Navigating the Ocean

Cold are the feet and forehead of the earth,
Temperate his bosom and his knees,
But huge and hot the midriff of his girth,
Where heaves the laughter of the belted seas,
Where rolls the heavy thunder of his mirth
Around the still unstirred Hesperides.

The Belted Seas, Arthur Colton
Lesson Objectives | Performance Tasks
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To explain how the speed of boats is affected by the basin in which they move | Create and conduct an experiment that measures the speed of a boat and analyze factors that impact the speed of boats on water.
To describe how early mariners navigated the open ocean using speed and direction | Describe how speed and direction were measured by early mariners.
To track Columbus’s first voyage to America | Manipulate and collect data from a visualizer that uses Columbus’s observed speeds and headings and accounts for magnetic declination and surface currents.
To describe the role of ocean explorers in gathering scientific information | Search captain William Bligh’s journal for his magnetic variation measurements and compare them to a computer model.

Materials:  
Student Guide (PDF file)  
Internet access  
10-foot long rain gutter, Fishing line  
3-gram weight (nickel or penny)  
2 pulleys, Ring stands with clamps  
Stopwatch and a Small Boat

Time: 80 minutes
Grade Level: high school
Courses Supported: Earth Science, History, Math, Physics

Glossary:  
astrolabe, controls, data, dead reckoning, dynamics, fluid, hypothesis, independent variable, laminar flow, latitude, longitude, magnetic declination, model

Introduction: How did they do that?

Historians believe that Pacific Islanders explored the entire South Pacific region well before the era of recorded history. Around 2500 B.C., historians speculate, Southeast Asians began to migrate throughout the Pacific. Their 30.5 meter long canoes, shown on the left, were navigated by men who were taught from childhood to decipher nautical information including; star positions, ocean currents, wave echoes, prevailing winds, and the habits of migratory birds. More than 1300 years ago, Polynesian explorers set out from Havai‘i (now Raiatea, in the Society islands) in great double-hulled canoes to cross the vast unknown expanse of the North Pacific Ocean. By chance, they discovered and subsequently colonized, the Hawaiian Islands. A long canoe voyage across the uncharted ocean must have required an exceptional degree of navigational skill. By observing the stars, winds and currents, ancient navigators could approximate their geographic position.

Ocean surface currents have played an important role in navigation from ancient times, through the exploration of the world by sail to present day. Today, most ships are propeller-driven and less dependent on the winds, but all ships benefit significantly when carried by ocean surface currents.

In Lesson 1, students will read about an experiment designed by Benjamin Franklin to discover factors that effect the speed of a boat and then design a similar experiment of their own. Students will also learn how Columbus sailed to the new world using tools such as a compass, an astrolabe, an hourglass, maps, and charts, dead reckoning, winds and currents. Students will read Captain William Bligh’s journal and find out how he survived after the mutiny on his ship the Bounty, set asea, in a small boat, near Tahiti without any instruments.
**Engage: Preconceptions Survey, “What do you know?”**

Students are asked to take an online survey consisting of eight questions. When they submit their responses online, a pop-up window appears that shows the correct response to each question and provides additional, clarifying information. All eight questions, the correct responses, and additional information are provided below.

Engagement activities such as this one are typically not graded. Student responses to this survey will help determine how much accurate information they already know about seafaring.

