Physics 9 — Wednesday, September 19, 2018

- HW#2 due Friday in class. Remember online feedback page.
- HW help sessions: Wed 4–6pm DRL **4C2** (Bill), Thu 6:30–8:30pm DRL 2C8 (Grace)
- For today, you read Eric Mazur chapter 17 (waves in 2D/3D)
- Course web page is `positron.hep.upenn.edu/physics9`
- Slides, etc.: `positron.hep.upenn.edu/physics9/files`
- I wrote (in **Processing**) a little animation of Monday's interference demonstration:

`http://positron.hep.upenn.edu/p9/files/acoustic_interferometer.html`

I put the Processing source code for it at

`http://positron.hep.upenn.edu/p9/files/acoustic_interferometer.pde`

- On Friday, 9/21, recent Penn ARCH/Music grad Davis Butner will speak about his developing career in arch. acoustics.
- On Monday, 9/24, Terry Tyson from Acentech Acoustics will speak with us. If you're curious, here's an article by him:

`https://insulation.org/io/articles/good-design-for-architectural-acoustics/`

Somewhat out of order, but useful for one homework problem: if you have a traveling wave

$$D(x,t) = A\sin\left(\frac{2\pi x}{\lambda} - 2\pi f t\right)$$

what is the vertical velocity vs. time of the "particle" at x?

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$$v_y(x,t) = -(2\pi f)A\cos(\frac{2\pi x}{\lambda} - 2\pi ft)$$

So what is the maximum up-and-down speed of a "particle" of the wave machine? (Or in the case of the homework it is a "human wave" at a football game.)

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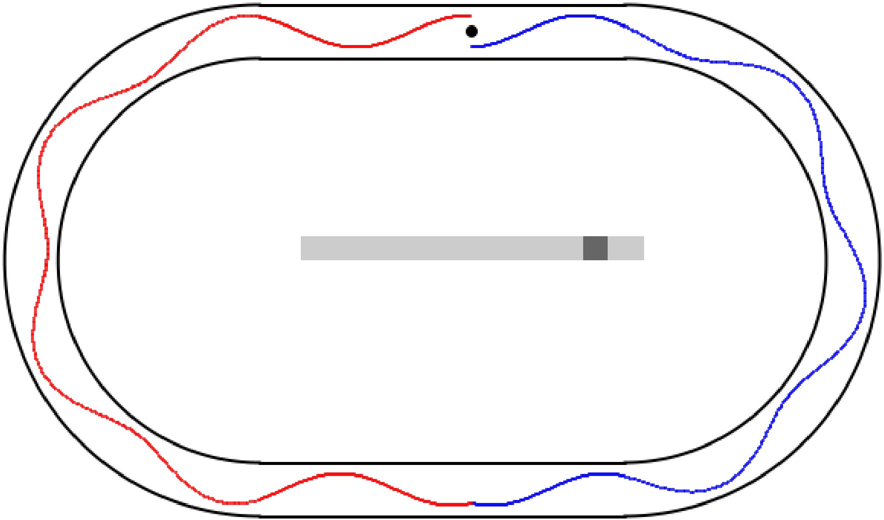
$$v_{\max} = (2\pi f)A$$



http://positron.hep.upenn.edu/p9/files/acoustic_interferometer.html

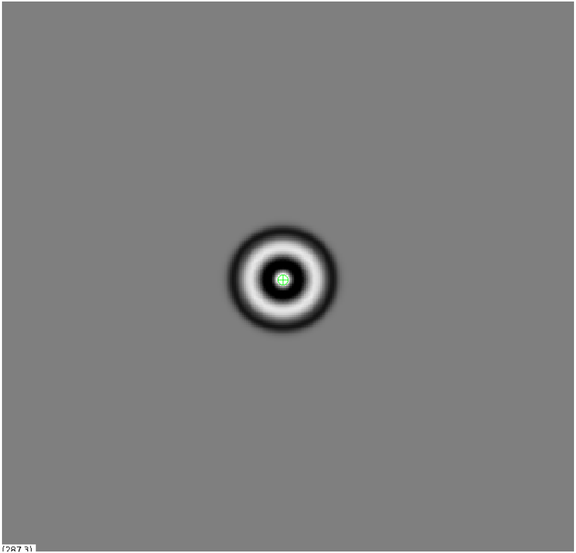
http://positron.hep.upenn.edu/p9/files/acoustic_interferometer.pde

(Note analogy with noise-canceling headphones.)

