Speech Science

COMD 6305

Weds 2:30 – 3:45

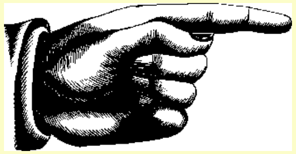
Fri 1:00 – 2:15

William F. Katz, Ph.D.

UTD

Chapter 1.
The Nature of Sound

INCLUDING



- *Definition of Speech Science*
- *Basic physics concepts*
- *Overview of sound*
- *Resonance*

What is ‘speech science’?

- *“Speech Science is the experimental study of speech communication, involving speech production and speech perception as well as the analysis and processing of the acoustic speech signal.”*

- Speech Science asks questions like:
  - How is speech planned and executed by the vocal system?
  - How do the acoustic properties of sounds relate to their articulation?
  - How and why do speech sounds vary from one context to another?
  - How and why do speech sounds vary between speakers?
  - How and why do speech sounds vary across speaking styles or emotions?
  - How do listeners recover the linguistic code from auditory sensations?
  - How do infants learn to produce and perceive speech?

(-M. Huckvale, UCL)

Physics Principles

Energy

= ability (power) to do work*

*(force to move a mass some distance in some amount of time)

Common Units:

Mass = kilograms (kg)

Distance = meters (m)

Time = seconds (sec)

Energy

- Measured many ways, typically Joules

$$Joules = \frac{kg * m^2}{s^2}$$

- Sound energy = vibrations moving through a medium
- Typically measured in decibels (dB)

  (more details later in PPT)

Physics Principles - cont'

Opposing Forces

- Affect objects in motion

1. Friction
2. Inertia
3. Elasticity

Friction

- Impedes or opposes movement

(not much friction here….)

In order to vibrate, an object must possess

1) Inertia
2) Elasticity

*Any object that can vibrate can produce sound

Inertia

"Tendency for mass at rest to remain at mass"

or

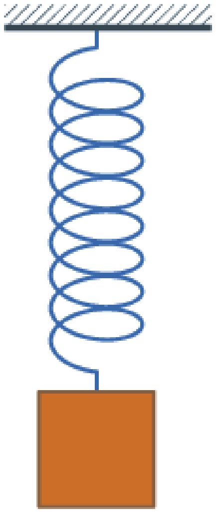
"Object in motion to remain in motion"

(*<u>Note</u>: Amount of inertia is related to mass*)

Elasticity:

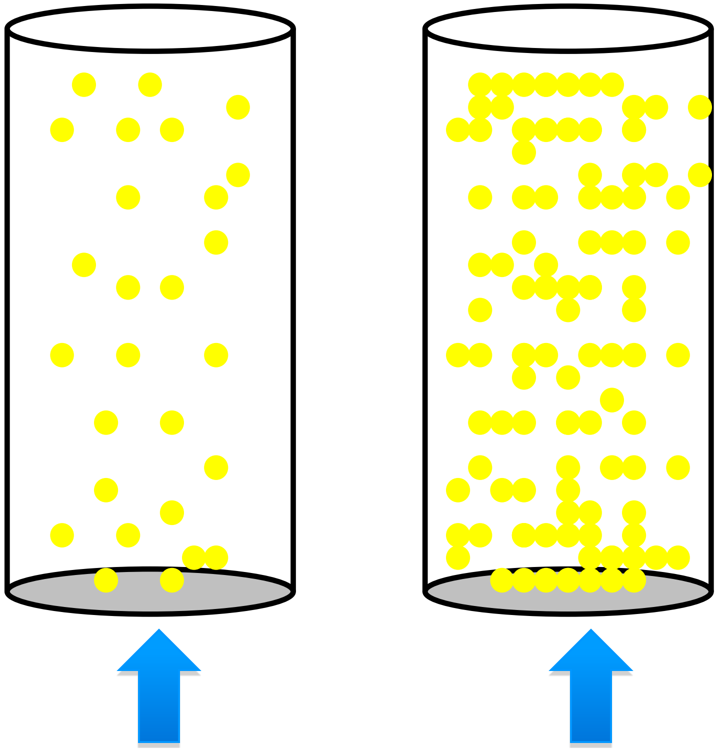
- Restoring force
- Ability of a substance to recover its original shape and size after distortion
- All solids are elastic; gases also behave as if elastic

Hooke's law – describes <u>elasticity</u> **-** *"restoring force is proportional to the distance of the displacement and acts in the opposite direction"*



(if not stretched beyond its elastic limit)

Density
(= mass per unit of volume)



Lower Density

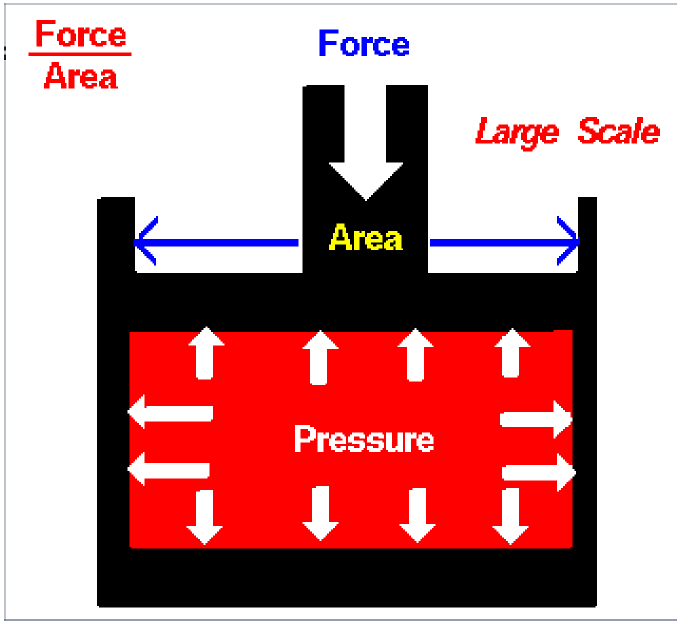
Higher Density

Pressure

- Pressure = Pa
- Pa = N/m^2, or *dyne (older literature)*
- N = $\frac{\text{kg x meter}}{\text{s}^2}$

(where N = Newton, a measure of force)

*See later **slide** for other measures of pressure!*

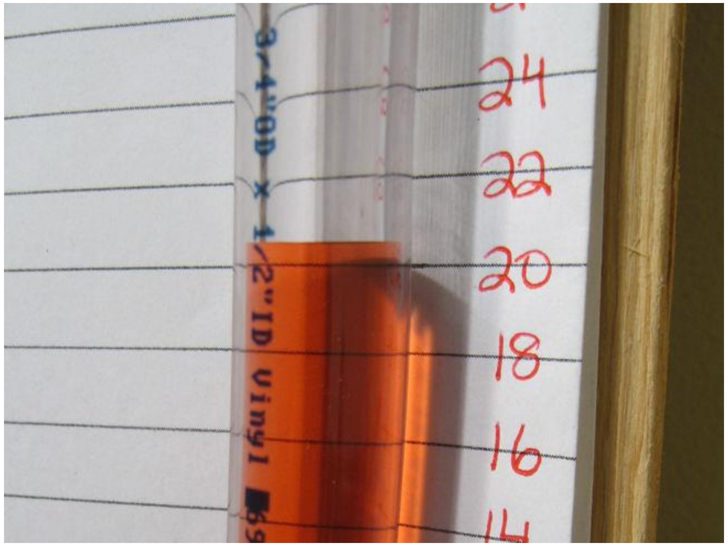


Measurement of air pressure

- Dynes* per sq centimeter dyne/cm^2
- Pounds per square inch psi
- Microbar μbar
- Pascal μPa
- Centimeters of water cm H_2O
- Millimeters of mercury mm Hg

*The <u>force</u> required to accelerate a mass of one gram at a rate of one cm/sec^2

Air pressure can also be measured in <u>cm of H_20</u> or <u>mm of Mercury (Hg)</u>



Two Units of Measure (pressure)

dynes/cm^2 — "microbar" (CGS system)

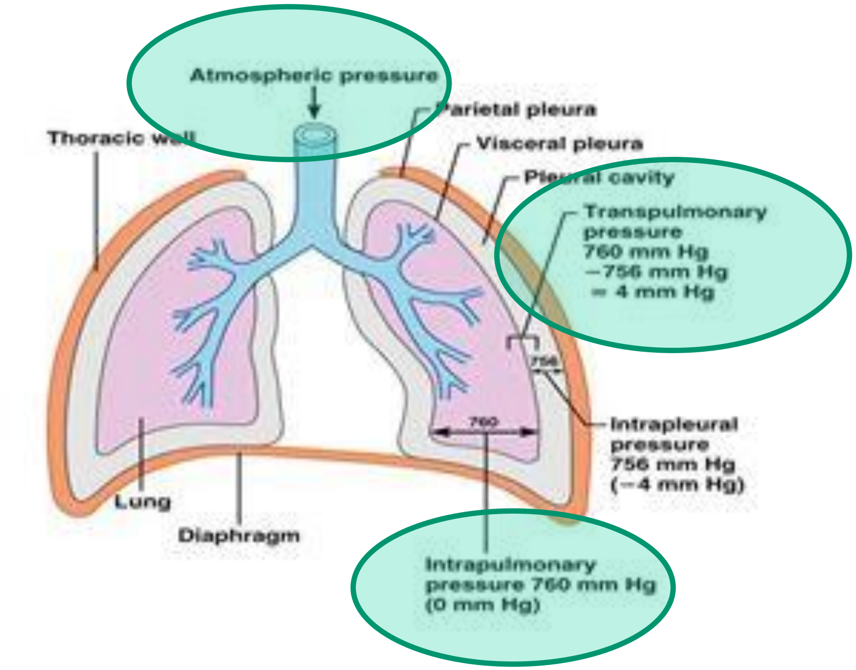
N/m^2 — "Pascal"* (MKS system)

*(For speech, micropascal is more commonly used)

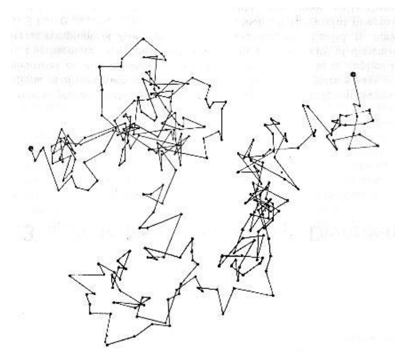
***M**eters/**K**ilograms/**S**ecs*
***C**entimeters/**G**rams/**S**ecs*

Pressure at different locations may vary

- P_{atmos}
- P_{oral}
- P_{trach}
- $P_{alveolar}$



Air



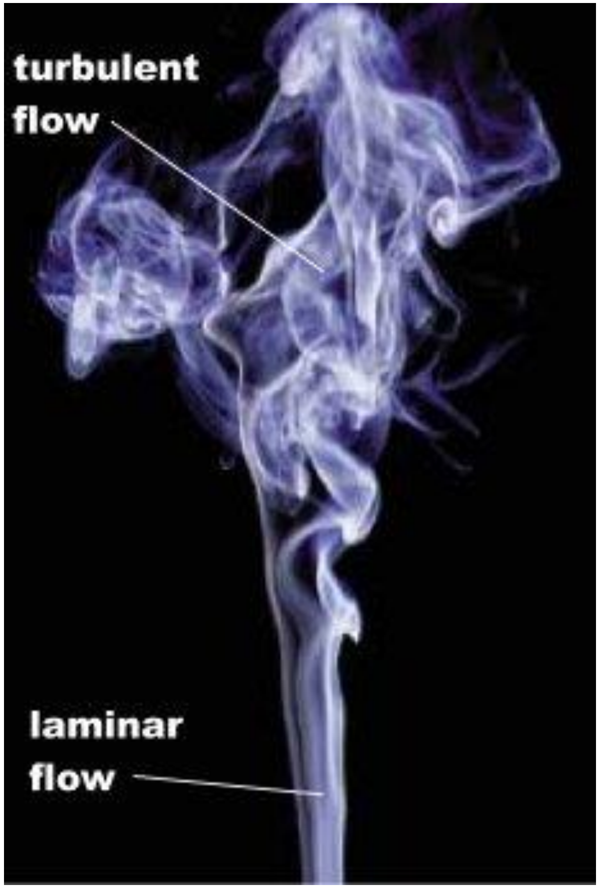
- Composed of gas molecules
- Particles travel in Brownian motion
- Has pressure (force per unit area)
  - Pressure related to speed of Brownian motion

"rapid changes in relatively static atmospheric pressure we call sound pressure or sound energy"

Air Movement

- driving pressure: (difference in pressure) high pressure FLOWS to low pressure
- volume velocity: rate of flow – e.g *liter/sec*
- laminar flow - in a parallel manner
- turbulent flow – in a non-parallel manner (flows around an object - eddies)

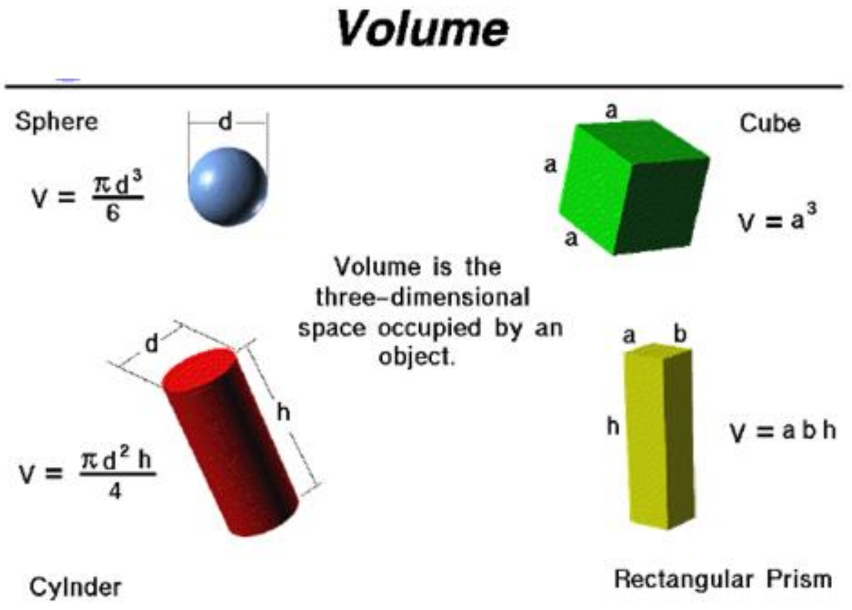
Flow



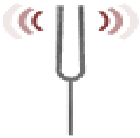
Air Pressure, Volume, Density

- Volume: amount of space in three dimensions
- Density: amount of mass per unit of volume
- Boyle's law - as volume decreases, pressure increases

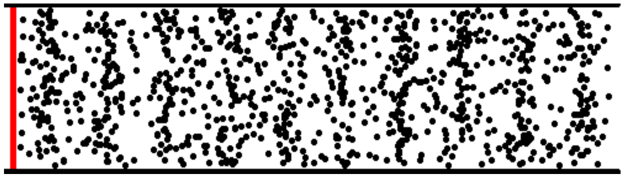
(*assuming constant temperature*)

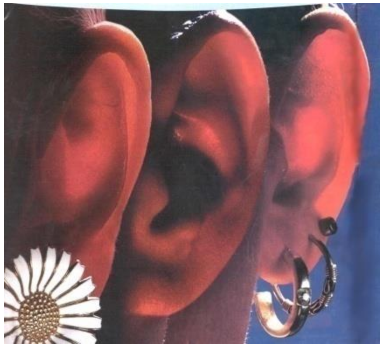


What is "sound?"