<table>
<thead>
<tr>
<th>True or False</th>
<th>Statement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 False</td>
<td>A westerly wind blows towards the west. <em>Winds are named according to the direction from which they blow. A westerly wind blows from the west in an eastward direction.</em></td>
</tr>
<tr>
<td>2 True</td>
<td>A compass is a magnet that can freely rotate. <em>A compass is a magnet balanced on a pivot with ends labeled N and S. The N end is the north-seeking pole of the magnet and it points towards Earth’s north magnetic pole. The pole is near, but not at, the north geographic pole. The geographic pole is along the Earth’s axis of rotation.</em></td>
</tr>
<tr>
<td>3 False</td>
<td>A compass points to the north geographic pole. <em>A compass points towards the Earth’s magnetic poles, which do not generally coincide with the Earth’s geographic poles, which are along the Earth’s axis of rotation.</em></td>
</tr>
<tr>
<td>4 False</td>
<td>Chicago and New Orleans are at a very similar latitude but very different longitude. <em>Latitude measures how far north or south you are relative to the Equator. Longitude measures how far east or west you are relative to Greenwich England. Philadelphia, Pennsylvania, and Lima, Per, are approximately equally distant west from Greenwich.</em></td>
</tr>
<tr>
<td>5 True</td>
<td>Tokyo and San Francisco are at a very similar latitude but very different longitude. <em>Latitude measures how far north or south you are relative to the Equator. Longitude measures how far east or west you are relative to Greenwich England. San Francisco and Tokyo are at an approximately equal distance north of the Equator.</em></td>
</tr>
<tr>
<td>6 False</td>
<td>Philadelphia, Pennsylvania, and Lima, Peru, are at a very similar latitude but very different longitude. <em>Latitude measures how far north or south you are relative to the Equator. Longitude measures how far east or west you are relative to Greenwich England. Philadelphia, Pennsylvania, and Lima, Peru, are approximately equally distant west from Greenwich.</em></td>
</tr>
<tr>
<td>7 False</td>
<td>Solar noon at your location is the time when your local time is 12:00 (between 11AM and 1PM). <em>Solar noon is the time when the sun appears highest in the sky above the horizon. Local time of 12:00 noon is not set by the sun but by time zone boundaries.</em></td>
</tr>
<tr>
<td>8 False</td>
<td>Sailing ships always sailed in the same direction as ocean surface water currents. <em>Sailing ships used the wind in their sails to move downwind or upwind. They did not always follow ocean currents. Currents would speed their journey so they would try to find favorable currents for long voyages.</em></td>
</tr>
</tbody>
</table>

| Overall Score (%) | 100 |

Ocean Motion | Teacher Guide | Lesson 1
Explore: A Basin Model
How does water depth affect the speed of canal boats?

Benjamin Franklin (1706 – 1790), one of the most prominent of America’s Founders, was noted for his curiosity, writings, ingenuity and diversity of interests, one of which was science and technology. On May 10, 1768, he wrote a letter (link to letter) to his friend Sir John Pringle, (1707 - 1782) a Scottish physician who was elected president of the Royal Society in November 1772. In that letter, Franklin recalled a trip that Pringle made from Holland.

“...you remarked, that the trackschuyl—a covered boat for goods and passengers, used in Dutch and Flemish canals—in one of the stages went slower than usual, and inquired of the boatman, what might be the reason; who answered, that it had been a dry season, and the water in the canal was low. On being again asked if it was so low as that the boat touched the muddy bottom; he said, no, not so low as that, but so low as to make it harder for the horse to draw the boat. We neither of us at first could conceive that if there was water enough for the boat to swim clear of the bottom, its being deeper would make any difference; but as the man affirmed it seriously as a thing well known among them...

After our return to England, as often as I happened to be on the Thames, I inquired of our watermen whether they were sensible of any difference in rowing over shallow or deep water. I found them all agreeing in the fact, that there was a very great difference, but they differed widely in expressing the quantity and difference...

...As I did not recollect to have met with any mention of this matter in our philosophical books, and conceiving that if the difference should really be great, it might be an object of consideration in the many projects now on foot for digging new navigable canals in this island, ...”

In 1768, Benjamin Franklin designed an experiment to find out if canal depth affected the speed of canal boats. Read his letter to Pringle to determine the design of his experiment, the materials he used, his setup and his results. In the following investigation, you will design an experiment to answer the question Franklin asked more than 200 years ago: “How does depth of water affect the speed of a boat?”

In a well-designed experiment you should:

• Ask a question that can be answered by conducting an experiment and that reflects background research and previous observations.

• State a hypothesis that has been developed directly from the question and is expertly expressed in “if-then” statement(s).

• Describe a procedure that is detailed, complete, and follows a logical step-by-step order.

• Include a list of all necessary materials.

• Use proper controls and test for the effects of only one independent variable at a time.

