AUDL 1001

Signals & Systems for Speech & Hearing

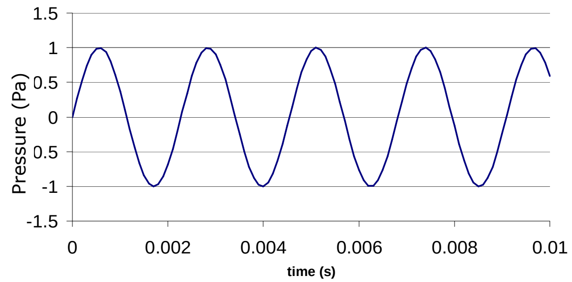
Week 2

Systems *(& a bit more about dB)*

http://www.phon.ucl.ac.uk/courses/spsci/sigsys
with links to related material

Reminder: signals as waveforms

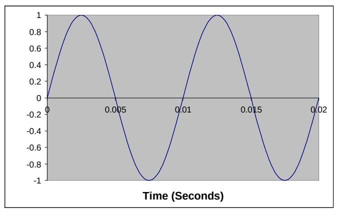
A graph of the *instantaneous* value of amplitude over time
- ◦ x-axis is always time (s, ms, µs)
- ◦ y-axis always a *linear instantaneous* amplitude measure (Pa, mPa, µPa, V, m)



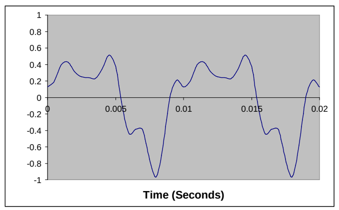
Waveforms are of two major types: periodic and aperiodic

- Periodic waveforms
  - Consist of a basic unit or *cycle* …
  - that repeats in time …
  - typically have a strong pitch …
  - and also come in two types

simple (= sinusoid)



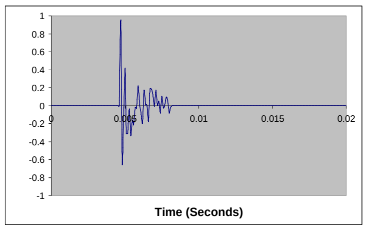
complex



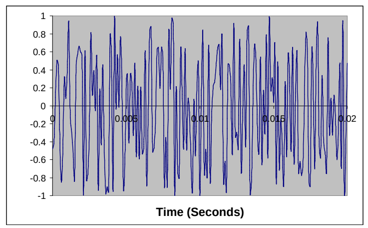
Waveforms are of two major types: periodic and aperiodic

- Aperiodic waveforms
  - do not repeat …
  - and also come in two types (but the distinction is not so important as for periodic waves)

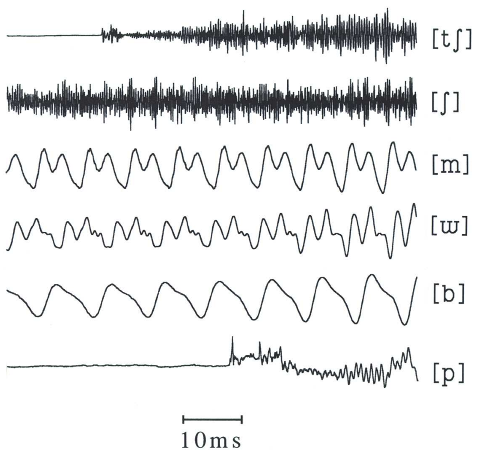
transient



continuous (can be random)

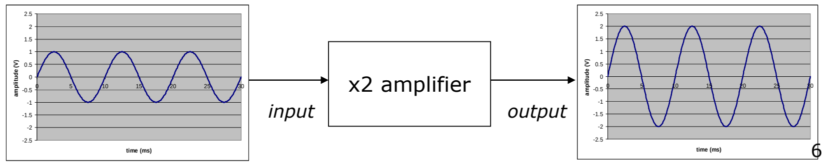


A variety of waveforms



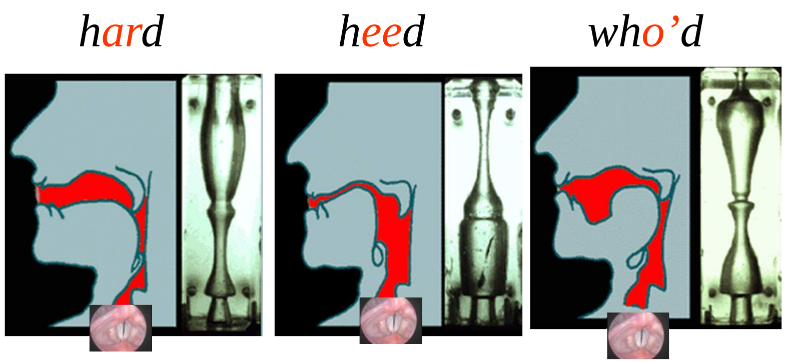
What is a system?

