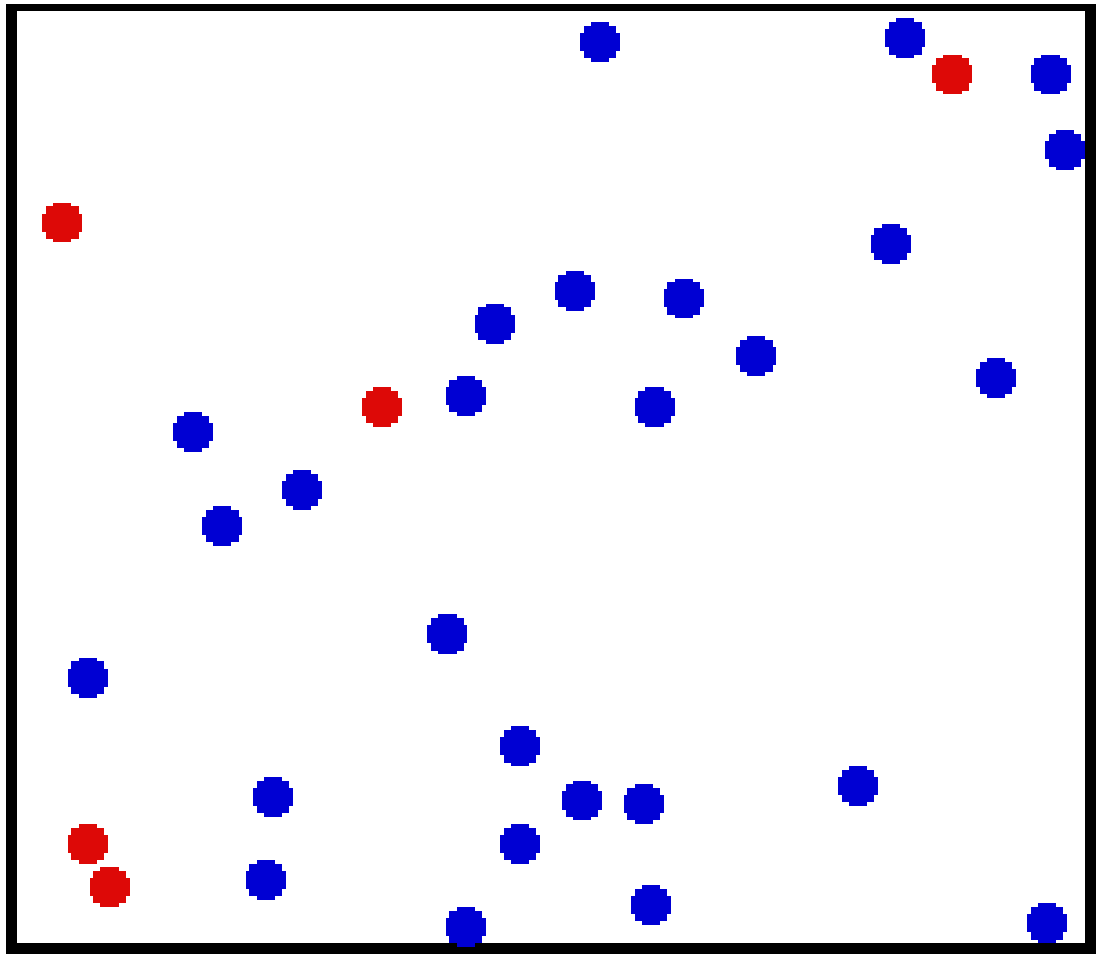
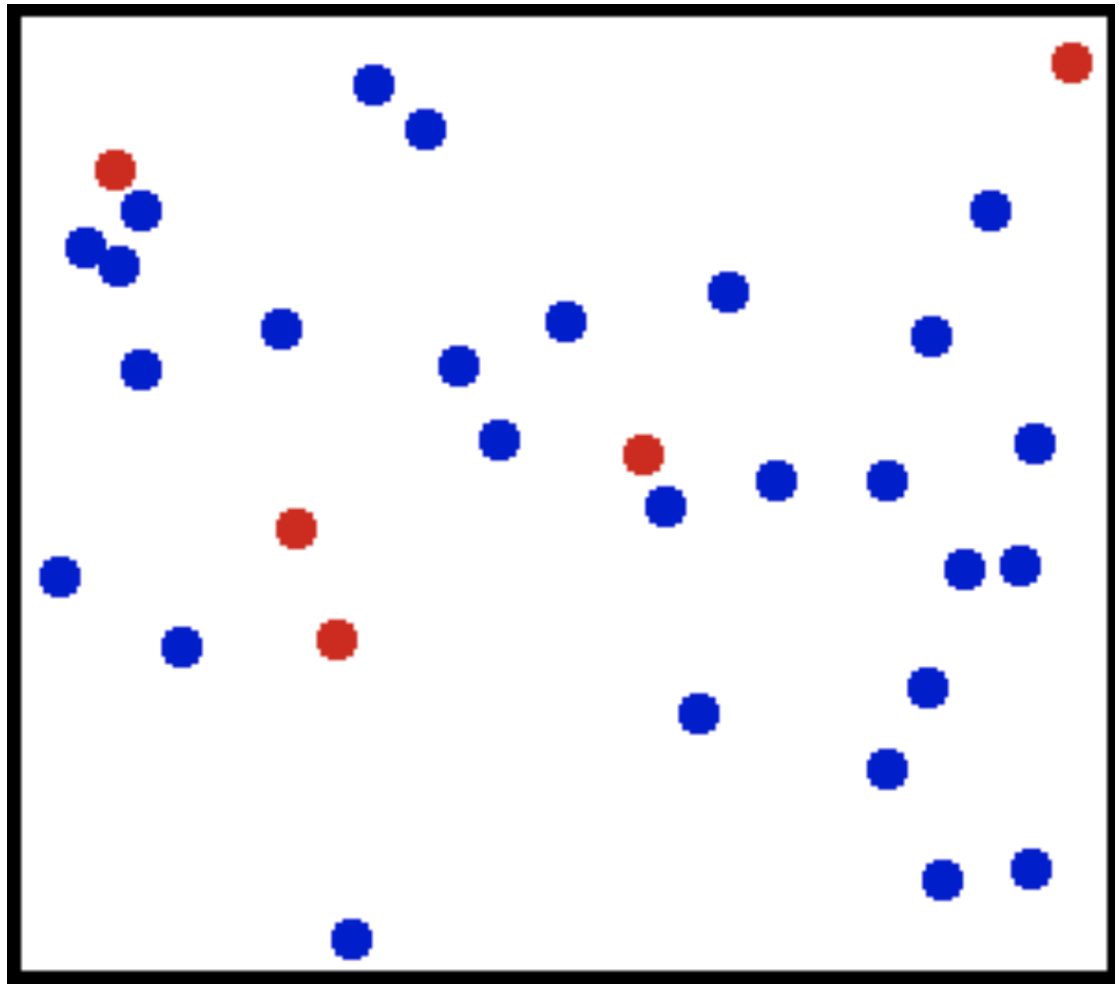
Science of Sound and Music

