



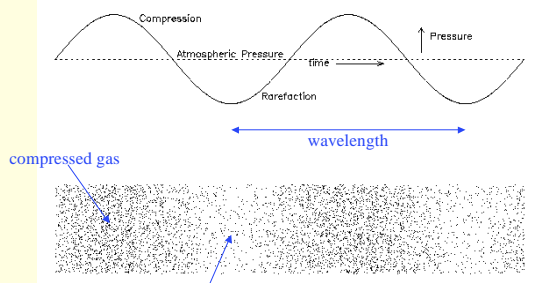
Sound

The Nature of Sound
Ears and Speakers

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What IS Sound?

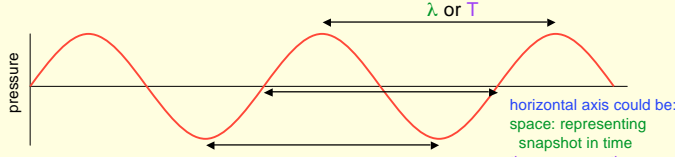
- Sound is really tiny fluctuations of air pressure
 - units of pressure: N/m^2 or psi (lbs/square-inch)
- Carried through air at 345 m/s (770 m.p.h) as **compressions** and **rarefactions** in air pressure



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Properties of Waves



- **Wavelength (λ)** is measured from crest-to-crest
 - or trough-to-trough, or upswing to upswing, etc.
- For traveling waves (sound, light, water), there is a **speed (c)**
- **Frequency (f)** refers to how many cycles pass by per second
 - measured in Hertz, or Hz: cycles per second
 - associated with this is period: $T = 1/f$
- **These three are closely related:**

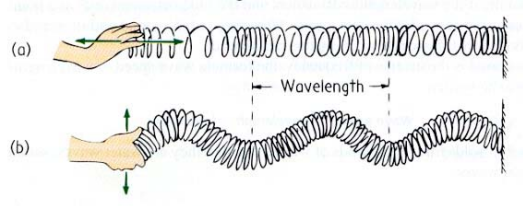
$$\lambda f = c$$

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Longitudinal vs. Transverse Waves

- Sound is a **longitudinal wave**, meaning that the motion of particles is **along** the direction of propagation
- **Transverse waves**—water waves, light—have things moving **perpendicular** to the direction of propagation



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Why is Sound Longitudinal?

- Waves in air can't really be transverse, because the atoms/molecules are **not bound** to each other
 - can't pull a (momentarily) neighboring molecule sideways
 - only if a "rubber band" connected the molecules would this work
 - fancy way of saying this: gases can't support shear loads
- Air molecules can really only bump into one another
- Imagine people in a crowded train station with hands in pockets
 - pushing into crowd would send a wave of compression into the crowd **in the direction of push** (longitudinal)
 - jerking people back and forth (sideways, over several meters) *would not* propagate into the crowd
 - but if everyone held hands (bonds), this transverse motion *would* propagate into crowd

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Sound Wave Interference and Beats

- When two sound waves are present, the superposition leads to **interference**
 - by this, we mean **constructive** and **destructive** addition
- Two similar frequencies produce beats
 - spend a little while in phase, and a little while out of phase
 - result is "beating" of sound amplitude

in phase: add

out of phase: cancel

signal A

signal B

A + B beat (interference)

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Speed of Sound

- Sound speed in air is related to the frantic motions of molecules as they jostle and collide
 - since air has a lot of empty space, the communication that a wave is coming through has to be carried by the motion of particles
 - for air, this motion is about 500 m/s, but only about 350 m/s directed in any particular direction
- Solids have faster sound speeds because atoms are hooked up by "springs" (**bonds**)
 - don't have to rely on atoms to traverse gap
 - spring compression can (and does) travel faster than actual atom motion

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Example Sound Speeds

Medium	sound speed (m/s)
air (20°C)	343
water	1497
gold	3240
brick	3650
wood	3800–4600
glass	5100
steel	5790
aluminum	6420

