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.

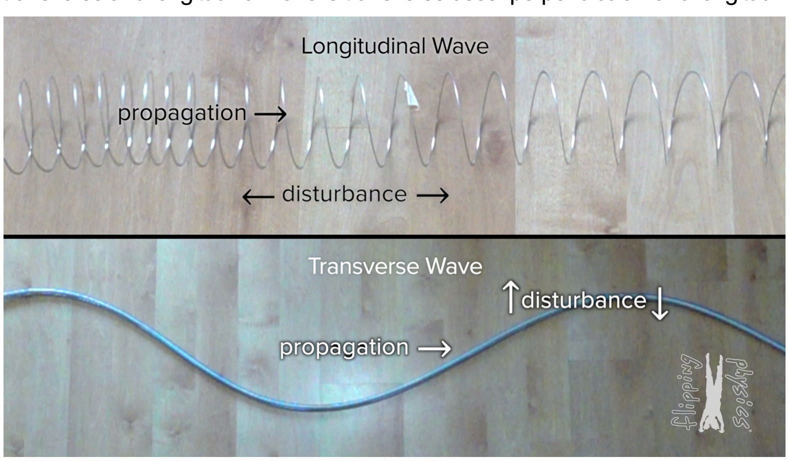
Please note that electromagnetic waves are not mechanical waves and do not require a medium to travel through. Visible light and radio waves are components of the electromagnetic wave spectrum. We will discuss these concepts in detail in later lessons. This lesson is about mechanical waves.

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.”)



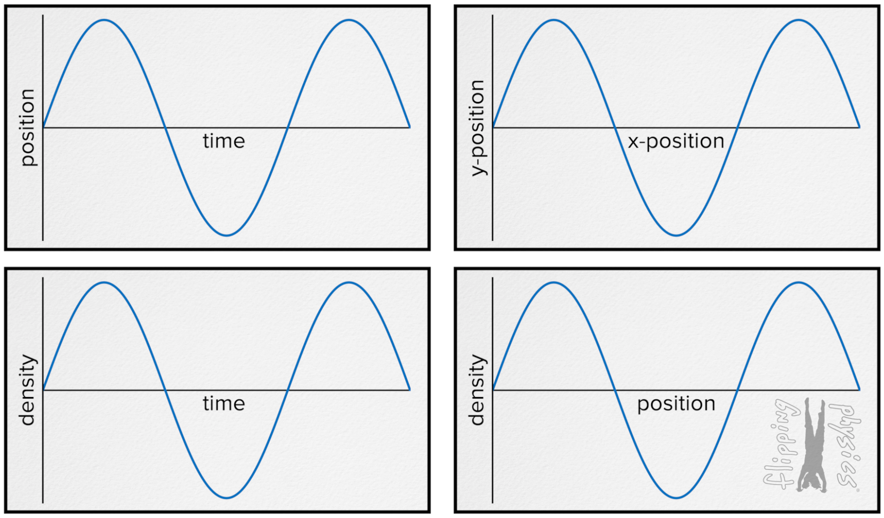
[1] https://dictionary.cambridge.org/us/dictionary/english/transverse
[2] https://dictionary.cambridge.org/us/dictionary/english/longitudinal
[3] https://dictionary.cambridge.org/us/dictionary/english/lengthwise

Flipping Physics Lecture Notes:

Wave Graphs - Longitudinal and Transverse - Wavelength and Period

https://www.flippingphysics.com/wave-graphs.html

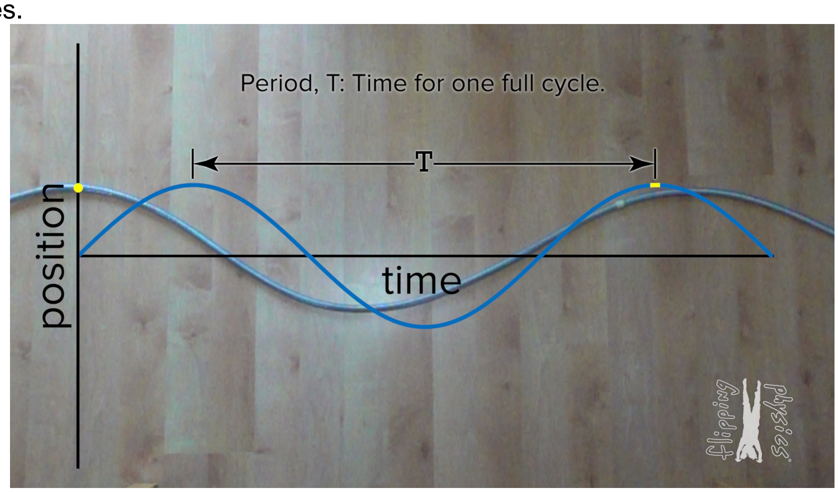
These are four graphs of mechanical waves which, at first, might look identical, however, it is very important that you understand the differences.