• Explain how collected data will be organized and displayed in appropriate graphic formats.

• Use appropriate statistical methods to manipulate the data.

• Present conclusions that are supported by the data in clear, complete statements...
Before you begin developing your experiment think about the following:

How did Franklin measure time during his model canal trials? As outlined in the letter to Pringle, what is his unit of time? Is his method a good example to follow? How would you measure time accurately in your investigation?

*His clock had no hand to measure seconds. He counted rapidly from 1 to 10 and used his fingers to keep track of the how many 10-counts were made. He created his own unit of time—the time required to count each number from 1 to 10.*

*His measurements would be hard to replicate because his unit of time depends on how fast Ben Franklin counted numbers. Most people, using his method, could be easily influenced to count slightly faster or slightly slower to make results come out as expected. Science relies on experimenters making unbiased measurements that can be repeated by other scientists. So Franklin’s data would be seen as questionable by today’s standards.*

Suggest a possible hypothesis to explain why canal boats would be more difficult to propel in a shallow-water canal as opposed to deep-water canal.

*As a boat moves along, its submerged hull, to some extent, drags along the water that is in contact with the surface. Nearby layers of water below will be pushed along by the movement of this layer. If the boat is in deep water then the water layers nearby are free to move and the boat feels little resistance. If the boat is in shallow water, then the moving layers of water near the boat hull will feel the drag of the static (not moving) water layers at the bottom of the canal or river.*

Shown below is an example of the equipment setup for the experiment. This setup consists of a 10-foot long rain-gutter purchased from the local hardware store to approximate the canal. Nylon fishing line is attached to the boat and to a 3-gram weight (Franklin used a coin as a weight; a penny or nickel may work for your equipment). Two pulleys (one at the end of the gutter and one attached on the ceiling) are positioned to allow the weight to pull the trial boat as the weight falls from the ceiling. The purpose of the falling weight is to apply a steady, small force to the trial boat. Like Franklin, you can measure the time it takes the weight to fall (or the time for the boat to move a fixed distance), which is inversely related to the average speed of your trial boat.

*Rain-gutter in fixed position  Pulley at end of rain-gutter  Ceiling Pulley*

*Note: Take care to keep the pulley at the end of the gutter at a fixed height above the water level. The experiment variable should be the water level, not the pulling angle. A study of how the trial boat speed varies with the pulling angle is another interesting investigation.*
Create and conduct your well-designed experiment.  
*The “Performance List” at the end of this lesson may be used to evaluate this section.*

1. What is the question you will test in your experiment?  
2. What is your hypothesis?  
3. What is your experimental design? Include materials you will use, setup of materials, and list of independent variable(s), dependent variable(s), control(s), and procedure.  
4. Create a table to record data collected.  
5. How will you manipulate your data for analysis to arrive at a conclusion?  
6. Put all your thinking and preparation to action. It is time to conduct your experiment.