- Something which performs an operation on, or transformation of, a signal
- Concentrate on systems with one input and one output
- Many useful examples in hearing and speech science



System = vocal tract

input = sound from vibrating vocal folds
output = sound emanating from the mouth



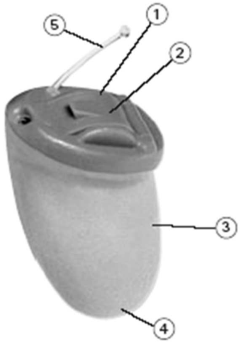
Different vocal tract shapes make different vowel sounds from the same input sound

A microphone
(a special name for this kind of system?)

In-The-Ear Hearing Aid

input = sound wave
(variations in pressure)

output = sound wave
(modified in some way)

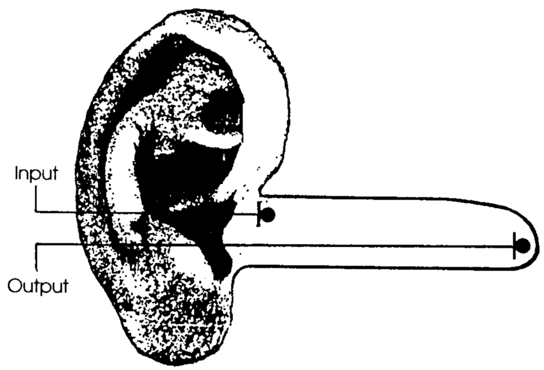


① Microphone
② Battery compartment and programming socket
③ Custom made shell
④ Receiver
⑤ Removal thread

Compare sounds as received by a microphone at a position corresponding to the centre of the listener's head, to that at the entrance to ear canal

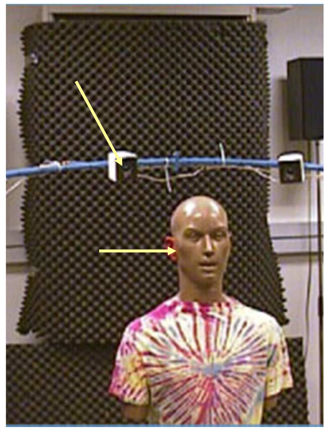
System =
head + pinna

Compare sounds at entrance to and at bottom of ear canal



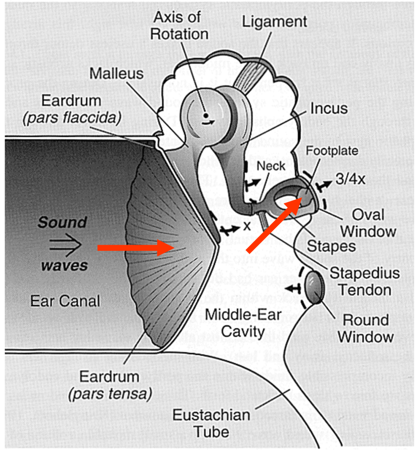
System = body + head + pinna + ear canal

input = sound from a particular place in space



output = sound at the eardrum

System = middle ear



Compare movement of ear drum to the movement of the stapes

The problem

- We want to be able to predict what a system will do to a wide variety of signals, without having to try each one.
  - For example, speech from different people through a hearing aid
- No solution for *all* possible systems.
- It *is* possible for a group of very special systems, known as *linear time-invariant (LTI) systems.*
- Amazing fact: For an LTI system, you only need to know what the system does to sine waves in order to predict the effect it will have on *any* signal.
- Linearity = homogeneity + additivity

