We will begin lecture 19 by repeating the Swinging Buzzer Demo for the Doppler Effect. Please look at the following simulation for the case of a moving source:

http://www.walter-fendt.de/ph11e/dopplereff.htm

You should be able to see that the frequency received by the person only depends on whether the ambulance is approaching or receding; it has nothing to do with the distance between the ambulance and the person. That distance affects the intensity of the arriving sound, but not the frequency.

Our final topic in Waves is SUPERPOSITION and INTERFERENCE. We will be adding waves from two or more different sources. We will find that the combined waves can be surprisingly different from the source waves; these differences are due to INTERFERENCE EFFECTS.

What does it mean to talk about ADDING WAVES from two different sources? It means that the two disturbances from the two sources arrive at the same location $\mathbf{r}$ at the same time. Of course, there is only one particle at a particular $\mathbf{r}$, and that particle can only behave in one way; so our question really is, "How does that particle behave when it is under the influence of both traveling waves at the same time?" This question is answered by the

PRINCIPLE OF LINEAR SUPERPOSITION

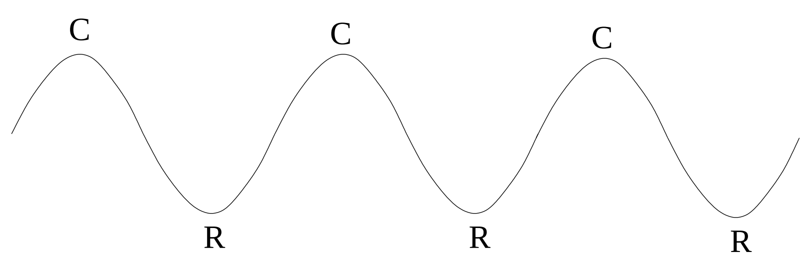
When two or more waves are present simultaneously at the same place, the resultant disturbance is the sum of the disturbances from the individual waves.

This is just a fancy way of saying that "disturbances add". Please Check Your Understanding (CYU) of this idea by doing Chapter 17, CYU 1 from page 486 of our textbook. You should complete that CYU successfully before continuing with this reading. If you have trouble, check out the following computer demo:

http://www.surendranath.org/Applets/Waves/Twave02/Twave02Applet.html

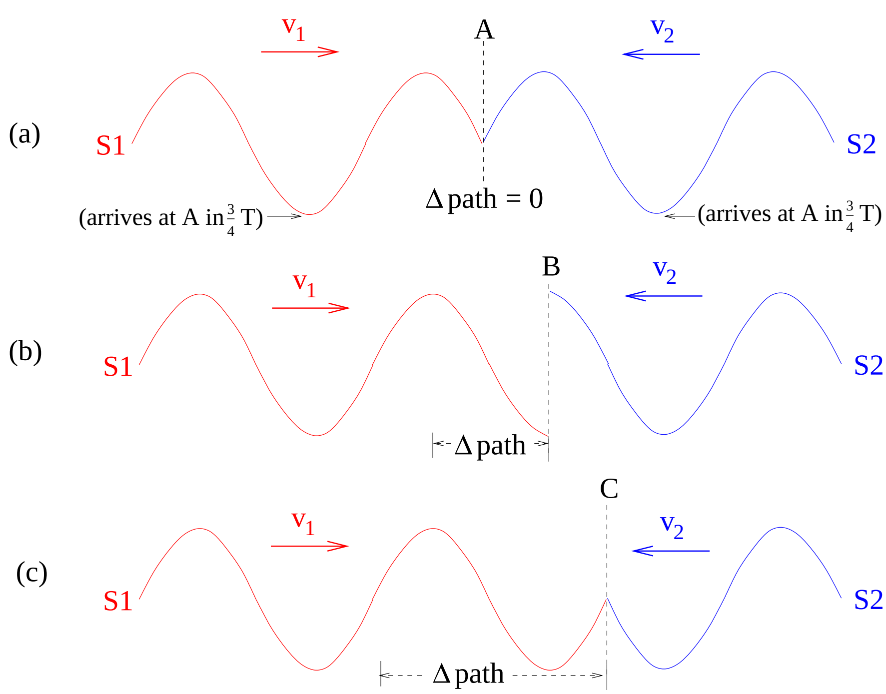
In this demo, the individual waves (or pulses) are shown in blue and red, the combined wave in yellow. We will look at this demo during lecture, where you will get a chance to ask questions.

A word of warning about this chapter. We will be drawing lots of waves. Because longitudinal waves are difficult to draw, and transverse waves are easy to draw, we adopt the habit of drawing the condensations as crests and the rarefactions as troughs; in this way, we can represent a longitudinal wave with a transverse drawing, as shown here:



But you must always remember that, for a longitudinal wave, the particles of the medium are moving back and forth along the direction of propagation. The habit is not really so bad, because the condensations are regions of higher particle density (and thus higher pressure) and the rarefactions are regions of lower particle density (and thus lower pressure). Therefore, the drawing can be regarded as a graph of density, or pressure, versus location; this is why many people like to think about sound waves as density, or pressure, waves.

