Physics 9 — Monday, September 17, 2018

- For today, you read/skimmed a very long excerpt from an architectural-acoustics book.
- For Wed, read Eric Mazur chapter 17 (waves in 2D/3D)
- My web server (positron) crashed this morning; I will get it back on the air as soon as I can!
- Course web page is `positron.hep.upenn.edu/physics9`
- Slides, etc.: `positron.hep.upenn.edu/physics9/files`
- 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.

Sound waves in room-temperature air travel at a wave speed of 343 m/s. (Much more on sound in the next week or so!)

Digression: About how long does it take for a pulse of sound (maybe a clap of thunder or the sound of a baseball bat hitting a ball) to travel 1 km?

What about a mile (1.61 km $\approx$ (5/3) km)?

What about one foot ((1/3.28) meter, or (1/5280) mile)?

Sound waves in room-temperature air travel at a wave speed of 343 m/s. (Much more on sound in the next week or so!)

Digression: About how long does it take for a pulse of sound (maybe a clap of thunder or the sound of a baseball bat hitting a ball) to travel 1 km?

What about a mile (1.61 km $\approx$ (5/3) km)?

What about one foot ((1/3.28) meter, or (1/5280) mile)?

Sound waves in air travel 1 km in 3 s, 1 mile in 5 s, 1 foot in 1 millisecond.

Sound waves in room-temperature air travel at a wave speed of 343 m/s. At a frequency of about 34 Hz (near the lower end of the range of frequencies people can hear), what is the wavelength?

(Young human ears can hear roughly 20 Hz — 20 kHz.)

Sound waves in room-temperature air travel at a wave speed of 343 m/s. At a frequency of about 34 Hz (near the lower end of the range of frequencies people can hear), what is the wavelength?

(Young human ears can hear roughly 20 Hz — 20 kHz.)

At a frequency of 34300 Hz (about $2\times$ above the upper limit of human hearing), what is the wavelength?

Sound waves in room-temperature air travel at a wave speed of 343 m/s. At a frequency of about 34 Hz (near the lower end of the range of frequencies people can hear), what is the wavelength?

(Young human ears can hear roughly 20 Hz — 20 kHz.)

At a frequency of 34300 Hz (about $2\times$ above the upper limit of human hearing), what is the wavelength?

What is the wavelength at 17150 Hz, which is close to the (roughly) 20 kHz upper range for young human ears?

Sound waves in room-temperature air travel at a wave speed of 343 m/s. At a frequency of about 34 Hz (near the lower end of the range of frequencies people can hear), what is the wavelength?

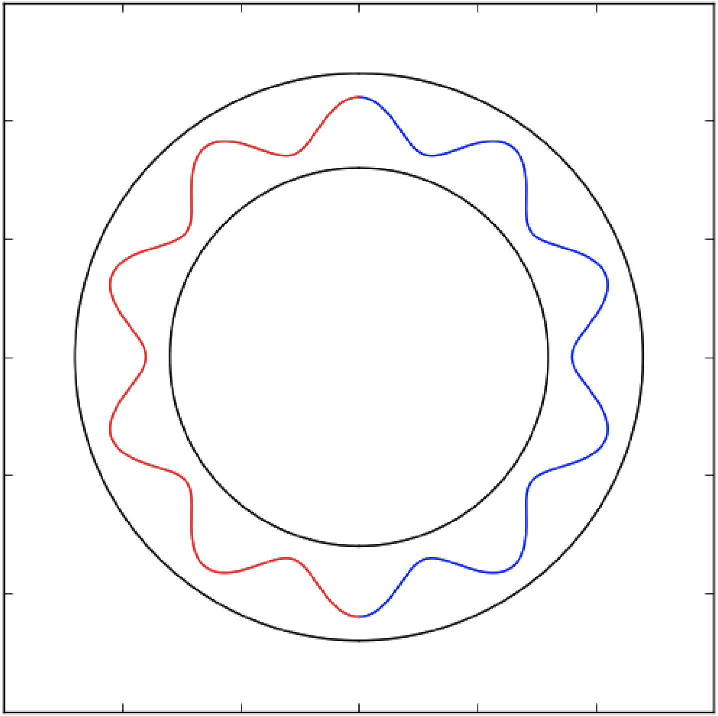
(Young human ears can hear roughly 20 Hz — 20 kHz.)