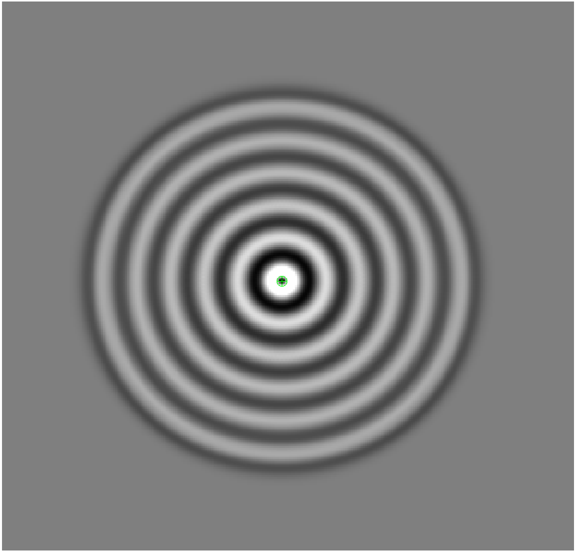
Uhoh, a dull slide full of text

- When a sound wave meets a wall, there is a (typically large) **reflected** wave and a (typically small) **transmitted** wave. So in an indoor space, sound waves bounce back and forth between the walls of the space — **reverberating**.
- You can model this using "ray tracing," in the same way that you would trace paths of light reflecting from mirrors, etc. This works best when the walls/obstacles are much wider than the wavelengths of interest. ("diffraction")
- Contrast with outdoors (no reflecting surfaces), where sound waves just spread out over larger and larger area. We'll see that outdoors, spherical wavefronts spread acoustic energy, at distance r from source, over surface area $4\pi r^2$.
- Trick to absorb reflected waves (reduce reverberation): place dissipative material (e.g. heavy curtains) about $\lambda/4$ from wall, near displacement (and velocity) antinode. So wall coatings work better for high f (small λ) than for low f (large λ).
- Meanwhile, as you read Sunday night, sound transmission through walls is usually undesirable — want to minimize.

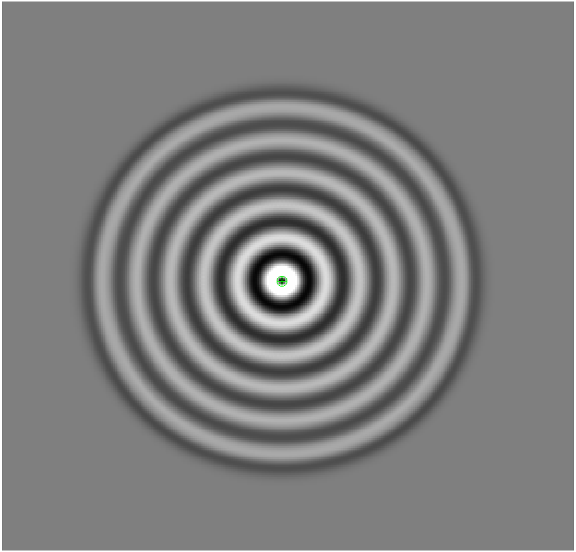
Suppose you drop a sequence of pebbles, one per unit time, onto a spot in the middle of a pond.



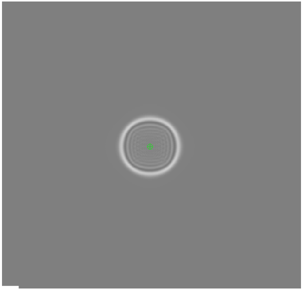
Each pebble starts a disturbance that travels outward — a wave! The **wavefront** corresponding to the pebble that hit the water at $t = 0$ is a circle of radius $r = vt$.

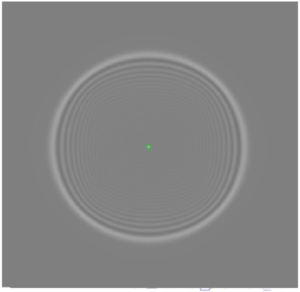


We know that waves carry energy. So the wave energy due to this first pebble is spread out over the circumference of a circle of radius $r = vt$.