Robin Rehagen

Visualizing a Gas



Visualizing a Gas



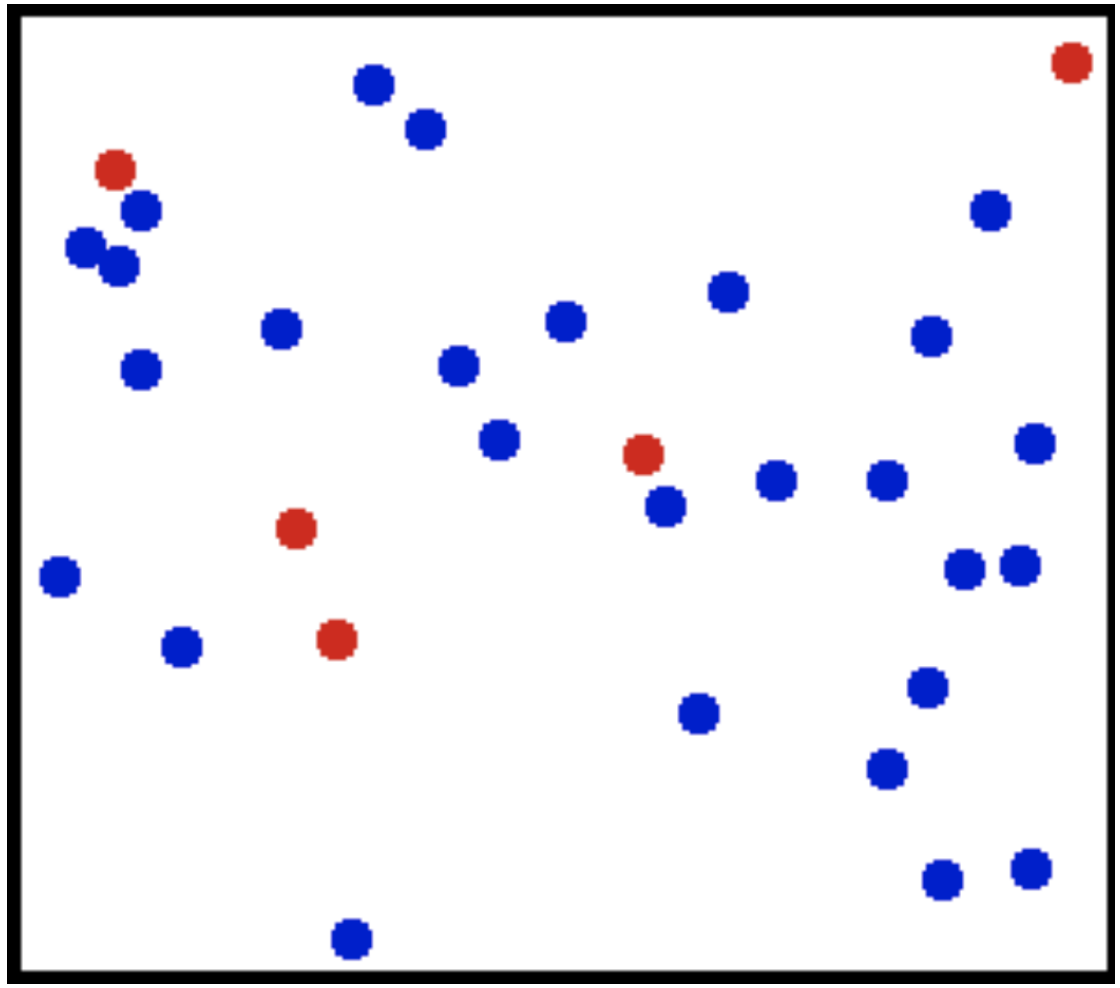
$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

Air Pressure =

average force exerted by the collisions of billions of air molecules

How can we change the air pressure?

