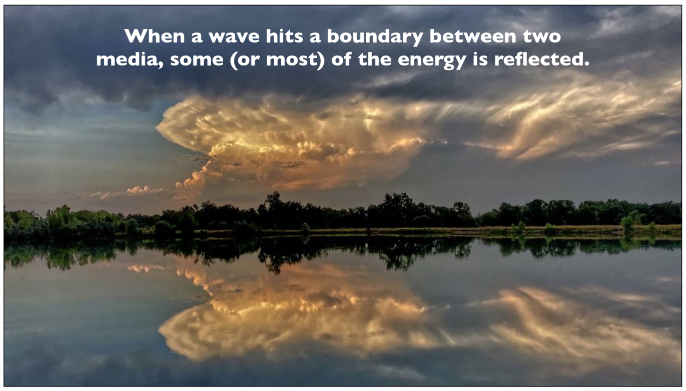
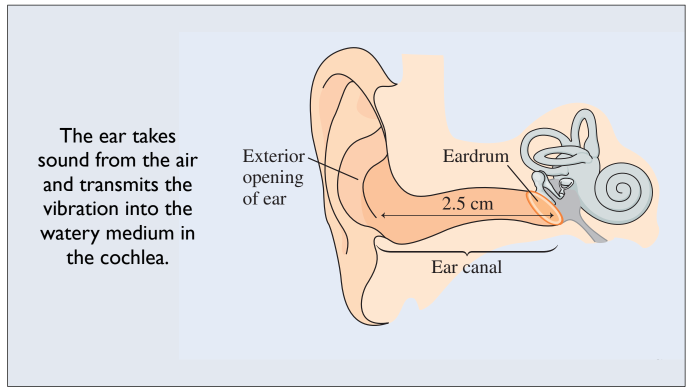
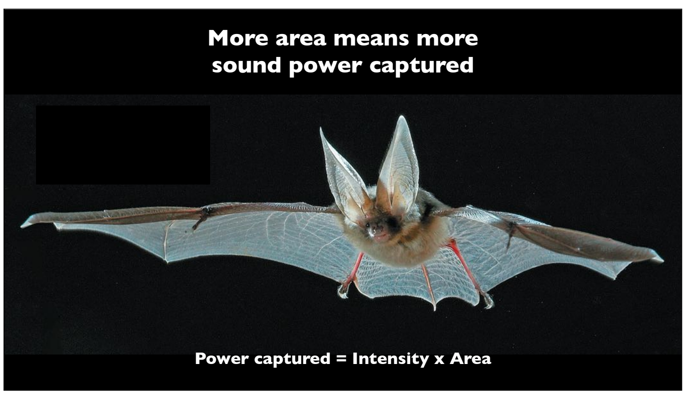

This Week: Sensing Sound
Your ability to produce and make sense of sounds are truly remarkable. The difference between a "t" sound and a "d" sound is a few hundredths of a second difference in the timing of one part of the sound, but you can easily distinguish the two. We sense sound with our ears, which are on the sides of our heads. But other animals sense sound quite differently: animals that live in water don't need external ears, owls have ears on the front of their faces, and spiders sense sounds with their legs. We'll explore the remarkable ways that animals—including humans—sense sounds and use them to analyze the world around them.


A warmup:
Why, and where, do we have ears?

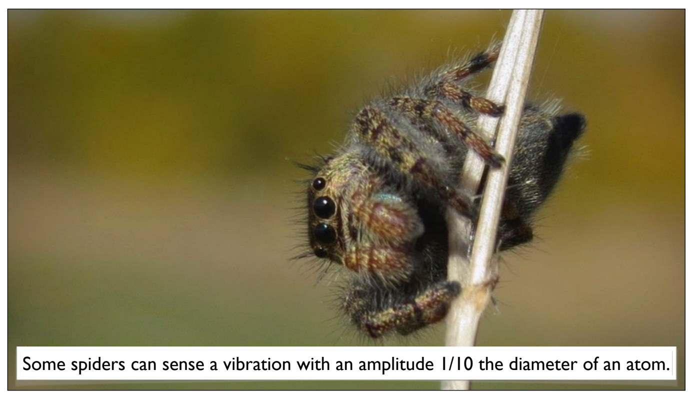

When a wave hits a boundary between two media, some (or most) of the energy is reflected.

