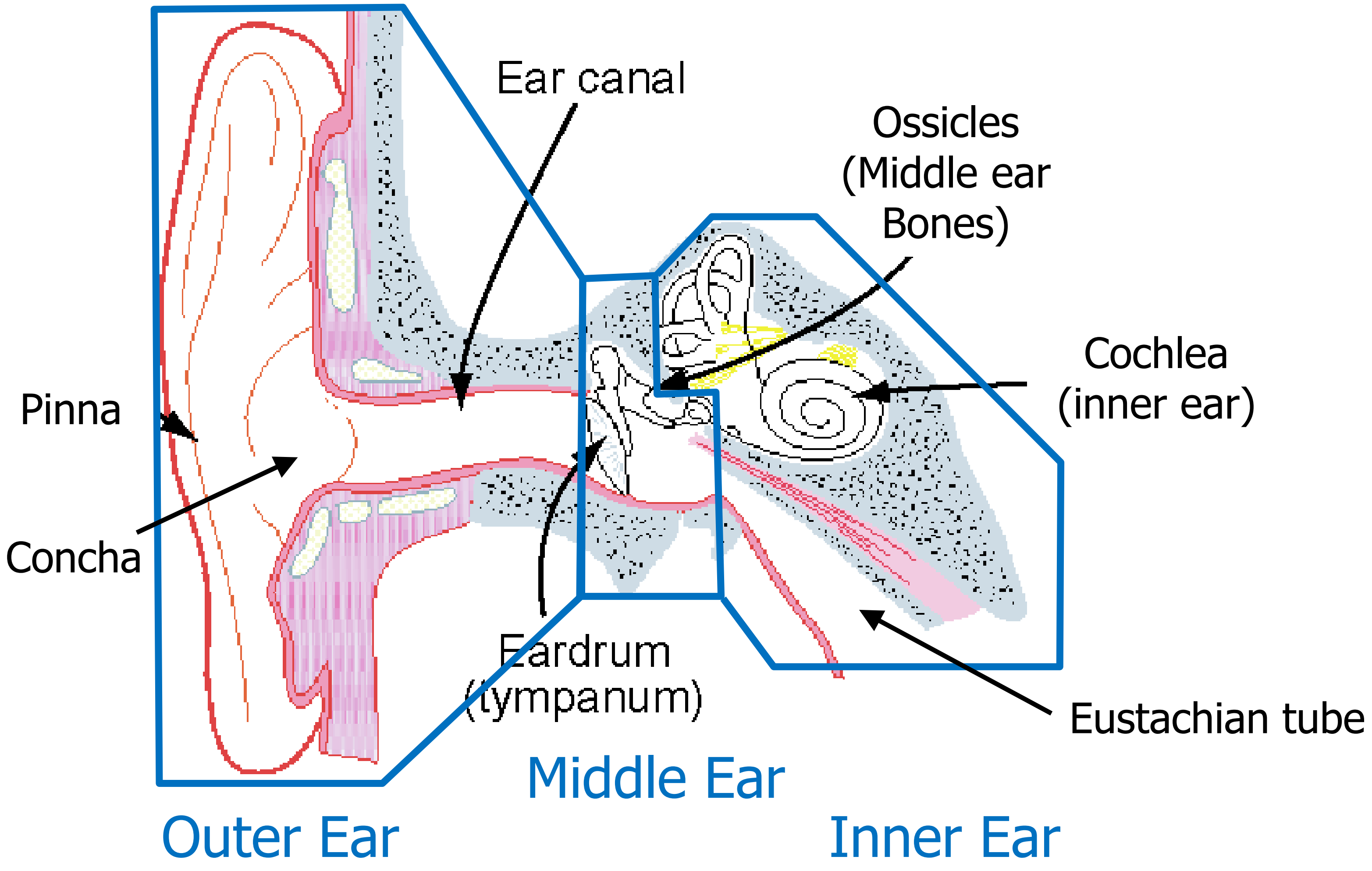
Topic 3

Human Auditory Sensation

(Some slides are adapted from Bryan Pardo's course slides on Machine Perception of Music)

The Ear


Ear canal
Ossicles
(Middle ear
Bones)
Cochlea
(inner ear)
Pinna
Concha
Eardrum
(tympanum)
Eustachian tube
Middle Ear
Outer Ear
Inner Ear

Function of the Ear

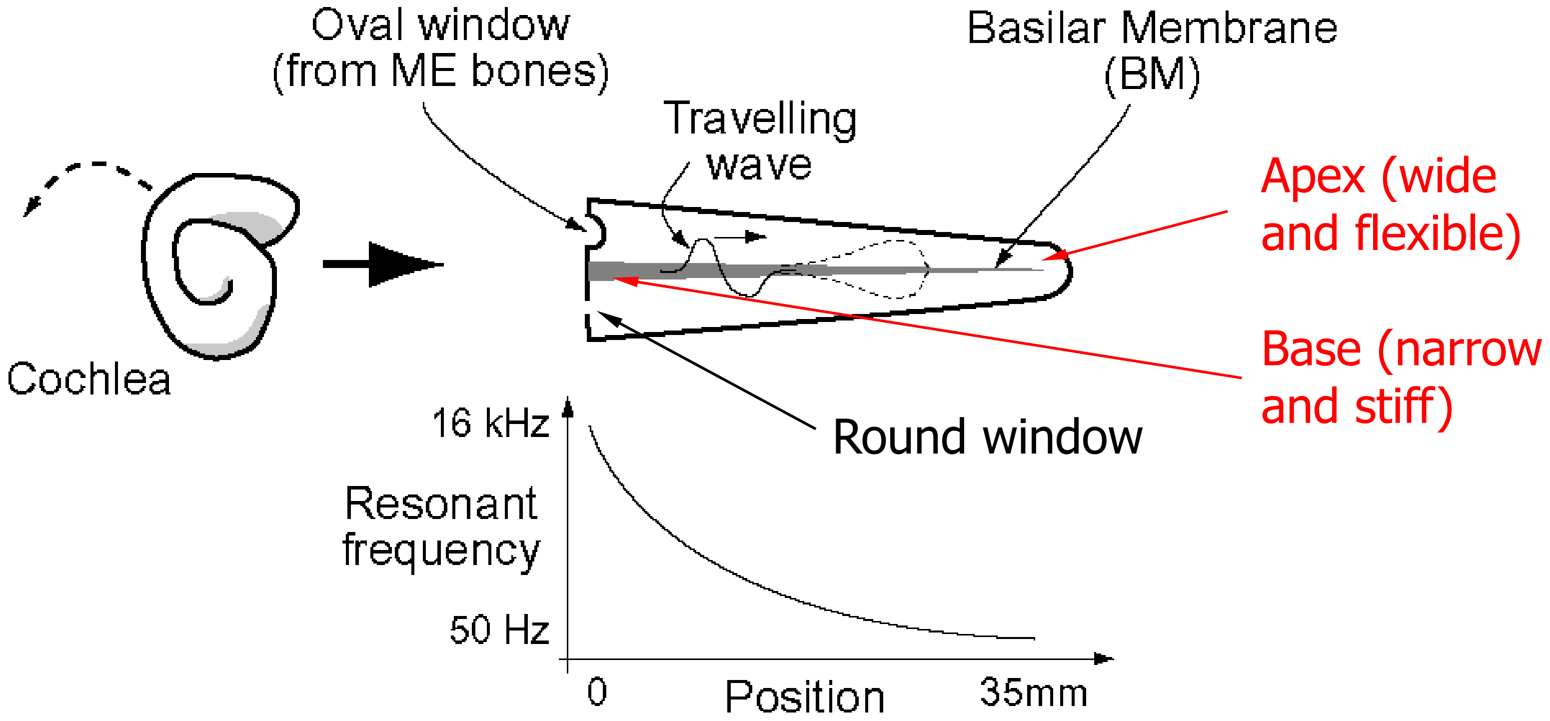
- Outer ear: shapes the sound spectrum
  - Torso, head, pinnae: head-related transfer function (HRTF). Interaural difference.
  - Concha, canal: increase sound level of about 10-15dB between 1.5k-7kHz, due to resonances
- Middle ear: effective and efficient transfer
  - Eardrum: effective area about 55 mm^2 (where the oval window is about 3 mm^2 size.
  - Three ossicles: a lever system
  - The last ossicle is called stapes, the smallest bone in the human body

Function of the Ear

- Inner ear:
  - Vestibular system: sense of balance
  - Eustachian tube: provides ventilation to middle ear
  - Cochlea: the primary auditory organ of inner ear

- Vestibular system starts to develop (around 8 weeks) much earlier than the auditory system (around 20 weeks) after conception!

The Cochlea

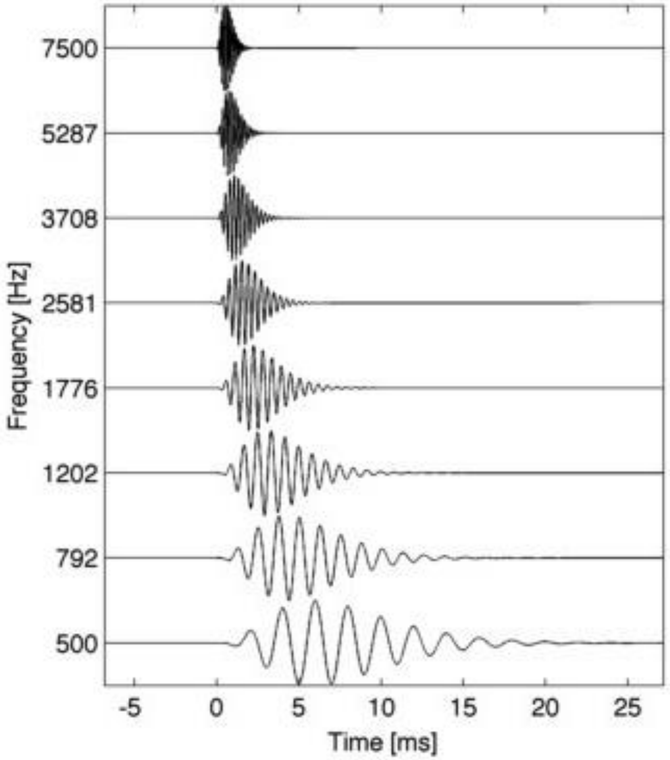


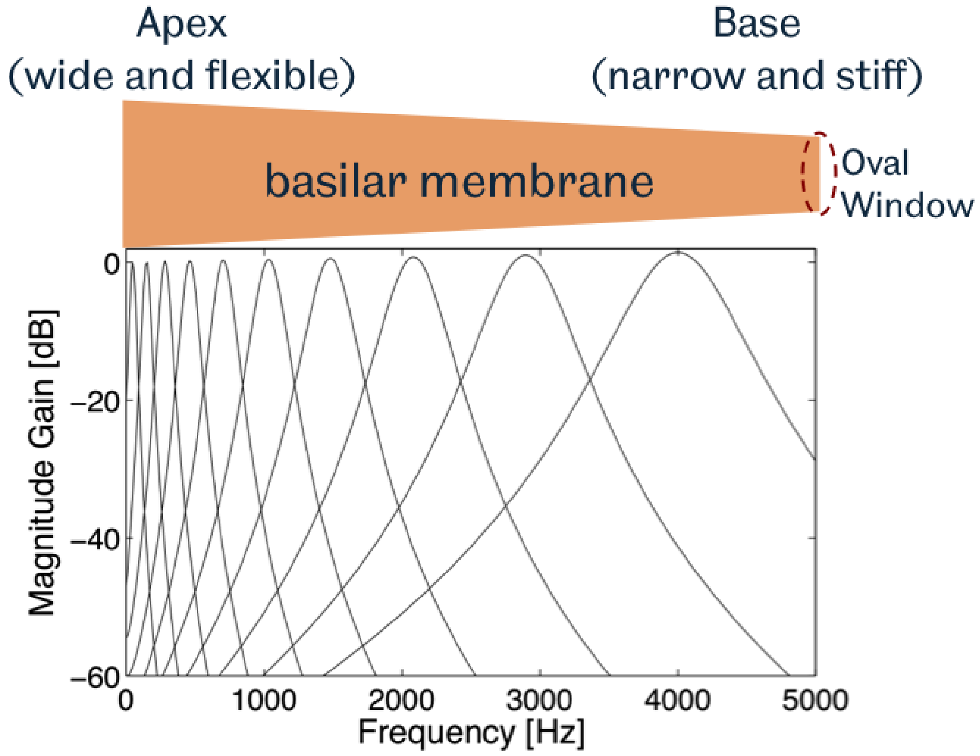
- Each point on the Basilar membrane resonates to a particular frequency
- At the resonance point, the membrane moves

Gammatone Filterbank

- Impulse response (n=4)

