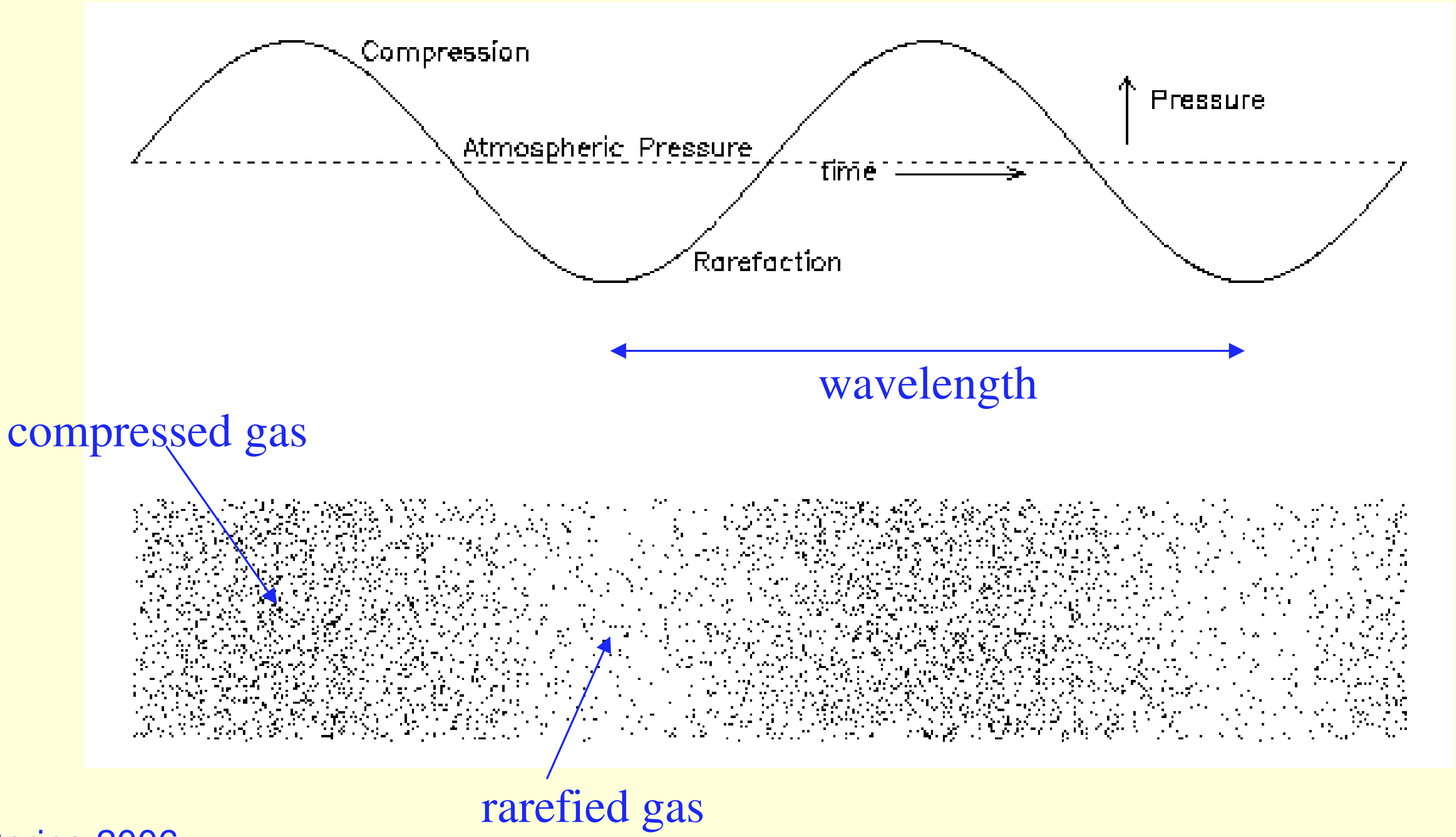
Sound

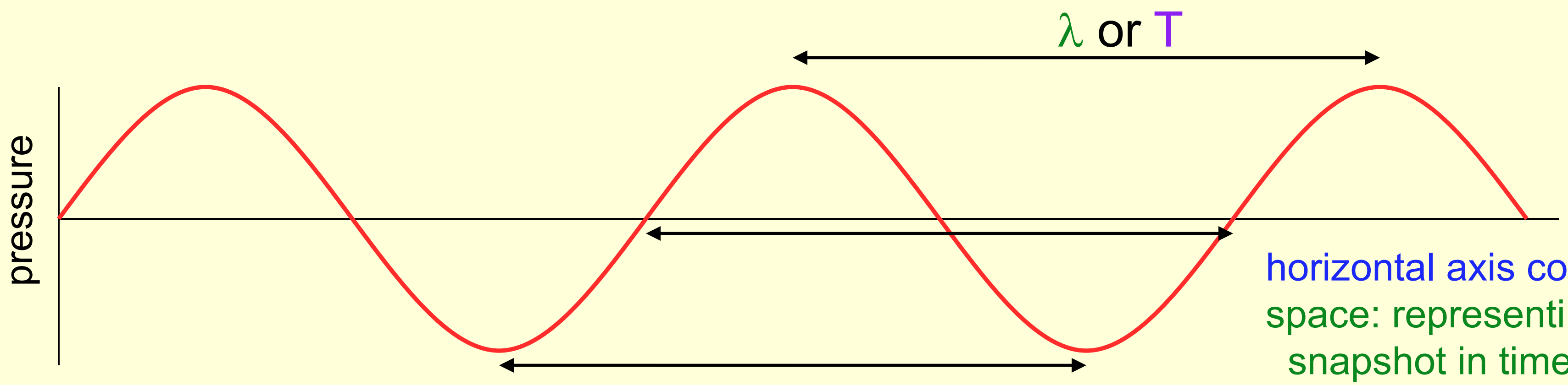
The Nature of Sound
Ears and Speakers

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



Properties of Waves



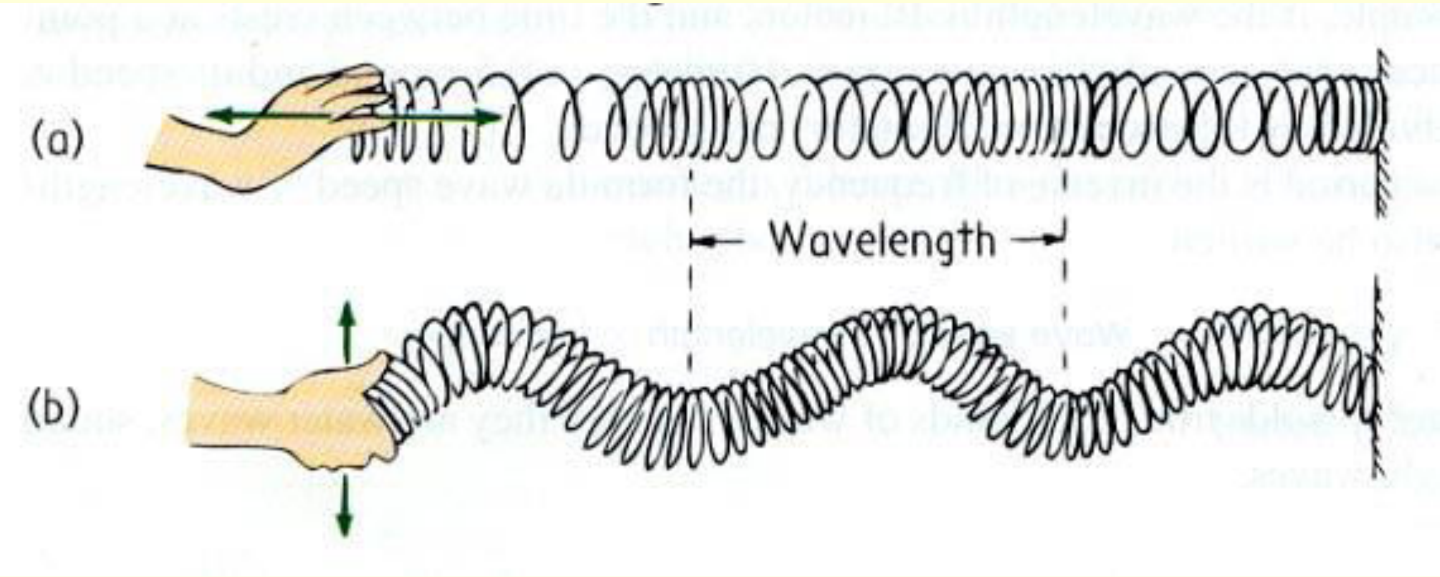
horizontal axis could be:
space: representing snapshot in time
time: representing sequence at a particular point in space

- 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:

$$\lambda f = c$$