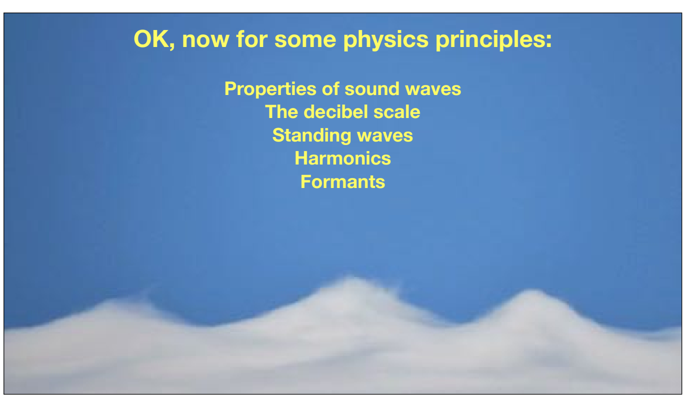

The ear takes sound from the air and transmits the vibration into the watery medium in the cochlea.
Exterior opening of ear
Eardrum
2.5 cm
Ear canal


More area means more sound power captured
Power captured = Intensity x Area


A difference in arrival time lets you determine location.


Where are the ears?





Frequency: Cycles, or oscillations, per second

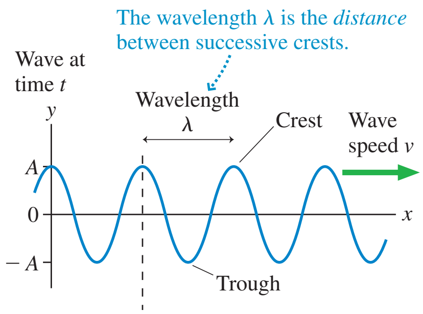
200 Hz

400 Hz

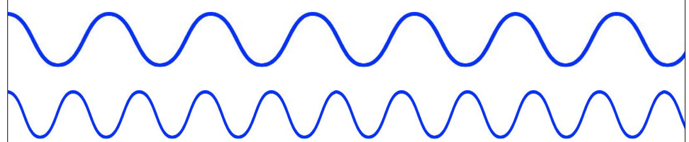
800 Hz

Pitch is to frequency as color is to wavelength

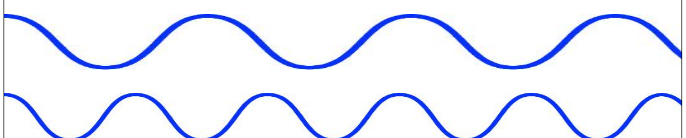
Symbol for frequency: f



Longer wavelengths have lower frequencies.



Increasing speed increases wavelength.



Here's an equation to bring this all together:

$$\lambda = \frac{v}{f}$$

You can locate the source of a sound with an uncertainty that is proportional to the wavelength:
Smaller wavelength means less uncertainty.

Discussion Question
Would you expect owls to have their most sensitive hearing at high frequencies or low frequencies?

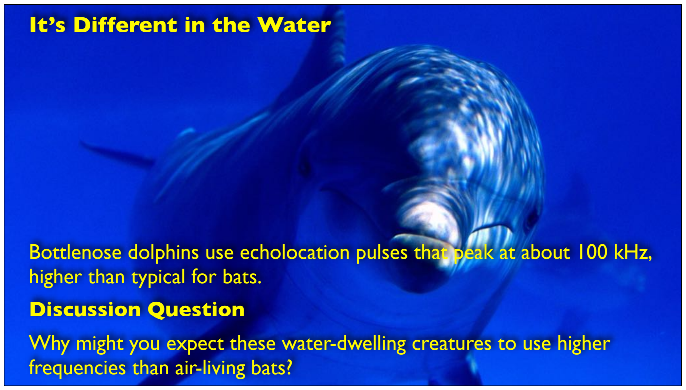
You can locate the source of a sound with an uncertainty that is proportional to the wavelength:
Smaller wavelength means less uncertainty.