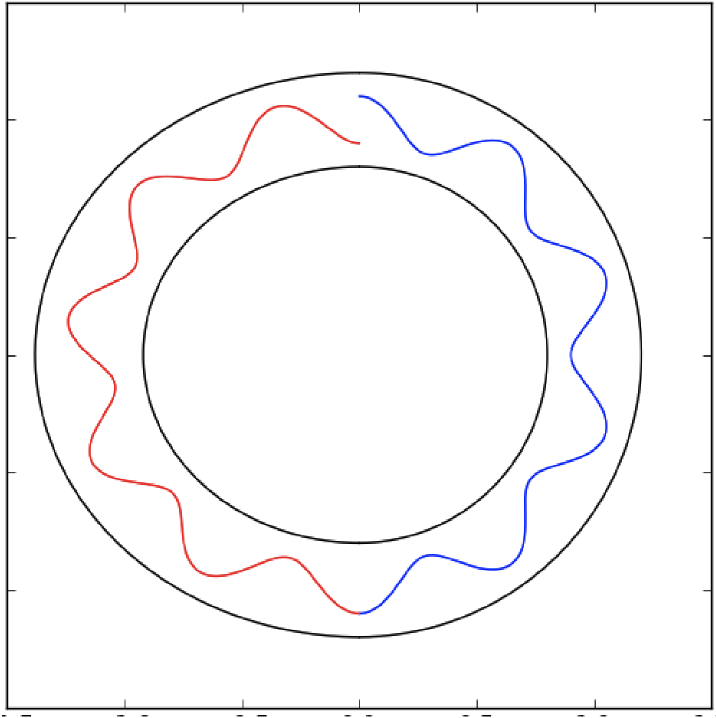
At a frequency of 34300 Hz (about $2\times$ above the upper limit of human hearing), what is the wavelength?

What is the wavelength at 17150 Hz, which is close to the (roughly) 20 kHz upper range for young human ears?

It turns out that the conventional telephone network only transmits sounds in the frequency range 300 Hz — 3400 Hz. What's the wavelength (for sound in air) at 343 Hz? At 3430 Hz?

- We saw earlier that when two waves overlap, the phases of the two waves can coincide, resulting in a larger amplitude ("constructive interference"), or the phases can be misaligned, resulting in a smaller (or even zero) amplitude ("destructive interference").
- You're adding two wave functions, each of which can be positive or negative, so the result can be larger in magnitude, smaller in magnitude, or zero.
- Imagine two sound waves meeting at a point: how can we vary their difference in path length to arrange for them to be "in phase" (constructive) or "180° out of phase" (destructive)?
- Important note: sound waves are **longitudinal** waves, but I've drawn transverse waves in the next two slides because it was easier for me to draw. Sorry!