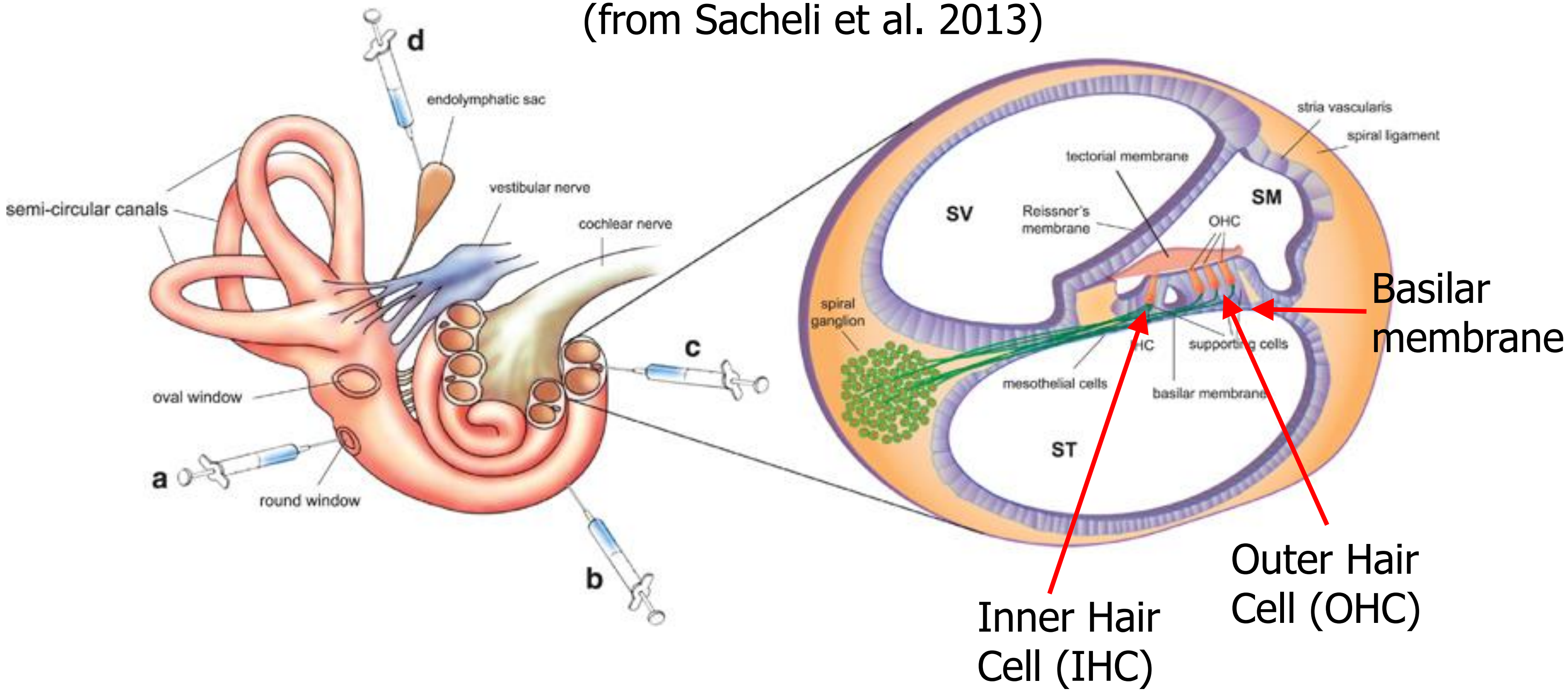
$$g(t) = \underbrace{a t^{n-1} e^{-2\pi b t}}_{\text{gamma}} \underbrace{\cos(2\pi f t + \varphi)}_{\text{tone}} u(t)$$





Cross Section of Cochlea

(from Sacheli et al. 2013)



- When the membrane moves, it moves hairs.
- When hairs move, they fire nerve impulses.

Hair Cells

- Inner hair cell
  - The actual transducer
- Outer hair cell
  - Makes small but very fast movements (maybe ~100kHz)
  - Feedforward amplifiers, nonlinear
- They are damaged by age and hard to regrow
- Let’s look at a dance by an outer hair cell!
  - http://www.youtube.com/watch?v=Xo9bwQuYrRo

Auditory Nerve Fibers

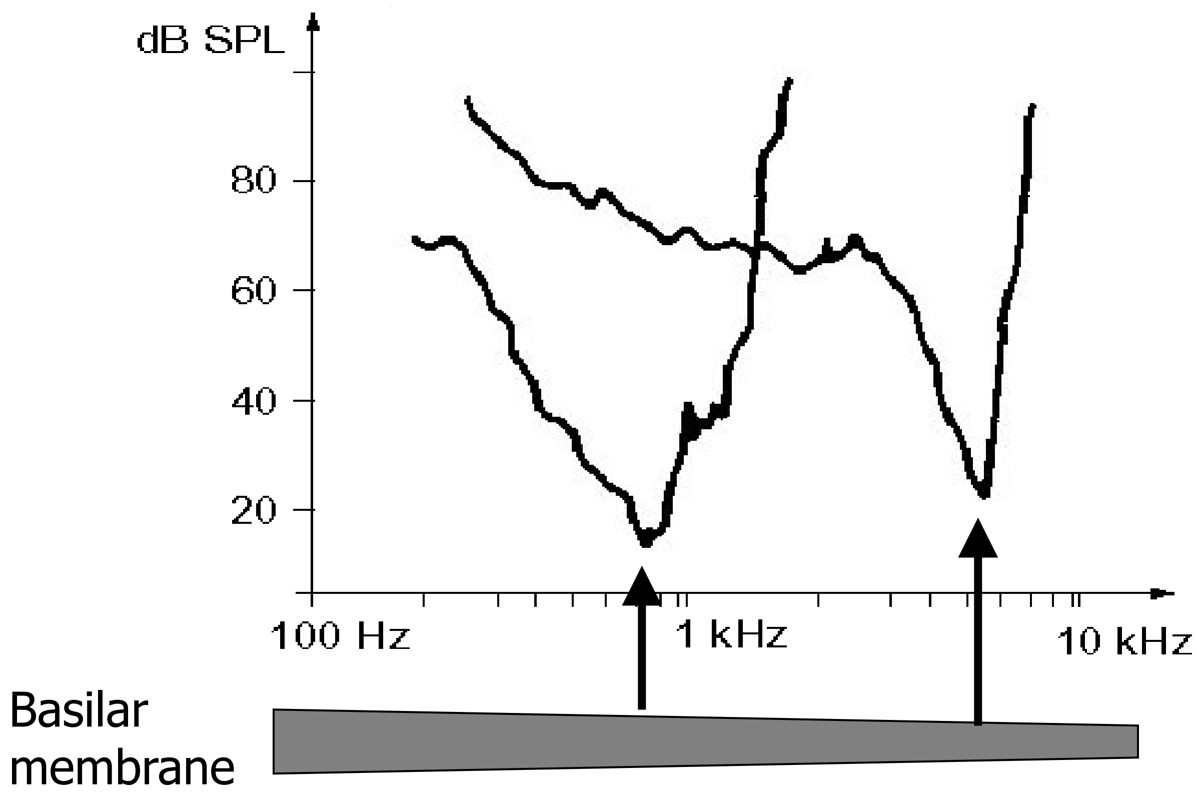
- Each IHC -> 10-20 type I fibers
- ~10 OHCs -> ~6 type II fibers

- This is an evidence that IHCs are the actual transducers

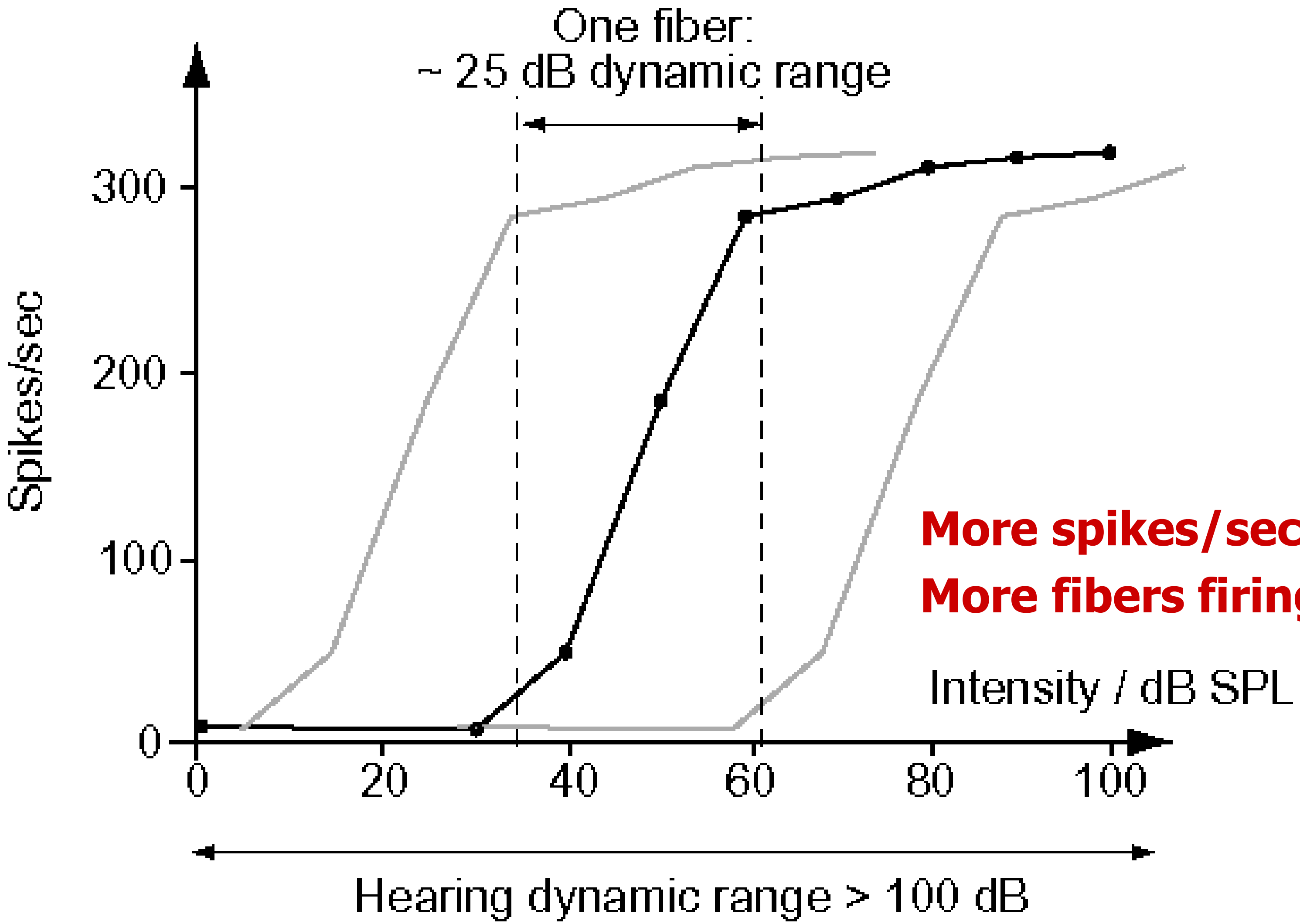
- Fibers are arranged to maintain the tonotopy of basilar membrane