**Elaborate: Modeling Fluid Dynamics**

*What are the difficulties in modeling fluid dynamics?*

Scale is another consideration with Franklin's physical model. Suppose you have the 10 x 10 squares shown below and you reduce the sides by a factor of 10 to make a 1/10-scale model. Draw, to the right of the 10 x 10 model, the area of a 1/10-scale model.

```
  10 x 10 model

  1/10-scale model
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*The area of the original will be reduced by 100 when it becomes the scale model!*  

7. To build a small model that actually performs like the real object, it is not enough to build an accurate scale model that reduces every dimension of the original by a fixed scale factor. Reduce all dimensions of an old sailing ship by 100 to determine how to build a model to accurate scale.

- a length of 1 meter would become ____1/100 or .01____ meters
- a sail area of 1 meter$^2$ would become ____1/10000 or .0001____ meter$^2$
- a boat volume of 1 meter$^3$ would become ____1/1000000 or .000001____ meter$^3$
- a boat speed of 2 knots = 1 meter per second (m/s) would become ____1/100 or .01____ meters/sec

The dynamic performance of a boat depends on these sizes. Lengths (dimensions) of the boat relate to its stability in open water. Areas relate to forces affecting the ship (wind on the sail surface, water viscosity on the hull surface) and the strength of materials (a thick, strong mast has a large cross section area). Volume relates to the mass of the boat moving on the water and the mass of water that the hull displaces.

8. Using these simple measures of boat performance (not considering fluid scaling effects for air and water), determine if the ratios of these measures would stay the same as you scale the model down so that all the dynamic effects stay properly balanced. Compute the following ratios and judge if the scaled model maintains the same proportions:
9. Does the scaled model maintain the same proportions as those of the original ship? 

No, the proportions are greatly changed. Because these proportions are different, the accurately replicated scaled copy of the old sailing ship will not respond the same as the original under wind and wave conditions. This means that data collected and lessons learned in scale model experiments cannot be readily applied to the full-scale object.

Boat scaling and fluid behavior scaling must be considered to design an accurate test. Much scientific progress has been made to learn how the performance of models in fluids scales with size. Unlike instruments, structures or vehicles that can be built, tested and reworked on land, failure in ships, airplanes and spacecraft is frequently catastrophic: ships sink; aircraft crash; and spacecraft miss their target. Both scale and computer model tests must be used to evaluate a new design before committing to large-scale construction. The need for scale modeling in fluid dynamics is complicated by the dominance of turbulent (disordered) flow in fluid motion problem.

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Original Ship Dimensions</th>
<th>1/100 Scale Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length/Area</td>
<td>1/1 = 1</td>
<td>(1/100)/(1/10000) = 100</td>
</tr>
<tr>
<td>Area/Volume</td>
<td>1/1 = 1</td>
<td>(1/10000)/(1/1000000) = 100</td>
</tr>
<tr>
<td>Volume/Speed</td>
<td>1/1 = 1</td>
<td>(1/10000000000)/(1/100) = 0.0001</td>
</tr>
</tbody>
</table>

Clipper Ship GREAT REPUBLIC, built 1853, East Boston, Massachusetts. Painted by J.E. Buttersworth

10. Turn on a faucet slightly and observe the water flow. Then gradually increase the water flow and note the differences compared with the low water flow. 

At low flow, the water is clear and flow seems uniform from the faucet. As the flow increases, it is more turbulent and much less uniform.

Fluids in slow motion generally follow laminar flow with all parts of the fluid moving on similar trajectories. As speed increases, fluid motion becomes more turbulent with complex swirling patterns dominating the motion. Scientists have had little success in accurately predicting the behaviors of turbulent fluids. For scale modeling to work, one needs to know the scaling rules for turbulent fluids.

While the behavior of trial boats in the gutter may be interesting (and sometimes exciting) to watch, it is not easy to apply the model results to real canal boats or boats on the open ocean. The gutters have smooth sides that are nearly perpendicular to the water surface. On some canals, the sides may be gently sloping and covered with vegetation.

11. How might the shape and surface of the sides affect waves in the gutter? How might the waves affect boat motion?

The steep, flat, solid sides will easily reflect waves. Vegetation and sloping sides would act to dampen or diminish reflected waves. Waves would cause random up and down movements that would tend to waste energy and slow the boat.
Explore: Dead Reckoning
How can one navigate—determine location—on the open ocean?