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



Why is Sound Longitudinal?

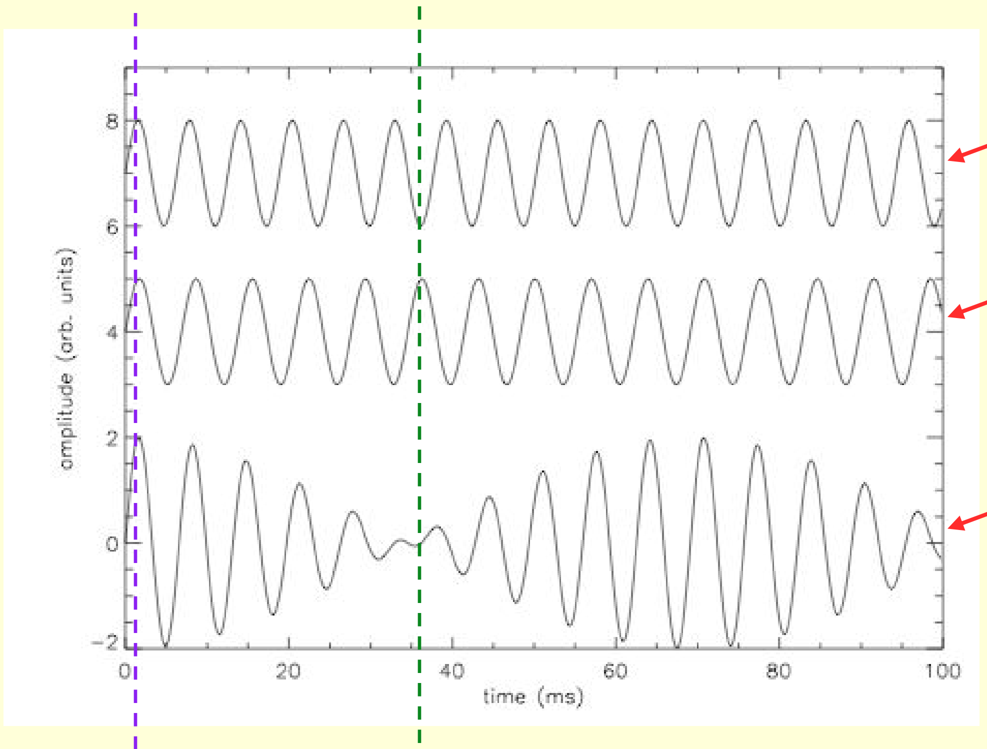
- Waves in air can’t really be transverse, because the atoms/molecules are not bound to each other
  - can’t pull a (momentarily) neighboring molecule sideways
  - only if a “rubber band” connected the molecules would this work
  - fancy way of saying this: gases can’t support shear loads
- Air molecules 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

