 km up.

GNSS

Global Navigation Satellite System, the general name for GPS and its counterparts: Russia's GLONASS, Europe's Galileo and China's BeiDou.

CORE IDEAS

The story. Over Labor Day weekend in 1973, in the nearly empty halls of the Pentagon, Air Force Colonel Bradford Parkinson gathered a dozen officers and engineers and told them not to leave until they had agreed on one design for a satellite navigation system. The Navy already had Transit and an experimental clock-carrying satellite program called Timation, led by Roger Easton of the Naval Research Laboratory; the Air Force had its own plans. Parkinson's team combined the best of them: a fleet of satellites, each carrying atomic clocks and broadcasting the exact time and its own position. On February 22, 1978, the first of these satellites, called Navstar, was launched from Vandenberg Air Force Base in California. For centuries finding one's place on the earth had taken a sextant, a chronometer, clear skies and a skilled navigator. GPS would make it take a few seconds and a device that fits in a pocket.

How it works: time becomes distance. Every GPS satellite broadcasts a message that says, in effect, "I am satellite number so-and-so, I am at this exact spot, and this message left me at this exact instant." Radio waves travel at the speed of light, about 299,792 km per second, or roughly 30 centimeters (one foot) every billionth of a second. A receiver notes when the message arrives, subtracts the time it was sent, and multiplies by the speed of light. A satellite directly overhead is about 20,200 km (12,550 miles) away, so its signal takes about 0.067 seconds to arrive. Knowing that distance puts the receiver somewhere on a huge imaginary sphere around that satellite. A second satellite gives a second sphere; two spheres meet in a circle. A third sphere cuts that circle at two points, and one of them is usually far out in space and can be thrown away. This is **trilateration**: position from distances, not angles.

Why four satellites. There is a catch. The satellites carry atomic clocks costing a fortune, but your phone has a cheap quartz clock. If the phone's clock is off by just one millionth of a second, every distance will be wrong by about 300 meters (nearly 1,000 feet). The answer is clever: the receiver treats its own clock error as a fourth unknown, alongside east-west, north-south and up-down position. Four unknowns need four measurements, so the receiver uses at least four satellites and solves for all four at once. As a bonus, every GPS receiver becomes an excellent clock, and power companies, phone networks and banks around the world now use GPS to keep their time. Even Einstein enters the story. The satellite clocks, moving fast and sitting higher in the earth's gravity, run faster than clocks on the ground by about 38 millionths of a second a day. Uncorrected, that would add an error of roughly 11 km (7 miles) every day, so the clocks are deliberately adjusted before launch to fit relativity.

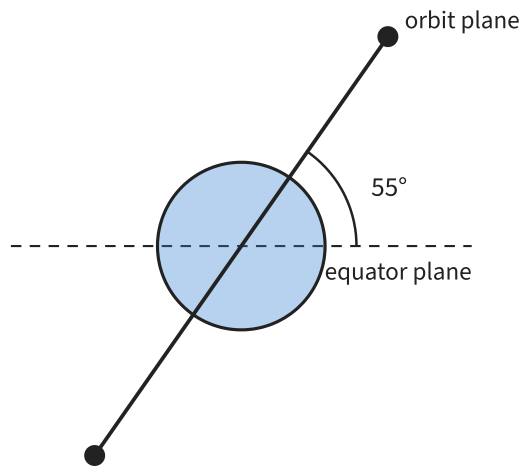
On the map: the constellation. GPS satellites fly in six orbital planes, each tilted 55° to the equator and spaced 60° apart around the earth, with at least four satellites in each plane. They circle about 20,200 km above the earth, making two orbits each day (one every 11 hours 58 minutes). The arrangement is designed so that at least four satellites are above the horizon from almost any place on earth at any time; usually there are eight or more. On

the ground, a master control station at Schriever Space Force Base near Colorado Springs, now run by the U.S. Space Force, receives data from monitor stations spread around the globe. The original monitor stations stood at Colorado Springs, Hawaii, Kwajalein in the Pacific, Diego Garcia in the Indian Ocean, Ascension Island in the Atlantic and Cape Canaveral, chosen so that every satellite could be watched as it circled. Notice that the location of these islands was a geographic decision: GPS needed far-flung patches of land in the middle of the oceans.

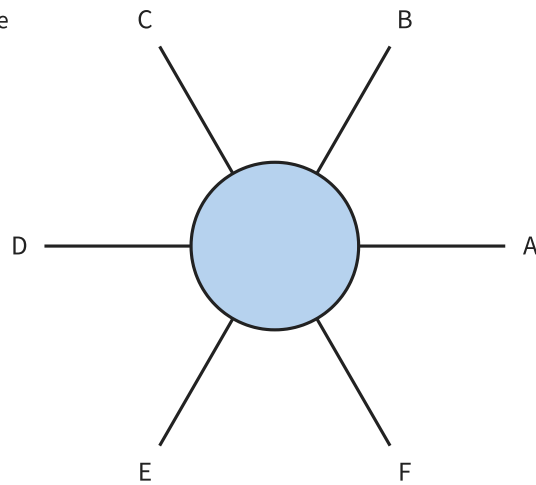
From soldiers to everyone. GPS was built for the military, but a tragedy changed that. On September 1, 1983, Korean Air Lines Flight 007, flying from Anchorage to Seoul, strayed hundreds of miles off course over Soviet territory and was shot down by a Soviet fighter, killing all 269 people aboard. On September 16, President Ronald Reagan announced that GPS would be made available for civilian use once it was complete. The full system was declared operational on April 27, 1995. For years the civilian signal was deliberately blurred, a policy called Selective Availability, which limited accuracy to about 100 meters. On May 1, 2000, President Bill Clinton announced it would be switched off, and overnight civilian accuracy improved roughly tenfold. Today a good smartphone under open sky is usually accurate to about 5 meters (16 feet). Other nations have built their own systems (GLONASS, Galileo and BeiDou), and many receivers now listen to several at once.

Technology overcoming geography, and its limits. GPS has overcome a problem older than the compass: *where am I?* A farmer's tractor can steer itself within inches down a row; a container ship can approach Singapore in fog; an airliner can fly a precise path over the Andes. Yet geography still has a vote. GPS signals are weak; by the time they reach the ground they are fainter than the natural radio noise around them, and they cannot pass through rock, earth or thick buildings. In a deep canyon, a forest or a city street lined with tall towers, satellites low in the sky are blocked and signals bounce off walls, so positions wander. Indoors, underground and under water, GPS does not work at all. The best fixes come when the satellites are spread across the whole sky; when they are bunched in one strip, the circles meet at a shallow angle and the answer blurs. The old surveyors' lesson still holds: good geometry makes good positions.

Side view

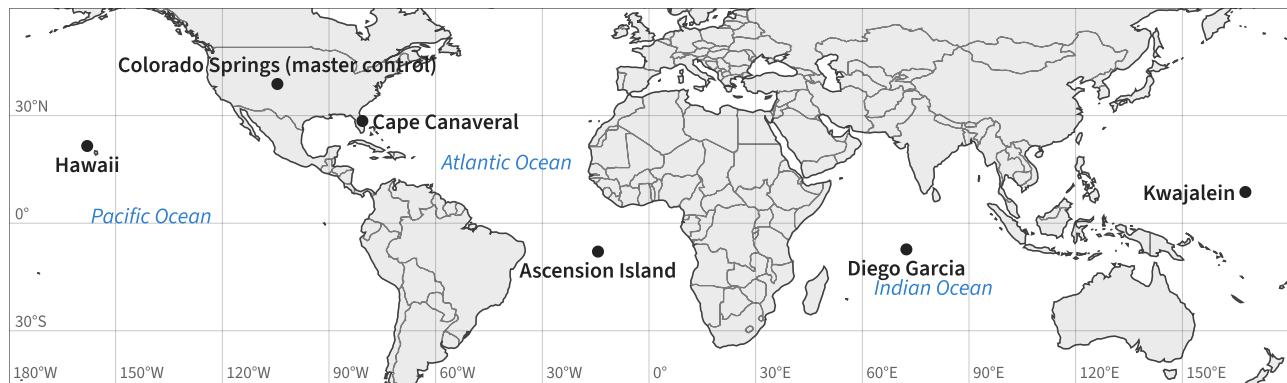


Looking down on the North Pole



Six planes (A to F), each tilted 55° , spaced 60° apart, about 20,200 km up. Not to scale.

The GPS constellation: six planes tilted 55° , spaced 60° apart, about 20,200 km up (not to scale).



The original GPS master control and monitor stations. Island bases let controllers watch every satellite as it circled.

PICTURE STUDY



Index Chart to the Great Trigonometrical Survey of India, Office of the Trigonometrical Survey of India (Survey of India), 1875 · Printed map · Published in the Account of the Operations of the Great Trigonometrical Survey of India, vol. II; image on Wikimedia Commons (via Google Arts & Culture)

Before satellites, the most accurate way to fix positions across a whole country was triangulation. Beginning in 1802, British surveyors led first by William Lambton and then by George Everest worked across India for decades, carrying a great theodolite that weighed about half a ton up hills and towers. They measured one baseline on the ground with painstaking care, then measured only angles from station to station, building chains of triangles that stretched for more than a thousand miles. Indian computers and surveyors did much of the work; the mathematician Radhanath Sikdar is remembered for his calculations of the Himalayan peaks.

This chart shows the whole web of triangles on one sheet. The survey's most famous result came in 1856, when Surveyor General Andrew Waugh announced that the mountain called Peak XV was the highest in the world, at 29,002 feet. It was later named Mount Everest. Modern surveys using GPS give 8,849 meters (29,032 feet), within about 30 feet of the old triangles.

Look closely

- Find the long chains of triangles. Which way do most of them run?
- Look at the far north of the chart, where the triangles reach the mountains. Why would surveyors stop at the foot of the Himalaya and sight the peaks from far away?
- Find the coastlines. Can you see where the chains reach the sea?
- Notice how the chains form a gridiron with open spaces between. Why might a survey save effort by building chains instead of covering every mile with triangles?

Talk about it

1. Triangulation measures angles; GPS trilateration measures distances. What did each method need to measure precisely?
2. The survey took most of the nineteenth century. A GPS fix takes seconds. What did the old surveyors have to overcome that GPS does not?
3. Why do you think the old height of Everest was so close to the modern one?

PROJECT: STRING-AND-TAPE GPS ON THE FLOOR

You will turn a floor or driveway into a map, set out three “satellites” and find a hidden position using nothing but distances and string, exactly the way a GPS receiver reasons. Because light travels about one foot in a nanosecond, your helper can even give you the distances as signal times in nanoseconds. Then you will add a clock error and discover why a real receiver needs a fourth satellite.

You will need

- Painter’s tape or masking tape (or sidewalk chalk outdoors)
- A long tape measure (25 feet or more)
- Three pieces of string, each about 15 feet long
- A marker and three index cards labeled A, B and C
- A coin or small object to mark the hidden spot
- Graph paper, ruler and compass (drawing tool) for your notebook
- A helper

Steps

1. Clear a floor space about 15 by 15 feet. Tape an x-axis along one wall side and a y-axis along the other, meeting at a corner you call (0, 0). Mark every foot along each axis.
2. Place satellite cards: A at (0, 0), B at (12, 0) and C at (0, 12). Tape them down. Copy the layout onto graph paper at 1 square = 1 foot.
3. Leave the room. Your helper places a coin at a secret spot inside the square, measures its distance to A, B and C to the nearest inch, then picks up the coin and marks the spot with a tiny dot only they can find.
4. Your helper gives you the distances as “signal times”: 1 nanosecond for each foot. (Light really travels about 11.8 inches in a nanosecond.) Convert the times to feet.
5. Tie a string at A and hold a marker at distance A on the string. Sweep an arc on tape strips across the floor. Do the same from B. Your two arcs cross at two points; mark both.
6. Sweep the arc from C. Only one of your two points lies on it. That is your position. Measure its coordinates and check against the helper’s dot. Record your error in inches.
7. Clock-error round: the helper secretly adds the same amount (for example, 2 feet) to all three distances, as if your receiver’s clock were 2 nanoseconds fast. Sweep the arcs

again. Notice that they no longer meet at one point but outline a small triangle.

8. Try subtracting the same amount from all three distances, 1 foot at a time, until the three arcs meet at a single point. The amount that works is your clock error. Write a paragraph explaining how this is the job of the fourth satellite in real GPS.
9. Redo the whole exercise on graph paper with a drawing compass for one more secret spot, and compare paper accuracy with floor accuracy.

Tips

- Keep the string tight and flat; a sagging string makes the distance too short.
- If two arcs cross at a very shallow angle, small errors make a big blur. Try a secret spot near the line between A and B and see how much worse the fix becomes. That is bad satellite geometry.
- Outdoors, sidewalk chalk on a driveway works well and allows a bigger map.

Check your work

- I can find a position from three distances by drawing arcs.
- I can convert signal times to distances using the speed of light.
- I can explain why a constant clock error makes the arcs miss and how a fourth measurement fixes it.

MAP NOTEBOOK

1. Draw the GPS constellation in two views: from the side (one plane tilted 55°) and from above the North Pole (six planes 60° apart). Label the height, 20,200 km.
2. On a world outline, mark the six original GPS control and monitor stations and label the ocean each island stands in.
3. Draw a three-circle trilateration diagram and, beside it, a triangulation diagram with a baseline and two angles. Write one sentence under each explaining what is measured.

From history. Rear Admiral Grace Hopper, a pioneer of computer programming, liked to hand audiences pieces of wire about 11.8 inches (30 cm) long. Each one, she explained, was a nanosecond: the distance light travels in one billionth of a second. She used them to show why signals take time even inside a computer, and why a message bounced off a satellite takes much longer. Her wires make the heart of GPS easy to hold in your hand: every nanosecond of timing error is about a foot of position error.

WORKED EXAMPLES

Example 1. A GPS satellite is directly overhead, 20,200 km away. How long does its signal take to reach you? Light travels 299,792 km/s.

1. Time = distance $\div$ speed = 20,200 km $\div$ 299,792 km/s.
2. 20,200 $\div$ 299,792 $\approx$ 0.0674 s.
3. In milliseconds: 0.0674 s $\times$ 1,000 $\approx$ 67.4 ms.
4. A satellite low on the horizon is farther away (about 25,800 km), so its signal takes about 25,800 $\div$ 299,792 $\approx$ 0.086 s.

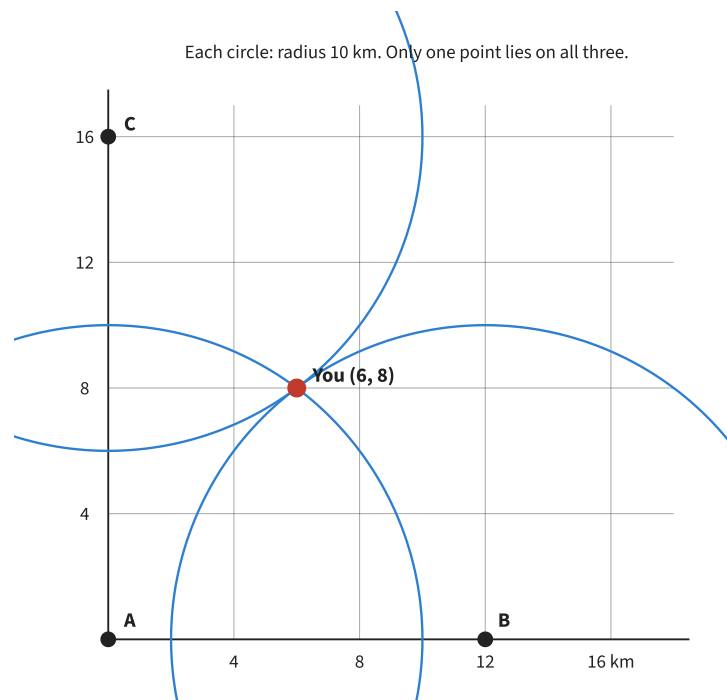
Answer: About 0.067 seconds (67 milliseconds) from overhead; somewhat more from a satellite near the horizon.

Example 2. (a) How far does light travel in 1 microsecond (one millionth of a second)? (b) In 10 nanoseconds? (c) Satellite clocks, if uncorrected, would gain about 38 microseconds a day because of relativity. How large a position error would that cause in one day?

1. (a) 299,792 km/s $\times$ 0.000001 s $\approx$ 0.300 km = 300 m (about 980 feet).
2. (b) 10 nanoseconds = 0.00000001 s. 299,792,000 m/s $\times$ 0.00000001 s $\approx$ 3.0 m (about 10 feet).
3. (c) 38 microseconds $\times$ 300 m per microsecond = 11,400 m $\approx$ 11.4 km.
4. In miles: 11.4 $\div$ 1.609 $\approx$ 7.1 miles.

Answer: (a) About 300 m. (b) About 3 m. (c) About 11 km (7 miles) a day, which is why the satellite clocks are corrected for relativity.

Example 3. On a flat map grid measured in kilometers, three radio beacons stand at A (0, 0), B (12, 0) and C (0, 16). A receiver measures that it is 10 km from each one. Where is it?



Two circles meet at two points; the third circle picks one.