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.

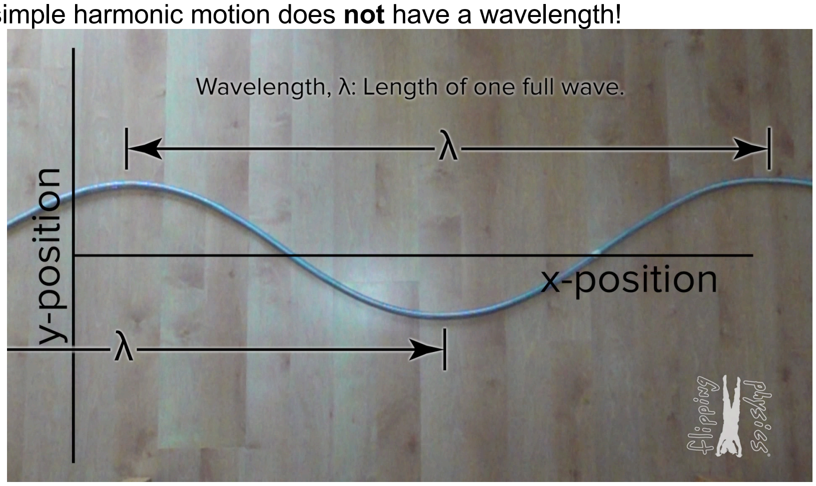
Let’s change the x-axis now to position in the x-direction. Notice this graph can no longer describe the motion of a mass-spring system moving in simple harmonic motion, because a mass-spring system only moves in one dimension. However, this graph can describe the motion of a mechanical wave. This graph 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:

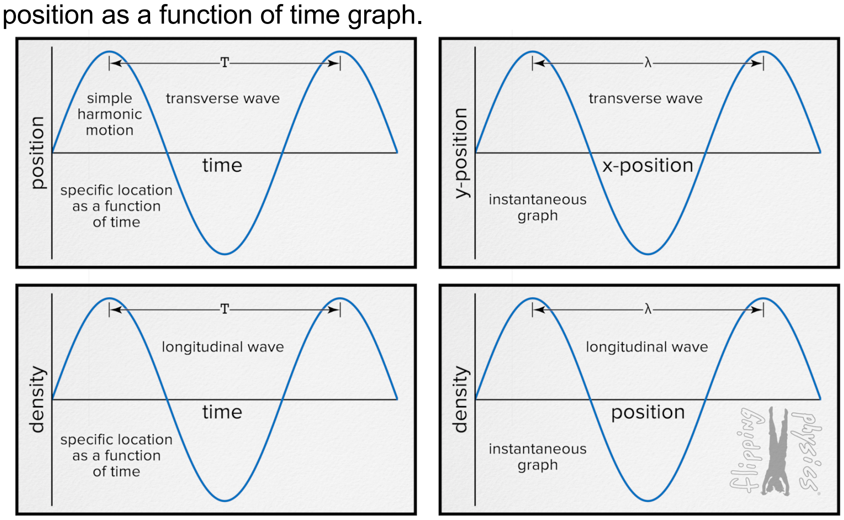
- Wavelength: The length of one complete wave cycle. Measured from crest to successive crest, trough to successive trough. In other words, measured from one point on the wave to the next corresponding point on the wave which is going in the same direction.
- Wavelength: The distance travelled by a wave 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 $v=f\lambda=\left(3.448276\right)\left(1.58\right)=5.448276\approx 5.4\frac{m}{s}$

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:

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

Flipping Physics Lecture Notes:

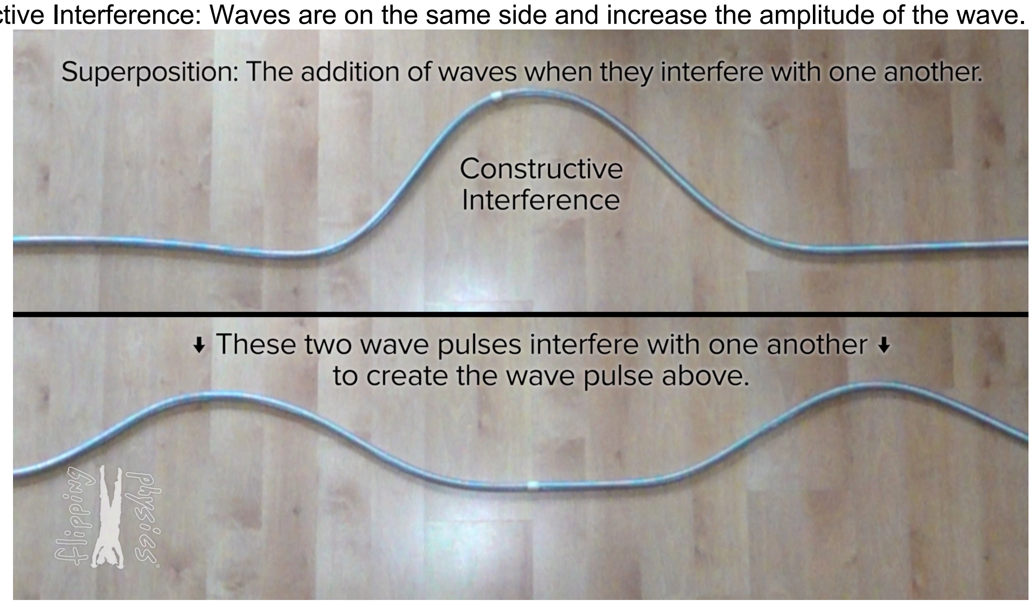
Wave Superposition Introduction

https://www.flippingphysics.com/wave-superposition.html

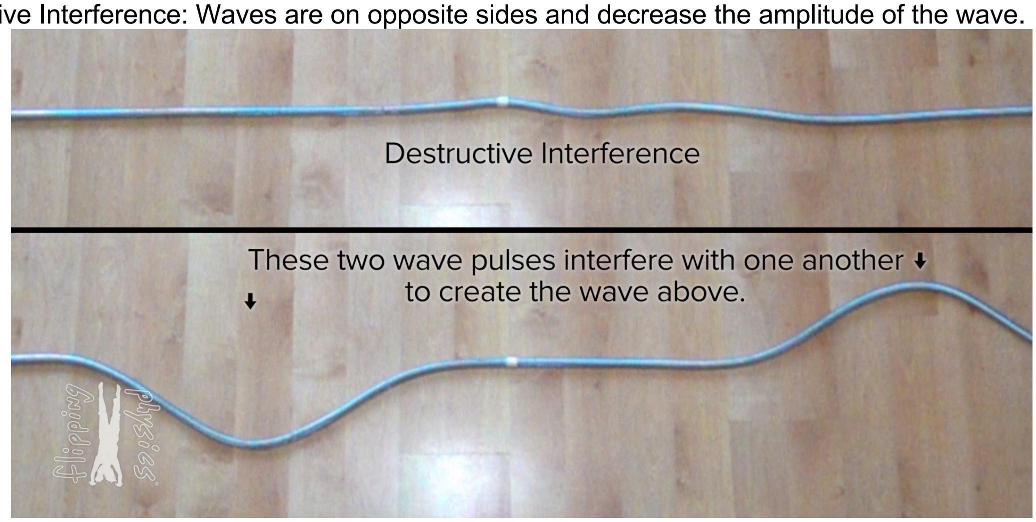
It is a rather well-established fact that two objects cannot occupy the same space at the same time. However, waves are not objects. Waves are a disturbance of a medium which travels through the medium transferring energy from one place to another. Which means waves *can* occupy the same space at the 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.



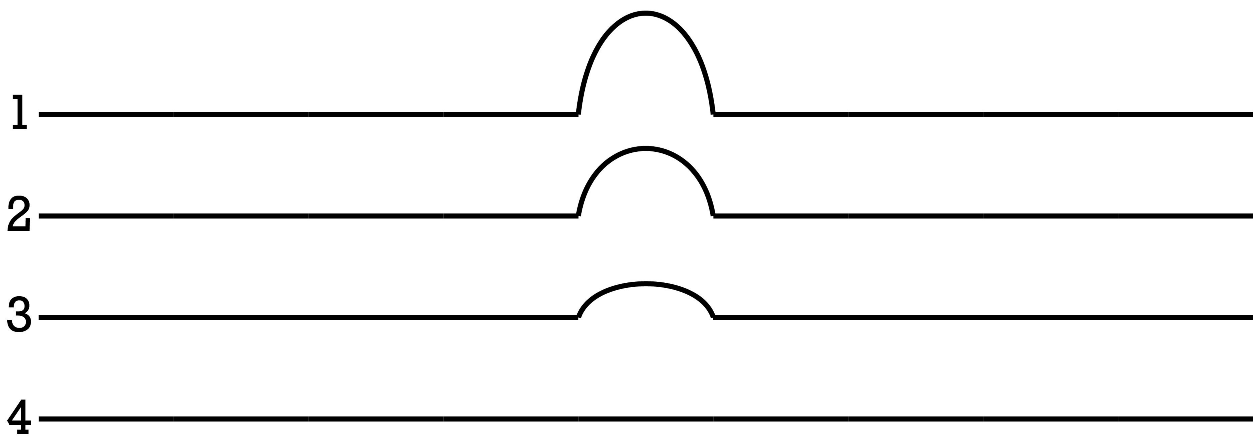
- *Total* Destructive Interference: Waves completely cancel one another out and the net result is no wave. This requires the waves to be mirror images of one another.