If you were successful with CYU 1, then you probably realize that the basic idea of adding waves is rather simple; but, this simple idea can give rise to fascinating effects. The key to these interesting effects are the ideas of IN PHASE and 180° OUT OF PHASE that we covered in lecture 18. Two points on a harmonic traveling wave are in phase if they are 1λ (or 2λ's, 3λ's, 4λ's, etc.) apart. Two points on a harmonic traveling wave are 180° OUT OF PHASE if they are $\frac{1}{2}\lambda$ (or $1\frac{1}{2}\lambda$'s, $2\frac{1}{2}\lambda$'s, $3\frac{1}{2}\lambda$'s, etc.) apart. (Note: Our book uses the phrase "exactly out of phase" instead of 180° out of phase. This choice is a bit strange; I don't think I have seen it anywhere else.) The pictures below indicate how interesting effects can be created with two harmonic sources of identical frequency that are IN PHASE with one another. These might be any kind of harmonic wave, tranverse or longitudinal, but I am thinking of sound waves as I draw the pictures. Sound waves from each source would be going in all spherical directions, but I have only drawn the part of the wave from each source going in the direction of interest for this example, i.e. directly towards the other source. The wave from source 1 (S1) is drawn in red; the wave from source 2 (S2) is drawn in blue. The wave from S1 is traveling to the right; the wave from S2 is traveling to the left. Both waves have the same amplitude. Three cases are shown; in each case the point of interest is indicated with a dotted line. In viewing my drawings, you must always remember that the two waves in each case are TRAVELING WAVES. My drawing is of the wave at one instant of time; YOUR IMAGINATION must supply mental pictures of the waves moving to the right (wave 1) and left (wave 2) respectively.



In case (a), the two waves travel the same distance to get to point A; we say that the PATH DIFFERENCE (Δpath) for the two waves is zero. At the instant of time that I have chosen for my drawing, the particle at point A is at its equilibrium position (or, in the density wave interpretation, the density at A is neither condensed nor rarified). However, $\frac{1}{4}$ of a period later, two crests will be arriving at point A; at that time, the two disturbances will add to give a combination crest that is twice as high as the crest from either of the individual waves. Another $\frac{1}{2}$ a period later, two troughs will arrive, giving a combination trough that is twice as low as the trough from either of the individual waves. So the particle at point A will vibrate in SHM with an amplitude which is twice as great as the amplitude of the individual waves. (In the density wave interpretation, the variations in density at point A will be twice as large as for either of the two traveling waves.) You should be able to see from part (c) of my drawing that the situation at point C is similar to the situation at point A; i.e. the two arriving waves will always be in phase at that point. However, in drawing (c), Δpath for the two waves is no longer zero; wave 1 has traveled exactly 1λ farther than wave 2, i.e. Δpath = 1λ. The positive reinforcement that occurs at points like A and C is given a name:

DEF CONSTRUCTIVE INTERFERENCE is the positive reinforcement that occurs at a given location $\mathbf{r}$ when two or more waves arriving at $\mathbf{r}$ are always in phase.

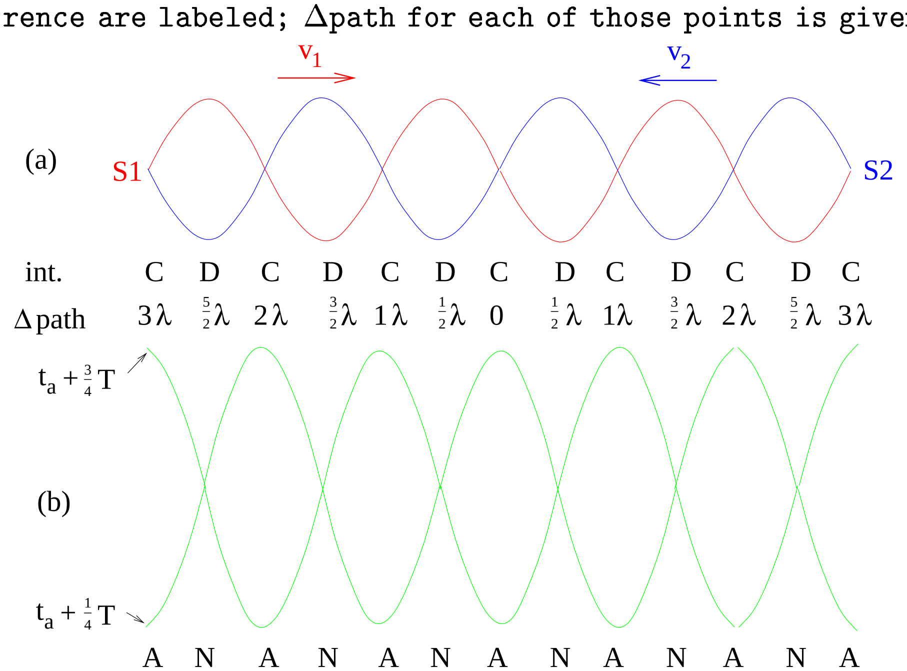
For two in-phase sources, constructive interference occurs at a location $\mathbf{r}$ whenever Δpath equals a whole number of wavelengths (0λ, 1λ, 2λ, 3λ, etc.).