1. From A: the receiver lies on a circle of radius 10 around (0, 0), so $x^2 + y^2 = 100$.
2. From B: it lies on a circle of radius 10 around (12, 0), so $(x - 12)^2 + y^2 = 100$.
Subtracting the first equation gives $-24x + 144 = 0$, so $x = 6$.
3. Then $36 + y^2 = 100$, so $y^2 = 64$ and $y = 8$ or $y = -8$. Two possible points: (6, 8) and (6, -8).
4. Check C: distance from (0, 16) to (6, 8) is $\sqrt{36 + 64} = 10$ km. ✓ Distance from (0, 16) to (6, -8) is $\sqrt{36 + 576} \approx 24.7$ km. ✗
5. Only (6, 8) fits all three distances.

Answer: The receiver is at (6, 8): 6 km east and 8 km north of A.

PRACTICE

1. **EASY** What is the difference between trilateration and triangulation? Which does GPS use?
2. **EASY** How many satellites does a receiver need for a full three-dimensional fix, and why that number?
3. **EASY** How far does light travel in one nanosecond? Give meters and feet.
4. **MEDIUM** A receiver's clock is off by 50 nanoseconds. How large is the resulting distance error?

5. **MEDIUM** A GPS satellite orbits 26,560 km from the earth's center once every 11 hours 58 minutes (43,080 s). Find its speed in km/s and mph.
6. **MEDIUM** How many orbital planes does GPS use, at what tilt, and how far apart are they around the equator? What is the minimum number of satellites in the design?
7. **MEDIUM** On a grid in km, beacon A is at (0, 0) and beacon B at (8, 0). A receiver is 5 km from each. Find the two possible positions. A third beacon C at (4, 6) is 3 km away. Which position is correct?
8. **HARD** A receiver's clock runs 1 millisecond fast, so it thinks a signal took 0.0700 s when it really took 0.0690 s. What distance does it compute, what is the true distance, and how big is the error?
9. **HARD** Under Selective Availability, civilian GPS was accurate to about 100 m. A modern smartphone under open sky is usually accurate to about 5 m. By what factor did accuracy improve, and what event in 2000 made most of the change?
10. **HARD** A hiker stands at the bottom of a narrow canyon running north and south. Explain why the GPS fix is poor, using the idea of satellite geometry.
11. **CHALLENGE** If the relativity correction (38 microseconds per day) were not built into the satellite clocks, how large would the position error grow in one week? Give km and miles.
12. **MEDIUM** In a short paragraph, explain how the loss of Korean Air Lines Flight 007 in 1983 changed who could use GPS.

COMMON MISTAKES

- Saying GPS uses triangulation. It measures distances (by timing), not angles, so the correct word is trilateration.
- Thinking the GPS receiver sends signals to the satellites. Receivers only listen; the satellites do not know who is using them.
- Forgetting the receiver's clock. With only three satellites and an imperfect clock, every distance is wrong by the same amount and the fix fails.

Make it a game • Human GPS. Three players are satellites standing at taped spots in a room or yard. A fourth player, the receiver, is blindfolded and led to a secret spot. Each satellite calls out its distance in steps ("Satellite A: six steps!"). The blindfolded player removes the blindfold and has thirty seconds to walk to the spot that fits all three distances. Score a point for landing within one step. For a hard round, all satellites add the same secret number of steps, and the receiver must find the spot and the "clock error."

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)

GPS can tell a sailor his position in the uttermost parts of the sea within a few meters. The psalmist knew something deeper: no place on earth is outside God's knowledge and care.

Our clever ways of finding our place are small pictures of the One who never loses track of us.

Practice answers

1. Trilateration finds a position from distances to known points; triangulation finds it from angles measured from a known baseline. GPS uses trilateration.
2. At least four: three for position (east-west, north-south, up-down) and one more to solve for the error in the receiver's own clock.
3. $299,792,000 \text{ m/s} \times 0.000000001 \text{ s} \approx 0.30 \text{ m}$, about 0.98 feet (roughly one foot).
4. $50 \times 0.30 \text{ m} = 15 \text{ m}$ (about 49 feet).
5. Circumference $2\pi \times 26,560 \approx 166,900 \text{ km}$. Speed $\approx 166,900 \div 43,080 \approx 3.87 \text{ km/s}$. That is about 13,900 km/h, or about 8,700 mph.
6. Six planes, tilted 55° to the equator, spaced 60° apart ($360^\circ \div 6$). The baseline design calls for 24 satellites (four per plane); about 31 are usually working.
7. From $x^2 + y^2 = 25$ and $(x - 8)^2 + y^2 = 25$: $x = 4$, $y = \pm 3$, so (4, 3) or (4, -3). Distance from C (4, 6) to (4, 3) is 3 km ✓; to (4, -3) is 9 km ✗. The receiver is at (4, 3).
8. Computed: $0.0700 \times 299,792 \approx 20,985 \text{ km}$. True: $0.0690 \times 299,792 \approx 20,686 \text{ km}$. Error $\approx 300 \text{ km}$ ($0.001 \text{ s} \times 299,792 \text{ km/s}$), the same for every satellite, which is exactly the shared error the fourth satellite lets the receiver solve for.
9. $100 \div 5 = 20$ times better. The biggest single step came when Selective Availability was switched off in May 2000; better receivers and more satellite systems did the rest.
10. The canyon walls block satellites low in the eastern and western sky, so the receiver hears only satellites in a narrow north-south strip, and some signals bounce off the rock. With the satellites bunched together, the distance spheres meet at shallow angles, so small timing errors spread into a large east-west error.
11. $38 \times 7 = 266$ microseconds. $266 \times 300 \text{ m} \approx 79,800 \text{ m} \approx 80 \text{ km}$, about 50 miles.
12. On September 1, 1983, KAL 007 strayed far off course over Soviet territory and was shot down, killing all 269 people aboard. Two weeks later President Reagan announced that GPS, then a military system still being built, would be made available for civilian use once complete, so that ordinary aircraft and ships could know their positions accurately. The system was declared fully operational in 1995, and the deliberate degrading of the civilian signal ended in 2000.

5.3 FIBER-OPTIC CABLES: THE INTERNET UNDER THE SEA

OBJECTIVES

- Tell the story of the glass fiber, from Charles Kao's 1966 prediction and Corning's 1970 breakthrough to TAT-8, the first transatlantic fiber cable, in 1988.
- Explain total internal reflection, signal loss in decibels and why light in glass is the fastest practical way to move information between continents.
- Read a world cable map, identify its landing points and choke points, and calculate travel time (latency) and capacity for real routes.

Warm-up. Fill a clear plastic bottle with water and shine a flashlight up through the bottom in a dark room. Look at the sides and the top. Then tilt the bottle and look at the water's surface from below through the side. Write down where the light escapes and where it seems trapped and bounced back.

Watch. *Fiber optic cables: How they work* (engineerguy, 5:35).

https://www.youtube.com/watch?v=0MwMkBET_5I

With How it works: total internal reflection and how light carries data in a glass fiber.

Backup video. *Watch what it takes to lay Google's super-fast submarine Internet cable* (IDG.tv, 2:57). <https://www.youtube.com/watch?v=0TZwiUwZwIE>

With On the map: a ship lays an undersea cable.

KEY TERMS

optical fiber

A strand of very pure glass, thinner than a human hair at its core, that carries information as pulses of light.

total internal reflection

When light inside a denser material (like glass) strikes the boundary at a shallow enough angle, it is reflected completely back inside instead of escaping.

attenuation

The gradual loss of signal strength along a cable, measured in decibels per kilometer (dB/km). Every 10 dB of loss cuts the power to one tenth.

repeater (amplifier)

A sealed device spliced into an undersea cable every 50 to 100 km or so to strengthen the fading light signal.

latency

The time a signal takes to travel from sender to receiver. It is limited by distance and the speed of light in the medium.

landing station

The building on shore where an undersea cable comes out of the sea and connects to the networks on land.

CORE IDEAS

The story. In December 1988 a new cable began carrying calls across the Atlantic Ocean in a new way. It was TAT-8, the eighth transatlantic telephone cable, built by a partnership of AT&T, British Telecom and France Télécom. It ran from Tuckerton, New Jersey, across the floor of the Atlantic, and split to land in England and France. Inside were not copper wires but hair-thin strands of glass carrying flashes of laser light. TAT-8 could carry about 40,000 telephone calls at once. The first transatlantic telephone cable, TAT-1 of 1956, had carried 36. Since the age of the 1866 telegraph cable you studied in Unit 4, people had wrapped the world in wires; now they began wrapping it in light.

How they figured it out. Light can be trapped in glass by **total internal reflection**. When a ray inside glass strikes the surface at a shallow angle, it does not escape but bounces back in, again and again, following the strand around gentle bends. The Swiss physicist Daniel Colladon showed the effect in 1842 by guiding light inside a falling stream of water. The problem was the glass itself. In the early 1960s the best glass lost almost all its light within a few meters. In 1966, at Standard Telecommunication Laboratories in Harlow, England, Charles Kao and George Hockham published a paper arguing that the loss came from impurities, not from glass itself, and that if the loss could be brought below 20 decibels per kilometer (so that 1 percent of the light survived a kilometer), glass fibers could carry telephone calls. Kao spent years urging glassmakers to try; he received the Nobel Prize in Physics in 2009. In 1970 three researchers at Corning Glass Works in New York, Robert Maurer, Donald Keck and Peter Schultz, made a fiber of ultra-pure fused silica that beat Kao's goal. Today's best fibers lose only about 0.2 dB per kilometer: 1 percent of the light survives not one kilometer but a hundred.

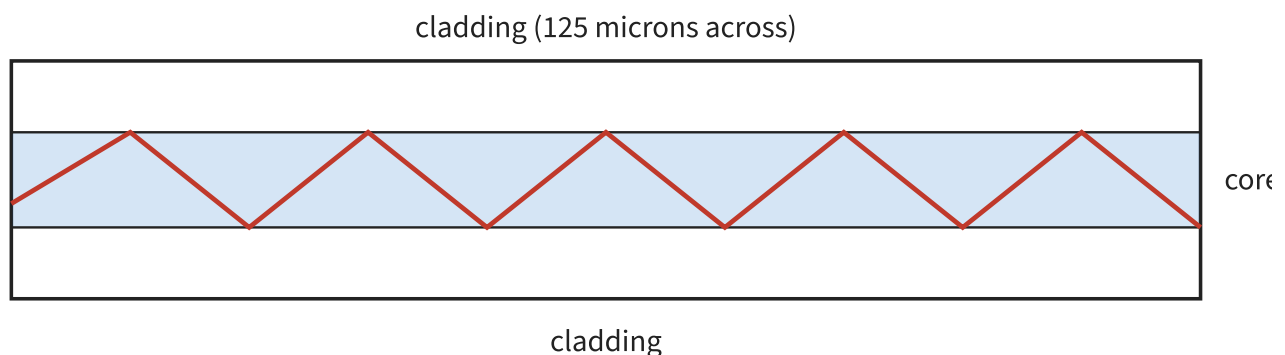
How it works. An undersea fiber cable is mostly protection. At its heart are a few pairs of glass fibers, each with a core about 9 microns across inside a cladding 125 microns across (about the width of a hair). Around them lie a copper conductor that carries electric power to the repeaters, steel wires for strength and layers of plastic. Near shore, where anchors, fishing trawlers and waves are a danger, the cable is wrapped in heavy steel armor and buried in a trench plowed into the seabed. In the deep ocean, where little disturbs it, the cable simply lies on the bottom and may be not much thicker than a garden hose. Every 50 to 100 km a **repeater** boosts the fading light. Since the 1990s these have been optical amplifiers that strengthen the light directly, and engineers send many colors of laser light down each fiber at once, each color a separate channel. A modern cable such as MAREA, which opened between Virginia Beach and Bilbao, Spain, in 2018, was designed to carry 160 terabits (160 million million bits) each second.

The big idea. We speak of "the cloud" and "wireless," but the internet between continents is neither in the sky nor wireless. Well over 95 percent of the data that crosses oceans travels through several hundred undersea cables, not through satellites. The reason is physics and geography. A geostationary satellite is 35,786 km up, so a signal bounced off it

travels more than 71,000 km; a cable from New York to London is less than 7,000 km long. Light in glass moves at about two-thirds of its speed in a vacuum, about 200,000 km per second, but the shorter path wins easily. A fiber also carries vastly more data than a radio beam. Satellites still matter for ships, aircraft, remote islands and places with no cables, but the main roads of the world's information run along the seabed.

On the map. Look at the world cable map. The cables bunch together like the old trade routes, because they follow the same geography. Cables from Europe to Asia run through the Mediterranean, cross Egypt by land between the Mediterranean and the Red Sea, pass through the narrow Bab-el-Mandeb, cross the Indian Ocean and squeeze through the Strait of Malacca to Singapore, the same path the steamships and the telegraph took after the Suez Canal opened in 1869. In East Asia many cables pass through the Luzon Strait between Taiwan and the Philippines. Where routes narrow, cables crowd together, and one disaster can cut several at once. On December 26, 2006, an earthquake off southern Taiwan set off undersea landslides that broke several cables in the Luzon Strait and slowed internet and banking traffic across East Asia for weeks. Most cable breaks, well over a hundred a year, are caused not by earthquakes but by fishing gear and ships' anchors near shore. Specialized cable ships stand ready to grapple up the broken ends and splice them.

Technology overcoming geography. In 1866 the *Great Eastern* laid a cable that sent a few words a minute, letter by letter. Today a single pair of fibers can carry the contents of a library across the Atlantic in seconds. Geography has been overcome as a barrier to *words* almost completely. Yet geography still decides *where* the cables lie: on gentle seabeds, away from earthquake zones where possible, through narrow straits and into the few coves where they can safely come ashore. And no technology can beat the speed of light. The distance from New York to Tokyo still costs a twentieth of a second each way, no matter how much is spent, and traders, engineers and gamers alike feel it.



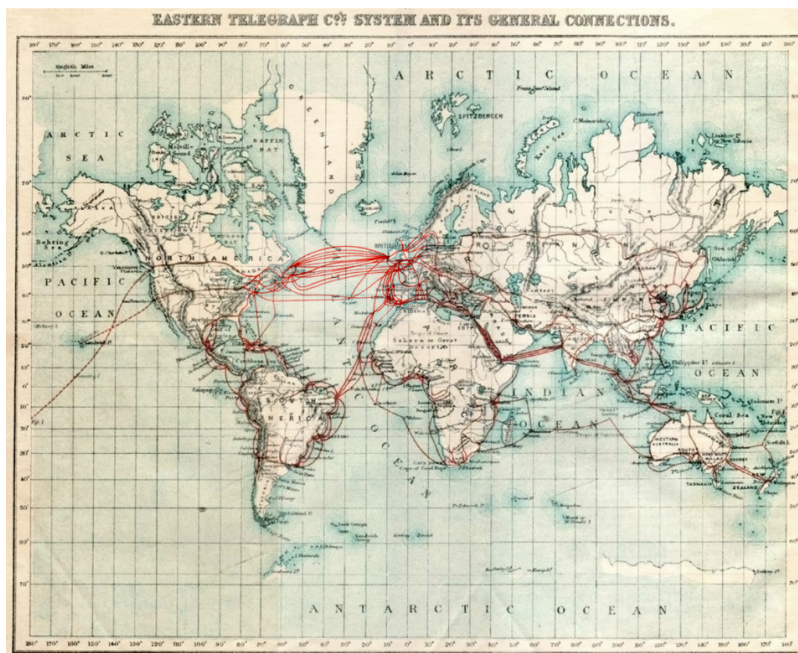
Light striking the core boundary at a shallow angle reflects back in. Core about 9 microns. Not to scale.

Total internal reflection keeps light trapped in the core of a fiber.



A simplified world cable map. Real cables number in the hundreds; this shows a few main routes and their choke points.

PICTURE STUDY



The Eastern Telegraph Company's System and Its General Connections, Eastern Telegraph Company, 1901 · Printed map · Printed in the A.B.C. Telegraphic Code, 5th edition (London, 1901); image on Wikimedia Commons via atlantic-cable.com

By 1901 Britain stood at the center of a web of undersea telegraph cables that reached nearly every port of its empire and many beyond it. The largest owner was the Eastern Telegraph Company and its partner companies, founded by the Scottish businessman John Pender, a backer of the 1866 Atlantic cable. This company map proudly shows their lines running from Cornwall to Gibraltar, Malta and Egypt, down the Red Sea to Aden, across to Bombay, and on to Singapore, China and Australia.

Set this map beside a modern fiber cable map and something remarkable appears. The glass has replaced the copper and the capacity has multiplied many millions of times, but many of

the routes are nearly the same. The geography that guided the telegraph engineers still guides cable engineers today.

Look closely

- Trace the route from Britain to India. Which seas and straits does it pass through?
- Find where the lines cross Egypt. Why would a cable company want a route here after 1869?
- Look for small islands where many lines meet. Why would a lonely island be valuable to a cable company?
- Find a region of the world with few or no lines. What might explain the gap?

Talk about it

1. Why do you think the old telegraph routes and the modern fiber routes are so similar?
2. What would it mean for a nation in 1901 if the cables to its colonies all ran through another nation's territory?
3. How is a cable map like a map of trade routes?

Safety first. Use only a low-power laser pointer (Class 2, under 1 milliwatt, usually labeled) and never point it at anyone's eyes, at a mirror, or at a shiny surface that could reflect into eyes. An adult should handle the laser. A bright LED flashlight works too, though the effect is fainter.

PROJECT: LIGHT IN A STREAM OF WATER, AND A CABLE MAP OF THE WORLD

First you will repeat Daniel Colladon's 1842 demonstration and trap a beam of light inside a falling stream of water, the same principle that guides light along an undersea fiber. Then you will use what you see to draw a world map of the main undersea cable routes and their choke points.