Barn owls are especially sensitive to frequencies around about 5 kHz—quite a high frequency. This corresponds to a wavelength of 6.8 cm, about 2.5 inches.

Discussion Question
Would you expect bats, which catch smaller prey, to rely on higher or lower frequencies than owls?

A little brown bat (*Myotis lucifugus*) emits echolocation pulses with a frequency of about 45 kHz, well above the range of human hearing. This corresponds to a wavelength of 0.75 cm, about ⅓ inch.

It's Different in the Water



Bottlenose dolphins use echolocation pulses that peak at about 100 kHz, higher than typical for bats.

Discussion Question

Why might you expect these water-dwelling creatures to use higher frequencies than air-living bats?

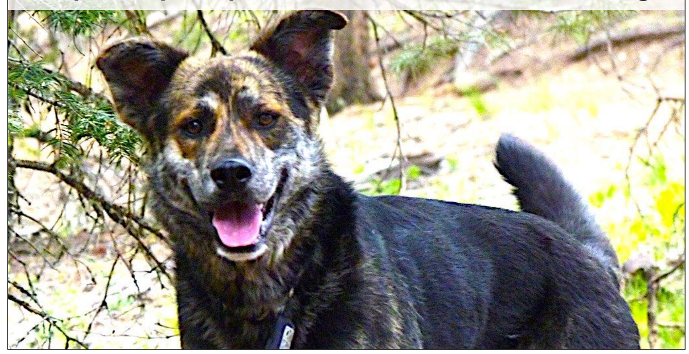
Sound intensity levels

Sound	β (dB)	I (W/m^2)
Threshold of hearing	0	1.0×10^{-12}
Person breathing, at 3 m	10	1.0×10^{-11}
A whisper, at 1 m	20	1.0×10^{-10}
Classroom during test, no talking	30	1.0×10^{-9}
Residential street, no traffic	40	1.0×10^{-8}
Quiet restaurant	50	1.0×10^{-7}
Normal conversation, at 1 m	60	1.0×10^{-6}
Busy traffic	70	1.0×10^{-5}
Vacuum cleaner, for user	80	1.0×10^{-4}
Niagara Falls, at viewpoint	90	1.0×10^{-3}
Pneumatic hammer, at 2 m	100	0.010
Home stereo at max volume	110	0.10
Rock concert	120	1.0
Threshold of pain	130	10

Some animals can do better.

Dogs may have a threshold of hearing of 1.0×10^{-13} W/m^2, corresponding to -10 dB.

Why would you expect Milo to have more sensitive hearing?



Your ears are super sensitive.

This candle gives off about 20 milliwatts of light

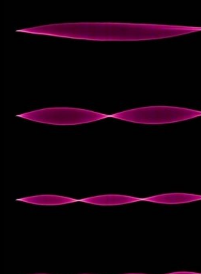
Your ears are super sensitive.

My phone, when it's on speaker mode, puts out about 20 microwatts, 1/1000 of the light power from this candle.

120 dB at 1 m
(10x the power of a person shrieking at the top of their lungs)

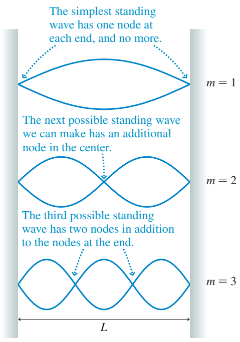
It's a good thing we can't hear them.

Standing waves with slinkies



Standing Waves on Strings

Only certain conditions work.



The frequencies have a specific relationship.