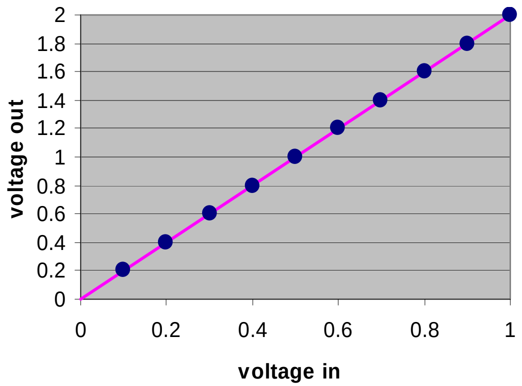
Linearity in a system: Homogeneity

- Homogeneity
  - for a particular pair of input and output signals, any change in the size of the input signal is matched by the same change in the size of the output
  - If $inp(t) \rightarrow outp(t)$
  - Then $k \cdot inp(t) \rightarrow k \cdot outp(t)$
- In other words …
  - Doubling the size of the input signal doubles the size of the output signal
  - Halving the size of the input signal halves the size of the output signal
- Nothing is implied about the relationship between the input and output waveforms!

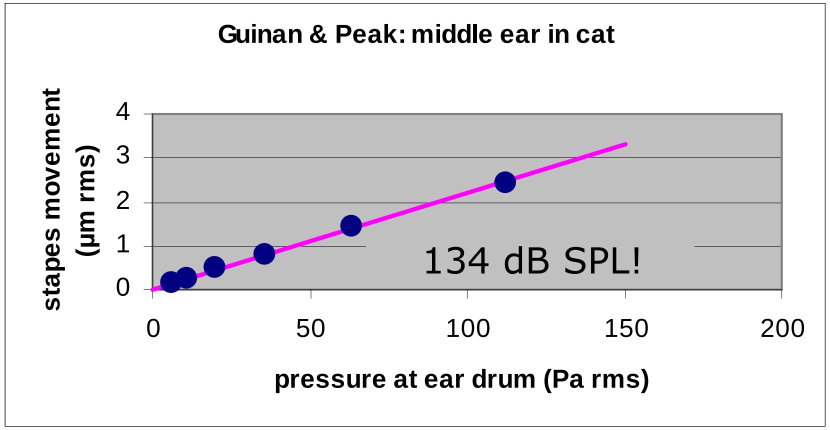
A typical test of homogeneity

- Present a sinewave of a particular frequency to a system (but it can be *any* fixed sound)
- Measure the level of the output signal as you vary the level of the input signal
- Plot the level of the output signal on the y-axis and the level of the input signal on the x-axis
  - *input/output function*
- If the input/output function is a straight line going through the origin (0,0), that behaviour is consistent with homogeneity
- Any other kind of curve means the system is *not* homogeneous and hence, cannot be linear.
- Would our perfect x2 amplifier be homogeneous?

An input/output function for a x2 amplifier

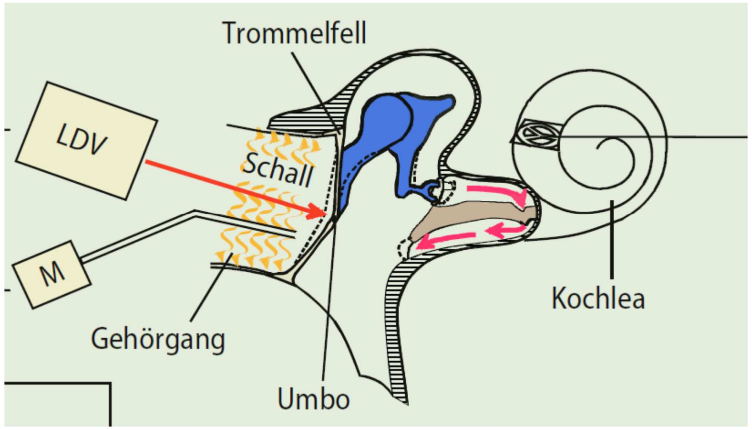


Homogeneity in the cat middle ear



Would homogeneity hold at high levels?