You will need

- A clear plastic soda bottle (1 or 2 liter)
- A nail or skewer to poke a hole (adult help)
- Tape, water and a basin or sink
- A low-power laser pointer or bright, narrow LED flashlight
- A dark room
- A large outline map of the world, colored pencils, and access to a public online cable map

Steps

1. With an adult, poke a round hole about 5 mm across in the side of the bottle, about 5 cm above the bottom. Cover it with tape.

2. Fill the bottle with water and set it on the edge of a sink or basin so the stream will fall into it.
3. Darken the room. Hold the laser against the bottle on the side opposite the hole, aiming straight through the water at the hole.
4. Remove the tape. The water pours out in an arc. Look at where the stream lands: a bright spot of light appears in the basin, because the light was trapped inside the curving stream.
5. Put your finger into the stream partway down. Notice the glowing spot on your finger where light escapes. Write why the light escapes there.
6. Using the online cable map, find and draw on your world map: two transatlantic routes, one route from Europe to Singapore and one route across the Pacific. Mark each landing city.
7. Circle the choke points where many cables bunch together: Egypt, the Bab-el-Mandeb, the Strait of Malacca and the Luzon Strait. Add one sentence for each about why cables crowd there.
8. Compare your map with the 1901 telegraph map from the picture study and write a paragraph on what has changed and what has not.

Tips

- A thin, smooth stream works best. If the stream breaks into drops, the light escapes; make the hole rounder or the water level higher.
- Adding a few drops of milk to the water makes the light path inside the bottle easier to see.

Check your work

- I can explain total internal reflection using the water stream.
- I can draw and label the main undersea cable routes and landing points.
- I can name at least three cable choke points and explain why they are risky.

MAP NOTEBOOK

1. Draw a cross-section of a deep-sea fiber cable and a shore-end cable side by side. Label the fibers, copper power conductor, steel wires, plastic and armor.
2. Copy the cable route map and draw a red circle around each choke point. Write the name of each beside it.
3. Make a two-column chart, "Telegraph 1866" and "Fiber today," comparing what the cable is made of, how the signal travels and how much it carries.

From history. The great Grand Banks earthquake of November 18, 1929, south of Newfoundland, set off an undersea landslide that raced down the continental slope and snapped a series of transatlantic telegraph cables over about thirteen hours. At the time no one knew why the cables farther down broke later. In 1952 the geologists Bruce Heezen and Maurice Ewing studied the exact break times recorded by the cable

companies and showed that a dense, muddy current, a turbidity current, had flowed down the slope at tens of kilometers an hour. The cables that men had laid to overcome the ocean ended up teaching scientists how the ocean floor itself moves.

WORKED EXAMPLES

Example 1. New York and London are about 5,570 km (3,460 miles) apart on a great circle. A real cable route between them is about 6,500 km long. Light in glass travels about 200,000 km/s. Find the shortest possible one-way time and the time along the real cable, in milliseconds. Then compare with one hop via a geostationary satellite (about 71,600 km at 299,792 km/s).

1. Great-circle time: $5,570 \div 200,000 = 0.0279 \text{ s} \approx 28 \text{ ms}$.
2. Real cable: $6,500 \div 200,000 = 0.0325 \text{ s} \approx 33 \text{ ms}$.
3. Satellite: $71,600 \div 299,792 \approx 0.239 \text{ s} \approx 239 \text{ ms}$.
4. Ratio: $239 \div 33 \approx 7.3$.

Answer: About 28 ms in theory and about 33 ms by the real cable, versus about 239 ms by geostationary satellite: the cable is roughly seven times faster even though light travels slower in glass.

Example 2. A modern fiber loses about 0.2 dB per kilometer. Repeaters are spaced 80 km apart. What fraction of the light reaches the next repeater? Compare with Kao's 1966 goal of 20 dB/km over just 1 km. (Rule: every 10 dB of loss divides the power by 10; fraction left = $10^{(-\text{dB}/10)}$.)

1. Total loss over 80 km: $80 \times 0.2 = 16 \text{ dB}$.
2. Fraction left: $10^{(-16/10)} = 10^{(-1.6)} \approx 0.025$, or 2.5 percent.
3. Kao's goal: 20 dB over 1 km gives $10^{(-2)} = 0.01$, or 1 percent left after only 1 km.
4. So today's glass sends light about 80 km and still keeps more than Kao's fiber kept after 1 km.

Answer: About 2.5 percent of the light reaches the next repeater 80 km away, more than the 1 percent Kao hoped to keep after a single kilometer.

Example 3. TAT-1 (1956) carried 36 telephone calls. TAT-8 (1988) carried about 40,000 calls at a total rate of 280 megabits per second. MAREA (2018) was designed for 160 terabits per second. By what factor did capacity grow from TAT-1 to TAT-8 (in calls), and from TAT-8 to MAREA (in bits)?

(Use the map or drawing “MAREA runs from Virginia Beach to the Bilbao area.” shown earlier in this lesson.)

1. TAT-1 to TAT-8: $40,000 \div 36 \approx 1,100$ times.
2. Convert units: 160 terabits = 160×10^{12} bits; 280 megabits = 280×10^6 bits.
3. TAT-8 to MAREA: $(160 \times 10^{12}) \div (280 \times 10^6) = (160 \div 280) \times 10^6 \approx 0.571 \times 10^6 \approx 571,000$ times.

Answer: About 1,100 times from TAT-1 to TAT-8, and about 570,000 times from TAT-8 to MAREA, in thirty years.

PRACTICE

1. **EASY** Explain total internal reflection in one or two sentences and say what keeps light inside an optical fiber.
2. **EASY** Who proposed in 1966 that glass fibers could carry communications, and what loss did he say was needed?
3. **EASY** Light travels 299,792 km/s in a vacuum. Glass slows it by a factor of about 1.47. How fast does light travel in fiber?
4. **MEDIUM** Los Angeles and Tokyo are about 8,800 km (5,470 miles) apart on a great circle. What is the shortest possible one-way time through fiber at 200,000 km/s?
5. **MEDIUM** MAREA is about 6,600 km long. If repeaters were spaced every 60 km, about how many would be needed?
6. **MEDIUM** A cable section has a total loss of 30 dB. What fraction of the light power remains?
7. **MEDIUM** Using the cable route map, name three choke points that a cable from Marseille to Singapore passes through or near.
(Use the map or drawing “Follow the route from Marseille to Singapore.” shown earlier in this lesson.)
8. **HARD** In 1929 an earthquake south of Newfoundland set off an undersea landslide that broke telegraph cables one after another down the slope, and scientists later used the break times to measure its speed. Suppose two cables 300 km apart down the slope broke 5 hours apart. How fast was the current? Give km/h and mph.
9. **HARD** TAT-1 carried 36 calls; TAT-8 about 40,000. By what factor did capacity grow, and over how many years?
10. **HARD** A cable carries 160 terabits per second. How long would it take to send 1 terabyte (8 terabits) of data, if the whole cable were used?
11. **CHALLENGE** In a conversation, a question goes one way and the answer comes back. Compare the round-trip delay by geostationary satellite (four legs of 35,786 km at

299,792 km/s) with a 6,500 km fiber cable each way (at 200,000 km/s). Why did people in the 1960s find satellite telephone calls awkward?

12. **MEDIUM** Write a short paragraph explaining why “the cloud” is a misleading word for the geography of the internet.

COMMON MISTAKES

- Believing most international internet traffic goes by satellite. Well over 95 percent crosses the oceans by undersea cable.
- Thinking light in a fiber travels at full vacuum speed. It moves about two-thirds as fast, around 200,000 km/s.
- Assuming cables are hard to damage because they are under the sea. Breaks are common, mostly near shore from anchors and fishing, and choke points let one accident cut several cables.

Make it a game · Cable Ship. Lay a long rope across the yard or floor as an undersea cable with three “landing stations” marked by cones. One player, blindfolded, is the cable ship; a partner gives directions to find a hidden knot (the break) by walking the rope from either end and timing how far a squeeze of the rope takes to reach them. Once found, the ship must “splice” it by tying a square knot within thirty seconds. Then switch roles and hide the break in a narrow “strait” between two chairs, where it is harder to reach.

Scripture. “Their line is gone out through all the earth, and their words to the end of the world. In them hath he set a tabernacle for the sun,” (Psalm 19:4, KJV)

David wrote that the heavens declare God’s glory without speech, yet their “line” reaches the whole earth. Our cables carry human words to the ends of the world in a fraction of a second. Like every gift, that reach can be used for truth and love or for lies and harm, so the stewardship belongs to us.

Practice answers

1. When light inside a denser material strikes the boundary with a less dense material at a shallow enough angle, it reflects completely back inside. In a fiber, the core glass is slightly denser optically than the cladding around it, so light bouncing along the core stays trapped.
2. Charles Kao (with George Hockham) at Standard Telecommunication Laboratories in England. He said loss must fall below 20 decibels per kilometer.
3. $299,792 \div 1.47 \approx 204,000$ km/s, about two-thirds of its vacuum speed.
4. $8,800 \div 200,000 = 0.044$ s = 44 ms. The real cable route is longer, so actual times are somewhat more.
5. $6,600 \div 60 = 110$, so about 110 repeaters (about 109 between the two ends).
6. Each 10 dB divides by 10, so 30 dB divides by 1,000: one thousandth (0.1 percent) remains.
7. The land crossing of Egypt (Mediterranean to the Red Sea at Suez), the Bab-el-Mandeb at the southern end of the Red Sea, and the Strait of Malacca.
8. $300 \text{ km} \div 5 \text{ h} = 60 \text{ km/h}$, about 37 mph.
9. $40,000 \div 36 \approx 1,100$ times, over 32 years (1956 to 1988).

10. $8 \div 160 = 0.05$ s, one twentieth of a second.
11. Satellite: $4 \times 35,786 = 143,144$ km $\div 299,792 \approx 0.48$ s. Fiber: $13,000 \div 200,000 = 0.065$ s. The satellite round trip is about 7 times longer; a pause of half a second made people talk over each other.
12. "The cloud" suggests data floating in the sky, but it is stored in large buildings (data centers) on real land and moves between continents through cables lying on the seabed. Those cables come ashore at a few landing stations, follow narrow routes through straits and canals, and can be cut by anchors, fishing gear or earthquakes. The internet has a physical map shaped by coasts, seabeds and choke points.

5.4 WHAT TECHNOLOGY HAS NOT OVERCOME

OBJECTIVES

- Analyze the grounding of the *Ever Given* in the Suez Canal (March 2021) as a case study in how choke points still govern world trade.
- Explain four limits that technology has not removed (mountains, weather, distance and choke points) with a real example of each.
- Calculate the cost of detours, headwinds, mountain grades and the speed of light, and weigh the Babel warning against the gift of human creativity.

Warm-up. Lay a ruler across two stacks of books to make a narrow bridge, and line up ten coins on one side. Push them across one at a time. Now set one coin crosswise on the bridge so it blocks the way. Write down how many coins are stuck, and what it would cost them to go the long way around the table instead.

Watch. *What Really Happened at the Suez Canal?* (Practical Engineering, 11:34).

<https://www.youtube.com/watch?v=Ty-m4pm8oog>

With Choke points still rule: what happened when the *Ever Given* blocked the Suez Canal in 2021.

Note: Practical Engineering includes a short sponsor message, and it mentions the pandemic once in passing.

KEY TERMS

choke point

A narrow passage, such as a strait or canal, through which a large share of traffic must pass, so that one blockage stops many ships.

grade

The steepness of a road or railroad, given as rise divided by distance, in percent. A 2 percent grade rises 2 meters for every 100 meters of track.

jet stream

A fast, narrow band of westerly wind high in the atmosphere, often over 160 km/h (100 mph), that speeds eastbound flights and slows westbound ones.

friction of distance

The idea that every extra mile adds cost, time or effort, so that contact and trade fall off with distance.

gravity model

A model of trade, used by the economist Jan Tinbergen in 1962, in which trade between two places grows with their size and shrinks with the distance between them.

Darién Gap

The stretch of swamp, river and rainforest on the border of Panama and Colombia, about 100 km (60 miles) wide, where the Pan-American Highway has never been built.

CORE IDEAS

The story. On the morning of March 23, 2021, the container ship *Ever Given* was steaming north through the Suez Canal near its southern end when a sandstorm and strong winds swept across the desert. The ship was 400 meters (1,312 feet) long, about as long as the Empire State Building is tall, and stacked high with containers that caught the wind like a sail. She swung sideways, drove her bow into the eastern bank and her stern toward the western bank, and stuck fast, wedged diagonally across the canal. For six days dredgers dug at the sand around her bow while tugboats pulled and pushed. Behind her, ships gathered at both ends of the canal until more than 350 were waiting, carrying oil, grain, cars, and everything that fills a store. Some gave up and turned south for the long voyage around Africa. On March 29, helped by the high spring tide that comes with a full moon, the tugs finally pulled her free. One ship, one gust of wind and one bank of sand had closed a route that carries roughly 12 percent of the world's trade.

Choke points still rule. The Suez Canal is a triumph of everything this course has studied: engineering, steam, steel and the container. Yet by making the route through Egypt so much shorter, it also made the world depend on a channel only a few hundred meters wide. The same is true elsewhere. The Strait of Hormuz, through which a large share of the world's seaborne oil passes, is about 33 km (21 miles) wide at its narrowest. The Strait of Malacca narrows near Singapore to a channel under 3 km (less than 2 miles) wide. The Bab-el-Mandeb and the Bosphorus are narrow gates too. As you saw in the last lesson, undersea cables crowd into the same straits. Technology did not abolish these places; it made them more important. Whoever can keep them open, or close them, holds great power, which is why the course on geopolitics returns to them again and again.

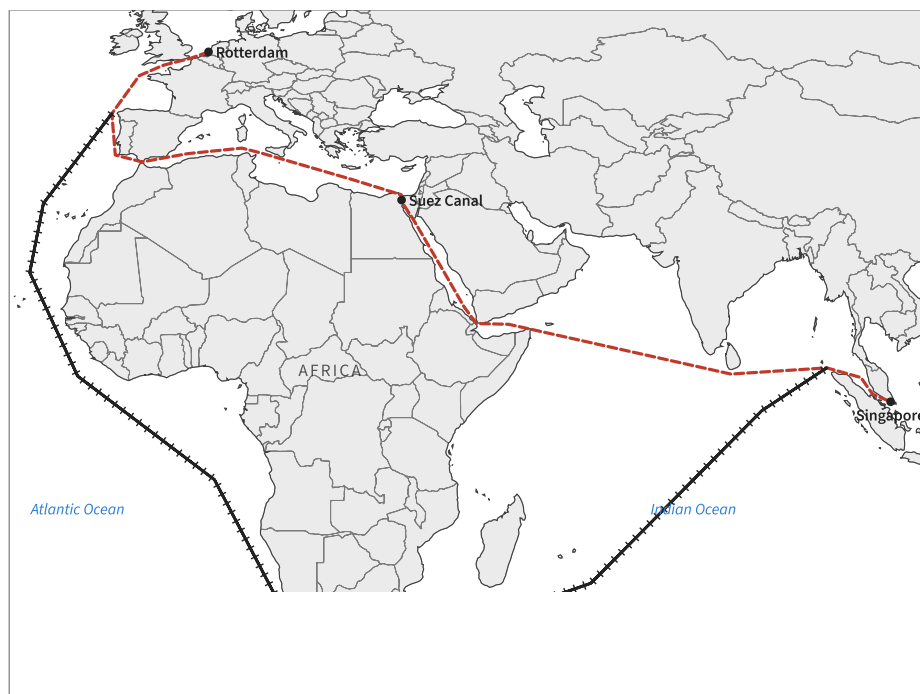
Mountains and wild land. Every railroad since Stephenson's has had to obey the grade. A heavy freight train on a main line struggles with anything steeper than about 2 percent, so climbing 1,000 meters takes at least 50 km of track. Engineers answer with long loops and switchbacks, or with tunnels that cost enormous sums and years of labor. China's Qinghai-Tibet Railway, opened to Lhasa in 2006, climbs to 5,072 meters (16,640 feet) at the Tanggula Pass, the highest railroad in the world, and had to be built with cooling pipes to keep its frozen ground from thawing. And some land has not been crossed at all. The Pan-American Highway runs from Alaska to the tip of South America except for one break: the Darién Gap between Panama and Colombia, where swamps, rivers and mountainous rainforest have defeated road builders for a century. Mountain passes in the Himalaya, the Andes and the Alps still close in winter snow.

Weather and the restless earth. In April 2010 the Icelandic volcano Eyjafjallajökull erupted under a glacier. The meltwater shattered the magma into fine glassy ash, and northwesterly winds, unusually steady that spring, carried it southeast over Europe. Jet engines that swallow ash can fail: in 1982 a British Airways 747 lost all four engines flying through ash from a volcano in Indonesia, and only restarted them after gliding thousands of feet. So for about six days most of Europe's airspace closed, and some 100,000 flights were cancelled. The jet stream still adds or subtracts hours from every flight across the Atlantic. Fog still closes airports and harbors. Hurricanes and typhoons still send ships around them.

In 2023 a dry year lowered Gatun Lake, whose rainwater fills the Panama Canal's locks, and the canal had to limit the number and depth of ships for months; each transit through the older locks uses about 50 million gallons (about 190,000 cubic meters) of fresh water. In dry autumns the Rhine falls so low that barges must sail half loaded.

