Physics 9 — Wednesday, September 26, 2018

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In an open field, if I go 2 times as far away from a sound source, by what factor is the intensity reduced? What if I go 10 times as far away from a sound source?

So the transmitted intensity is reduced by a factor of 4 (a 6 dB reduction in sound level) if

- you double your distance from the sound source;
- you double the mass-per-unit-area of the wall or window;
- the frequency of interest is an octave higher (when partially blocked by a typical wall or window).

- Going farther away decreases intensity like $1/r^2$.
- More massive partitions typically reduce intensity like $1/(\rho L)^2$.
- Higher frequencies are easier to stop than lower frequencies: typically intensity transmitted through wall or window scales like $1/f^2$.

Double-wall or double-window trick can get much better reduction of noise transmitted through wall or window.

For comparison, typical earplugs have transmission loss $\approx\ 30\ \mathrm{dB}$

$$(\text{decibels}) = 10\ \log_{10}\left(\frac{I_2}{I_1}\right)$$

One potentially confusing point about decibels:

- You can't take the logarithm of a number that has units. The argument of the logarithm has to be dimensionless.
- So decibels always measure the ratio of two things that have the same units: usually two intensities.
- If you're comparing the intensity on the two sides of an acoustic barrier, the "transmission loss" (in dB) is

$$\mathrm{TL} = 10\ \log_{10}\left(\frac{I_{\text{source}}}{I_{\text{receiver}}}\right)$$

- To measure just one intensity in dB ("intensity level"), you use "threshold of human hearing" as the denominator:

$$\mathrm{IL} = 10\ \log_{10}\left(\frac{I}{I_{\text{threshold}}}\right)$$

where $I_{\text{threshold}} = 10^{-12}\ \mathrm{W/m^2}$.

Another potentially confusing point about decibels!

- We have been using decibels to measure "intensity level", which is also called "sound level."

$$\mathrm{IL} = 10\,\log_{10}\left(\frac{I}{10^{-12}\ \mathrm{W/m^2}}\right)$$

- You might have noticed that the Architectural Acoustics text instead used dB to measure "sound pressure level."

$$\mathrm{SPL} = 20\,\log_{10}\left(\frac{\mathrm{pressure}}{2\times 10^{-5}\ \mathrm{N/m^2}}\right)$$

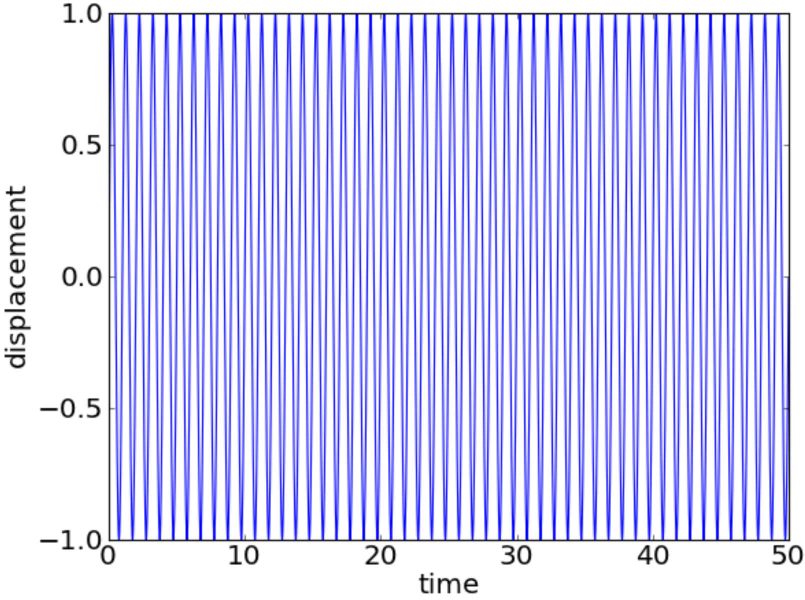
- Pressure is a measure of amplitude. Intensity $\propto$ (amplitude)^2. In air, a pressure amplitude of $2\times 10^{-5}\ \mathrm{N/m^2}$ (about 2×10^{-10} atmospheres) corresponds to an intensity of $10^{-12}\ \mathrm{W/m^2}$. The "10 $\log_{10}$" becomes "20 $\log_{10}$" to account for squaring the amplitude: $\times 10$ in amplitude corresponds to $\times 100$ in intensity. You don't need to remember this!

