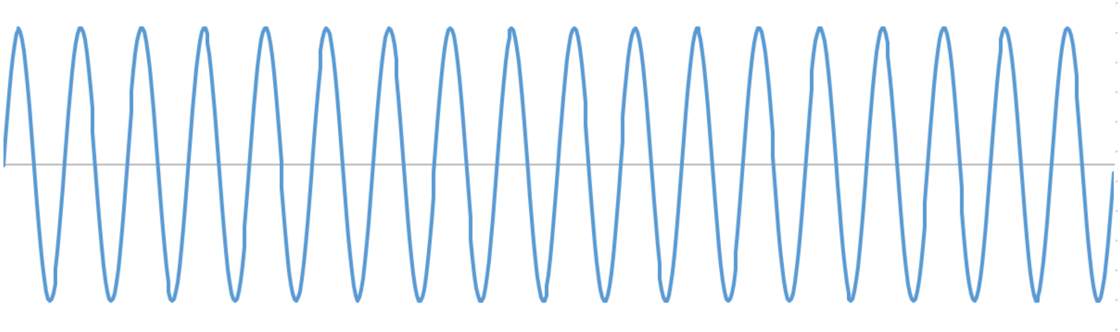
Pre-Lab: Doppler Effect

This Pre-Lab will introduce you to a physical phenomenon called the Doppler Effect. In the next two weeks' Activities, we will apply the Doppler Effect to astronomy to learn about the motions of distant objects.

Waves in one- and two-dimensions

STEP 1: Earlier we looked at waves along a one-dimensional line (the x-axis) that looked something like this:



As a review, complete the following sentences regarding the properties of a wave:

The wavelength is the distance from ___________________________________.

The frequency is the number of ___________________ per ________________.

If the above picture of a wave has a duration of one second, what is the frequency of the wave? Remember: the units for frequency are **Hertz** (Hz), which means "cycles per second".

Most waves actually travel in three dimensions. For our purposes today, though, two dimensions will suffice to understand the Doppler Effect. So let's first practice looking at waves in two dimensions, and then move on to the Doppler Effect.

At the right is a photograph showing ripples on the surface of water (like those created by tossing a stone into a pond) in which water waves are traveling outward from a central point (the **wave source**). Note that there are *alternating **peaks** (or crests) and **troughs***, just as we see in the one-dimensional wave pattern above.

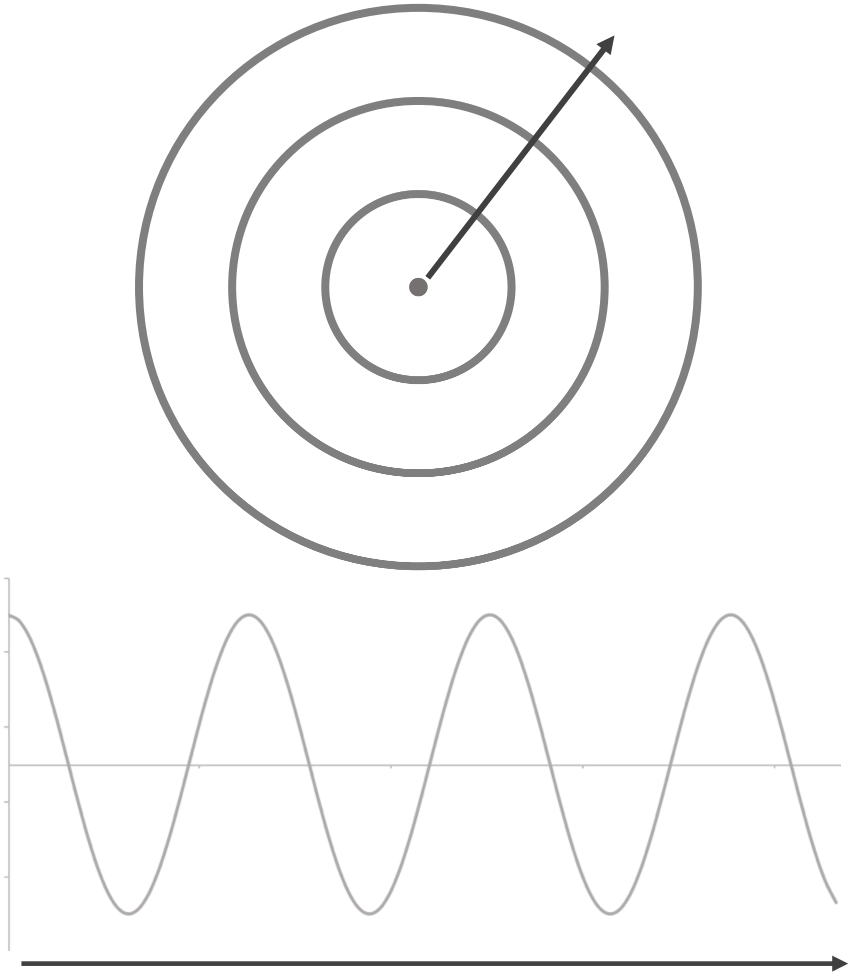
Focusing on just the crests, how would you describe the shape of the wave pattern in a few words?

