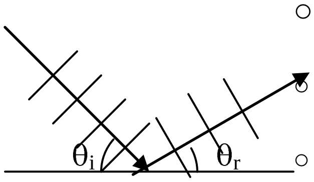
Th. 1/31: Ch 4 *Sound Propagation*	HW4: Ch 4: 1,3,4, Project… Ch 4: 8^w,10^w,11^w, 13	**Mon. 1/28** or **Tues. 1/29:** Lab 4 *Wind Instruments: Vibrating Air* (11.3, 12.1)
Tu. 2/5: Ch 5 *Intensity and Measurement* **Th. 2/7:** Ch 15 *Room Acoustics*	HW5: Ch5: 1^w,3^w,6^w,11^w,12,14^w Ch15: 2,3^W,4^W,7,8^W,12^W	**Mon. 2/4** or **Tues. 2/5:** Lab 5 *Diffraction & Attenuation Vibrating Air*

Materials
- 2 function generators (may want one to trigger the other)
- Torsion Wave demo
- 2 Speakers
- microphone
- Oscilloscope set for about 900 Hz
- Laptop (and usb cable to connect to o'scope)
- Laser and double slit (labjack and slide holder), can of smoke
- Set up computer to use LabView o'scope interface
- Doppler effect demo
- http://www.falstad.com/ripple/
- http://ngsir.netfirms.com/englishhtm/Interference.htm
- Ppt with slides of images at the end of this document.

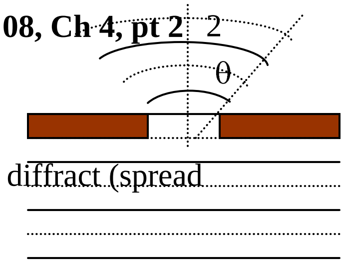
Last Time

Ch. 4 Sound Propagation
- We focus on how the waves can be modified in flight – reflecting, adsorbing, refracting, diffracting, interfering, stretching & compressing.

4.1 Reflection and Refraction
- **Sound reflection**
  - Like a ball bouncing off a wall, the wave reflects with an equal angle to that of impact.
  - **Smooth surface:** If the surface is smooth, relative to the wavelength, then the reflecton is smooth.
  - **Bumpy surface:** If the surface is bumpy relative to the wavelength, then the reflection is bumpy – scattered.



  - **Adsorption and Transmittance**
    - **Transmittance:** Some percent of sound wave's push gets transmitted to, into, and on through an obstruction, like a wall. The sound is transmitted through.
    - **Adsorption:** Some materials don't easily support sound waves, the coherent motion of atoms back and forth in the wave degenerates into random motion, a.k.a. heat.
- **Rarefaction**
  Since the speed of sound depends on the temperature of he air through which it moves, if a wave encounters a region with different temperature pockets, the portion of the wave traveling through the hot air will speed up and the portion in the cool air will slow. The wave as a whole, spanning these two regions, bends at the border. This redirects the propagation of the wave.



4.2 Diffraction

- Sound filling in behind an obstruction.

Clicker Question. When sound passes through a gap of width D, it will diffract (spread out) most if

a) D>λ

b) D<λ

- ½ angle of the beam's cone for a rectangular window: $\sin\theta \approx \frac{\lambda}{D}$
- ½ angle of the beam's cone for a round window**:** $\sin\theta \approx 1.22\frac{\lambda}{D}$

Qualitatively: if the wavelength is bigger than the opening, it fills the space; if it's smaller than the opening, it's confined.

This Time

4.4The Doppler Effect.

Q. Consider yourself out on the highway; you're driving 65 and everyone else is driving 70. Qualitatively, how does the frequency with which you get passed compare with if you were driving 55? Or standing still?

What about the oncoming traffic, you are racing ahead at 65, and they are racing your way at 65, how does the frequency with which you pass each other compare with if you were standing still?