- For sound waves **in 3D space**, if I clap my hands or fire a starter pistol in an open field, the pulse of sound energy will travel outward in a **spherical** wavefront.
- As the wavefront travels farther away from the source, the same energy is spread over larger surface area $4\pi r^2$
- So if you are farther from the source, a smaller fraction of the energy will reach your ear. That fraction $\propto 1/r^2$.
- A listener that is $2\times$ as far away will detect $1/4$ as much sound energy. A listener that is $10\times$ as far away will detect $1/100$ as much sound energy — the wave energy spreads out.

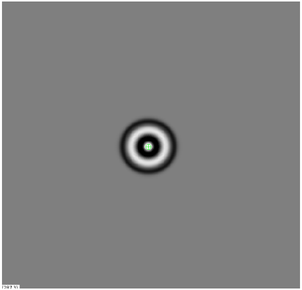
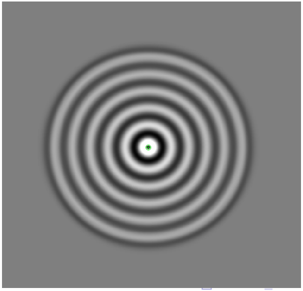




- Most sounds are not single pulses. Instead, they continue for some time. So we talk about **power** = energy per unit time.
- If the source is emitting acoustical power P (measured in watts), then a receiver at a distance r from the source will detect acoustical **power per unit area**

$$\frac{P}{4\pi r^2}$$

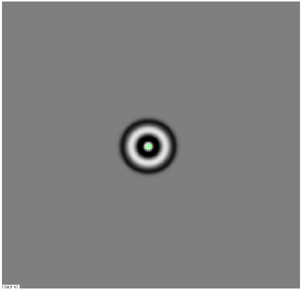
  (measured in watts per square meter)
- A listener who is 2 meters away will detect 1/4 as much **power per unit area** as a listener who is 1 meter away.

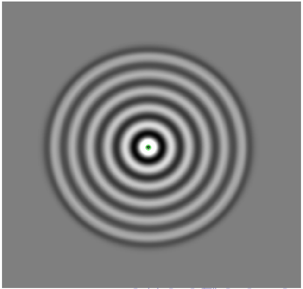



- It's awkward to keep saying **"power per unit area."** So we give this idea a name: **intensity**.
- If a source emits acoustical power P into the open air (no reflecting surfaces), then a listener at distance r hears **intensity**

$$I(r) = \frac{P}{4\pi r^2}$$

- Intensity is measured in watts per square meter
- If you go $10\times$ as far away from the source (in open air), then the intensity will be $1/100$ as large. (Spherical wavefronts.)





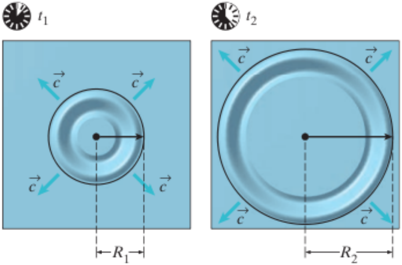


Figure 17.3 A surface wave moving at speed c. Because surface waves expand in two dimensions, the wave energy is distributed over a larger and larger circumference. (a) At t_1, the wave crosses a circle of radius R_1. (b) At t_2, the wave crosses a circle of radius $R_2 > R_1$.

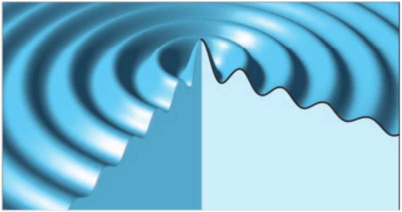


Figure 17.4 Cut-away view of a periodic surface wave. Because the energy in a given wavefront is spread out over an increasingly large circumference as the wavefront moves away from the source, the amplitude decreases as the wavefront moves away from the source.

r?

As a sound wave propagates outward in open air, the sound energy is spread out over spherical wavefronts of radius r. Since area of sphere is $4\pi r^2$, the intensity is

$$I = \frac{\text{power}}{4\pi r^2}$$

where "power" is the sound energy per unit time radiated by the source of the sound waves.

