Flipping Physics Lecture Notes: *Waves Introduction*
https://www.flippingphysics.com/waves.html

When one thinks of “waves” the most common visual which probably comes to mind is waves moving across a body of water like a lake or an ocean. A water wave is most definitely an example of a wave, however, there are many more. Sound waves are how you are currently hearing me, visible light is an electromagnetic wave and is how you see me, radio waves are also an electromagnetic wave and are likely how your electronic device is receiving this video, seismic waves are waves of energy which travel through the Earth’s crust, and waves on a string are electrical potential energy stored in the string being transferred from one location to another.

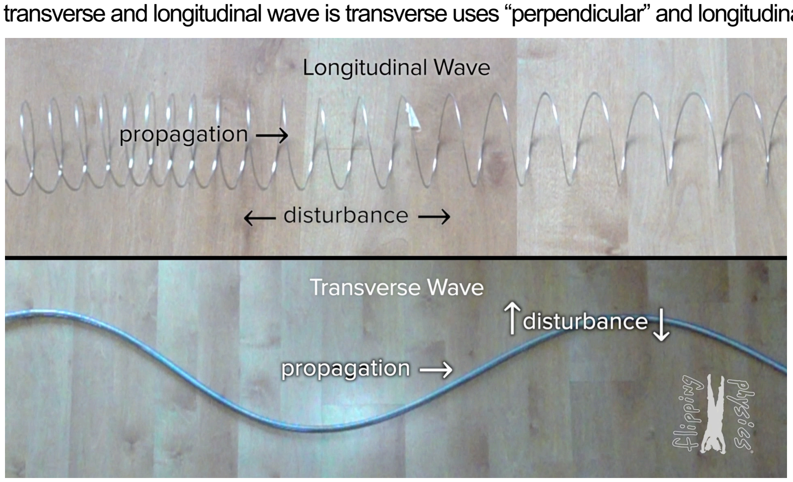
Please note that electromagnetic waves are not mechanical waves and do not require a medium to travel through. Visible light and radio waves are components of the electromagnetic wave spectrum. We will discuss these concepts in detail in later lessons. This lesson is about mechanical waves.

A mechanical wave is a disturbance of a medium which travels through the medium transferring energy from one place to another. Please realize waves transfer energy from one location to another, they do not move matter from one location to another. Wave motion is the motion of the disturbance of the medium, not the motion of the medium itself.

We will use waves on a spring to show the properties of mechanical waves. We will start with a single wave pulse traveling through the spring. The piece of tape which is on the spring is a part of the medium because it is attached to the spring. As the wave pulse travels along the spring, the tape moves up and then down, however, the overall displacement of the piece of tape is zero, because the medium does not change locations. The energy is contained in the disturbance of the medium travels along the spring. In other words, the wave is a pulse of energy traveling through the medium. The larger the amplitude of the wave, the more energy contained in the wave. Amplitude being the maximum displacement of the wave from equilibrium position. Equilibrium position being the position of the medium before and after the wave bases by that point.

A wave pulse is a single disturbance of a medium, whereas a periodic wave is a connected series of wave pulses. A periodic wave is also sometimes called a continuous wave.

Waves can be classified as either transverse or longitudinal. A transverse wave is where the direction of wave propagation is perpendicular to the direction of the disturbance of the medium. Transverse means “in a position or direction that is at an angle of 90° to something else”[1]. A longitudinal wave is where the direction of wave propagation is parallel to the direction of the disturbance of the medium. Longitudinal means “lengthwise[2]” or “in the direction of the longest side[3]” which means parallel. (Note: The only difference between the definitions of transverse and longitudinal wave is transverse uses “perpendicular” and longitudinal uses “parallel.”)

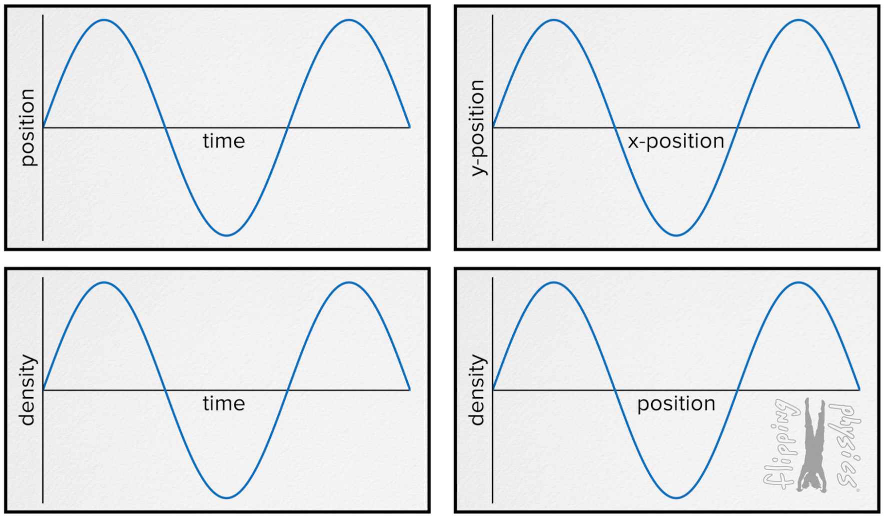


[1] https://dictionary.cambridge.org/us/dictionary/english/transverse
[2] https://dictionary.cambridge.org/us/dictionary/english/longitudinal
[3] https://dictionary.cambridge.org/us/dictionary/english/lengthwise

Flipping Physics Lecture Notes:

Wave Graphs - Longitudinal and Transverse - Wavelength and Period
https://www.flippingphysics.com/wave-graphs.html

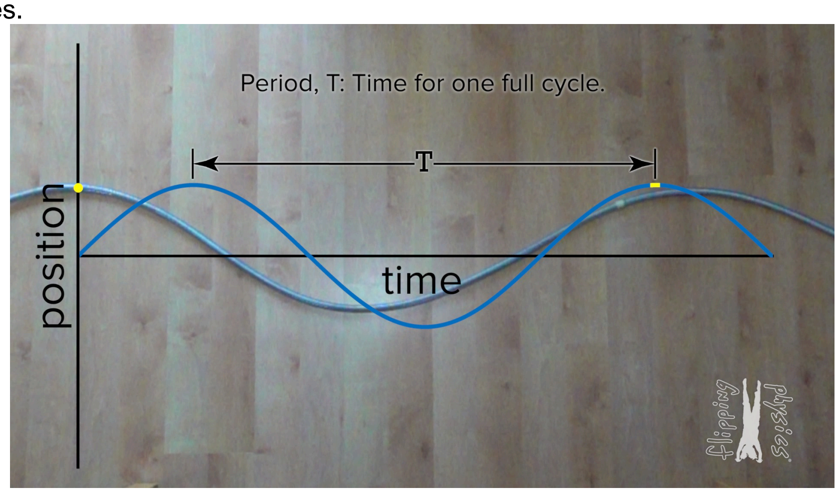
These are four graphs of mechanical waves which, at first, might look identical, however, it is very important that you understand the differences.



The key difference here is what is on the y and x axes. On the y-axis we have either position or density. On the x-axis we have either time or position. Let's start with understanding the position as a function of time graph. If we have a mass-spring system moving in simple harmonic motion, this could describe the position of a mass-spring system as a function of time. This could also describe the movement of a mechanical wave as a function of time. More specifically, this describes a transverse wave. A transverse wave is where the direction of wave propagation is perpendicular to the direction of the disturbance of the medium. This graph represents the position of a specific point on the transverse wave as a function of time.

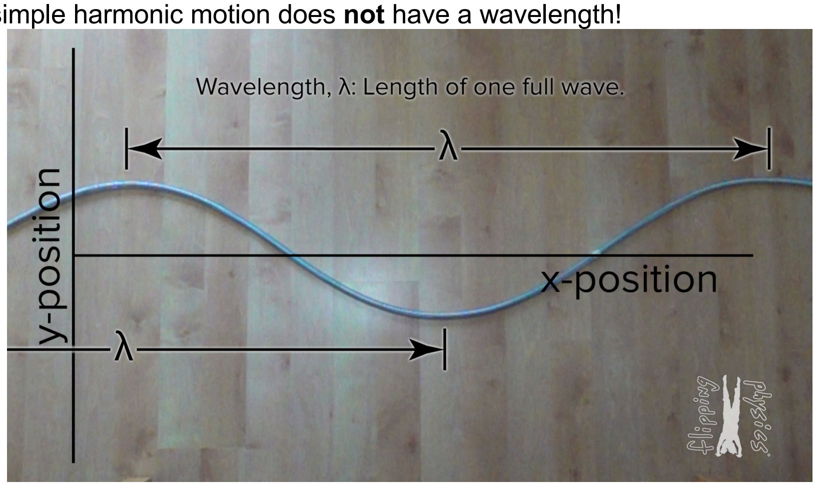
Let's change the x-axis now to position in the x-direction. Notice this graph can no longer describe the motion of a mass-spring system moving in simple harmonic motion, because a mass-spring system only moves in one dimension. However, this graph can describe the motion of a mechanical wave. This graph simply describes the location of all of the particles of a mechanical wave at one specific moment in time.

Now what about the measurement which extends between successive crests or successive troughs? Going back to the graph of position as a function of time, that measures the Period, T, or the time it takes for the system to oscillate through one full cycle. This is true for both simple harmonic motion and mechanical waves.



However, what is the measurement between successive crests for a graph of y-position as a function of x-position? This is called Wavelength:

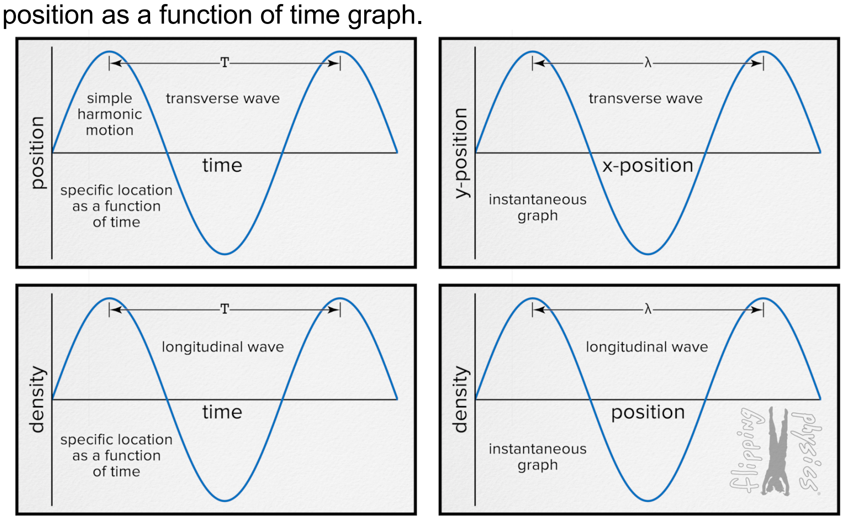
- Wavelength: The length of one complete wave cycle. Measured from crest to successive crest, trough to successive trough. In other words, measured from one point on the wave to the next corresponding point on the wave which is going in the same direction.
- Wavelength: The distance travelled by a wave during one period.
- The symbol for wavelength is λ, the lowercase Greek letter lambda.
- Notice because simple harmonic motion does not have a graph of y-position as a function of x-position, simple harmonic motion does **not** have a wavelength!



Let's now change the graph to density as a function of time. How is this different? This describes a mechanical wave and not simple harmonic motion, but how? This describes a longitudinal wave. A longitudinal wave is where the direction of wave propagation is parallel to the direction of the disturbance of the medium. In other words, a crest on the graph represents a location of higher density in a longitudinal wave; a location of compression. A trough on the graph represents a location of lower density in a longitudinal wave; a location of rarefaction. This represents the density of a specific location of the longitudinal wave as a function of time.

If we talk about the last graph which is density as a function of position, again this describes a mechanical, longitudinal wave, just the density of the whole wave at one specific point in time. The terms period and wavelength are still applicable for the longitudinal wave. Period for the density as a function of time graph. And wavelength for the density as a function of position graph.