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)

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

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

http://hypertextbook.com/physics/waves/sound/

Sound Intensity

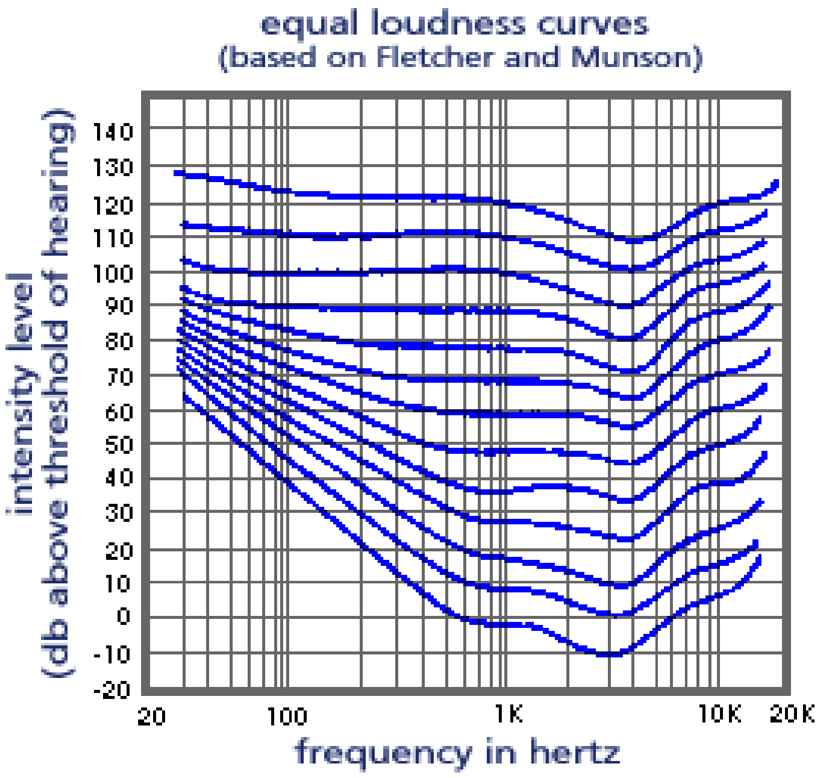
- Sound requires energy (pushing atoms/molecules through a distance), and therefore a power
- Sound is characterized in decibels (dB), according to:
  - sound level = $10\times\log(I/I_0)$ = $20\times\log(P/P_0)$ dB
  - $I_0 = 10^{-12}$ W/m^2 is the threshold power intensity (0 dB)
  - $P_0 = 2\times10^{-5}$ 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 $I = 10^{-6}$ W/m^2
    - and $\log(P/P_0) = 3$, so $P = 2\times10^{-2}$ N/m^2 = 0.0000002 atmosphere!!
  - 120 dB (pain threshold) means $\log(I/I_0) = 12$, so $I = 1$ W/m^2
    - and $\log(P/P_0) = 6$, so $P = 20$ N/m^2 = 0.0002 atmosphere
  - 10 dB (barely detectable) means $\log(I/I_0) = 1$, so $I = 10^{-11}$ W/m^2
    - and $\log(P/P_0) = 0.5$, so $P \approx 6\times10^{-5}$ N/m^2

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 1.5×10^{-4} mm = 150 nm = 1/4 wavelength of visible light!
  - threshold of hearing detects 5×10^{-8} 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