Frequency Sensitivity

- single nerve measurements
- (roughly) symmetric in log of frequency



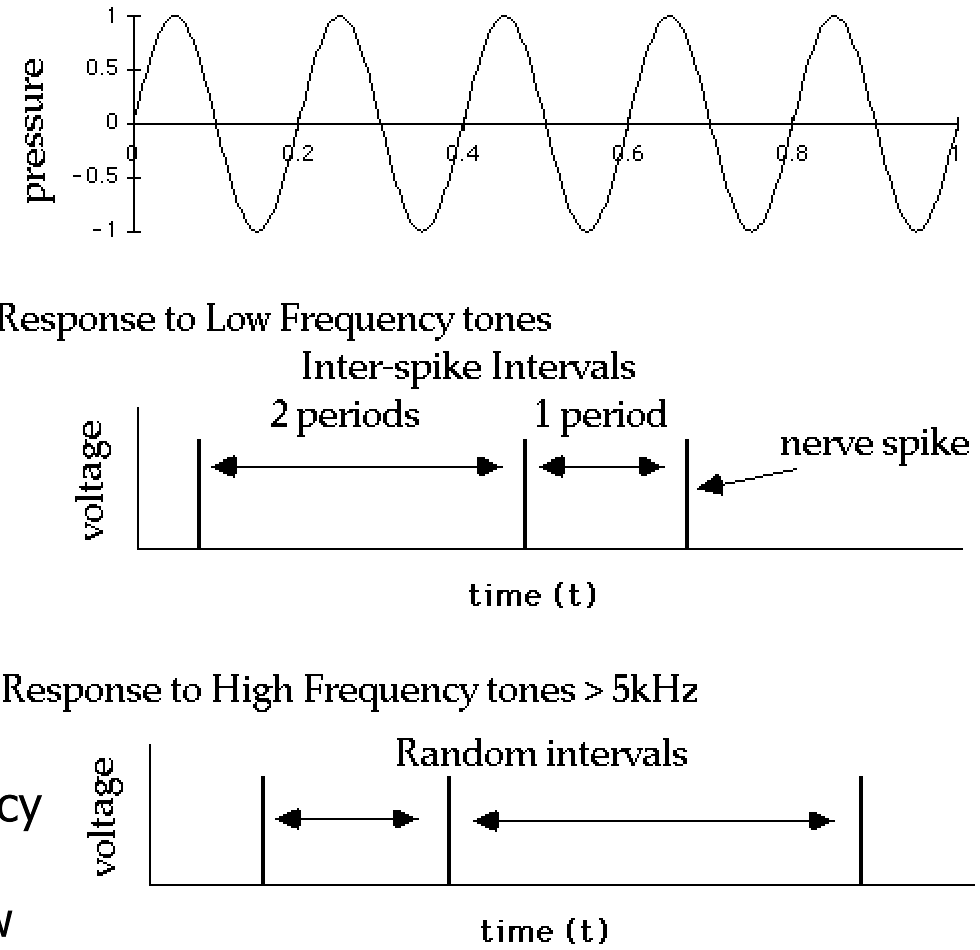
Encoding Loudness



More spikes/second = louder

More fibers firing = louder

Phase Locking



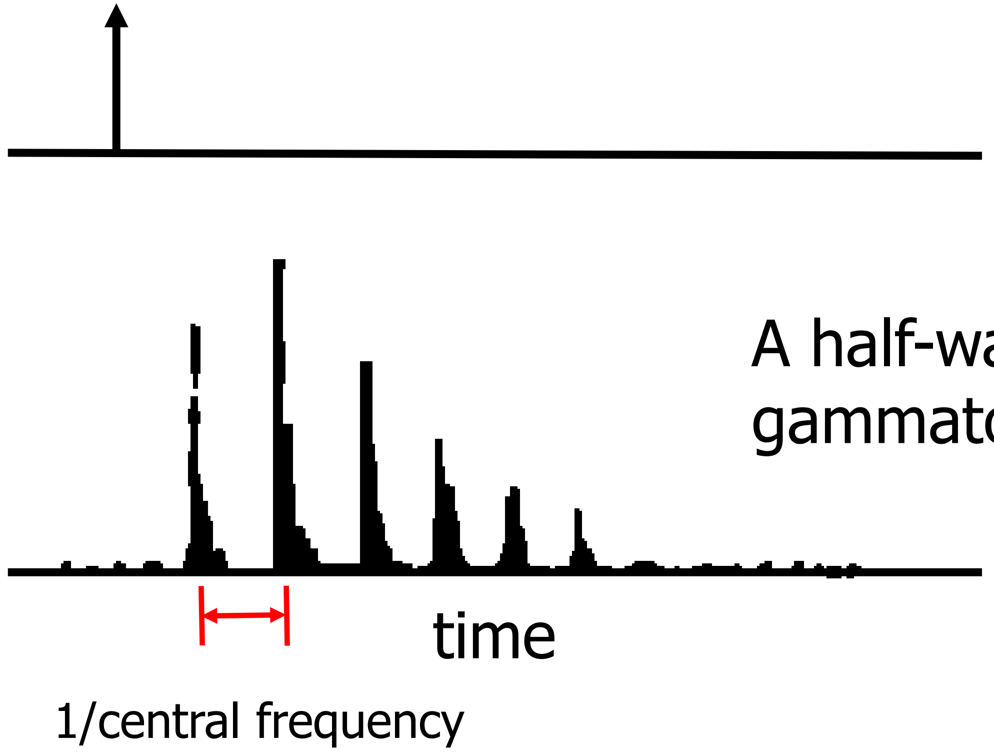
Half-wave rectification

For high frequency tones, the fibers phase lock to low frequency modulations.

(from Chris Darwin)

Poststimulus Time Histogram (PSTH)

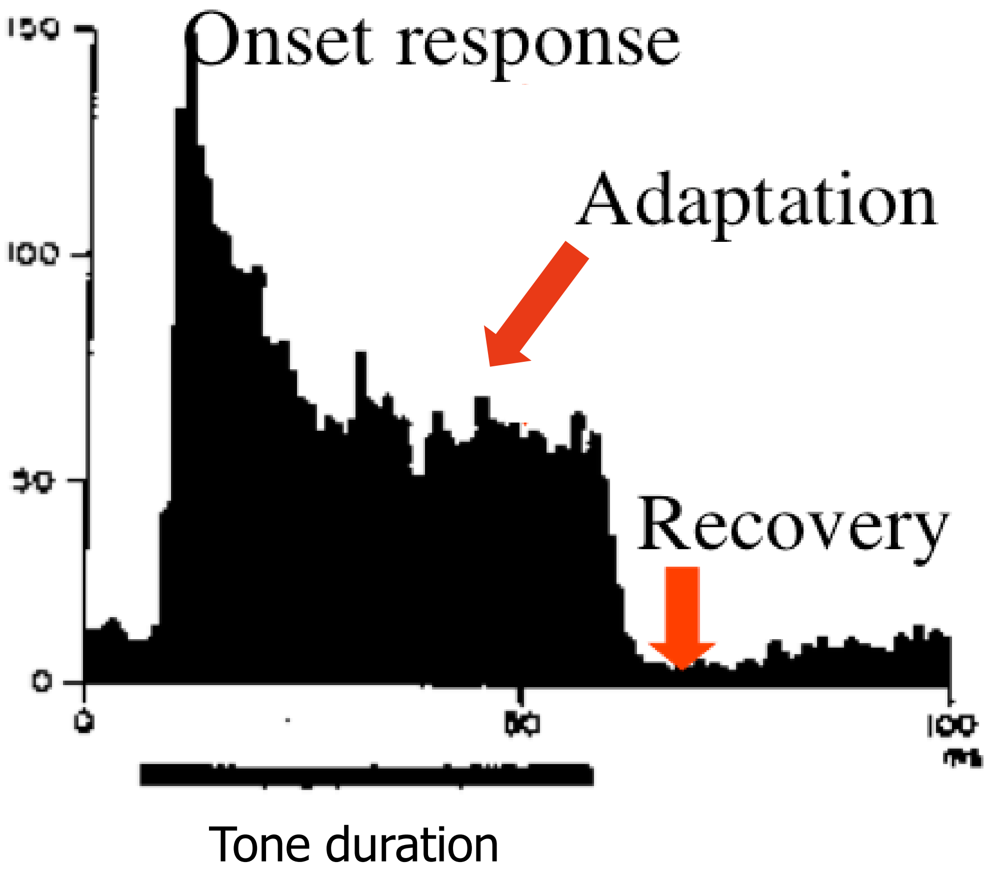
- Single fiber firing pattern to a click sound



A half-wave rectified gammatone function!

Histogram calculated by superimposing neural responses of repeated experiments

PSTH to a Tone Burst



(from Gelfand 1998)

Coding Frequency Information

- Frequencies under 5 kHz
  - Individual periods are resolved by the cochlea
  - Coded by *place* (which nerve bundles along the cochlea are firing)
  - Coded by *time* (nerves fire in synchrony to harmonics)
- Frequencies over 5 kHz
  - Individual periods can’t be resolved by the inner ear

Loudness

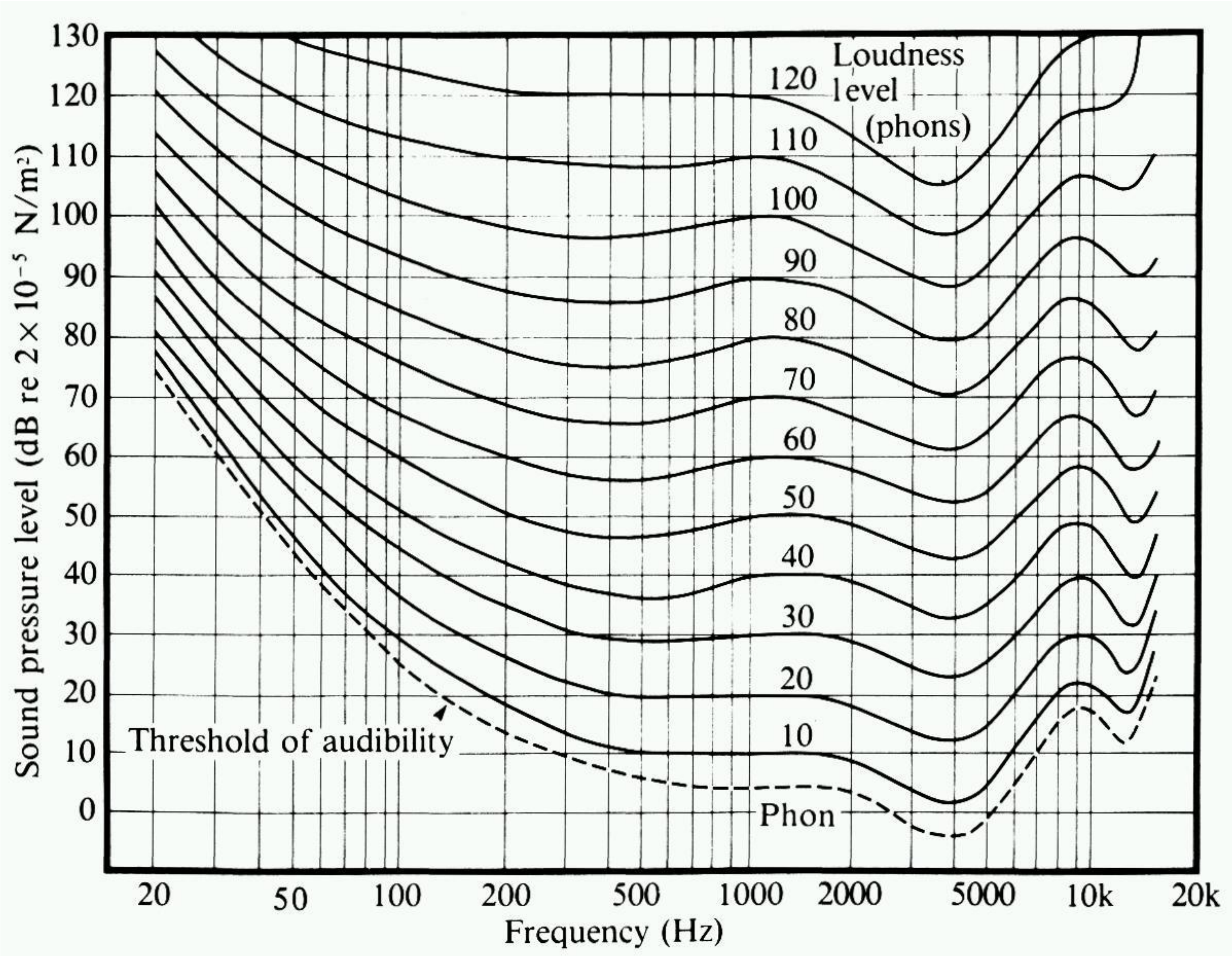
Loudness is a subjective measure of sound pressure (or intensity).

- How does the intensity of a sound relate to its perceived loudness?
  - Does frequency matter?
  - Is broadband noise different from narrow band?
  - How can we find out?