When not using the stars, sun or moon to determine their location, sailors and explorers navigated by deduced (or dead) reckoning. This was the method used by Columbus and most other sailors of his era. In dead reckoning, the navigator finds his position by measuring the course and distance he has sailed from some known point. Starting from a known point, the navigator measures out his course and distance from that point on a chart, pricking the chart with a pin to mark the new position. Each day’s ending position would be the starting point for the next day’s course-and-distance measurement. For this method to work the navigator needed a way to measure his course and to measure the distance sailed. Course was measured by a magnetic compass, which had been known in Europe since at least 1183.

Distance was determined by a time and speed calculation: the navigator multiplied the speed of the vessel by the time traveled to get the distance. (http://www1.minn.net/~keithp/)

12. To determine speed on old sailing boats, sailors often used a log line. Link to Navigation Log Line. Describe how a log line was used and draw what a log line looked like. A flat board was weighted along one edge to cause the edge to sink in water, and it was tied at its corners so that one of its flat sides would always face the ship when the rope was under tension. Knots were tied in the rope at regular intervals of about 40-50 feet to facilitate speed measurement. The flat board was necessary to maximize water “drag” or friction so that the board would remain stationary in the water after it was tossed overboard. Sailors would measure the speed of the ship using the count of knots in the rope unrolled from the spool in 30 seconds. Knowing speed, one can easily compute the distance traveled using the equation:

\[ \text{Distance} = \text{Speed} \times \text{Time} \]

The fundamental flaw in using this log line method to determine distance is that it does not account for the effects of surface currents. The log line method measures the speed of the ship relative to the surface water. It provides no means to estimate the speed of flow of the water itself. If a boat is carried westward by a strong current, the log line method will not reveal the existence of the current. If you travel steadily on a train along a straight track, you will be barely aware that you are in motion relative to the tracks. This fact is related to Newton’s First Law of Motion, which states that steady motion in a straight line is “natural” and undetectable without reference to an outside reference object.
13. How do you think a speedometer on a car measures speed? Are there any circumstances that might cause this measurement to be incorrect and not reveal the "true" speed of the car? The car speedometer may count how many times the wheels go around per second and may use this count to estimate the speed. If the wheels have a larger or smaller radius than the manufacturer recommends then the speed would be wrongly estimated. The speed during a skid would not be measured.

To determine their direction of travel, sailors used the compass. The compass is a magnet with ends labeled N and S. The N end points to the north magnetic pole of the Earth. This pole is situated in northern Canada and does not coincide with the north geographic pole (the "North Pole"). The north lies along the Earth’s axis of rotation and points in the direction of Polaris, the North Star.

14. Click the link to "Magnetic Declination" and write a definition. Include a drawing that shows the difference between geographic north and magnetic north. Magnetic declination, sometimes called magnetic variation, is the angle between magnetic north and true north. Declination is considered positive when east of true north and negative when west.

To plot their track on a map, sailors would observe the heading or direction of travel of their ship then compare this to the magnetic North direction revealed by a compass. Sailors were aware of the magnetic declination (sometimes described as magnetic variation by sailors) problem and tried to map magnetic declinations around the globe. North as measured by the compass would typically be wrong by several degrees; this variation depended on location and it changed over decades and centuries of time.

15. You may be accustomed to using deduced reckoning when you travel from one place to another. For example, suppose you are in a car or train and judge that you are “30 minutes from downtown.” What simple assumptions does this make about your travel? You are assuming that your travel will proceed at the normal pace and that no unusual or unforeseen events will delay or hasten your arrival.

To practice and test your skills of measurement and deduced reckoning, try conducting a closed loop survey activity. This activity can be done on a small desktop, as well as out of doors. Making measurements of your travels in a closed loop, where you end up at the point where you started provides a simple check of navigation methods. If you come back to the same point, your measurements should determine a path that draws a closed loop.