Flipping Physics Lecture Notes:

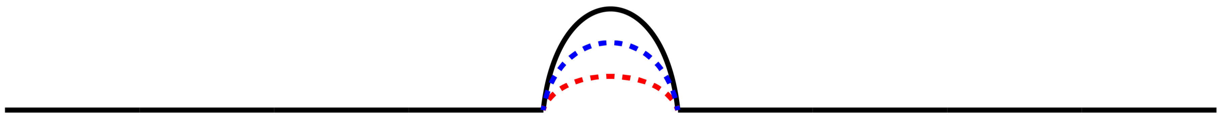
Wave Superposition Multiple Choice Problems

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.)

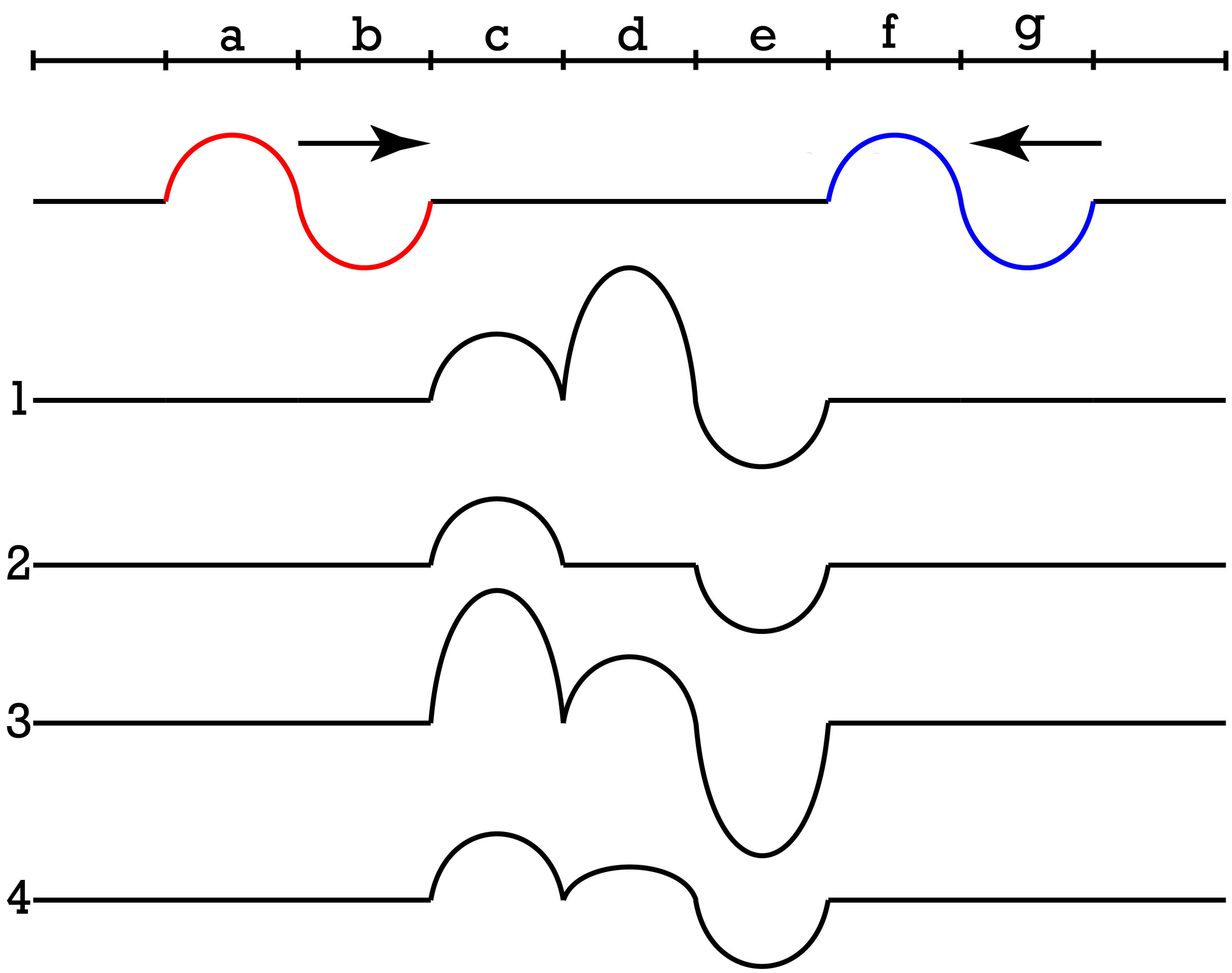


The correct answer is 1. This is wave interference via superposition. The two waves constructively interfere, and the resultant waveform is the addition of the two original waves:

1 

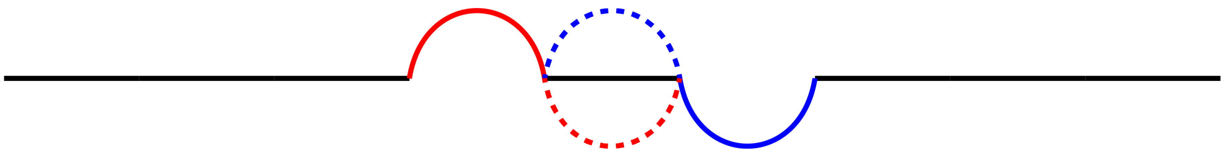
It is important to realize what happens after the two wave pulses interfere with one another. They will simply move on as if they never interfered in the first place. Which looks like this:

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.)