Measuring Frequency's Effect

- Pick a reference frequency (like 1000Hz)
- Play a sine wave of a defined intensity at that frequency (say, 30 dB-SPL)
- Pick another frequency (any one)
- Play a sine wave at the new frequency, f
- Adjust the intensity of the sine at f until its loudness equals the reference

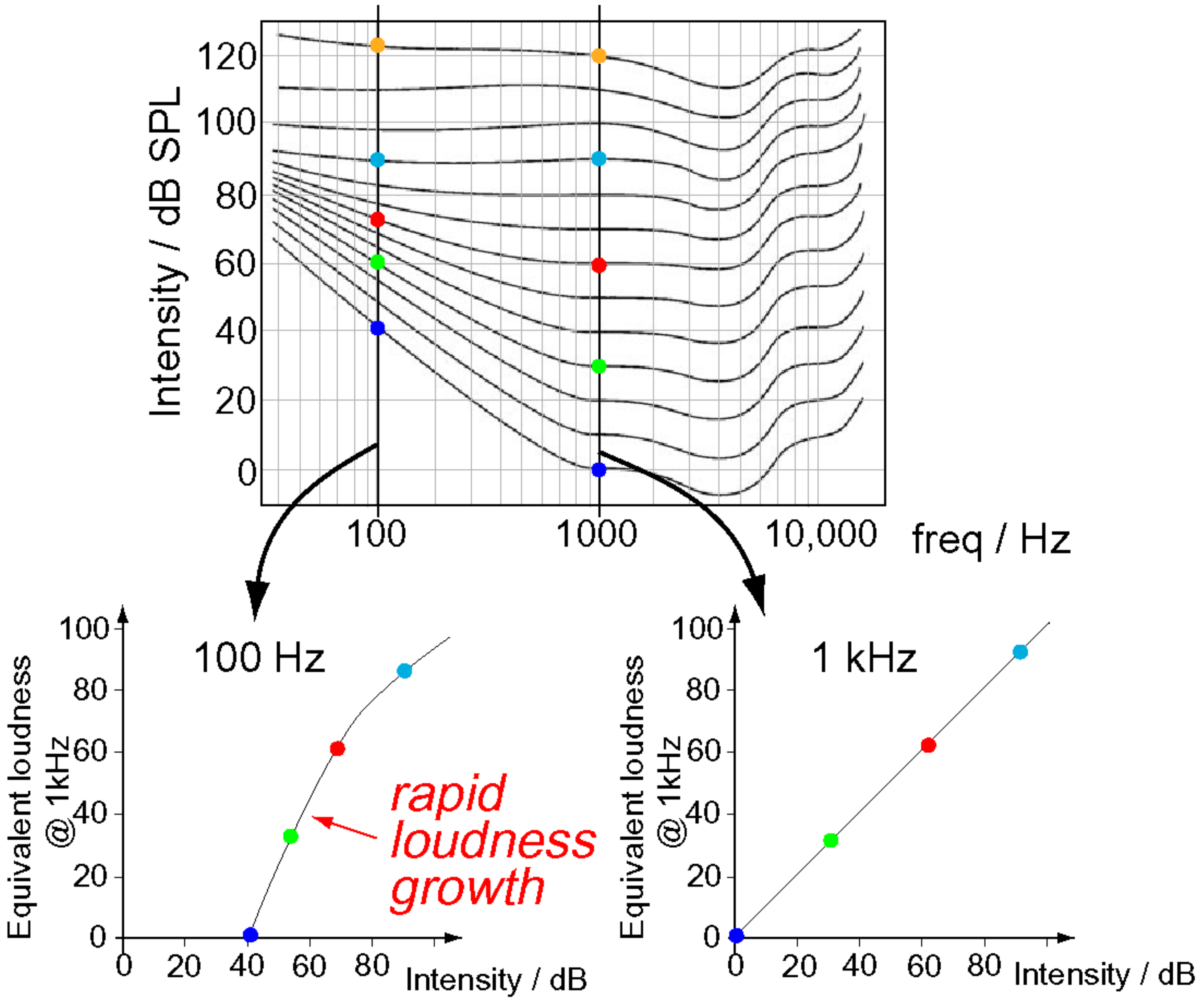
Equal Loudness Contours



Phons

The **phon** is a unit of perceived loudness for pure tones. The purpose of the phon scale is to compensate for the effect of frequency on the perceived loudness of tones. By definition, 1 phon is equal to 1 db-SPL at a frequency of 1000 Hz.

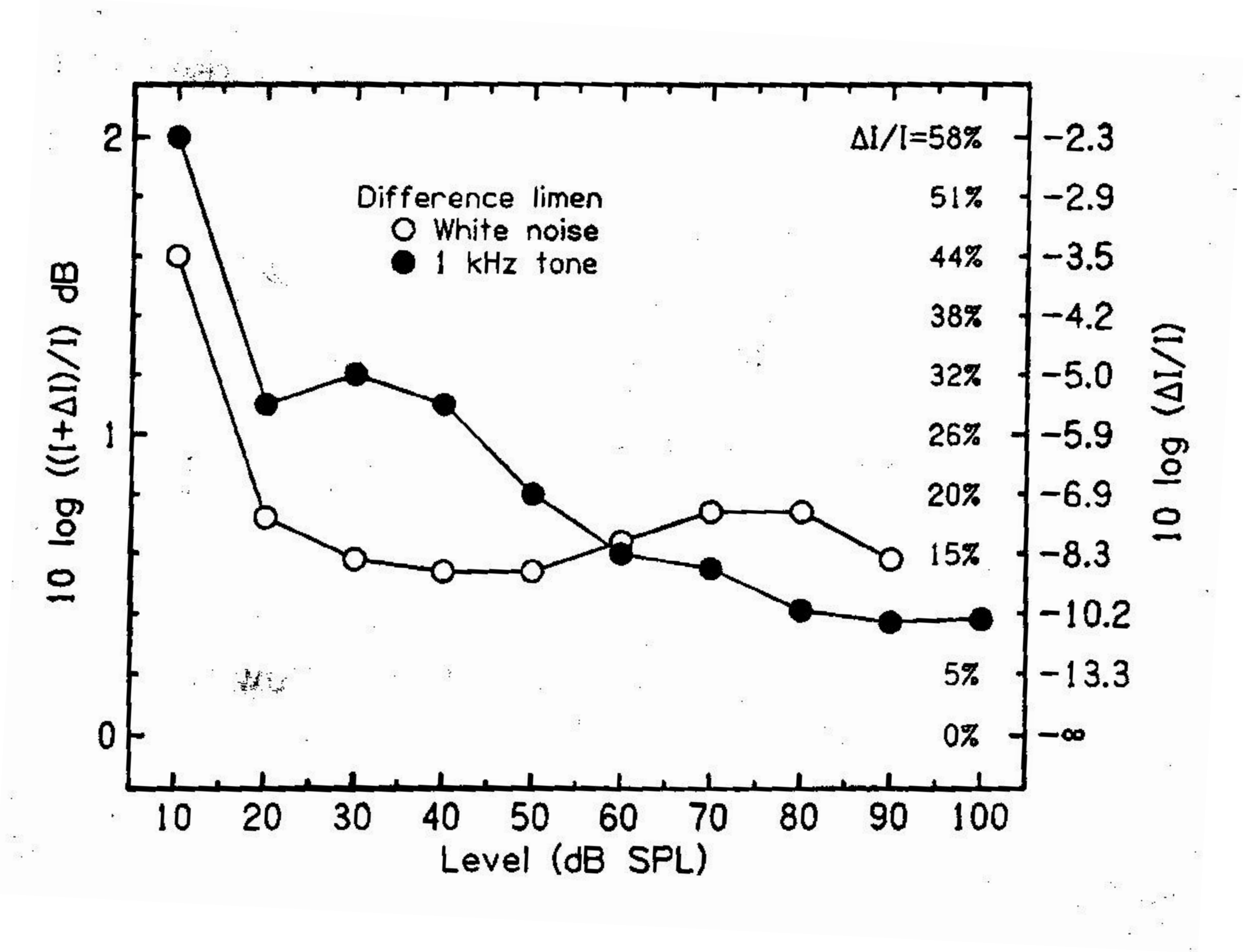
Sensitivity to Loudness



JND

The **just noticeable difference** (JND) is the smallest difference in sensory input that is detectable by a human being. It is also known as the **difference limen** (DL)

Difference Limens



Weber's Law

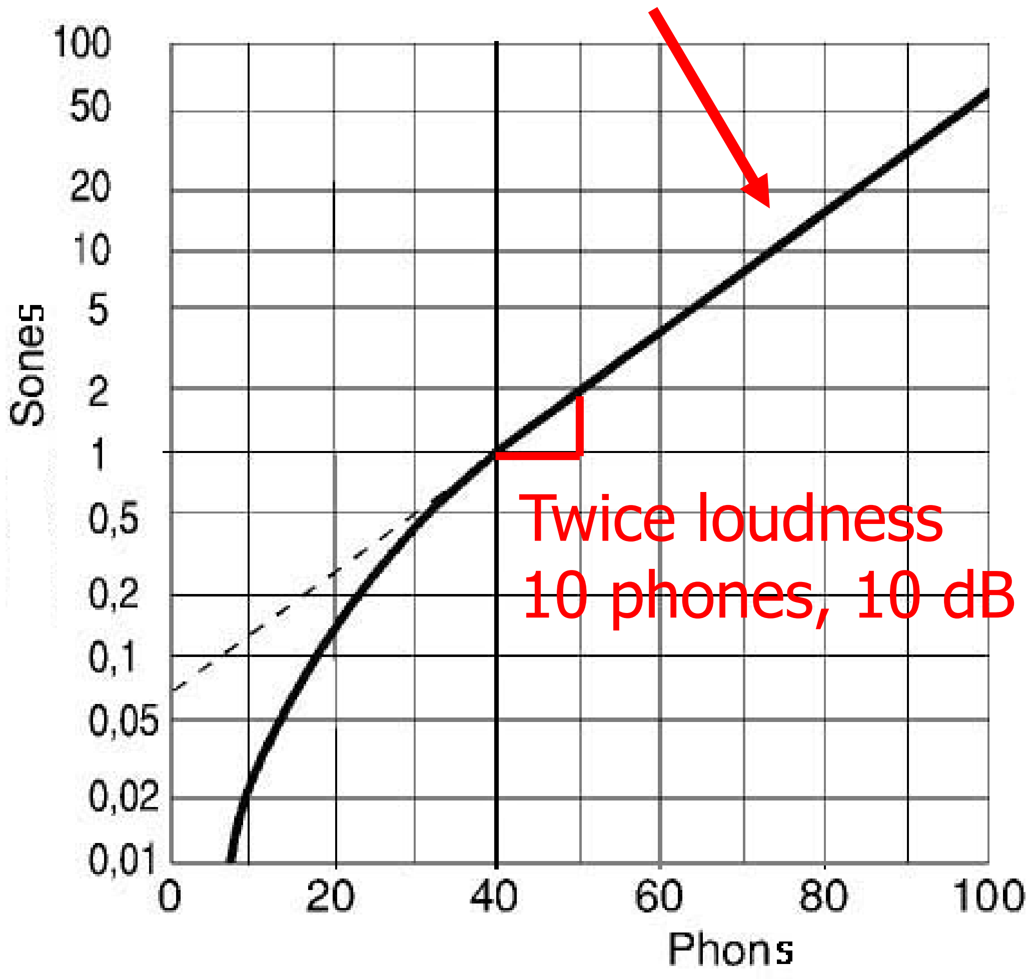
Weber's Law (named after Ernst Heinrich Weber, 1795-1878) attempts to describe the relationship between the physical magnitudes of stimuli and the perceived intensity of the stimuli.

- DL in intensity is proportional to the intensity itself, i.e., $\frac{\Delta I}{I}$ is constant.

The Sone

- The **sone** is a unit of perceived loudness, proposed by S. Stevens in 1936.
  - At 1kHz, 1 sone = 40 phons = 40 dB-SPL
  - A stimulus that is *n* sones loud is judged to be *n* times as loud as 1 sone.

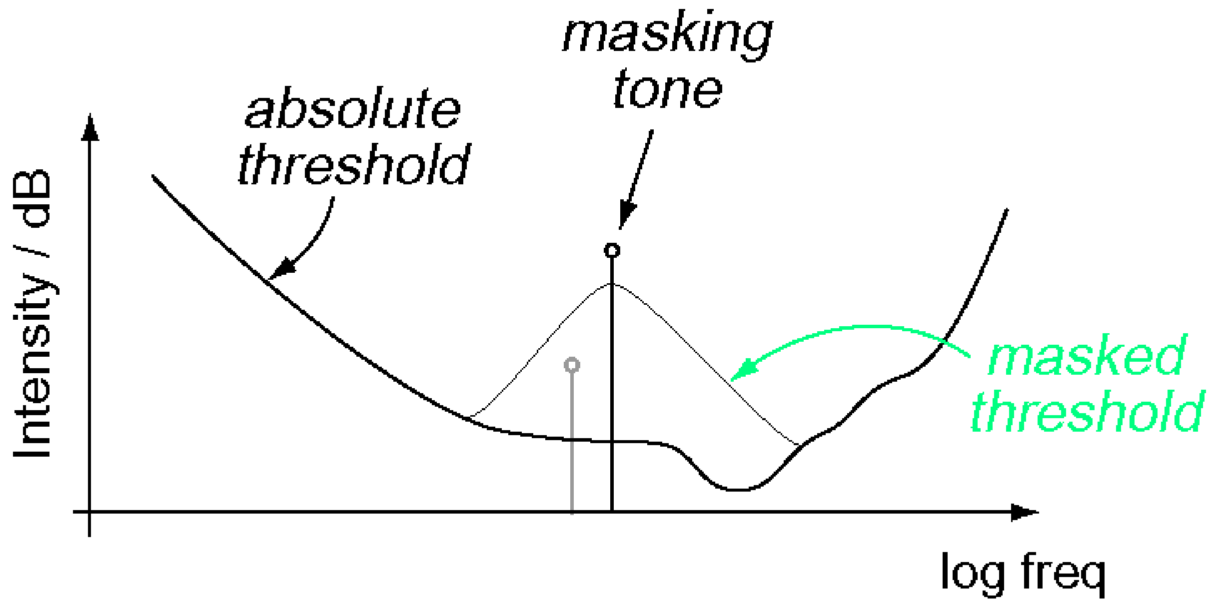
$$P_2 - P_1 = 10(\log_2 S_2 - \log_2 S_1)$$



Intensity ⇔ Sone

- Tone at 1kHz with intensity > 40 dB SPL
- To make the tone *n* times as loud, how many times should we increase the intensity?
  - We want to have $\frac{S_{new}}{S} = n$.
  - Therefore, we need $P_{new} - P = 10\log_2 n$.
  - That is, we need $10\log_{10}\frac{I_{new}}{I} = 10\log_2 n$.
  - So $\frac{I_{new}}{I} = 10^{\log_2 n} = 10^{\frac{\log_{10} n}{\log_{10} 2}} = n^{\log_2 10} \approx n^{3.32}$.
  - Roughly 8 people make as twice loud as 1 person.
- That's why some papers use $\sqrt[3]{I}$ to describe loudness.