Remember, the only one of these graphs which describes an object moving in simple harmonic motion is the first one, the position as a function of time graph.



Flipping Physics Lecture Notes:

Wave Speed Equation Derivation and Demonstration
https://www.flippingphysics.com/wave-speed.html

The equation for the magnitude of velocity is: $v=\frac{\Delta x}{\Delta t}$

If the magnitude of the displacement of the wave equals the wavelength of the wave, λ, then the time for that to occur is the period, T: $v=\frac{\Delta x}{\Delta t}=\frac{\lambda}{T}$

We know frequency and period are inversely related: $f=\frac{1}{T}$

Therefore, the equation for the magnitude of the velocity of a wave is: $v=\frac{\Delta x}{\Delta t}=\frac{\lambda}{T}=f\lambda \Rightarrow \boxed{v=f\lambda}$

The amplitude, frequency, and wavelength of the wave do not affect the speed of the wave. The only thing that affects the speed of the wave in the medium is the properties of the medium itself.

An important point to notice is that this equation describes the speed of the wave pulse, not the speed of the particles of the medium. Also, we use the symbol "v" for the speed of the wave here. Frequency and wavelength are both scalars, so "v" here cannot be velocity because velocity is a vector, however, we use the velocity equation to derive the speed of the wave, so the symbol "v" is typically what is used.

Looking at the demonstration of 1 wave passing through the screen we can take the following measurements:

The length of one wave measured on the screen: $\lambda=1.58\text{m}$

The time it takes 1 full wave to pass by a point is 0.29 seconds: $T=0.29\text{sec}$

Therefore: $f=\frac{1}{T}=\frac{1}{0.29}=3.448276\text{ Hz}$ and $v=f\lambda=(3.448276)(1.58)=5.448276\approx 5.4\frac{m}{s}$

The time it takes one wave to go across the entire screen is 0.35 sec: $\Delta t=0.35\text{sec}$
The width of the screen is 1.92 m: $\Delta x=1.92m$

Therefore: $v=\frac{\Delta x}{\Delta t}=\frac{1.92}{0.35}=5.485714\approx 5.5\frac{m}{s}$

The percentage difference between those two measurements is:

$$\%_{difference}=\frac{5.485714\text{-}5.448276}{(5.485714+5.448276)/2}\times 100=0.681150\approx 0.68\%$$

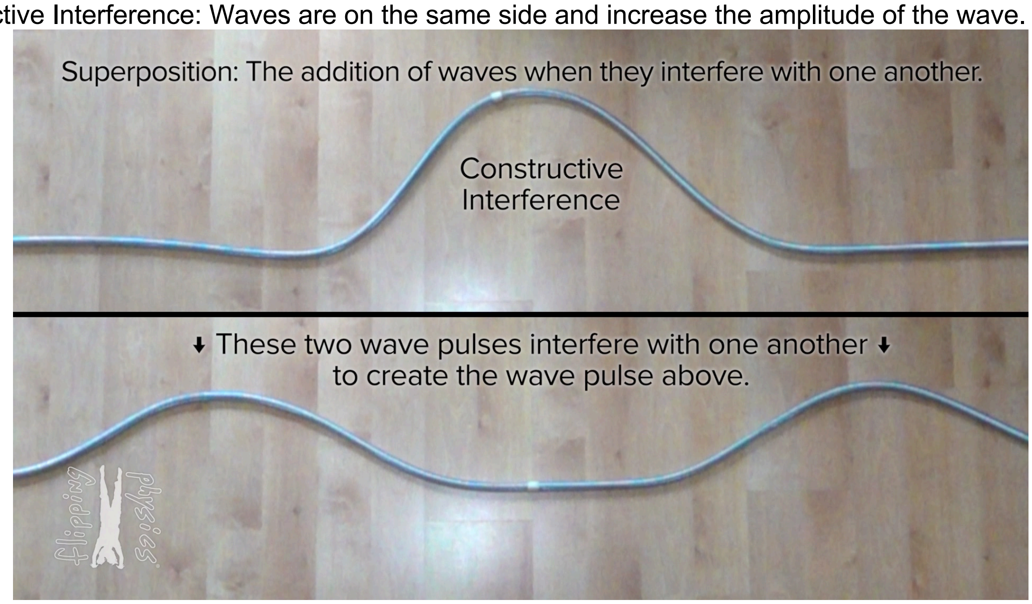
Flipping Physics Lecture Notes:

Wave Superposition Introduction
https://www.flippingphysics.com/wave-superposition.html

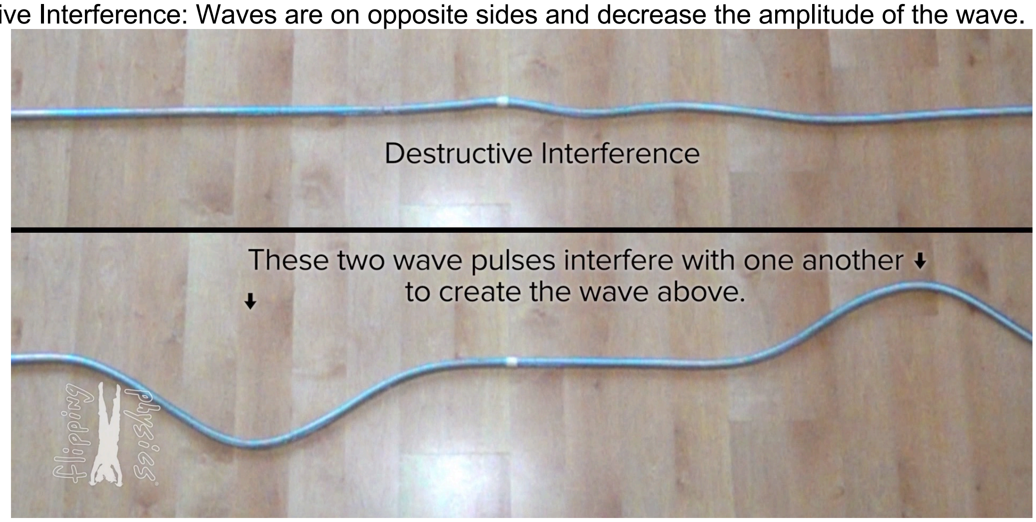
It is a rather well-established fact that two objects cannot occupy the same space at the same time. However, waves are not objects. Waves are a disturbance of a medium which travels through the medium transferring energy from one place to another. Which means waves *can* occupy the same space at the same time. If fact, waves pass right through one another and when they occupy the same space, they interfere with one another via what is called superposition.

Superposition simply means the amplitudes of the waves are combined. For example, if the two waves are on the same side of the spring, the two waves pulses will combine to create one larger amplitude wave. And after being in the same location and adding the amplitudes together, the two waves will continue on with the same shape and amplitude as before interfering with one another.

Constructive Interference: Waves are on the same side and increase the amplitude of the wave.



Destructive Interference: Waves are on opposite sides and decrease the amplitude of the wave.



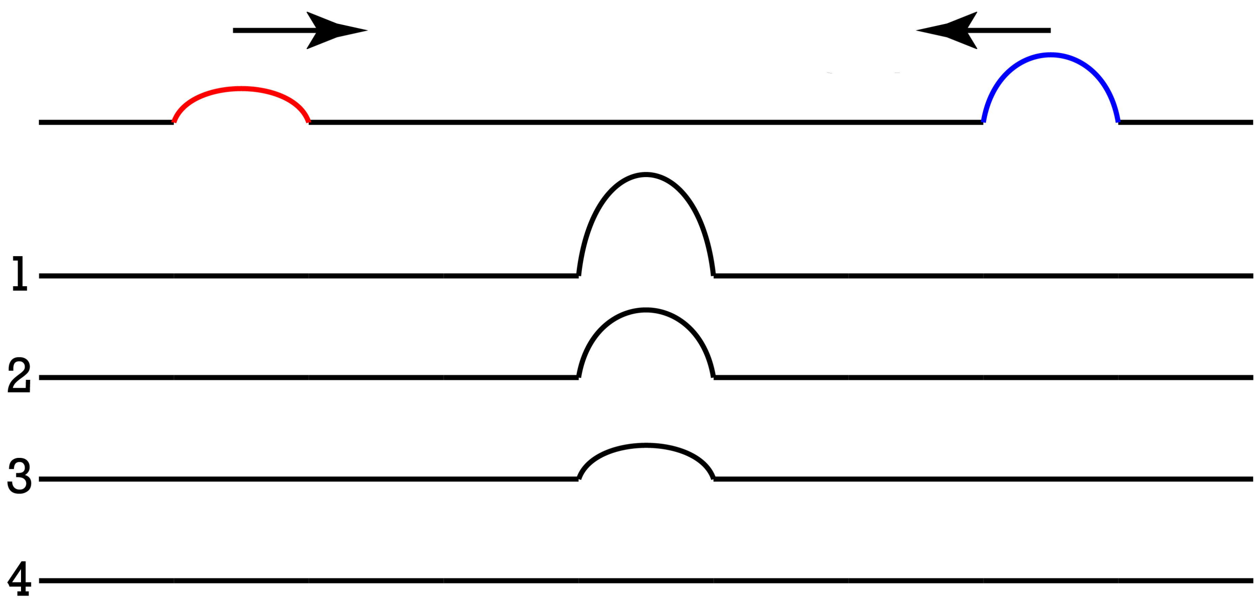
- *Total* Destructive Interference: Waves completely cancel one another out and the net result is no wave. This requires the waves to be mirror images of one another.

Flipping Physics Lecture Notes:

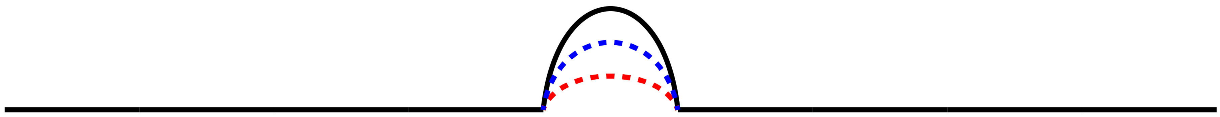
Wave Superposition Multiple Choice Problems

While I do prefer to show real demonstrations of physics concepts, wave interference via superposition is an Problem where we should go over some idealized multiple-choice problems. So here goes.

First Problem: Two wave pulses on the same string are headed towards one another as shown. When both occupy the same space, which diagram best describes the resulting wave form?
(Wave pulses are shown with different colors to make them easier to visualize and talk about.)