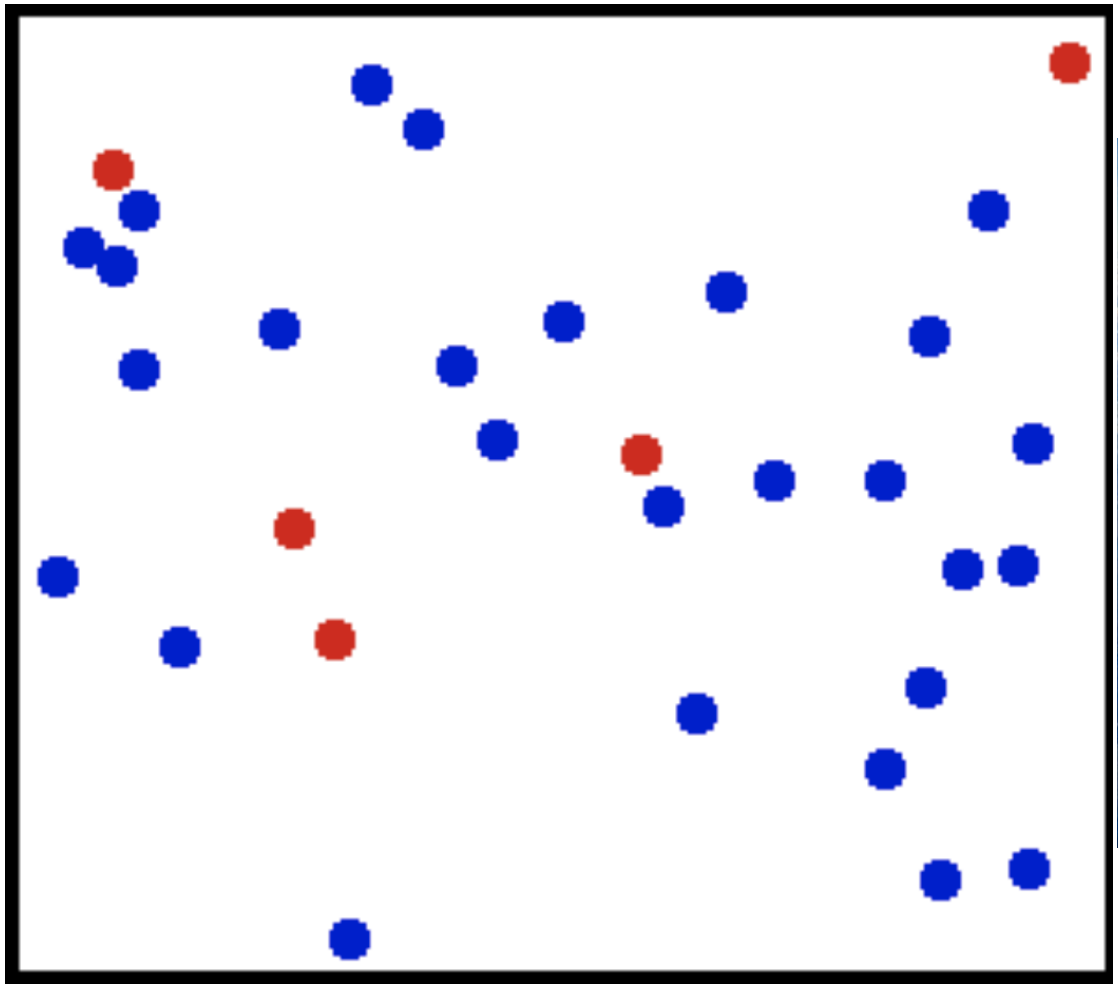
Visualizing a Gas

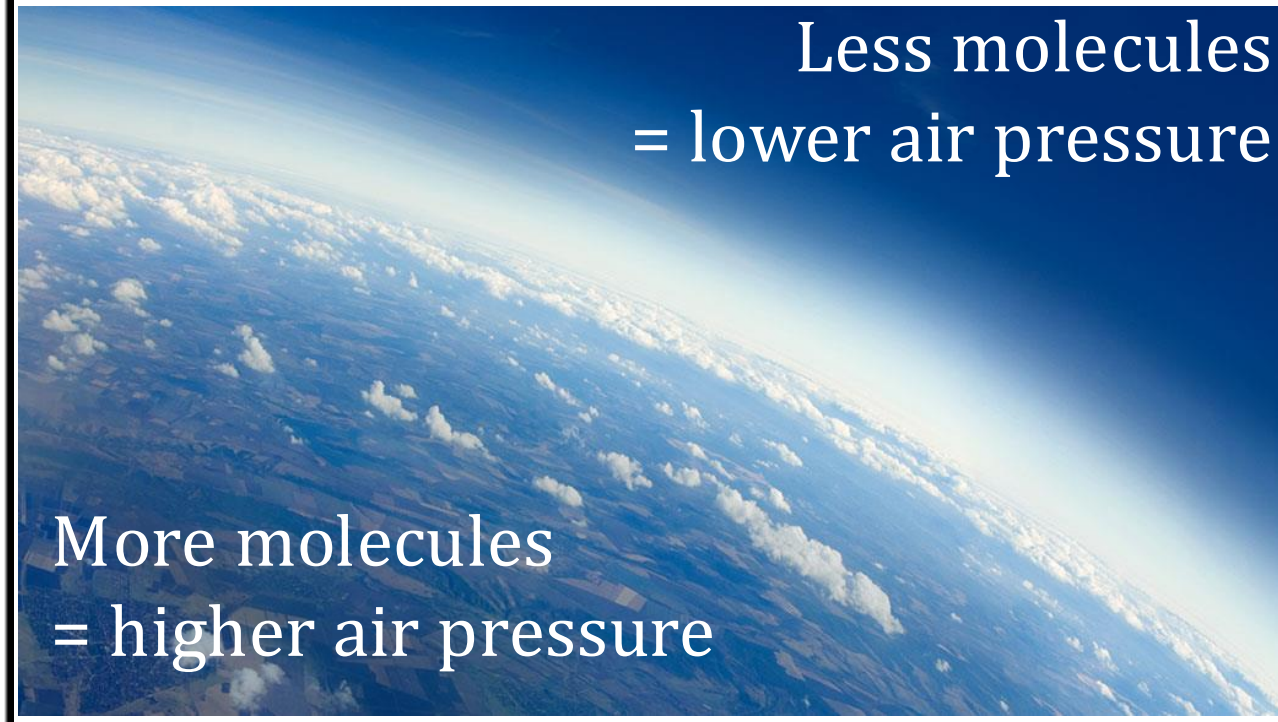


Pressure Cooker

Hotter air =
= Faster molecules
= more collision force
= higher pressure

Visualizing a Gas

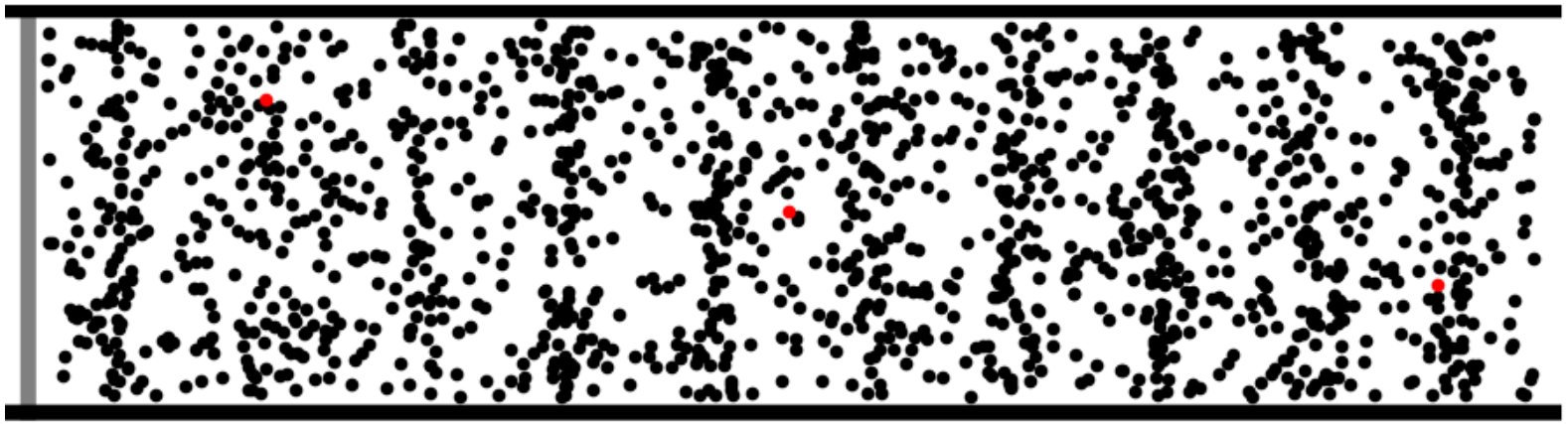




What is a Sound Wave?

A periodic compression of air molecules.

https://www.acs.psu.edu/drussell/Demos/waves/wavemotion.html



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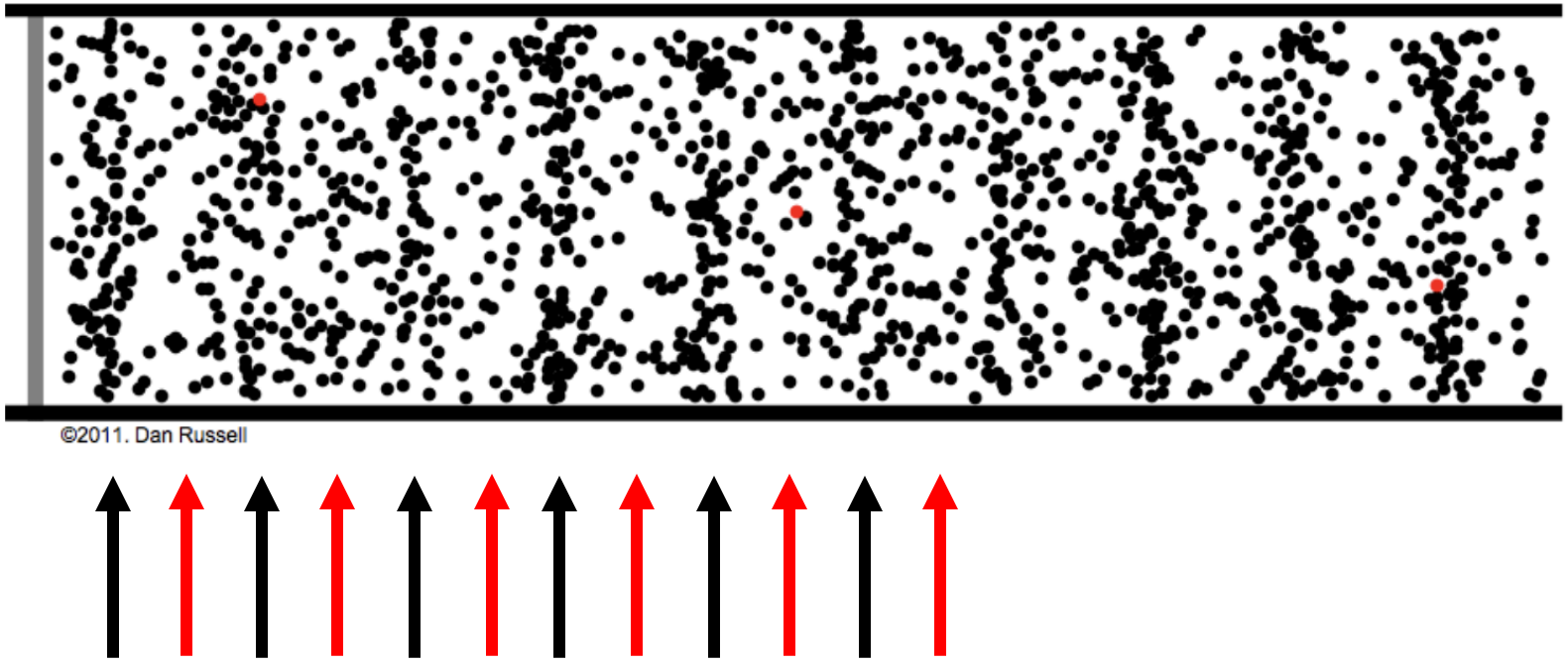

Compression

(more molecules, higher air pressure)

Rarefaction

(fewer molecules, less air pressure)

What is a Sound Wave?

A periodic compression of air molecules.