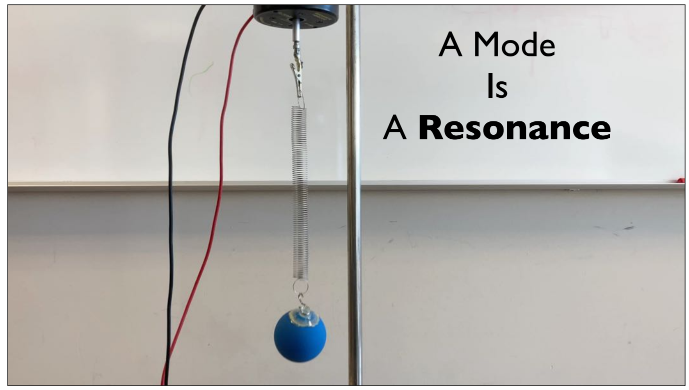
Suppose f_1 = 100 Hz.

Then:

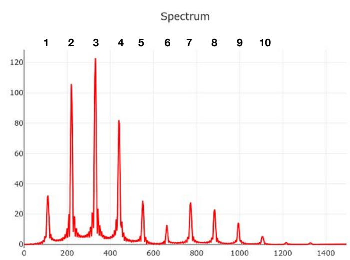
f_1 = 100 Hz
f_2 = 200 Hz
f_3= 300 Hz

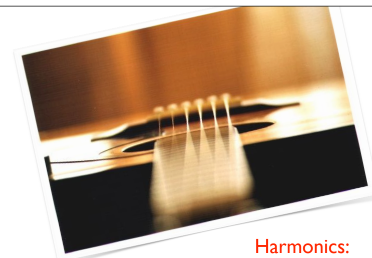
And so on.

A Mode Is A **Resonance**



When you pluck a guitar string—or any musical instrument string—you get all of the modes, all of the frequencies.





Fundamental:
It's a low A.

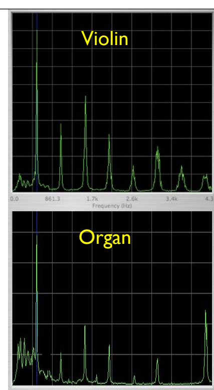
110 Hz

Harmonics:
It's a guitar.

220 Hz
330 Hz
440 Hz
⋮

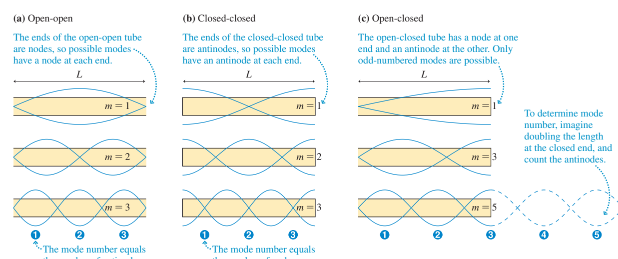
Fundamental and Harmonics

Same Note, Different Sounds



Standing Sound Waves

Only certain conditions work…. Similar math to waves on strings.

