Making Waves

Wave Generation Activity: Teacher Guide

Class time: Approximately 30 to 60 minutes

Purpose: This activity uses water waves to model how gravitational waves are created and behave, and also how two light waves can interfere with each other.

Notes to the teacher: Waves on the surface of water in a clear container are most easily visible if the container is on an old-fashioned overhead transparency projector that is focused on a screen, so the ripples show up on the screen. If you only have one projector or none, students can still see the waves by setting the clear container on a dark surface and shining a flashlight at an angle at the water's surface. If you have an ELMO projector, use it to illuminate the water's surface and project the waves. The related activity "Dropping in with Gravitational Waves" by NASA's Jet Propulsion Laboratory can be used for additional background information.

Use Blackline Master 5 to help guide your students though the wave exploration.

Materials:

- Overhead transparency projector(s), ELMO projector or flashlights (in lieu of projectors and screens if those are not available)
- If using a projector: projection screens or blank walls, whiteboards or white poster boards on which to project
- Shallow clear glass baking dishes or clear plastic containers with flat bottoms (as large as possible)
- Water from a classroom sink, pitchers or beakers
- Marbles (or other small objects) to drop into the water
- Corks, Ping-Pong balls or other small objects to float in water
- Pencils
- Tape
- Stiff rulers
- Small binder clips or large paper clips
- Tuning forks (if available)
- Optional: students' cellphones to make video recordings of the ripples

Directions:

1. Help the students fill the clear containers about halfway full with water and visualize the water's surface by projecting it on a screen or by shining a flashlight across the surface.
2. Explain that waves produced on the water's surface can be a model for exploring the production of

ripples in spacetime. Explain to your students that water does not bend with gravity, as spacetime does, rather water is displaced by objects set on its surface. This model is best used for conceptualizing wave generation and interference.

3. Explain that objects disrupting the water's surface can generate waves, just as masses disrupting spacetime can generate gravitational waves.
4. Help the students understand that objects that are just sitting there create alterations in the surface (spacetime) but no ripples (gravitational waves in spacetime).
5. Guide the students to understand that objects must move around in the right ways to create ripples or gravitational waves. In this simple model, any motion will generate ripples. Under general relativity, acceleration or deceleration of a massive object is required to produce gravitational waves.
6. Let the students try many different ways of creating ripples, as outlined in Blackline Master 5. Have students observe the effects of each.
7. Help the students understand how water waves affect the relative positions of two corks or Ping-Pong balls floating on the water. (In this model, the water's surface moves and the objects will bob up and down as a wave passes.) How does this compare and contrast with how objects will move as gravitational waves pass by in spacetime. (In general relativity, the empty space between two objects can slightly expand and contract, even if the two objects stayed right where they were the entire time. See the earth oscillating in the Stephen Colbert and Brian Greene video.)
8. Guide the students to understand that the water ripples are analogous to light waves, and that two water waves can interfere with each other just as two light waves can interfere with each other. Two water waves can produce constructive and destructive interference patterns, just as two light waves can produce interference patterns in a laser interferometer.
9. When finished, have the students carefully pour the water down a sink or into containers and dry everything off.

SN
IN HIGH SCHOOLS
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1. Fill a shallow clear tank about half full with water.
2. Listen to your teacher for instructions on how you should illuminate the water so that you are able to see ripples on its surface.
3. Add a small object that floats on the water or breaks the surface of the water.
4. Define spacetime. In what ways is this a good model for spacetime?
5. What aspects of spacetime does this system not model accurately?
6. Does a stationary object generate water ripples? Does a stationary black hole create gravitational waves?
7. Describe the waves produced by a sudden event, such as a marble dropping into the water or a star exploding in space.
8. If you have a cellphone, you might use it to record video of the waves and play back the video in slow motion.
9. How do ripples affect the relative positions of two corks or Ping-Pong balls floating on the water? Compare and contrast the affect from water waves with the affect from gravitational waves in spacetime.
10. Tape three pencils together side-by-side, such that the two outer pencils stick up by the same amount and higher than the pencil in the middle. Your pencil contraption should look like a two-pronged fork.
11. Hold your pencil contraption vertically so that the outer two pencils stick down into the water and the middle pencil is not in the water. Rotate the contraption so that the outer two pencils circle each other in the water, like an eggbeater or like the two orbiting black holes in the video. Find a method that gives good rotary motion while minimizing side-to-side motion in the water. (The two outer pencil "black holes" should just orbit each other, not drift off or jitter around.)
12. Describe the waves produced by the two outer pencil "black holes" as they orbit each other at various speeds.
13. If you have a tuning fork, bang the two prongs against a table edge, or hit them with a pencil. What do the two prongs do?
14. Bang the tuning fork's prongs and stick just the tips of the prongs in the water. Describe the waves produced.