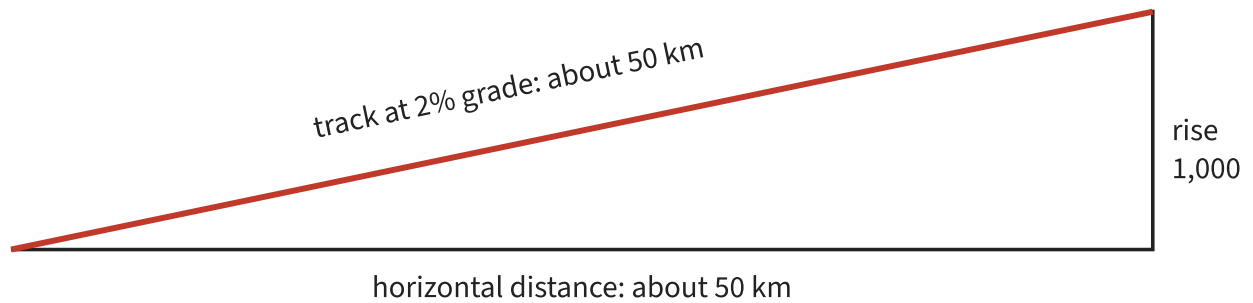
Distance itself. In 1966 the Australian historian Geoffrey Blainey wrote *The Tyranny of Distance*, arguing that remoteness from Europe had shaped his country's whole history. Containers, jets and cables have weakened that tyranny but not ended it. Economists using the **gravity model** have found, again and again, that trade between two countries falls off with the distance between them. Fuel is burned by the mile; crews are paid by the day; perishable goods spoil by the hour. Nor can any invention change the shape and spin of the earth. In winter, when it is nine in the morning in New York, it is eleven at night in Tokyo. And the speed of light is a hard wall: a signal through fiber from New York to Tokyo needs at least about 54 thousandths of a second, however much money is spent.

The big idea: mastering and humility. Look back over the course and you will see that every great technology overcame geography by *working with* it: sails used the wind, canals used rivers and rain, ships followed great circles, satellites obeyed the laws of orbit, cables followed the straits. Genesis 1:28 gives people the calling to fill and subdue the earth, and human creativity is part of bearing God's image. But Genesis 11 tells of the builders of Babel, who said, "let us make us a name," trusting their tower to keep them from being scattered. The lesson is not that building is wrong. It is that pride forgets limits. A wise engineer, merchant or nation plans for the sandstorm, the drought and the narrow strait, because the earth is the Lord's, and we are its stewards, not its masters.



Rotterdam to Singapore: through Suez, about 8,300 nautical miles; around the Cape of Good Hope, about 11,700.

Grade = rise ÷ distance = 1,000 m ÷ 50,000 m = 0.02 = 2%. Height greatly exaggerated.



A 2 percent grade: to climb 1,000 m, a railroad needs about 50 km of track.

PICTURE STUDY



Snow Storm: Steam-Boat off a Harbour's Mouth, Joseph Mallord William Turner, exhibited 1842 · Oil on canvas · Tate Britain, London

Turner gave this painting a long title that tells its story: *Snow Storm: Steam-Boat off a Harbour's Mouth making Signals in Shallow Water, and going by the Lead. The Author was in this Storm on the Night the Ariel left Harwich*. Turner later told a friend that he had had himself lashed to a mast for hours to watch the storm. Many historians doubt that the story is literally true, but the painting makes us feel it.

In Unit 1 you saw Turner's *Fighting Temeraire*, where a steam tug tows an old sailing warship to be broken up: the triumph of steam. Here steam is no triumph. The paddle steamer, the most modern machine of its day, is a small dark shape caught in a vortex of wind, snow and sea. Some critics mocked the painting as a mess of soapsuds and whitewash; Turner answered that they had never been in such a storm.

Look closely

- Find the steamboat. How much of the painting does it take up?
- Follow the great curves of the storm with your finger. Where do they lead your eye?
- Find the mast and the light near it. The title says the boat is “making signals.” What might it be signaling?
- The title says the boat is “going by the lead,” measuring the depth with a weighted line. Why would a captain do that near a harbor in a storm?

Talk about it

1. How does this painting answer the confident mood of *The Fighting Temeraire*?
2. What does the painting suggest about the limits of technology against weather?
3. Is a storm at sea any less dangerous today, with GPS and radar, than in 1842? What has changed and what has not?

PROJECT: OVER, AROUND OR THROUGH: A MODEL MOUNTAIN ROUTE

Engineers who meet a mountain have three choices: climb over it with a long, gentle road, go around it, or tunnel through it. You will build a model mountain, lay out a road that obeys a grade limit, measure a tunnel, and compare the costs in distance and effort.

You will need

- Modeling clay, salt dough or a large potato cut flat on one side
- A sturdy board or tray
- Ruler, metric tape measure and a piece of string about 2 m (6 ft) long
- Straight pins or toothpicks
- A wooden skewer
- Notebook and calculator

Steps

1. Build a mountain on the board about 10 cm (4 in) high and 25 to 30 cm (10 to 12 in) across at the base. Decide on a scale: 1 cm = 100 m, so your mountain is 1,000 m high.
2. Mark a town at the foot of the mountain on one side and a town on the other side, directly opposite.
3. Measure the straight path over the top with string, from town to summit to town. Compute its average steepness on the way up: $\text{rise} \div \text{path length}$.
4. Now lay out a road that never climbs steeper than 10 percent (1 cm of rise for every 10 cm of road). Mark heights every 2 cm up the mountain with pins, and lay the string in switchbacks so that each 10 cm of string rises no more than 1 cm. Measure the total road length from town to town.
5. Push the skewer straight through the base of the mountain from town to town to make a tunnel. Measure the tunnel's length.
6. Measure a route around the base of the mountain with the string.

7. Convert all four lengths to real kilometers with your scale. Make a table: route, length, steepest grade, what it would cost to build and what it would cost to use.
8. Write a paragraph recommending one route for a railroad and one for a footpath, explaining your reasoning.

Tips

- A real main-line railroad would want 2 percent or less, five times gentler than your 10 percent model road. Multiply your road length by about five to imagine the railroad.
- Tunnels are short but very costly per kilometer; switchbacks are cheap to build but slow and long to use. Your recommendation should weigh both.

Check your work

- I can calculate a grade as rise divided by distance.
- I can lay out a route that obeys a grade limit and measure its length.
- I can explain the trade-off between going over, around or through a mountain.

MAP NOTEBOOK

1. Draw a world map and mark five choke points: Suez, Panama, Hormuz, Malacca and the Bab-el-Mandeb. Beside each, write what technology made it busier.
2. Sketch the *Ever Given* wedged across the canal, with arrows showing the wind, and a line of waiting ships at each end.
3. Make a four-box chart, "Mountains, Weather, Distance, Choke Points," with one real example from this lesson and one technology that tried to overcome it in each box.

From history. On June 24, 1982, British Airways Flight 9, a Boeing 747 flying at night over Indonesia, flew into ash from the volcano Galunggung. All four engines stopped. The crew glided for many minutes while trying to restart them, and finally succeeded at lower altitude after the ash had cooled and broken off inside the engines. The airliner landed safely at Jakarta. That flight taught the world's airlines that volcanic ash is a deadly hazard, which is why Europe's skies closed in 2010.

WORKED EXAMPLES

Example 1. A ship sails from Rotterdam to Singapore at 15 knots (15 nautical miles per hour). Through the Suez Canal the voyage is about 8,300 nautical miles; around the Cape of Good Hope it is about 11,700. How many extra days does the Cape route take, and how many extra kilometers?

(Use the map or drawing “The detour around Africa adds about 3,400 nautical miles.” shown earlier in this lesson.)

1. Extra distance: $11,700 - 8,300 = 3,400$ nautical miles.
2. Distance per day at 15 knots: $15 \times 24 = 360$ nautical miles.
3. Extra time: $3,400 \div 360 \approx 9.4$ days.
4. In kilometers (1 nautical mile = 1.852 km): $3,400 \times 1.852 \approx 6,300$ km (about 3,900 statute miles).

Answer: About 9 to 10 extra days and about 6,300 km (3,900 miles) more, with all the extra fuel and crew wages that go with them.

Example 2. New York to London is about 3,000 nautical miles (5,570 km). An airliner cruises at 480 knots through the air. On a winter day the jet stream adds a 100-knot tailwind eastbound and a 100-knot headwind westbound. Find the flying time each way.

1. Eastbound ground speed: $480 + 100 = 580$ knots. Time = $3,000 \div 580 \approx 5.2$ hours (about 5 h 10 min).
2. Westbound ground speed: $480 - 100 = 380$ knots. Time = $3,000 \div 380 \approx 7.9$ hours (about 7 h 54 min).
3. Difference: $7.9 - 5.2 \approx 2.7$ hours.

Answer: About 5.2 hours eastbound and 7.9 hours westbound: the same distance, nearly three hours apart, because of the wind. (Airlines plan routes each day to ride the jet stream or avoid it.)

Example 3. A railroad must climb from a valley at 500 m to a pass at 1,500 m. What length of track is needed at a 2 percent grade? At a 1.5 percent grade? If the straight-line distance from valley to pass is only 15 km, how much extra track must loops and switchbacks add at 2 percent?

(Use the map or drawing “Grade = rise ÷ distance.” shown earlier in this lesson.)

1. Rise = $1,500 - 500 = 1,000$ m.
2. At 2 percent: length = rise ÷ grade = $1,000 \text{ m} \div 0.02 = 50,000 \text{ m} = 50 \text{ km}$ (31 miles).
3. At 1.5 percent: $1,000 \div 0.015 \approx 66,700 \text{ m} \approx 67 \text{ km}$ (41 miles).
4. Extra track at 2 percent: $50 - 15 = 35 \text{ km}$ of loops and curves, unless a tunnel or a steeper line is built.

Answer: 50 km at 2 percent, about 67 km at 1.5 percent; at 2 percent the line needs about 35 km more than the straight distance.

PRACTICE

1. **EASY** When did the *Ever Given* block the Suez Canal, for how long, and what caused the grounding?
2. **EASY** Name the four kinds of limits studied in this lesson and give one example of each.
3. **EASY** What is the Darién Gap, and why has the road never been built across it?
4. **MEDIUM** A railroad must climb 600 m at a grade no steeper than 1.5 percent. What is the shortest possible length of track?
5. **MEDIUM** If each transit of the older Panama locks uses about 50 million gallons of fresh water, how much do 36 transits in a day use? Give gallons and cubic meters (1 gallon = 3.785 liters; 1 cubic meter = 1,000 liters).
6. **MEDIUM** New York and Tokyo are about 10,850 km apart on a great circle. What is the shortest possible one-way signal time through fiber (200,000 km/s)? Through a vacuum (299,792 km/s)?
7. **MEDIUM** New York is on UTC−5 in winter and Tokyo on UTC+9. When it is 9:00 a.m. Monday in New York, what time is it in Tokyo?
8. **HARD** Using the worked example, how many extra days would the Cape route take for a faster ship at 20 knots?
(Use the map or drawing “Compare the two routes.” shown earlier in this lesson.)
9. **HARD** Explain why an eruption in Iceland in 2010 closed airports as far away as Germany and Italy. Use the words prevailing winds and jet engine in your answer.
10. **HARD** In a simple gravity model, predicted trade = $k \times (\text{size of A} \times \text{size of B}) \div \text{distance}$. If two countries’ sizes stay the same but the shipping distance doubles, what happens to predicted trade? If the distance is halved?
11. **CHALLENGE** A mountain road may not be steeper than 8 percent. It must climb 400 m up a slope whose straight horizontal distance is 1.5 km. How long must the road be, and

about how many switchback legs of about 1 km each will it need?

12. **MEDIUM** In a paragraph, explain how the story of Babel (Genesis 11) and the command of Genesis 1:28 together help us think about technology and geography.

COMMON MISTAKES

- Thinking a shortcut like Suez makes trade safer in every way. It saves distance but concentrates traffic, so one accident can stop hundreds of ships.
- Treating weather and climate as problems only of the past. Wind, ash, fog, drought and storms still close airports, canals and rivers.
- Assuming faster technology can beat any distance. Time zones and the speed of light set limits no invention can remove.

Make it a game · Choke Point. Set up a “sea” on a table with two books forming a narrow strait in the middle. Each player has five toy boats or coins to move from one end to the other, one move per turn through the strait (one boat at a time). The game master rolls a die each turn: a 1 means a storm or grounding closes the strait for two turns. Players may instead go “around Africa” along the table edge, which takes three extra turns but never closes. First to get all boats across wins. Afterward, discuss when the long way was the wiser choice.

Scripture. “Go to now, ye that say, To day or to morrow we will go into such a city, and continue there a year, and buy and sell, and get gain: Whereas ye know not what shall be on the morrow. For what is your life? It is even a vapour, that appeareth for a little time, and then vanisheth away. For that ye ought to say, If the Lord will, we shall live, and do this, or that.” (James 4:13–15, KJV)

James wrote to merchants who planned their travel and trade with confidence. He did not forbid planning; he warned against forgetting who governs tomorrow. Every shipper who waited at Suez in 2021 learned the same lesson.

Practice answers

1. From March 23 to March 29, 2021, about six days. Strong winds and a sandstorm pushed the 400-meter ship, with its high stacks of containers, sideways into the canal banks.
2. Mountains (the Darién Gap or the 2 percent railroad grade), weather (the 2010 Iceland ash cloud, the jet stream, the 2023 Panama drought), distance (time zones, the speed of light, Blainey’s “tyranny of distance”), and choke points (Suez, Hormuz, Malacca, the Bab-el-Mandeb).
3. It is a stretch of about 100 km (60 miles) on the Panama-Colombia border where the Pan-American Highway is broken. Swamps, rivers and mountainous rainforest make road building very hard and costly.
4. $600 \div 0.015 = 40,000 \text{ m} = 40 \text{ km}$ (about 25 miles).
5. $50 \text{ million} \times 36 = 1.8 \text{ billion gallons}$. $1.8 \times 10^9 \times 3.785 \text{ L} \approx 6.8 \times 10^9 \text{ L} \approx 6.8 \text{ million cubic meters}$.

6. Fiber: $10,850 \div 200,000 \approx 0.054$ s (54 ms). Vacuum: $10,850 \div 299,792 \approx 0.036$ s (36 ms). No technology can do better than the vacuum figure.
7. The difference is 14 hours, so it is 11:00 p.m. Monday in Tokyo.
8. $20 \times 24 = 480$ nautical miles a day. $3,400 \div 480 \approx 7.1$ extra days.
9. The eruption under a glacier produced very fine, glassy ash that rose high into the air. The prevailing winds, which that spring blew steadily from the northwest, carried it southeast over Europe. Ash melts inside a hot jet engine and can make it fail, as nearly happened to a British Airways 747 in 1982, so authorities closed airspace until the ash cleared.
10. Doubling the distance halves predicted trade; halving the distance doubles it.
11. $400 \div 0.08 = 5,000$ m = 5 km. With legs of about 1 km each, it needs about 5 legs (4 hairpin turns), zigzagging across a slope only 1.5 km deep.
12. Genesis 1:28 calls people to fill and subdue the earth, and human creativity, including ships, canals and satellites, is part of bearing God's image. Babel warns against pride: the builders wanted to "make us a name" and refused to be scattered. Good technology works with the earth God made and plans humbly for its limits (storms, droughts, mountains, narrow straits), rather than assuming people have conquered nature for good.

5.5 FINAL PROJECT AND EXAM: ONE TECHNOLOGY AND THE GEOGRAPHY IT OVERCAME

OBJECTIVES

- Look back over the whole course from the vantage point of Apollo 8 and *Earthrise* (December 24, 1968), and state the four questions that every lesson asked.
- Plan, research and write a paper on one technology, using primary and secondary sources, a map and a quantitative before-and-after comparison.
- Review the course's key calculations (time, distance, speed, cost and angle) in preparation for the final exam.

Warm-up. Hold a coin (a quarter or a 1-euro coin, about 2.4 cm across) at arm's length, about 70 cm from your eye, and close one eye. That is roughly how big the earth looked to the Apollo 8 crew from the moon. Now look around the room and list three things your coin could cover at arm's length. Write one sentence on how you think it would feel to cover the whole earth with your thumb.

Watch. *Apollo 8: A Story of Christmas Around the Moon* (NASA, 7:00).

<https://www.youtube.com/watch?v=Of1lau2VVp4>

With the story: NASA's account of the Apollo 8 Christmas Eve broadcast and the Genesis reading.

Backup video. *Apollo 8's Christmas Eve 1968 Message* (NASA Video, 2:01).

<https://www.youtube.com/watch?v=ToHhQUhdyBY>

The broadcast itself: the crew read Genesis 1 from lunar orbit on December 24, 1968.

KEY TERMS

primary source

A document or object from the time being studied, made by someone who took part or saw it: a letter, journal, patent, photograph, map, treaty, ship's log or the machine itself.

secondary source

A later work that studies and explains primary sources, such as a history book or a scholarly article.

thesis

The one arguable sentence that states what your paper will prove.

before-and-after comparison

A table or calculation showing time, distance, cost or capacity before a technology and after it, from reliable sources.

citation

A note telling the reader exactly where a fact or quotation came from, so it can be checked.