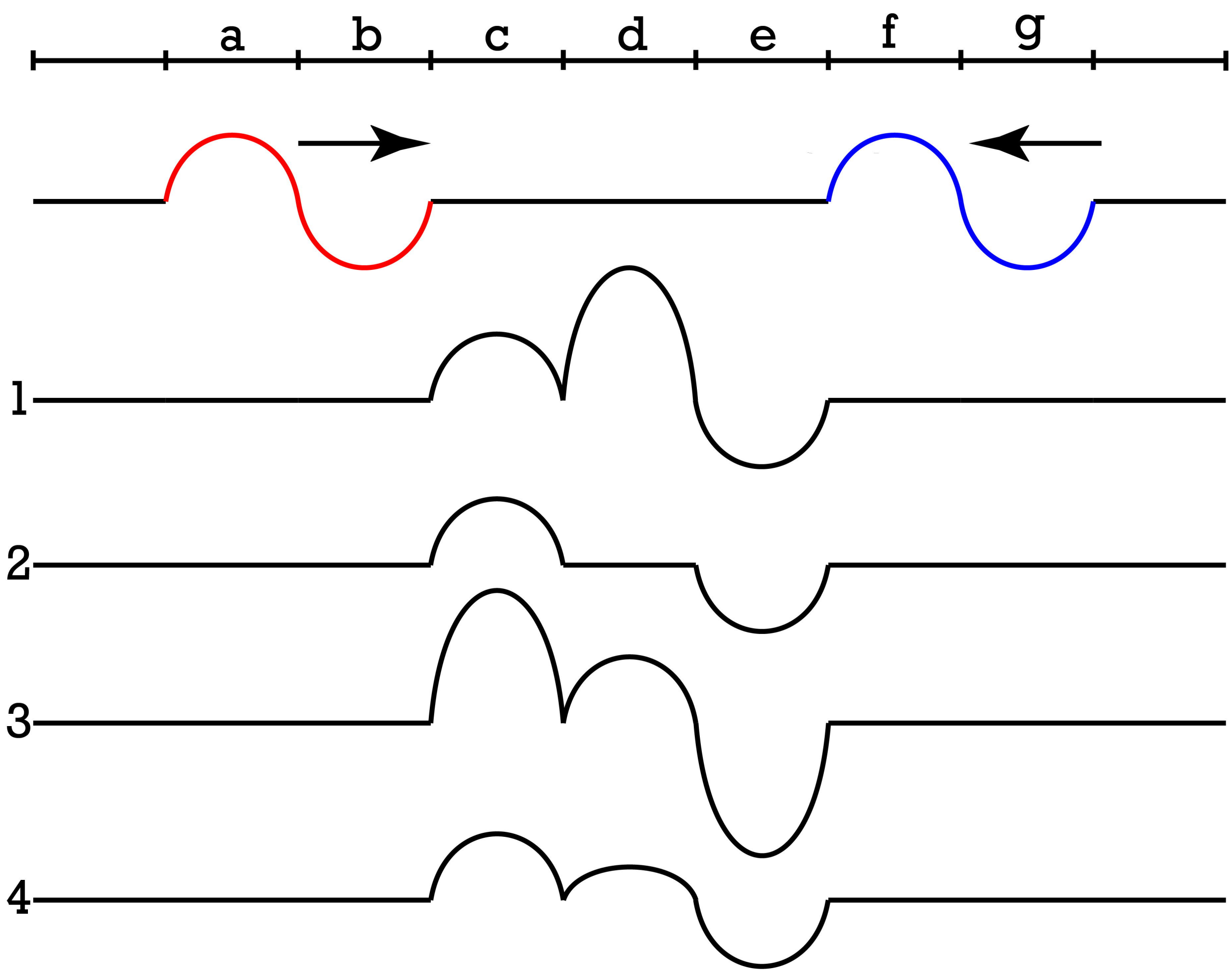


The correct answer is 1. This is wave interference via superposition. The two waves constructively interfere, and the resultant waveform is the addition of the two original waves:

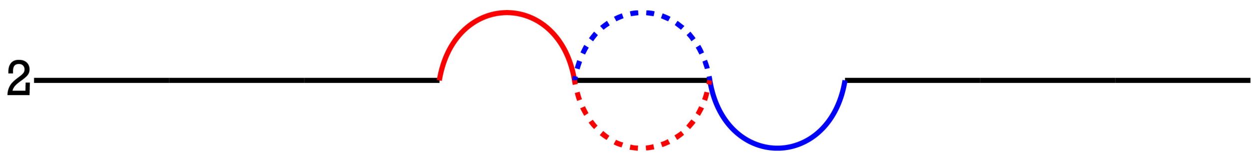
1 

It is important to realize what happens after the two wave pulses interfere with one another. They will simply move on as if they never interfered in the first place. Which looks like this:

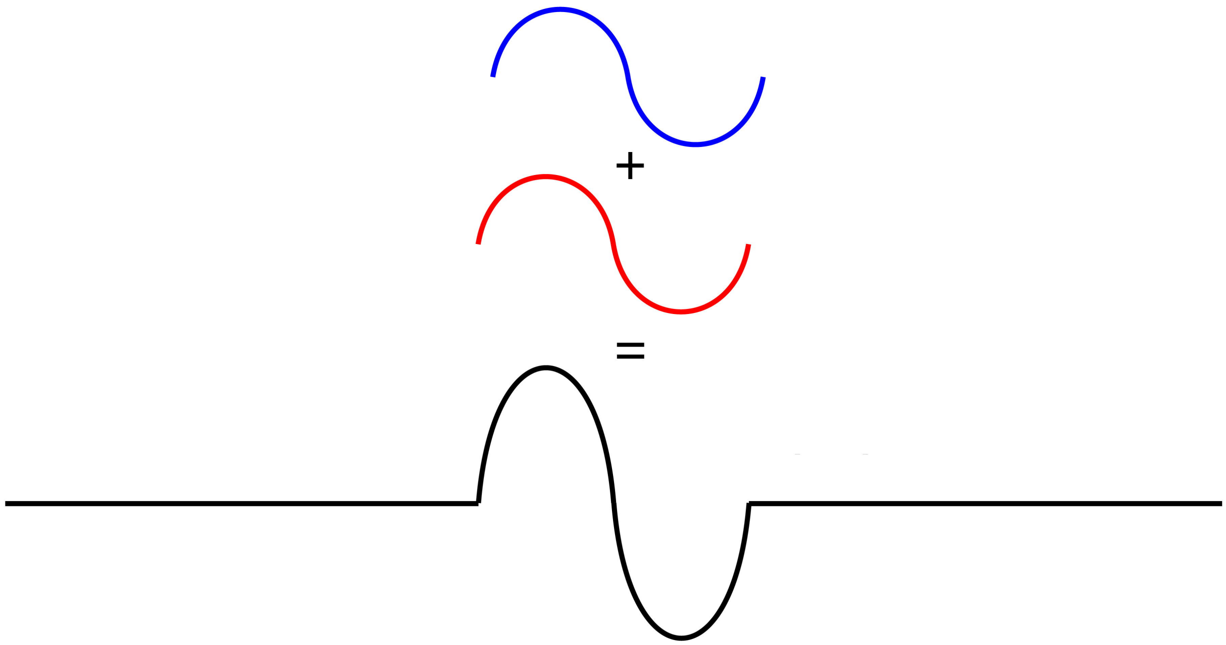
Second Problem: Two waves on the same string are headed towards one another as shown. When the red wave occupies locations c and d and the blue wave occupies locations d and e, which diagram best describes the resulting wave form?
(Wave pulses are shown with different colors to make them easier to visualize and talk about.)



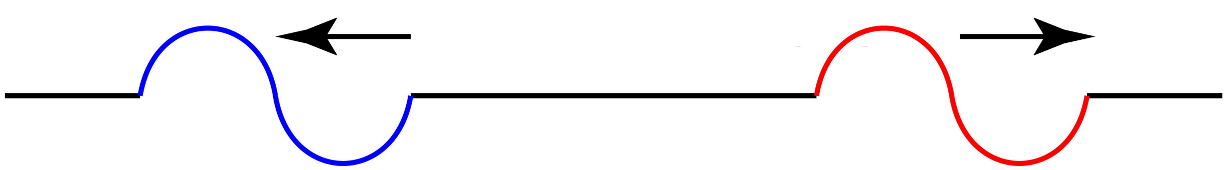
The correct answer is 2: Again, this is wave interference via superposition. However, the two waves only interfere with one another when they occupy the same space. They do **not** occupy the same space in regions c and e. They only occupy the same space in region d. Therefore, the original waves are still there in regions c and e. In region d, the two waves destructively interfere, and the resultant waveform is the addition of the two original waves. In fact, in this case, because the two waves have the same shape and amplitude, however, are on opposite sides of the string, the result is total destructive interference in region d. In other words, the string is completely flat in region d.



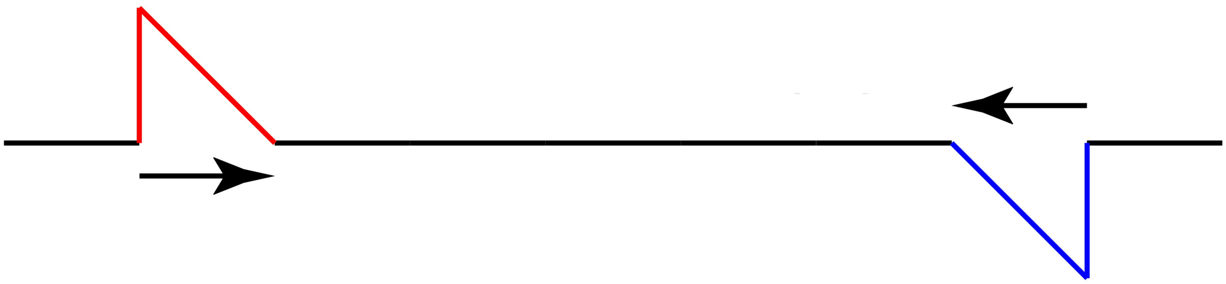
And here is what the two waves will look like while they occupy the same space which is halfway through c to halfway through e:

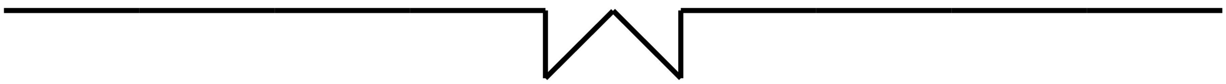


Again, it is important to realize what happens after the two wave pulses interfere with one another. They will simply move on as if they never interfered in the first place. Which looks like this:

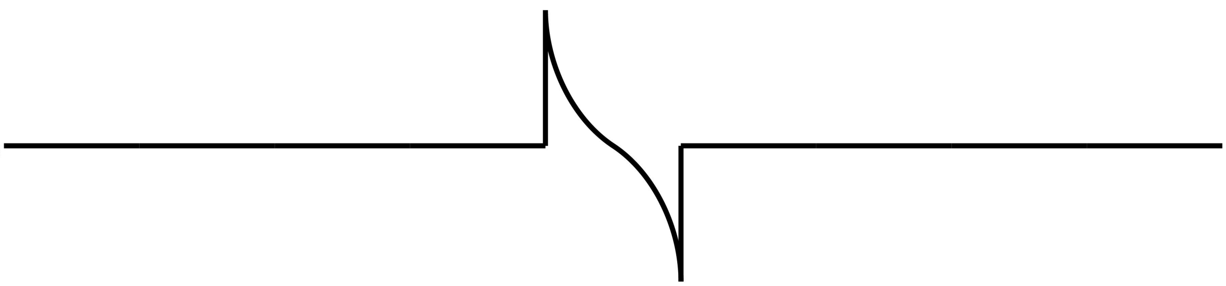


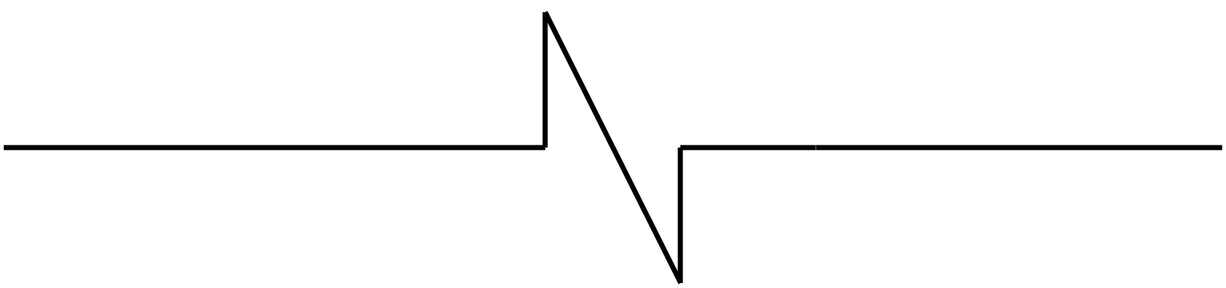
Third Problem: Two wave pulses on the same string are headed towards one another as shown. When both occupy the same space, which diagram best describes the resulting wave form?
(Wave pulses are shown with different colors to make them easier to visualize and talk about.)