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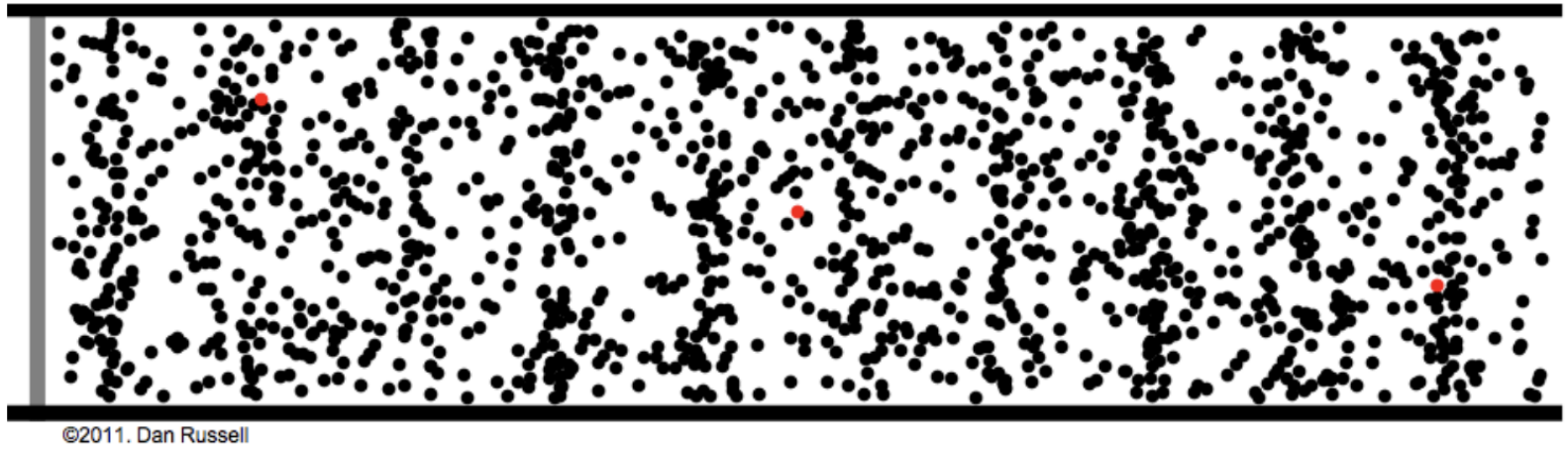
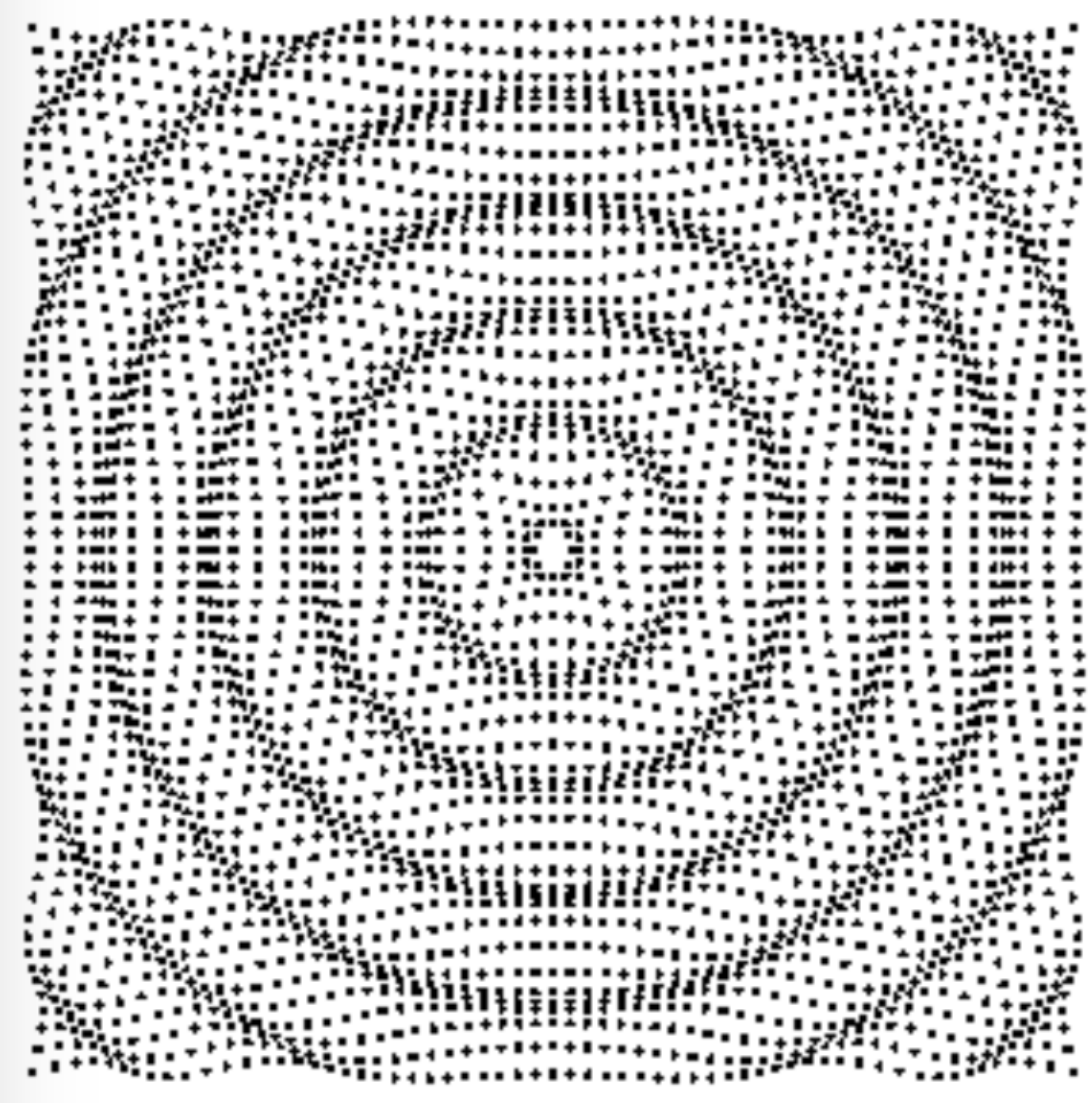


Sound waves in 2D and 3D

What if the air is not contained in a tube, but the sound wave can spread everywhere?



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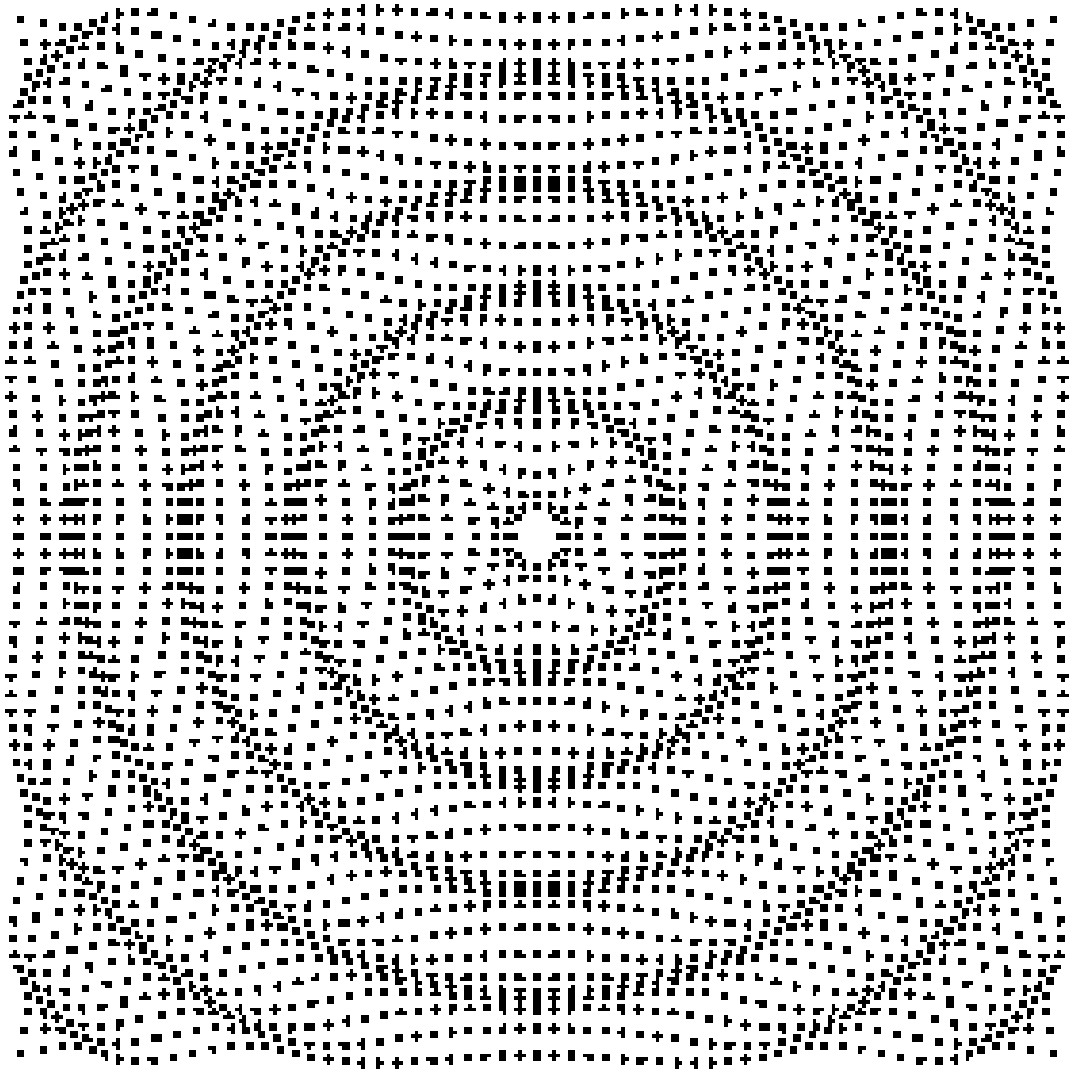