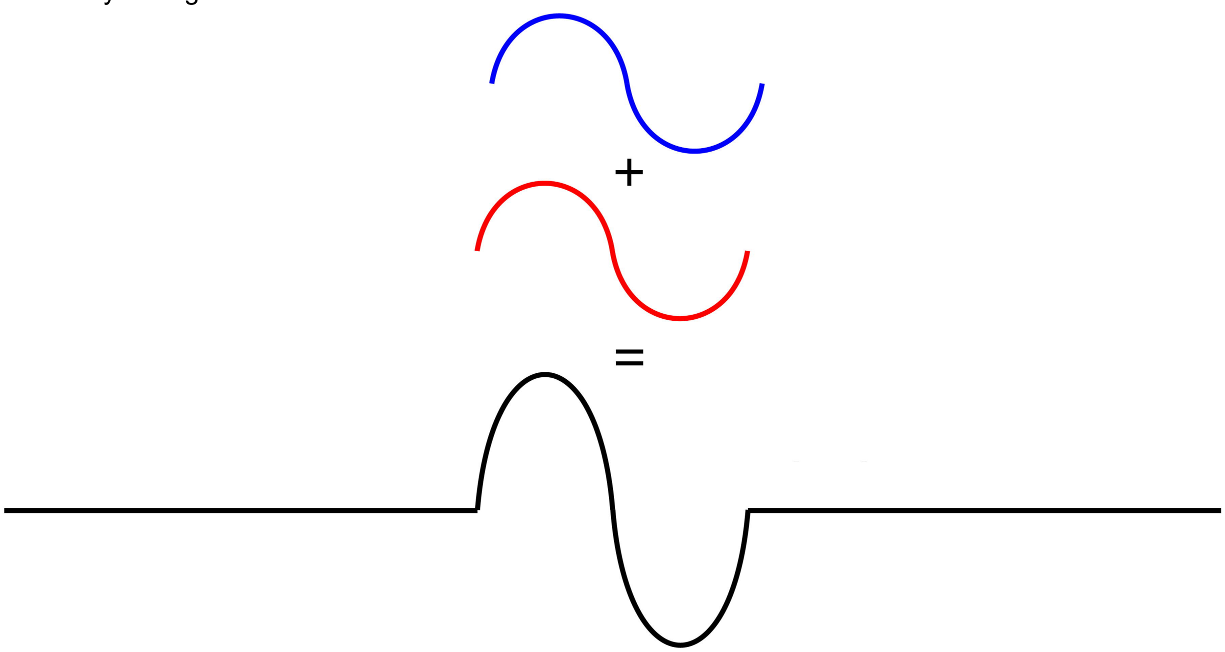


The correct answer is 2: Again, this is wave interference via superposition. However, the two waves only interfere with one another when they occupy the same space. They do **not** occupy the same space in regions c and e. They only occupy the same space in region d. Therefore, the original waves are 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.

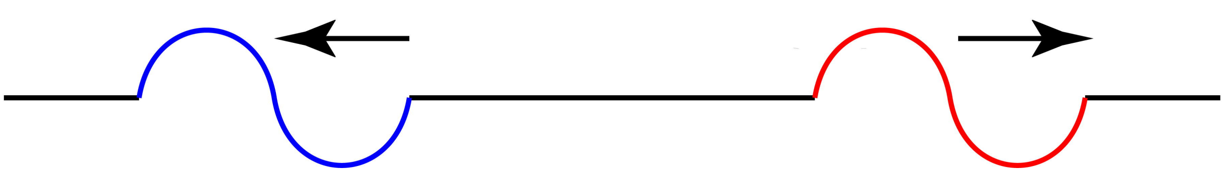
2



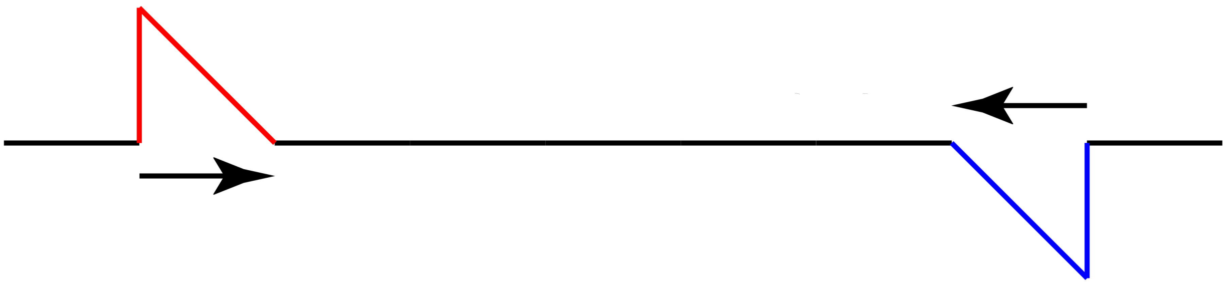
And here is what the two waves will look like while they occupy the same space which is halfway through c to halfway through e:



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.)