Laser Doppler Velocimetry of the human eardrum



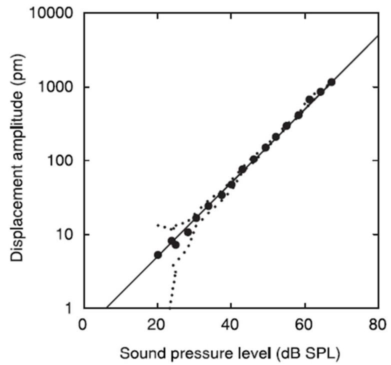
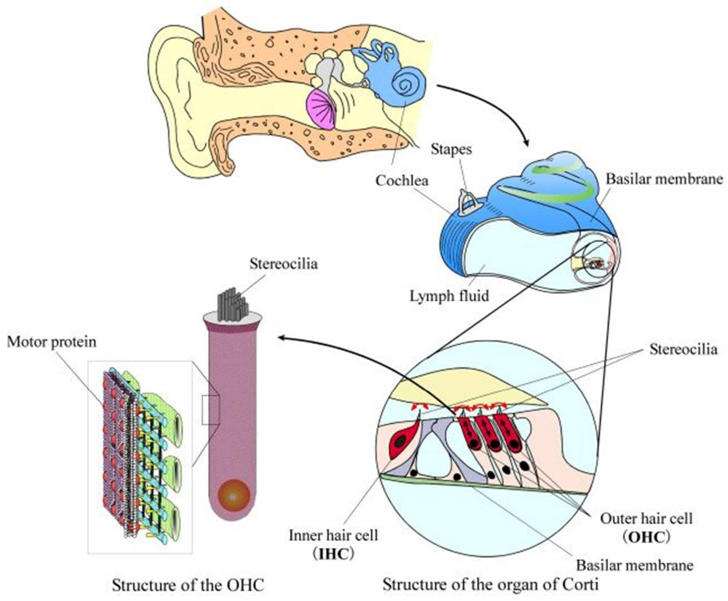
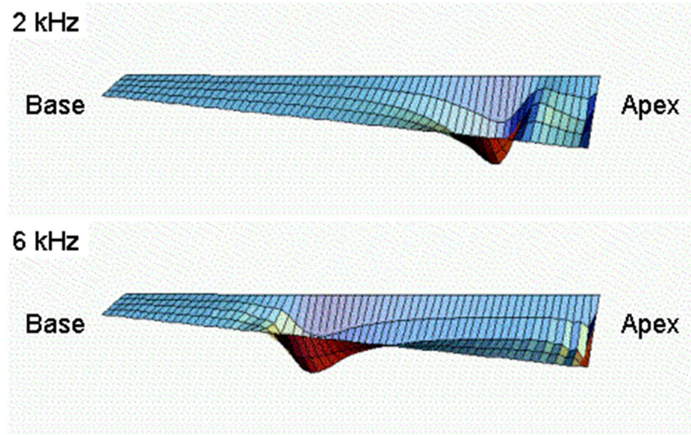


Fig. 1. Dependence of umbo displacement amplitude on SPL for single-tone stimulation (3.5 kHz) measured for an open sound field. The linear regression line of unity slope (1 dB/dB) indicates that the measured umbo response is linear. The dotted lines delineate the maximum noise level in the 100-Hz sidebands adjacent to the stimulus frequency. A reflector was not placed on the umbo. (Subject identifier: JT.)

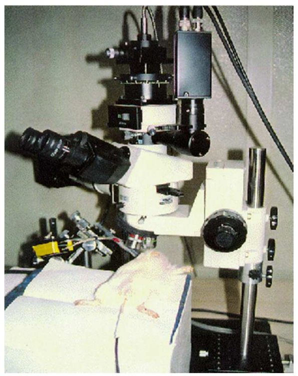
Dalhoff et al. (2007) *PNAS* 104, 1546-1551