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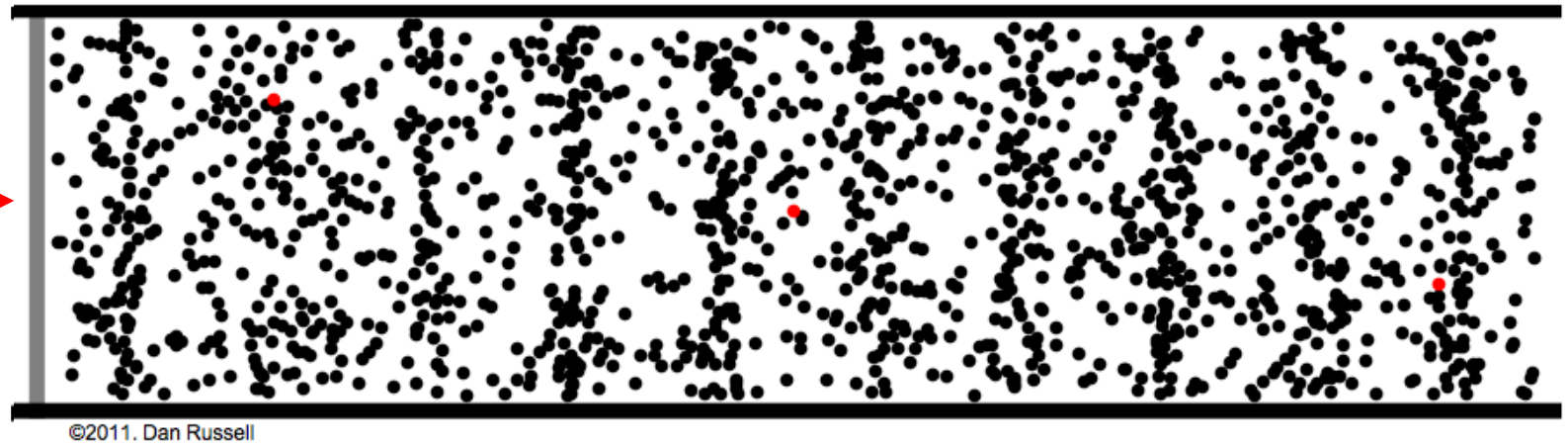
Sound Waves are created by Vibrations

Vibrating Object →



Animation: https://www.acs.psu.edu/drussell/Demos/waves/wavemotion.html

Sound Waves are created by Vibrations

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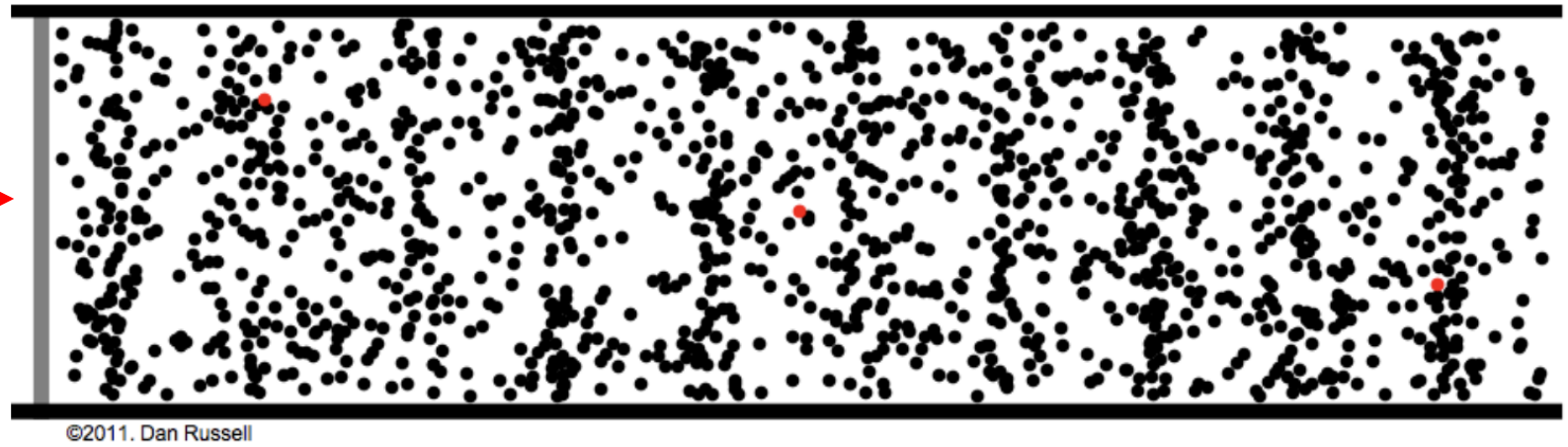

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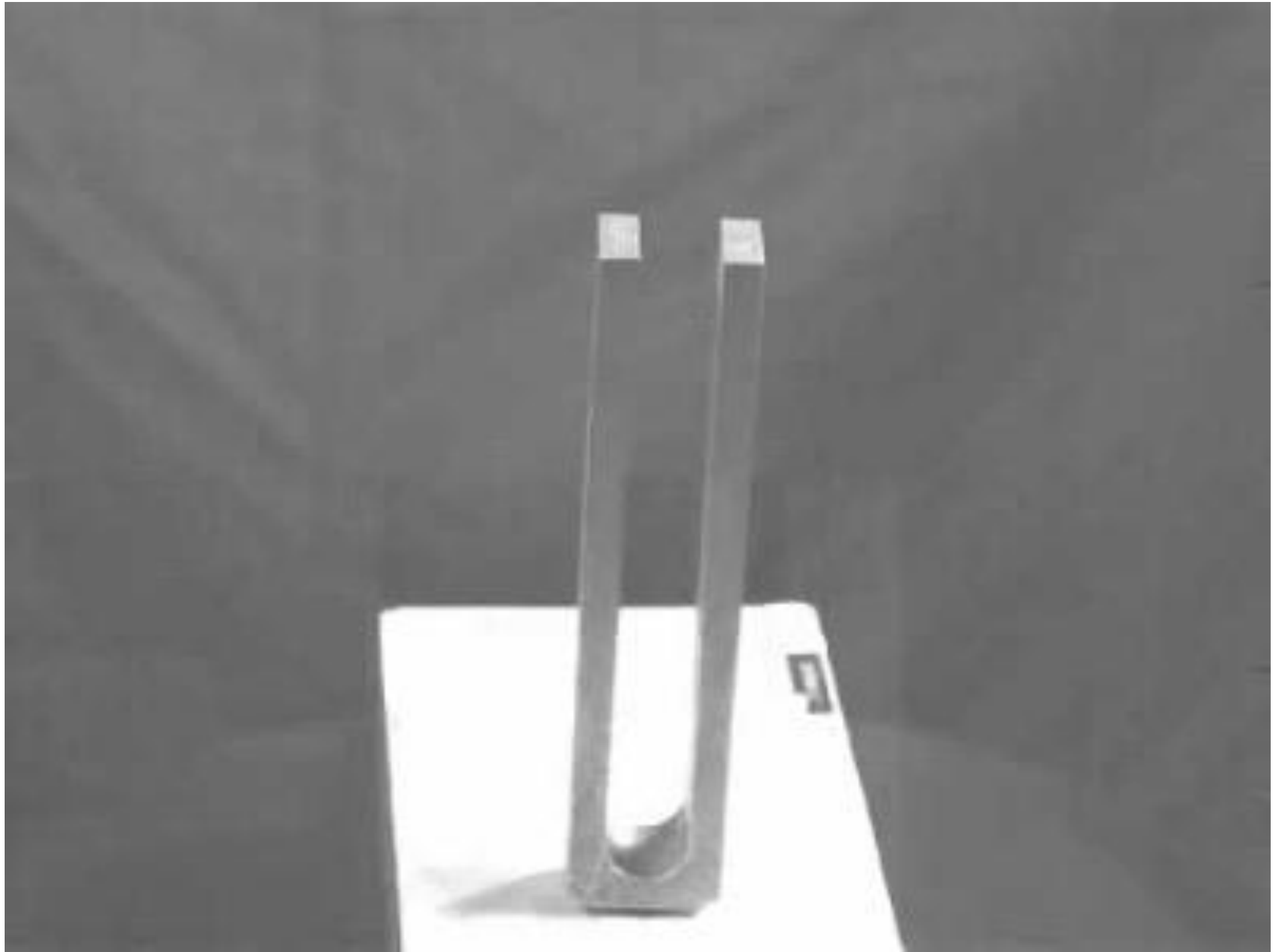