- **Intensity** is the physical property of sound that most closely relates to our ears' perception of "loudness."
- Intensity is **power per unit area**: $\mathrm{W/m^2}$.
- Human ears are sensitive to an **enormous** range of sound intensity. The somewhat painful sound of a loud rock concert has an intensity that is 10^{12} times (a trillion times) the smallest intensity that we can hear.
- Also, what our ears perceive as "about twice as loud" physically corresponds to about $10\times$ larger intensity.
- So we "compress the scale" by using a logarithmic measure of intensity, called the **decibel** (dB).
- When we use decibels to describe intensity, we call that **"intensity level"** to avoid confusion.
- So intensity is measured in $\mathrm{W/m^2}$, while "intensity level" is measured in decibels. Sometimes people say "sound level" as a synonym for the intensity level of sound waves.
- **Decibels are ubiquitous in architectural acoustics.** The logarithmic definition is confusing, but it's worth learning.

"Sound level" a.k.a. "intensity level" β is measured in *decibels*.

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

We use "threshold of human hearing" to define 0 dB. $(\log_{10}(1) = 0.)$

Source of the Sound	Sound Level (dB)	Intensity ($\mathrm{W/m^2}$)
Jet plane at 30 m	140	100
Threshold of pain	120	1
Loud rock concert	120	1
Siren at 30 m	100	1×10^{-2}
Auto interior, at 90 km/h	75	3×10^{-5}
Busy street traffic	70	1×10^{-5}
Talk, at 50 cm	65	3×10^{-6}
Quiet radio	40	1×10^{-8}
Whisper	20	1×10^{-10}
Rustle of leaves	10	1×10^{-11}
Threshold of hearing	0	1×10^{-12}

It's quite useful to understand the use of decibels to quantify sound intensity, because one encounters decibels in architectural acoustics, soundproofing, etc.

"Threshold of human hearing" $= I_0 \equiv 10^{-12}\ \mathrm{W/m^2}$

For intensity I (unit $= \mathrm{W/m^2}$), the *sound level* (unit = dB) is

$$\beta = 10 \log_{10} \left(\frac{I}{I_o} \right)\ \mathrm{dB}$$

And remember

$$\log_{10}(1000) = +3$$
$$\log_{10}(100) = +2$$
$$\log_{10}(10) = +1$$
$$\log_{10}(1) = 0$$

$$\log_{10}(0.1) = -1$$
$$\log_{10}(0.01) = -2$$
$$\log_{10}(0.001) = -3$$

etc.

Remember definition:

$$\beta \;=\; 10\log_{10}\left(\frac{I}{I_o}\right)\ \mathrm{dB} \;=\; 10\log_{10}\left(\frac{\mathrm{intensity}}{10^{-12}\ \mathrm{W/m^2}}\right)\ \mathrm{dB}$$

where $I_0 = 10^{-12}\ \mathrm{W/m^2}$.

Question:

The sound intensity in a quiet living room is $I = 10^{-9}\ \mathrm{W/m^2}$. Express this intensity as a "sound level" (also called "intensity level") in decibels (dB).

Question

The threshold of human hearing is $I_0 = 10^{-12}\ \mathrm{W/m^2}$.

Intensity level (in dB) is

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

If the intensity is $I = 10^{-4}\ \mathrm{W/m^2}$, what is the intensity level β (measured in dB)?

Question

The threshold of human hearing is $I_0 = 10^{-12}\ \mathrm{W/m^2}$.

Intensity level (in dB) is

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

If the intensity is $I = 10^{-7}\ \mathrm{W/m^2}$, what is the intensity level β (measured in dB)?

Question

The threshold of human hearing is $I_0 = 10^{-12}\ \mathrm{W/m^2}$.

Intensity level (in dB) is

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

Useful fact: $\log_{10}(2) = 0.3016 = 0.3$.

If the intensity is $I = 2 \times 10^{-7}\ \mathrm{W/m^2}$, what is the intensity level β (measured in dB)?

Question

The threshold of human hearing is $I_0 = 10^{-12}\ \mathrm{W/m^2}$.

Intensity level (in dB) is

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

Useful fact: $\log_{10}(2) = 0.3016 = 0.3$.

If the intensity is $I = 0.5 \times 10^{-7}\ \mathrm{W/m^2}$, what is the intensity level β (measured in dB)?