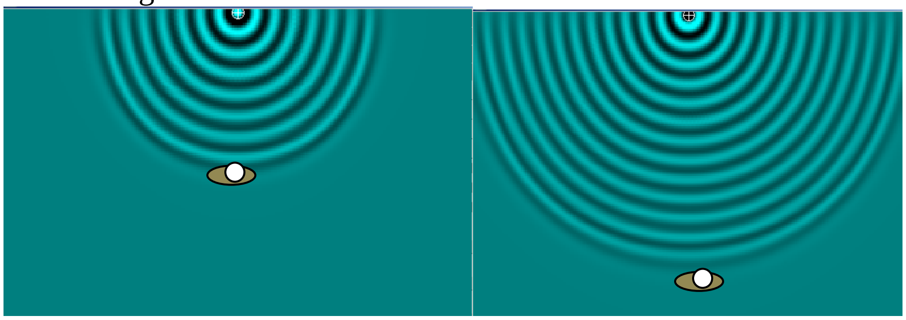
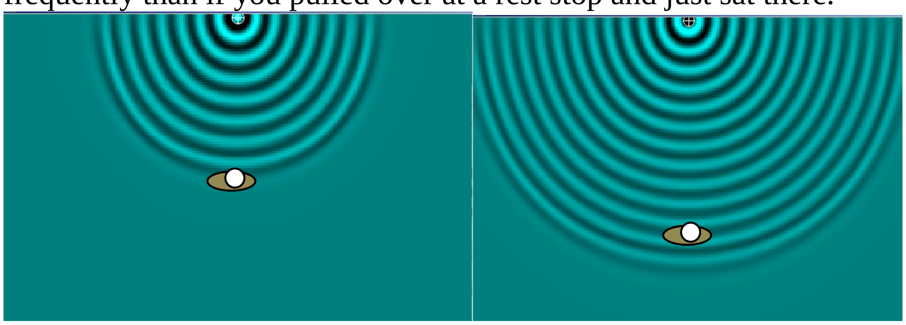
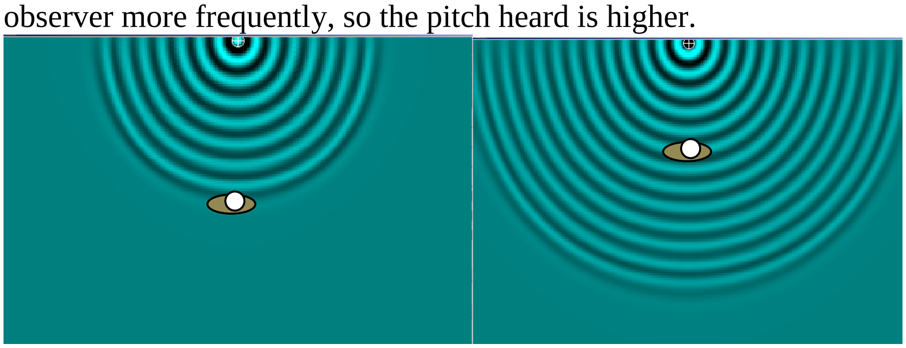
That's the core of the Doppler Effect.

Instead of considering other cars on the road, consider undulations of a sound wave.

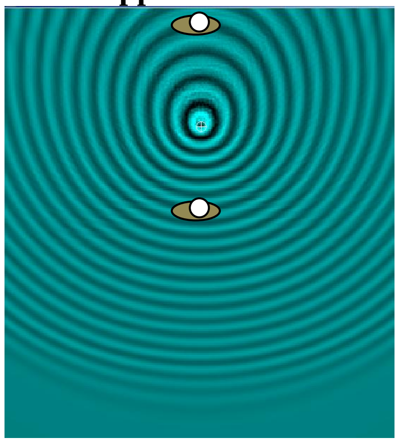
Doing the math can be awkward, but understanding the Doppler Effect is fairly simple.

This is the effect whereby a the ripples of a sound wave wash over you more frequently (i.e., you hear a higher pitch) if you are approaching the source (or vice versa), and less frequently if you're running away from the source (or vice versa).