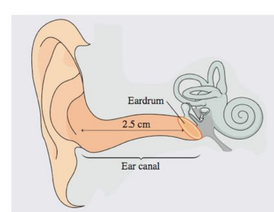


Palm Pipes

A very simple musical instrument

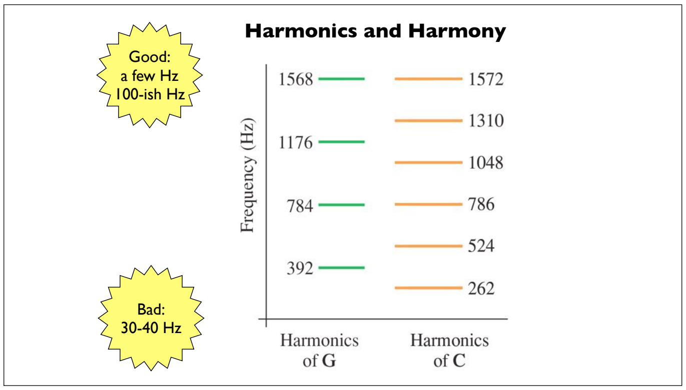
Increased sensitivity of the ear

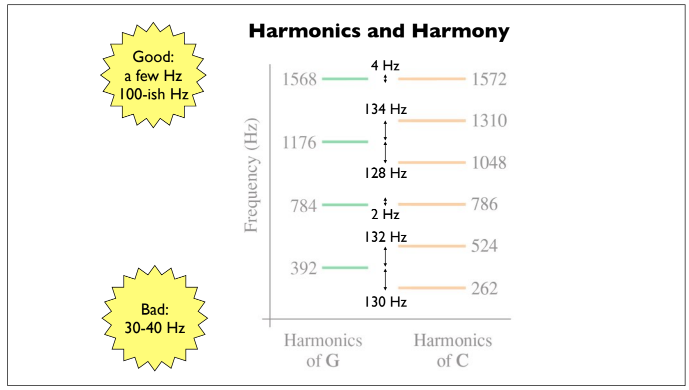
Your ear canal is an open-closed tube. It has certain resonances that increase the amplitude at certain frequencies—including, for most folks, about 3,400 Hz.