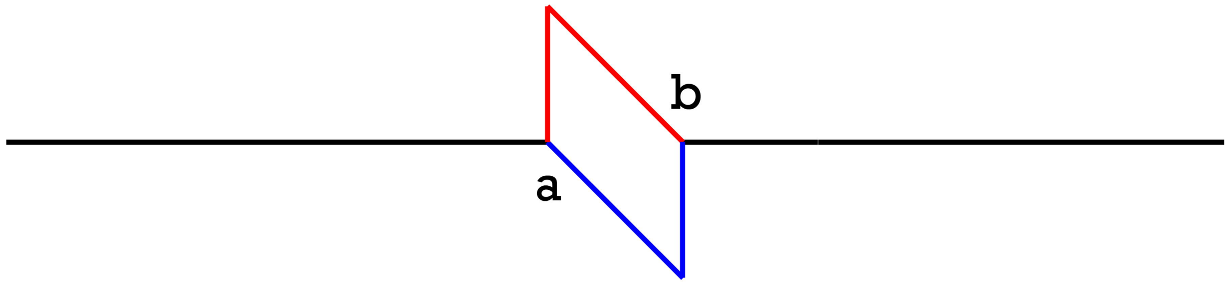
1 

2

3 

4 

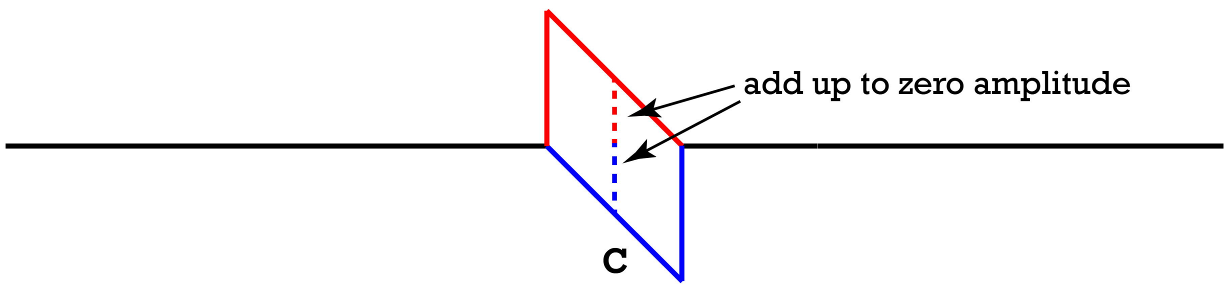
Again, again, this is wave interference via superposition. This is what the two waves look like individually when they occupy the same space. (Before we figure out the superposition.)



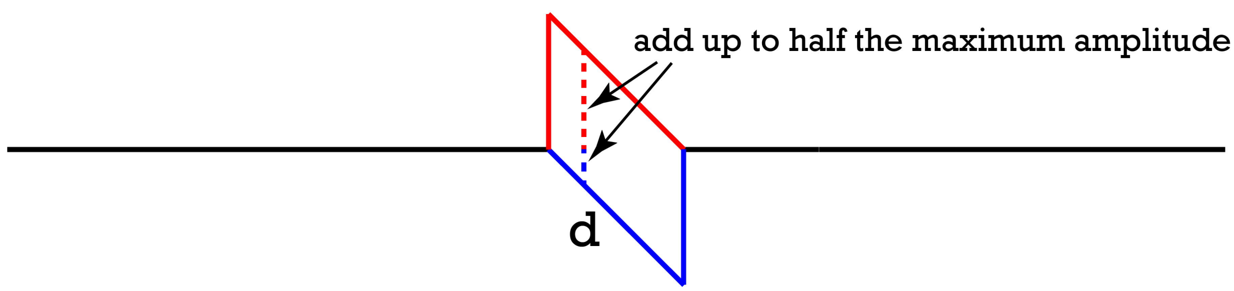
Let's look at a few points to see how they interfere via superposition.

- Location a: The left edge of the two waves. The amplitude of the red wave is at a maximum and the amplitude of the blue wave is zero. Add those together and you get the maximum amplitude of the red wave.
- Location b: The right edge of the two waves. The amplitude of the red wave is zero and the amplitude of the blue wave is at a maximum. Add those together and you get the maximum amplitude of the blue wave.
- At this point we know the answer is either 3 or 4.

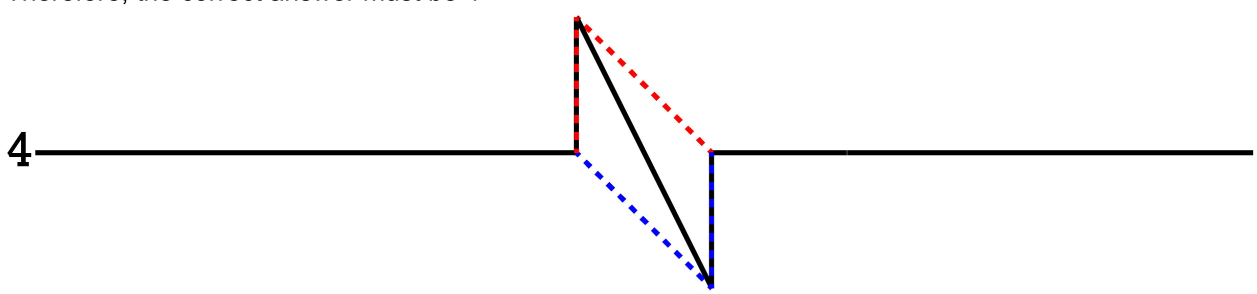
Location c: Right in the middle of the two waves. The amplitude of the red wave is half its maximum height. The amplitude of the blue wave is half its maximum height. However, the red wave is above the string and the blue wave is below the string. These two amplitudes cancel one another out and the net amplitude right in the middle of the two waves is zero. At this point we *still* know the answer is either 3 or 4. ☺



Location d: One quarter of the way from left edge. Red wave is $3/4^{ths}$ of the maximum amplitude above equilibrium. Blue wave is $1/4^{th}$ of the maximum amplitude below equilibrium. Those add up to ½ the maximum amplitude above equilibrium.



Therefore, the correct answer must be 4



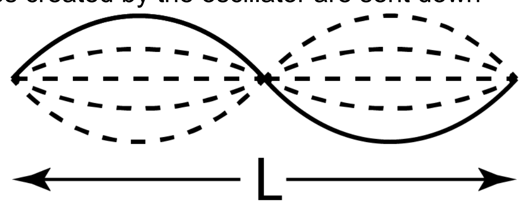
Flipping Physics Lecture Notes:

Standing Waves Introduction
https://www.flippingphysics.com/standing-waves.html

Before we can learn about standing wave patterns, we first need to understand what happens when a wave encounters an end.

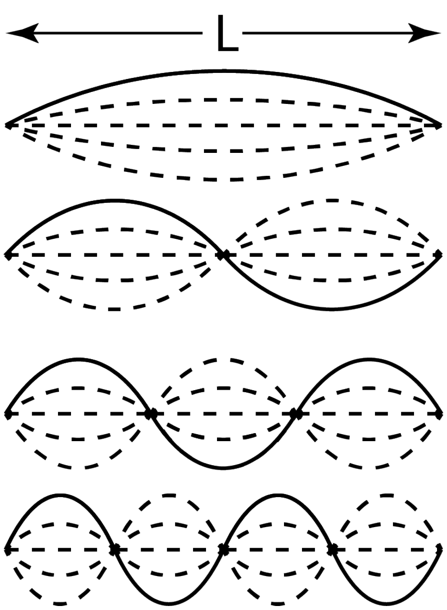
- When a wave pulse comes to a fixed end, it will be reflected and inverted.
  - Fixed end = reflection with inversion.
- When a wave pulse comes to a free end, it will be reflected, however, it will not be inverted.
  - Free end = reflection without inversion.

Today's demonstration involves two fixed ends. In other words, the wave pulses are continuously reflected and inverted. One end is at a constant tension and the other end is oscillating up and down in simple harmonic motion at a known frequency. The wave pulses created by the oscillator are sent down the string, reflected and inverted, and then sent back down the string and interfere with the pulses being sent by the oscillator. At certain frequencies this demonstration sets up standing wave patterns in the string. How does this work? Let's start with this visual of a standing wave pattern:



The length of the string is L. And you can see there is one wavelength in the length of the string.

- Nodes: Locations where the wave interferences cause total destructive interference.
  - There are 3 nodes in the above standing wave.
- Antinodes: Locations where the wave interferences cause constructive interference.
  - There are 2 antinodes in the above standing wave.



Standing wave patterns can only be created at specific wavelengths. This is because, in the case of a string, both ends are fixed and are therefore nodes. To the left are some options for possible standing wave patterns in a string.

Notice each standing wave pattern is comprised of an integer multiple of half wavelengths.

- The 1st standing wave pattern has 1 half wavelength.
- The 2nd standing wave pattern has 2 half wavelength.
- The 3rd standing wave pattern has 3 half wavelength.
- The 4th standing wave pattern has 4 half wavelength.
- The 5th standing wave pattern would have 5 half wavelengths.
- And I bet you can guess the pattern.

It is very important to understand that standing wave patterns will only be created at specific wavelengths and therefore only specific frequencies. In the example of a string vibrating with two nodes on either end, the standing wave pattern must have an integer multiple of half a wavelength.

They are called standing wave patterns because the waves appear to stand still. However, please realize, standing waves are not "standing still". They are the constructive and destructive interference of the waves which are traveling back and forth through the medium.

Flipping Physics Lecture Notes:

Determining the Speed of a Standing Wave – Demonstration

https://www.flippingphysics.com/standing-wave-speed.html

Today we will be building on what we learned last time about standing wave patterns.
http://www.flippingphysics.com/standing-wave.html

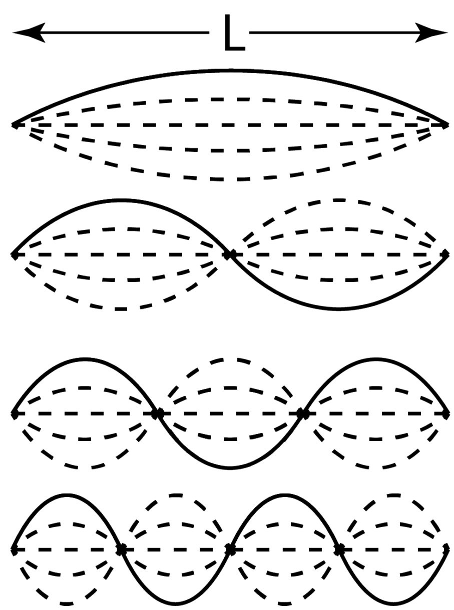
As we demonstrated before, standing wave patterns can only be created at specific wavelengths. To the right are some options for possible standing wave patterns in a string.

The equation for the speed of a wave is: $v = f\lambda$

- The speed "v" of the wave on the string is constant, therefore:
- as the frequency of the wave increases,
- the wavelength of the wave decreases.

Because standing wave patterns will only be created at specific wavelengths and therefore only specific frequencies. Frequencies that will create standing wave patterns on this string are:

- The 1st standing wave pattern: $L = 1\left(\frac{1}{2}\lambda\right) \Rightarrow \lambda = 2L$
- The 2nd standing wave pattern: $L = 2\left(\frac{1}{2}\lambda\right) \Rightarrow \lambda = L$
- The 3rd standing wave pattern: $L = 3\left(\frac{1}{2}\lambda\right) \Rightarrow \lambda = \frac{2L}{3}$
- The 4th standing wave pattern: $L = 4\left(\frac{1}{2}\lambda\right) \Rightarrow \lambda = \frac{L}{2}$
- The 5th standing wave pattern: $L = 5\left(\frac{1}{2}\lambda\right) \Rightarrow \lambda = \frac{2L}{5}$



Notice we can use this information to determine the speed of the wave on the string:

Frequency, f (Hz)	Wavelength, λ (m)	Velocity (m/s)
15	$\lambda_{15} = 2L = (2)(0.865) = 1.73\text{m}$	$v = f_{15}\lambda_{15} = (15)(1.73) = 25.95\frac{m}{s}$
30	$\lambda_{30} = L = 0.865m$	$v = f_{30}\lambda_{30} = (30)(0.865) = 25.95\frac{m}{s}$
45	$\lambda_{45} = \frac{2L}{3} = \frac{(2)(0.865)}{3} = 0.57\bar{6}\text{m}$	$v = f_{45}\lambda_{45} = (45)(0.57\bar{6}) = 25.95\frac{m}{s}$
61	$\lambda_{61} = \frac{L}{2} = \frac{0.865}{2} = 0.4325\text{m}$	$v = f_{61}\lambda_{61} = (61)(0.4325) = 26.815\frac{m}{s}$
76	$\lambda_{76} = \frac{2L}{5} = \frac{(2)(0.865)}{5} = 0.346\text{m}$	$v = f_{76}\lambda_{76} = (76)(0.346) = 26.296\frac{m}{s}$

$$v_{average} = \frac{(25.95 + 25.95 + 25.95 + 26.815 + 26.296)}{5} = 26.1922 \approx 26\frac{m}{s}$$

But remember, standing wave patterns are constructive and destructive interference of the waves which are traveling back and forth through the medium. So, we can also measure the speed of this wave by measuring the speed of a wave pulse moving through the medium.