Question

The threshold of human hearing is $I_0 = 10^{-12}\ \mathrm{W/m^2}$.

Intensity level (in dB) is

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Useful fact: $\log_{10}(2) = 0.3016 = 0.3.$

If the intensity is $I = 5 \times 10^{-8}\ \mathrm{W/m^2}$, what is the intensity level β (measured in dB)?

Remember definition:

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where $I_0 = 10^{-12}\ \mathrm{W/m^2}$ = threshold of human hearing.

Question:

Suppose the sound intensity level of a gasoline lawn mower at a distance of 1 meter is 90 dB (with respect to the threshold of human hearing). What is the sound intensity in $\mathrm{W/m^2}$?

Remember definition:

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What is the intensity $(\mathrm{W/m^2})$ at a distance of 10 meters?

Remember definition:

$$\beta = 10\log_{10}\left(\frac{I}{I_o}\right)\ \mathrm{dB} = 10\log_{10}\left(\frac{\mathrm{intensity}}{10^{-12}\ \mathrm{W/m^2}}\right)\ \mathrm{dB}$$

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What is the **intensity level** (dB) at 10 meters?

Remember definition:

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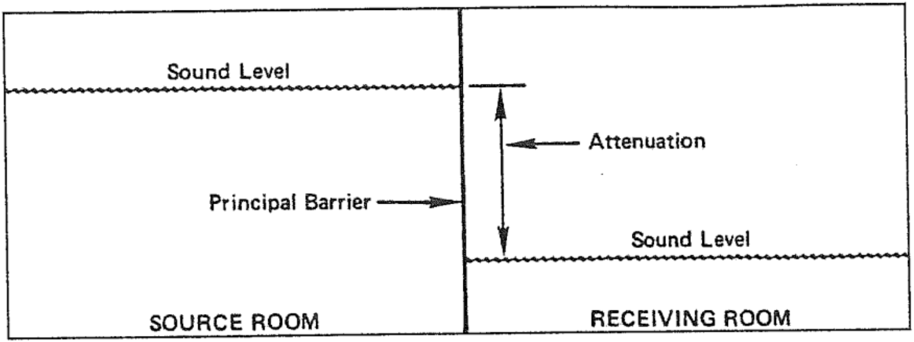
What is the intensity $(\mathrm{W/m^2})$ at a distance of 10 meters?

What is the **intensity level** (dB) at 10 meters?

What are the intensity $(\mathrm{W/m^2})$ and intensity level (dB) at 2 meters?

- In open air, with no reflecting surfaces nearby, intensity level drops 6 dB for each doubling of distance from the source, because of the inverse-square law due to spherical wavefronts.
- If you triple the distance from the source, the intensity level drops $\approx 10\ \mathrm{dB}$ (since $\frac{1}{3} \times \frac{1}{3} \approx \frac{1}{10}$).
- If you go $10\times$ as far away from the source, the intensity level drops 20 dB (since $\log_{10}(\frac{1}{100}) = -2$).

- This also happens inside a specially padded testing studio called an "anechoic chamber," whose every surface is designed to be nearly perfectly sound-absorbent.
- But in a typical enclosed space, the walls reflect most of the incident sound energy, so the sound bounces many times from the walls — like a bright light in a mirror-lined room.
- So in a room, the intensity falls $\propto 1/r^2$ for very short distances from the source (e.g. a couple of meters). Beyond that, the intensity has only slight dependence on distance — depending on degree of carpeting, wall covering, etc.



- So if someone in the room on the left is making noise, the intensity level in that "source room" is roughly the same everywhere in that room. What about the right room?
- Sound waves are constantly bouncing from the wall that separates the left and right rooms. When a wave hits the wall from the left, **a fraction** T of the incident energy is **transmitted** through the wall to the room on the right, and a fraction $R = 1 - T$ of the incident energy is **reflected** by the wall back into the left room. Even $T \approx 0.1\%$ is annoying!