CORE IDEAS

The story. On December 21, 1968, Frank Borman, James Lovell and William Anders rode the first crewed Saturn V rocket off its launch pad in Florida and became the first human beings to leave the earth's orbit. Three days later, on December 24, their Apollo 8 spacecraft was circling the moon about 110 km (69 miles) above its gray, cratered surface. On their fourth orbit, as the spacecraft came around from the far side, Anders saw the earth rising over the lunar horizon, blue and white against the black of space. He grabbed a camera loaded with color film and took the photograph we now call *Earthrise*. That evening, on their ninth orbit, the crew spoke to the largest television audience in history up to that time. Anders began reading, "In the beginning God created the heaven and the earth," and Lovell and Borman took turns until they had read the first ten verses of Genesis. Borman closed by wishing a Merry Christmas and God's blessing to "all of you on the good Earth."

How they got there. Apollo 8 brings together almost every theme of this course. The crew were navigators in the old tradition: Lovell sighted on stars through a sextant and telescope built into the spacecraft, just as ship's officers had fixed their positions with sextants since the eighteenth century, and the onboard computer turned his angles into a position. On earth, great dish antennas tracked the ship from California, Spain and Australia, stations spaced roughly a third of the way around the world from one another so that one of them could always see the spacecraft as the earth turned. The speed, the timing and the geometry were all problems you have met: Harrison's problem of keeping time, the great-circle problem of the shortest path, the satellite problem of orbits. The difference was the distance: about 384,000 km (239,000 miles) to the moon.

The big idea: four questions. Every lesson in this course has asked the same four questions about a breakthrough. *What problem did geography pose?* (an ocean too wide to cross against the wind, a mountain too steep for a train, an isthmus between two oceans, a distance too great for a message). *How did the technology solve it?* (the stern rudder, the lock, the chronometer, the cable, the container, the satellite). *What did it cost?* (money, years, lives, and sometimes the livelihoods of those who were displaced). *What changed in the world?* (trade routes, the rise and fall of ports, the strategy of nations, ordinary people's lives). Your final paper asks those same four questions about one technology of your choosing, and answers them with evidence.

How to write the paper. Begin with a **thesis**: one sentence that a reasonable person could argue against. "The Erie Canal was important" is not a thesis. "By cutting the cost of shipping from Buffalo to New York City by roughly nine-tenths, the Erie Canal made New York the leading port of the United States" is. Gather at least two **primary sources**, such as a traveler's account, an engineer's report, a patent, a treaty, a ship's log or a historic photograph (Project Gutenberg, the Library of Congress and NASA all offer many for free), and at least three good **secondary sources**. Build at least one **before-and-after comparison** with real numbers: days of travel, miles saved, cost per ton, words per minute,

calls per cable. Draw a map that shows the geography the technology overcame. Tell the costs honestly, including the workers who died building a canal or railroad, and do not exaggerate the gains. Cite every fact so a reader can check it. Finally, include what the technology did *not* overcome: the limits from Lesson 5.4.

On the map. Every paper must include a map that you make yourself, by hand or carefully on a computer. The best maps show a *before and after*: the long route and the short one (around Cape Horn and through Panama), the travel time in 1800 and in 1857, the sailing ship's path with the wind and the steamship's straight line, the scattered telegraph offices and the cable that joined them. Use a title, a scale bar, a north arrow, a key and a source line. A good map is an argument in pictures; a reader should be able to see your thesis by looking at it.

Technology overcoming geography, seen from the moon. Anders later said, in effect, that the crew had come all that way to explore the moon and had discovered the earth. From a quarter of a million miles away, the borders, mountain ranges and oceans that have filled this course disappeared into one small, bright sphere that an astronaut could hide behind his thumb. That view teaches two things at once. It is a monument to what human creativity can do: in the span of one long life, people went from the first airplane to orbiting the moon. And it is a lesson in humility. The whole human story, every voyage, canal and railroad, has taken place on that one small world, where God "hath made of one blood all nations of men" and "hath determined the times before appointed, and the bounds of their habitation" (Acts 17:26). The final exam, given separately, will cover the whole course; the paper is your chance to tell one part of that story well.



Evenly spaced for reading; not drawn to a time scale.

Some of the breakthroughs of this course. Choose one for your final paper, or propose another.

PICTURE STUDY



Earthrise, William Anders, Apollo 8, December 24, 1968 · Color photograph (70 mm film, Hasselblad camera) · NASA (photograph AS08-14-2383)

William Anders took this photograph from lunar orbit on Christmas Eve 1968, minutes after the earth appeared over the moon's horizon. He had been photographing craters in black and white for future landing sites; when he saw the earth, he asked for a roll of color film and took a few frames. This is the most famous of them.

Out in space there is no up or down. Anders took the picture with the moon's horizon running up the side of the frame; it is usually printed turned, with the moon at the bottom, so that the earth seems to rise like the sun. The photograph became one of the most widely reproduced images of the twentieth century.

Look closely

- Find the line between day and night on the earth. Which part is lit by the sun?
- Look for clouds. Can you make out any land or ocean beneath them?
- Compare the colors of the earth and the moon. What does the contrast make you feel?
- Notice how small the earth is in the frame. Every place you have studied in this course is somewhere on that small disk.

Talk about it

1. Why do you think this photograph moved so many people in 1968?
2. Apollo 8's crew chose to read Genesis 1. Why might those words have seemed fitting at that moment?
3. After a semester of studying how people overcame distance, how does this picture change the way you think about distance?

PROJECT: FINAL RESEARCH PAPER: ONE TECHNOLOGY AND THE GEOGRAPHY IT OVERCAME

Your final project is a research paper of about 1,800 to 2,500 words on one technology from this course, or another approved by your teacher, and the geography it overcame. The paper answers the course's four questions with evidence, includes a map you made and a before-and-after comparison with real numbers, and ends with the limits that remained. Begin it in this lesson and finish it over the following two to three weeks, alongside your review for the final exam.

You will need

- A notebook or digital document for research notes
- Access to a library and free online collections (Project Gutenberg, the Library of Congress, NASA, the National Park Service)
- Graph paper, colored pencils, ruler and an atlas for your map
- A calculator
- The course timeline figure and your notes from all five units

Steps

1. Choose your technology. Suggested topics: the stern rudder and the carrack; the magnetic compass and the portolan chart; Harrison's chronometer; the steamship and coaling stations; the clipper ship; Roman roads; the Canal du Midi or the Erie Canal; the railroad and the *Rocket*; the Transcontinental or the Trans-Siberian Railroad; the Gotthard, the Forth Bridge or the Channel Tunnel; the Suez or the Panama Canal; the Kiel or Corinth Canal; the telegraph or the Atlantic cable; the airplane and air routes; the jet and polar routes; the container; satellites, GPS or fiber-optic cables.
2. Write the four questions at the top of a page and jot what you already know under each.
3. Find at least two primary sources and three secondary sources. Record full citations as you go (author, title, date, publisher or website, page).
4. Gather numbers for a before-and-after table: distance, time, cost, speed or capacity. Note the source of every number.
5. Write a thesis sentence that is specific and arguable. Have a parent or teacher check it before you go on.
6. Outline the paper: introduction and thesis; the geography (the problem); the technology (how it worked, with one worked calculation); the cost; what changed; what was not overcome; conclusion.
7. Draw your map with title, scale bar, north arrow, key and source line.
8. Write the first draft. Put your before-and-after table and your map where they support the argument.
9. Revise: check every number, every date and every quotation against your sources. Remove anything you cannot support.
10. Add a bibliography and turn in the paper with your notes and map.

Tips

- Narrow topics make strong papers. “Transportation” is too broad; “How the Panama Canal changed the voyage from New York to San Francisco” is just right.
- A quotation from a primary source is worth more than a paragraph of summary, but quote exactly and cite it. If you are not sure of the exact words, paraphrase without quotation marks.
- Present costs and wrongs honestly and without exaggeration. Name the workers who built the thing and what they suffered, and let the facts speak.

Check your work

- My thesis is one specific, arguable sentence.
- I used at least two primary and three secondary sources, all cited.
- My paper includes a map I made and a before-and-after table with sourced numbers.
- My paper answers all four questions and names at least one limit the technology did not overcome.

MAP NOTEBOOK

1. Copy the course timeline and add a small sketch beside each entry (a lock, a locomotive, a cable ship, a satellite).
2. Draw *Earthrise* from memory, then write Acts 17:26 beneath it.
3. Draw a rough version of the map for your final paper and list three things it must show.

From history. In May 1969 the United States Post Office issued a six-cent stamp honoring Apollo 8. It showed the earth rising over the moon, based on the crew’s photographs, with the words “In the beginning God...” across the bottom, recalling the crew’s Christmas Eve reading. Millions of letters carried that picture of the whole earth, and those four words, to homes across the country.

WORKED EXAMPLES

Example 1. Before the Panama Canal, a ship from New York to San Francisco had to sail around Cape Horn, about 13,000 miles (20,900 km). Through the canal the voyage is about 5,200 miles (8,400 km). How many miles are saved, and what percent of the old voyage is that?

1. Miles saved: $13,000 - 5,200 = 7,800$ miles.
2. In kilometers: $20,900 - 8,400 = 12,500$ km.
3. Percent of the old voyage: $7,800 \div 13,000 = 0.60 = 60$ percent.

Answer: About 7,800 miles (12,500 km) saved, 60 percent of the voyage. This is the kind of before-and-after number a strong paper puts in its comparison table.

Example 2. In 1956 Malcom McLean calculated that loading loose cargo onto a ship cost about \$5.83 per ton, while loading the *Ideal X* with containers cost about 15.8 cents per ton. By what factor was container loading cheaper, and what percent was saved?

1. Write both in dollars: \$5.83 and \$0.158.
2. Factor: $5.83 \div 0.158 \approx 36.9$, so about 37 times cheaper.
3. Savings: $5.83 - 0.158 = 5.672$. Percent: $5.672 \div 5.83 \approx 0.973 = 97.3$ percent.

Answer: About 37 times cheaper, a saving of about 97 percent per ton.

Example 3. The earth is about 12,742 km in diameter and was about 384,400 km from Apollo 8. How large did it look, in degrees? Compare with the moon seen from earth (diameter 3,474 km at the same distance). (For small angles, angle in radians $\approx$ diameter $\div$ distance; 1 radian $\approx 57.3^\circ$.)

1. Earth from the moon: $12,742 \div 384,400 \approx 0.0331$ radians. $0.0331 \times 57.3 \approx 1.9^\circ$.
2. Moon from the earth: $3,474 \div 384,400 \approx 0.00904$ radians. $0.00904 \times 57.3 \approx 0.52^\circ$.
3. Ratio: $1.9 \div 0.52 \approx 3.7$.

Answer: The earth looked about 1.9° across, about 3.7 times as wide as the full moon looks to us, small enough to hide behind a thumb at arm's length.

PRACTICE

1. **EASY** State the four questions this course has asked about every technology.
2. **EASY** Classify each as a primary or secondary source: (a) the Wright brothers' 1903 photograph of their first flight; (b) a 2005 history of the Panama Canal; (c) Harrison's H4 watch; (d) a magazine article written in 2020 about the 1866 Atlantic cable.
3. **EASY** A navigator sees the sun at its highest (local noon) when the chronometer, set to Greenwich time, reads 4:00 p.m. What is the ship's longitude?
4. **MEDIUM** In 1838 the *Great Western* crossed from Bristol to New York in about 15 days. A modern jet flies London to New York in about 7 hours. How many times faster is the jet?
5. **MEDIUM** The Gatun Locks of the Panama Canal lift ships about 85 feet (26 m) in three steps. About how much does each step lift?
6. **MEDIUM** A commonly cited figure says the Erie Canal cut freight costs from Buffalo to New York City from about \$100 a ton to about \$10 a ton. What percent reduction is that? How would you check whether the figure is reliable?
7. **MEDIUM** Use the worked example's method to find how wide the moon (diameter 3,474 km) would look from 192,200 km away, halfway to the moon.
8. **MEDIUM** On May 24, 1844, Samuel Morse sent a message over his line between Washington and Baltimore. What was the message, where did the words come from,

and about how long was the line?

9. **HARD** Which is the stronger thesis, and why? (a) “The transcontinental railroad was an amazing achievement.” (b) “By cutting the trip from New York to San Francisco from months to about a week, the transcontinental railroad bound California to the Union and opened the interior West to settlement and trade.”
10. **HARD** A student writes, “As the Roman emperors liked to say, ‘All roads lead to Rome.’” What is wrong, and how should it be fixed?
11. **CHALLENGE** Before 1869 an overland journey by wagon from the Missouri River to California took about 5 months; after 1869 a train from New York to San Francisco took about a week. Roughly how many times faster was the railroad trip? What other changes besides speed should a paper on the railroad discuss?
12. **MEDIUM** Write a thesis statement for a paper on one technology from this course. It must name the technology, the geography it overcame and one change it caused.

COMMON MISTAKES

- Choosing a topic too broad to finish well. Narrow it to one technology, one place and one change.
- Using numbers or quotations without sources, or copying a dramatic figure from one website. Check every number in at least two good sources.
- Writing only about the triumph. A complete paper also counts the costs and names the limits that geography still imposed.

Make it a game · Course Quiz Bowl. Write each technology from the course timeline on a card, and on separate cards write a fact or number that belongs to it (a date, a distance, a person, a place). Shuffle the fact cards. Two teams take turns drawing a fact card and matching it to the right technology within fifteen seconds. Score one point for a correct match and a bonus point for naming the geography that technology overcame. The team with the most points chooses the first topic for the paper presentations.

Scripture. “And God blessed them, and God said unto them, Be fruitful, and multiply, and replenish the earth, and subdue it: and have dominion over the fish of the sea, and over the fowl of the air, and over every living thing that moveth upon the earth.” (Genesis 1:28, KJV)

This blessing stands behind every sail, canal, railroad, cable and satellite in this course. People made in God’s image are called to fill the earth and to rule it wisely. The Apollo 8 crew read the chapter that contains this verse while looking back at the whole earth, a fitting place to end a course on how people have learned to cross it.

Practice answers

1. What problem did geography pose? How did the technology solve it? What did it cost? What changed in the world?
2. (a) primary; (b) secondary; (c) primary (an artifact); (d) secondary.

3. Local time is 4 hours behind Greenwich, so the ship is west. $4 \times 15^\circ = 60^\circ$ W.
4. $15 \text{ days} \times 24 = 360 \text{ hours}$. $360 \div 7 \approx 51$ times faster.
5. $85 \div 3 \approx 28$ feet; $26 \div 3 \approx 8.7$ m per step.
6. $(100 - 10) \div 100 = 90$ percent. Check it by finding it in more than one good secondary source and, if possible, tracing it to a primary source such as canal or freight records from the 1820s, and by noting what years and goods the figures describe.
7. $3,474 \div 192,200 \approx 0.0181$ radians $\times 57.3 \approx 1.04^\circ$, twice its usual size.
8. "What hath God wrought," from Numbers 23:23 (chosen by Annie Ellsworth). The line was about 40 miles (64 km) long.
9. (b). It is specific, it makes a claim that can be argued and tested with evidence, and it names the geography (the distance across the continent) and the change. (a) is an opinion that cannot really be proved or disproved.
10. The saying is a medieval proverb, not something documented from Roman emperors. The student should drop the false attribution, for example: "The later proverb 'All roads lead to Rome' captures how the Roman road network centered on the capital." Every quotation needs a real, checkable source.
11. 5 months ≈ 150 days; $150 \div 7 \approx 21$ times faster (even though the train covered a longer distance). A paper should also discuss cost and safety for travelers, freight and trade, the growth of towns, the workers (including Chinese and Irish crews) and those who died, the effect on Native nations and the buffalo, and the land grants that paid for the line.
12. Answers will vary. Example: "By laying a working telegraph cable across the Atlantic in 1866, Cyrus Field and the *Great Eastern* cut the time for news between London and New York from about ten days by steamship to minutes, tying the markets and governments of two continents together."

UNIT 5 TEST

Answer each question. Show your work for all calculations, give units, and use complete sentences for explanations. Use the speed of light 299,792 km/s in space and 200,000 km/s in glass, and the earth's radius 6,371 km. The test is worth 100 points.

1. (5 pts) When and where was Sputnik 1 launched, and why did its launch alarm many Americans?
2. (8 pts) A satellite orbits 400 km above the earth once every 92.6 minutes. Treating the orbit as a circle, find its speed in km/s and mph.
3. (5 pts) How did the tracking of Sputnik lead to the first satellite navigation system?
4. (6 pts) At what height do geostationary satellites orbit, and why must they be above the equator? Name one job they do.
5. (8 pts) (a) A GPS satellite is 22,000 km from a receiver. How long does its signal take to arrive? (b) A receiver's clock is wrong by 20 nanoseconds. How large is the distance error?
6. (8 pts) On a grid in km, beacons stand at A (0, 0), B (6, 0) and C (0, 8). A receiver is 5 km from each. Find its position and show how beacon C settles the question.
7. (6 pts) Explain why GPS needs signals from at least four satellites, and why that is trilateration rather than triangulation.
8. (6 pts) Describe two events that opened GPS to civilians and improved its accuracy, with their years.
9. (8 pts) A cable route from Marseille to Singapore is about 12,000 km long. (a) What is the one-way signal time through the fiber? (b) Compare it with one hop through a geostationary satellite (about 71,600 km).
10. (6 pts) A modern fiber loses 0.2 dB per km. What is the total loss over 100 km, and what fraction of the light is left? Who first argued that glass fibers could carry communications, and when?
11. (6 pts) Name three choke points where undersea cables between Europe and Asia crowd together, and explain why crowding is a risk.
12. (8 pts) When the Suez Canal is closed, a ship from Rotterdam to Singapore must sail around the Cape of Good Hope, adding about 3,400 nautical miles. How many extra days does that add at 12 knots? Give the extra distance in km (1 nmi = 1.852 km).
13. (6 pts) A railroad must climb 450 m with a grade no steeper than 1.8 percent. What is the shortest possible track length? Name two ways engineers fit that length into a mountain valley.
14. (8 pts) Write a paragraph giving one real example each of mountains, weather, distance and choke points still limiting technology, and end with one sentence on what the story of Babel teaches about the limits.
15. (6 pts) (a) Give one example of a primary source and one of a secondary source for a paper on the Panama Canal. (b) Rewrite this weak thesis so that it is specific and arguable: "The Panama Canal was very important."