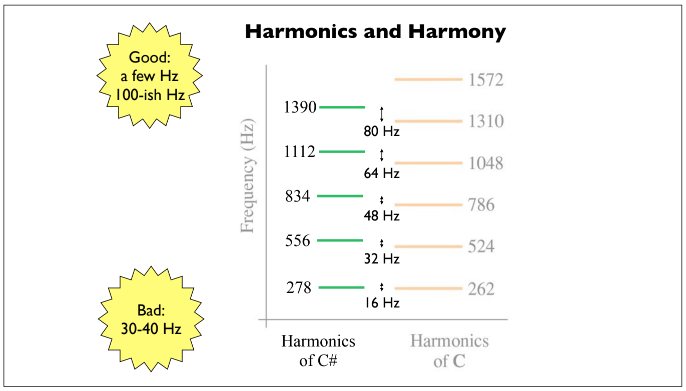


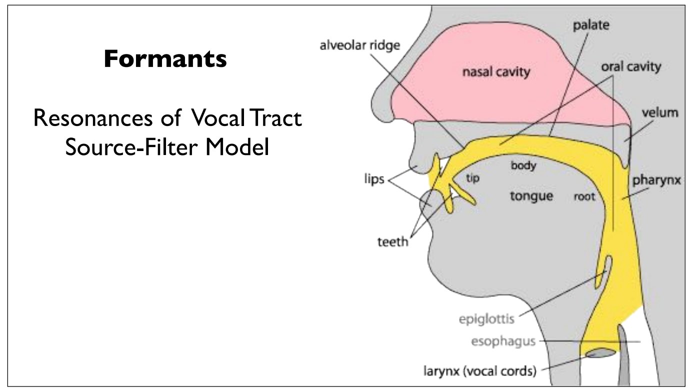
Tones:
2000 Hz
3400 Hz
5000 Hz

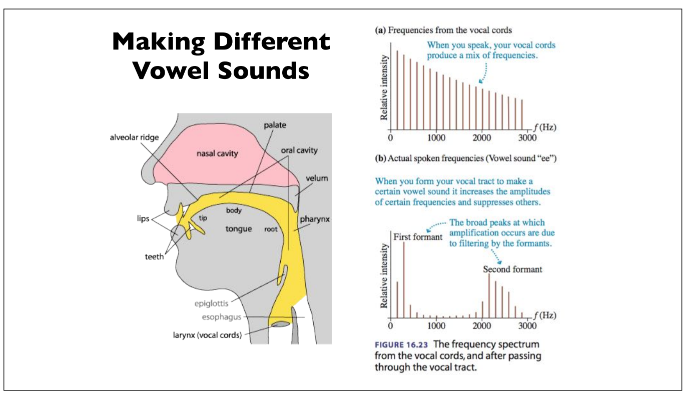
$$f_1 = 3{,}400 \text{ Hz}$$

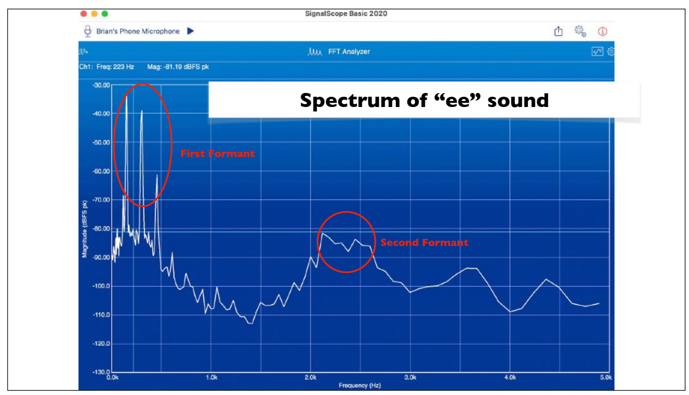

Harmonics and Harmony
Good:
a few Hz
100-ish Hz
Bad:
30-40 Hz
Frequency (Hz)
1568
1176
784
392
1572
1310
1048
786
524
262
Harmonics of G
Harmonics of C

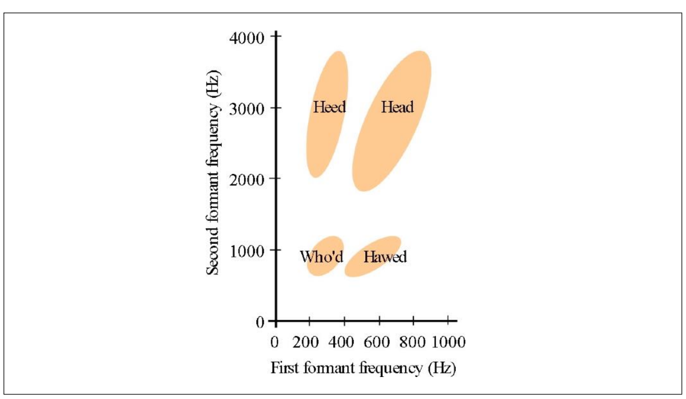

Harmonics and Harmony
Good:
a few Hz
100-ish Hz
Bad:
30-40 Hz
Frequency (Hz)
1568
1176
784
392
1572
1310
1048
786
524
262
4 Hz
134 Hz
128 Hz
2 Hz
132 Hz
130 Hz
Harmonics of G
Harmonics of C

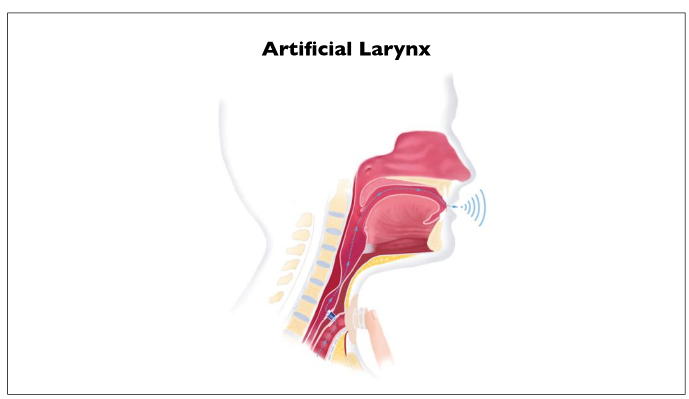

Harmonics and Harmony
Good:
a few Hz
100-ish Hz
Bad:
30-40 Hz
Frequency (Hz)
1390
1112
834
556
278
1572
1310
1048
786
524
262
80 Hz
64 Hz
48 Hz
32 Hz
16 Hz
Harmonics of C#
Harmonics of C


Formants
Resonances of Vocal Tract
Source-Filter Model
alveolar ridge
palate
nasal cavity
oral cavity
velum
lips
tip
body
tongue
root
pharynx
teeth
epiglottis
esophagus
larynx (vocal cords)


Making Different Vowel Sounds
alveolar ridge
palate
nasal cavity
oral cavity
velum
lips
tip
body
tongue
root
pharynx
teeth
epiglottis
esophagus
larynx (vocal cords)
(a) Frequencies from the vocal cords
When you speak, your vocal cords produce a mix of frequencies.
Relative intensity
0
1000
2000
3000
f (Hz)
(b) Actual spoken frequencies (Vowel sound "ee")
When you form your vocal tract to make a certain vowel sound it increases the amplitudes of certain frequencies and suppresses others.
First formant
The broad peaks at which amplification occurs are due to filtering by the formants.
Second formant
FIGURE 16.23 The frequency spectrum from the vocal cords, and after passing through the vocal tract.