- **Common Experience.** We've all experienced the Doppler effect, often in a context as the book describes – a train or emergency vehicle passes by us and we here a change in pitch of the horn / siren.
  - **Demo: flying speakers**
    - **Spin speakers slowly**
    - **Spin speakers quickly**
    - **Spin speakers at them**
    - **Spin speakers perpendicular to them**

- **Demo:** wave tank simulation.
  - **Observer Receding at v_{sound}.** Think of this far case. Say you are moving at the speed of sound away from a speaker. Then the wave fronts of alternating high pressure, push, and low, never come to you, so you don't hear a thing.
  - 
    - No ripples have passed observer
  - **Observer Receding slower than v_{sound}.** Now say you're going just a little slower. It takes a while, but eventually the first front overtakes you. And it takes a while, but eventually the next one overtakes you. Much more time elapses between when these two fronts overtake you than would normally. You of course translate the time delay, the period, into a particular tone. In this case the period is longer, so the tone seems lower as you flee from the source. Just like your driving down the highway at 65mph, if everyone else is traveling at 70 mph, they pass you much less frequently than if you pulled over at a rest stop and just sat there.
  - 
    - Two ripples have passed observer
  - **Observer Approaching Source.** Now the wave fronts wash over the observer more frequently, so the pitch heard is higher.
  - 
    - Seven ripples have passed observer

- **Moving Source**
  - **Demo: applet**



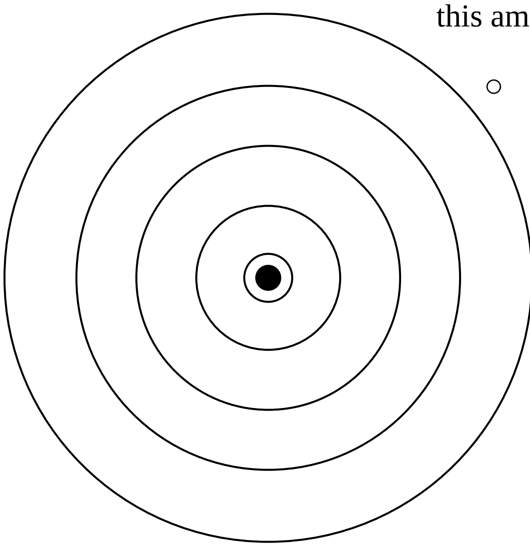
Wavelengths are longer behind the source – takes longer for each wave front to wash over the listener – lower frequency

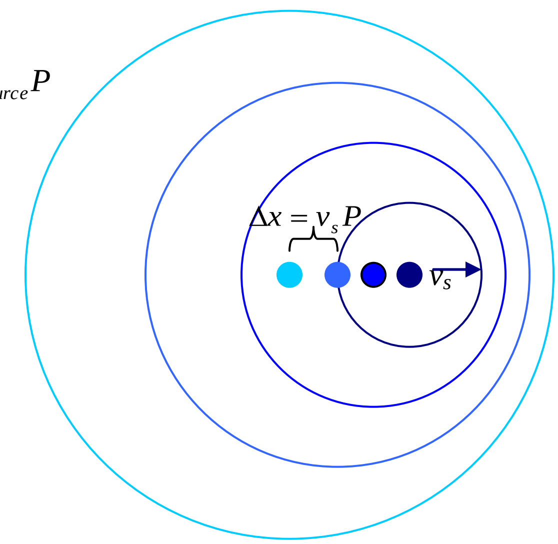
Wavelengths are shorter in front of the source – takes less time for each wave front to wash over the listener – higher frequency

  -
    - Separation of ripples (the wavelength) is *compressed* in the direction that I'm moving my finger
    - It is *stretched* in the opposite direction.
    - Perpendicular, it is mostly *unaffected*.
  - **Derive Equation for moving source**
    - Focus on the wave radiating forward of the source. The wavelength is shrunk because each new ripple is produced further ahead, specifically it is produced a distance $\Delta x = v_s P$ ahead, where v_s is the speed with which the source moves ahead and T is the period of time between wave fronts being produced. So the separation of wavefronts is shrunk by this amount:

$$\lambda'_{front} = \lambda - \Delta x$$

$$\lambda'_{front} = \lambda - v_{source} P$$





Similarly the wavelength behind the moving source stretches by the same amount.

$$\lambda_{o.back} = \lambda_{source} + \Delta x$$

$$\lambda_{o.back} = \lambda_{source} + v_{source} P$$

(subscripted for "observed")

  - What effect does this have on the frequency?