- Form of energy
- Waves produced by vibration of an object
- Transmission through a medium (gas, liquid, solid)
- Has no mass or weight
- Travels in longitudinal wave





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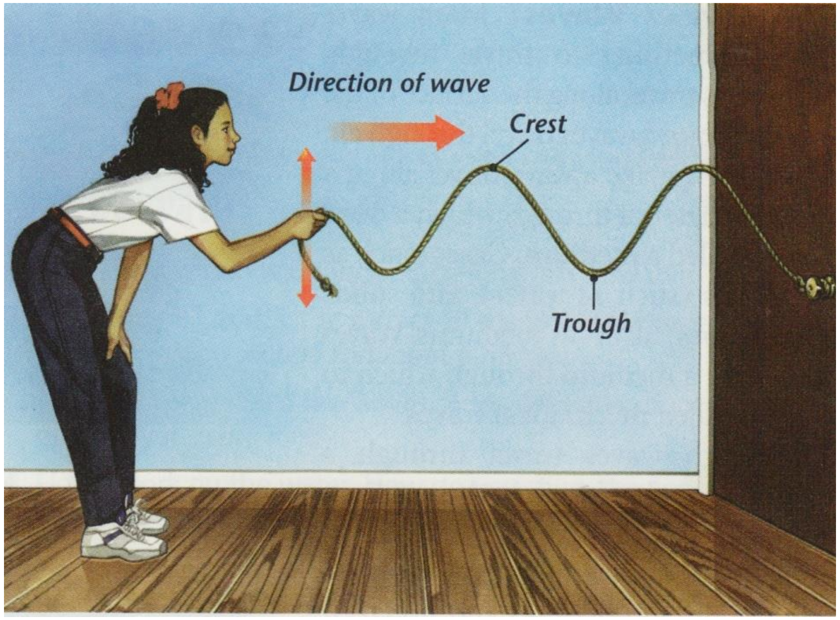
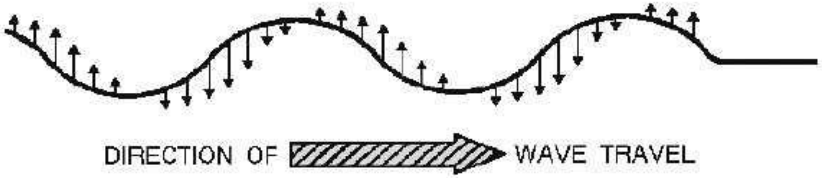
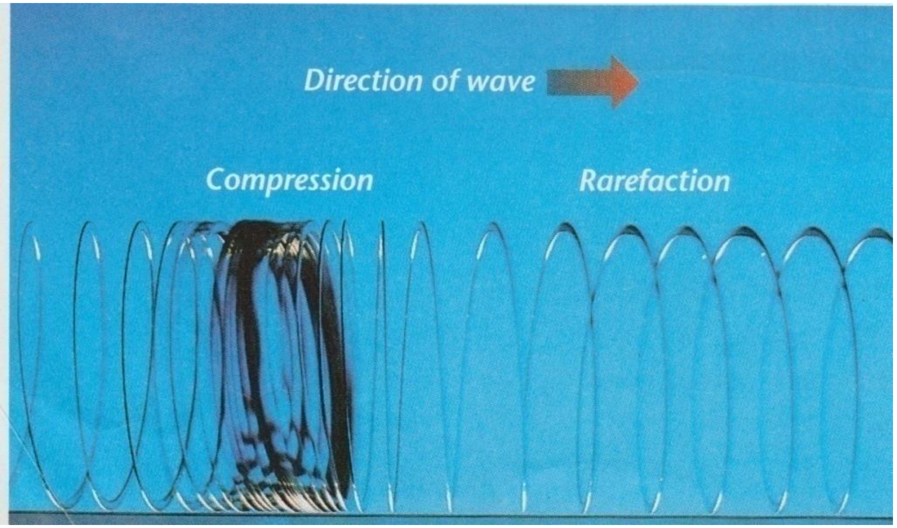
Transverse vs. Longitudinal Wave

Transverse



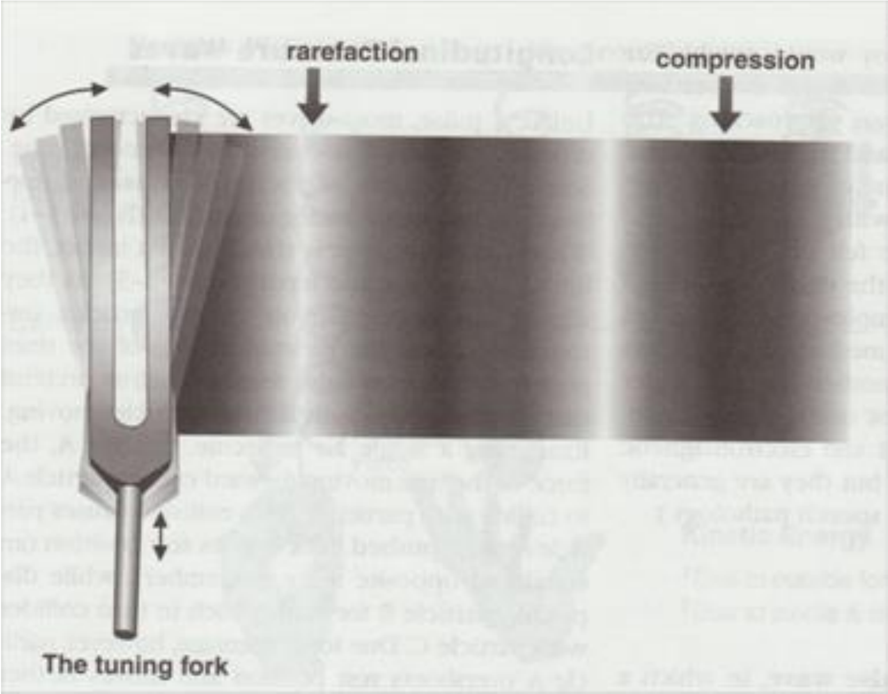


Longitudinal – SOUND!

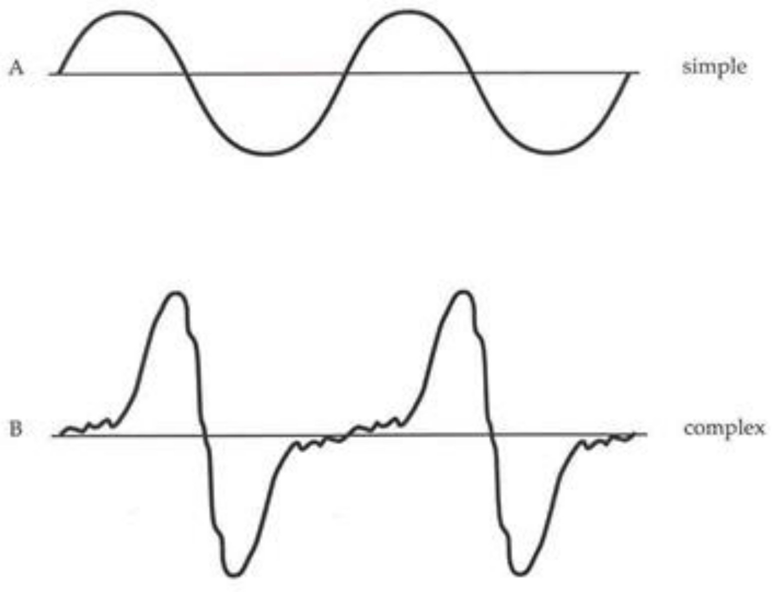


Air Pressure Changes from Sound

- Compression
- Rarefaction



Periodic waves



- Simple (sine; sinusoid)
- Complex (actually a composite of many overlapping simple waves)

Sinusoid waves

- Simple periodic motion from perfectly oscillating bodies
- Found in in nature (e.g., swinging pendulum, sidewinder snake trail, airflow when you whistle)
- Sinusoids sound ‘cold’ (e.g. flute)

Simple waves - key properties

- Frequency = cycles per sec (cps) = Hz
- Amplitude – measured in decibels (dB), 1/10 of a bel

(Note: dB is on a log scale, increases by powers of 10)

- Frequency = $\frac{\text{cycles}}{\text{second}}$

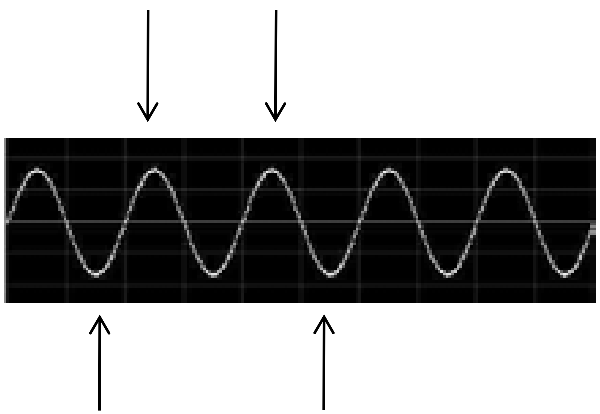
  Or "cps" or "Hertz (Hz)"

  ⇨ Higher frequency ~ higher pitch

- Intensity
  - Magnitude *(amplitude)* of vibration
  - Amount of change in pressure
- Frequency and intensity are independent!

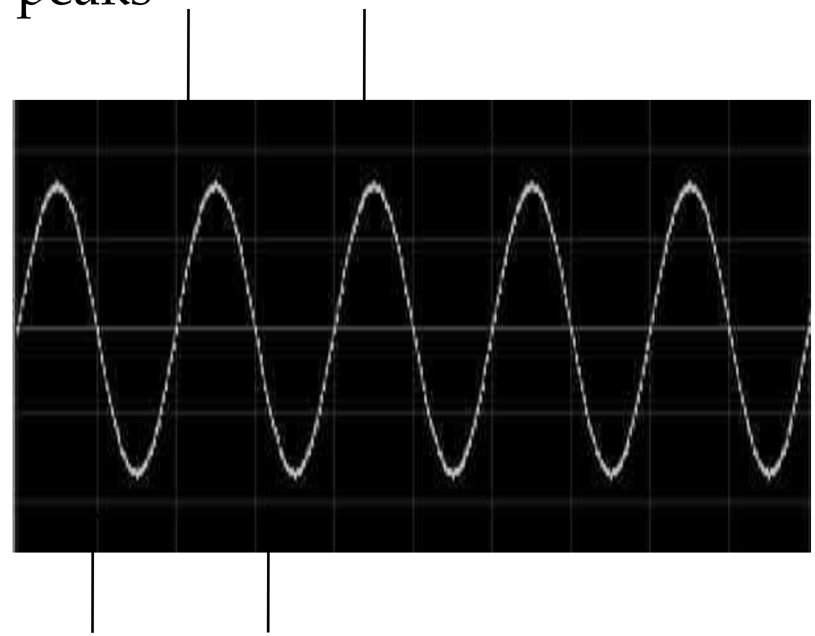
Amplitude (intensity)