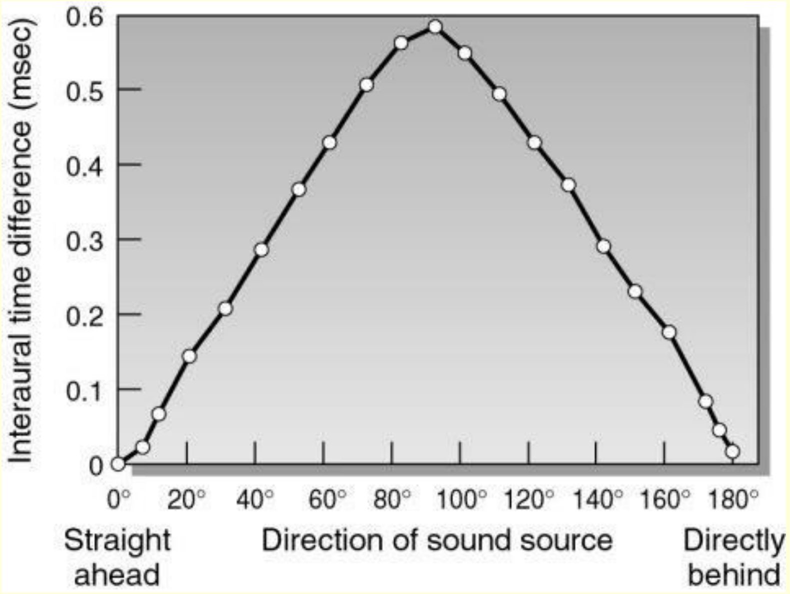
Sensitivity of the Human Ear

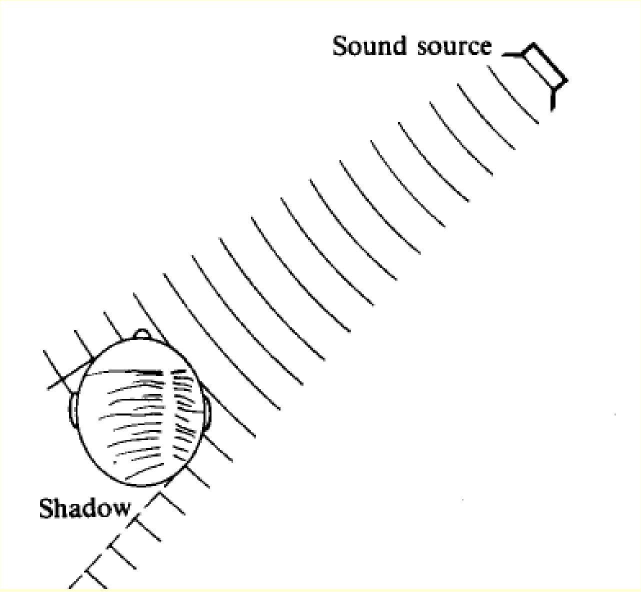
- We can hear sounds with frequencies ranging from 20 Hz to 20,000 Hz
  - an impressive range of three decades (logarithmically)
  - about 10 octaves (factors of two)
  - compare this to vision, with less than one octave!



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.