- **Demo: flying speakers**
  - **Spin speakers slowly**
  - **Spin speakers quickly**
  - **Spin speakers at them**
  - **Spin speakers perpendicular to them**
  - The frequency rises for the source moving toward the observer and lowers for the source moving away from the observer.
  - The frequency with which the sound waves wash over the observer can be found as a function of the frequency with which the source produces the sound waves and the speed of the source.
    - The properties of the medium don't care about how fast the source is moving, it still transmits the sound at the same speed relative to it, Considering the source moving toward the observer,

$$v_{sound} = \lambda_o f_o = (\lambda_{source} - v_{source}P) f_o$$

$$f_o = \frac{v_{sound}}{(\lambda_{source} - v_{source}P)} = \frac{v_{sound}}{\lambda_{source}\left(1 - \frac{v_{source}P}{\lambda_{source}}\right)}$$

$$f_o = \frac{v_{sound}}{\lambda_{source}} \frac{1}{\left(1 - \frac{v_{source}}{\lambda_{source}/P}\right)} = f_{source}\frac{1}{\left(1 - \frac{v_{source}}{v_{sound}}\right)}$$

    - For a source moving away from the observer, the same equation holds, only the speed of the source becomes negative.

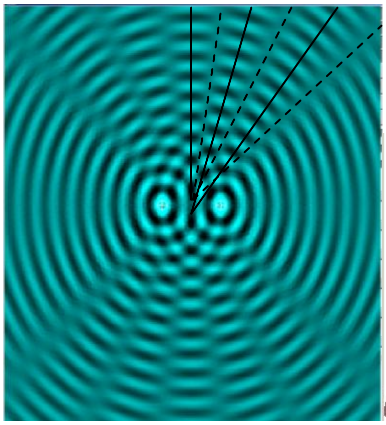
4.5 Interference and beats

Intro. Last week, I used the idea of interference, constructive and destructive, to explain how a traveling wave, say along a string, can interfere with its reflection and produce a standing wave.

1-D Demo: Torsion waves interfering with reflection: Standing wave with some points of constructive interference – anti-nodes, and some points of destructive interference – nodes. These points are locked in space.

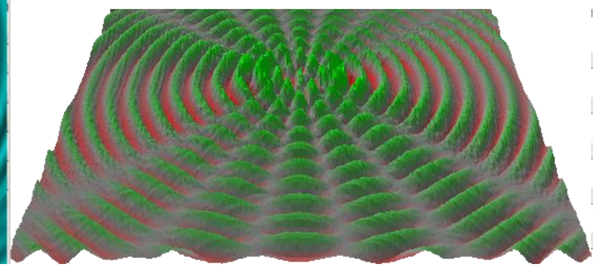
That, of course, is a very special case; now we're going to broaden out and consider interference patterns that can be set up through space.

Say we have two sources of sound, to make it simple, we'll say they are in-synch, like two speakers driven by the same stereo. How do these sound waves interact?



- - - - Nodal Lines – always *destructive* interference (one source tells water to move up while other tells it to move down)

______ Antinodal Lines – always *constructive* interference (one source tells water to move up while other tells it to move up)



3-D Demo: constructive & destructive sound waves.