Knowns: $L = 0.865m \;\&\; \Delta t = 0.068\text{sec}$

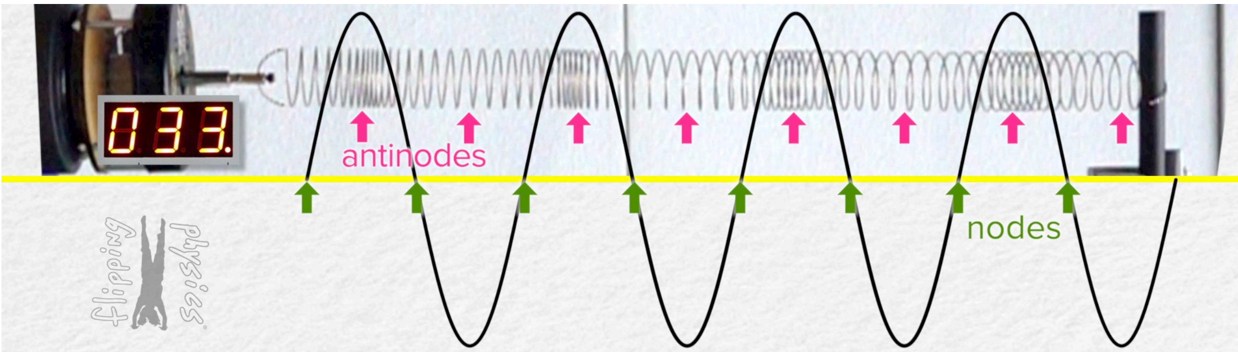
$$speed = \frac{distance}{time} = \frac{2L}{\Delta t} = \frac{(2)(0.865)}{0.068} = 25.441 \approx 26\frac{m}{s}$$

$$\%_{difference} = \frac{26.1922 - 25.441}{(26.1922 + 25.441)/2} \times 100 = 2.910 \approx 2.9\%$$

Flipping Physics Lecture Notes:

Longitudinal Standing Waves Demonstration

I have a picture from the video in these lecture notes, however, you really need to see the motion of the longitudinal standing waves and how they compare to the standing wave pattern animation to understand what is going on here. So please, visit:
http://www.flippingphysics.com/standing-wave-longitudinal.html



In case you wanted to perform some calculations, the length of the coils of the stretched spring is 41.8 cm.

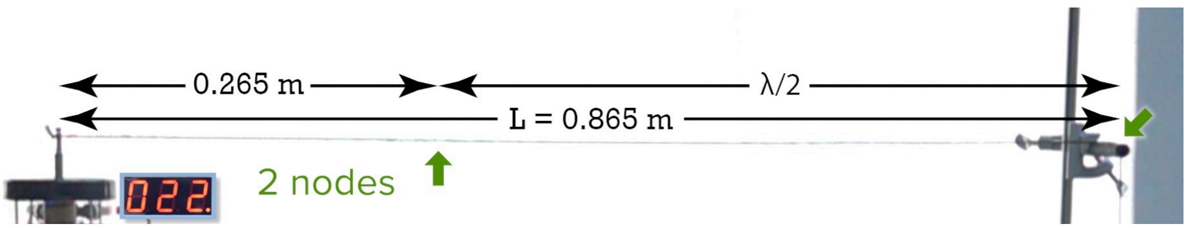
Flipping Physics Lecture Notes:

How Is This Standing Wave Possible?
https://www.flippingphysics.com/standing-wave-impossible.html

In a previous lesson we showed standing wave patterns on a string and explained that standing wave patterns are only able to be created at specific wavelengths and therefore frequencies.[1] For example, standing waves were possible at 15, 30, and 45 hertz on this string. However, while working on this demonstration, I noticed that I was able to set up a standing wave pattern at 22 hertz. So, here is the question.

If standing waves are only "allowed" at 15 and 30 hertz and nowhere in between on this string, then why do we see a standing wave pattern at 22 hertz?

Remember, the reason standing wave patterns are only "allowed" at certain frequencies on this string is because we stated that both ends of the string are fixed ends and therefore are a node or a location of total destructive interference. However, when you look at the left end of the string, it is attached to the oscillator which is moving up and down 22 times every second. In other words, the left end of this string is not truly a node!



The nodes we can see on this string are at the right end and one 0.265 meters to the right of the oscillator. That means we can determine the wavelength of this wave:

$$\frac{1}{2}\lambda = 0.865 - 0.265 = 0.60m \Rightarrow \lambda = 1.2m$$

We now have the frequency and wavelength of the wave, so we can determine the speed of the wave.

$$v = f\lambda = (22)(1.2) = 26.4 \approx 26\frac{m}{s}$$

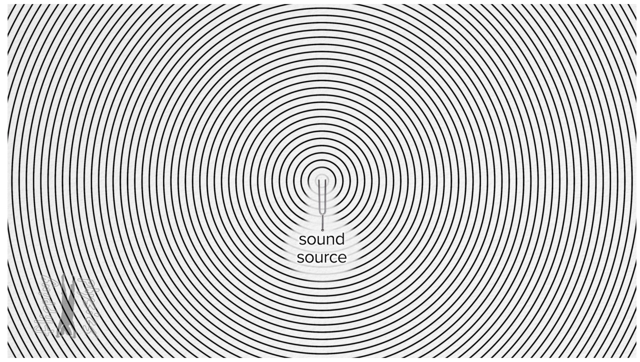
Which compares nicely to the average velocity we calculated in a previous lesson for this string:

$$v_{average} = 26.1922 \approx 26\frac{m}{s}$$

[1] See https://www.flippingphysics.com/standing-waves.html

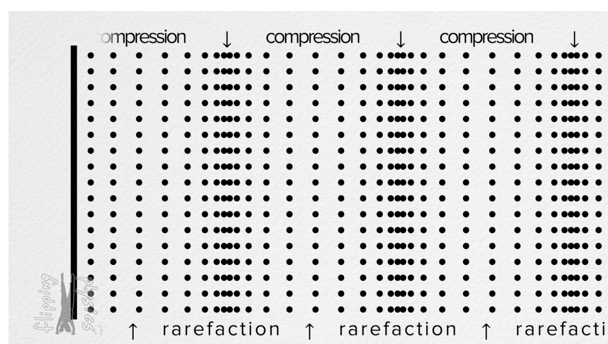
Flipping Physics Lecture Notes:

What is Sound?
https://www.flippingphysics.com/sound.html



A tuning fork is the simplest way to understand sound. After you bang a tuning fork against something, the tines of the tuning fork oscillate back and forth in simple harmonic motion at a defined frequency. Often, the sound waves which spread out from a sound source like a tuning fork are represented by a ring of circles increasing in size. But what does this animation[1] really represent?

In order to understand this animation, we need to take a closer look at what is happening to the tuning fork. The frequency of this tuning fork is 440 Hz. That means the tines of this tuning fork are going back and forth 440 times every second. Even when I slow the video down to 32 times slower than real speed, it is difficult to see the motion of the tuning fork. On a side note (he he), the reason I chose 440 Hz is because that is typically what is considered to be “concert pitch” and is the note you will hear orchestras play when they are all trying to tune to one another. The frequency of a sound is interpreted by our brains as “pitch”. A higher frequency means a higher pitch. 440 Hz or “concert pitch” is the A above the middle C on a piano. Okay, in order to see what is happening with the tuning fork, let’s actually switch to a speaker creating the same 440 Hz frequency and then lower that frequency down to where we can actually see the movement of the speaker. Let’s choose 55 Hz which is an A, 3 octaves below concert pitch. Now we can show the speaker moving back and forth at 55 Hz slowed down 32 times slower than real speed. What you see here is the cone of the speaker going back and forth in simple harmonic motion 55 times per second just like the tines of the tuning fork. What you hear as sound is the air being compressed and rarified, 55 times every second.

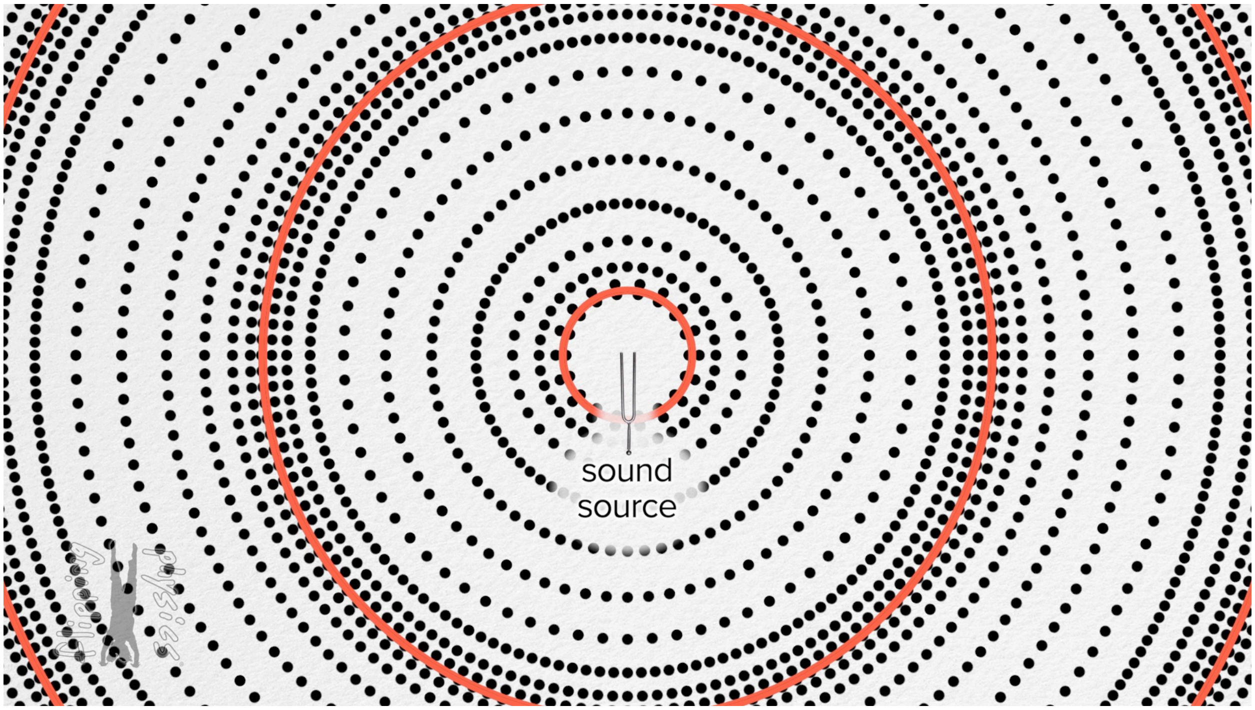


Unfortunately, you cannot see what is happening with the air to cause you to hear the 55 Hz frequency. So, I am going to show an animation of the speaker, represented by the vertical line, moving back and forth in simple harmonic motion and moving the air particles. You can see it compresses and rarifies the air particles in a simple harmonic motion pattern. Where the air is compressed, the air pressure is higher than atmospheric pressure, and where the air is rarified, the air pressure is lower than atmospheric air pressure. That is why a sound wave is often also called a pressure wave. A sound wave is also a longitudinal wave because the direction of the disturbance of the medium is parallel to the direction of wave propagation.