Peaks (condensations)
= increases in pressure

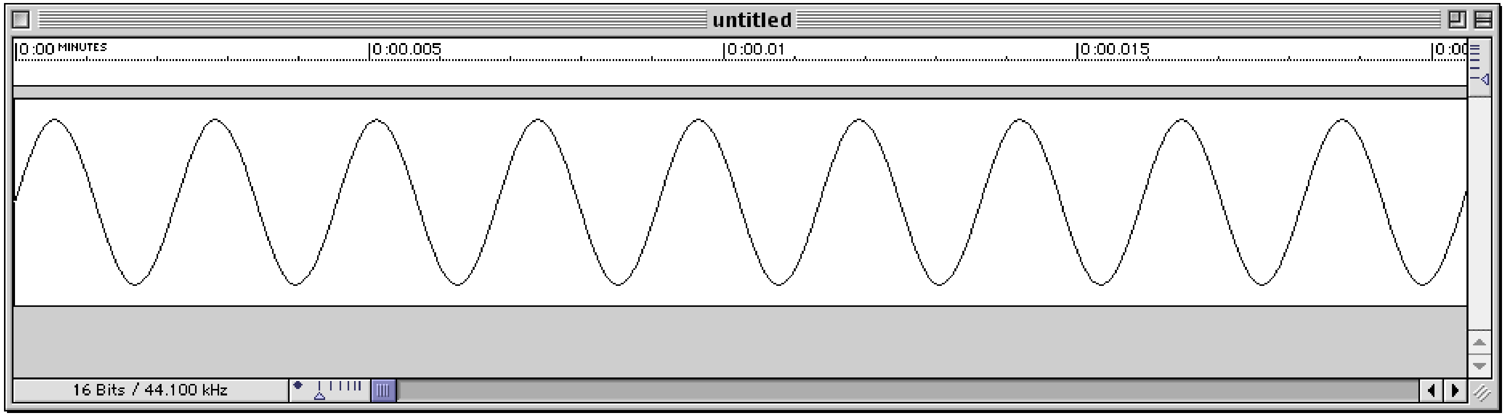


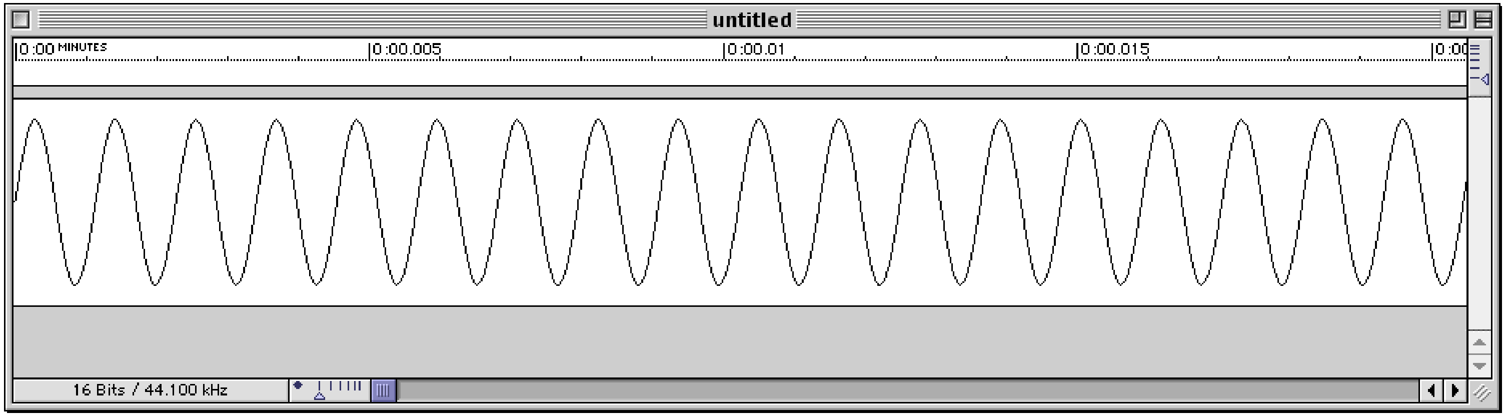
Troughs (rarefactions)
= decreases in pressure

More force is applied and this <u>increases</u> pressure at peaks

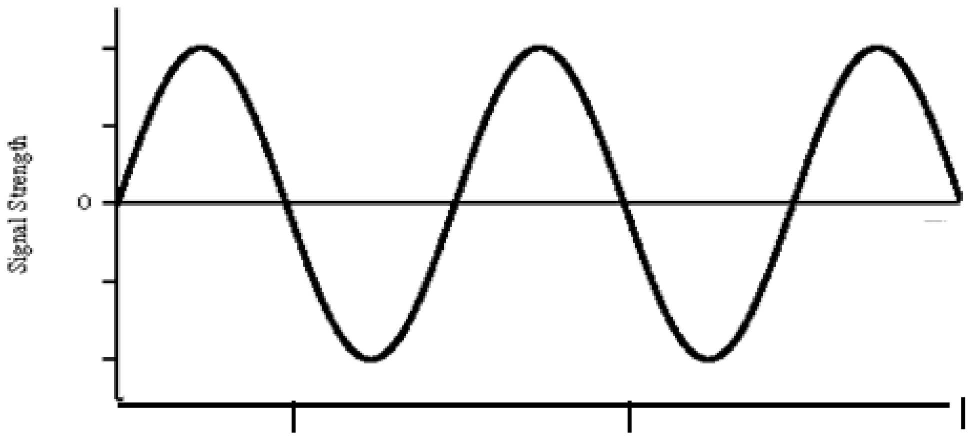


Frequency - Tones





Quickie Quiz!



10 msec

Q: What is the frequency of this wave ?

HINT: It repeats 2.5x in 10 msec

Answer:

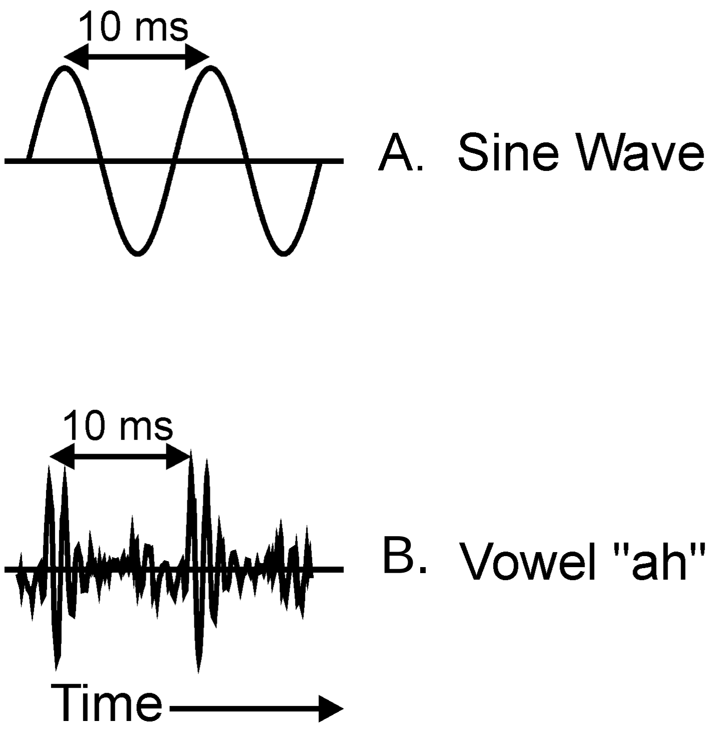
- 250 Hz!

(2.5 cycles in .01 sec = 250 cps)

Periodic waves

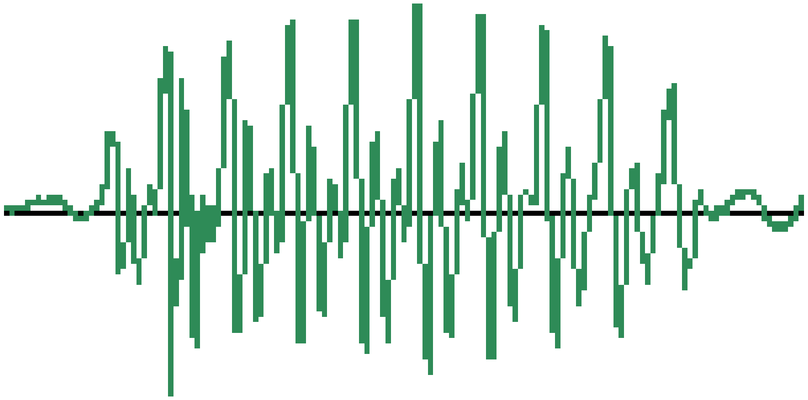
Panels A and B are periodic waves, though Panel B is complex periodic

(and not sinusoidal)



Complex periodic waves

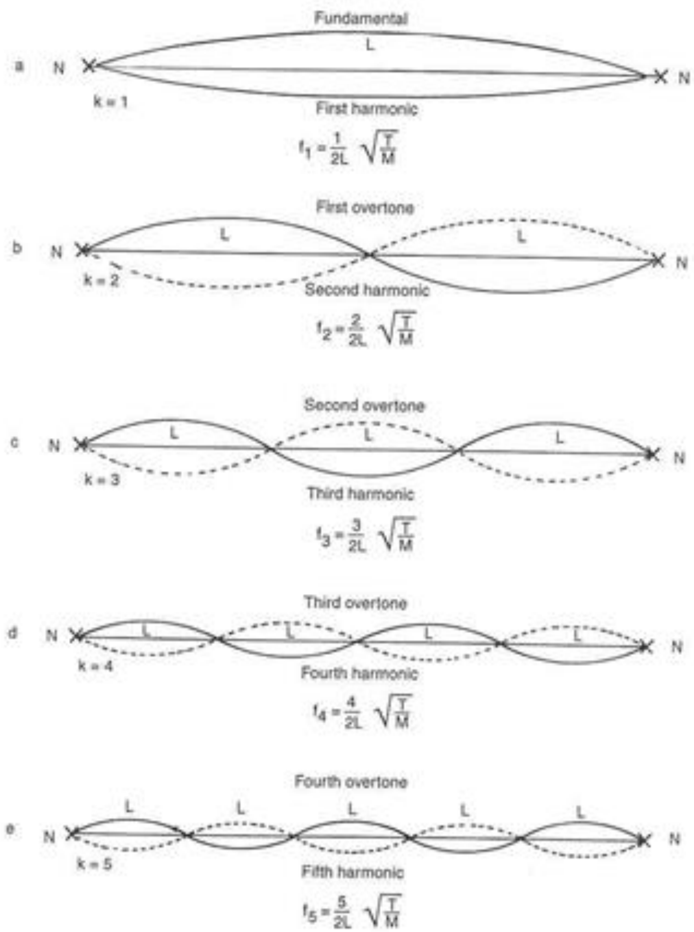
- Result from imperfectly oscillating bodies
- Demonstrate simple harmonic motion
- Examples - a vibrating string, the vocal folds



Complex periodic waves – cont’d

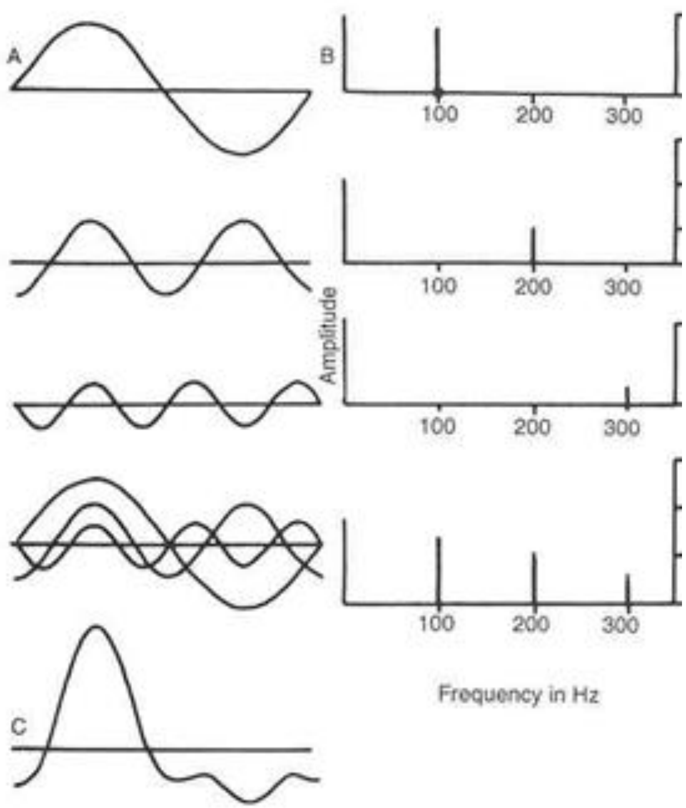
- Consists of a fundamental (F_0) and harmonics
- Harmonics (“overtones”) consist of energy at integer multiples of the fundamental (x2, x3, x4 etc…)

Harmonic series



- Imagine you pluck a guitar string and could look at it with a very precise strobe light
- Here is what its vibration will look like

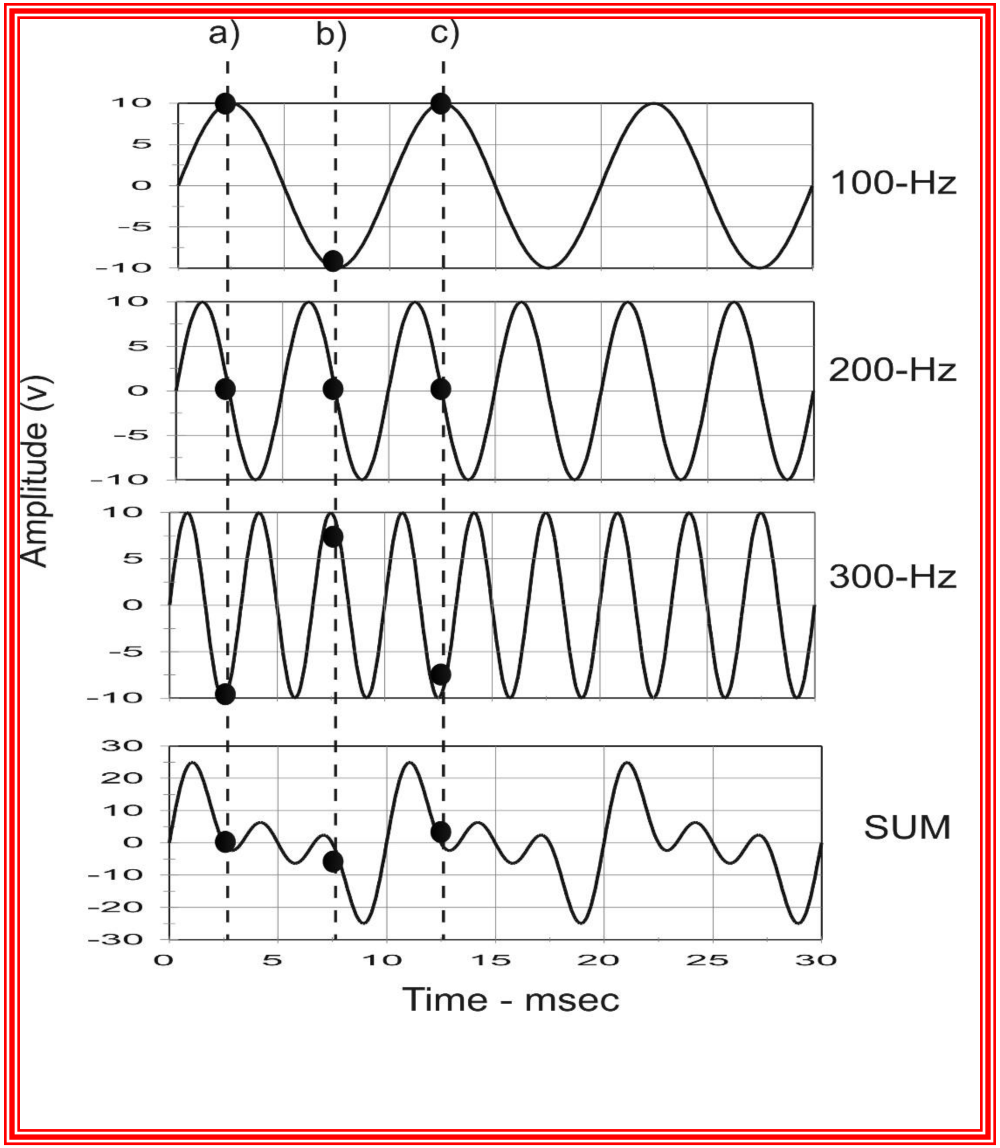
From simple waves → complex (showing power spectra)