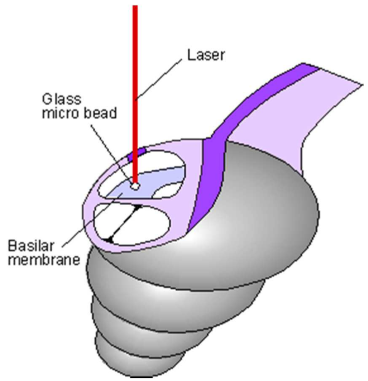


Basilar membrane motion to two sinusoids of different frequency



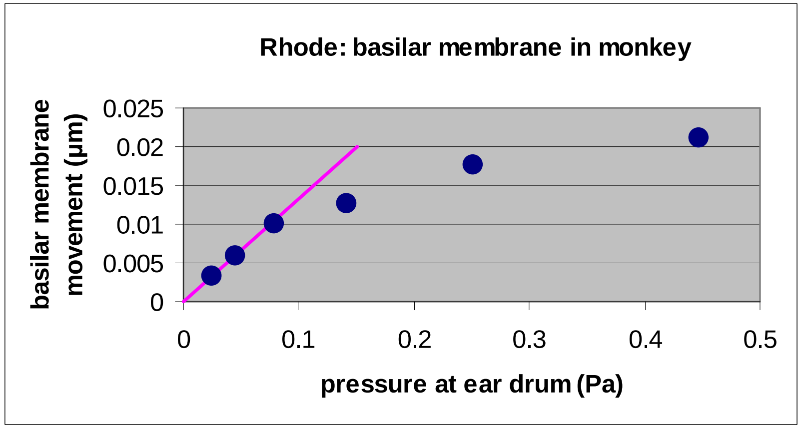
Laser Doppler Velocimetry on the basilar membrane





http://www.wadalab.mech.tohoku.ac.jp/bmldv-e.html

Homogeneity in the monkey inner ear?



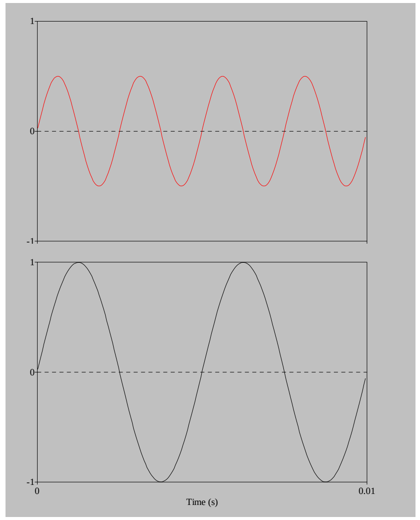
Linearity Part II: Additivity

But first, what does it mean to add two waves?

Adding Waveforms

400 Hz
½ V

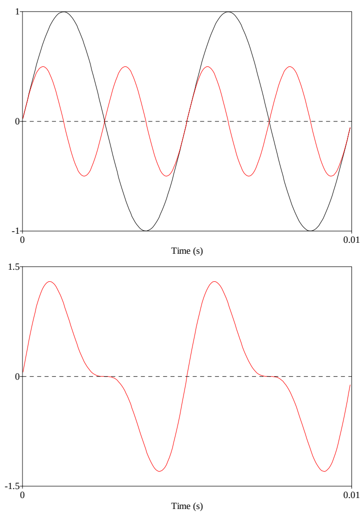
200 Hz
1 V



Adding Waveforms

sinusoids

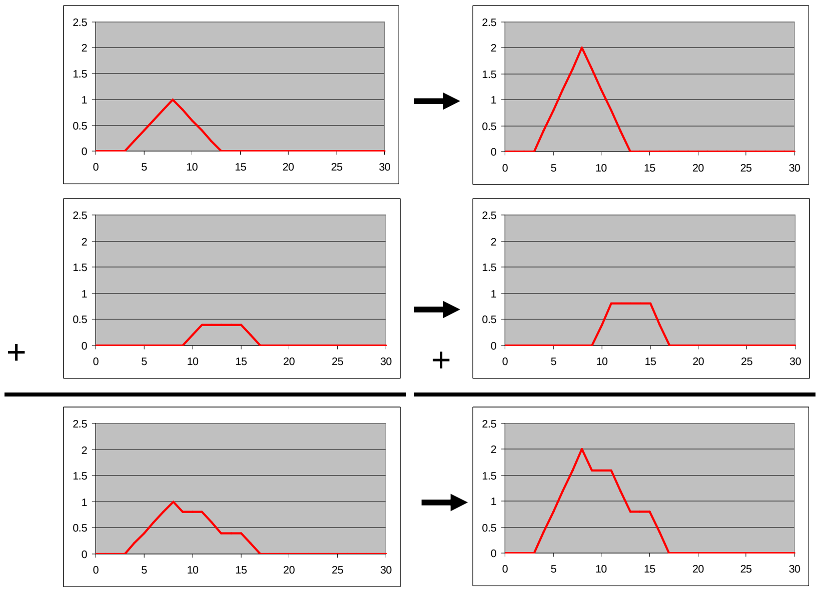
complex waveform



Linearity in a system: Additivity

- Additivity (principle of superposition)
- The output of a system to two input signals added together, is the same as the separate output signals for each of the inputs on their own, added together.
- In other words, signals don't interact.
- In simple equations:
  - If $inp_1(t) \rightarrow outp_1(t)$ & $inp_2(t) \rightarrow outp_2(t)$
  - Then $inp_1(t) + inp_2(t) \rightarrow outp_1(t) + outp_2(t)$