But we still have not connected this back to the original sound wave animation. So, looking at the speaker and air animation, notice how there are vertical lines of high density or high-pressure air. Those correspond to crests on a sinusoidal wave which represents the pressure of the air. Those vertical lines of high pressure, or crests on the sinusoidal wave, move linearly away from the speaker. But that is only from a very local perspective. A more accurate representation is that the sound waves move out in all directions from the sound source. In other words, the sound waves move out in a spherical shape away from the sound source. However, the medium you are looking at to understand sound waves is not three-dimensional, it is a two-dimensional space. And a two-dimensional slice of a sphere is a circle.

[1] Please watch the video so you can see the animations, really. https://www.flippingphysics.com/sound.html

So, coming back to the original animation of the circles increasing in diameter and emanating from the sound source. Those represent the crests of the pressure wave that our brains interpret as sound. And the crests represent locations of high pressure or high-density air. These circles, or rather spheres, are also called a wave fronts. This is a sphere of air which is all at the same location on the sinusoidal wave. So theses spheres are wave fronts of high pressure air which move away from the sound source.



But, we definitely need to answer the question “What is sound?” Sound is pressure waves travelling through a medium. For humans, the medium is typically air, however, sound can travel through any solid, liquid, or gas. The “pitch” of the 440 Hz tuning fork is your brain’s interpretation of that air pressure oscillating from high pressure, to low pressure, and back to high pressure 440 times every second.

It is important to remember that the medium is not displaced, only the disturbance of the medium moves through the medium, not the medium itself. And that disturbance of the medium, the wave front, is energy traveling through the medium.

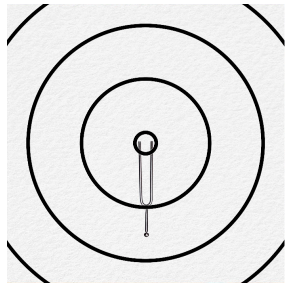
Another important item to remember is that without the medium, the pressure waves that are sound, have no way to propagate. In other words, sound will ***not*** propagate through a vacuum. Sound can propagate through solids, liquids, and gases, however, sound will not propagate in the absence of a medium to compress and rarify to create high and low pressure waves.

End note: There is a term called “pressure amplitude” which is simply the amplitude of the pressure wave. That means it is the maximum difference between the local pressure of the air and the atmospheric pressure. This can be illustrated on the sinusoidal wave, just like all other wave amplitudes. Therefore, a higher pressure amplitude means greater pressure amplitudes and therefore a larger amount of energy transferred by the sound wave. Oh, and it’s louder too.

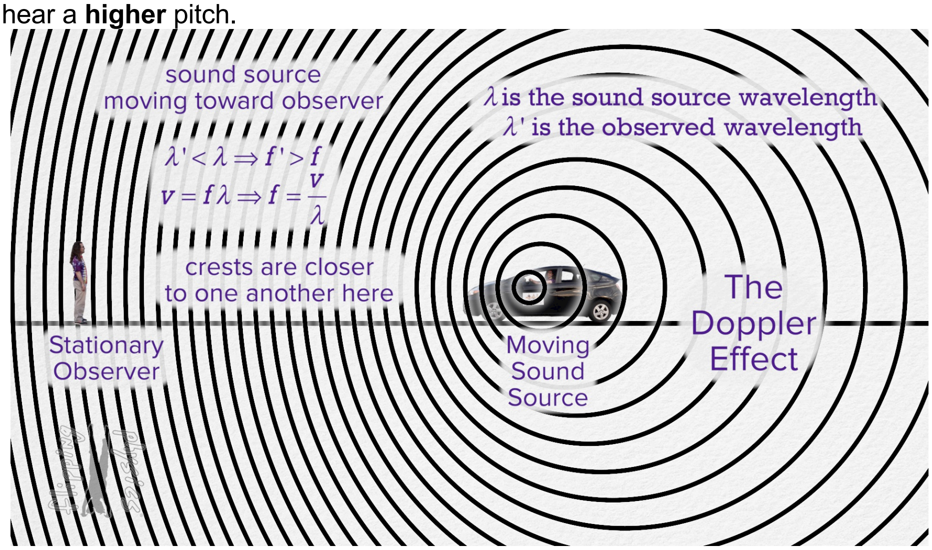
Flipping Physics Lecture Notes: Doppler Effect Demonstrations
https://www.flippingphysics.com/doppler-effect.html
(really, you need to ***hear*** The Doppler Effect!)

Remember from *What is Sound?*[1] that:

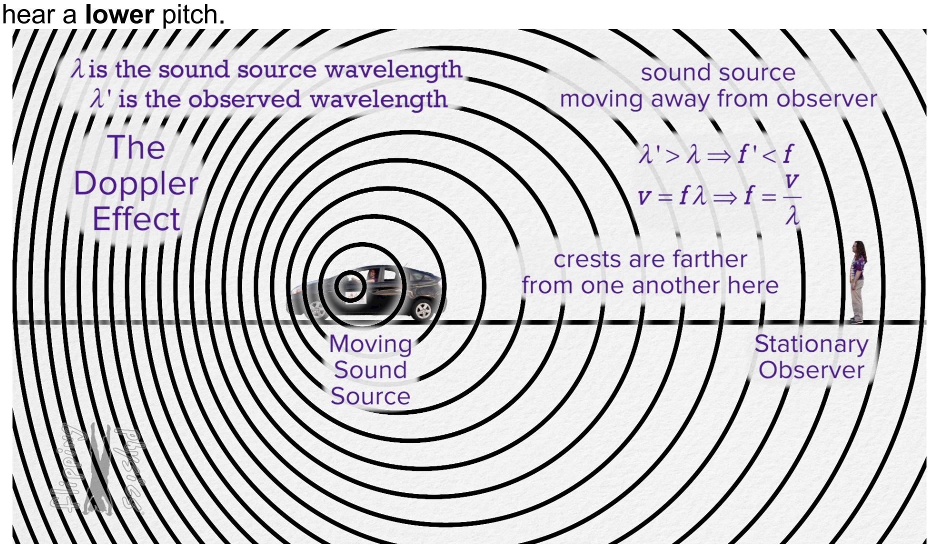
- Sound is a longitudinal, pressure wave.
- The lines are crests or wave fronts.
- Sound is periodic changes in pressure.
- Each crest is a location of high pressure.
- Sound is energy.
- This sound is in simple harmonic motion.
- Each circle is actually a sphere.



When the sound source is moving **toward** the observer, the wave fronts are observed to be **closer** to one another which makes the observed wavelength **smaller** and therefore the observed frequency **larger** and therefore we hear a **higher** pitch.



When the sound source is **away from** the observer, the wave fronts are observed to be **farther** from one another which makes the observed wavelength **larger** and therefore the observed frequency **smaller** and therefore we hear a **lower** pitch.

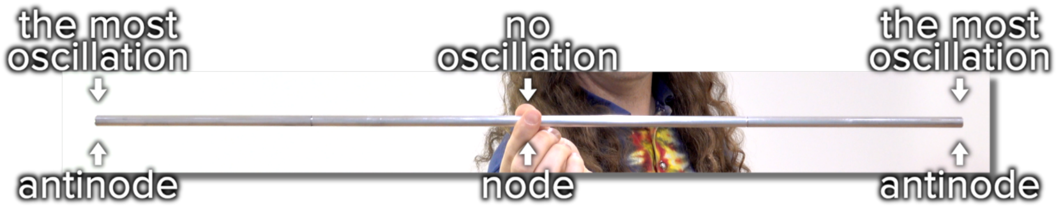


[1] Feel free to review Flipping Physics video "What is Sound?" at https://www.flippingphysics.com/sound.html

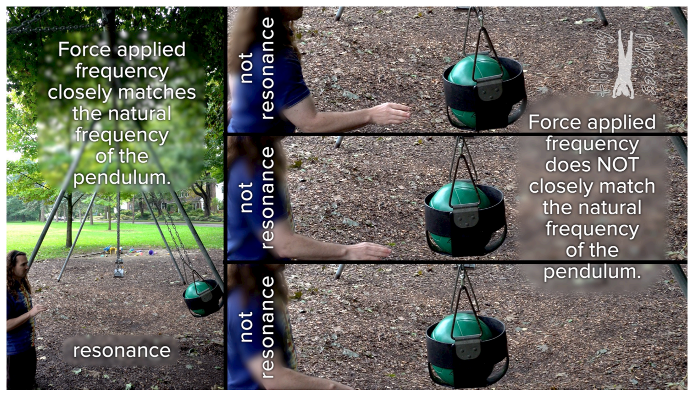
Flipping Physics Lecture Notes:
Resonance Introduction using 9 Demonstrations
https://www.flippingphysics.com/resonance.html
(really, you need to see and hear these demonstrations)

Resonance involves standing wave patterns. So, if you have not learned about standing waves, please enjoy my video about standing waves.[1]

The first example is called a “Singing Rod”. The vibration of the friction between my fingers and the aluminum rod set up a standing wave in the rod at its “resonance frequency” or its “natural frequency”. My fingers in the middle force a node at that point, and the two ends have their maximum amplitude vibration and are therefore antinodes.

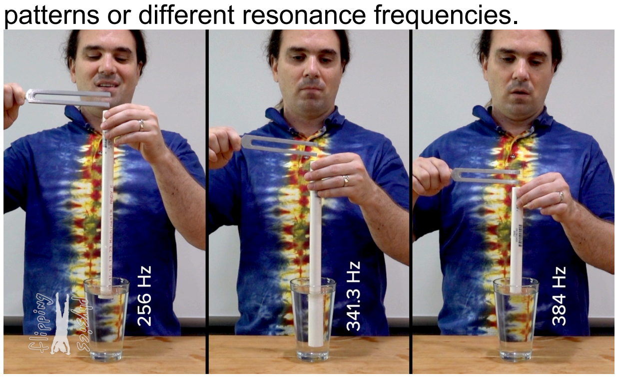


The second example is a swing. A swing is a pendulum which has a natural frequency of oscillation. If I apply a force to the swing at a frequency which closely matches the natural frequency of the pendulum, the force will amplify the oscillations. If I apply a force to the swing at a frequency which **does not** closely match the natural frequency of the pendulum, the force will **not** amplify the oscillations.



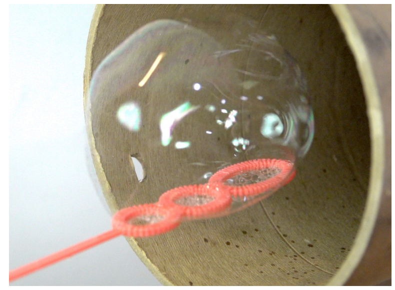
The third example is a goblet. Rubbing a damp finger along the rim of a goblet will cause standing wave patterns in the goblet which is the goblet vibrating at its resonance frequency. Adjusting the amount of water in the goblet will change the resonance frequency of the goblet.

The fourth example uses a tuning fork to oscillate a column of air inside a hollow tube. The water at the bottom of the hollow tube seals of that end of the tube. Therefore, moving the tube up and down adjusts the amount of the tube which is out of the water and therefore adjust the length of the air column inside the tube. Different air column lengths will have standing wave patterns or different resonance frequencies.