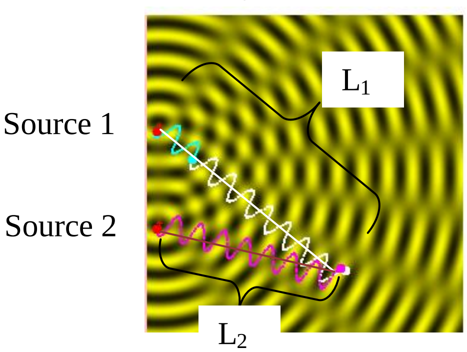
- Set speakers some distance apart, & drive with function generator, in phase with each other, set wavelength at about ¼ m, so people can move their heads a full wavelength: f = 900 Hz.
- Move microphone around & see on oscilloscope how the amplitude changes.
- You should be able to hear the same effect as the microphone is picking up. Move from side to side and listen for the difference in loudness.

- **(applet)** what you're doing is moving between these points of constructive and destructive interference.

- **Mathematical.** Now, we can mathematically phrase the conditions for constructive and destructive interference.
    - **2-D Demo: applet (**http://ngsir.netfirms.com/englishhtm/Interference.htm

)- clicking on different spots shows how waves from sources propagate to the spot and constructively or destructively interfere. With two sources side by side, there are points where one source would drive the wave up and so would the other – constructive interference, but there are also points where they disagree – destructive interference, and the water doesn't move at all.

Constructive Interference



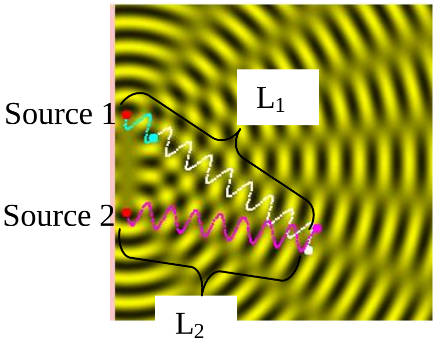
For *constructive* interference, need the signals from both sources to agree – both tell the bit of water to move up or down at the same time. That's what we're seeing when the white ball and magenta ball move together.

Now the distance from Source 1 to the point we're looking at, L_1, is longer than that from Source 2, L_2. The length difference is green: Notice that *it's* two ends are moving in synch; that's because that path difference is two wavelengths long.

More generally, to get *constructive* interference at a point, need

$$|L_1 - L_2| = n\lambda \text{ where n = 0,1,2,3,…}$$

Destructive Interference.



For *destructive* interference, need the signals from both sources to disagree – while one tells the water to bulge up, the other tells it to trough down, and vice versa. That's what we're seeing when the white ball and magenta ball move opposite of each other.
Again the distance from Source 1 to the point we're looking at, L_1, is longer than that from Source 2, L_2. The length difference is green: Notice that *it's* two ends are moving in opposite of each other; that's because that path difference is three-half wavelengths long.

More generally, to get *destructive* interference at a point, need

$$|L_1 - L_2| = n\frac{\lambda}{2} \text{ where n = 1,3,5,… (note: just } \textit{odd} \text{ integers)}$$

So, when I was blasting you with two speakers of 900Hz 'music', and you wobbled back and forth, you were moving from locations where moving between these locations of constructive interference and destructive interference, where the difference between how far you were from one speaker and the other was an integer number of wavelengths (constructive) or a half integer number of wavelengths (destructive).

Example. Say you and the speakers are positioned such that you're 3m from one and 3.5m from the other. To what frequency might I tune the speakers to you experience *constructive* interference – here it the loudest?

Let's take that in two steps; first, what *wavelength* should the sound have, and with that in hand, we can determine the corresponding frequency.
For *constructive* interference,

$$|L_1 - L_2| = n\lambda \Rightarrow \frac{|L_1 - L_2|}{n} = \lambda_n$$ where n = 0,1,2,3,…, so a whole family of possible wavelengths (and corresponding frequencies) will do the job)

$$\lambda_n = \frac{|L_1 - L_2|}{n} = \frac{|3m - 3.5m|}{n} = \frac{0.5m}{n}$$

Now, to get the frequencies, we know

$$v = f\lambda \text{ so } \frac{v}{\lambda} = f$$ and the wave speed, v, is going to be the speed of sound in air, 344m/s (unless otherwise specified, it's safe to assume that the temperature is 20°C)
So,

$$f_n = \frac{344m/s}{\frac{0.5m}{n}} = n\frac{344m/s}{0.5m} = n \cdot 688Hz = 688Hz, 1{,}376Hz, 2{,}064Hz, \ldots$$