Masking



- A loud tone masks perception of tones at nearby frequencies

1000 Hz   1000_975_20dB   1000_975_6dB   1000_475_20dB

Critical Band

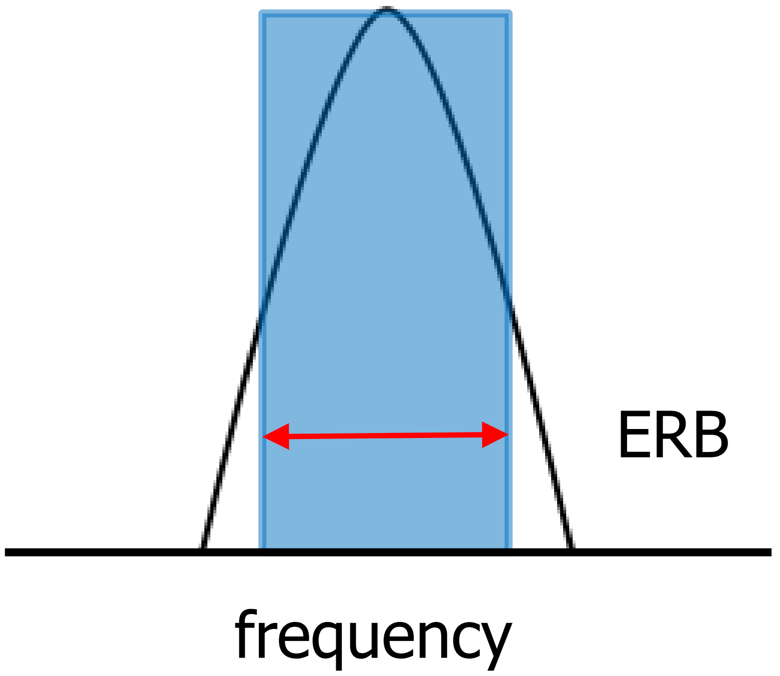
- **Critical band** – the frequency range over which a pure tone interferes with the perception of other pure tones.

- Think about the masked threshold as a band-stop filter.

- How to measure the bandwidth?

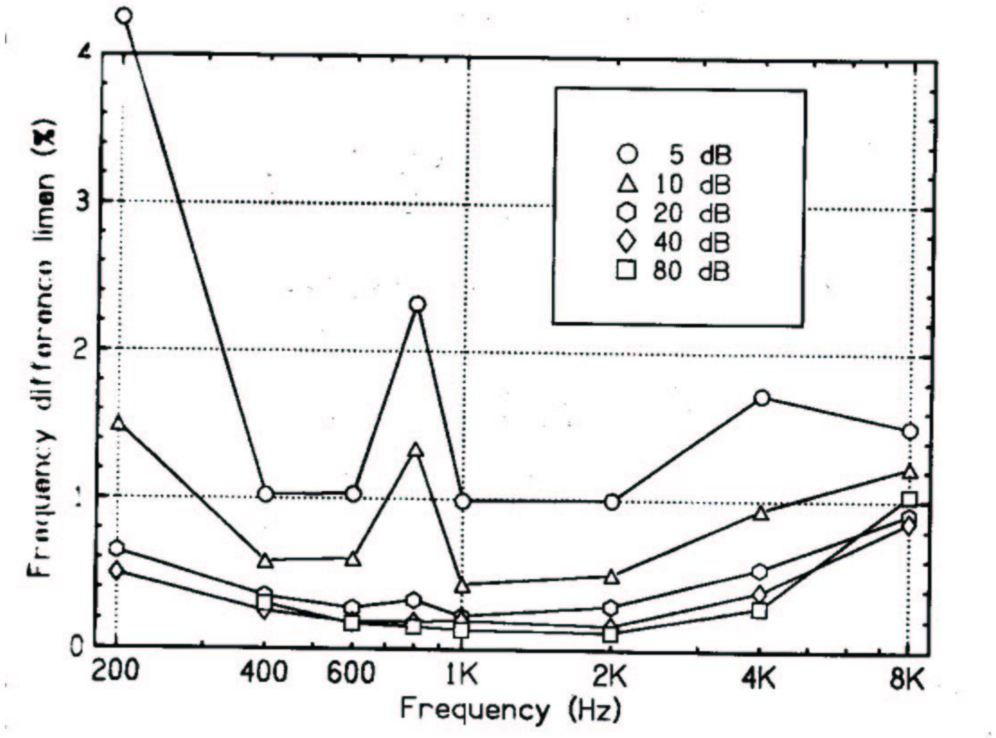
Equivalent Rectangular Bandwidth (ERB)

- $\mathrm{ERB(Hz)} = 24.7(4.37\ \mathrm{f(kHz)} + 1)$
- The bandwidth increases with frequency.



Frequency Difference Limen

- The smallest difference between the frequencies of two sine tones that can be discriminated correctly 75% of the time.



1000Hz

1001Hz

1002Hz

1005Hz

Pitch (ANSI 1994 Definition)

- That attribute of auditory sensation in terms of which sounds may be ordered on a scale extending from low to high. Pitch **depends mainly on the frequency** content of the sound stimulus, but **also depends on the sound pressure and waveform** of the stimulus

Pitch (Operational)

- A sound has a certain pitch if it can be reliably matched to a sine tone of a given frequency at 40 dB SPL

Pitch and Intensity

- Stevens Rule
  - The pitch of low frequency (below 1000Hz) sine tones decreases with increasing intensity -- (low loud sounds go flat)
  - The pitch of high frequency tones (over 3000 Hz) increases with intensity -- (high loud sounds go sharp)

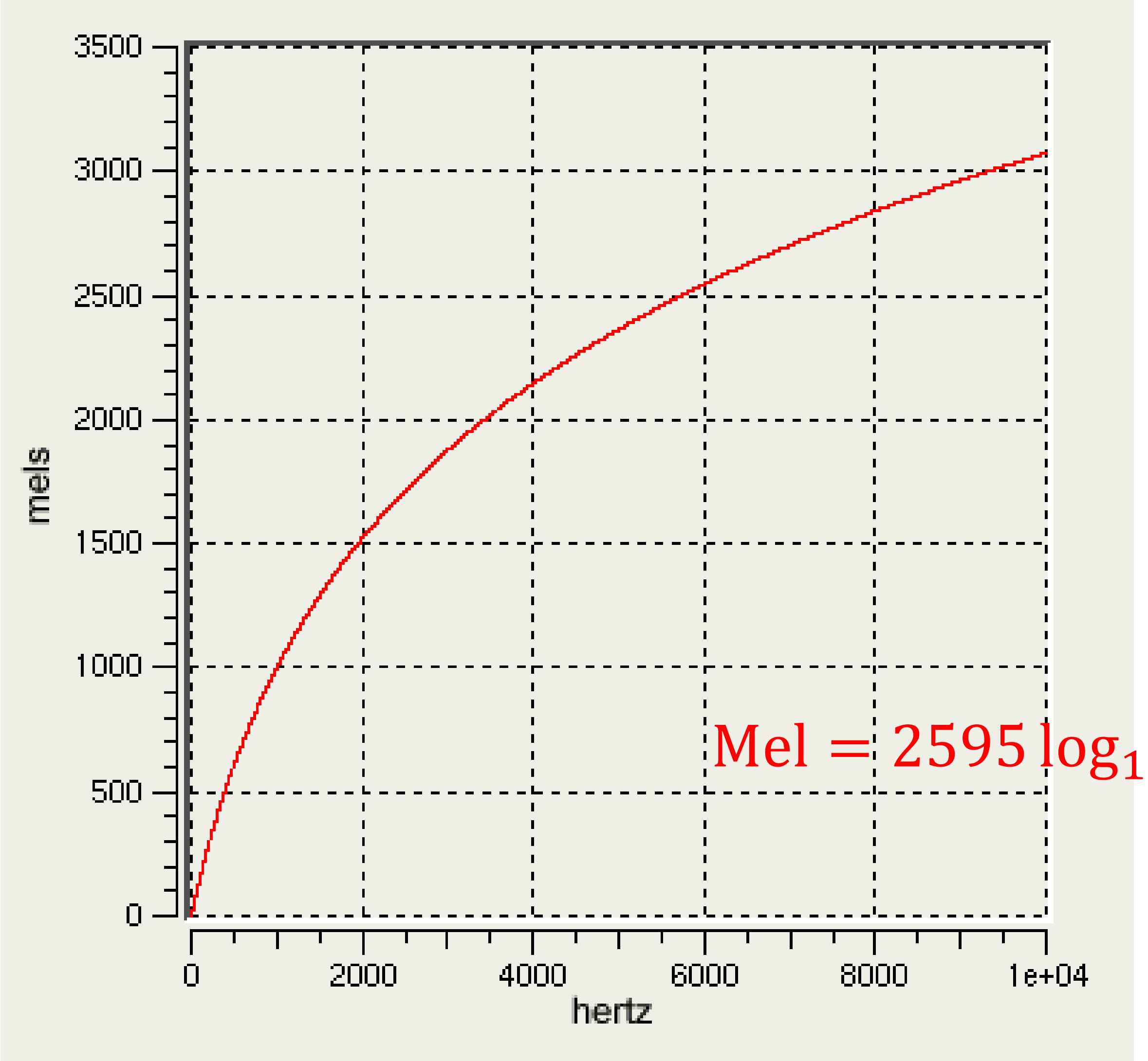
220Hz

7040Hz

Mel Scale

- A perceptual scale of pitches judged by listeners to **be equal in distance** from one another. The reference point between this scale and normal frequency measurement is defined by equating a 1000 Hz tone, 40 dB SPL, with a pitch of 1000 mels.

Mel Scale



$$\text{Mel} = 2595\log_{10}(1+\frac{f}{700})$$

Mel Scale

- Above about 500 Hz, larger and larger intervals are judged by listeners to produce equal pitch increments.
- The name **mel** comes from the word **melody** to indicate that the scale is based on pitch comparisons.
- Proposed by Stevens, Volkman and Newman (Journal of the Acoustic Society of America 8(3), pp 185-190, 1937)

Ear Craziness

- Binaural Diplacusis
  - Left ear hears a different pitch from the right
  - Can be up to 4% difference in perceived pitch
- Otoacoustic Emissions
  - Healthy ears can make noise
  - Thought to be a by-product of the sound amplification system (e.g., outer hair cells) in the inner ear
  - Widely used in hearing tests for infants and children

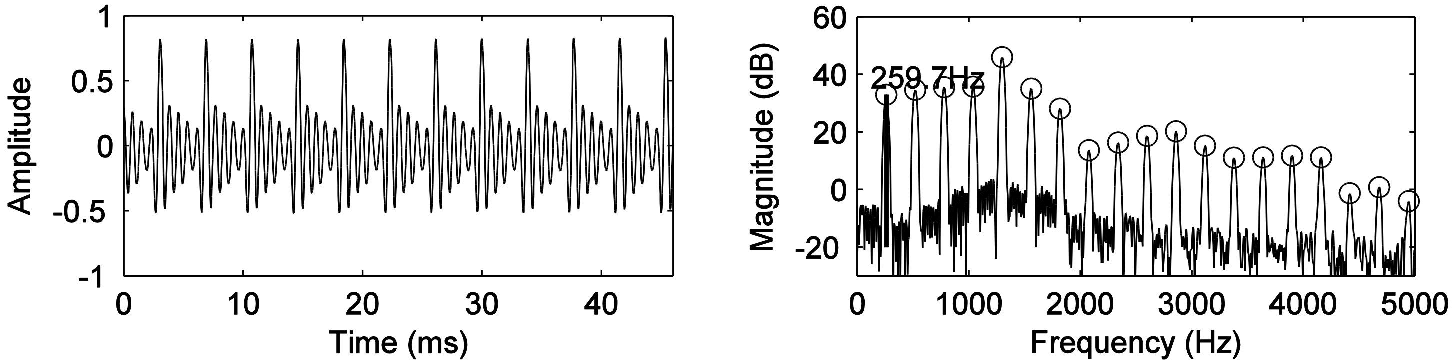
Harmonic Sound

- A sound with strong sinusoidal components at integer multiples of a fundamental frequency. These components are called **harmonics** or **overtones**.