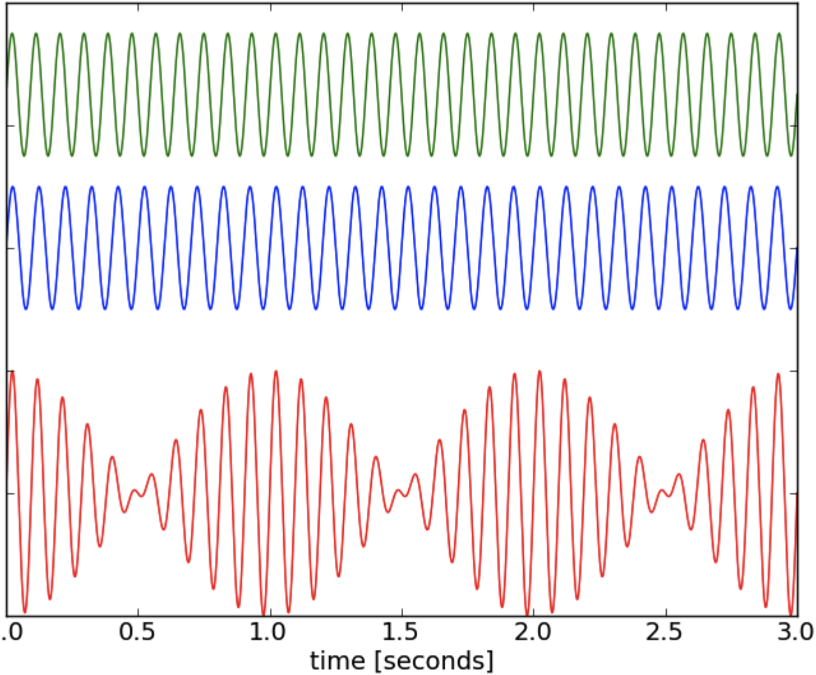


- We've seen that when two waves overlap, the phases of the two waves can coincide, resulting in a larger amplitude ("constructive interference"), or the phases can be misaligned, resulting in a smaller (or even zero) amplitude ("destructive interference").
- You're adding two wave functions, each of which can be positive or negative, so the result can be larger in magnitude, smaller in magnitude, or zero.
- Imagine two sound waves, at only slightly different frequencies, produced at the same place and time. How often will they be "in phase" (constructive interference) or "180° out of phase" (destructive interference)?

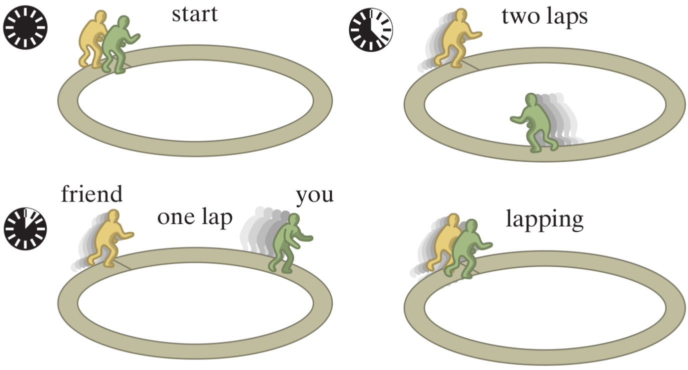
When you add together two tones of comparable amplitude and slightly different frequency, instead of hearing two separate tones, your ear hears the average of the two frequencies, *modulated* by the difference of the two frequencies. **"Beats."**

$$\sin(\alpha) + \sin(\beta) = 2\cos\left(\frac{\alpha - \beta}{2}\right)\sin\left(\frac{\alpha + \beta}{2}\right)$$

11 Hz sine, 10 Hz sine, and sum of the two sines



Analogy from Mazur ch17 (read tomorrow): you run around a track faster than your friend does. How often do you overtake your friend?



Beat frequency is the difference between the two frequencies:

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

Tuning forks, speaker, guitar, etc.

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

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

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

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

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

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

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

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.)

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

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

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

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

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.)

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

Also somewhat out of order, but useful for the homework:

- What stays the same and what changes as a harmonic (i.e. sinusoidal) wave crosses the boundary from one medium to another (e.g. different mass per unit length)?
- Does the wave speed stay the same?
- Does the frequency stay the same?
- Does the wavelength stay the same?
- Guitar string in slow motion: https://www.youtube.com/watch?v=6sgI7S_G-XI

- We saw earlier that when a wave meets another wave, the two waves add up (constructively or destructively), and pass through one another, whereas two objects would bounce off of one another.
- We also saw what happens when a wave meets the end of a medium: reflection from "fixed" end vs. "free" end.
- Then we considered what changes and what doesn't when a sinusoidal wave crosses the boundary between two media whose wave speeds differ.
- We know that the speed of sound is much higher in building materials (glass, wood, drywall, concrete) than in air, because those materials are so much harder to compress than air is. So what happens when a sound wave encounters a wall? Does it go through? Does it bounce back? Or some of both?