Case (b) is different from either (a) or (c). At point B, the two waves are always 180° out of phase when they arrive. At the instant shown in my drawing, a crest from S2 is arriving at the same time as a trough from S1; but $\frac{1}{2}$ a period later, a trough from S2 will arrive together with a crest from S1. As a result, the particle at point B will never be disturbed (or the particle density at B will never change). In case (b), the wave from S1 has traveled $\frac{1}{2}$ a wavelength farther than the wave from S2 (Δpath = $\frac{1}{2}\lambda$); but the result would have been the same had I selected a point with Δpath = $1\frac{1}{2}\lambda$'s or Δpath = $2\frac{1}{2}\lambda$'s, etc. The negative reinforcement that occurs at points like B is given a name:

DEF DESTRUCTIVE INTERFERENCE is the negative reinforcement that occurs at a given location **r** when two or more waves arriving at **r** are always 180° out of phase.

For two in-phase sources, destructive interference occurs at a location **r** whenever Δpath equals a half-integer number of wavelengths ($\frac{1}{2}\lambda$, $1\frac{1}{2}\lambda$, $2\frac{1}{2}\lambda$, $3\frac{1}{2}\lambda$, etc.).

So what is the result of all this interference on the line between sources S1 and S2? The two traveling waves combine to create an INTERFERENCE PATTERN which is called a STANDING WAVE, because the pattern is fixed in space and does not travel. This pattern is drawn for you in part (b) of the figure below. Part (a) of the figure shows the two traveling waves, drawn at a particular instant of time which I now call t_a. The points of constructive (C) and destructive (D) interference are labeled; Δpath for each of those points is given.



This standing wave is the combination of the two traveling waves in (a).

The motion of particles at the points of constructive interference (the C points) is SHM with an amplitude twice that of either of the traveling waves; particles at the D points do not move. (For the density wave interpretation, the density variation at the C points is twice as large as for either of the traveling waves; the density at the D points does not vary). Part (b) of the figure represents the combination wave, (i.e. the standing wave) with two green lines; these two lines represent the two extreme situations for the combination wave. One occurs at a time of $\frac{1}{4}$ of a period after t_a; the other occurs at a time of $\frac{3}{4}$ of a period after t_a (at t_a the combination disturbance is zero everywhere). Standing waves are almost always drawn in this manner; by drawing the combination wave in these two extreme situations. By looking at this drawing, you can immediately see that those particles which are at the D points never move (or the density at those points never varies); in the standing wave these points are called NODES (labeled N in the figure).

DEF In a standing wave, the NODES are the points of zero variation, resulting from destructive interference between the traveling waves from which the standing wave is created.

The drawing of the combination wave also shows that the particles at the C points are moving with an amplitude which is twice the amplitude of either of the traveling waves (or the density at the C points has twice the variation of the density in the traveling waves); in the standing wave these points are called ANTINODES (labeled A in the figure).

DEF In a standing wave, the ANTINODES are the points of maximum variation, resulting from constructive interference between the traveling waves from which the standing wave is created.

Now that we have finished this example with two in phase sources, answer the question, "How would the interference pattern be different if the two sources were 180° OUT OF PHASE, but everything else was unchanged?" For the answer, see our Even-Numbered Answers web page. You can simulate a standing wave created by sources which are 180° out of phase with the applet at

http://www.surendranath.org/Applets/Waves/Twave02/Twave02Applet.html

Use options "Continuous" and "Out of Phase". The standing wave appears in yellow.

During lecture, I will demonstrate 1D standing waves on a string, talk about standing sound waves in 1D pipes, and demonstrate standing sound waves in 3D as created by two in-phase speakers. We will finish with a traveling INTERFERENCE pattern called BEATS. Assuming the internet is working, we will use the following DEMOs from my home page: "2D Interference", "Standing Sound Waves", and "Beats".

I will finish this reading with a few words about DIFFRACTION, which refers to the spreading of waves around the edges of a barrier. Your book has a decent picture of diffraction on page 490, but you will find a much better picture at

http://www.public.asu.edu/ gbadams/diffraction.html

A nice explanation of how diffraction is created by interference can be found below the picture. You experience diffraction everyday when you hear around corners. The main thing that you need to know about diffraction is that long wavelengths spread out more easily (or bend around corners more easily) than do short wavelengths. For example, low frequencies are more easily heard around corners than high frequencies. As another example, light waves appear not to spread out at all around corners because the wavelengths of visible light are very short (they do spread out a little, as you will learn in 112). I will not ask you any questions about diffraction in 111, but it is an important topic in 112 and it is often covered by the MCAT's.