A potentially confusing point about intensities:

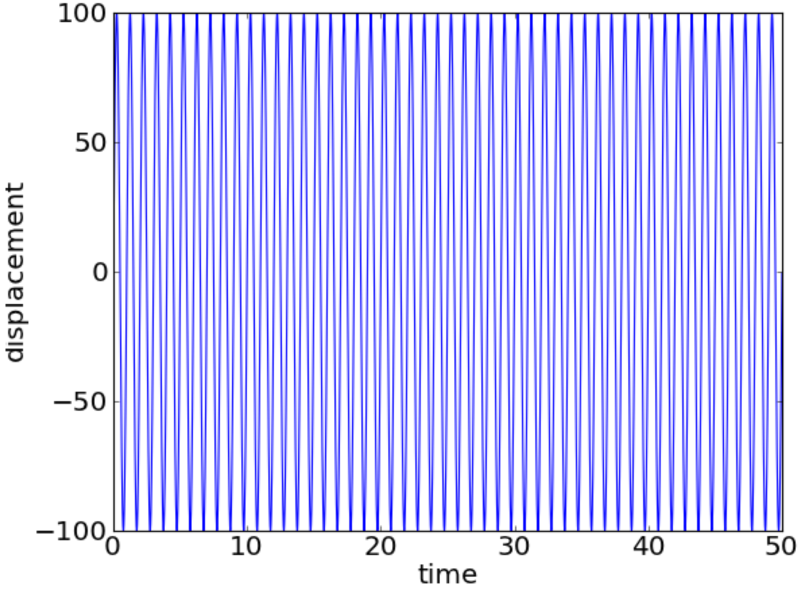
- Suppose I have one small loudspeaker playing out a 110 Hz tone ($\lambda \approx 3\ \mathrm{m}$).
- Now I wire up 9 additional small loudspeakers, all playing out precisely the same sine wave, with the same amplitude, all separated by just a few cm.
- In this case, the waves from the 10 loudspeakers will add "coherently." The waves are all in phase with one another. Their pressures add up algebraically, in the same way as we saw wave displacements add up on the wave machine.
- Since the waves have "constructive interference" everywhere, their combined amplitude will be $10\times$ as large as the single loudspeaker. So then the combined intensity will be $100\times$ as large as that of the single loudspeaker, because intensity $\propto$ (amplitude)^2.
- This happens if you have *n* copies of **exactly the same motion**, with a definite relationship between the phases of the *n* copies. For example, the same sound taking *n* equal-length paths from *A* to *B* in an elliptical "whispering gallery."

- In real life, if you have ten (non-electronic) musical instruments playing side-by-side, they will not play out precisely the same waveform.
- Even if ten flutes are playing the same note, the ten frequencies will not be precisely the same: they will probably differ by some fraction of a Hz.
- And the ten musicians will be separated by some non-simple-fraction number of wavelengths.
- And they will have started playing their notes at times that differ by a human reaction time, on the order of $0.1\ \mathrm{s}$.
- In this case, we don't know the relative phases of the ten waveforms, and the relative phases vary with time. So, on average, we do not see constructive or destructive interference.
- When we have no particular phase relationship between the n sources, we add them "incoherently:" we simply add the intensities.
- If you have 76 trombones playing side-by-side, you get $76\times$ the intensity (not $76\times$ the amplitude) of a single trombone.

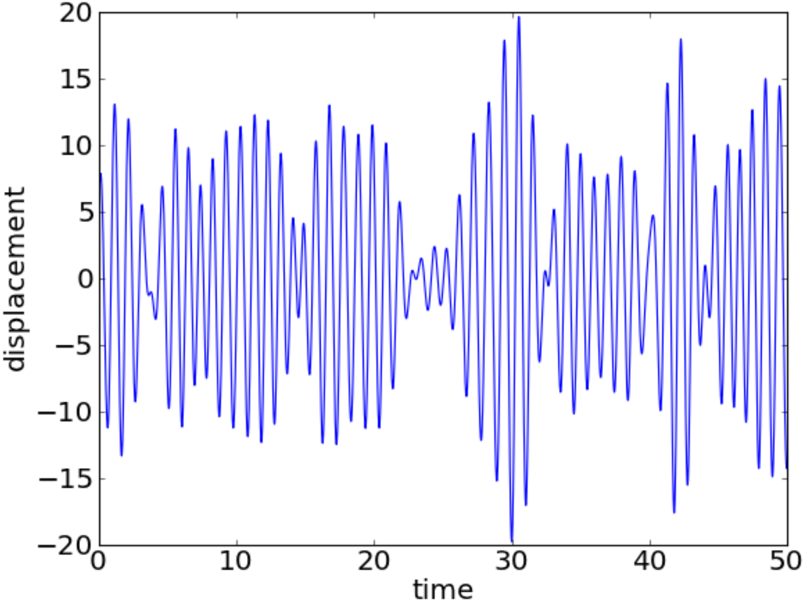
Here's a 1 Hz sine wave, of amplitude 1.