Vibrating Oboe Reed

SCI

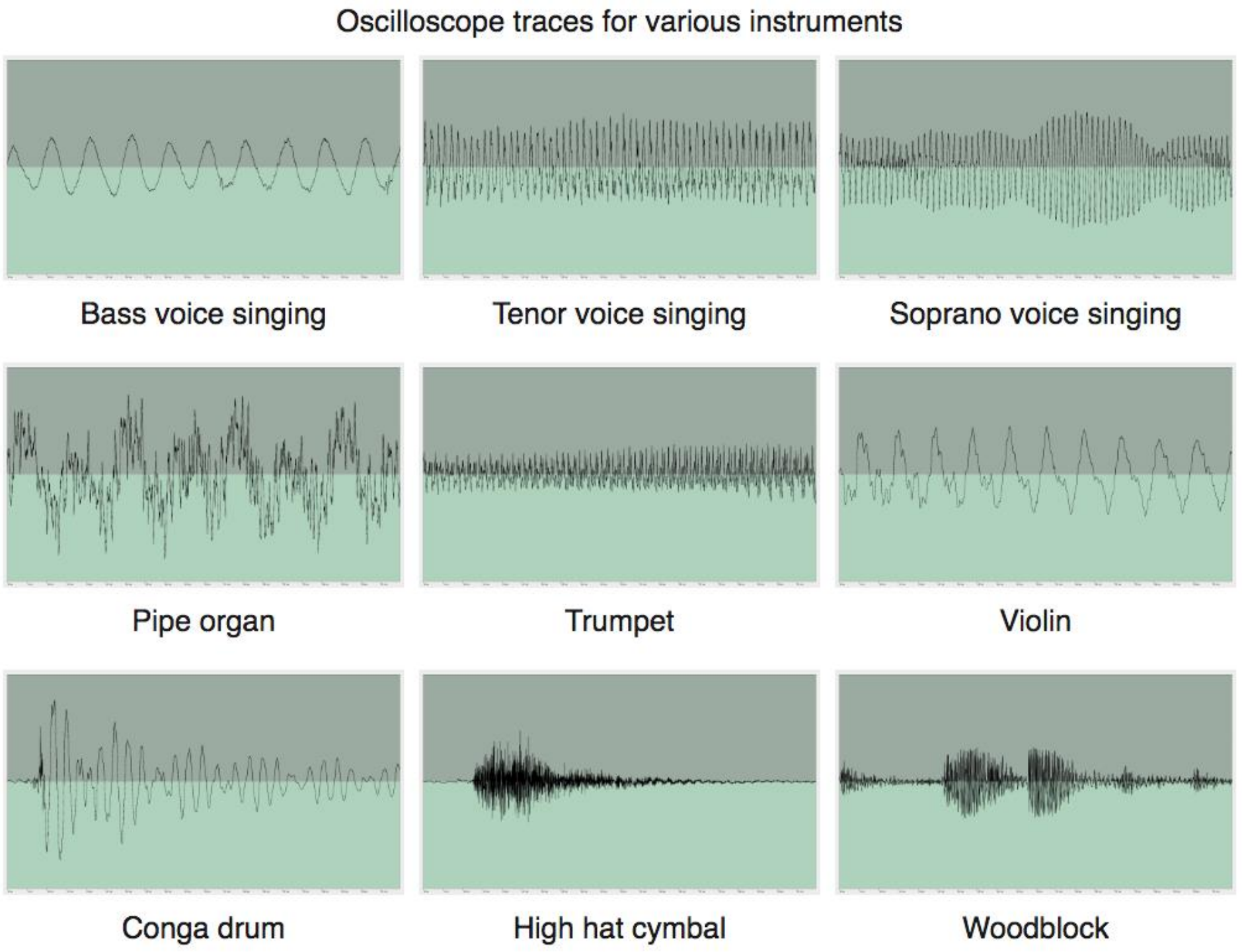
Vibrations on a 2D surface

Vibrations on a String

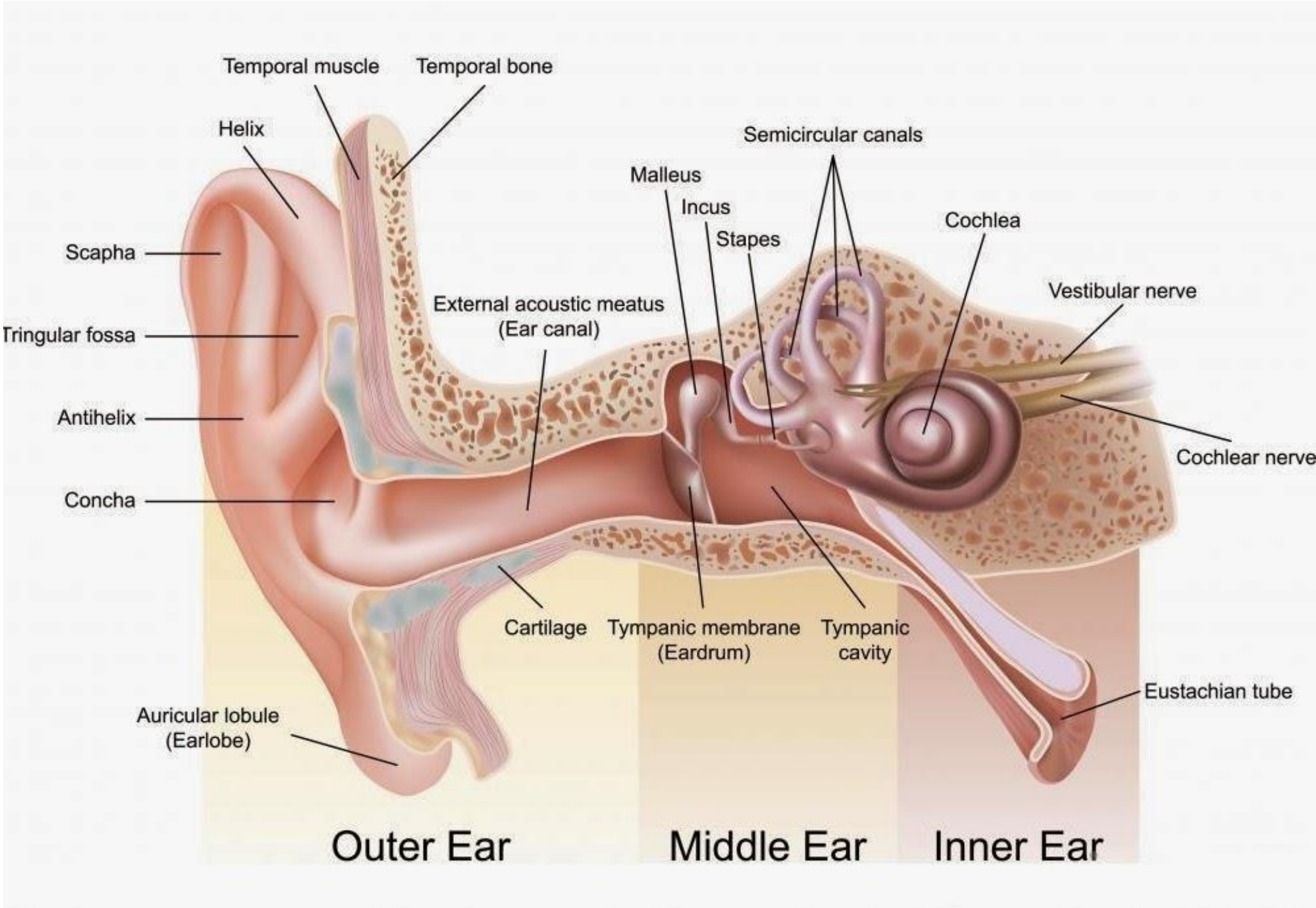
Demo!