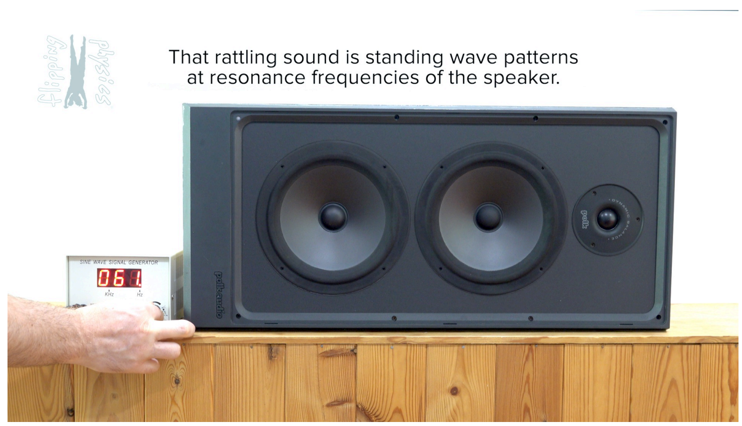
[1] “Standing Waves” video from Flipping Physics: https://www.flippingphysics.com/standing-waves.html

The fifth example uses a fixed length hollow tube which is open at both ends and speaker to adjust the sinusoidal frequency at which the speaker oscillates. At 68 hertz, a standing wave pattern is setup in the air column in the hollow tube which is a resonance frequency for this length hollow tube open at both ends. A soap bubble is used to show that the air is oscillating at the end of the tube.



The sixth example is a seashell. When you listen to a seashell, what you hear is various frequencies from the ambient noise setting up standing waves in the seashell at resonance frequencies for the air column inside the seashell. And the frequencies which do not match the resonance frequencies in the air column in the seashell are dampened. That results in an echoey sound some people call “The sound of the sea”.

The seventh example is a speaker which was dropped too many times and now has unidentified items which are loose and causing resonance in the speaker. This is not ideal for a speaker. This particular speaker has resonance frequencies below roughly 120 Hz. Above that frequency there appear to be no resonance frequencies in the speaker. In other words, do not drop your speakers, duh!



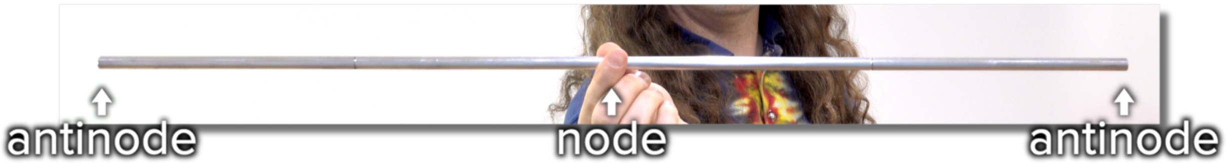
The eighth example is of resonance of the human body using a key fob. When I hold the key fob away from my body and I press the button, it sends out radio waves, and those radio waves should reach the car to lock and unlock the car, but unfortunately I am just a little bit too far away for that to work. What I can do instead is I can hold the key fob to my body, when I do so I can now lock and unlock the car. The radio waves which are sent out by the key fob have a wavelength and frequency which approximately match a resonance frequency and wavelength of my body, and therefore set up a standing wave pattern in my body which amplifies the signal and makes it so the signal can reach the car. The frequency used by key fobs for North American made vehicles is:

$$f_{fob} = 315 MHz = 315 \times 10^{6} Hz$$

And radio waves are electromagnetic radiation which move at the speed of light: $v_{radiowaves} = c = 3.0 \times 10^{8} \frac{m}{s}$

Therefore, the wavelength of key fob radio waves is:

$$v = f\lambda \Rightarrow \lambda = \frac{v}{f} = \frac{3.0 \times 10^{8}}{315 \times 10^{6}} = 0.95238 \approx 0.95\text{m}$$



The last thing we do is return to the very first example and perform some calculations. Because the rode has two antinodes and one node, half a wavelength fits on the rod. The length of the rod is 0.750 m and audio analysis gives 3310 Hz for the frequency emanating from the resonating rod:

$$L = \frac{\lambda}{2} \Rightarrow \lambda = 2L \;\&\; v = f\lambda = f\left(2L\right) \;\&\; L = 0.750m;\; f = 3310Hz$$

$$\lambda = 2L = \left(2\right)\left(0.75\right) = 1.50m \Rightarrow v = f\lambda = \left(3310\right)\left(1.5\right) = 4965 \approx 4960\frac{m}{s}$$

Therefore, the speed of sound in the rod is 4960 meters per second.

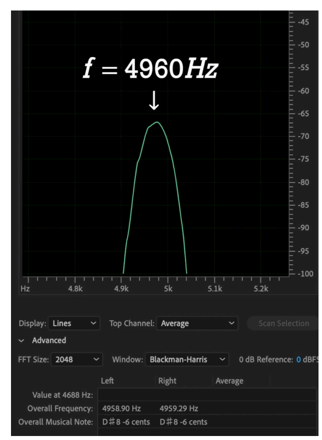
According to EngineeringToolbox.com[2], the speed of sound in rolled, extensional Aluminum, which is what this rod is made of, equals 5000 meters per second.

The ninth example decreases the length of the rod, however, the material is the same so the speed of sound in the rod should be the same. We can predict that a shorter rod should give a higher frequency:

$$L_2 < L_1 \Rightarrow \lambda_2 < \lambda_1 \;\&\; \lambda = \frac{v}{f} \Rightarrow f_2 > f_1$$

We can also predict the frequency which should come from the resonating shorter rod:

$$L_1 = 0.750m \Rightarrow \lambda_1 = 1.50m \;\&\; f_1 = 3310Hz \Rightarrow v_1 = 4960\frac{m}{s} \;\&\; L_2 = 0.500m \Rightarrow f_2 = ?$$



$$L_2 = \frac{\lambda_2}{2} \Rightarrow \lambda_2 = 2L_2 = \left(2\right)\left(0.5\right) = 1.00m$$

$$v_1 = 4960\frac{m}{s} = v_2 = v = f\lambda \Rightarrow f_2 = \frac{v}{\lambda_2} = \frac{4960}{1} = 4960Hz$$

And audio analysis of the sound gives 4960 Hz because, the physics works!

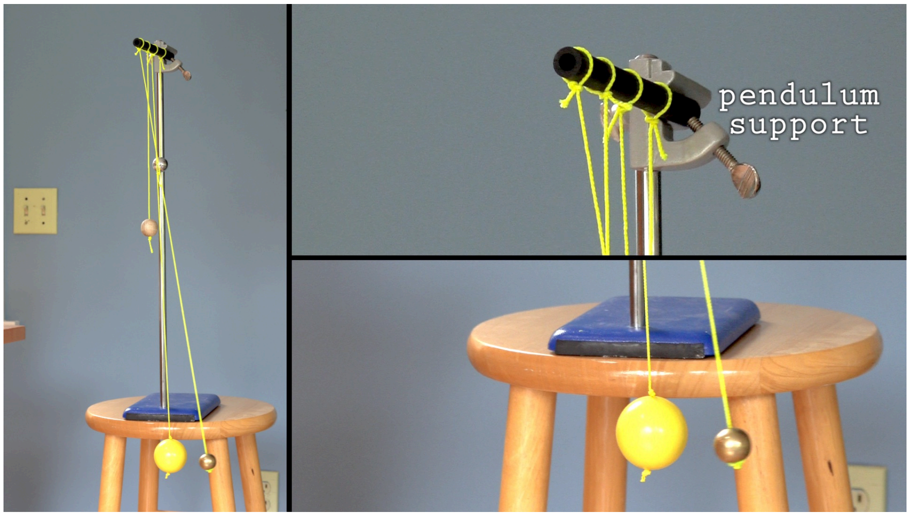
[2] https://www.engineeringtoolbox.com/sound-speed-solids-d_713.html

Flipping Physics Lecture Notes:

Sympathetic Vibrations by Bobby
https://www.flippingphysics.com/sympathetic-vibrations.html

Sympathetic vibrations are when an object begins to oscillate or vibrate because of an external vibration which matches the resonance frequency of the object. In other words, when the resonance[1] of one object causes another object to resonate, that is sympathetic resonance or sympathetic vibrations.

The example shown in the video is that a pendulum oscillating can cause small oscillations of its support. If other pendulums are attached to the same support, pendulums with similar resonance frequencies.



In the above picture, the oscillating brass pendulum is causing a slight motion of the pendulum support which is then causing the yellow pendulum to oscillate.

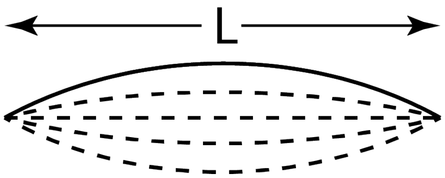
Another example is that a single plucked string of a guitar will cause other strings in the guitar to also vibrate. This is because the original plucked string will cause the guitar to vibrate and therefore cause other strings with similar resonance frequencies to also vibrate.

[1] Resonance Introduction using 9 Demonstrations - https://www.flippingphysics.com/resonance.html

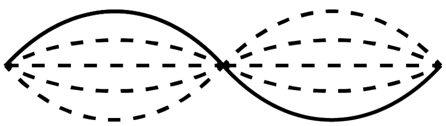
Flipping Physics Lecture Notes:

Stringed Instrument Frequencies
https://www.flippingphysics.com/stringed-instrument.html

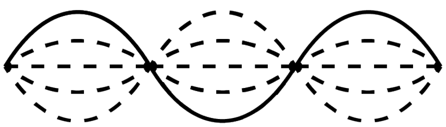
Stringed instruments set up standing wave patterns on the strings to create frequencies or what we hear as pitch. These instruments have strings which are fixed in place on either end. This means the ends of the strings must be nodes.



$$\frac{1}{2}\lambda_1 = L \Rightarrow \lambda_1 = 2L \;\&\; v = f\lambda \Rightarrow f_1 = \frac{v}{\lambda_1} = \frac{v}{2L} = 1\left(\frac{v}{2L}\right)$$



$$\lambda_2 = L \Rightarrow f_2 = \frac{v}{\lambda_2} = \frac{v}{L} = 2\left(\frac{v}{2L}\right)$$



$$\frac{3}{2}\lambda_3 = L \Rightarrow \lambda_3 = \frac{2L}{3} \;\&\; f_3 = \frac{v}{\lambda_3} = \frac{v}{2L/3} = \frac{3v}{2L} = 3\left(\frac{v}{2L}\right)$$

$$\boxed{f_n = n\left(\frac{v}{2L}\right)}$$

The frequencies created by a stringed instrument:

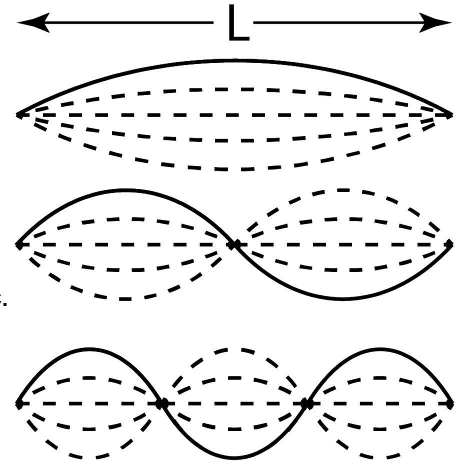
- v is the speed of the wave on the string.
- L is the length of the string.
- n is the *harmonic number*.
- n = 1 is the *first harmonic* and the *fundamental frequency*.
- n = 2 is the *second harmonic*.
- n = 3 is the *third harmonic* … and so on.
- Each of the harmonics is an integer multiple of the fundamental frequency.
    -

$$f_1 = 1\left(\frac{v}{2L}\right) = \frac{v}{2L} \;\&\; f_2 = 2\left(\frac{v}{2L}\right) = 2f_1 \Rightarrow f_2 = 2f_1 \;\&\; f_3 = 3f_1 \;\&\; etc.$$

Wind Instrument Frequencies

https://www.flippingphysics.com/wind-instrument.html

Previously we determined the equation for the harmonic frequencies of stringed instruments.
https://www.flippingphysics.com/stringed-instrument.html



$$f_n = n\left(\frac{v}{2L}\right)$$

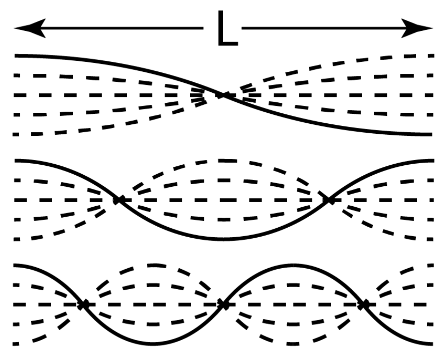
This is based on the fact that the ends of strings are fixed and therefore must be nodes. This means the standing wave patterns of the first three harmonics look like the diagrams on the right.