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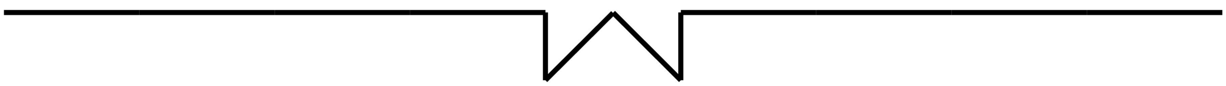

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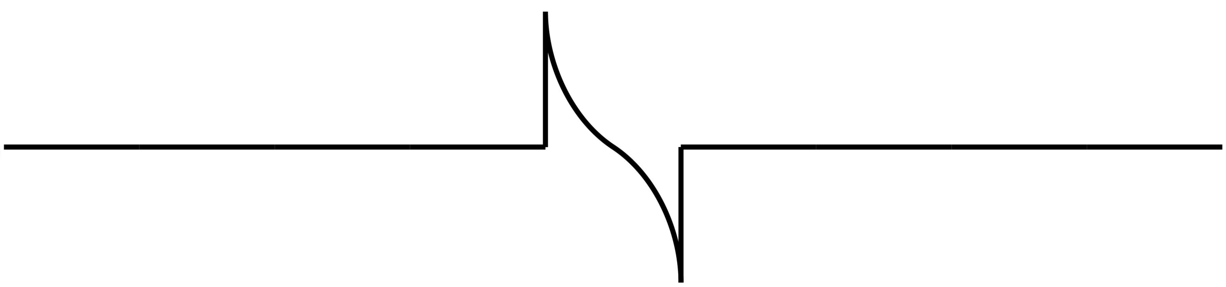

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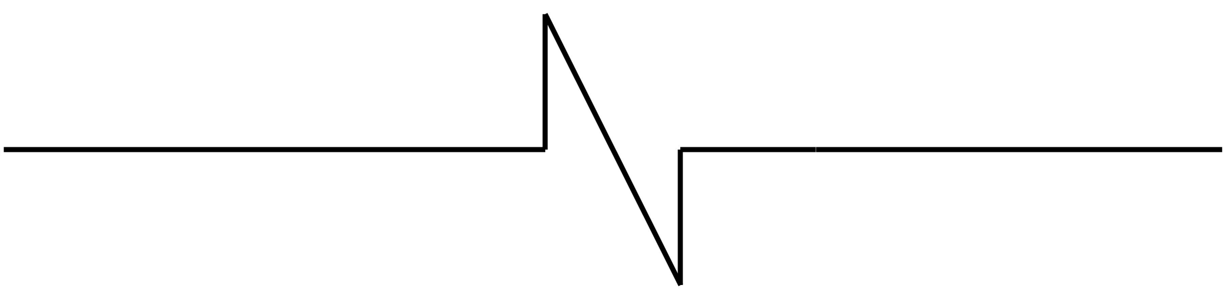
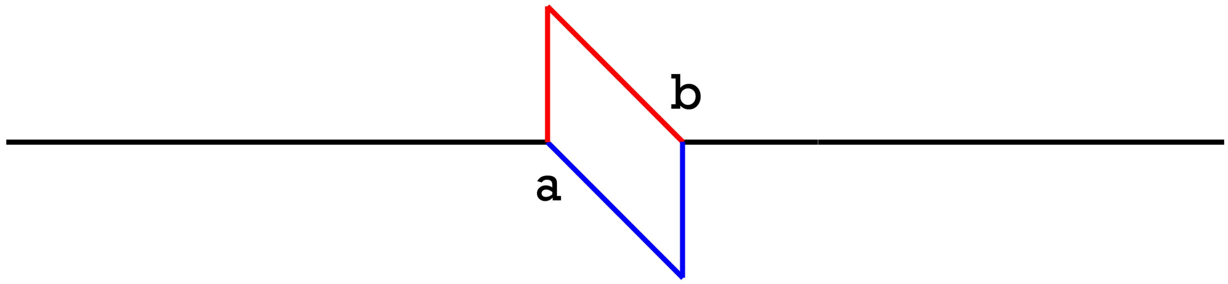