- Also known as a "line spectrum"
- At bottom is a complex wave with an F_0 of 100 Hz
- Note energy at 200 Hz (second harmonic) and 300 Hz (third harmonic)

Fourier's Theorem

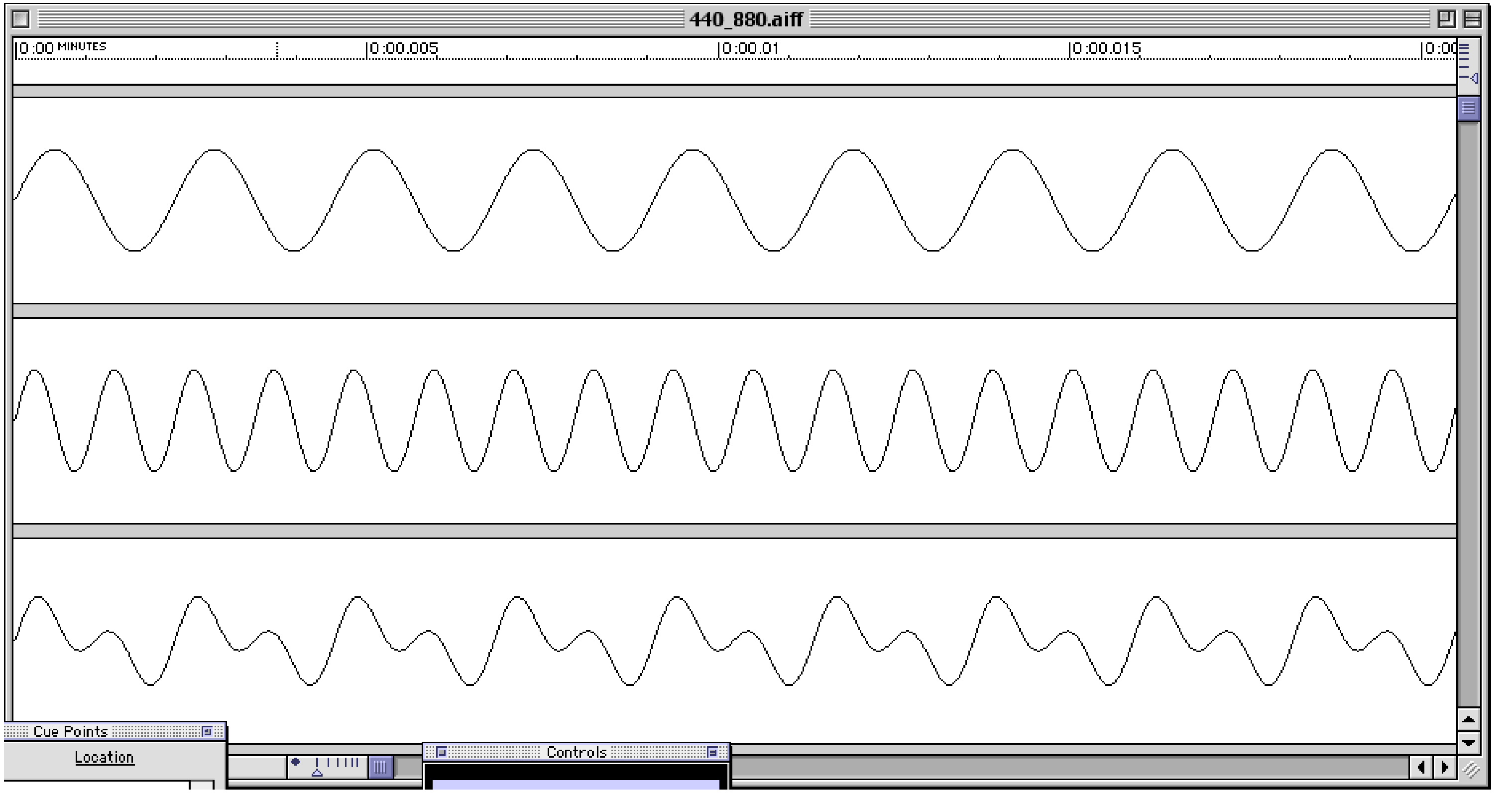
Fourier Synthesis

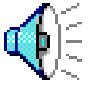


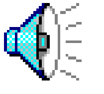
Fourier Analysis

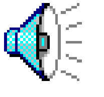
Complex waveform

Frequency – Tones/ Adding

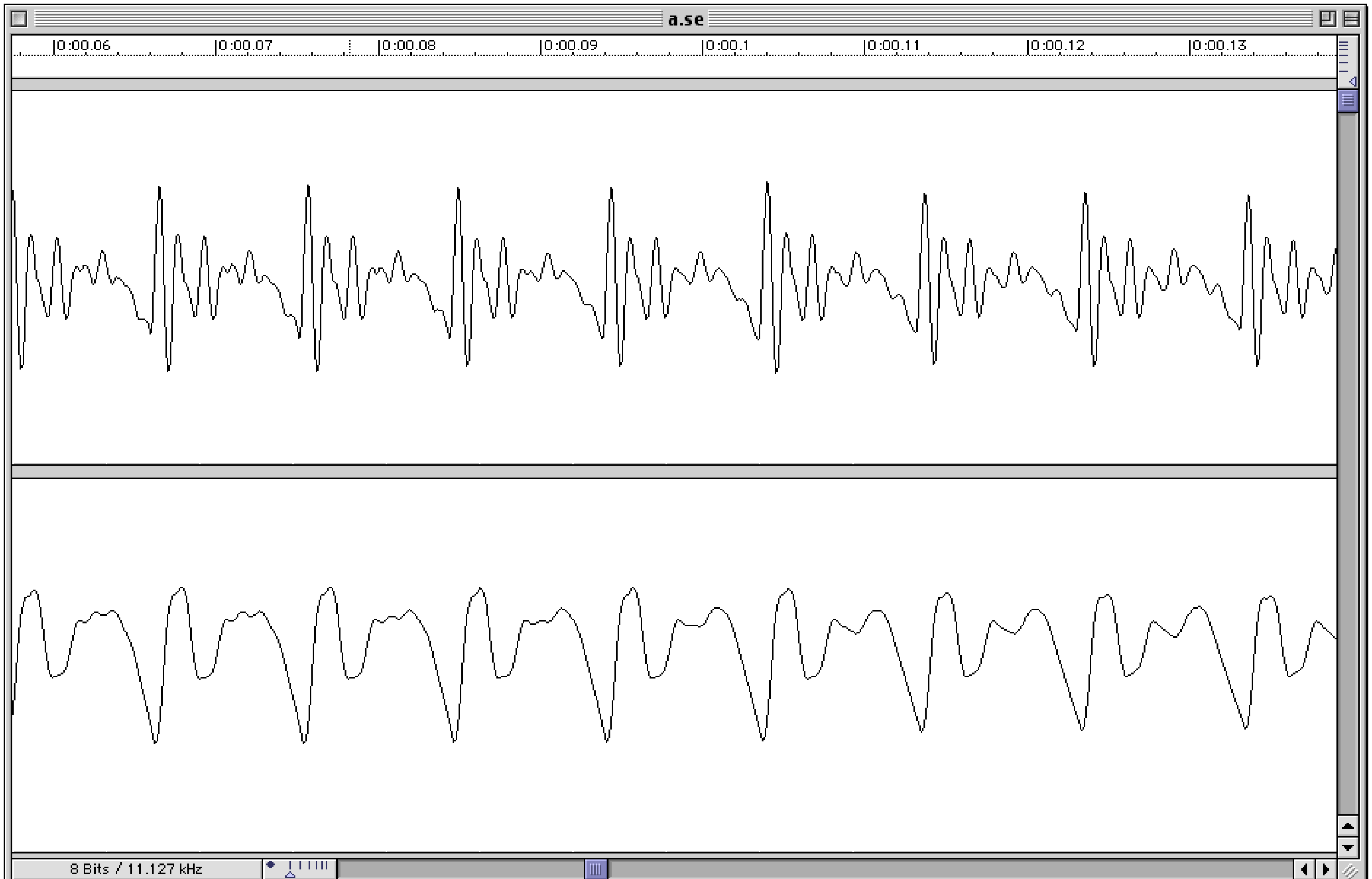




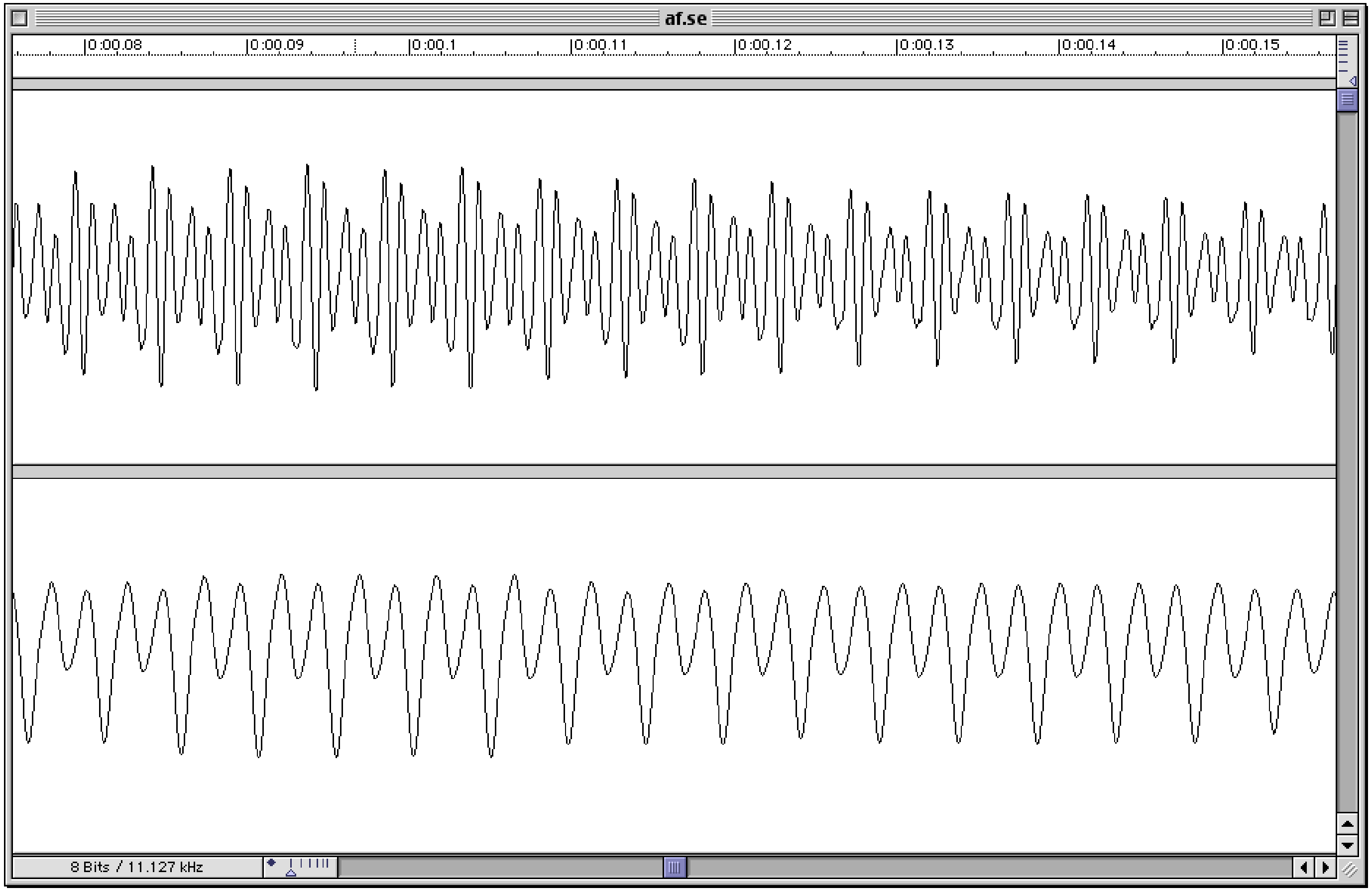




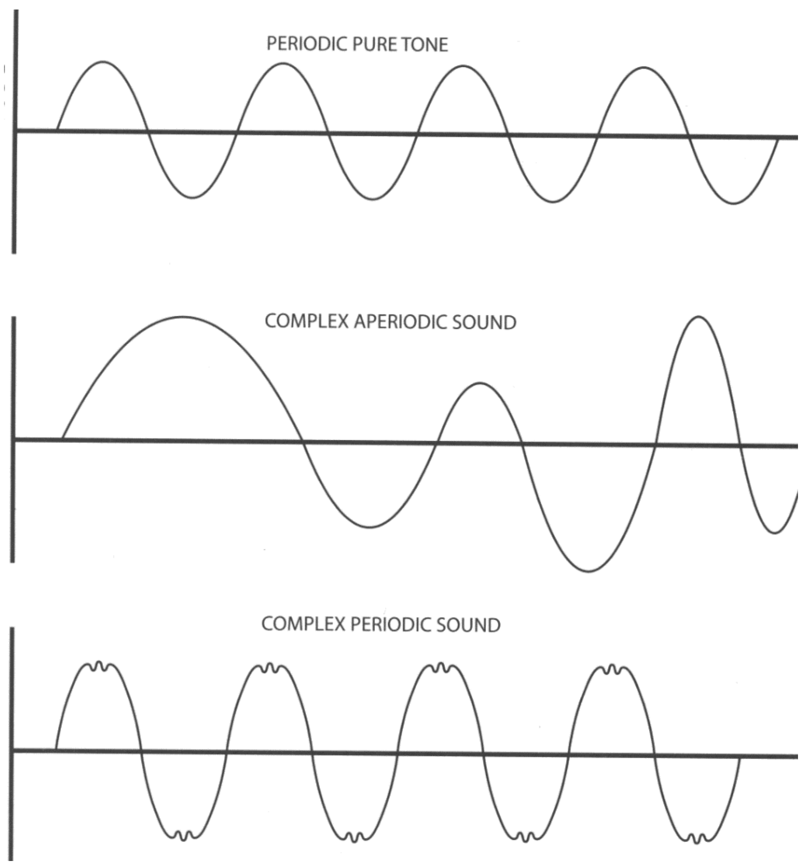
Frequency - Male Vowels



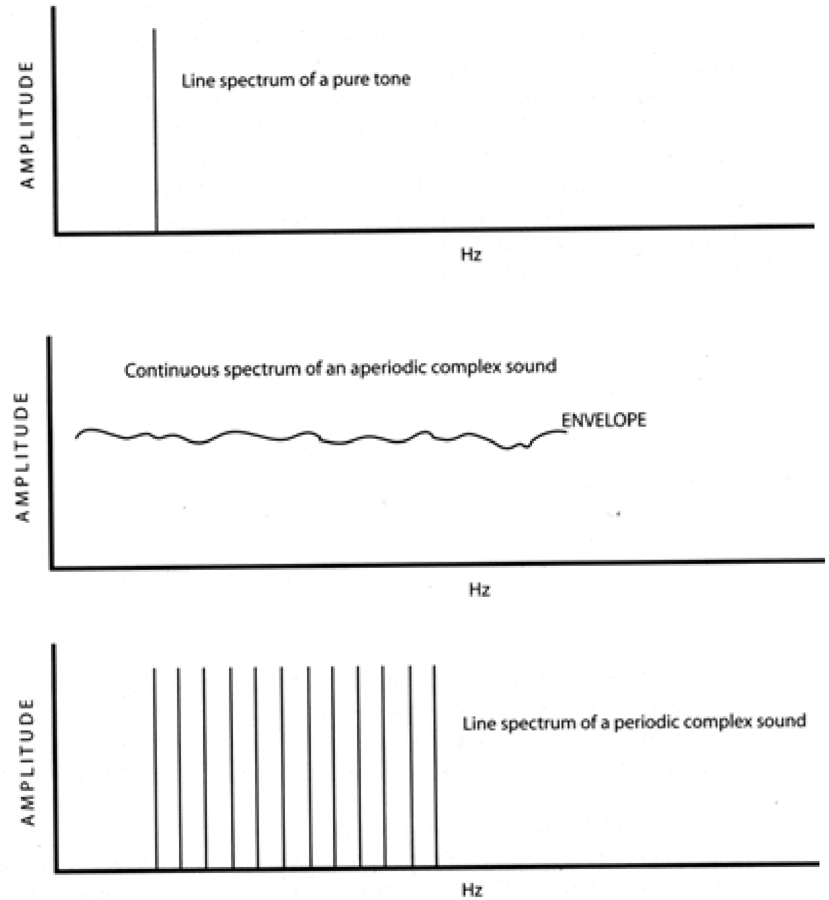
Frequency - Female Vowels



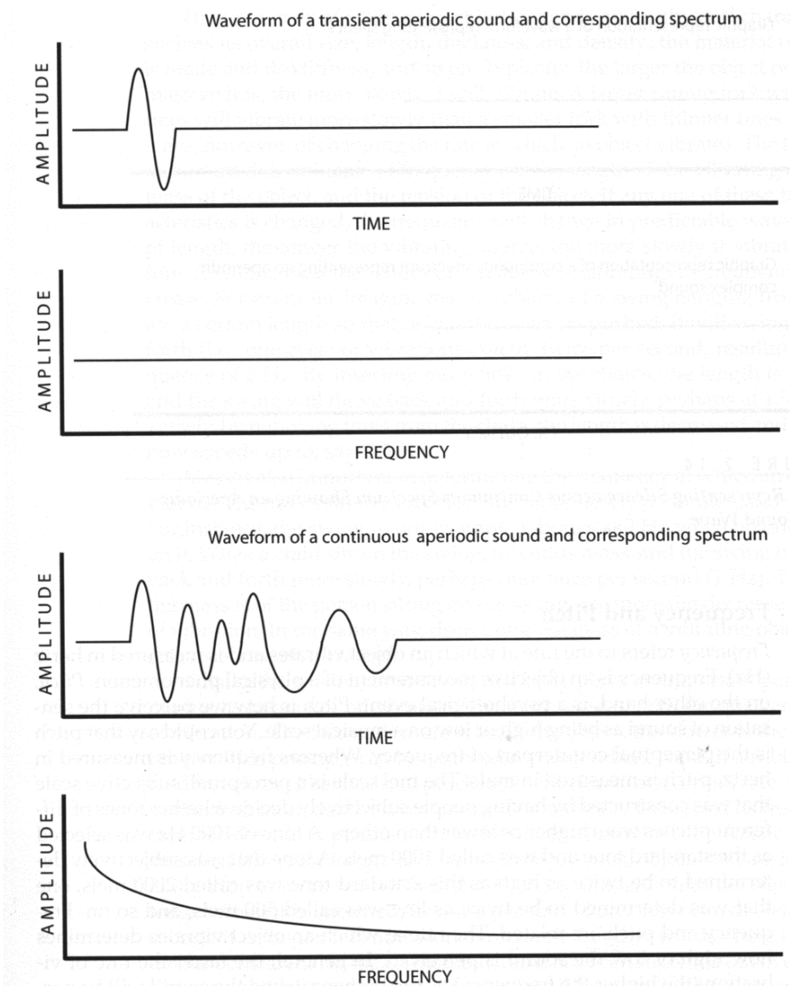
Periodic and aperiodic waveforms



Spectra of periodic and aperiodic sounds

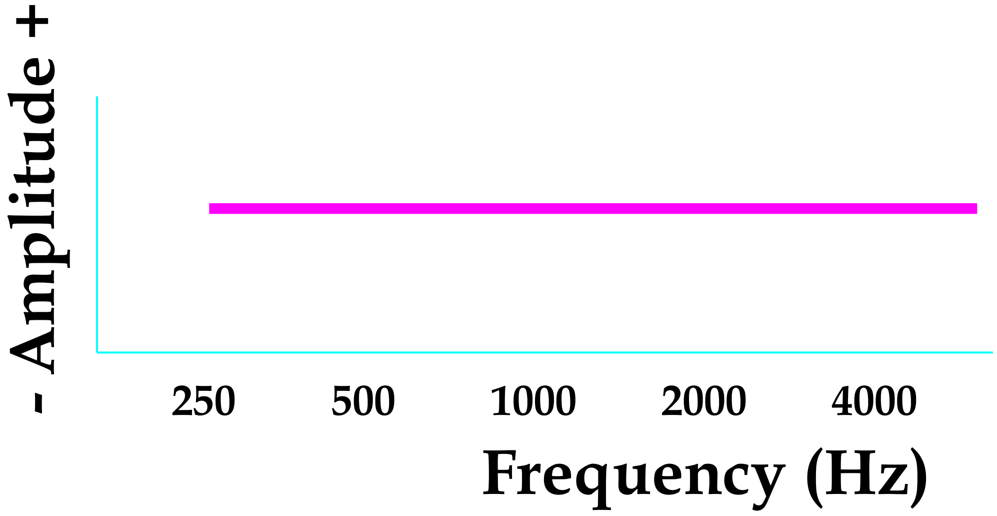


Transient vs. continuous signal



Continuous spectrum – cont’d

- Energy is present across a continuum of frequencies (noise)



(..not necessarily equal energy at all frequencies, as shown in this”flat” example)

Decibels (dB)

- Unit used to express intensity or pressure of sound
  1) Ratio of 2 numbers:

  $10 \log_{10} (S_1/S_2)$, where S_1 and S_2 are the intensity of the two sounds

  1) Exponential or logarithmic scale
  2) Expressed in terms of a specified reference value

Linear vs. Logarithmic Scale

Linear

- Incremental amount between units