Sailors knew that surface currents affected the accuracy of their navigation predictions. They would call the difference between their deduced and astronomically determined positions ship drift. Astronomical determination of positions on Earth using the Sun and the stars is possible because the stars appear fixed and the Sun follows a cyclical, predictable motion. The measured differences between positions determined by dead reckoning and astronomical methods provided the earliest estimates of ocean surface currents.
Elaborate: The Astronomical Fix
How can you determine where you are located?

The stars, moon, and Sun provide reference points necessary to determine position accurately. As Earth rotates, the astronomical objects seem to follow a path in the sky. The time they reach determined positions may be used to determine your longitude and latitude on Earth.

Our Earth is a sphere, and angles are used to specify the location of sites on the surface of the Earth. In the east-west direction, one measures longitude with 0° set at Greenwich, England. Moving westward (towards America), longitude angles are negative: between -180° and 0°. Moving eastward (towards Europe, the Middle East and Russia), longitude angles are positive: between 0° and +180°.

In the north-south direction, one measures latitude with 0° set at the equator of Earth. Northward (towards the North Pole), positive latitude angles are between 0° and 90°. Southward (towards the South Pole), negative latitude angles are between -90° and 0°.

Over the course of 24 hours, Earth rotates through 360 degrees, and the stars appear to rotate in the opposite direction. The positions of the stars, moon, and Sun in the sky at any specific time will depend on your location on the surface of the Earth. By making careful measurements of astronomical object positions and the times, you can find your latitude and longitude. This is called an "astronomical fix" for your position. The easiest to determine are the positions and times when the astronomical bodies pass overhead or reach their highest elevation above the horizon for the day or night. Solar noon is when the Sun is highest in the sky at a location, on a clear day, the time of solar noon may be easily determined. As an activity, measurements of the Sun around solar noon may be used to determine your longitude and latitude.
In celestial navigation, the navigator observes celestial bodies (Sun, Moon and stars) to measure latitude. (In Columbus's day, it was usually impossible to measure your longitude.) Even in ancient times, it was fairly easy to find your latitude by looking at the Sun and stars, as long as you weren't too concerned about accuracy. Each star has a celestial latitude or declination. Knowing the declination of a star that is directly overhead enables you to know your latitude on earth. Even if a star isn't directly overhead, by measuring the angle between the star and the overhead point (called the zenith), you can still determine your latitude — provided you measure the star at the time of night when the star is highest in the sky. (http://www1.minn.net/~keithp/)

Use Table 1 (below) to attempt a re-creation of Columbus's travels with the Voyager model. To make the re-creation as accurate possible, this model provides three tools: ocean current data, a historical model of the Earth’s magnetic field, and physics kinematic equations to trace a ship’s movements. Because the ocean currents of Columbus’s time are unknown, this model uses monthly surface current data based on ship drift observations made mostly in the 20th century. Observed current fluctuations (i.e., the “Variable Current” in the model) are simulated with random numbers. This model does not simulate the effect of winds. Rather, it uses speeds measured by Columbus and his crew. These log-line speeds reflect both the wind conditions and the way the ship was being sailed.

To determine his direction (or heading), Columbus relied on a compass, and his readings were not corrected for the difference between magnetic north and the geographic north. Voyager includes a magnetic model that predicts Earth’s magnetic field on Earth’s surface between 5000 BC and 1950 AD.

Historical records provide navigation details about the voyages of Columbus (1, 2). Table 1 is based on Columbus’s record of his first voyage to the Americas. Values have been adapted and simplified from the website of Keith A. Pickering

16. Begin a simulation of Columbus’s voyage by manipulating the Voyager model and record the values for longitude and latitude for 34 days in 1492. On the left side of the model, you will input the following:

- Year: 1492
- Month: September
- Initial Longitude: -17.0
- Initial Latitude: -28.0
- Compass Heading
- Log Line Speed (meters/second) as indicated in Table I for each of the days.
- After putting in the data for the first day, click the Start button.
- For each following day, enter the compass heading and logline speed from the table and click continue.
The columns on the right side of the model control panel show, current, longitude and latitude at the day’s end and magnetic field information. The magnetic variation is labeled as the “magnetic field declination”. Record the final longitude and latitude values in Table 1.