15. Do the waves from one tuning fork prong interfere with the waves from the other prong?
16. How is that similar to or different from the interference between two light waves in a laser interferometer gravitational-wave detector?
17. Lay a ruler on the end of the water tank such that half the ruler sticks out over the water like a diving board or pirate plank. Now give the end of the ruler two “snake fangs” that stick down into the water. Two small binder clips work well, with both clipped to the end of the ruler and one metal arm of each binder clip sticking down into the water. Alternatively, you could bend two large regular paper clips and attach or tape them to the end of the ruler.
18. Hold the ruler on the edge of the water tank like a diving board, gently lift the end over the water with your finger (don’t poke yourself with a paper clip), and let the ruler oscillate.
19. Describe the waves produced by the ruler with two “fangs.”
20. Describe the waves produced by the ruler if it only has one “fang.”
21. When the ruler has two fangs, do the waves from one fang interfere with the waves from the other fang?
22. What have you learned about gravitational waves from this experiment?
23. What have you learned about interferometers from this experiment?

Wave Detection Activity: Teacher Guide

Class time: Approximately 30 to 60 minutes

Purpose: In this activity, students will design, build, test and optimize a simple optical seismometer, as an analogy for a gravitational-wave detector.

Notes to the teacher: If you have plenty of time, this is a great opportunity for the students to have the freedom to create their own designs using a variety of materials and techniques with minimal guidance. If you have less time, you can guide the students toward specific design choices. For additional background information, explore this Physics Central page on Gravitational Waves from the American Physical Society.

Use Blackline Master 6 to help guide your students through the wave detection exploration.

Materials:

- Stationary stands from which to hang a pendulum. Ring stands with a protruding arm, burette clamp or ring are ideal. Music stands will also work. If necessary, pendulums could hang from camera tripods, stools, chairs or so on.
- String to hang a pendulum. If you would like to give your students more options and more time, you could also provide wires of varying stiffness, ranging from electromagnet wire to coat hanger wire.
- Scissors and/or wire cutters to cut the string or wire.
- Flat mirrors. Small classroom optical mirrors or makeup mirrors are ideal. Alternatives are anything that is very flat and very shiny. Shiny butter knives work well, as do shiny pie servers. If necessary, students could wrap aluminum foil shiny-side-out around a small piece of flat cardboard.
- Weights to weigh down the mirror as a pendulum. Metal washers, fishing weights or pennies work well.
- Small plastic bags (Ziploc snack bags, for example) to contain the weights.
- Tape. Blue painter's tape is by far the easiest to get off mirrors and silverware, but Scotch or masking tape could be used if necessary. Duct tape will leave a lot of sticky residue.
- Flashlights with a tightly focused beam. Many newer LED flashlights can be focused down to a very tight beam. Red laser pointers are also a possibility, but ensure that the students never accidentally or intentionally shine the pointer or its reflection in their or someone else's eyes. Green laser pointers are much too bright and should not be used.
- Books, small boxes or other props to position the flashlights.
- Light-colored screens, wall, poster boards or sheets on which the light can shine.
- Rulers
- Optional: students' cellphones to make video recordings of the output light signal
- Optional: clear glass or plastic sheets to shield the pendulum from air currents

Directions:

1. Students should set up the mirror as a pendulum, with the mirror approximately vertical and hanging by a string or wire from the stand (a diagram has been included in the student guide).
2. Students should set the flashlight on its side on books or other props, so that its tightly focused beam bounces off the mirror (at some angle) and hits the screen.
3. After everything settles down, the pendulum should be essentially motionless, and the light beam should essentially stay in one spot on the screen.
4. Help the students realize that small vibrations in the classroom can create small motions of the mirror, which can produce much larger and more easily detected changes in the position of the light beam on the screen.
5. Allow the students to optimize their designs to make them more or less sensitive to vibrations, for example by adjusting the length or stiffness of the string/wire, attaching weights to the hanging mirror, adjusting the angle and path length of the light beam and so on. Use the Engineering Design Process protocol by Advancement Courses for additional design support.
6. Discuss how to make the designs as sensitive as possible to vibrations of interest (such as talking close to the mirror or a light tap on the table) and how to make them as resistant as possible to other stimuli such as air currents.
7. Discuss the similarities and differences between the students' designs and a laser interferometer for detecting gravitational waves. [*In both systems, a very small wave can cause a much larger and more easily detected change in a light beam. In the students' system, there is one beam of light containing many different wavelengths, and it indicates wave vibrations by changing its position on the screen. In the LIGO gravitational wave detectors, there are two beams of laser light at the exact same wavelength, and they indicate gravitational waves when they interfere with each other in certain ways.*]

SN
IN HIGH SCHOOLS
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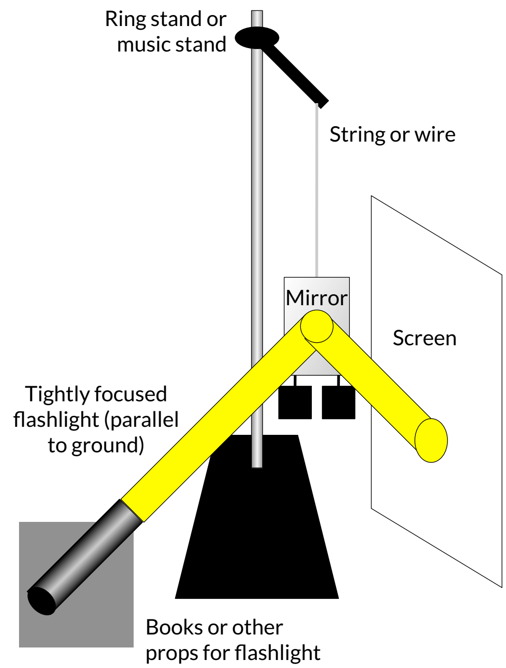
Wave Detection Activity: Student Guide

1. Set up a ring stand or music stand with an arm or surface sticking out at the top.
2. Tape or tie a string to the arm or surface sticking out at the top of the stand. Tape the bottom of the string to a mirror such that the mirror hangs vertically and is near the table surface but does not drag on the surface.
3. Make a flashlight beam as narrowly focused as possible. Put the flashlight on its side (on books or other props) such that the beam bounces off the mirror at an angle and then shines on a screen, board or white sheet.
4. Using the ruler, approximately how many millimeters does the mirror move from small vibrations, such as a tap on the table?
5. Using the ruler, approximately how far does the light beam on the screen move due to those mirror vibrations?
6. If you have a cellphone, you can use it to make videos of the motions of the mirror and/or light on the screen and play them back in slow motion.
7. Why is the light beam useful for measuring small vibrations?



8. Let the mirror come to a complete rest. Tap the table more lightly than you did the first time, can your system detect that? How sensitive is it?
9. Let the mirror come to a complete rest. If you stomp on the floor, can your system detect that? How sensitive is it?
10. Let the mirror come to a complete rest. If you talk at the mirror at close range, can your system detect that? How sensitive is it?
11. What sorts of vibrations would you like your system to detect?
12. What sorts of stimuli would you like your system not to detect?
13. How can you make your system as sensitive as possible to what you want it to detect, and as resistant as possible to other stimuli? You can:
    - Choose the surface on which your system sits
    - Adjust the length of the string

- Use wires of varying stiffness instead of string
- Try other types of mirrors
- Tape weights to your mirror
- Adjust the angles of the light beam
- Adjust the path lengths of the light beam
- Adjust the surroundings around your system
- Choose something else to modify

14. Explain your design:
15. Explain how well it worked on your selected stimuli:
16. How is your system similar to a gravitational wave detector?
17. How is your system different from a gravitational wave detector?