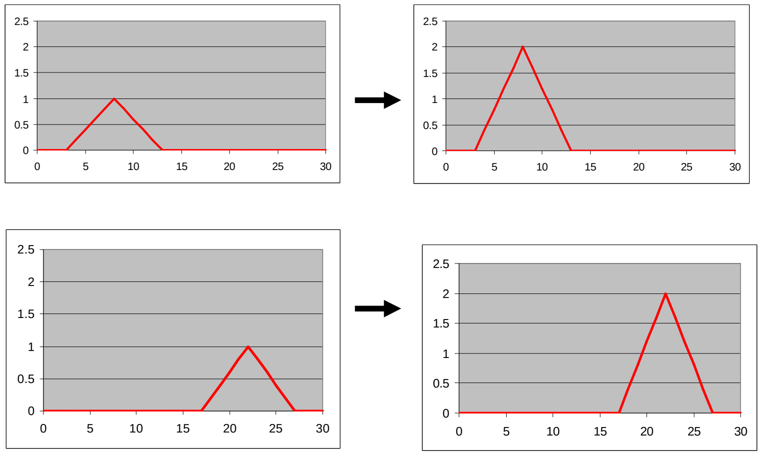
Additivity: A simple example



Requirement 3: Time-invariance

- For a particular pair of input and output signals, delaying the input signal by a particular amount also delays the output signal by the same amount.
- The system's behavior does not change in time

Time invariance: A simple example



Next week: We show how an LTI system can be completely characterised by its response to sinusoids

Today's laboratory: Measure thresholds with a simple audiometer'

A little more about dB

dB SPL examples: a reminder

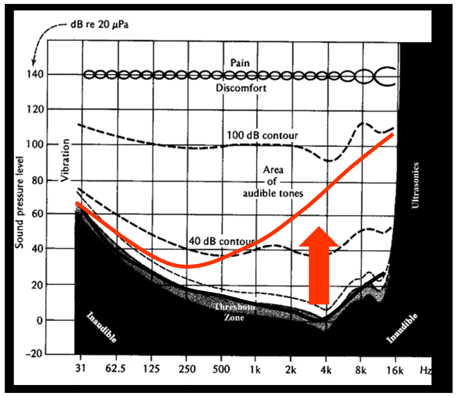
- Threshold of Hearing (20 μPa)
  $20 \times \log_{10}(20\ \mu Pa/20\ \mu Pa)$
  $= 20 \times \log_{10}(1) = 20 \times 0$
  $= 0$ dB SPL
- Threshold of Pain (200 Pa)
  $20 \times \log_{10}(200\ Pa/20\ \mu Pa)$
  $= 20 \times \log_{10}(10000000) = 20 \times 7$
  $= 140$ dB SPL
- An inaudible sound (2 μPa)
  $20 \times \log_{10}(2\ \mu Pa/20\ \mu Pa)$
  $= 20 \times \log_{10}(0.1) = 20 \times -1$
  $= -20$ dB SPL

dB SPL: working backwards db SPL $\rightarrow$ Pa

- If threshold of hearing for a 125 Hz sinusoid is 30 dB SPL, how many Pa is this?
  - 30 dB SPL $= 20 \times \log_{10}(\theta\ \mu Pa/20\ \mu Pa)$
  - $30/20 = \log_{10}(\theta\ \mu Pa/20\ \mu Pa)$
  - Note: $10^{\log 10\ (\theta)} = \theta$
    - *e.g.,* $10^{\log 10\ (100)} = 10^{\log 10\ (10^2)} = 10^2 = 100$
  - $10^{30/20} = (\theta\ \mu Pa/20\ \mu Pa)$
  - $20 \times 10^{30/20} = \theta$
  - $20 \times 10^{30/20} = 20 \times 10^{1.5} = 20 \times 31.62 = 632.5\ \mu Pa$