<table>
<thead>
<tr>
<th>1st Column</th>
<th>Compass Heading</th>
<th>Speed (m/s)</th>
<th>Final Long, Lat</th>
<th>2nd Column</th>
<th>Compass Heading</th>
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<th>Final Long, Lat</th>
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<tbody>
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<td></td>
<td></td>
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<td></td>
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<td>0.92</td>
<td>-42.9, 27.2</td>
<td>Oct 8</td>
<td>247.5</td>
<td>0.66</td>
<td>-69.3, 26.3</td>
</tr>
<tr>
<td>Sep 22</td>
<td>292.5</td>
<td>2.06</td>
<td>-44.7, 27.6</td>
<td>Oct 9</td>
<td>248.2</td>
<td>1.80</td>
<td>-70.8, 25.8</td>
</tr>
<tr>
<td>Sep 23</td>
<td>315</td>
<td>1.83</td>
<td>-46.0, 28.6</td>
<td>Oct 10</td>
<td>247.5</td>
<td>3.38</td>
<td>-73.6, 24.6</td>
</tr>
<tr>
<td>Sep 24</td>
<td>270</td>
<td>0.83</td>
<td>-46.9, 28.5</td>
<td>Oct 11</td>
<td>257.7</td>
<td>2.83</td>
<td>-75.9, 23.9</td>
</tr>
</tbody>
</table>

2.67 nautical mile = 1 league; 1 nmi = 1852 meters

Final Longitude and Latitude: -73.7, 22.2
17. When you have completed recording all longitudes and latitudes, use these values and trace the simulated voyage on the map below.

Note: If you repeat the voyage or have several teams of students use the model, you will notice that the final predicted location (longitude and latitude) of the ship on October 11 varies. This variation is due to the measured uncertainty in the current data. The model deliberately simulates current fluctuations unless you turn off this feature by setting Variable Current to "No."

You may use the same model to simulate a voyage that begins from a location anywhere else on the globe. With no knowledge of the wind conditions at another site, you might set the "log line" speed to Columbus's mean speed.
**Elaborate: Voyage Speeds**

*What can we learn from Columbus’s recorded speeds?*

The mean speed of Columbus’s voyage was 1.91 m/s. This speed is as measured with a log line device and does not include ocean surface currents. Unlike today’s self-powered boats, which burn coal, gas or oil, Columbus’s boats relied on wind power. Wind power has the disadvantage that it is variable and the advantage that it is freely available even in the middle of the ocean. The figure, on the right, shows a histogram of the voyage speeds: the horizontal axis shows speed and the vertical axis the number of days at each speed. Note that Columbus’s speed varied greatly, perhaps largely a reflection of the varying wind and sailing conditions.

18. Measure your walking speed. How does your walking speed compare to Columbus’s mean speed? *Most people have walking speeds near 1 meter per second that is nearly half of Columbus’s speed on his voyage to America.*

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**Elaborate: The Voyage of the Bounty—Tracking Captain Bligh**

*What kind of information did explorers collect during their voyages?*

The famous voyage of Captain William Bligh, left, on the HMS Bounty to Tahiti provides an example in which astronomical fixes and dead reckoning played an important role in navigation. After having sailed halfway around the world, some of Bligh’s crew mutinied, putting the captain and his loyal crewmembers a sea in a small boat near Tahiti.

While on the Bounty, Captain Bligh had access to an accurate clock that kept Greenwich, England, time so that as he sailed, he could compute his longitude based on the time difference between solar noon and Greenwich time. Because the Earth rotates once (360°) in 24 hours, every degree in longitude is equivalent to a time shift of solar noon relative to Greenwich of 24 hr/360° or 4 minutes of time per degree of longitude. Bligh had to bring a clock along on his voyage to keep in time with Greenwich. Today, Greenwich time has been replaced by Universal time and we can find the current Universal time over the Internet (http://aa.usno.navy.mil/faq/docs/UT.html).

After the mutiny, Bligh and the loyal members of his crew, deprived of access to a clock, used estimates of his small sailboat’s speed and direction to estimate degrees of longitude and latitude referenced to a nearby islands and landmarks.
Use Captain Bligh’s diary from his voyage to reproduce a portion of his travels. The text of his diary is available in an interactive Bounty Log form, pictured above. Using Bligh’s words, we track a portion of his voyage and learn about his magnetic variation measurements.

Select one of the following date links. The links will produce a map on which you may plot Bligh’s voyage.

December 1787, January 1788, February 1788, March 1788, May 1788, July 1788,

August 1788, September 1788, October 1788, May 1789

Access Bligh’s diary for the month by using Select Date on the form and pressing the GO button. The diary text for the month will appear in the Text Selection area. Search through the diary text for Captain Bligh’s longitude, latitude and magnetic variation (magnetic variation is the same as magnetic declination) values. Each should be converted to decimal degrees using the Degree, Minutes, Seconds, and Converter.