Similarly, we could ask what frequency sounds would *destructively* interfere at your location – producing the *quietest* sound?
For *destructive* interference,

$$|L_1 - L_2| = n\frac{\lambda}{2} \Rightarrow 2\frac{|L_1 - L_2|}{n} = \lambda_n$$ where n = 1,3,5,… (note: just the *odd* integers).

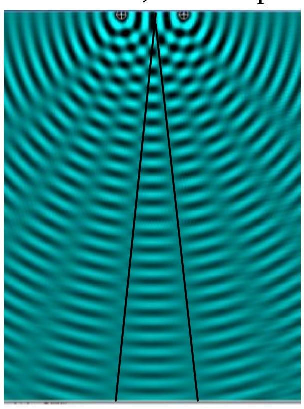
From there, the work would go just about the same except for that factor of 2 and only odd integers for *n*.

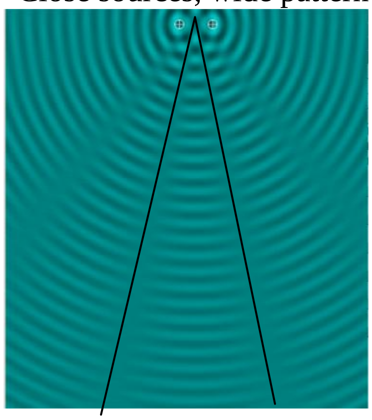
After 2 speaker constructive interference – back to Diffraction

Now we are conceptually equipped to take a second look at Diffraction and better understand why the gap width matters. The gap can be thought of as a line of point sources of waves, each radiating radially. But see how two interfere to produce a beam of constructive interference?

Demo: 2 sources (start with 7 sources and pile some on top of each other.) Notice how the separation between the two sources changes the angular width of the central beam:

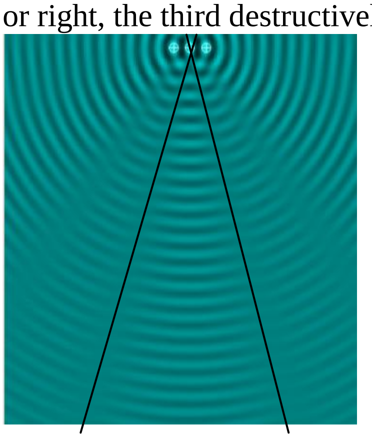
Far sources, narrow pattern Close sources, wide pattern



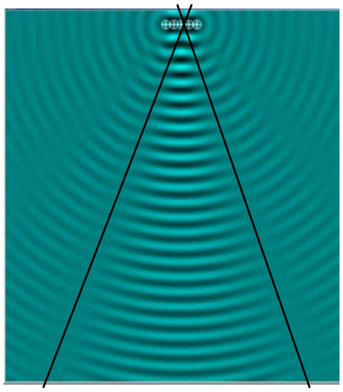


And using our understanding that the difference in path length from the two sources to a point on the first nodal line must be a half wavelength, we could mathematically describe the angel at which that nodal line radiates