UNIT PROJECT: MASTERING LOCATION: MY GPS FLOOR MAP AND FINAL RESEARCH PAPER

Assemble a portfolio for the course's last unit. Include your string-and-tape GPS trilateration record from Lesson 5.2 (the floor layout, the distances, your computed positions, your error in inches and your clock-error round), your scale model notes from Lesson 5.1, and your world cable map with its choke points from Lesson 5.3.

At the center of the portfolio place your final research paper on one technology and the geography it overcame, with its hand-made map, its before-and-after comparison table and its bibliography. Close with a one-page reflection on *Earthrise*: what the course has taught you about what people can do, and about what they cannot.

- **Accuracy:** Calculations, positions, dates, numbers and quotations are correct and every fact in the paper is cited to a checkable source.
- **Argument:** The paper has a clear, arguable thesis and answers all four questions (problem, solution, cost, change) and names at least one limit that remained.
- **Maps and records:** The trilateration record is complete and dated; the cable map and paper map have titles, scale bars, north arrows, keys and sources.
- **Care and reflection:** The work is neat and well organized, costs and wrongs are presented honestly, and the *Earthrise* reflection thinks seriously about creativity and humility.

Answer key

1. October 4, 1957, from Tyuratam (Baikonur) in Kazakhstan, by the Soviet Union. A rocket that could put a satellite in orbit could also send a nuclear warhead anywhere on earth, so the oceans no longer protected the United States as before, and the Soviets appeared to lead in science and rocketry.
2. Radius $6,371 + 400 = 6,771$ km. Circumference $2\pi \times 6,771 \approx 42,540$ km. Time $92.6 \times 60 = 5,556$ s. Speed $\approx 42,540 \div 5,556 \approx 7.66$ km/s, or about 27,600 km/h $\approx 17,100$ mph.
3. At Johns Hopkins, Guier and Weiffenbach used the Doppler shift of Sputnik's radio signal to calculate its orbit. Frank McClure reversed the idea: if the satellite's orbit is known, the Doppler shift lets a receiver calculate its own position. The Navy built this into Transit, in service from 1964.
4. About 35,786 km (22,236 miles). Only an orbit in the plane of the equator, circling once a day in the direction the earth turns, keeps a satellite over the same spot. They relay television and communications and watch the weather.
5. (a) $22,000 \div 299,792 \approx 0.0734$ s (73 ms). (b) Light travels about 0.30 m per nanosecond, so $20 \times 0.30 = 6$ m (about 20 feet).
6. From A and B: $x^2 + y^2 = 25$ and $(x - 6)^2 + y^2 = 25$ give $x = 3$, $y = \pm 4$: (3, 4) or (3, -4). Distance from C (0, 8) to (3, 4) = $\sqrt{9 + 16} = 5$ ✓; to (3, -4) = $\sqrt{9 + 144} \approx 12.4$ ✗. The receiver is at (3, 4).
7. Each signal's travel time gives a distance, placing the receiver on a sphere. Three spheres fix position in three dimensions only if the receiver's clock is perfect; since it is not, the clock error is a fourth unknown, and four unknowns need four measurements. It is trilateration because GPS measures distances (by timing), not angles.

8. After Korean Air Lines Flight 007 strayed over Soviet territory and was shot down on September 1, 1983, President Reagan announced that GPS would be made available for civilian use. In May 2000 Selective Availability, the deliberate degrading of the civilian signal, was switched off, improving civilian accuracy roughly tenfold.
9. (a) $12,000 \div 200,000 = 0.060$ s (60 ms). (b) $71,600 \div 299,792 \approx 0.239$ s (239 ms), about four times longer, even though the cable spans a third of the way around the world.
10. $100 \times 0.2 = 20$ dB, which divides the power by 100: 1 percent is left. Charles Kao (with George Hockham), in 1966.
11. The land crossing of Egypt between the Mediterranean and Red Sea, the Bab-el-Mandeb, and the Strait of Malacca (also the Luzon Strait in East Asia). When many cables share a narrow route, one earthquake, landslide or dragging anchor can cut several at once, as the 2006 Taiwan earthquake did in the Luzon Strait.
12. $12 \times 24 = 288$ nmi per day. $3,400 \div 288 \approx 11.8$ days. $3,400 \times 1.852 \approx 6,300$ km.
13. $450 \div 0.018 = 25,000$ m = 25 km (about 15.5 miles). Engineers use long loops, curves and switchbacks, or bore tunnels (including spiral tunnels) to gain length or cut through the mountain.
14. Answers will vary but should include real examples such as: mountains, the Darién Gap or the 2 percent railroad grade; weather, the 2010 Eyjafjallajökull ash cloud, the jet stream or the 2023 Panama Canal drought; distance, time zones, the speed of light or the gravity model of trade; choke points, the Ever Given in the Suez Canal (March 2021), Hormuz or Malacca. Babel warns that pride forgets limits: people should build and create as God's image-bearers, but humbly, planning for the earth's limits rather than boasting that they have conquered it.
15. (a) Primary: a 1913 photograph of the Culebra Cut, Goethals's or Gorgas's reports, or a worker's letter. Secondary: a modern history book on the canal. (b) Example: "By cutting the sea voyage from New York to San Francisco from about 13,000 miles to about 5,200, the Panama Canal turned the United States into a two-ocean trading and naval power."

MIDTERM EXAM

Units 1-3 · 100 minutes

You have 100 minutes. A calculator is allowed; no notes, maps or books. Use 1 nautical mile (nm) = 1.852 km = 1.151 statute miles, 1 mile = 1.609 km, 1 Roman mile = 1.48 km, 1 knot = 1 nm per hour, and 15° of longitude = 1 hour of time. For every calculation, write the setup, show your work with units, and give the answer in the units asked (give km and miles wherever a distance is asked). Points are earned for correct setup and work as well as the final answer, so correct reasoning earns partial credit even if a number slips. Identification items earn full credit for the correct name, date or term plus the brief explanation asked. Essays are graded on a clear thesis, accurate facts from the course, and fair weighing of evidence on more than one side. The exam has 25 problems worth a total of 100 points.

1. (4 pts) A harbor lies 24 nautical miles directly upwind. Ship A has a lateen (fore-and-aft) rig and can sail 45° from the wind; Ship B is square-rigged and can sail no closer than 67° from the wind. Both make 6 knots through the water. Ignoring leeway and current, how far must each sail and how long does each take? Give the distances in nm, km and miles.
2. (3 pts) Identify: (a) the sturdy one-masted, flat-bottomed merchant ship of northern Europe, with one square sail and a stern rudder, that was the workhorse of the Hanseatic League; (b) the large three- or four-masted ship of the 1400s-1500s that combined square sails with a lateen sail at the stern; (c) the side of a ship named for the old steering oar, and one reason the stern-post rudder was better than that oar on a large ship.
3. (4 pts) A ship leaves a known position and steers due south (180°) at 7 knots for 4 hours, then due west (270°) at 7 knots for 3 hours. Find her dead-reckoning position relative to the start, her straight-line distance from the start (nm, km and miles) and the bearing from the start to her position. Then name two things that could make this dead-reckoning position wrong.
4. (3 pts) (a) A navigator in the Northern Hemisphere measures Polaris 51.5° above the horizon. What is his approximate latitude? (b) On a day when the sun's declination is 20° N, another navigator measures the noon sun 62.0° above the southern horizon. What is his latitude? (c) Why could latitude be found at sea long before longitude?
5. (4 pts) A navigator at latitude 20° N observes local noon when his chronometer, set to Greenwich time, reads 16:40. (a) What is his longitude? (b) How many nautical miles, km and miles is one degree of longitude at 20° N? (c) If his chronometer had been 2 minutes in error, how large would his longitude error be, in minutes of arc and in nm, km and miles?
6. (3 pts) Briefly identify each: (a) H4; (b) the lunar-distance method and the man who made it practical; (c) the International Meridian Conference of 1884, including why Greenwich was chosen.
7. (5 pts) (a) A steamer carries 800 tonnes of coal and burns 40 tonnes a day at 10 knots. Her captain keeps 25 percent of the coal as a reserve. Find her range in nm, km and

miles. Could she steam from Britain to the Cape of Good Hope (well over 5,000 nm) without coaling? (b) Using Brunel's square-cube reasoning, a second ship is built with every dimension 3 times as large. Assuming coal burned per day grows with hull surface and coal carried grows with volume, how does her range compare with the first ship's?

8. (4 pts) Using round figures, the London-China voyage took about 150 days in 1800, about 100 days for the best clippers in 1866 and about 35 days by mail steamer through Suez in 1900. (a) By what percent did the voyage time fall from 1800 to 1900, and how many times faster was the 1900 voyage? (b) By what percent did it fall from 1866 to 1900? (c) If a clipper covered 14,000 nm in 100 days, find her average speed in knots, km/h and mph.
9. (3 pts) Explain why wooden hulls could not grow much beyond about 90 m (300 ft) and why iron removed that limit. Then name two new problems that iron hulls created and how sailors dealt with each.
10. (4 pts) Vegetius says a legion was expected to march about 20 Roman miles in five hours, and a normal day's march was about 20 Roman miles. (a) How far does a legion march in 6 days, in km and modern miles? (b) What was its marching speed in km/h and mph? (c) How many days would a cursus publicus courier making 50 Roman miles a day need for the same distance?
11. (3 pts) Describe how a great Roman road such as the Via Appia was built, including the purpose of its crown and ditches. Then explain why "All roads lead to Rome" is not a Roman saying.
12. (4 pts) (a) An Erie Canal lock chamber is 90 ft long and 15 ft wide. How much water flows down from the upper pound when a boat is raised 12 ft? Give the answer in cubic feet, gallons and cubic meters ($1 \text{ ft}^3 = 7.48 \text{ gal} = 0.0283 \text{ m}^3$). (b) The Erie Canal's 83 locks raised boats a net 568 ft (173 m). What was the average lift per lock in feet and meters?
13. (3 pts) (a) List in order the steps by which a pound lock raises a boat, and explain why miter gates point upstream. (b) In words, explain why the Erie Canal followed the Mohawk Valley, and name the barriers it avoided.
14. (4 pts) (a) A railway must climb 240 m (about 790 ft) to cross a ridge. How many km and miles of track are needed at a ruling grade of 1%? How long would a road at 6% need to be? Why do railways need such gentle grades? (b) Plymouth lies at about 4.1° W and London at about 0.1° W . Before railway time, how far apart were their local clocks, and which was behind? When did North American railroads adopt standard time zones?
15. (3 pts) Under the Pacific Railway Act (1862) the government lent \$16,000 per mile on level ground, \$32,000 per mile on the high plateau between the Rockies and the Sierra Nevada and \$48,000 per mile in the mountains. A company builds 400 miles of level line, 150 miles of plateau line and 100 miles of mountain line. How much does it receive in bonds, and what does the rate scale reveal about geography?
16. (4 pts) A train leaves Vladivostok (UTC+10) on Wednesday at 08:00 local time and runs 150 hours to Moscow (UTC+3), about 9,289 km (5,772 miles). What is the day and local time of arrival in Moscow, and what is the average speed in km/h and mph?

17. (4 pts) (a) A train crosses the Gotthard Base Tunnel, about 57 km (35.4 miles) long, at 200 km/h. How many minutes does it spend in the tunnel? Why can a base tunnel be crossed nearly flat while the 1882 line needed spiral tunnels? (b) Steel expands about 12 millionths of its length per °C. How much longer does the 2,500 m Forth Bridge become on a day 25 °C warmer, in meters and feet?
18. (3 pts) (a) In a cantilever bridge such as the Forth Bridge, which members carry compression and which carry tension? (b) What happened on the Tay Bridge on December 28, 1879, what did the inquiry find, and how did it change the design of the Forth Bridge?
19. (4 pts) London to Bombay is about 10,700 nm around the Cape of Good Hope and about 6,300 nm through the Suez Canal. A steamer averages 12 knots and burns 35 tons of coal a day. Find the distance saved (nm, km, miles and percent), the days each route takes, and the coal saved. Then give two reasons the isthmus allowed a canal without locks.
20. (4 pts) (a) A storm drops 15 cm (about 6 in) of rain in one day on 800 km² of the Chagres watershed. What volume of water is that, and how does it compare with the roughly 52 million m³ held by the whole 1869 Suez channel? (b) In words, compare the geography of Panama and Suez in at least three respects, and explain why de Lesseps's sea-level plan failed.
21. (4 pts) (a) The Gatun Locks lift ships about 26 m (85 ft) in three equal steps. What is each step? (b) A Pedro Miguel chamber is 305 m by 33.5 m with a lift of 9.5 m. How much water does one lockage use, in m³ and U.S. gallons (1 m³ = 264.2 gal)? (c) Gatun Lake covers about 425 km². If 36 ships a day each use about 200,000 m³ and no rain falls, how much does the lake fall per day and over a 100-day dry season?
22. (4 pts) (a) The Kiel Canal saves about 250 nm compared with the route around Jutland. A ship cruises at 14 knots at sea but must slow to 8 knots in the 98 km (52.9 nm) canal. Ignoring time in the locks, how many hours does she save? (b) Why does the Kiel Canal have locks even though its water lies close to sea level? (c) Why does the Corinth Canal carry little trade today?
23. (4 pts) (a) New York to San Francisco is about 13,000 nm by Cape Horn and about 5,200 nm by Panama. Find the distance saved in nm, km and miles, and the days saved at 12 knots. (b) The original Panama chambers are 33.5 m wide and a Panamax ship is 32.3 m wide; the 2016 chambers are 55 m wide and a Neopanamax ship 49 m wide. Find the space on each side of each ship. (c) Explain in one or two sentences how a canal can create a choke point.
24. (7 pts) **Short essay.** "Steam freed ships from the wind and chained them to coal." Using specific evidence from Unit 1, weigh how far the steamship overcame geography and how far it simply created a new geography. Consider both gains and limits.
25. (8 pts) **Short essay.** The French failed at Panama (1881-1889) and the Americans succeeded (1904-1914). Weigh the main reasons, considering at least three of these: disease and medical knowledge, the engineering plan, geography, organization and leadership, and the labor force. Was the American success due more to better science, better engineering or better circumstances?

Answer key

- Distance sailed = upwind distance $\div$ cos(angle to wind).
Ship A: $24 \div \cos 45^\circ = 24 \div 0.7071 = \mathbf{33.9 \text{ nm}}$ (62.9 km, 39.1 mi); time = $33.9 \div 6 = \mathbf{5.7 \text{ h}}$.
Ship B: $24 \div \cos 67^\circ = 24 \div 0.3907 = \mathbf{61.4 \text{ nm}}$ (113.8 km, 70.7 mi); time = $61.4 \div 6 = \mathbf{10.2 \text{ h}}$.
The square-rigger sails nearly twice as far, which is why the carrack carried a lateen sail at the stern.
- (a) The **cog** (e.g., the Bremen Cog, about 1380). (b) The **carrack** (e.g., *Santa María*, *Victoria*, *Mary Rose*). (c) **Starboard** (steer-board). The stern-post rudder hangs on the centerline, stays under water whichever way the ship leans, and can be built bigger as ships grow; a side oar lifts out of the water when the ship heels and is hard to hold on a big ship. (1 point each.)
- Leg 1: $7 \times 4 = 28 \text{ nm}$ south. Leg 2: $7 \times 3 = 21 \text{ nm}$ west.
Distance = $\sqrt{(28^2 + 21^2)} = \sqrt{(784 + 441)} = \sqrt{1,225} = \mathbf{35 \text{ nm}}$ (64.8 km, 40.3 mi).
Angle west of south: $\tan^{-1}(21 \div 28) = \tan^{-1} 0.75 = 36.9^\circ$, so the bearing is $180^\circ + 36.9^\circ \approx \mathbf{217^\circ}$ (southwest).
Sources of error (any two): currents, leeway (wind pushing the ship sideways), careless steering, unknown magnetic variation, a misjudged speed. Errors add up and grow with distance until land is sighted.
- (a) About **51.5° N** (the altitude of Polaris is nearly equal to the latitude).
(b) Latitude = $90^\circ - \text{altitude} + \text{declination} = 90^\circ - 62.0^\circ + 20^\circ = \mathbf{48.0^\circ \text{ N}}$.
(c) Latitude comes straight from the sky: the height of Polaris or the noon sun (with declination tables) gives it with a quadrant or astrolabe. Longitude requires knowing the time at a home meridian, and no clock could keep accurate time at sea until the chronometer.
- (a) Local noon came 4 h 40 min = 4.667 h after Greenwich noon, so he is west: $4.667 \times 15^\circ = \mathbf{70^\circ \text{ W}}$.
(b) $60 \text{ nm} \times \cos 20^\circ = 60 \times 0.9397 = \mathbf{56.4 \text{ nm}}$ (104.4 km, 64.9 mi).
(c) 1 minute of time = 15' of arc, so 2 min = **30' = 0.5°**; $0.5 \times 56.4 = \mathbf{28.2 \text{ nm}}$ (52.2 km, 32.4 mi). This half degree is exactly the error the Longitude Act of 1714 allowed for the £20,000 prize.
- (a) John Harrison's large-watch sea clock, finished in 1759; on the 1761-62 voyage of HMS *Deptford* to Jamaica it was only about 5 seconds slow after correcting for its rate (about a nautical mile of longitude).
(b) Finding Greenwich time by measuring the angle between the moon and a star or the sun and using printed tables; Nevil Maskelyne, whose *Nautical Almanac* (first for 1767) made it practical.
(c) Delegates of 25 nations met in Washington, D.C., in October 1884 and voted 22 to 1 (2 abstaining: France and Brazil; San Domingo against) to make the Greenwich meridian 0° . Most of the world's sea charts already used Greenwich because the British *Nautical Almanac* was reckoned from it. (1 point each.)
- (a) Usable coal = $800 \times 0.75 = 600 \text{ t}$. Days = $600 \div 40 = 15 \text{ days}$. Distance per day = $10 \times 24 = 240 \text{ nm}$. Range = $15 \times 240 = \mathbf{3,600 \text{ nm}}$ (6,670 km, 4,140 mi). **No**: she would need a coaling station on the way, which is why stations such as Gibraltar, Cape Town and Aden mattered.
(b) Surface grows $3^2 = 9$ times; volume $3^3 = 27$ times. She carries 27 times the coal but burns about 9 times as much per day, so she can steam $27 \div 9 = \mathbf{3 \text{ times as far}}$ (about 10,800 nm at the same speed). Bigger steamers were more economical.
- (a) $(150 - 35) \div 150 = 115 \div 150 = \mathbf{76.7\%}$; $150 \div 35 = \mathbf{4.3 \text{ times}}$ as fast.
(b) $(100 - 35) \div 100 = \mathbf{65\%}$.