Musical Pitch:

A repeating wave pattern



Anatomy of the Human Ear



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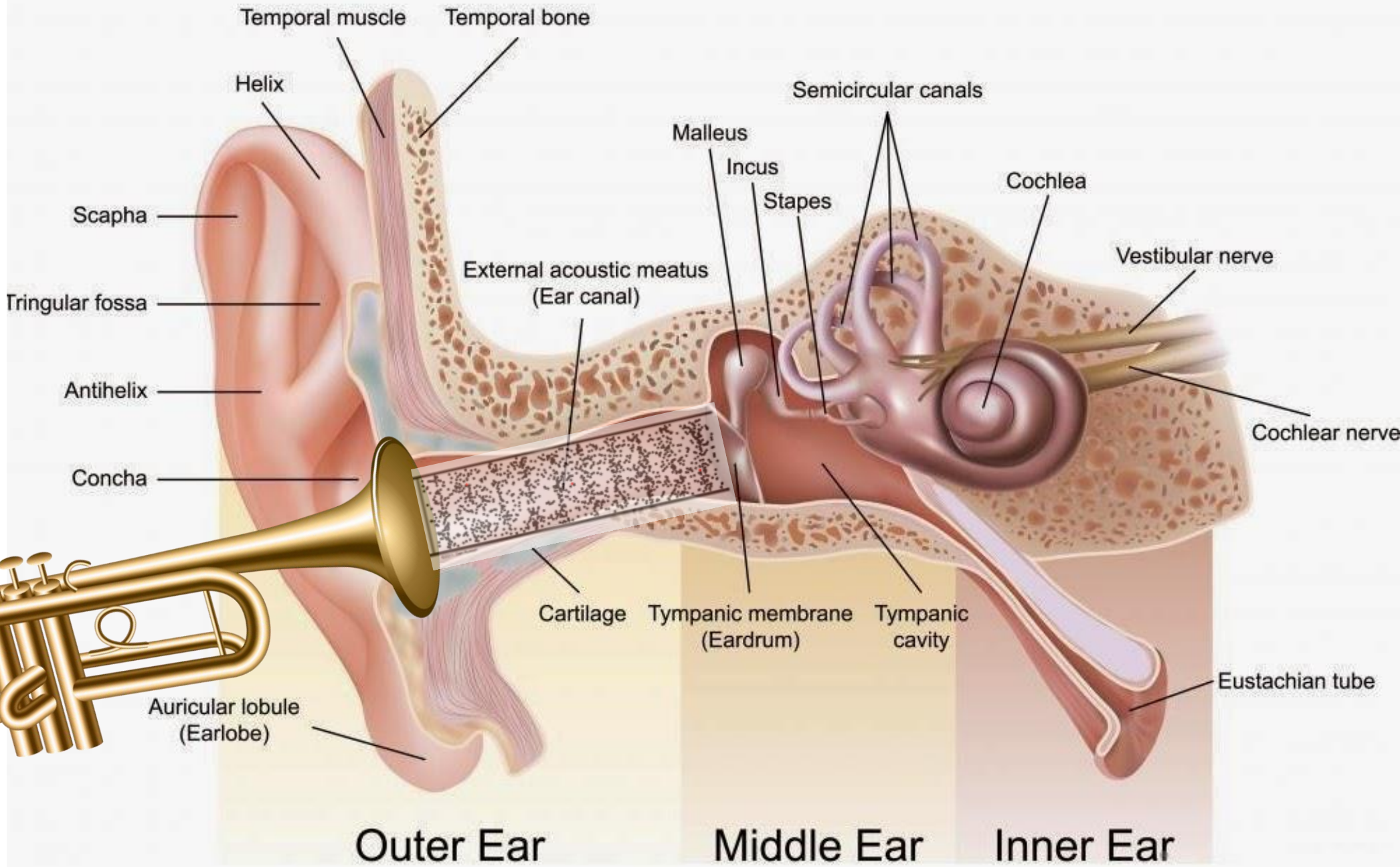


Natural Frequency and Resonance

Natural Frequency and Resonance

Natural Frequency and Resonance

Wine Glass Resonance

https://www.youtube.com/watch?v=sH7XSX10QkM

Musical Pitch is determined by the Natural Vibration Frequency

A = 440 Hz

means the tuning fork is vibrating back and forth 440 times every second!

To change the natural frequency, we can change:

- Dimensions (length, width)
- Density (material)
- Tension

Natural frequency: (for a string)

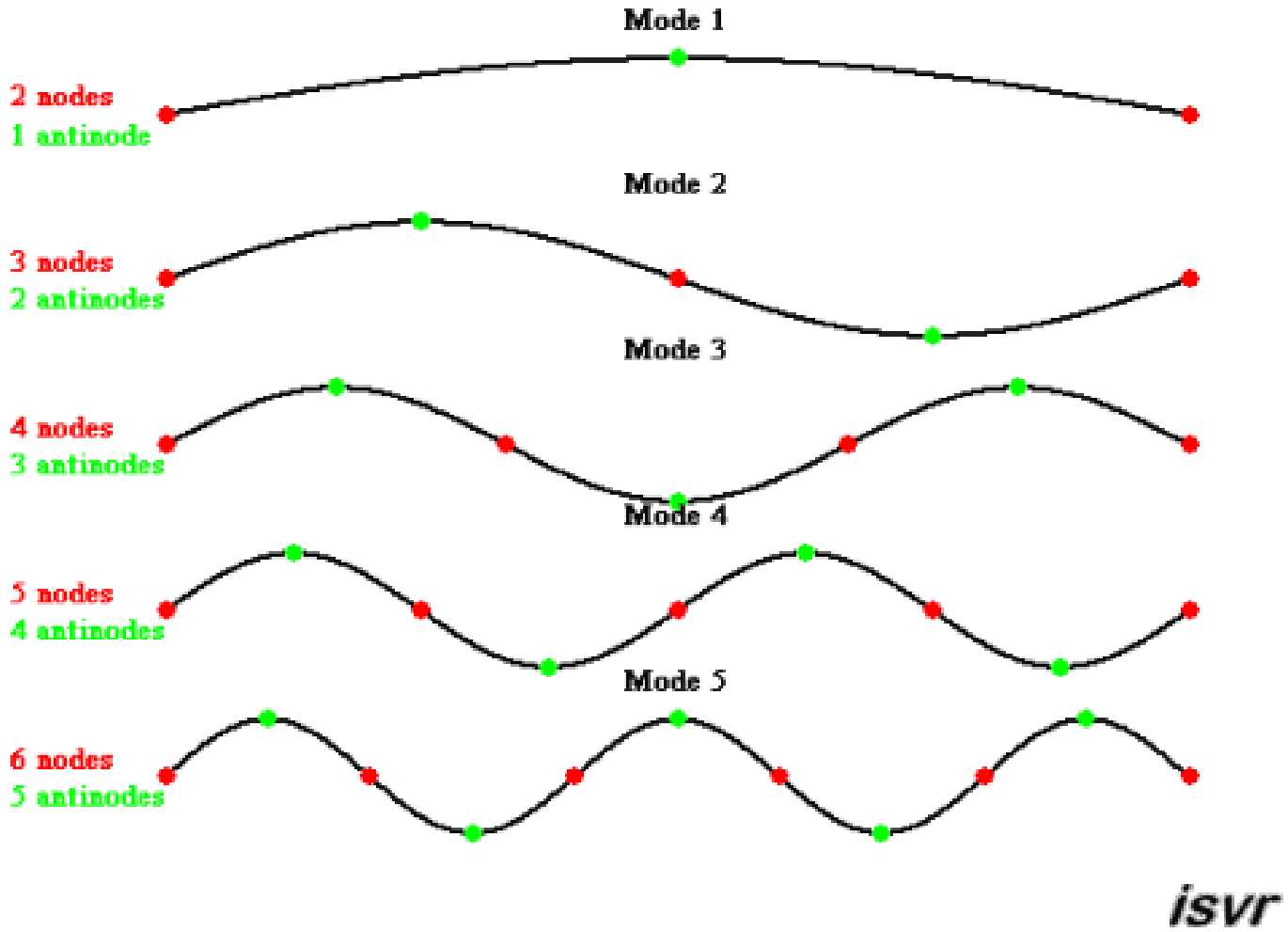
$$f = \frac{1}{2L}\sqrt{\frac{T}{\mu}}$$

Large Instrument = Low Sound

Natural frequency: (for a string)

$$f = \frac{1}{2L}\sqrt{\frac{T}{\mu}}$$

Can an object have more than one natural frequency?