Linear Scale

1,000

1,000

2,000

1,000

3,000

Logarithmic

- Increments NOT EQUAL
- Based on exponents of a given number

Log Scale

10^2

900

10^3

9,000

10^4

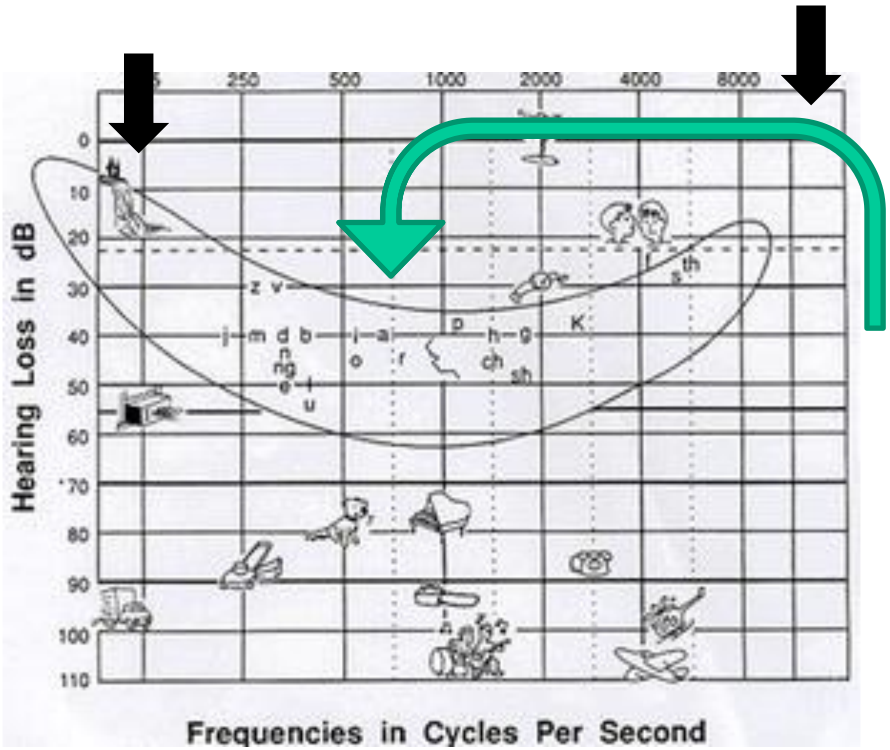
90,000

10^5

Why use log scale for sound?

- Large dynamic range between pressure of smallest audible sound and largest tolerable sound
- Difficult to express in interval scale
- For example, a 60-dB, or 6-bel, sound, such as normal speech, is six powers of 10 (i.e., 106, or 1,000,000) times more intense than a barely detectable sound, such as a faint whisper, of 1 dB.

dB x freq range

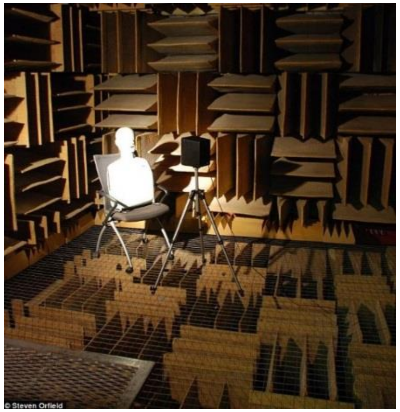


- Midrange frequencies can be perceived when they are <u>less intense</u>
- ..whereas a very low or high frequency sound must have <u>more intensity</u> to be audible
- Why you need to boost the bass on your stereo system if you turn the volume down low -- otherwise the lows become inaudible.

The ‘speech banana’

More dB facts

- Threshold of hearing = "softest sound of a particular frequency a pair of human ears can hear 50% of the time under ideal listening conditions"
- A-weighting (dBA) – considers human hearing in the best way– values of sounds at low frequencies are reduced because the human ear is less sensitive to sounds below 1000 Hz
- Typically tested with a sound level meter →
- FACT: There can be a negative dB value!