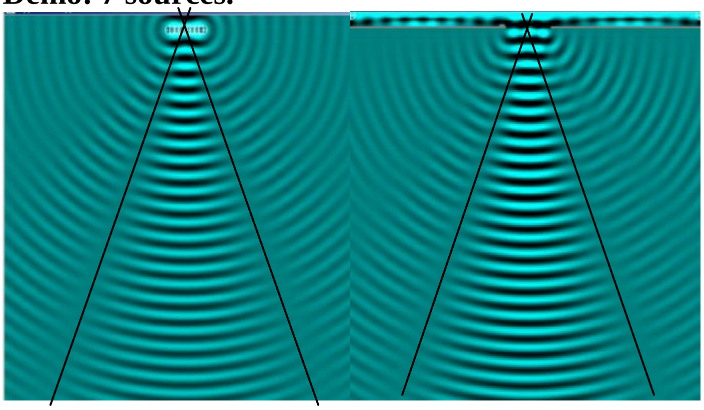
Demo: 3 sources. If I put a third source right between the two, but don't change the separation of the outer two. That *slightly widens* the *angle* of the nodal lines, and it makes the central beam much stronger than the two on its left and right; that's because *all three* constructively interfere along the center but while two constructively interfere on the left or right, the third destructively interferes with them.



Demo: 5 sources. Again, the angular width of the nodal lines are *slightly widened*, but the central region is even more pronounced.



Demo: 7 sources.



One can (we certainly won't in this class) go through this process mathematically and take it to the limit of an infinite number of little sources all lined up, in other words, a small stretch of a plane wave such as one passing through a gap, and you end up with

$$\sin\theta \approx \frac{\lambda}{D}.$$

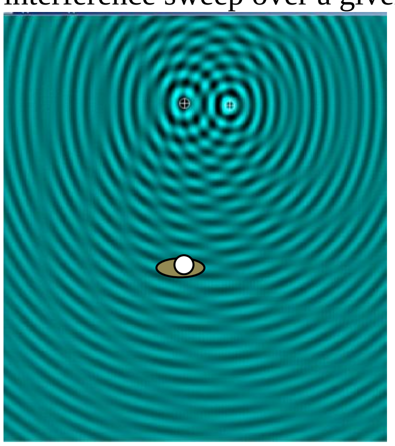
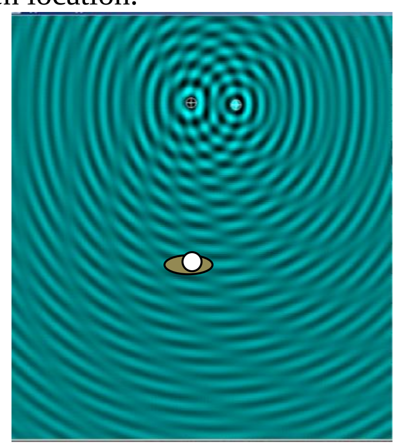
I've certainly not derived this, but hopefully you get a sense of how one might start with an understanding of how two

What if we had 8, or 10^{26} (air particles) Then we'd expect to see a *very* strong beam up the middle, and its width would be just the same as if we only had the two end sources.

17.1 Beats

- So you experienced and used beats in lab yesterday, now we'll try to understand them.
- We've looked at the case of two sources with the exact same frequency, and we've seen and heard how their constructive and destructive interference points, nodes and anti-nodes, set up through space giving a standing wave. We can ask, what happens if the frequencies aren't the same, not by a little, or not by a lot.