- More generally
  - λ dB SPL $= 20 \times \log_{10}(\theta\ \mu Pa/20\ \mu Pa)$
  - $\lambda/20 = \log_{10}(\theta\ \mu Pa/20\ \mu Pa)$
  - $10^{\lambda/20} = (\theta\ \mu Pa/20\ \mu Pa)$
  - $20 \times 10^{\lambda/20} = \theta\ \mu Pa$

Measuring hearing loss



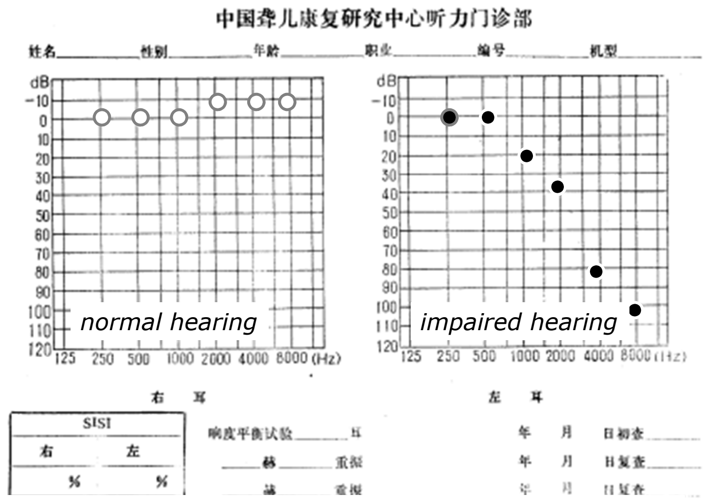
Poorer hearing leads to higher thresholds

- Someone with a hearing loss would have higher thresholds
- Here, for example, the loss is small at low frequencies and great at high (a typical pattern)
- We're interested in **differences** to normal thresholds

Displaying a threshold curve in a clinically relevant way — the *audiogram*

- For clinical purposes, it's easier to judge *deviations* from normality.
- Use dB Hearing Level (HL) instead of dB SPL
- To calculate a person's Hearing Level ...
  - Find the absolute threshold in dB SPL ….
  - Subtract the normal value of the absolute threshold (again in dB SPL) ...
  - And plot increasing positive values downward (higher thresholds = more hearing loss = points further down the page).

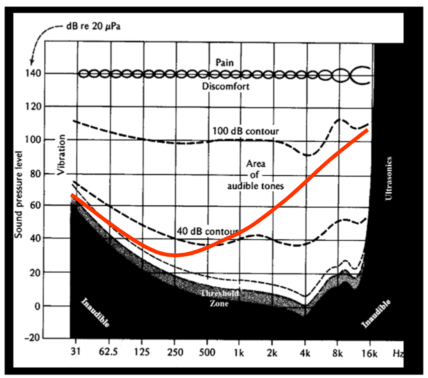
Example audiograms

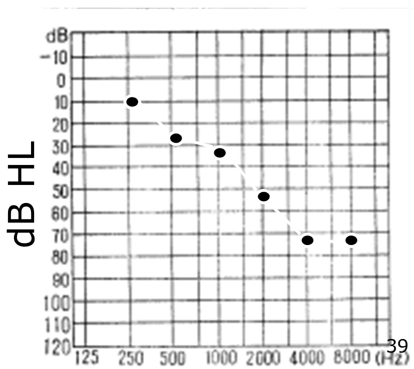


From the China Rehabilitation Research Center for Deaf Children, Beijing.

Constructing an audiogram (converting dB SPL to dB HL)

	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz
patient SPL	30	38	42	60	73	92
'normal' SPL	20	10	8	4	0	20
patient HL	10	28	34	56	73	72





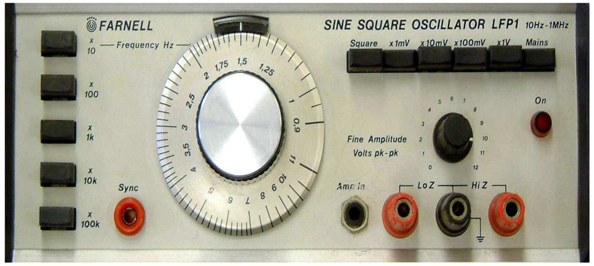
dB SPL vs. dB HL for sinusoids

- dB SPL = 20 x $\log_{10}(p/20\ \mu\text{Pa})$
  - the same reference level for every frequency
- dB HL = 20 x $\log_{10}(p/\theta\ \mu\text{Pa})$
  - where θ μPa is the normal absolute threshold *for that particular frequency*
  - so reference level typically is different for every frequency