SignalScope Basic 2020
FFT Analyzer
Spectrum of "ee" sound
First Formant
Second Formant
Frequency (Hz)


Second formant frequency (Hz)
4000
3000
2000
1000
0
Heed
Head
Who'd
Hawed
0
200
400
600
800
1000
First formant frequency (Hz)


Artificial Larynx

The Importance of Higher Harmonics

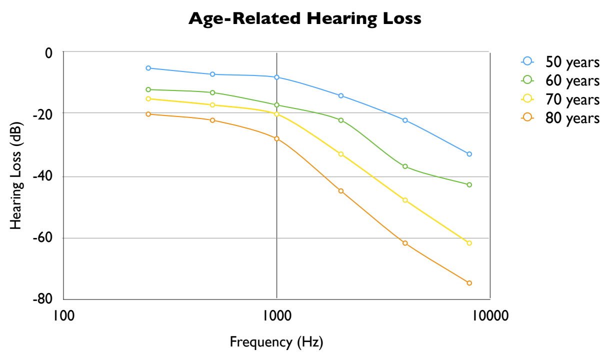
The higher harmonics determine the "tone quality" of a musical instrument, or the vowel sounds and plossives of speech.

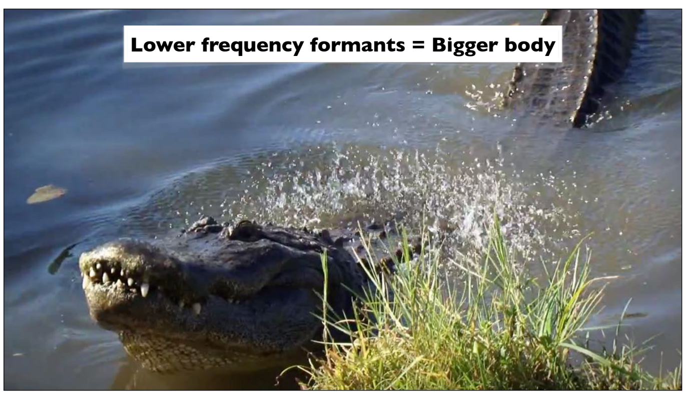
As people age, their hearing gets less sharp. The higher frequencies are the first to go. The loss makes speech hard to interpret.

The first sound has had all frequencies > 1000 Hz removed.

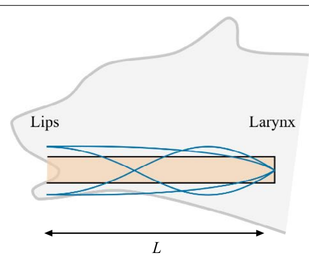
The second sound has all harmonics intact.

The final sound has frequencies < 1000 Hz removed.

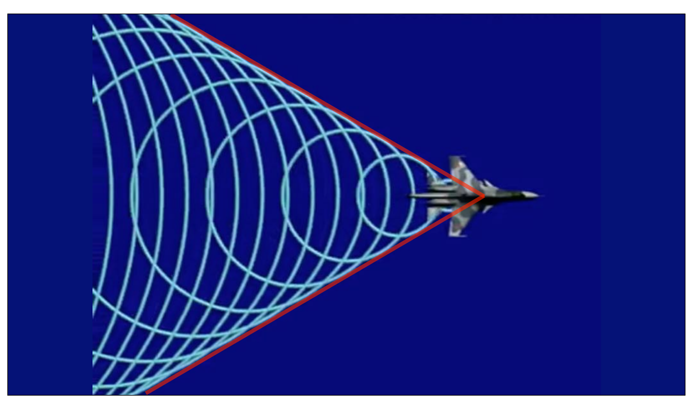




What are the frequencies of the first two formants?



Breed	Mass (kg)	L (m)
Westie	8	0.13
Doberman	38	0.24




Faster than the
speed of sound...