We are now determining the equations for the harmonic frequencies of wind instruments. Wind instruments create a frequency and pitch by creating standing waves in the air columns of instruments. Wind instrument examples are trumpets, tubas, clarinets, flutes, oboes, etc. There are two categories of wind instruments:

- Open Pipe. (Open on both ends.)
- Closed Pipe. (Closed on one end and open on the other.)

An open end creates an antinode and a closed end creates a node.

Let's begin with an open pipe instrument like a flute. Considering both ends are open and an open end is an antinode, this is what the first three standing wave patterns look like:



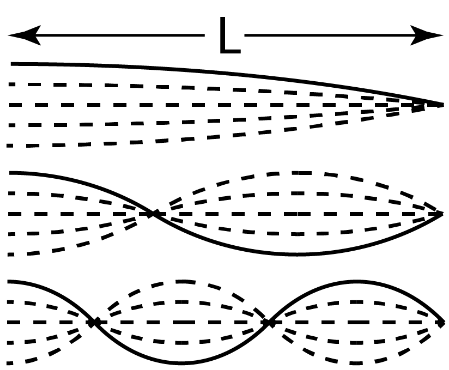
Notice the pattern actually ends up being exactly the same. The first standing wave pattern has half a wavelength in the open pipe. The second standing wave pattern has one wavelength. The third standing wave pattern has one and a half wavelengths. This means the equation for an open pipe instrument is exactly the same as the equation for a stringed instrument.

$$f_n = n\left(\frac{v}{2L}\right)$$

- Same equation.
- Same harmonic number "n".
- v is the speed of sound in air.

This is the equation for the harmonic frequencies of stringed instruments and open pipe wind instruments.

Closed pipe instruments, like a clarinet, have one closed end and one open end. The open end has an antinode and the closed end has a node. This means the first three standing wave patterns look like this:



$$\frac{1}{4}\lambda_1 = L \Rightarrow \lambda_1 = 4L \;\&\; v = f\lambda \Rightarrow f_1 = \frac{v}{\lambda_1} = \frac{v}{4L} = 1\left(\frac{v}{4L}\right)$$

$$\frac{3}{4}\lambda_3 = L \Rightarrow \lambda_3 = \frac{4L}{3} \;\&\; f_3 = \frac{v}{\lambda_3} = \frac{v}{4L/3} = 3\left(\frac{v}{4L}\right)$$

$$\frac{5}{4}\lambda_5 = L \Rightarrow \lambda_5 = \frac{4L}{5} \;\&\; f_5 = \frac{v}{\lambda_5} = \frac{v}{4L/5} = \frac{5v}{4L} = 5\left(\frac{v}{4L}\right)$$

The equation for the harmonic frequencies for a closed pipe is:

$$f_m = m\left(\frac{v}{4L}\right)$$

- v is the speed of the wave on the string.
- L is the length of the string.
- m is the *harmonic number*.
- m = 1 is the *first harmonic* and the *fundamental frequency*.
- m = 3 is the *third harmonic*.
- m = 5 is the *fifth harmonic* … and so on.
    - Only ***odd*** integer harmonics are possible in a closed pipe instrument.
- Each of the harmonics is an ***odd*** integer multiple of the fundamental frequency.
    - $$f_1 = 1\left(\frac{v}{4L}\right) = \frac{v}{4L} \;\&\; f_3 = 3\left(\frac{v}{4L}\right) = 3f_1 \Rightarrow f_3 = 3f_1 \;\&\; f_5 = 5f_1 \;\&\; etc.$$

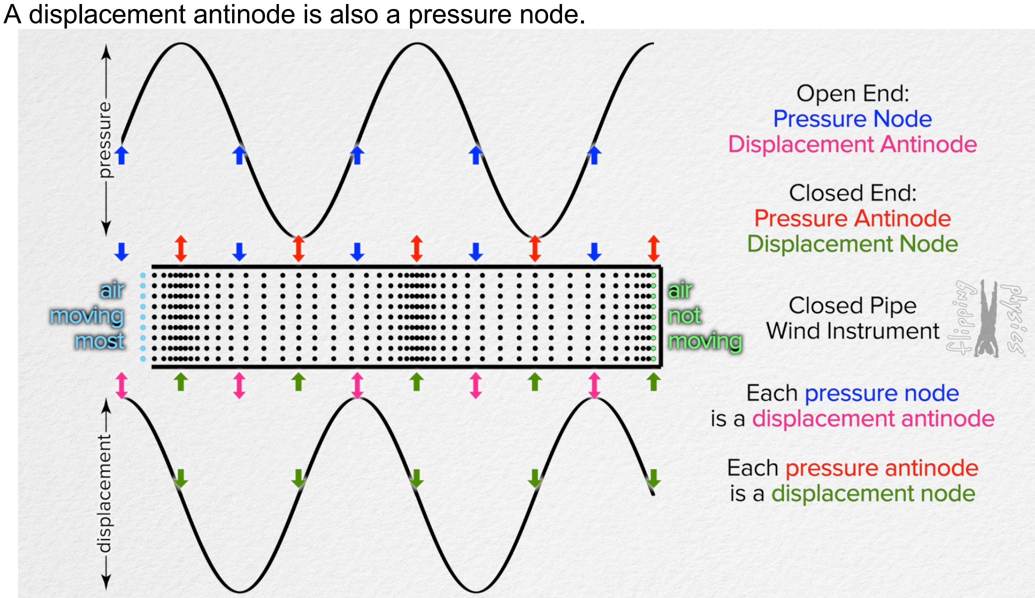
In standing waves in air columns, it is important to understand the difference between:

- Pressure nodes and antinodes.
- Displacement nodes and antinodes.

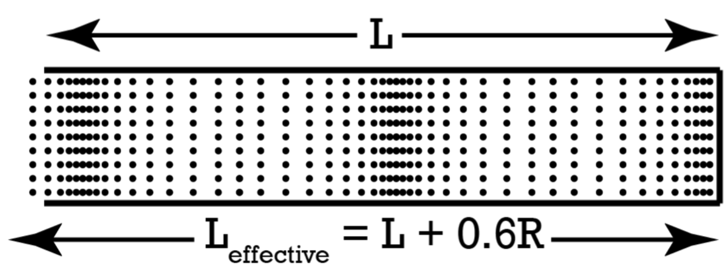
A closed end is a displacement node because the air cannot move through the closed end. This makes the open end of a pipe a displacement antinode. In other words, all of the illustrations we have used so far are in terms of displacement nodes and antinodes.

An open end is a pressure node because the open end is open to the atmosphere and therefore is constant at atmospheric pressure. This makes the closed end of a pipe a pressure antinode. To be clear:

- A displacement node is also a pressure antinode.
- A displacement antinode is also a pressure node.



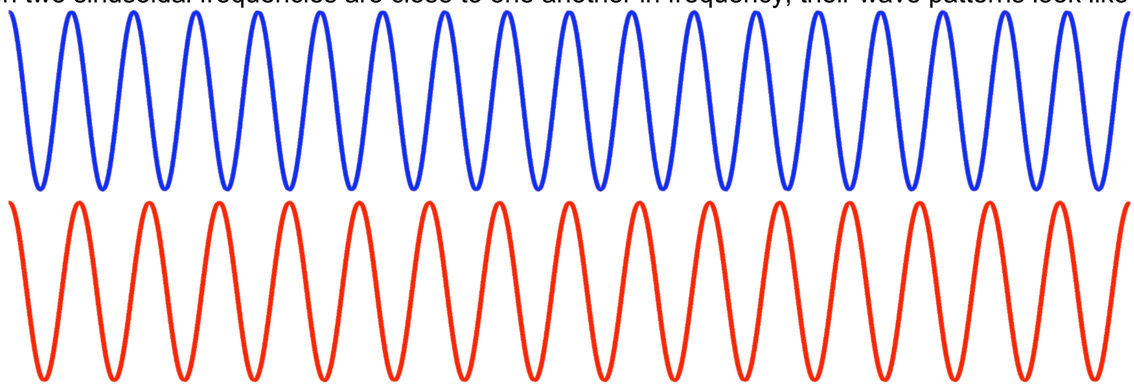
Lastly, know that the open end of a pipe is not quite where the location of the pressure node and displacement antinode is. The air does actually oscillate outside the end of the pipe a little bit. In other words, the length of the oscillating column of air in a wind instrument or the effective length of a pipe is a little bit longer than the measured length of the pipe. For a circular cross section pipe, an end correction of 0.6R needs to be added to the length of the pipe for each open end.



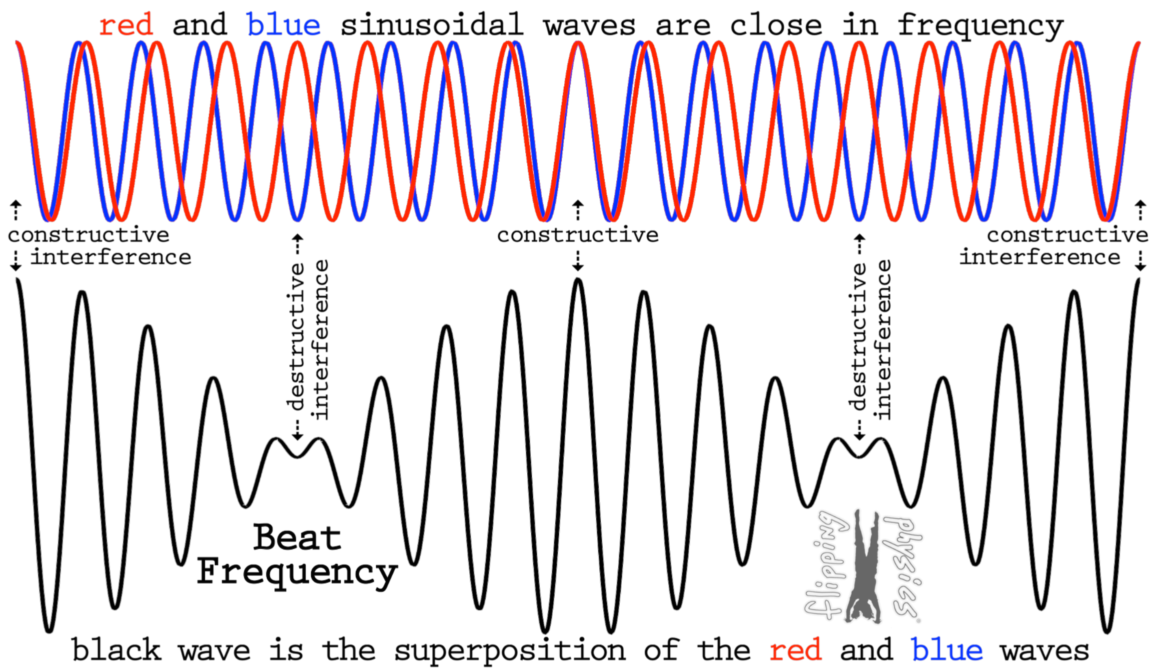
Flipping Physics Lecture Notes:

Beat Frequency by Bo
https://www.flippingphysics.com/beat-frequency.html

When two sinusoidal frequencies are close to one another in frequency, their wave patterns look like this:



When overlapped, you can see that the two waves alternate between being in phase and therefore constructively interfering with one another to create a larger amplitude and then being out of phase and therefore destructively interfering with one another to create a smaller amplitude. When this happens, the amplitude of the two combined waves increases and decreases at the beat frequency and that is why you hear “beats”.



Beats can be used to tune musical instruments, like a guitar. The fourth harmonic of the low E string is the same frequency as third harmonic of the A string. If the two harmonics are played and the two frequencies are slightly off from one another, the beat frequency will be heard. You can adjust the frequency of one string until beats are no longer heard. When that occurs, the two strings are now in tune with one another.