For the locations where the magnetic variation is available, compare its value to the predictions of the magnetic model in Voyager Model.

20. Fill in Table 2 with your data.

<table>
<thead>
<tr>
<th>Date</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Magnetic Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Degrees (°)</td>
<td>Decimal Degrees (°)</td>
<td>Degrees (°)</td>
</tr>
<tr>
<td>April 7</td>
<td>75°, 54’ W</td>
<td>-75.9</td>
<td>60°, 24’ S</td>
</tr>
<tr>
<td>1788</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>76°, 58’ W</td>
<td>-76.97</td>
<td>59°, 31’ S</td>
</tr>
<tr>
<td>13</td>
<td>76°, 1’ W</td>
<td>-76.02</td>
<td>58°, 9’ S</td>
</tr>
<tr>
<td>21</td>
<td>70°, 7’ W</td>
<td>-70.12</td>
<td>58°, 31’ S</td>
</tr>
<tr>
<td>25</td>
<td>57°, 4’ W</td>
<td>-57.07</td>
<td>54°, 16’ S</td>
</tr>
</tbody>
</table>

Table 2 - Tracking Captain Bligh
21. During your selected month, trace Captain Bligh’s voyage on the map. Draw arrows to show his direction of travel.

22. How well do the predictions of magnetic variation match Captain Bligh’s observations? April had only one observation of magnetic variation. The model and Bligh disagree considerably for the April 7, 1788 date. The model fits magnetic data over the whole Earth and for 7 millennia. To judge the model for 1788, you would need more data both from Bligh and other sources.
### Performance Criteria

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>Assessment</th>
<th>Points</th>
<th>Self</th>
<th>Teacher</th>
<th>Other(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The question has been developed in such a way that it can be answered by conducting an experiment(s).</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>2</td>
<td>The hypothesis has been developed directly from the question and is expressed in (an) &quot;If-then&quot; statement(s).</td>
<td></td>
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</tr>
<tr>
<td>3</td>
<td>The design of the experiment tests the hypothesis.</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>4</td>
<td>The procedures follow a logical step-by-step sequence and include a list of all necessary materials.</td>
<td></td>
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</tr>
<tr>
<td>5</td>
<td>The procedures are written clearly enough so that another person could repeat this experiment.</td>
<td></td>
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<tr>
<td>6</td>
<td>The procedures show that repeated trials were done.</td>
<td></td>
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<tr>
<td>7</td>
<td>Both the dependent and independent variables have been identified.</td>
<td></td>
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<tr>
<td>8</td>
<td>The experimental design uses proper controls and tests for the effects of only one independent variable at a time.</td>
<td></td>
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</tr>
<tr>
<td>9</td>
<td>The conclusions of the experiment are written in clear and complete statements and are supported by the inferences.</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>10</td>
<td>Language is used purposefully, and the question, hypothesis, procedures, results, and conclusions are written in complete sentence.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Total**
### Evaluation: Matrix for Grading Lesson 1

**Questions 7 - 22**

<table>
<thead>
<tr>
<th>Score</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td><strong>Expert</strong> Responses show an in-depth understanding of the models and explorations used to explain the scientific concepts and processes used in the lesson. Data collection and analyses are complete and accurate. Predictions and follow through with accuracy of predictions are explained and fully supported with relevant data and examples.</td>
</tr>
<tr>
<td>3</td>
<td><strong>Proficient</strong> Responses show a solid understanding of the models and explorations used to explain scientific concepts and processes in the lesson. Data collection and analyses are mostly complete and accurate. Predictions and follow through with accuracy of predictions are explained and mostly supported with relevant data and examples.</td>
</tr>
<tr>
<td>2</td>
<td><strong>Emergent</strong> Responses show a partial understanding of the models and explorations used to explain the scientific concepts and processes in the lesson. Data collection and analyses are partially complete and sometimes accurate. Predictions and follow through with accuracy of predictions are sometimes explained and supported with relevant data and examples.</td>
</tr>
<tr>
<td>1</td>
<td><strong>Novice</strong> Responses show a very limited understanding of the models and analogies used to explain scientific concepts and processes in the lesson. Data collection and analyses are partially complete and sometimes accurate. Predictions and follow through with accuracy of predictions are not well explained and are not supported with relevant data and examples.</td>
</tr>
</tbody>
</table>