One thing we see in soundproofing discussions is that a ratio I_2/I_1 of two intensities (like inside vs. outside the closed window) can be expressed as a difference in decibels:

$$\beta_1 = 10\log_{10}\left(\frac{I_1}{I_o}\right)\ \mathrm{dB}$$

$$\beta_2 = 10\log_{10}\left(\frac{I_2}{I_o}\right)\ \mathrm{dB}$$

$$\beta_2 - \beta_1 = 10\left(\log_{10}\left(\frac{I_2}{I_o}\right) - \log_{10}\left(\frac{I_1}{I_o}\right)\right)\ \mathrm{dB} = 10\log_{10}\left(\frac{I_2}{I_1}\right)\ \mathrm{dB}$$

(Remember that $\log(A/B) = \log(A) - \log(B)$.)

So you can use $\Delta\beta = 10\log_{10}(I_2/I_1)\ \mathrm{dB}$ for the ratio after/before passing through a wall or window. $-\Delta\beta$ for a wall, window, etc., is called "transmission loss" (TL) in architectural acoustics.

Question

If a wall permits only $\frac{1}{10000}$ of the sound intensity to reach the other side, what is the change $\Delta\beta$ (in decibels) in the sound level from one side to the other?

Notice that a 30 dB window (pretty typical for a window, at frequencies around 500 Hz) will reduce 70 dB busy street traffic down to 40 dB level of quiet radio.

What fraction of sound intensity (power/area) is transmitted by a 30 dB window?

A pretty good wall will reduce sound intensity (for frequencies around 500 Hz) by about 50 dB. That reduces the 65 dB sound level of someone talking on the other side of the wall to about 15 dB, which is quieter than a whisper.

What fraction of sound intensity (power/area) is transmitted by a 50 dB wall?

Soundproofing!

When a sound wave hits a wall, most of it is reflected back. Some of it is transmitted through to the other side of the wall.

Have you ever lived in a poorly soundproofed room?

Putting up a wall as a sound barrier is not so different from putting a mass onto the middle of the wave machine.

Soundproofing $\leftrightarrow$ wave machine

Boundary conditions at the point where I add the mass:

- displacement is same on both sides of mass
- tension $\times$ (change in slope) $=$ mass $\times$ acceleration

Working out the math*, I get fraction of intensity transmitted is

$$\frac{I_{\text{transmitted}}}{I_{\text{incident}}} = \frac{1}{1 + \left(\frac{\pi\mu f}{c\rho}\right)^2} \approx \left(\frac{c\rho}{\pi\mu f}\right)^2$$

where ρ is density of air, c is wave speed, μ is mass/area of wall.

(On the wave machine, ρ becomes mass/length and μ becomes the added mass in the middle.)

* http://positron.hep.upenn.edu/p9/files/masslaw.pdf

The "mass law" of preventing sound transmission

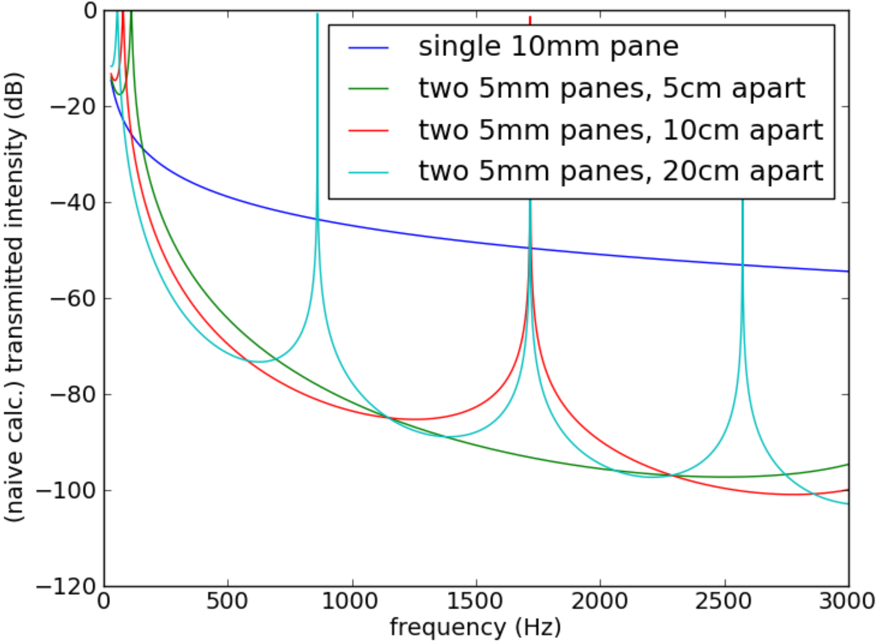
For a single wall or window, the transmitted intensity scales like

$$T_{\text{intensity}} \propto \frac{1}{\mu^2 f^2}$$

So higher frequencies are easier to stop than lower frequencies, and more mass-per-unit-area stops more sound.