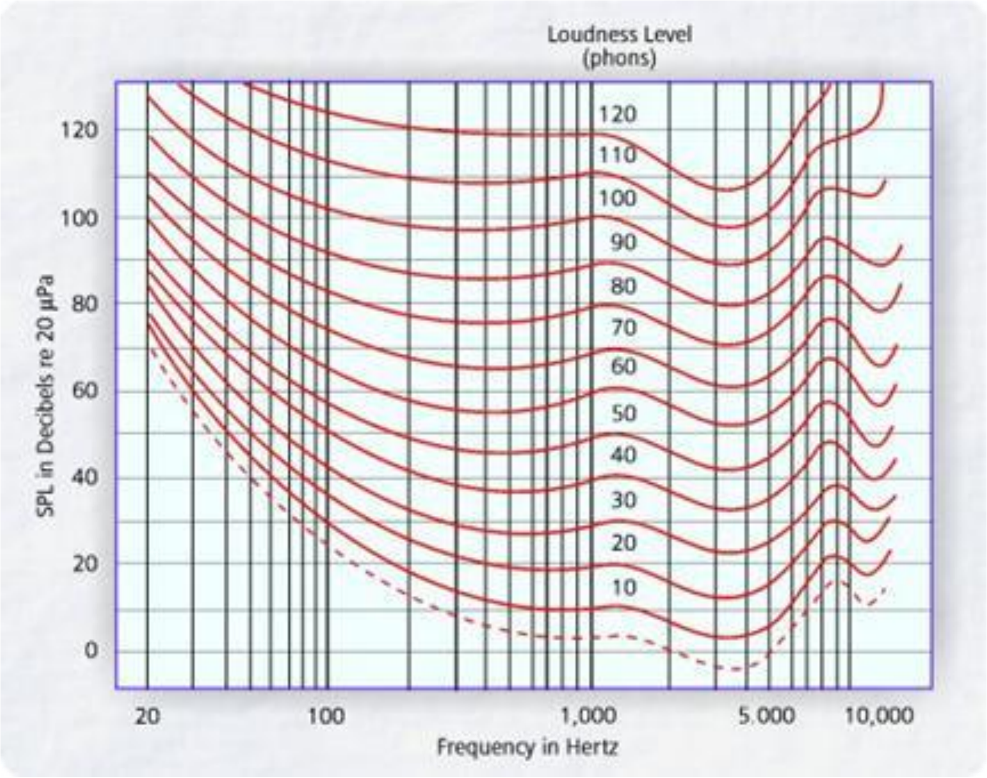


Orville Labs, Minneapolis
-9.4 dBA

Physical vs. perceptual

PHYSICAL	PERCEPTUAL
• Fundamental frequency (F_0) →	“Pitch”
• Amplitude/ Intensity →	“Loudness”
• Duration →	“Length”

Phon Scale



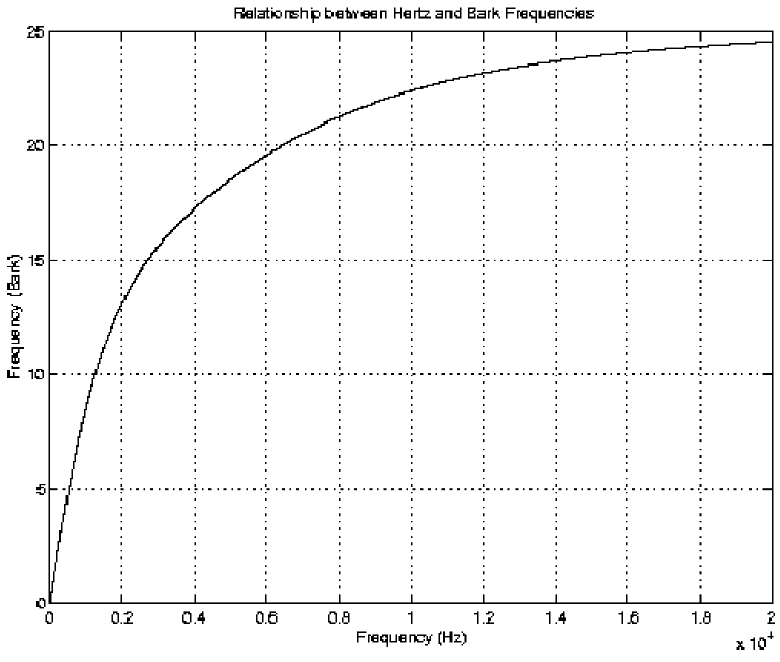
- If a given sound is perceived to be as loud as a 60 dB sound at 1000 Hz, then it is said to have a "loudness of 60 phons"
- 60 phons means "as loud as a 60 dB, 1000 Hz tone"
- Instrumentation reference

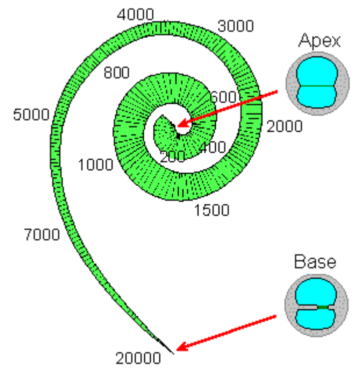
Psychoacoustic scale for loudness level

Bark scale (pitch)

- A psychoacoustical scale for pitch
- Basically log-linear
- Ranges from 1 to 24 and corresponds to the first 24 critical bands of hearing.
- Similar to Mel Scale

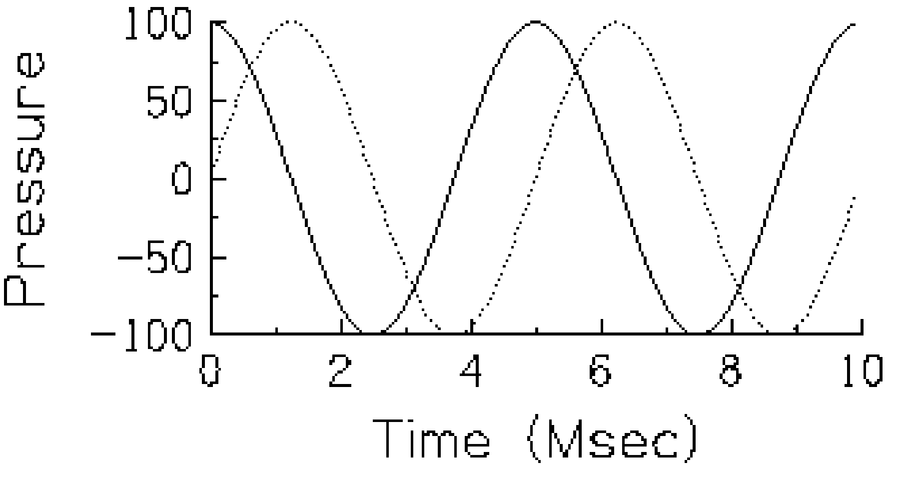
(1961)



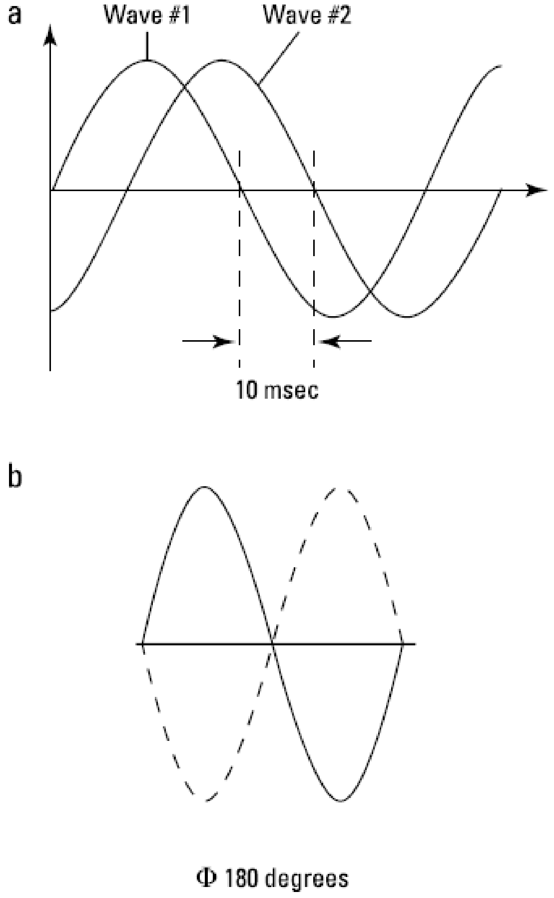


Phase

- A measure of the position along the sinusoidal vibration
- These two waveforms are slightly out of phase (approx. 90^0 difference)
- Important for sound localization



Phase examples



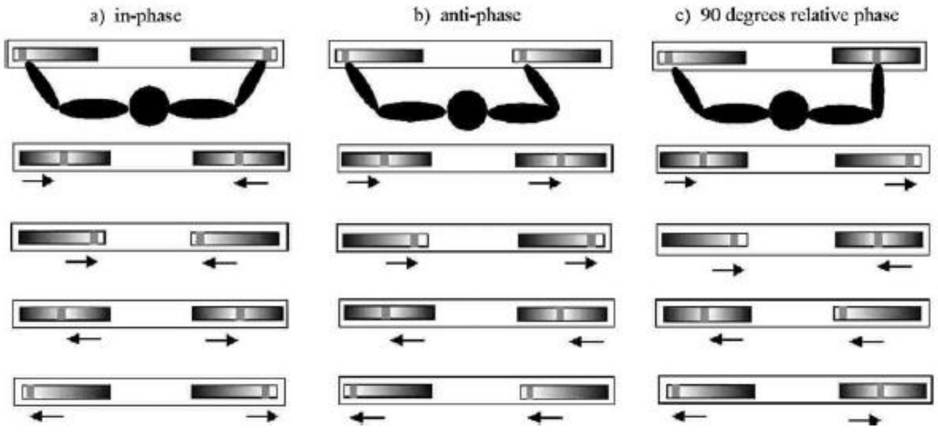
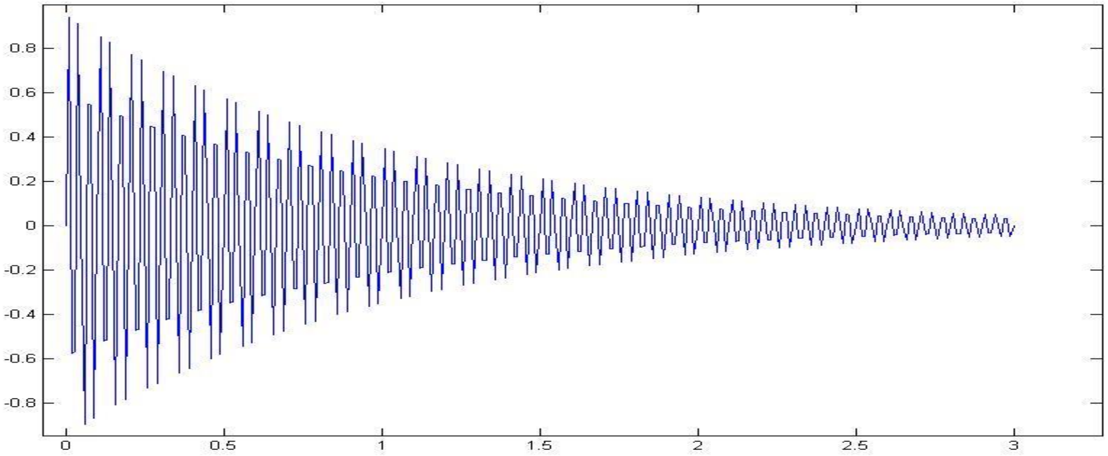


Fig. 1. Illustration of the in-phase, anti-phase and 90° bimanual coordination tasks.

Damping - example



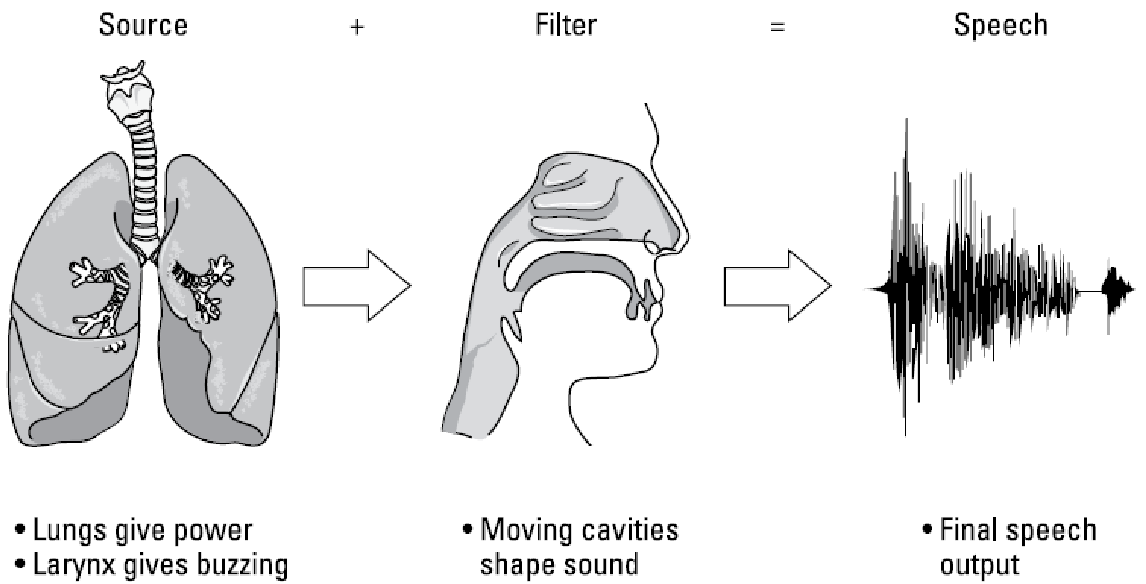
(Loss of vibration due to friction)

Review of <u>source</u> characteristics

- Simple waves are a good way to learn about basic properties of frequency, amplitude, and phase.
- Examples include whistling; not really found much in speech

- Complex waves are found in nature for oscillating bodies that show simple harmonic motion (e.g., the vocal folds)

Source-filter theory



- Vocal tract model demo
- https://www.youtube.com/watch?v=wR41CRbIjV4
- See chapter 6 in book for more info

Let's look at the filter

- In speech, the filter is the supralaryngeal vocal tract (SLVT)
- The shape of the oral/pharyngeal cavity determines vowel quality (via resonance)
- SLVT shape is chiefly determined by tongue movement, but lips, velum and (indirectly) jaw also play a role

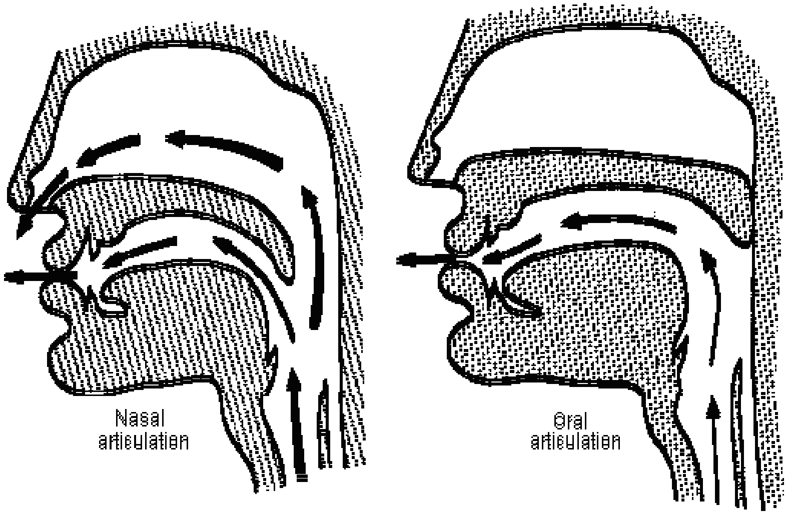
Resonance

- Resonance = reinforcement or shaping of frequencies as a function of the boundary conditions through which sound is passed
- To get a basic idea of resonance, try producing a vowel with and without a paper towel roll placed over your mouth! The ‘extra tube’ changes the resonance properties.