(c) $14,000 \div 100 = 140$ nm per day; $140 \div 24 = \mathbf{5.8 \text{ knots}}$ = 10.8 km/h = 6.7 mph. The clipper's best days were much faster; calms, light winds and tacking dragged the average down, the weakness that steam removed.

9. Long wooden hulls bend as waves support them in the middle (**hogging**) and at the ends (**sagging**), working the seams open until they leak. Iron plates riveted to iron frames are far stronger for their weight, take up less room inside and can be built to almost any size (SS *Great Britain*, *Great Eastern*).

Problems (any two, with remedy): **compass deviation** from the ship's own iron, corrected with magnets near the compass as George Airy showed in 1838; **fouling** by weed and barnacles in warm seas, one reason tea clippers such as *Cutty Sark* stayed composite (iron frame, wooden planks sheathed in copper alloy); iron could not simply be sheathed in copper because of corrosion.

10. (a) $6 \times 20 = 120$ Roman miles $\times 1.48 = \mathbf{177.6 \text{ km}}$; $177.6 \div 1.609 = \mathbf{110 \text{ miles}}$.
(b) $20 \times 1.48 = 29.6$ km in 5 h = **5.9 km/h** (3.7 mph).
(c) $120 \div 50 = \mathbf{2.4 \text{ days}}$.
11. Surveyors laid the line with a *groma*; workers (often soldiers) dug a trench to firm ground and filled it in layers: large stones, then rubble and gravel (sometimes bound with lime), then finer gravel or sand, and near cities a top of tightly fitted many-sided blocks of hard volcanic stone, held by curbs. The **crown** (higher in the middle) sheds rain to the side **ditches** so the roadbed does not soak and fail. The proverb is **medieval** (a twelfth-century Latin form is credited to Alain de Lille), when Rome was the center of the Western Church and pilgrims filled the roads; many Roman provincial roads ran between forts, ports and provincial capitals, not toward Rome.
12. (a) $90 \times 15 \times 12 = \mathbf{16,200 \text{ ft}^3} \approx 121,000$ gallons ($16,200 \times 7.48 = 121,176$) $\approx \mathbf{458 \text{ m}^3}$. This water leaves the upper pound every lockage, up or down.
(b) $568 \div 83 = \mathbf{6.8 \text{ ft}}$; $173 \div 83 = \mathbf{2.1 \text{ m}}$.
13. (a) The boat enters through the open lower gates; the lower gates close; paddles (sluices) in the upper gates let water in from the upper pound until the chamber matches the upper level; the upper gates open and the boat leaves. The gates meet in a V pointing upstream so the higher water pushes them together and seals them.
(b) The Mohawk is the one low, water-level gap through the Appalachian barrier, running east from central New York to the Hudson. The canal avoided the Adirondacks to the north and the Catskills and Allegheny Plateau to the south, then crossed the lowlands south of Lake Ontario to Buffalo.
14. (a) Run = rise $\div$ grade: $240 \div 0.01 = \mathbf{24 \text{ km (14.9 mi)}}$; road: $240 \div 0.06 = \mathbf{4 \text{ km (2.5 mi)}}$. A locomotive can pull only as hard as the grip of its driving wheels on the rails, and on a steep climb that grip runs out, so lines need cuttings, embankments, viaducts, loops and tunnels.
(b) $4.0^\circ \times 4 \text{ min} = \mathbf{16 \text{ minutes}}$; Plymouth, to the west, was **behind**. North American railroads adopted time zones on **November 18, 1883**.
15. $400 \times \$16,000 = \$6,400,000$; $150 \times \$32,000 = \$4,800,000$; $100 \times \$48,000 = \$4,800,000$. Total = **\$16,000,000**. A mountain mile earned three times a level mile because building through the Sierra Nevada and Rockies (granite tunnels, snow, avalanches) cost far more.
16. $150 \text{ h} = 6 \text{ days } 6 \text{ hours}$. Wednesday 08:00 + 6 days = Tuesday 08:00; + 6 h = Tuesday 14:00 Vladivostok time. Moscow is 7 hours behind: **Tuesday 07:00 Moscow time**. Speed = $9,289 \div 150 = \mathbf{61.9 \text{ km/h}}$; $5,772 \div 150 = \mathbf{38.5 \text{ mph}}$.
17. (a) $57 \div 200 = 0.285 \text{ h} \times 60 = \mathbf{17.1 \text{ minutes}}$. A base tunnel is bored near the level of the valley floors on each side, so trains do not climb to a high summit tunnel; the 1882 line had to climb to the summit tunnel at Göschenen-Airolo, and spiral tunnels let it gain height at a gentle grade.

(b) $2,500 \times 0.000012 \times 25 = \mathbf{0.75\ m} \approx \mathbf{2.5\ ft}$, taken up by sliding bearings and expansion joints.

18. (a) The great steel tubes at the bottom carry **compression**; the open lattice girders above carry **tension**. Arms reach out from three piers, balanced against each other, with short suspended spans between their tips.

(b) The central girders collapsed in a gale and a train fell into the river; all aboard died (75 by the count at the time; later research identified 59). The inquiry found it badly designed, built and maintained, with too little allowance for wind. Bouch's Forth suspension design was dropped, and Fowler and Baker designed the Forth Bridge to resist a wind pressure of 56 lb per square foot.

19. Saved: $4,400\ \text{nm} = \mathbf{8,150\ km} = \mathbf{5,060\ mi}$; $4,400 \div 10,700 = \mathbf{41\%}$.

Cape: $10,700 \div 12 = 892\ \text{h} = \mathbf{37.2\ days}$. Suez: $6,300 \div 12 = 525\ \text{h} = \mathbf{21.9\ days}$. Saved $\approx 15.3\ \text{days} \times 35 = \mathbf{about\ 535\ tons}$ of coal.

Reasons (any two): the two seas stand at nearly the same level (the 1847 survey disproved Le Père's 10 m claim); the isthmus is low and nearly flat; it is dry with no great river to flood the works; sand is easy to dig; natural basins (Lake Timsah, the Bitter Lakes) saved digging.

20. (a) $800\ \text{km}^2 = 800,000,000\ \text{m}^2$; $\times 0.15\ \text{m} = \mathbf{120\ million\ m}^3$, about **2.3 times** the whole Suez channel, in one day.

(b) Any three: **relief** (Suez flat; Panama must be cut through the continental divide at Culebra); **rivers** (Suez none; Panama the flood-prone Chagres down whose valley the route ran); **rainfall** (Suez almost none; Panama's Caribbean side over 3 m a year); **rock** (Suez sand that stays put; Culebra's clays and shales slid into the cut); **disease** (yellow fever and malaria). De Lesseps carried his Suez formula to a place where geography fought back; floods and slides defeated the sea-level cut, and the company collapsed in 1889.

21. (a) $26 \div 3 = \mathbf{8.7\ m}$ ($85 \div 3 = 28.3\ \text{ft}$).

(b) $305 \times 33.5 = 10,218\ \text{m}^2$; $\times 9.5 = \mathbf{about\ 97,100\ m}^3 \approx \mathbf{25.6\ million\ gallons}$.

(c) $36 \times 200,000 = 7,200,000\ \text{m}^3 \div 425,000,000\ \text{m}^2 = 0.017\ \text{m} = \mathbf{1.7\ cm/day}$ (about 2/3 in); $\times 100 = \mathbf{1.7\ m\ (5.6\ ft)}$, before evaporation and city water. The canal depends on the rainy season to refill the lake.

22. (a) Sea time for 250 nm: $250 \div 14 = 17.9\ \text{h}$. Extra canal time: $52.9 \div 8 = 6.6\ \text{h}$ versus $52.9 \div 14 = 3.8\ \text{h}$, a loss of 2.8 h. Net saving $\approx \mathbf{15\ hours}$, plus avoiding the stormy waters off Skagen.

(b) They are **tide locks**: the Elbe mouth has about a 3 m North Sea tide twice a day, while the nearly tideless Baltic changes with wind; without locks the canal would run like a river first one way, then the other.

(c) It is narrow (about 21–25 m wide, 8 m deep), with strong currents and rock slides; it opened in 1893 just as ships were growing fast, so most cargo ships cannot fit and still sail around the Peloponnese.

23. (a) $13,000 - 5,200 = \mathbf{7,800\ nm} = 14,450\ \text{km} = 8,980\ \text{mi}$ (60% of the voyage). $7,800 \div 12 = 650\ \text{h} = \mathbf{27.1\ days}$.

(b) Old: $(33.5 - 32.3) \div 2 = \mathbf{0.6\ m}$ (2 ft) per side; new: $(55 - 49) \div 2 = \mathbf{3\ m}$ (10 ft). Lock size sets the largest ship, so designers build to it.

(c) By concentrating a great share of traffic in one narrow passage, a canal lets one blockage (e.g., the *Ever Given*, 2021) or one controlling power stop or control many ships.

24. **Grading points (7)**: clear thesis that takes a weighed position (1); at least two specific gains (2), e.g., steamers crossed against the wind, through calms and up rivers; *Great Western* (1838) crossed in 15 days on its own coal; Cunard's *Britannia* (1840) ran on fixed dates; the westbound Atlantic fell from 4–6 weeks to about 2; steam plus Suez cut London–China to about 35 days; at least two specific limits or new geography (2), e.g., range limited by

bunkers, every ton of coal displaced cargo; chains of coaling stations (Aden seized 1839, Gibraltar, Malta, Cape Town, Singapore, Hong Kong, Port Said); barren islands (Ascension, St. Helena, Falklands) gained value; navies needed to guard stations; hard coaling labor; fair conclusion that weighs both sides (2).

Model answer (summary): Steam overcame the wind's control of timing and direction, turning seasonal passages into printed schedules. But it did not abolish geography; it rewrote it. A steamer could go only as far as its coal, so routes followed coaling stations, and harbors and islands rose or fell in value according to where coal could be stored. On balance steam was a true victory over the winds, yet it replaced one geographic master with another until larger, more efficient engines and ships widened the range.

25. **Grading points (8):** thesis that answers the final question (1); disease (2): the French believed in miasma, and in the Ancón hospital bed legs stood in pans of water that bred mosquitoes; after Finlay's proposal (1881), Reed's commission (1900) and Ross (1897), Gorgas used screens, fumigation, drainage, oil on standing water and piped water, ending yellow fever by 1906 and cutting malaria; engineering (2): the French sea-level plan fought the Chagres and the Culebra slides (Godin de Lépinay's lake plan was outvoted); the American lock plan dammed the Chagres at Gatun, raised ships 26 m to Gatun Lake and shrank the Culebra excavation; Stevens treated it as a railroad problem and built housing; Goethals finished it; circumstances (1): the Americans inherited French excavation, surveys, Chagres records, machines and the railroad, and had government backing (Roosevelt) rather than private shareholders; labor (1): most of the work on both projects was done by West Indian laborers, many of whom died; fair weighing and conclusion (1).

Model answer (summary): Science was decisive first: without the mosquito discovery the Americans would likely have suffered like the French. Engineering was decisive second: the lock-and-lake plan turned the Chagres from enemy into water supply. Circumstances helped: French work, government funding and strong leadership. A strong answer concludes that all three combined, with the medical breakthrough as the precondition for everything else.

FINAL EXAM

Units 1-5 · 120 minutes

You have 120 minutes. A calculator (with trigonometric functions) is allowed; no notes, maps or books. Use 1 nautical mile (nm) = 1.852 km = 1.151 statute miles, 1 mile = 1.609 km, 1° of a great circle = 60 nm = 111.2 km, 15° of longitude = 1 hour ($1^\circ = 4$ minutes), the speed of light = 299,792 km/s in space and about 200,000 km/s in glass fiber, and the spherical law of cosines: $\cos d = \sin \varphi_1 \sin \varphi_2 + \cos \varphi_1 \cos \varphi_2 \cos \Delta\lambda$. For every calculation, write the setup, show your work with units, and give the answer in the units asked (give km and miles wherever a distance is asked). Points are earned for correct setup and work as well as the final answer, so correct reasoning earns partial credit. Identification and map-reasoning items earn full credit for accurate facts with the brief explanation asked. Essays are graded on a clear thesis, accurate course evidence and fair weighing of more than one side. The exam is cumulative, with emphasis on Units 4 and 5. It has 27 problems worth a total of 100 points.

1. (3 pts) A navigator observes local noon (the sun at its highest) when his chronometer, set to Greenwich time, reads 08:20. What is his longitude, and how do you know whether it is east or west?
2. (3 pts) On a day when the sun's declination is 10° S, a pilot measures the noon sun 40° above the southern horizon. What is his latitude? What instrument would a Portuguese pilot of the late 1400s have used, and why was it built as an open, heavy ring?
3. (3 pts) A canal must climb 60 m (197 ft) over a ridge using locks that each lift 2.5 m. How many locks are needed? If each chamber is 30 m long and 5.5 m wide, how much water does one lockage use, in m^3 and gallons ($1 \text{ m}^3 = 264.2 \text{ gal}$)? Why must a canal's summit level be fed?
4. (3 pts) A railway must climb 300 m (about 980 ft) at a ruling grade of 1.25%. How many km and miles of track are needed? If the valley and the summit are only 10 km apart in a straight line, how might engineers fit the line in?
5. (3 pts) Identify: (a) Promontory Summit; (b) the Trans-Siberian Railway (length and number of time zones); (c) break of gauge, and the gauge Russia chose.
6. (3 pts) Explain how the American Panama Canal turned the Chagres River "from an enemy into the canal's water supply." Name the dam, the lake and its height, and explain how water enters a lock chamber.
7. (3 pts) In the age of local solar time, a telegram leaves Washington (77.0° W) at exactly noon Washington time and arrives in Chicago (87.6° W) within minutes. What is the local solar time in Chicago? What problem did such mismatches create, and how did the telegraph help solve it?
8. (3 pts) Describe how Morse's telegraph carried a message from key to sounder, naming at least four parts of the circuit. What did the telegraph separate for the first time in history?
9. (4 pts) (a) By Thomson's law of squares, how much more does each signal smear out on a 2,000-mile cable than on a 400-mile cable? (b) A 120-word message is sent at the

1858 rate of about 0.1 word per minute and at the 1866 rate of about 8 words per minute. How long does each take? (c) What did engineers do instead of forcing signals with high voltage, as Whitehouse had in 1858?