From here on let's look straight down at the wave pattern from above and just draw the crests, as shown in the diagram on the next page. The wave source (e.g., the stone that dropped into the pond) is the solid dot at the center and the wave crests are drawn in concentric circles around the source.

The arrow in the diagram indicates the direction the waves are moving.

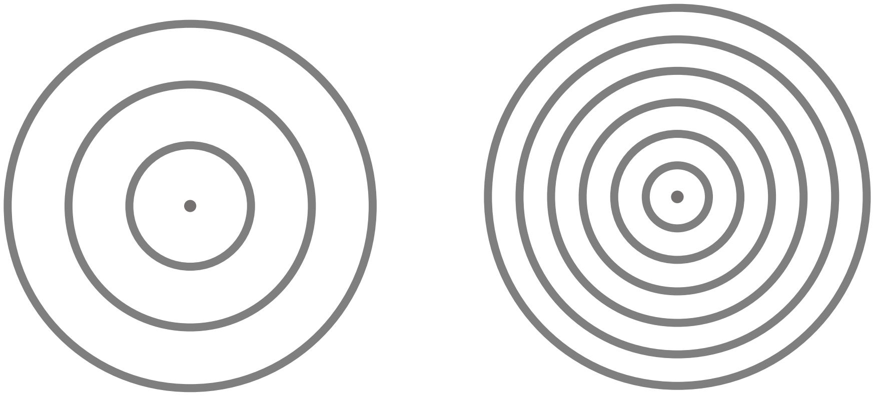
STEP 2: Correlate the peaks in the two diagrams below by drawing an arrow from each peak of the two-dimensional wave (top) to the corresponding peak of the one-dimensional wave (bottom).

> Suggested Procedure: For the 1D wave, the wave source is located at the far left, so you can immediately draw a line connecting the leftmost peak of the 1D wave to the wave source (central dot) of the 2D wave. Now work your way from left to right (on the 1D wave) and from the center to the outer edge (on the 2D wave), correlating peaks with peaks by connecting them with lines.



Although we’ve used the analogy of waves on the surface of a pond, the waves being represented by the drawing above might just as easily be sound waves or light (electromagnetic) waves emanating from a sound or light source. We’ll come back to that point later.

STEP 3: Since we’ve only drawn peaks in our 2D diagram, then the troughs must appear in the *space between circles.* On the diagrams above, draw an arrow correlating each trough on the top 2D wave to a trough on the bottom 1D wave.



STEP 4: Recalling the definition of wavelength and frequency, consider the two 2D waves above. Assuming both pictures are the same size, which of the waves has the larger wavelength? How can you tell?

Which of the above waves has the higher frequency? How can you tell?

The Doppler Effect

STEP 5: What happens to the wave pattern if the *source* of the wave is *moving*? This is the origin of the **Doppler Effect**, which we will explore now. Open the following online simulation in your web browser:

https://ophysics.com/waves11.html

Scroll all the way to the bottom of the page to find the simulation applet.

The blue dot is the wave source which will be producing sound waves (so the blue dot could be a speaker, for example, or the siren on a police car, or the horn on a train). The horizontal slider called “Source Velocity” adjusts the speed of this wave source (blue dot). The speed is given in units of meters per second (m/s).

The red dot is the receiver or observer. So the red dot could be a microphone, for example, or the human ear. Make sure the Observer Velocity slider is set to 0.

Notice at the bottom it tells you that the **speed of sound** is 343 m/s.

First, set the Source Velocity slider to 0. Then press the Start button. You should see the blue dot stay stationary and produce a wave pattern that looks like those we’ve already seen. What is the frequency of the wave as measured at the source (the blue dot) in waves per second (aka Hertz)? You can read this off of the simulation where it says “Source Frequency”.

STEP 6: The red dot is the Observer. Think of it as a microphone that measures the frequency of the waves as they pass by. In other words, the microphone tells you the frequency of the waves right at that point where the red dot is located.

What is the wave frequency as measured by the Observer (microphone / red dot) in waves per second (Hz)? This is labeled at the bottom as the “Perceived Frequency”.

Comparing your last two answers, how do they compare? How does this make sense with regards to the spacing that you see in the waves at the two locations -- the location of the sound source / blue dot and the location of the microphone / red dot?

STEP 7: Now let’s set the sound source in motion. On the Source Velocity slider, slide it up to a speed of about half the speed of sound (i.e., roughly 172 m/s; it doesn’t have to be precise). Press Start.