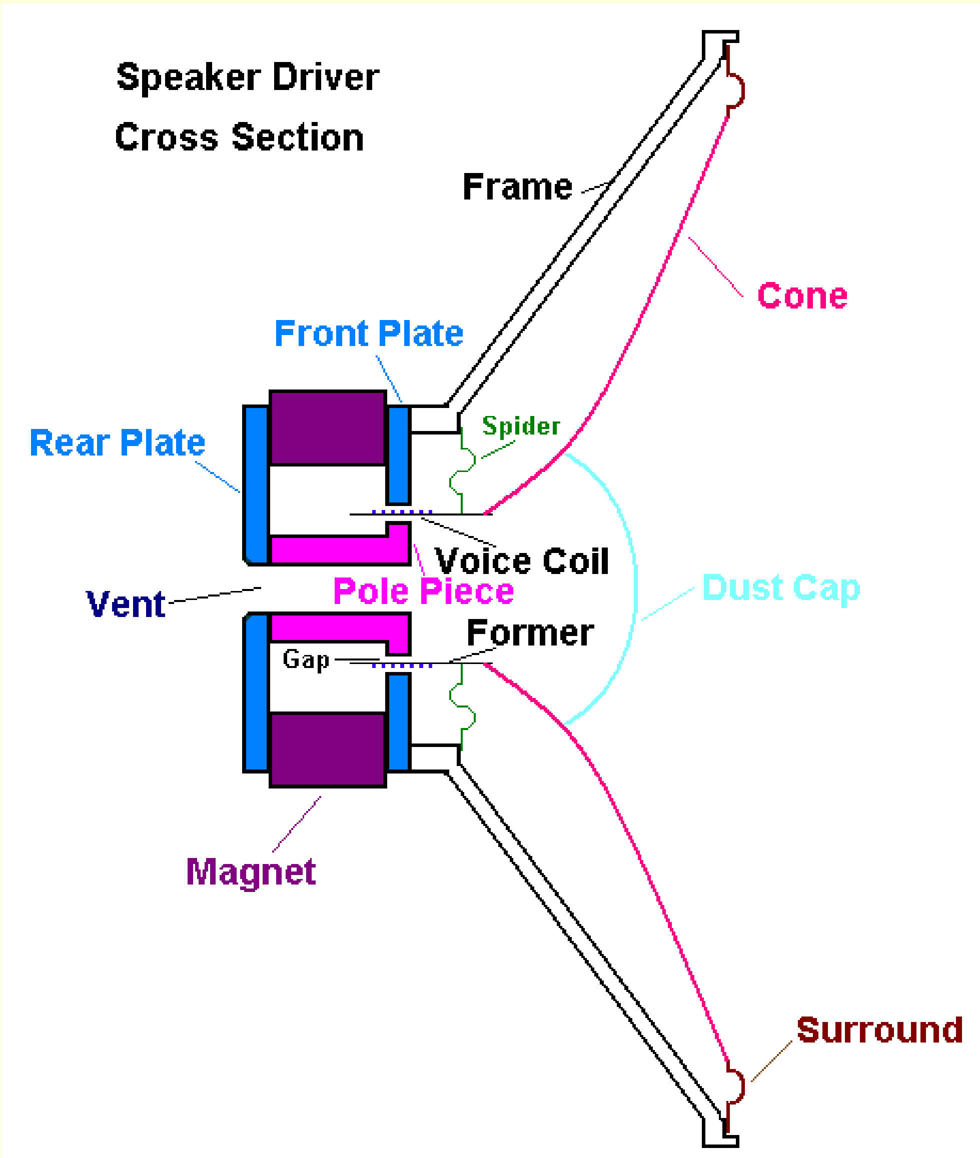




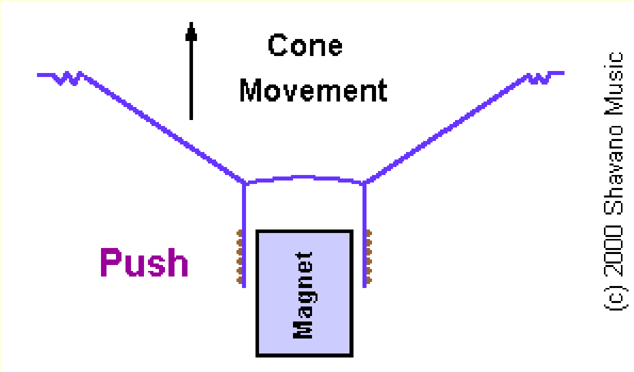
Speakers: Inverse Eardrums

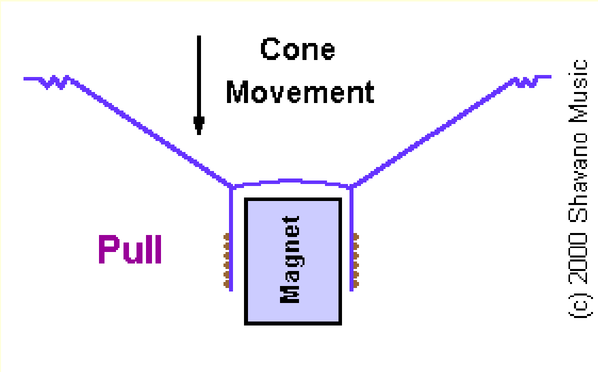
- Speakers vibrate and push on the air
  - pushing out creates compression
  - pulling back creates rarefaction
- Speaker must execute complex motion according to desired waveform
- Speaker is driven via "solenoid" idea:
  - electrical signal (AC) is sent into coil that surrounds a permanent magnet attached 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