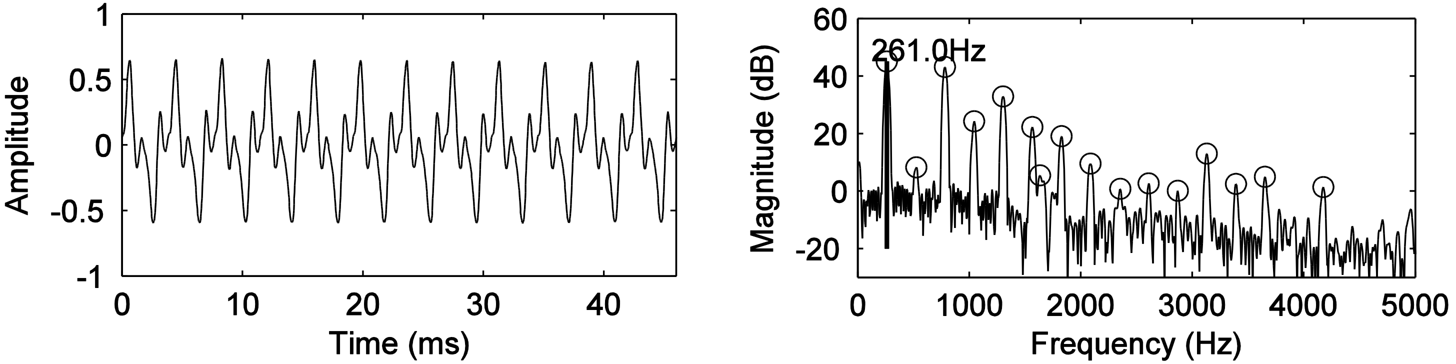
- Harmonic sounds are the sounds that may give a perception of “pitch”.

Classify Sounds by Harmonicity

- Sine wave
- Strongly harmonic



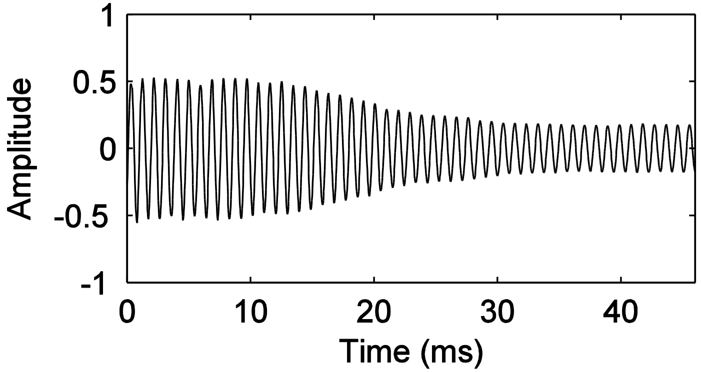
Oboe

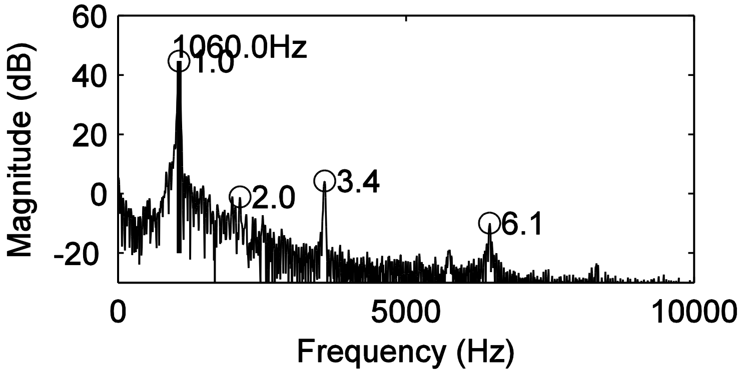


Clarinet

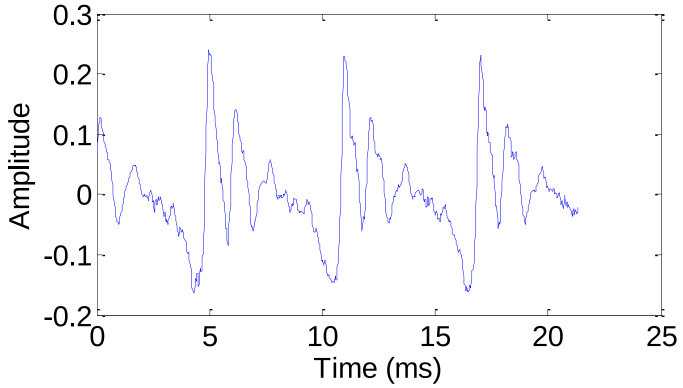
Classify Sounds by Harmonicity

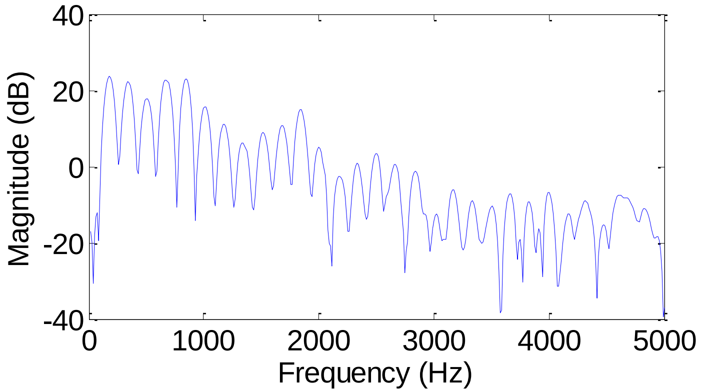
- Somewhat harmonic (quasi-harmonic)





Marimba

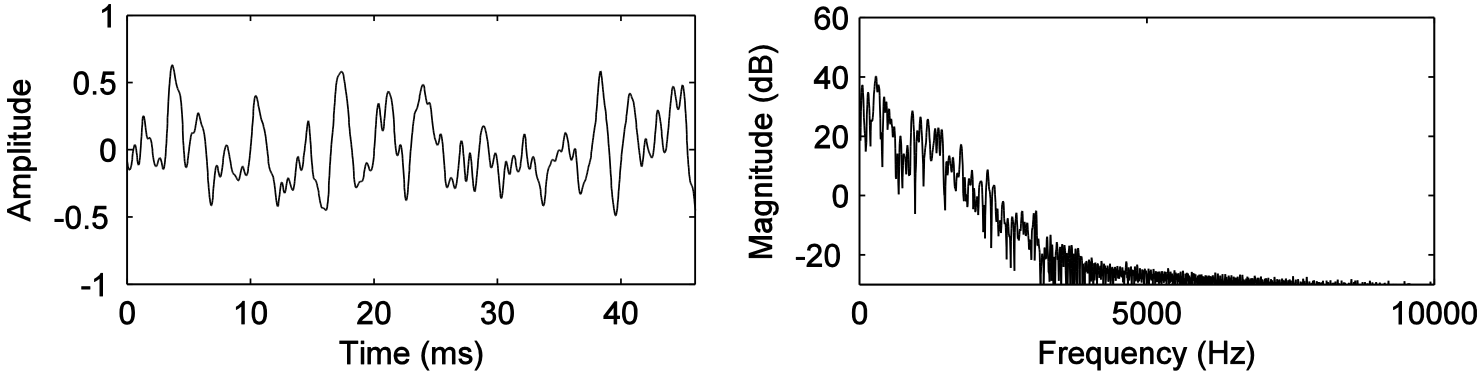




Human voice

Classify Sounds by Harmonicity

- Inharmonic



Gong

Sounds	Instrument family	Instruments
Harmonic	Woodwind	Piccolo, flute, oboe, clarinet, bassoon, saxophone
	Brass	Trumpet, horn, euphonium, trombone, tuba
	Arco string	Violin, viola, cello, double bass
	Pluck string	Piano, guitar, harp, celesta
	Vocal	Voiced phonemes
Quasi-harmonic	Pitched percussive	Timpani, marimba, vibraphone, xylophone
Inharmonic	Non-pitched percussive	Drums, cymbal, gong, tambourine

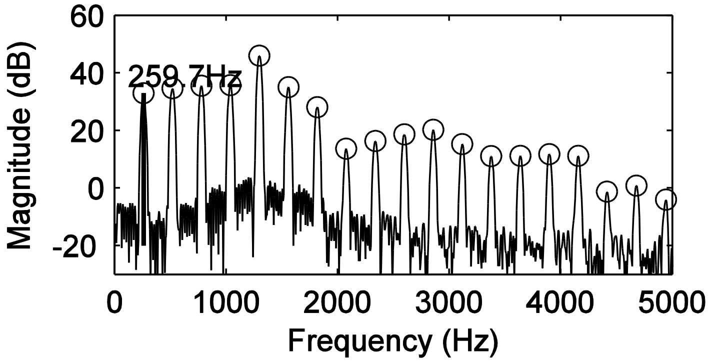
What determines pitch?

- Complex tones
  - Strongest frequency?
  - Lowest frequency?
  - Something else?