The wave source will move to the right while still emitting wave crests (circles) as it did before. The wave crests are still traveling at the same wave speed as before (the speed of sound). However, between each peak that is emitted, the source moves a little to the right before it emits another peak. Therefore, the source “catches up” a little bit with the wave crests that are moving to the right before it emits the next wave crest.

a) What effect does this have on the spacing of the wave crests that are moving to the right (in the same direction as the source is moving) as compared to their spacing when the source was at rest?

b) And therefore, what effect does this have on the wave frequency of the wave crests moving to the right?

c) Before the source reaches the microphone (red dot) and while it is moving towards the microphone, look at the Perceived Frequency. What frequency does the microphone detect?

d) Is your answer in (c) smaller or greater than the wave frequency at the source? Does this agree with what you predicted in (b)?

STEP 8: With the source still moving at a speed of 0.5, let's look at the effect on wave peaks that are moving *to the left* (in the direction opposite the source is moving).

As the wave source moves to the right, what happens to the spacing of the peaks that are moving to the left as compared to their spacing when the source was at rest?

And therefore, what effect does this have on the wave frequency of the wave peaks moving to the left?

STEP 9: After the source passes the observer, and the left-moving waves are now crossing the red dot, write down the Perceived Frequency.

Does this perceived frequency agree with what you predicted in STEP 8 by looking at the spacing of the wave peaks?

SQ1: Let's summarize the Doppler Effect below.

As a wave source moves (toward / away from) a detector, the frequency of the detected wave is (greater / less) than the frequency at the source.

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STEP 10: We actually do experience the Doppler Effect on a regular basis with regards to sound waves. Our ears are good detectors of the frequency of a sound wave. Our brain interprets the auditory signal from our inner ear as follows:

A *high frequency* sound wave is experienced as a *high-pitched* sound.

A *low frequency* sound wave is experienced as a *low-pitched* sound.

Any time a vehicle approaches and passes us, we'll hear the Doppler Effect. As an example, watch the following video of a train passing (make sure you have the sound on so that you can hear the Doppler Effect):

https://youtu.be/NnsrDwNGsgg?t=16

a) *Ignoring the sound's volume*, how does the *pitch* of the sound when the train's horn comes toward the camera compare to the *pitch* when the train's horn is moving away from the camera? Use "higher" and "lower" to describe pitch.

Toward: Away:

b) Therefore, how does the *frequency* of the sound compare when it's moving toward versus moving away from the camera?

Toward: Away:

STEP 11: When a person *walks* toward you while talking, we don't hear a Doppler effect (test that out if you like). Let's examine why not.

a) The train in the video is traveling 79 mph. Roughly how many mph is a person traveling when they walk?

b) The speed of sound is about 770 mph. How does the train's speed compare to the speed of sound and how does the walker's speed compare to the speed of sound? Let's write them as rough percentages.

Train speed = % speed of sound

Walking speed = % speed of sound

c) Which one is “catching up” with the sound wave crests more, the train or the person walking? Remember, the sound wave crests are traveling at the speed of sound, by definition.

d) There *is* a Doppler effect when someone walks toward you while talking, but it’s not noticeable. Why do you think that is?

We notice a clear Doppler effect with fast-moving sources (like vehicles) and not slow-moving sources (like people). But the Doppler Effect is there in either case!

The Sonic Boom

STEP 12: As we saw in the previous steps, a moving sound source “catches up” a little bit with the waves it is emitting, which causes the Doppler Effect. What happens if the sound source moves *faster* than the waves and “outruns” them? Let’s find out.

Press Reset on your simulation. Set the speed slider to about 150% the speed of sound (i.e., about 515 m/s). Press Start.

Look at the pattern of wave crests (circles) that’s being created by the source that’s moving faster than the waves. Draw the circles that make up the wave pattern below.

Ignoring what the simulation tells you about source and perceived frequencies, do you think the microphone will detect any sound while the sound source is moving toward it but hasn’t reached it yet? Why or why not?

STEP 13: Notice what happens when the sound source passes the observer.

At some point in time, the microphone will detect a group of closely-spaced waves. In other words, a lot of circles (wave peaks) will cross the observer all at once as the sound source passes by.

This cluster of wave peaks is a large amount of sound energy that's been piled up together. We call this a **sonic boom** because it can carry a very large amount of sound energy.

On your drawing of the wave pattern above, highlight the part(s) of the pattern along which the wave crests have piled up and label it "sonic boom". Your highlights should trace along the edges of a cone or wedge shape.

STEP 14: Look at the image at the right of an F-18 *breaking the sound barrier*. What that means is, this image was taken at the moment the aircraft's speed surpassed the speed of sound.

Notice that the F-18 is producing a cone-shaped disturbance in the air. This is the same cone-shaped region as the region you highlighted in your drawing of the wave pattern above. It is the "shock front" of the sonic boom. When that front, which is the piled-up sound energy, crosses your position, you will hear the sonic boom.

Figure 1: F-18 Breaking the Sound Barrier

Do you think the pilot of the F-18 will hear the sonic boom at the moment the aircraft breaks the sound barrier? Why or why not?