10. (3 pts) Map reasoning, in words: explain why the 1866 cable ran from Valentia, Ireland, to Heart's Content, Newfoundland, and why its route appears as a curve bending northward on most flat maps.
11. (3 pts) An airliner of the 1930s cruises at an airspeed of 160 mph (257 km/h) on a 1,200-mile (1,931 km) route. The prevailing westerlies give a 40 mph headwind westbound and a 40 mph tailwind eastbound. Find the flying time each way and for the round trip, and compare with a calm day.
12. (3 pts) Identify: (a) wing warping and why it mattered; (b) why the Wright brothers chose Kill Devil Hills near Kitty Hawk; (c) the Douglas DC-3 and why it mattered.
13. (4 pts) Two cities lie on latitude 50° N, 100° of longitude apart. (a) Find the distance along the parallel (rhumb line). (b) Use the spherical law of cosines to find the great-circle distance. (c) How much does the great circle save, in km, miles and percent? Give distances in km and miles.
14. (4 pts) A jet cruises at an airspeed of 880 km/h (547 mph) on the 5,570 km (3,460 mile) route between New York and London. The jet stream gives a 120 km/h (75 mph) tailwind eastbound and a 120 km/h headwind westbound. Find both flight times in hours and minutes, and explain which direction is faster and why.
15. (3 pts) Map reasoning, in words: why did SAS in 1954 fly from Copenhagen to Los Angeles by way of Greenland and the Canadian Arctic? What made navigation there difficult, how did navigators solve it, and why did Anchorage become a crossroads of world air routes?
16. (4 pts) (a) A ship carries 2,200 forty-foot containers and 1,500 twenty-foot containers. What is its load in TEU? (b) The terminal must make 3,600 container moves with 4 cranes, each making 30 moves an hour. How long is the ship at the berth? (c) Using 1956 figures of \$5.86 a ton by break-bulk and \$0.16 a ton by container, find the cost of loading 1,500 tons each way and the percent saved.
17. (3 pts) Explain, in words, how containerization moved the port of New York from Manhattan and Brooklyn to the New Jersey side. What did the new ports need, and what was the human cost of the change?
18. (4 pts) A satellite circles 400 km above the earth once every 92.6 minutes (earth's radius 6,371 km). (a) Find its speed in km/s, km/h and mph. (b) How many orbits does it make per day? (c) How many degrees of longitude does its ground track shift west each orbit, and about how far is that at the equator (111 km per degree)?
19. (3 pts) Identify: (a) Sputnik 1 (date and why it alarmed Americans); (b) Explorer 1 and its discovery; (c) Transit, and how it grew out of listening to Sputnik.
20. (4 pts) (a) A GPS satellite is 22,500 km from a receiver. How long does its signal take to arrive? (b) If the receiver's clock is off by 2 microseconds, how large is the error in each measured distance, in meters and feet? (c) Explain why a receiver needs signals from at least four satellites.
21. (4 pts) On a flat grid measured in km, beacons stand at A (0, 0), B (10, 0) and C (20, 12). A receiver measures that it is 13 km from A, 13 km from B and 15 km from C. Find its

position, showing how the third distance decides between two possible points. Is this trilateration or triangulation, and why?

22. (4 pts) (a) New York and Tokyo are about 10,850 km apart on a great circle. Find the shortest possible one-way fiber time. A real cable route is about 14,000 km; find its one-way and round-trip times. Compare with one hop via a geostationary satellite (about 71,600 km at 299,792 km/s). (b) A fiber loses 0.2 dB per km and repeaters are 60 km apart. What fraction of the light reaches the next repeater? (Fraction left = $10^{(-\text{dB}/10)}$.)
23. (3 pts) Map reasoning, in words: describe the path most Europe-Asia undersea cables follow and the choke points along it. Why can one disaster cut several cables at once, and what actually causes most cable breaks?
24. (4 pts) When a canal is blocked, a ship from Rotterdam to Singapore must go around the Cape of Good Hope, about 11,700 nm instead of about 8,300 nm through Suez. At 12 knots, burning 60 tonnes of fuel a day, how many extra days does the detour take, how much extra fuel does it burn, and how far is the extra distance in km and miles?
25. (3 pts) (a) Classify each as a primary or secondary source: Columbus's journal (in Las Casas's summary); a 2005 history of the Erie Canal; the 1862 Pacific Railway Act; the *Earthrise* photograph. (b) Which is a thesis, and why? (i) "The Erie Canal was important." (ii) "By cutting the cost of shipping from Buffalo to New York City by about nine-tenths, the Erie Canal made New York the leading port of the United States." (c) State the four questions every lesson of this course asked.
26. (8 pts) **Short essay.** "Technology has overcome geography." Weigh this claim using at least three specific examples from different units, including at least one from Unit 4 or 5 and at least one limit from Lesson 5.4. Reach a balanced conclusion.
27. (8 pts) **Short essay.** The telegraph and Atlantic cable overcame distance for words; the container overcame it for goods. Which did more to change world trade? Support your answer with specific evidence about each, and weigh both the benefits and the costs.

Answer key

1. Local noon came 3 h 40 min = 3.667 h *before* Greenwich noon, so the sun reached him first: he is **east**. $3.667 \times 15^\circ = 55^\circ \text{ E}$.
2. Latitude = $90^\circ - \text{altitude} + \text{declination} = 90^\circ - 40^\circ + (-10^\circ) = 40^\circ \text{ N}$. He would use the **mariner's astrolabe**; its heavy, open brass ring kept the wind from swinging it about.
3. $60 \div 2.5 = 24$ **locks**. Water = $30 \times 5.5 \times 2.5 = 412.5 \text{ m}^3 \approx 109,000$ **gallons**. Every lockage lets a chamber-full run down from the upper pound, so the summit loses water constantly and must be refilled by feeders (as Riquet did with the Montagne Noire streams and the Saint-Ferréol reservoir on the Canal du Midi).
4. $300 \div 0.0125 = 24,000 \text{ m} = 24 \text{ km (14.9 mi)}$. The extra 14 km must come from curving along valley sides, loops or spiral tunnels (as on the Gotthard), or a tunnel or cuttings that reduce the climb.
5. (a) The place in Utah Territory, north of the Great Salt Lake, where the Central Pacific and Union Pacific were joined on **May 10, 1869**. (b) Moscow to Vladivostok, begun 1891, about **9,289 km (5,772 mi)**, crossing **seven time zones**, the longest railway line in the world. (c) A place where railways of different track widths meet, forcing passengers and freight to

change trains; Russia chose a broad gauge of **5 ft (1,524 mm, today 1,520 mm)**, wider than the standard 4 ft 8½ in. (1 point each.)

6. The earthen **Gatun Dam** across the Chagres created **Gatun Lake**, about **26 m (85 ft)** above sea level. Ships climb three steps at Gatun, cross the lake and the Culebra Cut, and descend at Pedro Miguel and Miraflores. Water flows from the higher level through large culverts in the walls and floor into the chamber **by gravity alone**, with no pumps. The rain that flooded the French works now fills the lake that lifts the ships.
7. $\Delta\lambda = 87.6^\circ - 77.0^\circ = 10.6^\circ$; $\times 4 \text{ min} = 42.4 \text{ min}$. Chicago is west, so behind: $12:00 - 0:42 \approx$ **11:18 a.m.** Instantly crossing longitudes showed that every town's clock differed; telegraphed time signals helped railroads adopt **standard time zones** in 1883.
8. A **battery** pushes current through the **key** (a spring switch); pressing it sends current along a single **line wire** on poles to an **electromagnet** at the far station, which pulls an iron lever down with a click; the current returns through the **earth**, so one wire suffices. Short and long presses make dots and dashes of **Morse code**; **relays** renew weak current on long lines. It separated **communication from transportation**: words now moved almost instantly while goods and people still moved at the speed of trains and ships.
9. (a) Length ratio $2,000 \div 400 = 5$; smearing ratio $5^2 =$ **25 times**.
(b) $120 \div 0.1 = 1,200 \text{ min} =$ **20 hours**; $120 \div 8 =$ **15 minutes** (80 times faster).
(c) They built a heavier cable with a thicker copper core and more and better gutta-percha insulation, tested it constantly, signaled carefully, and used very sensitive receivers such as Thomson's mirror galvanometer; and the *Great Eastern* carried the whole cable, so no mid-ocean splice was needed.
10. Ireland is the westernmost large piece of Europe and Newfoundland juts far east from North America, so together they give the shortest open-ocean crossing (about 1,655 nm, 3,070 km, 1,905 mi). The route crossed what Maury called the fairly even "Telegraph Plateau" (really the northern part of the Mid-Atlantic Ridge, then poorly sounded), and Heart's Content offered a sheltered harbor on deep Trinity Bay. The route is close to a **great circle**, the shortest path on a globe, which appears on most flat maps as a curve bending toward the pole.
11. Westbound: $160 - 40 = 120 \text{ mph}$; $1,200 \div 120 =$ **10 h**. Eastbound: $160 + 40 = 200 \text{ mph}$; $1,200 \div 200 =$ **6 h**. Round trip **16 h** versus $2,400 \div 160 =$ **15 h** on a calm day. The wind costs more against than it gives with, because more time is spent flying into it.
12. (a) Twisting the wingtips in opposite directions so one wing gains lift and the other loses it, letting the pilot bank and steer; it solved **control**, the missing piece of flight. (b) The U.S. Weather Bureau showed it had steady strong winds; it also offered soft sand for landings and privacy. (c) An airliner first flown December 17, 1935, carrying 21 passengers at about 180 mph with a range of about 1,500 miles; the first airliner that could profit from passengers alone, crossing the U.S. in about 15–17 hours with stops. (1 point each.)
13. (a) 1° of longitude at $50^\circ \text{ N} = 111.2 \times \cos 50^\circ = 111.2 \times 0.6428 = 71.5 \text{ km}$; $\times 100 =$ **7,148 km (4,443 mi)**.
(b) $\cos d = \sin^2 50^\circ + \cos^2 50^\circ \cos 100^\circ = 0.5868 + 0.4132 \times (-0.1736) = 0.5868 - 0.0717 = 0.5151$; $d =$ **59.0°**; $59.0 \times 111.2 =$ **6,561 km (4,078 mi)**.
(c) Saving $\approx$ **587 km (365 mi)**, about **8.2%**. The great circle bends toward the pole.
14. Eastbound: $880 + 120 = 1,000 \text{ km/h}$; $5,570 \div 1,000 =$ **5.57 h $\approx$ 5 h 34 min**.
Westbound: $880 - 120 = 760 \text{ km/h}$; $5,570 \div 760 =$ **7.33 h $\approx$ 7 h 20 min**.
Eastbound is faster (by about 1 h 46 min) because the jet stream blows from west to east in the middle latitudes; planners route to ride it eastbound and avoid its core westbound.
15. The **great circle** between the two cities bends far north over Greenland and the Canadian Arctic; on a globe, Europe, North America and Asia ring a small Arctic Ocean, so the polar

route is shorter. Near the north magnetic pole the compass swings wildly, and near the geographic pole meridians converge so true north changes direction quickly; navigators used **grid navigation** with a gyroscope checked by a sky compass, plus gnomonic charts and celestial navigation. Anchorage lay on the great circles between Europe or North America and East Asia; during the Cold War Western airlines generally could not cross Siberia, so Europe–Japan flights refueled there; later it became a great cargo airport.

16. (a) $2,200 \times 2 + 1,500 = \mathbf{5,900 \text{ TEU}}$.
 (b) $4 \times 30 = 120 \text{ moves/h}$; $3,600 \div 120 = \mathbf{30 \text{ hours}}$.
 (c) Break-bulk $1,500 \times \$5.86 = \mathbf{\$8,790}$; container $1,500 \times \$0.16 = \mathbf{\$240}$; saving $\$8,550 = \mathbf{97.3\%}$ (about 37 times cheaper).
17. The old finger piers sat on crowded streets with no room to stack thousands of boxes or bring in trucks and trains. In 1962 the Port Authority opened a container terminal at Elizabeth, New Jersey, beside Port Newark, with acres of flat land, highway and rail links and a dredged channel; within decades almost all of New York's cargo moved through New Jersey. New ports needed deep water, flat land for stacking and fast inland connections. Thousands of longshoremen whose families had worked the docks for generations lost their jobs, and the Manhattan and Brooklyn waterfronts emptied (similar shifts: Oakland over San Francisco, Felixstowe over London).
18. (a) $r = 6,771 \text{ km}$; circumference $= 2\pi \times 6,771 \approx 42,540 \text{ km}$; time $= 92.6 \times 60 = 5,556 \text{ s}$; speed $\approx \mathbf{7.66 \text{ km/s} \approx 27,600 \text{ km/h} \approx 17,100 \text{ mph}}$.
 (b) $1,440 \div 92.6 \approx \mathbf{15.6 \text{ orbits}}$ a day.
 (c) $92.6 \div 60 = 1.543 \text{ h} \times 15^\circ/\text{h} \approx \mathbf{23.1^\circ}$ west per orbit $\approx 2,570 \text{ km}$ (1,600 mi) at the equator.
19. (a) The first artificial satellite, launched by the Soviet Union on **October 4, 1957**, from near Tyuratam on an R-7 missile; a nation that could orbit a satellite could send a warhead anywhere, so the oceans no longer sheltered America. (b) The first U.S. satellite, launched January 31, 1958; James Van Allen's Geiger counter found the radiation belts around the earth. (c) Guier and Weiffenbach used the **Doppler** shift of Sputnik's signal to calculate its orbit; McClure reversed the idea so a listener who knew the satellite's orbit could find his own position; the Navy built Transit (first success 1960, service 1964, merchant ships from 1967), the forerunner of GPS. (1 point each.)
20. (a) $22,500 \div 299,792 \approx \mathbf{0.075 \text{ s (75 ms)}}$.
 (b) Light travels about 300 m per microsecond: $2 \times 300 = \mathbf{600 \text{ m (about 1,970 ft)}}$.
 (c) The receiver has four unknowns: east-west, north-south and up-down position, plus its own cheap clock's error. Four unknowns require four distance measurements, solved together; three spheres alone would give a position only if the receiver had a perfect clock.
21. From A: $x^2 + y^2 = 169$. From B: $(x - 10)^2 + y^2 = 169$. Subtracting: $-20x + 100 = 0$, so $x = 5$; then $y^2 = 144$, $y = \pm 12$. Candidates (5, 12) and (5, -12).
 Check C: (5, 12) is $\sqrt{(15^2 + 0^2)} = 15 \text{ km} \checkmark$; (5, -12) is $\sqrt{(15^2 + 24^2)} = \sqrt{801} \approx 28.3 \text{ km} \times$.
 Position: **(5, 12)**, 5 km east and 12 km north of A. This is **trilateration**, because the position comes from distances, not angles.
22. (a) $10,850 \div 200,000 = \mathbf{54 \text{ ms}}$. Real route: $14,000 \div 200,000 = \mathbf{70 \text{ ms}}$ one way, **140 ms** round trip. Satellite: $71,600 \div 299,792 \approx \mathbf{239 \text{ ms}}$ one way, over three times the real cable even though light is slower in glass.
 (b) $60 \times 0.2 = 12 \text{ dB}$; $10^{(-1.2)} \approx \mathbf{0.063}$, **about 6.3%**.
23. They run through the Mediterranean, cross Egypt by land to the Red Sea, pass the Bab-el-Mandeb, cross the Indian Ocean and squeeze through the Strait of Malacca to Singapore, the same path as steamships and the telegraph after Suez; in East Asia many pass the Luzon Strait. Where routes narrow, cables crowd together; the December 26, 2006, earthquake off southern Taiwan set off landslides that broke several cables in the Luzon Strait and slowed

traffic across East Asia for weeks. Most breaks (well over a hundred a year) are caused by fishing gear and ships' anchors near shore.

24. Extra distance 3,400 nm = **6,300 km = 3,910 mi**. Per day: $12 \times 24 = 288$ nm; $3,400 \div 288 = \mathbf{11.8 \text{ days}}$. Fuel: $11.8 \times 60 \approx \mathbf{708 \text{ tonnes}}$, plus extra crew wages.
25. (a) Primary: the journal, the Act, the photograph; secondary: the 2005 history. (b) **(ii)**, because it is one arguable claim a reasonable person could dispute, with evidence named; (i) is too vague to argue. (c) What problem did geography pose? How did the technology solve it? What did it cost? What changed in the world? (1 point each part.)
26. **Grading points (8):** clear, arguable thesis (1); at least two specific, accurate examples of geography overcome (3), e.g., the chronometer and Greenwich grid; Suez cutting London-Bombay 41%; Panama saving 7,800 nm; the telegraph and 1866 cable turning ten days into minutes; jets and polar routes; the container cutting loading costs about 97%; GPS answering "where am I?"; fiber carrying data at near light speed; at least one specific, accurate limit (2), e.g., the *Ever Given* blocking Suez for six days (2021); choke points such as Hormuz and Malacca; the 2023 Gatun Lake drought; Eyjafjallajökull ash closing European airspace (2010); the jet stream; railway grades and the Darién Gap; the speed of light (at least 54 ms New York-Tokyo); the gravity model; balanced conclusion (2).

Model answer (summary): Technology has overcome geography as a *barrier* to an astonishing degree, especially for words and information, but not as a *force*. Each success worked with geography (sails with wind, canals with rivers and rain, routes along great circles, satellites by the laws of orbit) and often made the world more dependent on a few narrow places. The best conclusion: geography has been tamed in cost and time but still sets the routes and the limits.

27. **Grading points (8):** thesis that chooses and defends a position (1); telegraph/cable evidence (2), e.g., May 24, 1844 "What hath God wrought!"; the 1861 line ending the Pony Express; the Associated Press (1846); 1866 cable at about 8 words a minute versus about 10 days by steamer; Liverpool and New York cotton and grain traders seeing each other's prices the same day; London as center of a world network; container evidence (2), e.g., *Ideal X* (April 26, 1956); loading cost from about \$5.86 to \$0.16 a ton; turnaround from a week to a day or two; standard sizes and free twist-lock patents; ships over 24,000 TEU; factories located wherever skills and materials are best; costs on at least one side (1), e.g., early cable messages were very expensive; lost dock jobs in older ports; dependence on a few ports and straits; fair weighing and conclusion (2).

Model answer (summary): Either answer can earn full credit. The telegraph changed trade first by making information instant, letting markets and governments act across oceans the same day; the container changed it more in volume by making the cost of moving goods a tiny part of their price. A strong answer might conclude that the telegraph created a world market in information and the container a world market in goods, with the container doing more to rearrange where things are made, at the cost of jobs in older ports and greater dependence on choke points.