Speaker Geometry

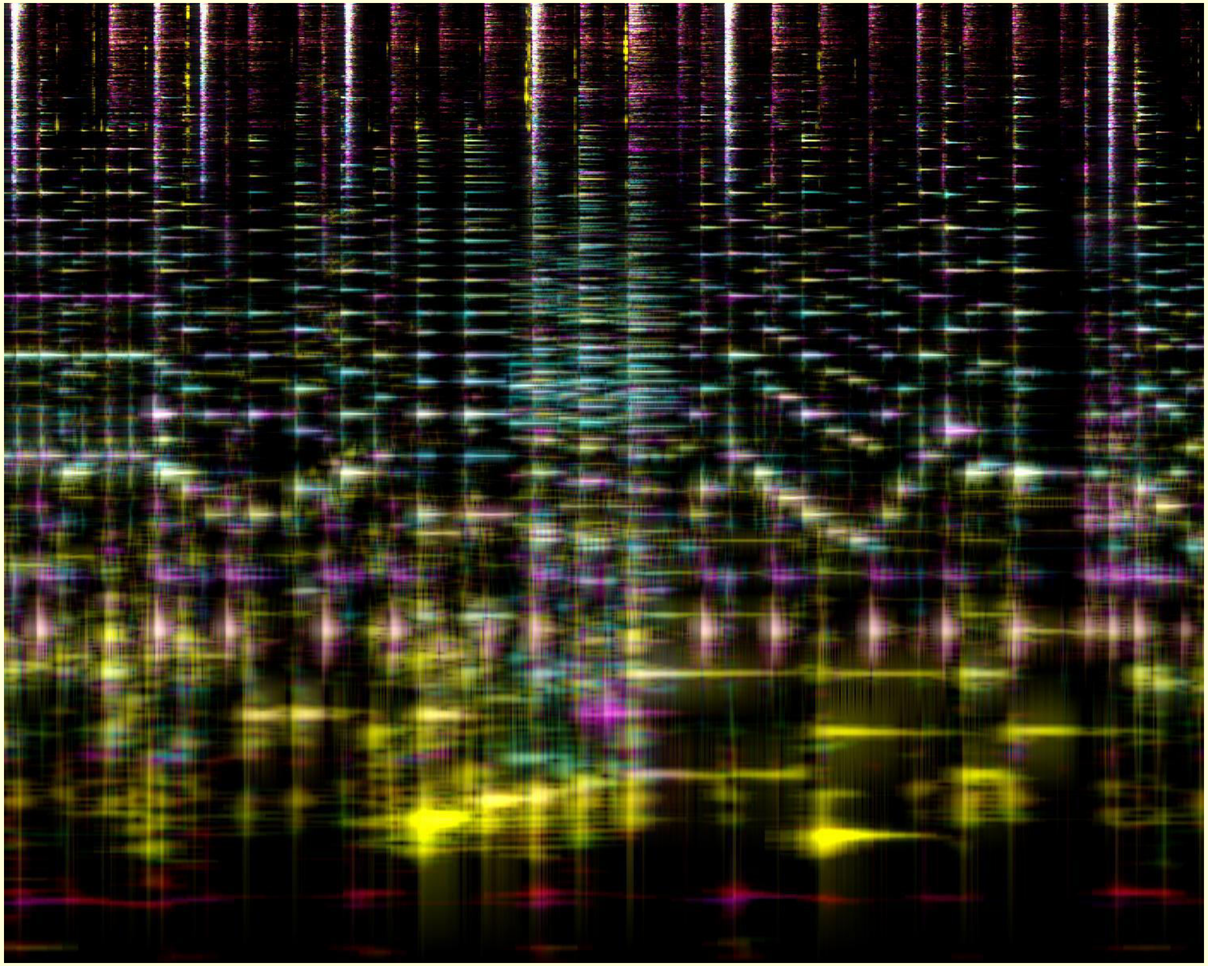


Push Me, Pull Me





- **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



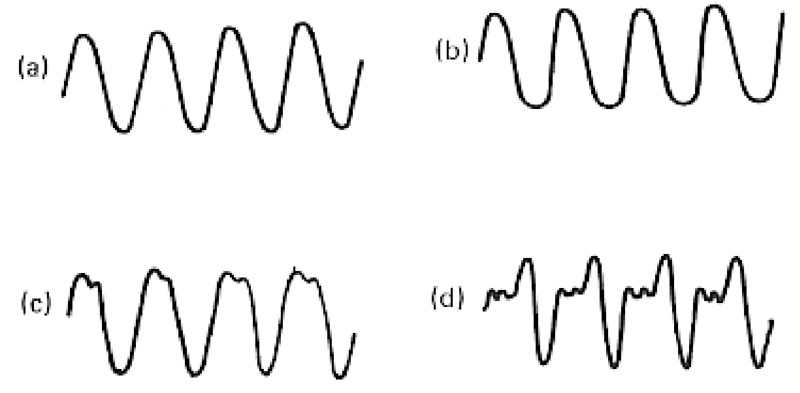
The Look of Sound

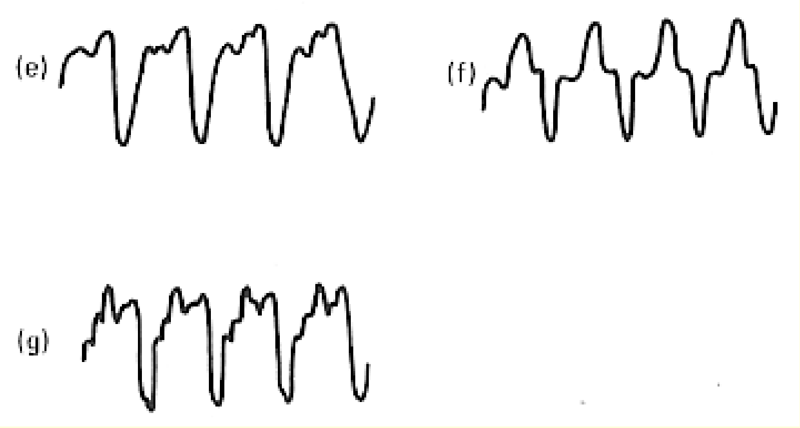
Sound Waveforms

Frequency Content

Digital Sampling

All Shapes of Waveforms

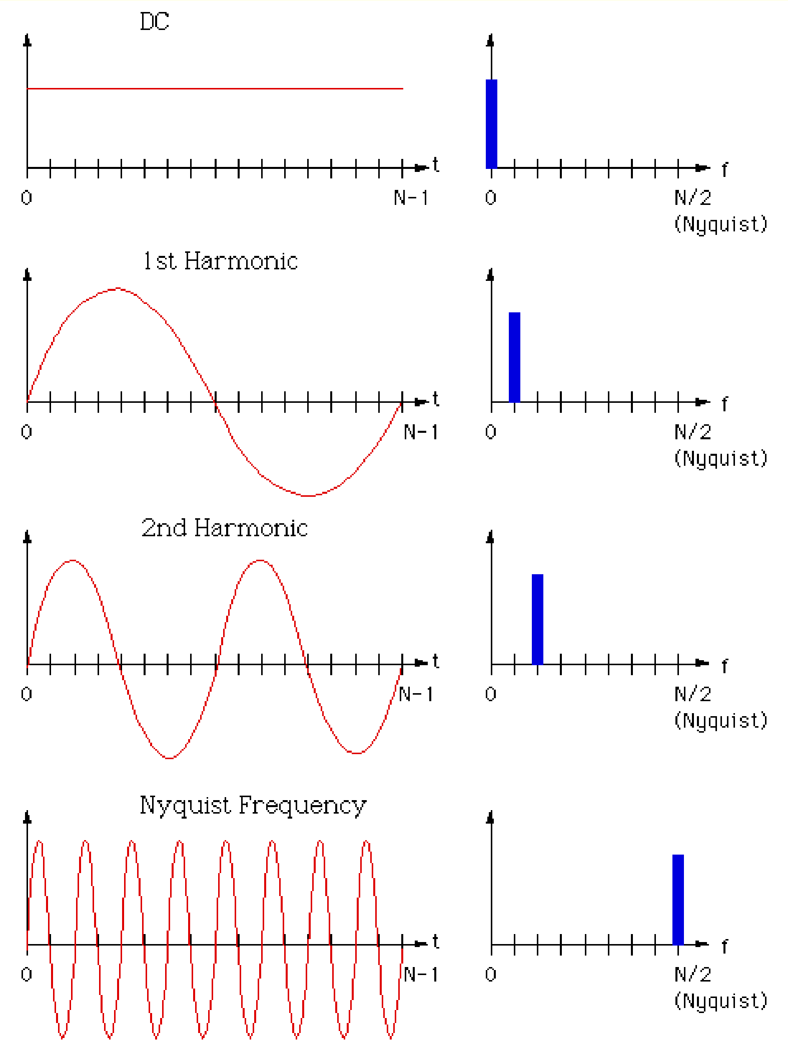




- Different Instruments have different waveforms
  - a: glockenspiel
  - b: soft piano
  - c: loud piano
  - d: trumpet
- Our ears are sensitive to the detailed shape of waveforms!
- More waveforms:
  - e: french horn
  - f: clarinet
  - g: violin