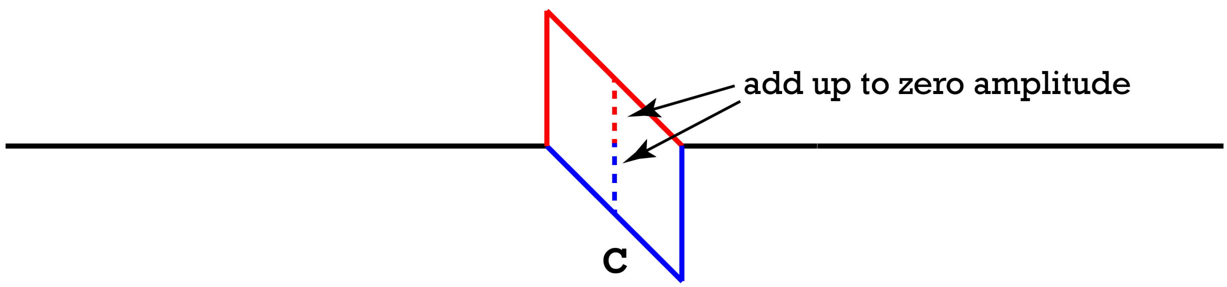
Again, again, this is wave interference via superposition. This is what the two waves look like individually when they occupy the same space. (Before we figure out the superposition.)



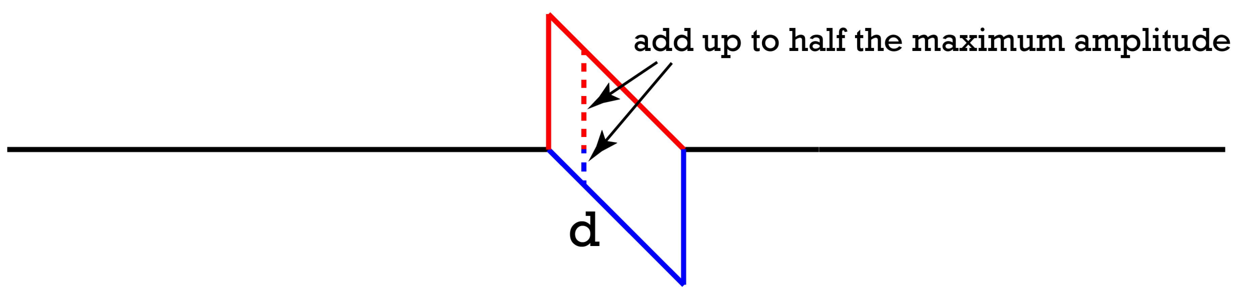
Let's look at a few points to see how they interfere via superposition.

- 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.

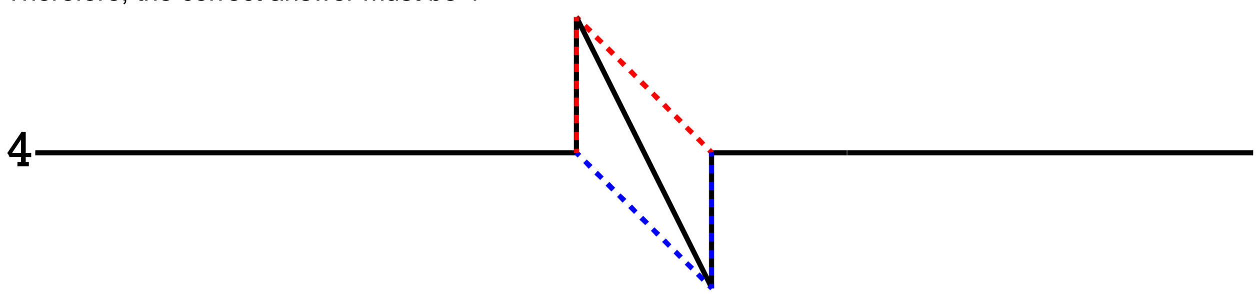
Location c: Right in the middle of the two waves. The amplitude of the red wave is half its maximum height. The amplitude of the blue wave is half its maximum height. However, the red wave is above the string and the blue wave is below the string. These two amplitudes cancel one another out and the net 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 1/4th of the maximum amplitude below equilibrium. Those add up to ½ the maximum amplitude above equilibrium.



Therefore, the correct answer must be 4



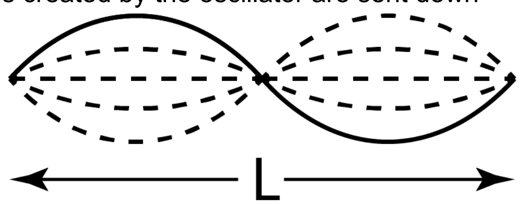
Flipping Physics Lecture Notes:

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.