Here's the sum of 100 identical copies of that sine wave.



Here's the sum of 100 sine waves (amplitude 1) whose starting times are randomized and whose frequencies vary by about 1%.



Suppose one trombone plays with an intensity level of 70 dB. What is the intensity level of two trombones (playing equally loudly)?

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How about 10 trombones?

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How about 10 trombones?

How about 100 trombones?

How about 76 trombones?

Doppler effect (illustrate)

http://www.acs.psu.edu/drussell/Demos/doppler/doppler.html

http://galileoandeinstein.physics.virginia.edu/more_stuff/flashlets/doppler.htm

$$f_{\text{observed}} = f_{\text{emitted}} \left(\frac{c \pm v_{\text{observer}}}{c \mp v_{\text{source}}} \right)$$

Where c is the speed of sound. Upper sign ($f_{\text{observed}} > f_{\text{emitted}}$) when moving toward one another; lower sign ($f_{\text{observed}} < f_{\text{emitted}}$) when moving away from one another.

Radio waves and visible light are other examples of waves in three dimensions. The frequency (i.e. color!) of light is shifted for distant stars: infer relative velocity. Police radar uses Doppler shift of radio waves bounced off of your car to infer your speed.

- Next time, we'll start talking about light (optics), which is another wave phenomenon.
- But wavelengths for visible light are so short (about 0.5 $\mu\mathrm{m}$) that wave effects like interference and diffraction can be less obvious for light than they are for sound.
- Also, for architecture, I think the wave nature of sound is probably more relevant than the wave nature of light: for example, diffraction of sound waves is important in modeling an auditorium or in modeling e.g. the barriers that block highway noise.
- In most everyday situations, light travels in straight lines (except at a boundary between air/glass, etc.), whereas low-frequency sound waves diffract around obstacles.
- So let's use a simulation to illustrate some wave effects in two and three dimensions that affect both sound and light. We'll see them again next week in the context of light.

- “Ripple Tank Applet” setup “wja 1” shows reflection from barrier, similar to last week’s sound waves reflecting from a wall. You can see that higher frequencies are easier to stop than lower frequencies.
- “wja 2” shows double wall.
- “wja 3” shows constructive interference of waves in circular tube.
- “wja 4” shows incoming “plane wave” going through an opening in a barrier: angular spread (in radians) $\approx \lambda/D$.
- “two sources” is like the two speakers in the room, but notice that effect is ruined when you add reflective walls
- “obstacle” shows how low-frequency sounds diffract around e.g. a column in an auditorium, or a noise wall along a highway, while high-frequency sounds show a “shadow”
- “half plane” more resembles highway noise barrier
- “ellipse” is like HW3/q7 whispering gallery

- “refraction” shows waves “bending toward the slower medium” as described by Richard Muller’s PTFP.
- “internal reflection” is like the sound channels described by Richard Muller: waves that start out in the slow medium and strike the boundary at a glancing angle can’t escape (“total internal reflection”) — that’s how fiber-optics cables work.
- “doppler effect 1,” and “doppler effect 2,” and “sonic boom”
- “temperature gradient 2” shows sound traveling more slowly in cool air (blue). Waves “bend toward the slower medium.”
- “temperature gradient 1” is like a “temperature inversion”
- “temperature gradient 4” is like the sound channel described by Muller. Compare source inside vs. outside the channel!
- “temperature gradient 3” is the opposite of a sound channel.
- “parabolic mirror 2” and “parabolic mirror 1” are fun: see waves focus as you expect rays to focus

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