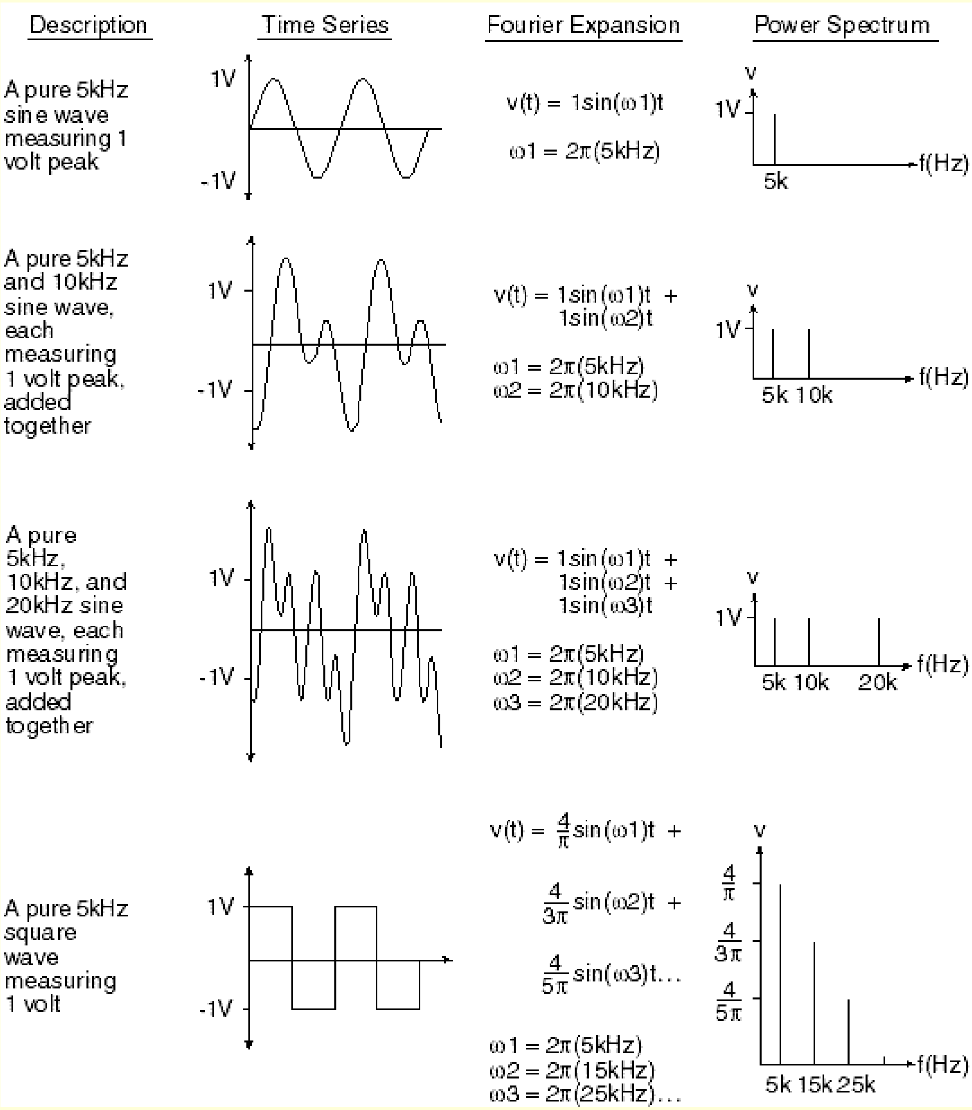
http://www.st-and.demon.co.uk/AudioMisc/asymmetry/asym.html

How does our ear know?