- Let’s listen and explore…

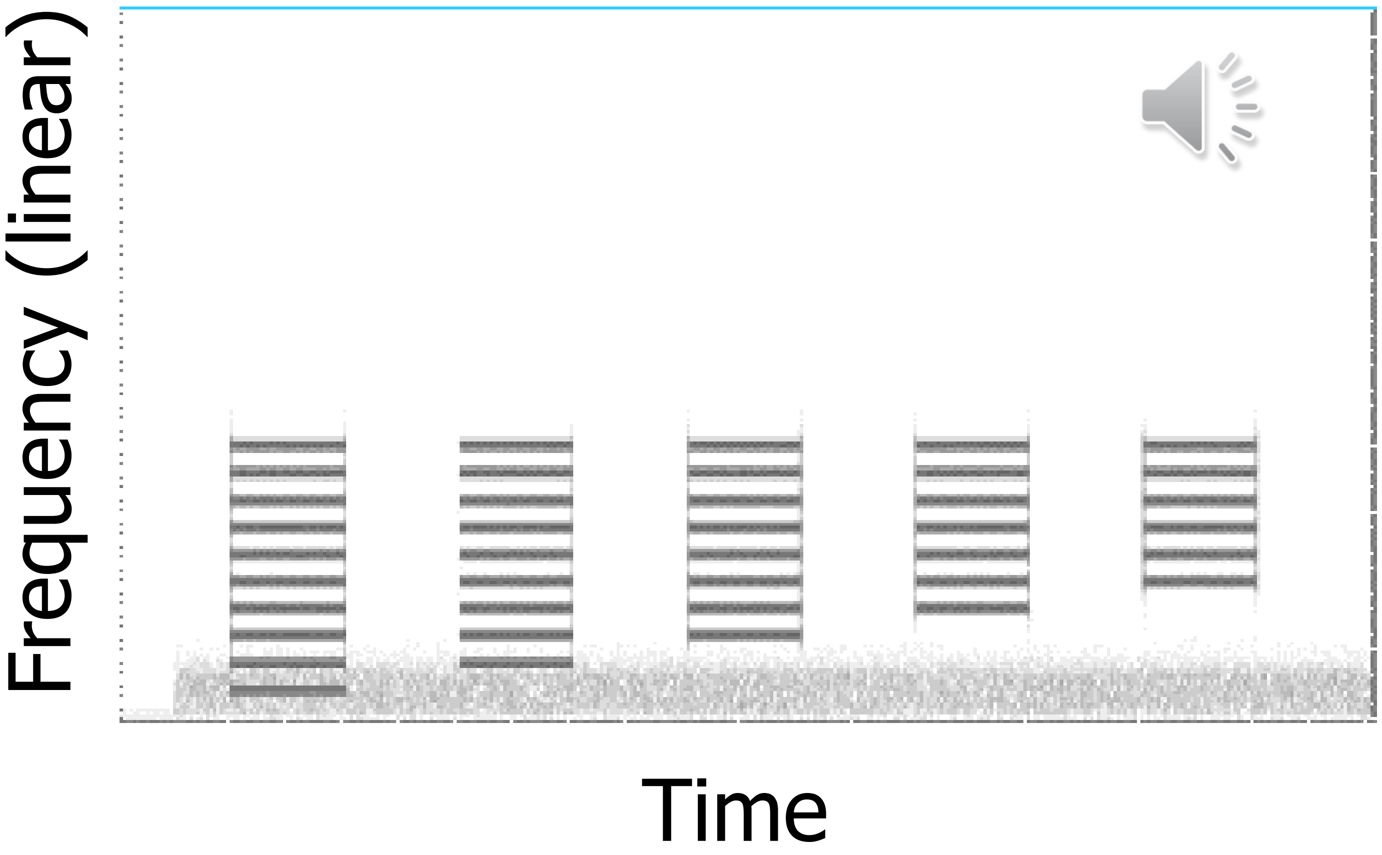
Hypothesis

- Pitch is determined by the lowest strong frequency component in a complex tone



Oboe

The Missing Fundamental



Hypothesis

- Pitch is determined by the lowest strong frequency component in a complex tone

- The case of the missing fundamental proves that it’s not always so

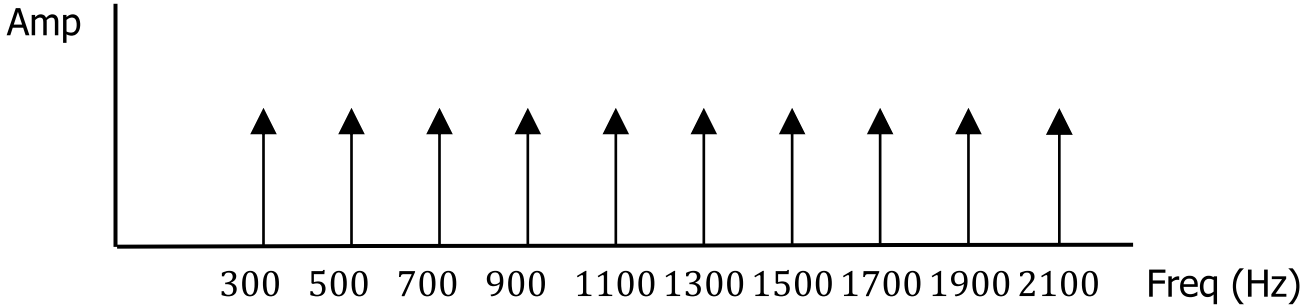
Hypothesis – “It’s complicated”

- by the loudest frequency
- by the common frequency that divides other frequencies
- by the space between regularly spaced frequencies

300:200:2100 Hz

200Hz

300Hz



Pitch and Music

- How do we tune pitch in music?
- How do we represent pitch in music?
- How do we represent the relation of pitches in music?

Equal Temperament

- Octave is a relationship by the power of 2
- There are 12 half-steps in an octave

$$f(n) = 2^{\frac{n}{12}} f_{\text{ref}}$$

number of half-steps from the reference pitch (n)

frequency of desired pitch ($f(n)$)

frequency of the reference pitch (f_{ref})

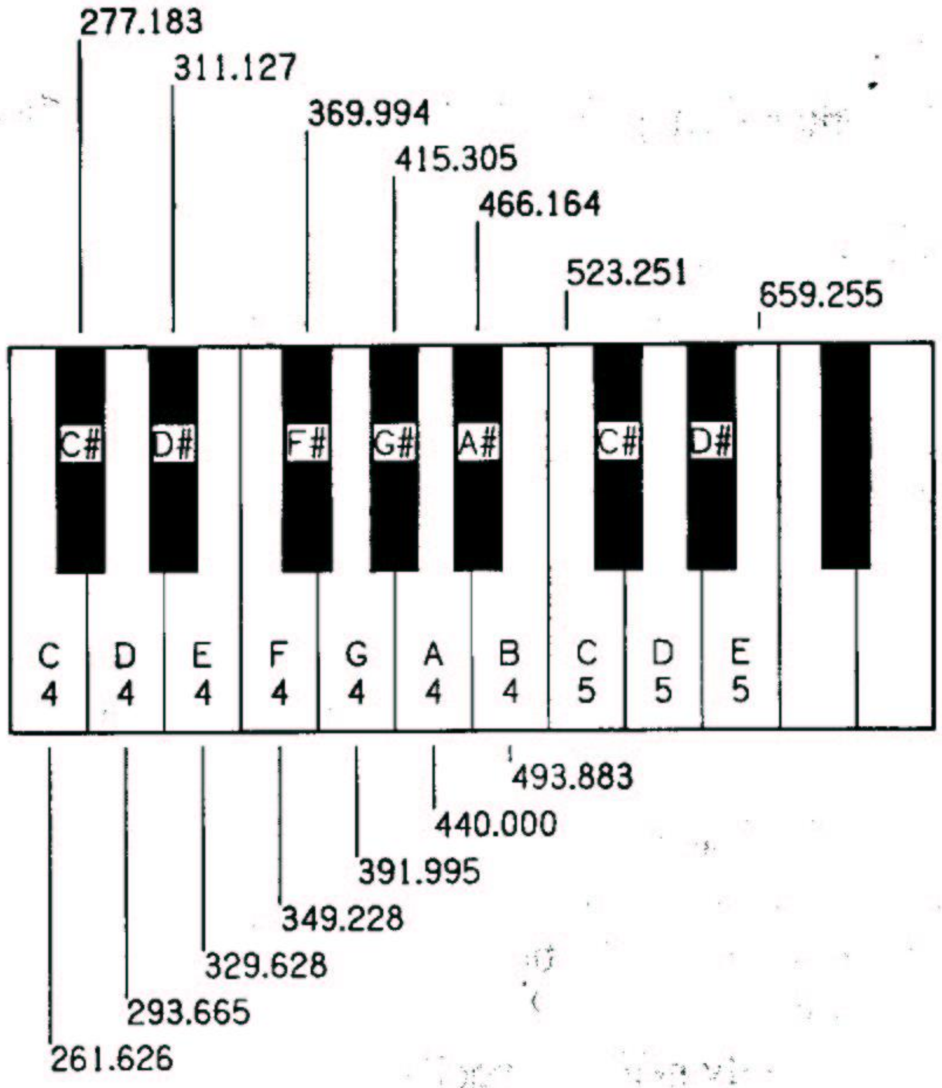
Measurement

- 100 Cents in a half step
- 2 half steps in a whole step
- 12 half steps in an octave

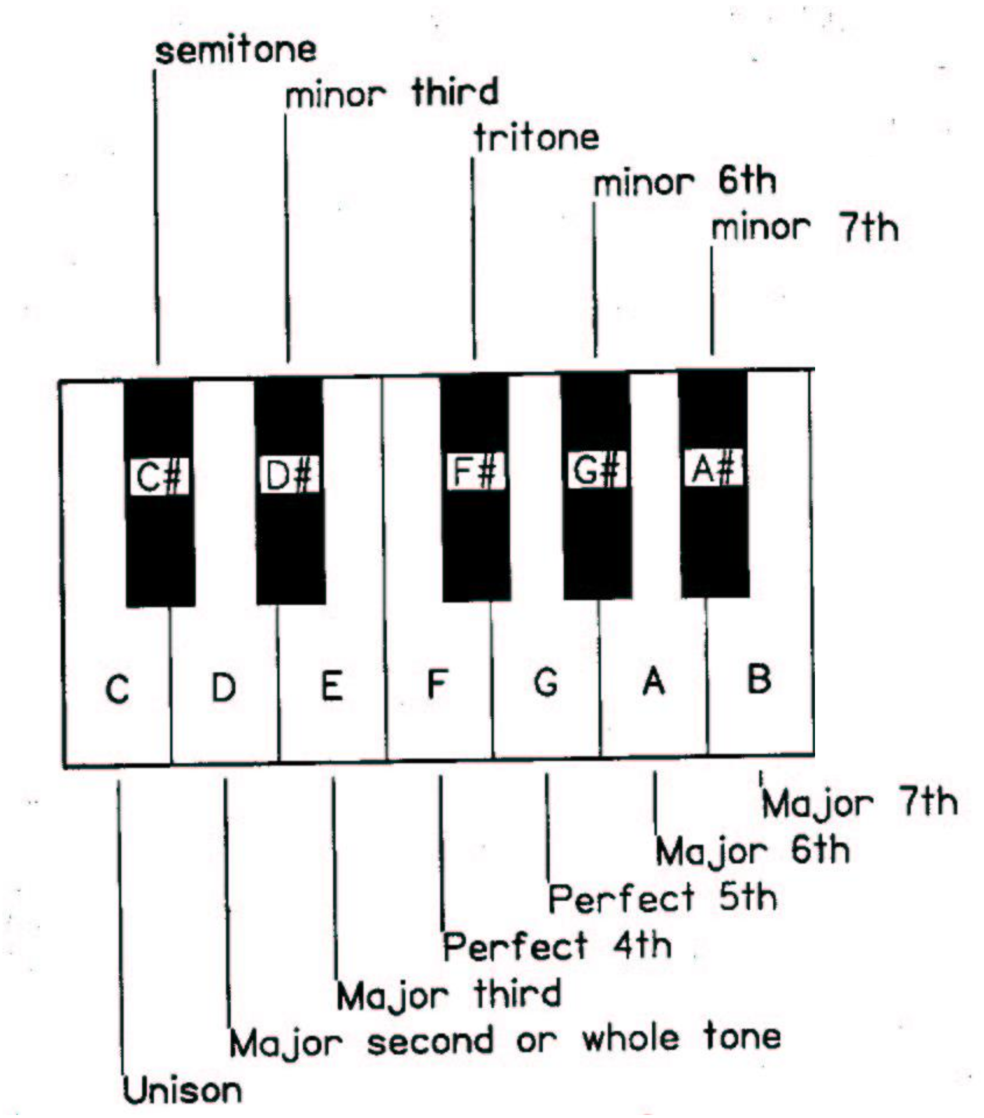
Number of cents

$$c = 1200 \log_2 \left(\frac{f}{f_{\mathrm{ref}}} \right)$$

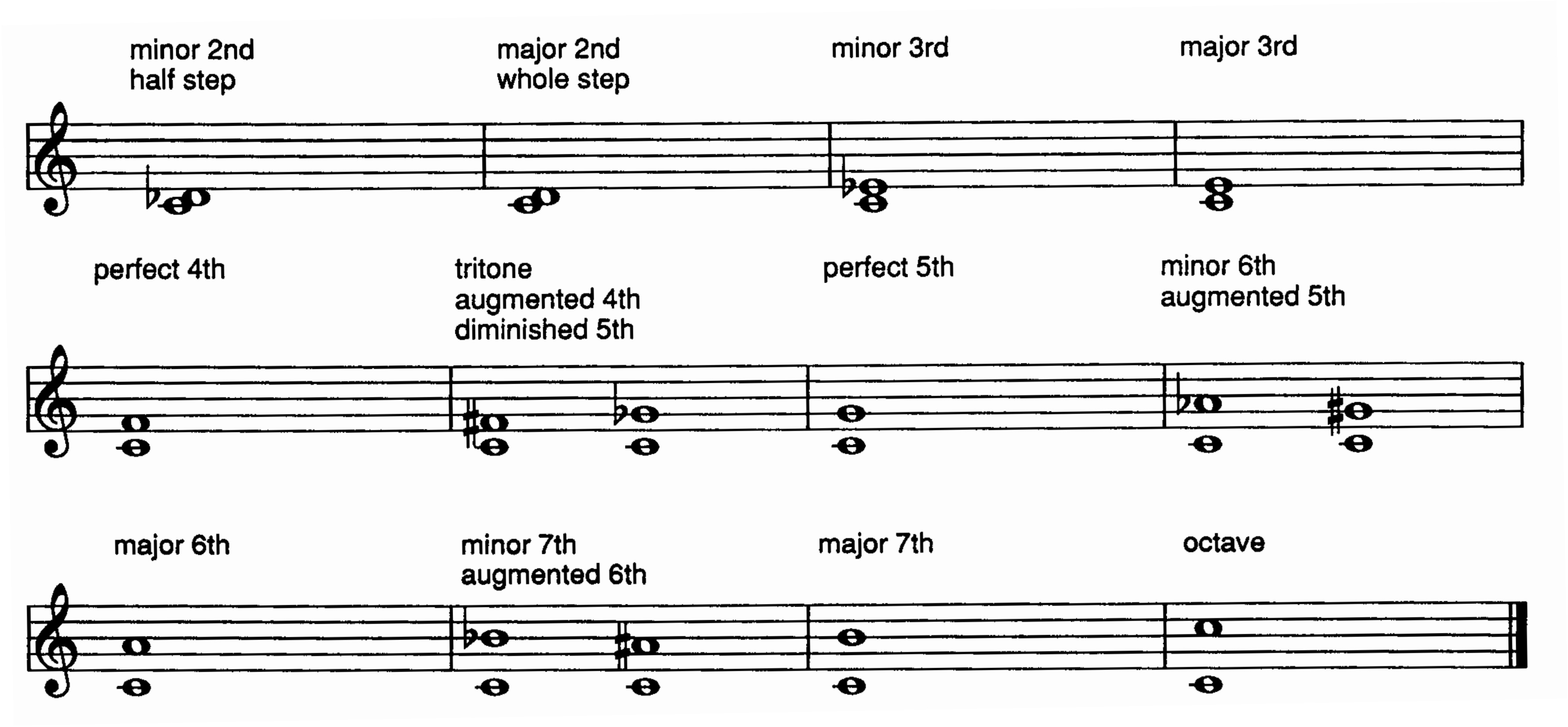
A=440 Equal Temperament Tuning



Musical Intervals (from C)