Resonance – cont'd

- The SLVT can be modeled as a kind of bottle with different shapes… as sound passes through this chamber it achieves different sound qualities
- The resonances of speech that relate to vowel quality are called <u>formants</u>.   Thus, R1 = F1 ("first formant). R2 = F2, etc.
- F1 and F2 are critical determinants of vowel quality

Resonators



Resonance - concepts

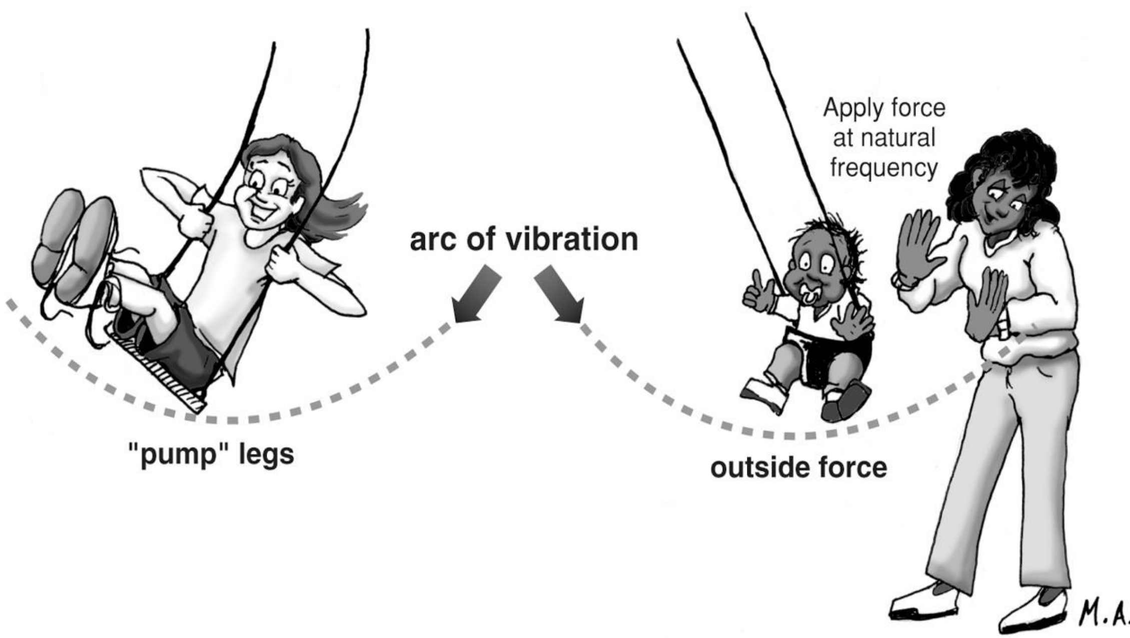
- Natural frequency

(Resonant frequency RF)

- Mechanical (vibrating body, e.g. vocal folds)
- Acoustic (air-filled space)

Resonance

- Child's swing behaves like a pendulum and can help us understand resonance
- Restorative & displacement forces, inertia & equilibrium
- Two ways to inject energy into the oscillation:



Resonance

- Resonance: large increase in vibration when a force is applied at a natural frequency of the medium

- Set an object into vibration (hit, drop, etc) and the rate at which it vibrates ~ natural frequency (or set of frequencies).

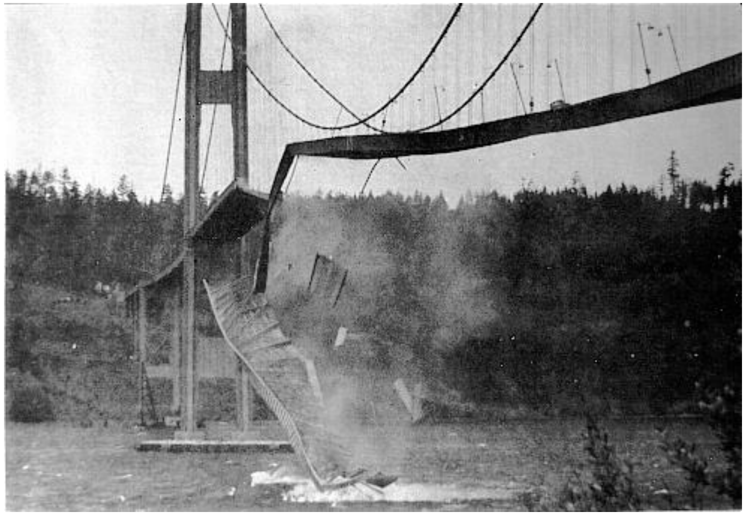
Vibration

Free vibration – no additional force is applied after an object is set into motion.

Forced vibration – when forces "drive" the motion to vibrate at its natural frequency. (e.g., guitar string).

Forced Vibration

The Tacoma-Narrows Bridge twisting in sympathetic resonance with the wind (left) and stretching to the point of breaking (right).



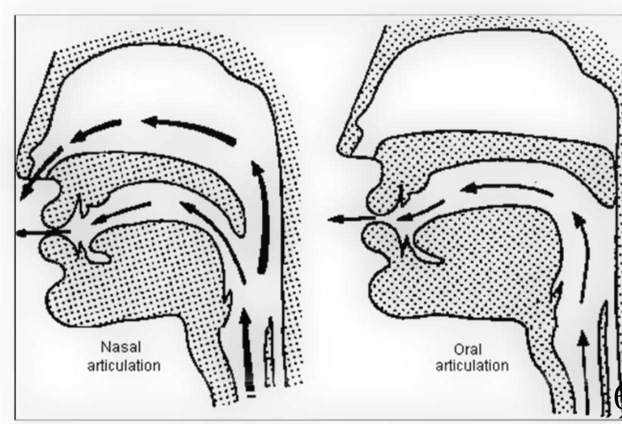
http://www.youtube.com/watch?v=3mclp9QmCGs

Resonant Freq of Glass

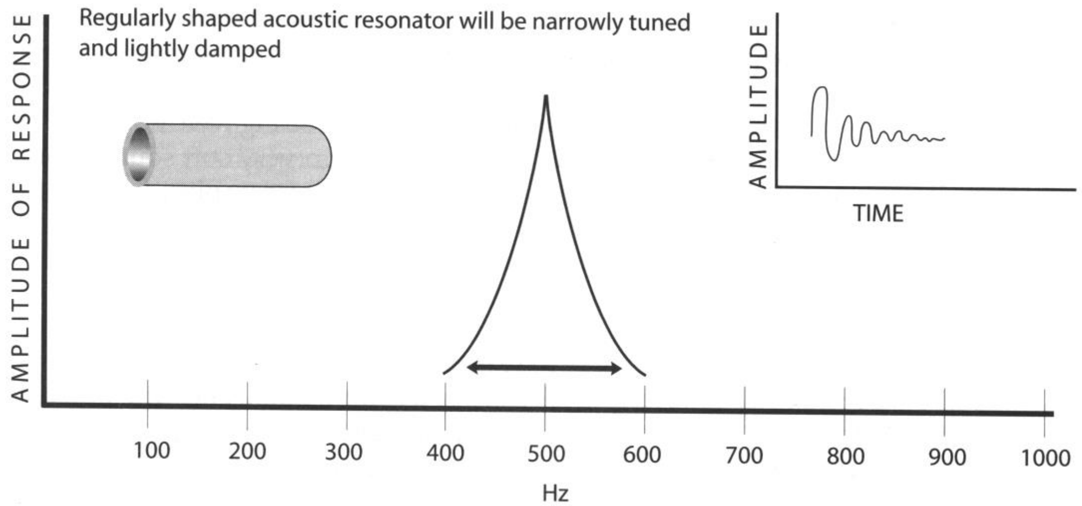
- Breaking glass with sinusoid sound
- Freaky deaky guy actually breaks glass with voice (Mythbusters)
- Typical case of faking it

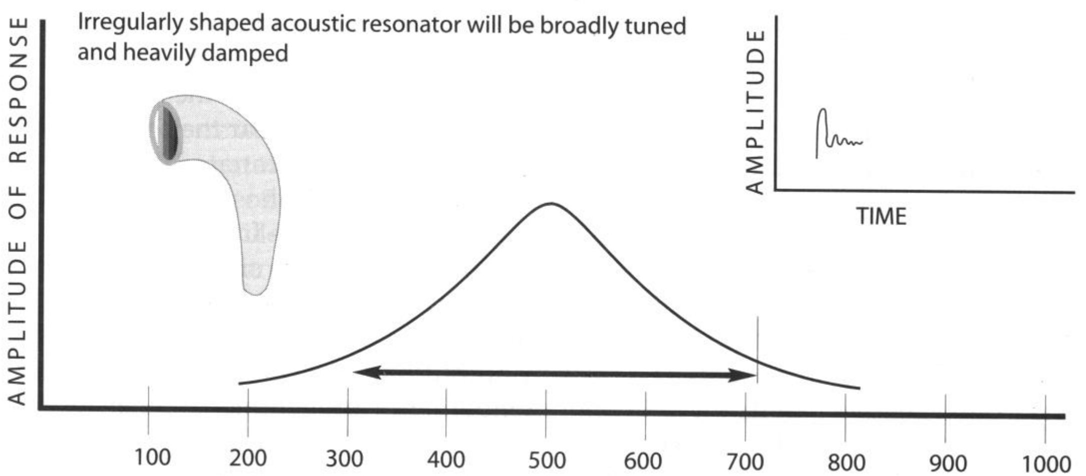
Why is resonance important?

- In vocal tract, allows some frequencies to be magnified over others.
- In the auditory system (ear canal) allows for certain sounds to be amplified as compared to others.

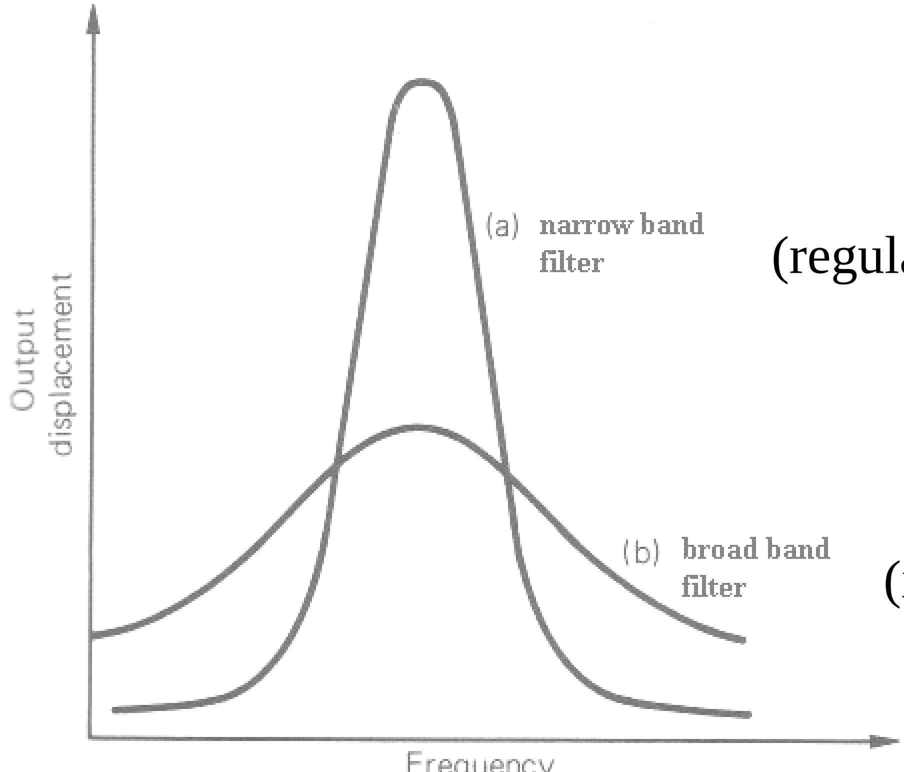


Acoustic Resonators / Bandwidth





Narrow vs. Broad Filter

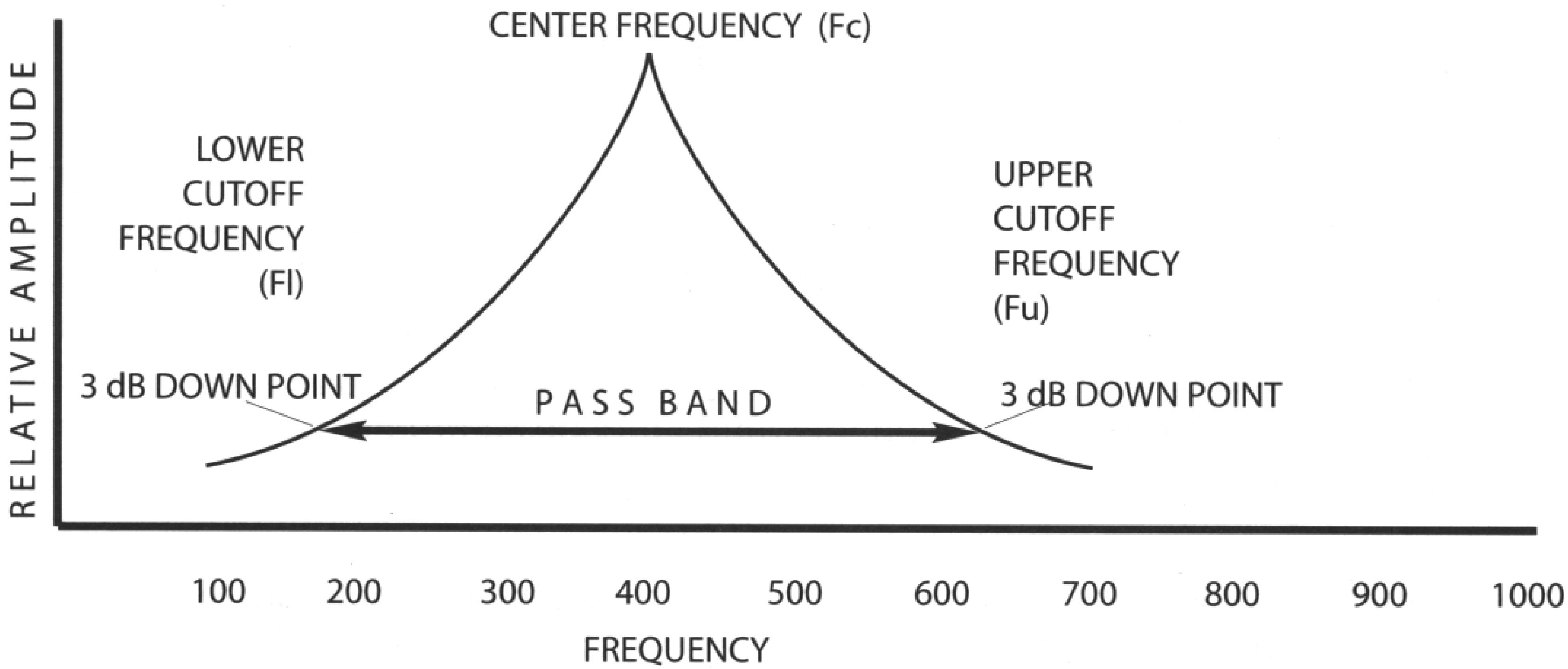


Source: Clark & Yallop (1995)