Doubling the mass/area blocks $4\times$ the intensity: reduction of 6 dB per doubling of mass. $10\log_{10}(4) \approx 6$

Much better trick: use two independent layers of material separated by several inches (e.g. notice that a studio sound booth window has two widely separated layers of glass).



single 10mm pane
two 5mm panes, 5cm apart
two 5mm panes, 10cm apart
two 5mm panes, 20cm apart
(naive calc.) transmitted intensity (dB)
frequency (Hz)
0
−20
−40
−60
−80
−100
−120
0
500
1000
1500
2000
2500
3000

On previous slide's graph, notice:

- Two separate panes (same total amount of glass) stop hugely more sound than one pane.
- Low-frequency cutoff is quite sensitive to separation distance.
- Double-wall trick suffers from "resonances" at frequencies for which an integer number of half-wavelengths just fits between the two walls. At these resonant frequencies (sometimes called "coincidence dips" in acoustics books), sound gets through.
- I believe that making the two layers not quite parallel reduces this "coincidence dip." It is also improved by putting dissipative material into the cavity between the two layers (for a wall) or by using laminated glass for each layer of a window — each of which tends to dissipate the sound energy within the wall or window.

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 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

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

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

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

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

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."

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

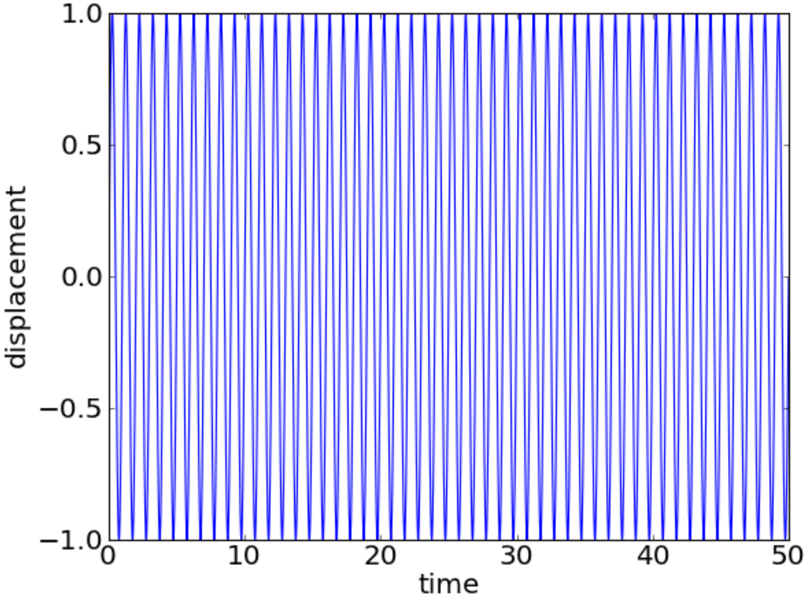
- Pressure is a measure of amplitude. Intensity $\propto$ (amplitude)^2. In air, a pressure amplitude of $2 \times 10^{-5}\ \mathrm{N/m^2}$ (about 2×10^{-10} atmospheres) corresponds to an intensity of $10^{-12}\ \mathrm{W/m^2}$. The "10 $\log_{10}$" becomes "20 $\log_{10}$" to account for squaring the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

A potentially confusing point about intensities:

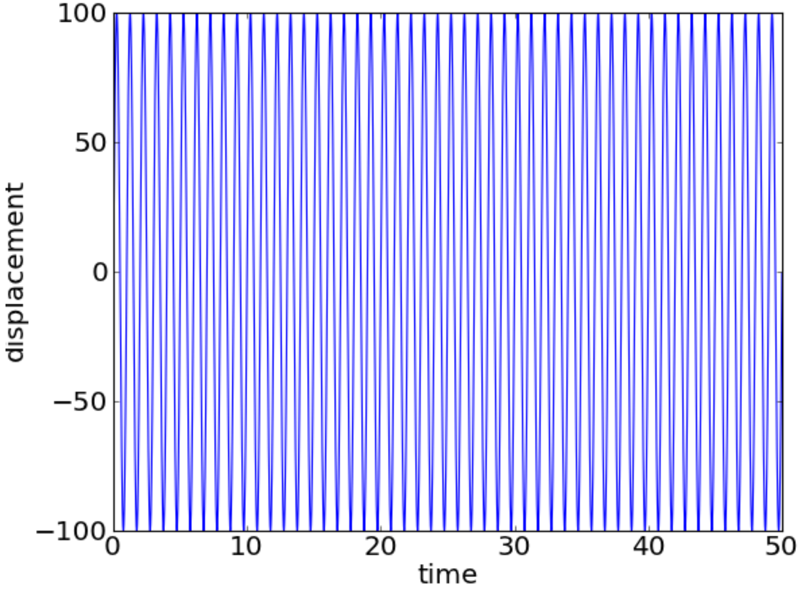
- Suppose I have one small loudspeaker playing out a 110 Hz tone ($\lambda \approx 3 \text{ m}$).
- Now I wire up 9 additional small loudspeakers, all playing out precisely the same sine wave, with the same amplitude, all separated by just a few cm.
- In this case, the waves from the 10 loudspeakers 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.

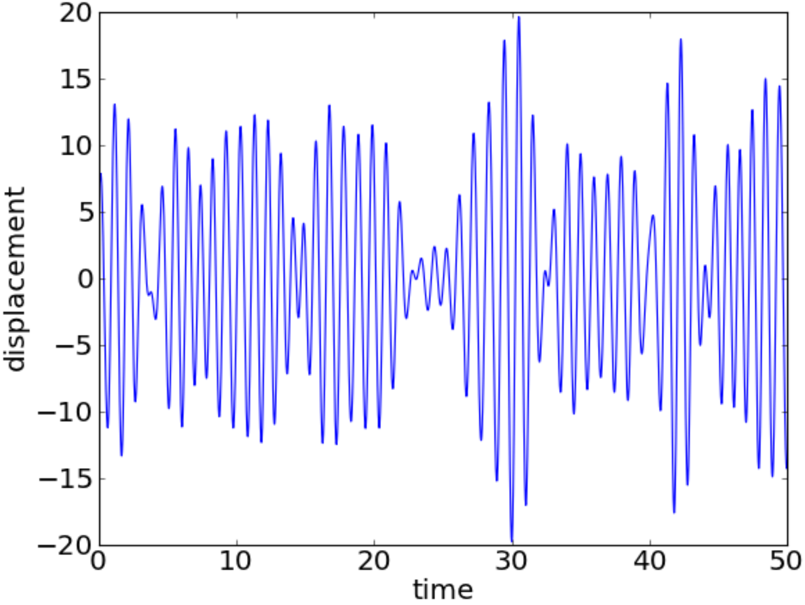
Here's a 1 Hz sine wave, of amplitude 1.



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)?

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

How about 10 trombones?

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

How about 10 trombones?

How about 100 trombones?

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

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`

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

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

Physics 9 — Wednesday, September 19, 2018

- HW#2 due Friday in class. Remember online feedback page.
- HW help sessions: Wed 4–6pm DRL **4C2** (Bill), Thu 6:30–8:30pm DRL 2C8 (Grace)
- For today, you read Eric Mazur chapter 17 (waves in 2D/3D)
- Course web page is `positron.hep.upenn.edu/physics9`
- Slides, etc.: `positron.hep.upenn.edu/physics9/files`
- I wrote (in **Processing**) a little animation of Monday's interference demonstration:

`http://positron.hep.upenn.edu/p9/files/acoustic_interferometer.html`

  I put the Processing source code for it at

`http://positron.hep.upenn.edu/p9/files/acoustic_interferometer.pde`

- On Friday, 9/21, recent Penn ARCH/Music grad Davis Butner will speak about his developing career in arch. acoustics.
- On Monday, 9/24, Terry Tyson from Acentech Acoustics will speak with us. If you're curious, here's an article by him:

`https://insulation.org/io/articles/good-design-for-architectural-acoustics/`