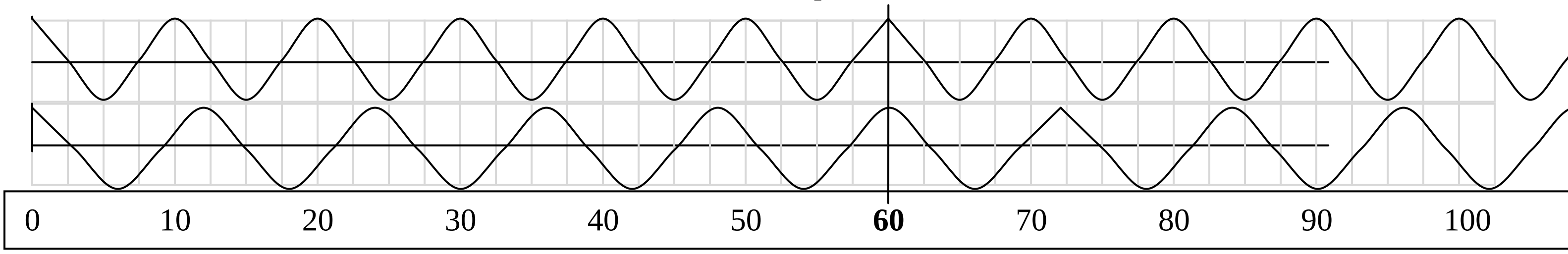
- The principle of linear supper position still holds, so the medium's response to the combination of sources of different frequencies is the sum of its response to the individual sources.
- **Demo: Adding two waves in 1-D**
    - Two function generators attached to an Oscilloscope.
    - Show two waves simultaneously
    - Show their addition
    - Do this for two waves with very different frequencies & for waves with very similar frequencies.
    - Note: as the two frequencies approach, it takes longer for them to migrate from completely in phase to completely out of phase,
- **Demo: Adding two waves in 3-D**
    - Two speakers hooked-up to the two function generators hooked-up to the oscilloscope
    - Hear how our perception changes: 1) we just hear two independent notes, 2) we hear a third note (at the frequency of their difference) 4) we hear one wavering note 5) we hear one note.
    - See on the oscilloscope how the patterns change through these different perceptions.
- **Demo: 2-D visualization (http://www.falstad.com/ripple/)** Select 2 sources, 2 frequencies and move sources near each other. See how the regions of destructive interference sweep over a given location.

Now the constructive and destructive nodal lines are bent and they rotate over time. So at one moment, you may be sitting at a location of *constructive* interference and at a later moment, *dstructive* interference has washed over you.

- **Beat Frequency**
    - At what frequency does the combination of two waves repeat?
    - It is easiest to see an example considering the *periods* so we'll do that first:

Example: Say we have one wave with a period of 10 sec. and another with a period of 12 sec. Say the two waves start out in phase. How long until the two peak at the same time again? Well the first one peaks once every 10 seconds and the other peaks once every 12 seconds, so when do these two patterns cross?



First one peaks: T = 0, 10, 20, 30, 40, 50, **60**, 70,…

Second one peaks: T = 0, 12, 24, 36, 48, **60**, 72,…

After 60 seconds they are both peaked at the same time again. 60 is the least common multiple of both 10 and 12 (multiply 10 by 6 or multiply 12 by 5.) The least common multiple of two numbers is found by:

$$P_{beat} = \frac{P_1 P_2}{P_1 - P_2}.$$

In this case,

$$P_{beat} = \frac{12s \cdot 10s}{12s - 10s} = \frac{120\,s^2}{2s} = 60s$$

The mathematical relationship actually looks much cleaner if we invert it

$$\frac{1}{P_{beat}} = \frac{P_1 - P_2}{P_1 P_2} = \frac{P_1}{P_1 P_2} - \frac{P_2}{P_1 P_2} = \frac{1}{P_2} - \frac{1}{P_1}$$

$$f_{beat} = f_2 - f_1$$

The frequency with which the two waves line-up is just the difference of their individual frequencies.

A refinement: a frequency can't be negative, so it's really the absolute value of this difference:

$$f_{beat} = | f_2 - f_1 |$$

As a practical matter, say you have two sources which differ by 10Hz, it doesn't matter which of the two is higher/lower than the other – either way you get the 10Hz beat frequency.

- **Example:** Tuning
  - Tuning your guitar against a hand-held function generator, you count 6 beats in 10 seconds when tuning the open G-string to 196 Hz. What frequencies could the string be playing?
  - **Quantities**
    - f_b = 0.6/s
    - f_{tuner} = 196 Hz.
    - f_{string} = ?
  - **Relations**
    - $f_{beat} = |f_2 - f_1| \Rightarrow f_2 = |f_{beat} \pm f_1|$ That is to say, the guitar could $f_g = |f_t \pm f_{beat}|$ be f_{beat} higher or lower than the tuner and still produce the same beat
  - **Algebra/Numbers**
    - $f_g = |f_t \pm f_{beat}| = 196\,Hz \pm 0.6Hz = 196.6Hz, 198.4Hz$