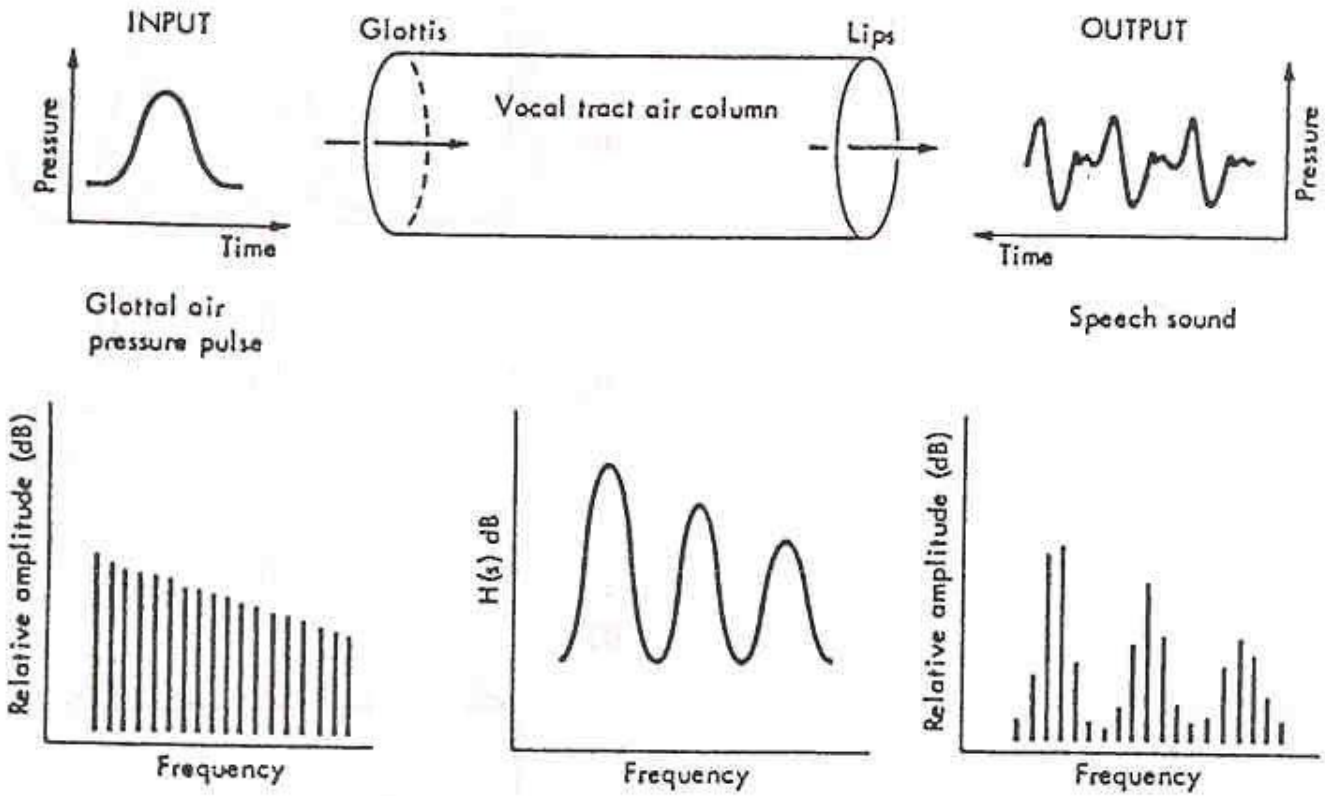
(regular resonator)

(irregular resonator)

Passband Resonator



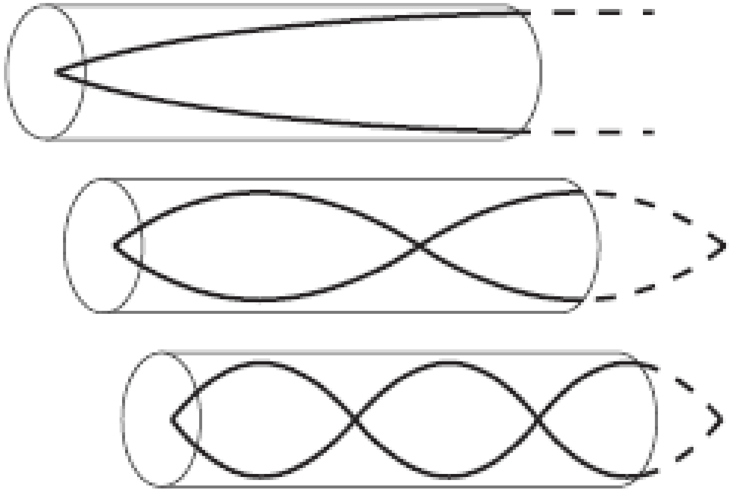
Input → SLVT → speech output



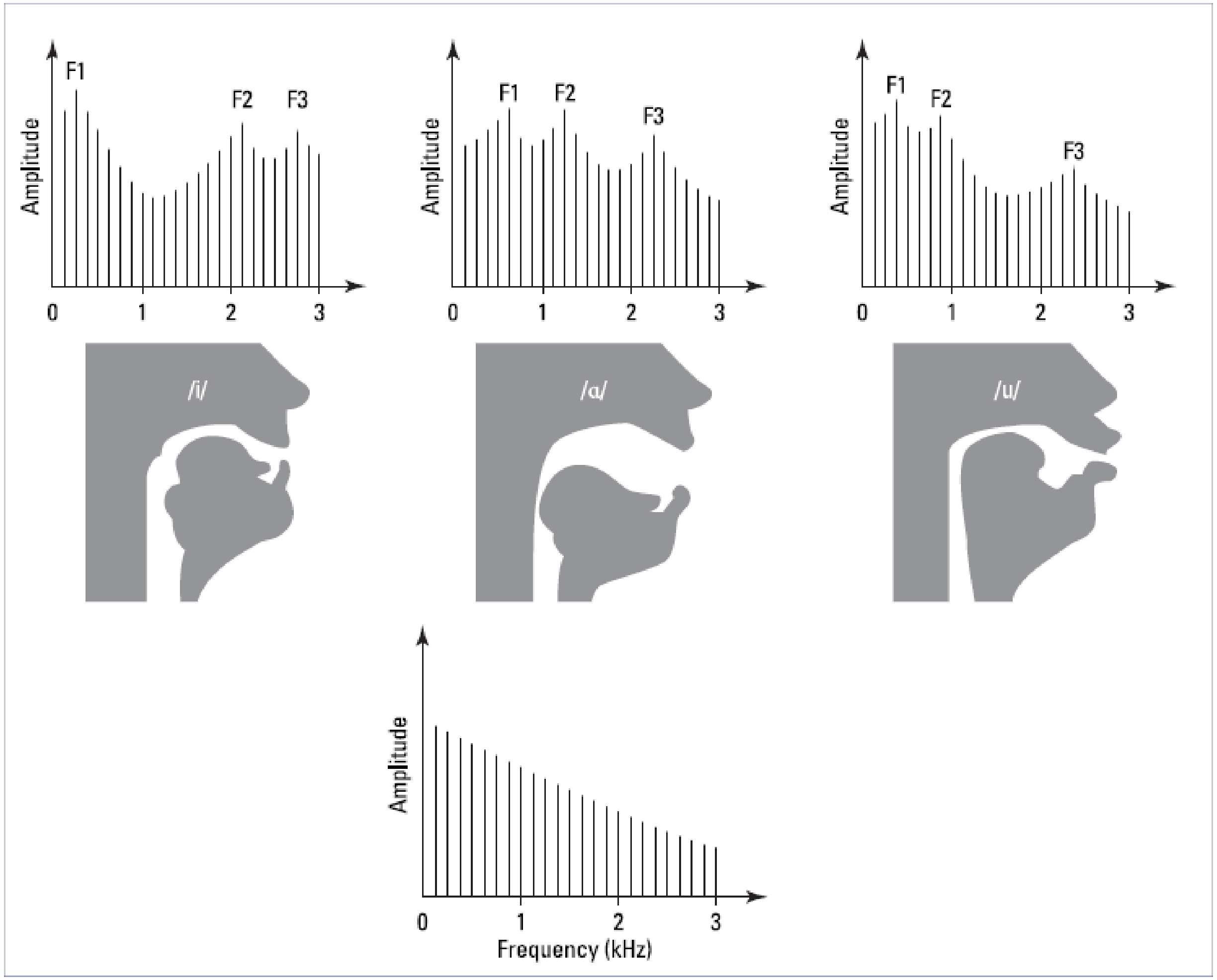
Application: Sound spectrograms, speech analysis

F1 through F3

- Closed-tube model of the VT, showing first three resonances (formants)



Formants for three GAE vowels



Formants – ‘HAR’

✓ **H:** *Height* relates inversely to F1.

✓ **A:** *Advancement* relates to F2.

✓ **R:** *Rounding* is a function of lip protrusion and lowers all formants - through lengthening of the vocal tract by approximately 2 to 2.5 cm.

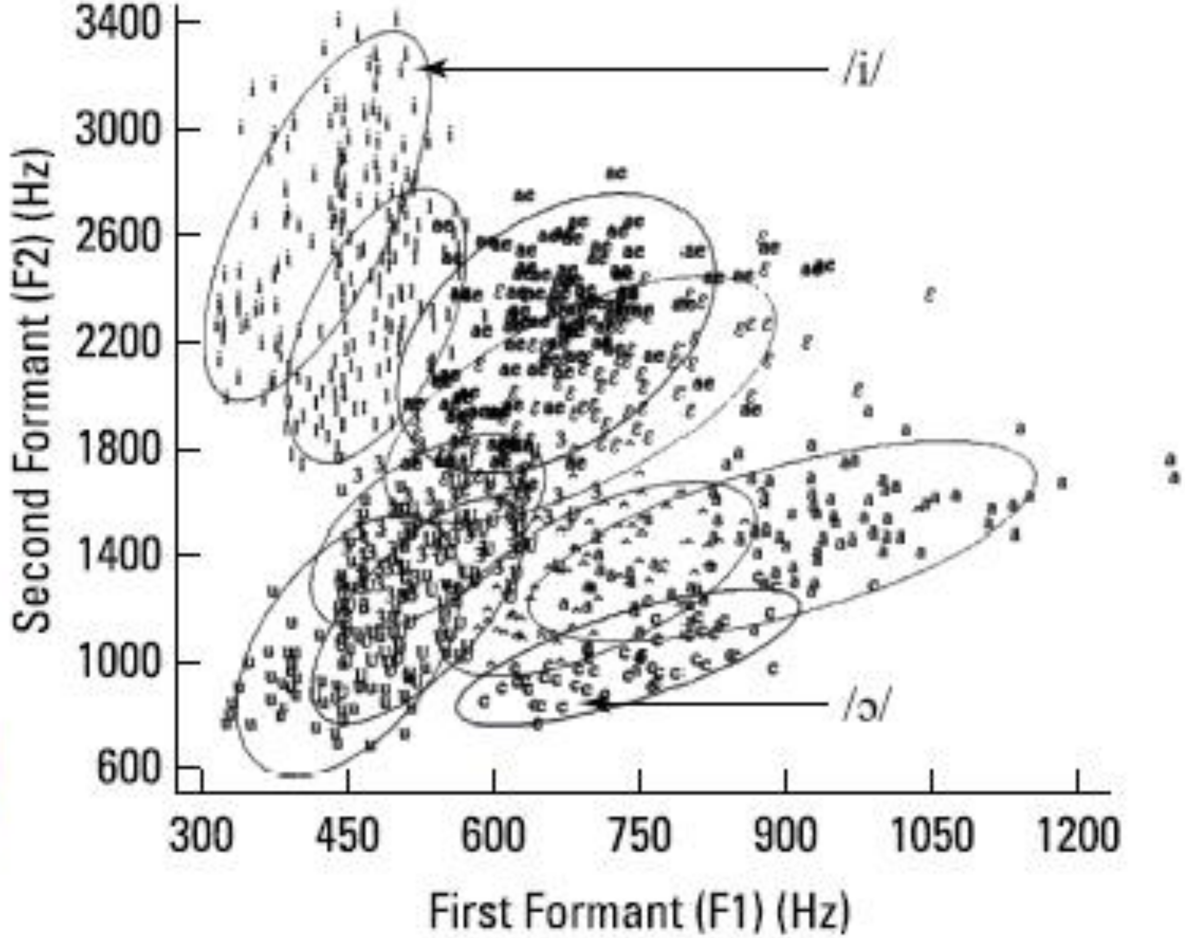


Figure 12-8: F2 x F1 plot — American English vowels.

Peterson & Barney, 1952

To be continued…

- We have described resonance and formant frequencies with respect to vowels
- Also important for consonants
- Because consonants require more spatial and temporal precision, these details will be covered later…