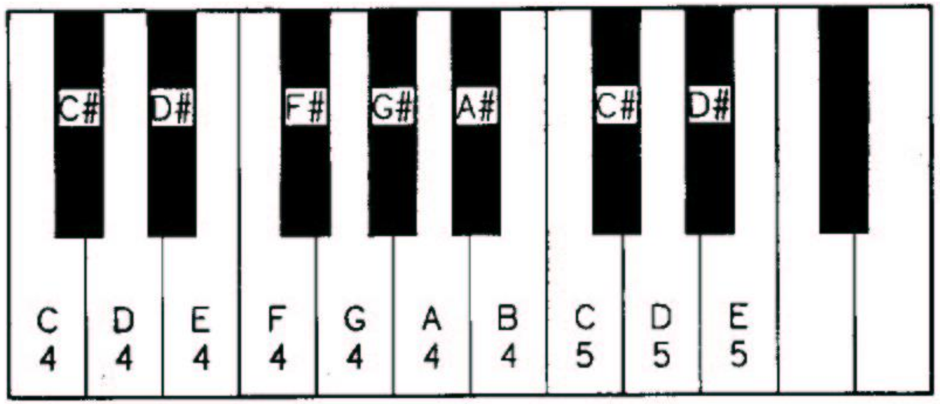


Interval Names



Some Magic

Half-steps: 0 1 2 3 4 5 6 7 8 9 10 11 12



C → C: 12 half-steps, $2^{\frac{12}{12}} = \frac{2}{1}$

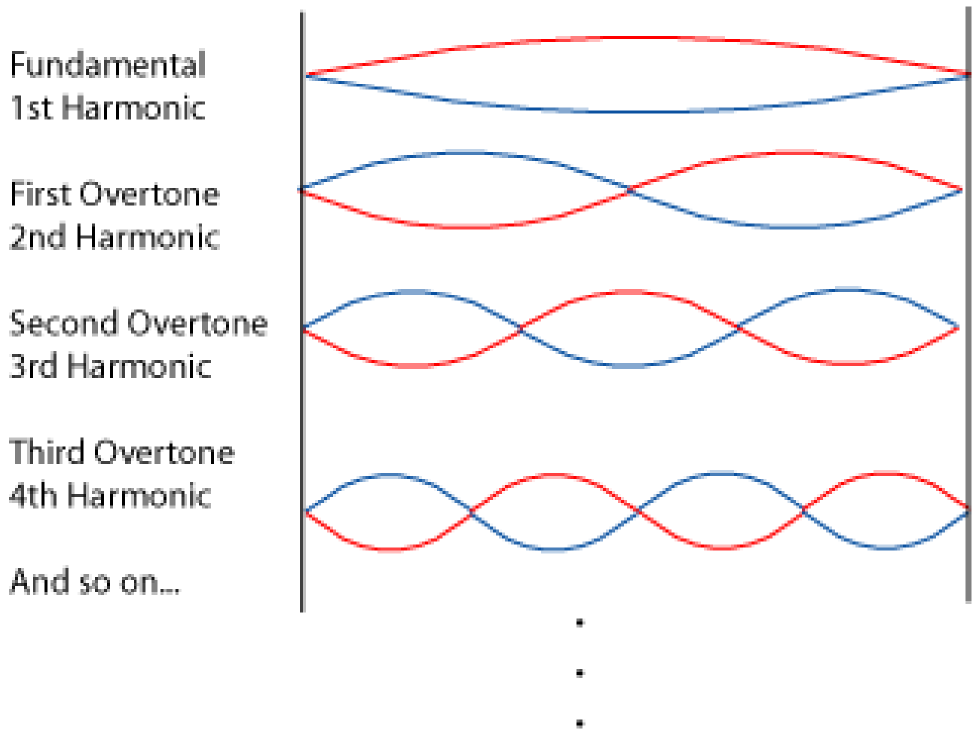
C → G: 7 half-steps, $2^{\frac{7}{12}} = 1.4983 \approx \frac{3}{2}$

C → F: 5 half-steps, $2^{\frac{5}{12}} = 1.3348 \approx \frac{4}{3}$

C → E: 4 half-steps, $2^{\frac{4}{12}} = 1.2599 \approx \frac{5}{4}$

Are these just coincidence?

Related to Standing Waves

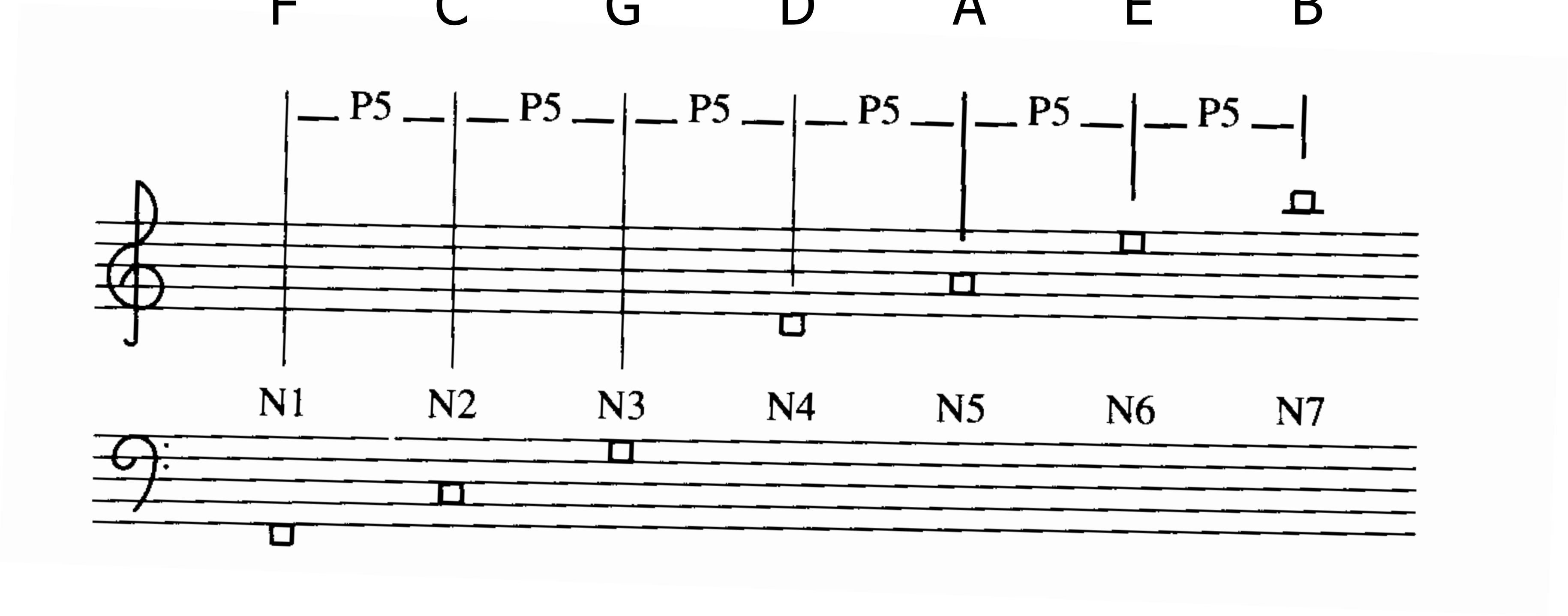


- How about defining pitches this way, so that they sound more harmonic?

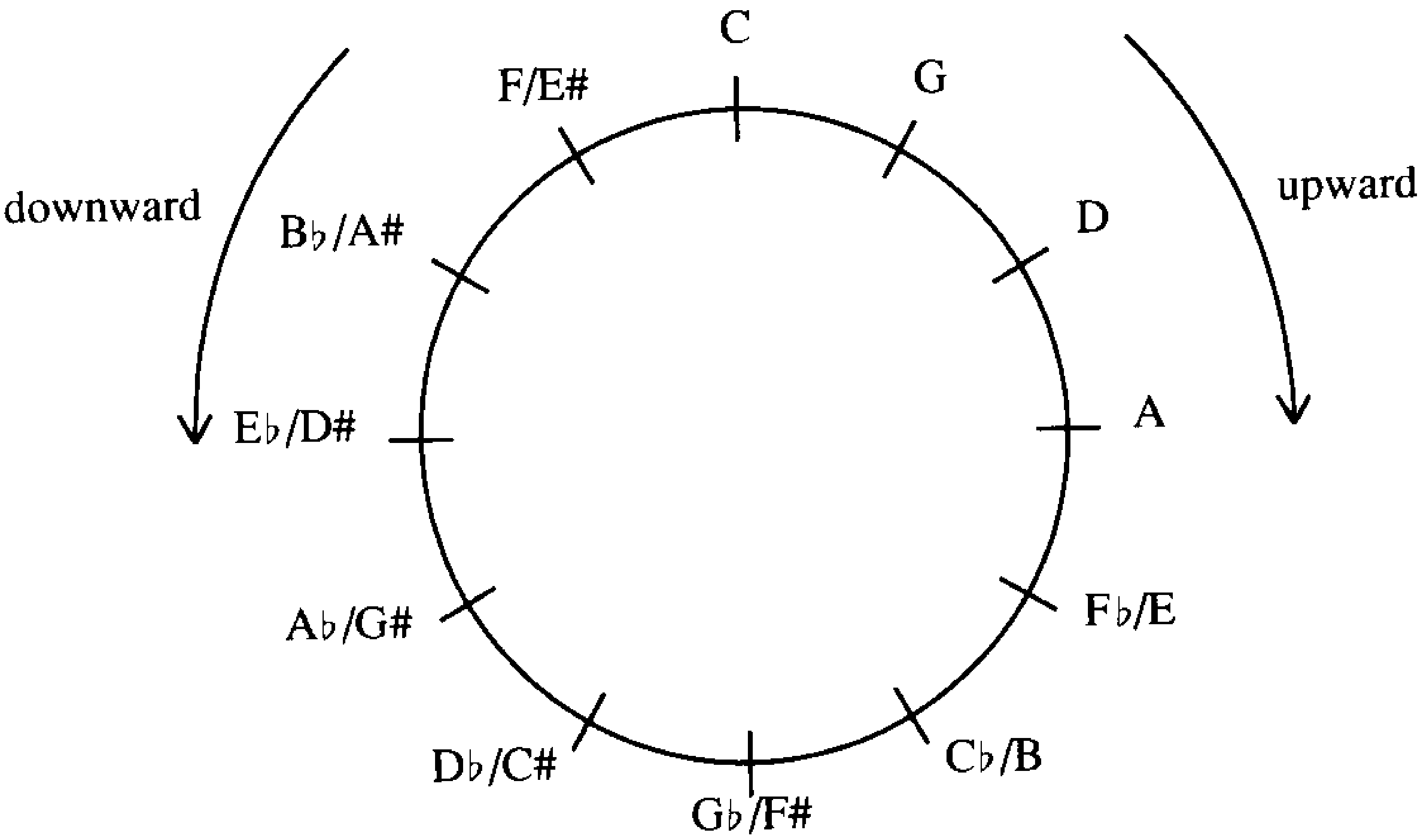
Pythagorean Tuning

- Frequency ratios of all intervals are based on the ratio 3:2, i.e., perfect fifth (P5), which is 7 half-steps.

F C G D A E B



Circle of Fifths



Problem with Pythagorean Tuning

- One octave = 2f
- A perfect 5th = (3/2)f

- What happens if you go around the circle of 5ths to get back to your original pitch class?

- $(3/2)^{12}$ = 129.75
- Nearest octave is 2^7 = 128
- 128 != 129.75

- Not convenient for key changes

Overtone Series

- Approximate notated pitch for the harmonics (overtones) of a frequency