Spring 2006<http://hypertextbook.com/physics/waves/sound/>8

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Sound Intensity

- Sound requires energy (pushing atoms/molecules through a distance), and therefore a power
- Sound is characterized in decibels (dB), according to:
 - sound level = $10 \times \log(I/I_0) = 20 \times \log(P/P_0)$ dB
 - $I_0 = 10^{-12} \text{ W/m}^2$ is the threshold power intensity (0 dB)
 - $P_0 = 2 \times 10^{-5} \text{ N/m}^2$ is the threshold pressure (0 dB)
 - atmospheric pressure is about 10^5 N/m^2
- Examples:
 - 60 dB (conversation) means $\log(I/I_0) = 6$, so $I = 10^{-6} \text{ W/m}^2$
 - and $\log(P/P_0) = 3$, so $P = 2 \times 10^{-2} \text{ N/m}^2 = 0.0000002$ atmosphere!!
 - 120 dB (pain threshold) means $\log(I/I_0) = 12$, so $I = 1 \text{ W/m}^2$
 - and $\log(P/P_0) = 6$, so $P = 20 \text{ N/m}^2 = 0.0002$ atmosphere
 - 10 dB (barely detectable) means $\log(I/I_0) = 1$, so $I = 10^{-11} \text{ W/m}^2$
 - and $\log(P/P_0) = 0.5$, so $P = 6 \times 10^{-5} \text{ N/m}^2$

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Sound hitting your eardrum

- Pressure variations displace membrane (eardrum, microphone) which can be used to measure sound
 - my speaking voice is moving your eardrum by a mere $1.5 \times 10^{-4} \text{ mm} = 150 \text{ nm} = 1/4$ wavelength of visible light!
 - threshold of hearing detects $5 \times 10^{-8} \text{ mm}$ motion, one-half the diameter of a single atom!!!
 - pain threshold corresponds to 0.05 mm displacement
- Ear ignores changes slower than 20 Hz
 - so though pressure changes even as you climb stairs, it is too slow to perceive as sound
- Eardrum can't be wiggled faster than about 20 kHz
 - just like trying to wiggle resonant system too fast produces no significant motion

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Sensitivity of the Human Ear

- We can hear sounds with frequencies ranging from **20 Hz to 20,000 Hz**
 - an impressive range of **three decades** (logarithmically)
 - about **10 octaves** (factors of two)
 - compare this to vision, with less than one octave!

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Localization of Sound

- At low frequencies (< 1000 Hz), detect phase difference
 - wave crest hits one ear before the other
 - “shadowing” not very effective because of diffraction
- At high frequencies (> 4000 Hz), use relative intensity in both ears
 - one ear is in sound shadow
 - even with one ear, can tell front vs. back at high freq.

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Speakers: Inverse Eardrums

- **Speakers vibrate and push on the air**
 - pushing out creates compression
 - pulling back creates rarefaction
- **Speaker must execute complex motion according to desired waveform**
- **Speaker is driven via “solenoid” idea:**
 - electrical signal (AC) is sent into coil that surrounds a permanent magnet attached to speaker cone
 - depending on direction of current, the induced magnetic field either lines up with magnet or is opposite
 - results in pushing or pulling (attracting/repelling) magnet in coil, and thus pushing/pulling on center of cone

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Speaker Geometry

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Push Me, Pull Me

- **When the center of the speaker cone is kicked, the whole cone can't respond instantaneously**
 - the fastest any mechanical signal can travel through a material is at the speed of sound in the material
- **The whole cone must move into place well before the wave period is complete**
 - otherwise, different parts of the cone might be moving in while others are moving out (thus canceling the sound)
 - if we require the signal to travel from the center to the edge of the cone in $1/N$ of a wave cycle (N is some large-ish number):
 - available time is $\Delta t = 1/Nf = \lambda/Nc_{air}$
 - ripple in cone travels $c_{cone}\Delta t$, so radius of cone must be $< \lambda c_{cone}/Nc_{air}$
 - basic point is that speaker size is related to wavelength of sound
 - low frequency speakers are big, high frequency small

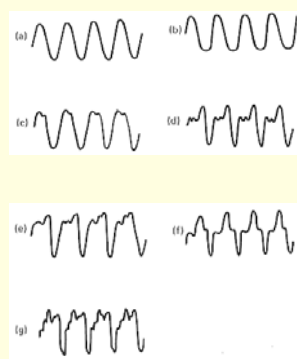
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The Look of Sound

Sound Waveforms
Frequency Content
Digital Sampling

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All Shapes of Waveforms



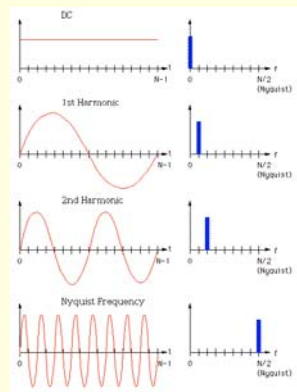
- Different Instruments have different waveforms
 - a: glockenspiel
 - b: soft piano
 - c: loud piano
 - d: trumpet
- Our ears are sensitive to the detailed shape of waveforms!
- More waveforms:
 - e: french horn
 - f: clarinet
 - g: violin

<http://www.st-and.demon.co.uk/AudioMisc/asymmetry/asym.html>

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How does our ear know?