- 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 last night, sound transmission through walls is usually undesirable — want to minimize. We'll come back to this point when we discuss decibels.

Intensity of sound waves

- We've seen many times now that **frequency** is the physical property of sound waves that most closely relates to our sensation of "pitch."
- By contrast, **intensity** is the physical property of sound that most closely relates to our ears' perception of "loudness."
- Intensity is defined as energy per unit time per unit area.
- Since energy per unit time equals power, intensity is also equal to **power per unit area**.
- The SI units of intensity are W/m^2 (watts per square meter).
- 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 (that's a trillion times, i.e. a million million) 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**.

Intensity Level

The human ear is sensitive to a huge range of sound intensity.

Commonly encountered sound intensities differ by many powers of ten! So it makes sense to define a logarithmic measure of sound intensity.

Source of the Sound	Sound Level (dB)	Intensity (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}

"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. $(\log_{10}(1) = 0.)$

It's quite useful to understand the use of decibels to quantify sound intensity, because you will encounter 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.

Question

If the intensity is $I = 10^{-5}\ \mathrm{W/m^2}$, what is the sound level β?

Question

If the intensity is $I = 10^{-5}\ \mathrm{W/m^2}$, what is the sound level β?

$$\beta = 10 \log_{10} \left(\frac{10^{-5}\ \mathrm{W/m^2}}{I_o} \right)\ \mathrm{dB}$$

$$\beta = 10 \log_{10} \left(\frac{10^{-5}\ \mathrm{W/m^2}}{10^{-12}\ \mathrm{W/m^2}} \right)\ \mathrm{dB}$$

$$\beta = 10 \log_{10} \left(10^{7} \right)\ \mathrm{dB}$$

$$\beta = 70\ \mathrm{dB}$$

Remember definition:

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

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

Question:

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

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

Question:

The sound intensity level in a busy business office is 60 dB (with respect to the threshold of human hearing). What is the sound intensity in $\mathrm{W/m^2}$?

One thing you'll 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" 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?

- Cover this next time:
- Spherical wavefronts: intensity $\propto \; 1/r^2$
- The "mass law" for transmission loss of a wall or window.
- How intensity relates to amplitude (pressure amplitude or displacement amplitude).
- Confusing: using decibels for amplitude vs. for intensity. (This appeared in "architectural acoustics" introduction.)
- Combining "coherent" vs. "incoherent" sound sources.

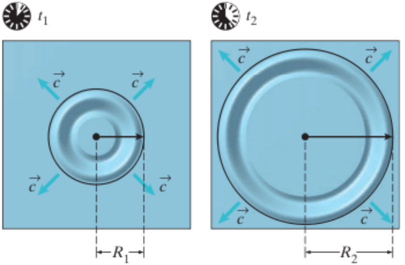


Figure 17.3 A surface wave moving at speed c. Because surface waves expand in two dimensions, the wave energy is distributed over a larger and larger circumference. (a) At t_1, the wave crosses a circle of radius R_1. (b) At t_2, the wave crosses a circle of radius $R_2 > R_1$.

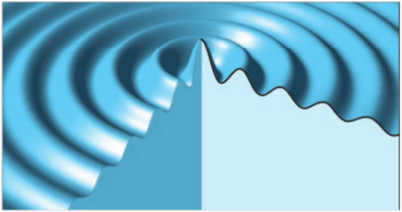


Figure 17.4 Cut-away view of a periodic surface wave. Because the energy in a given wavefront is spread out over an increasingly large circumference as the wavefront moves away from the source, the amplitude decreases as the wavefront moves away from the source.

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.

Physics 9 — Monday, September 17, 2018

- For today, you read/skimmed a very long excerpt from an architectural-acoustics book.
- For Wed, read Eric Mazur chapter 17 (waves in 2D/3D)
- My web server (positron) crashed this morning; I will get it back on the air as soon as I can!
- Course web page is `positron.hep.upenn.edu/physics9`
- Slides, etc.: `positron.hep.upenn.edu/physics9/files`
- 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.