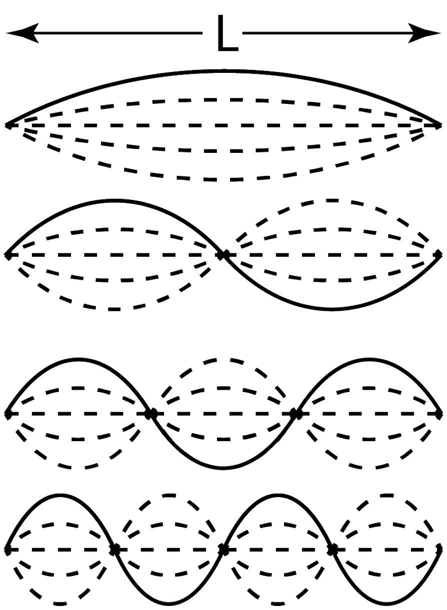
- When a wave pulse comes to a fixed end, it will be reflected and inverted.
  - Fixed end = reflection with inversion.
- When a wave pulse comes to a free end, it will be reflected, however, it will not be inverted.
  - Free end = reflection without inversion.[1]

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.

[1] https://phet.colorado.edu/en/simulation/wave-on-a-string

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

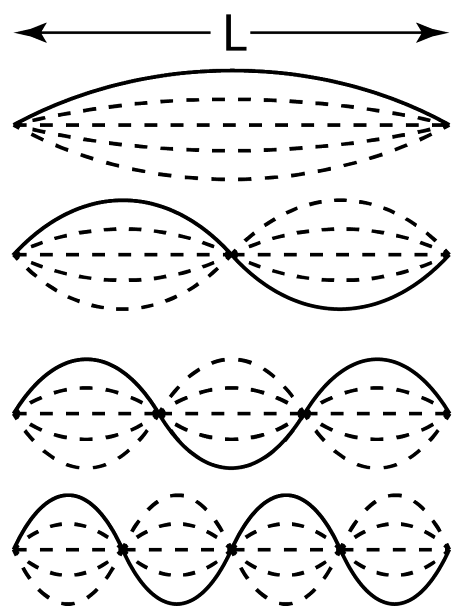
As we demonstrated before, standing wave patterns can only be created at specific wavelengths. To the right are some options for possible standing wave patterns in a string.

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	$\lambda_{15} = 2L = (2)(0.865) = 1.73\text{m}$	$v = f_{15}\lambda_{15} = (15)(1.73) = 25.95\dfrac{m}{s}$
30	$\lambda_{30} = L = 0.865m$	$v = f_{30}\lambda_{30} = (30)(0.865) = 25.95\dfrac{m}{s}$
45	$\lambda_{45} = \dfrac{2L}{3} = \dfrac{(2)(0.865)}{3} = 0.57\bar{6}\text{m}$	$v = f_{45}\lambda_{45} = (45)(0.57\bar{6}) = 25.95\dfrac{m}{s}$
61	$\lambda_{61} = \dfrac{L}{2} = \dfrac{0.865}{2} = 0.4325\text{m}$	$v = f_{61}\lambda_{61} = (61)(0.4325) = 26.815\dfrac{m}{s}$
76	$\lambda_{76} = \dfrac{2L}{5} = \dfrac{(2)(0.865)}{5} = 0.346\text{m}$	$v = f_{76}\lambda_{76} = (76)(0.346) = 26.296\dfrac{m}{s}$

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

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

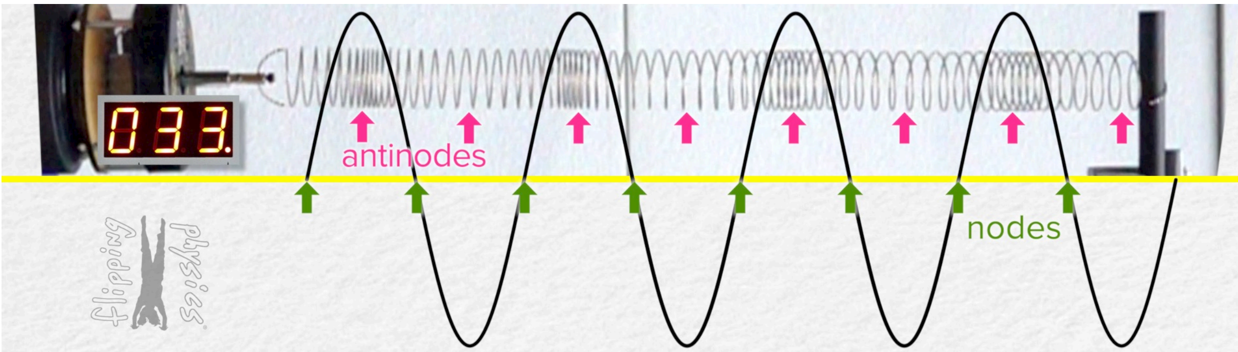
$$speed = \frac{distance}{time} = \frac{2L}{\Delta t} = \frac{(2)(0.865)}{0.068} = 25.441 \approx 26\frac{m}{s}$$

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

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-waves-longitudinal.html



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