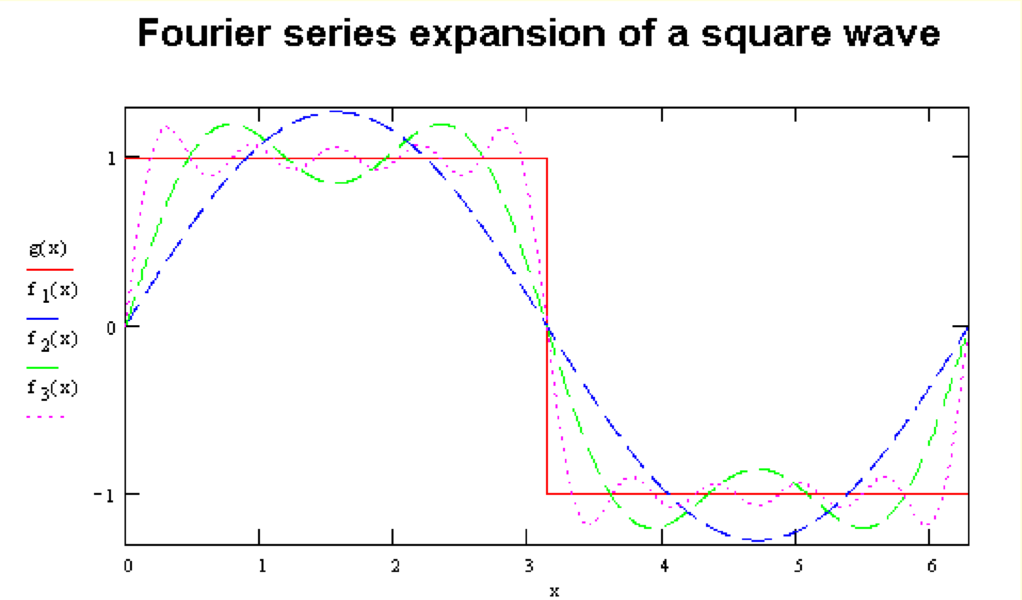
- Our ears pick out frequency components of a waveform
- A DC (constant) signal has no wiggles, thus is at zero frequency
- A sinusoidal wave has a single frequency associated with it
- The faster the wiggles, the higher the frequency
- The height of the spike indicates how strong (amplitude) that frequency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

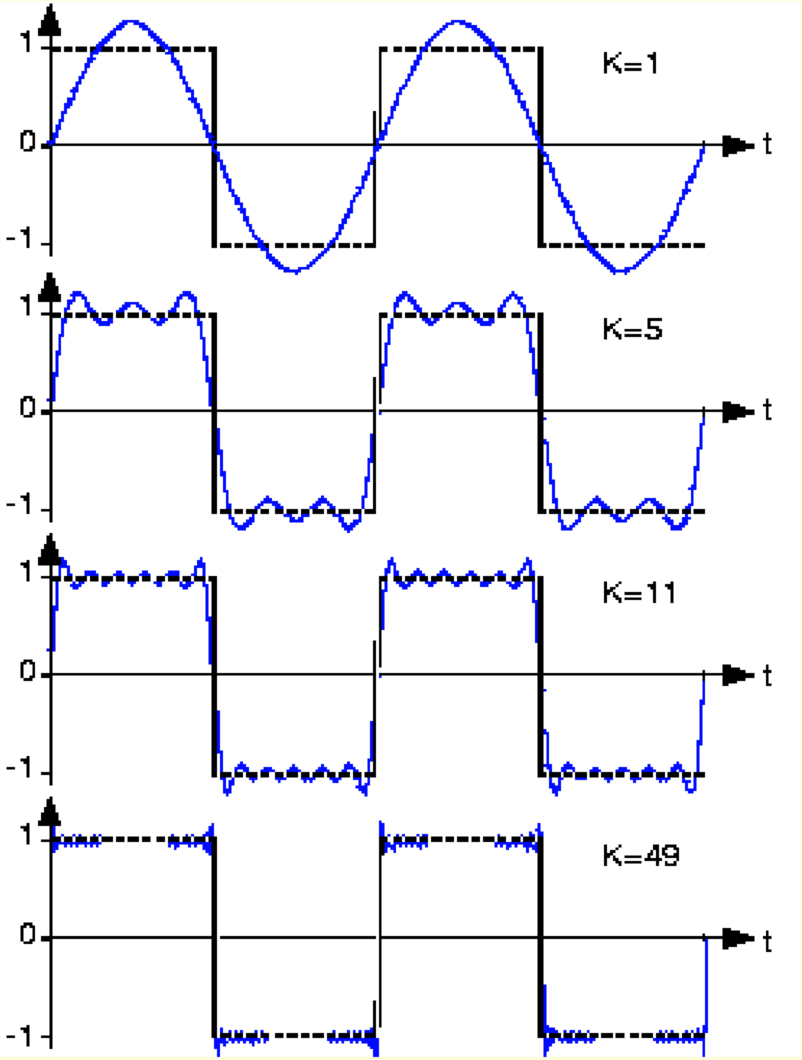
Composite Waveforms



- 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

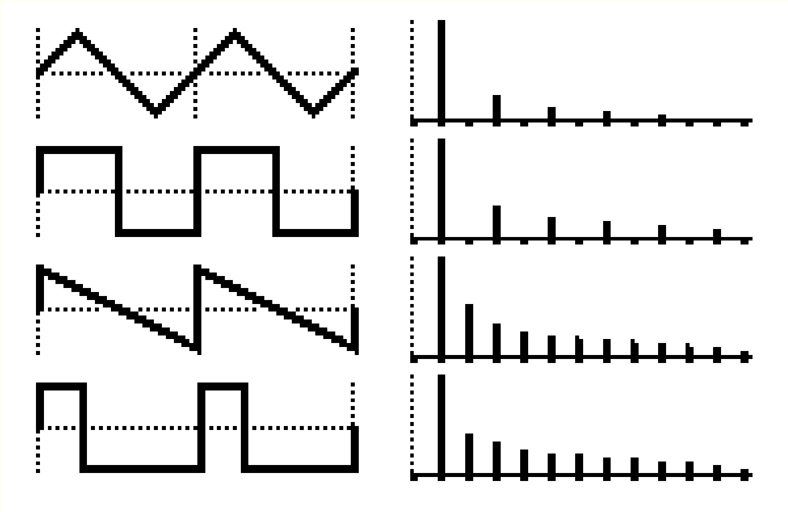
Decomposing a Square Wave





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

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

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