- Our ears pick out **frequency** components of a waveform
- A DC (constant) signal has no wiggles, thus is at zero frequency
- A sinusoidal wave has a single frequency associated with it
- The faster the wiggles, the higher the frequency
- The height of the spike indicates how strong (amplitude) that frequency component is

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Composite Waveforms

Description	Time Series	Fourier Expansion	Power Spectrum
A pure 5kHz sine wave measuring 1 volt peak.		$v(t) = 1\sin(\omega t)$ $\omega = 2\pi(5\text{kHz})$	
A pure 5kHz and 10kHz sine wave, each measuring 1 volt peak, added together.		$v(t) = 1\sin(\omega_1 t) + 1\sin(\omega_2 t)$ $\omega_1 = 2\pi(5\text{kHz})$ $\omega_2 = 2\pi(10\text{kHz})$	
A pure 5kHz, 10kHz, and 20kHz sine wave, each measuring 1 volt peak, added together.		$v(t) = 1\sin(\omega_1 t) + 1\sin(\omega_2 t) + 1\sin(\omega_3 t)$ $\omega_1 = 2\pi(5\text{kHz})$ $\omega_2 = 2\pi(10\text{kHz})$ $\omega_3 = 2\pi(20\text{kHz})$	
A pure 5kHz square wave measuring 1 volt.		$v(t) = \frac{4}{\pi} \sin(\omega t) + \frac{4}{3\pi} \sin(3\omega t) + \frac{4}{5\pi} \sin(5\omega t) + \dots$ $\omega_1 = 2\pi(5\text{kHz})$ $\omega_2 = 2\pi(15\text{kHz})$ $\omega_3 = 2\pi(25\text{kHz})$	

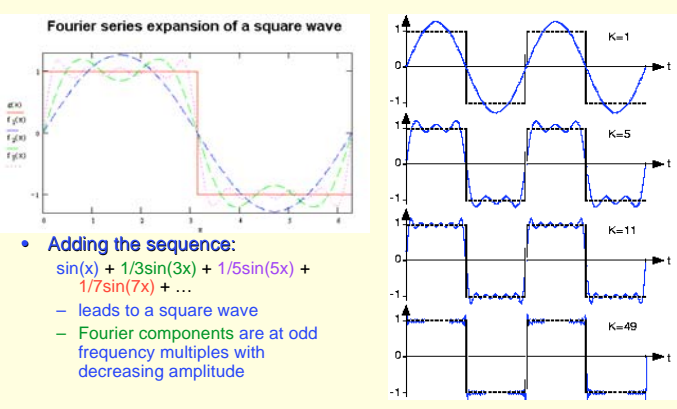
- A single sine wave has only one frequency represented in the "power spectrum"
- Adding a "second harmonic" at twice the frequency makes a more complex waveform
- Throwing in the fourth harmonic, the waveform is even more sophisticated
- A square wave is composed of odd multiples of the fundamental frequency

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Decomposing a Square Wave

Fourier series expansion of a square wave

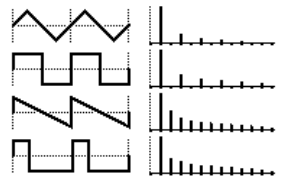


- Adding the sequence:
 - $\sin(x) + 1/3\sin(3x) + 1/5\sin(5x) + 1/7\sin(7x) + \dots$
 - leads to a square wave
 - Fourier components are at odd frequency multiples with decreasing amplitude

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The ear assesses frequency content



- Different waveforms look different in frequency space
- The sounds with more high-frequency content will sound raspier
- The exact mixture of frequency content is how we distinguish voices from one another
 - effectively, everyone has their own waveform
 - and corresponding spectrum
 - though an “A” may sound vastly similar, we’re sensitive to very subtle variations

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Assignments

- Read pp. 404–406, 489–492
- Midterm 05/04 (Thu.) 2PM WLH 2005
 - have posted study guide on course website
 - will have review session Wednesday 7:00–8:50, Center 113
 - Use light-green Scantron: Form No.: X-101864
 - Bring #2 pencil, calculators okay

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