An example of dB HL

- Normal threshold of hearing at 125 Hz = 632.5 μPa)
- Suppose someone's threshold is 356 μPa, then
  - $20 \times \log_{10}$(356 μPa/632.5 μPa) = -5 dB HL
  - So dB HL just has a different reference level than dB SPL
- But also note
  - $20 \times \log_{10}$(356 μPa /20 μPa) = 25 dB SPL
  - $20 \times \log_{10}$(632.5 μPa /20 μPa) = 30 dB SPL
- So, you can also obtain dB HL by subtracting the normal threshold from the obtained one:
  - 25 dB SPL - 30 dB SPL = -5 dB HL

Today's laboratory: Measure thresholds with a simple audiometer'



Measuring thresholds I

- Set oscillator to desired frequency and attenuator to 0 (maximum level)
- Present a tone for about 1 s by pressing the button
- The 'patient' indicates having heard the tone by raising a finger

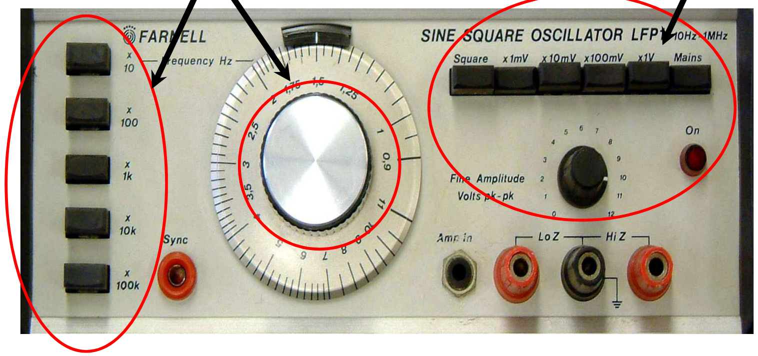
Measuring thresholds II

- If heard, decrease level by 10 dB (2 clicks clockwise)
- If not heard, increase level by 5 dB (1 click counter-clockwise)
- Present tone
- Repeat steps above to find lowest level at which the 'patient' hears the tone on 2 of 2, 3 or 4 tries on the ascent (at least 50%)
- Do all the frequencies specified

Observe!

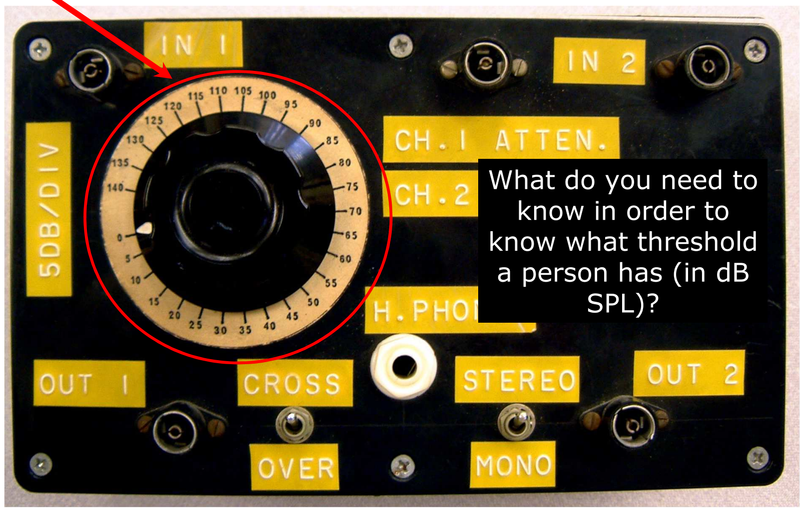
Adjust frequency with these buttons and dial

Do not touch these buttons



Observe!

Adjust level with this dial



What do you need to know in order to know what threshold a person has (in dB SPL)?

Things you need to know

- Keep the data from any lab you do. You will need some of it to do your exercise sets.
- Today: 6 set-ups available in sound-proof rooms (work in pairs)
- Once you have your thresholds as attenuation values, come back to the lab (do not do your calculations in the cubicles). Ensure you write down the calibrated values from the particular set of equipment you used.
- Finish ‘Explore signals’ (lab sheet from last week) while you are not doing the lab.