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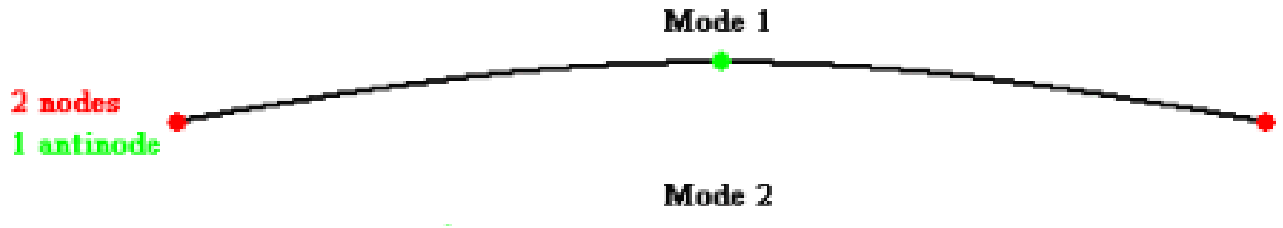

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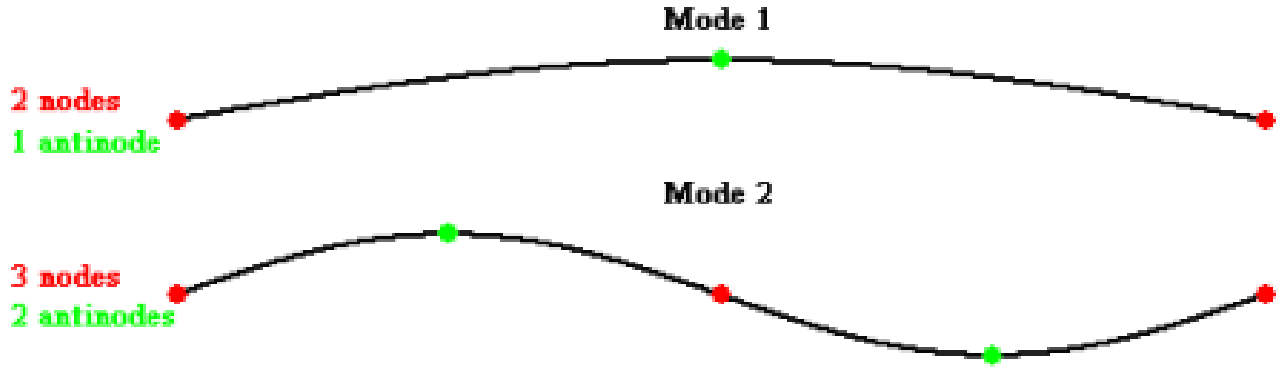

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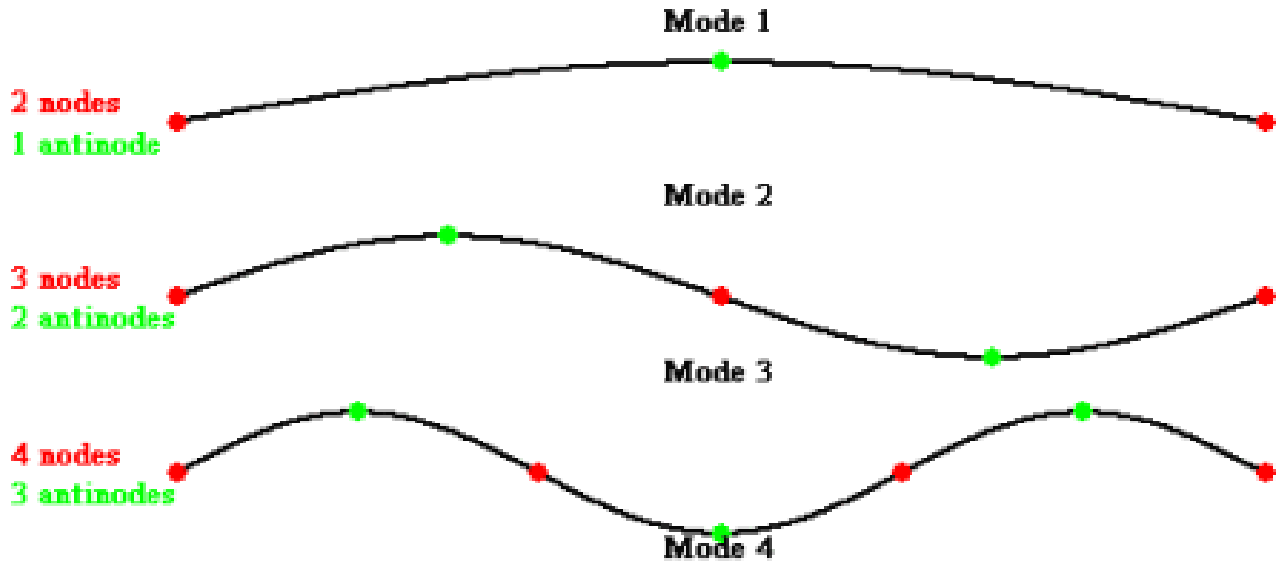

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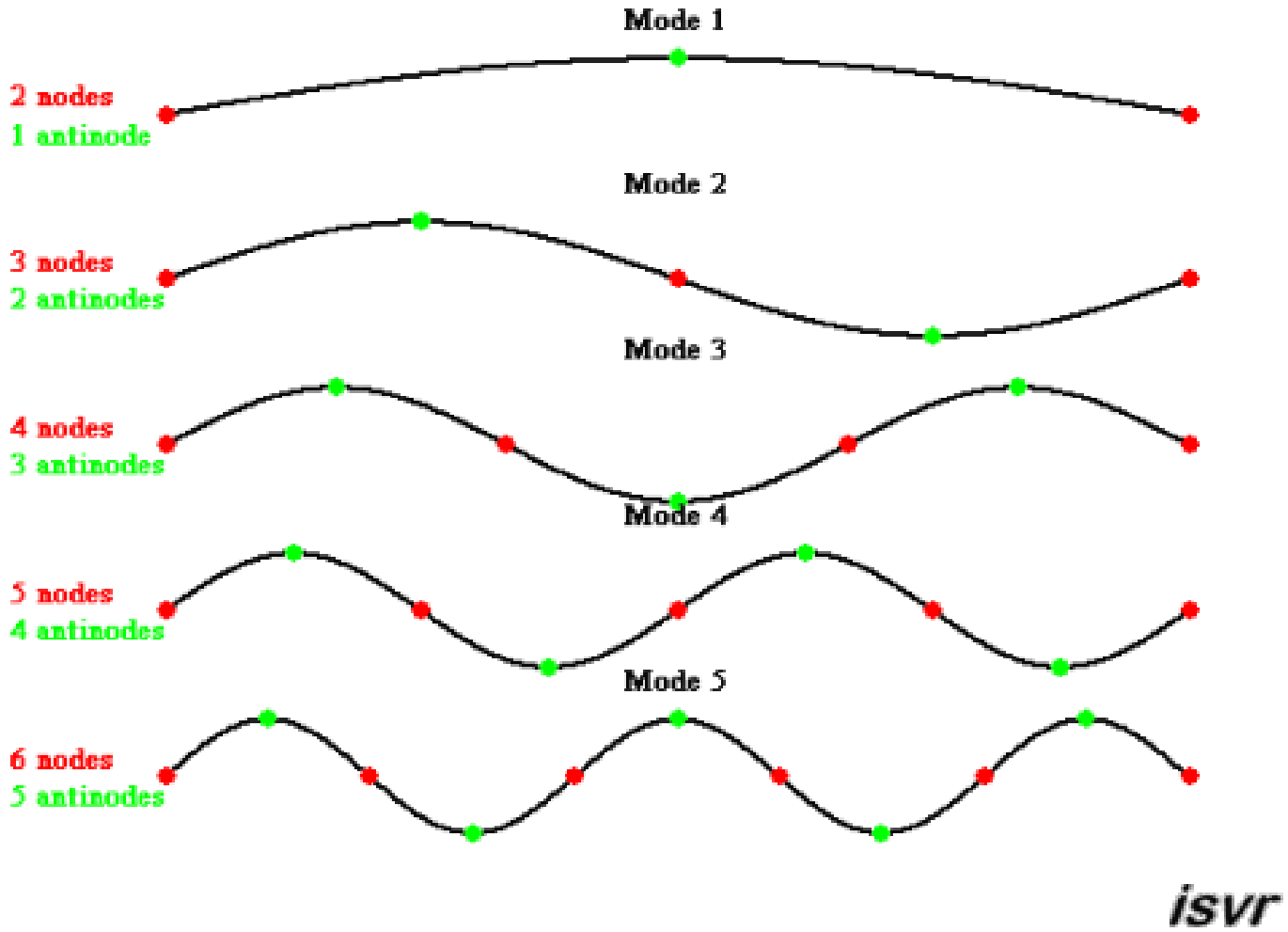
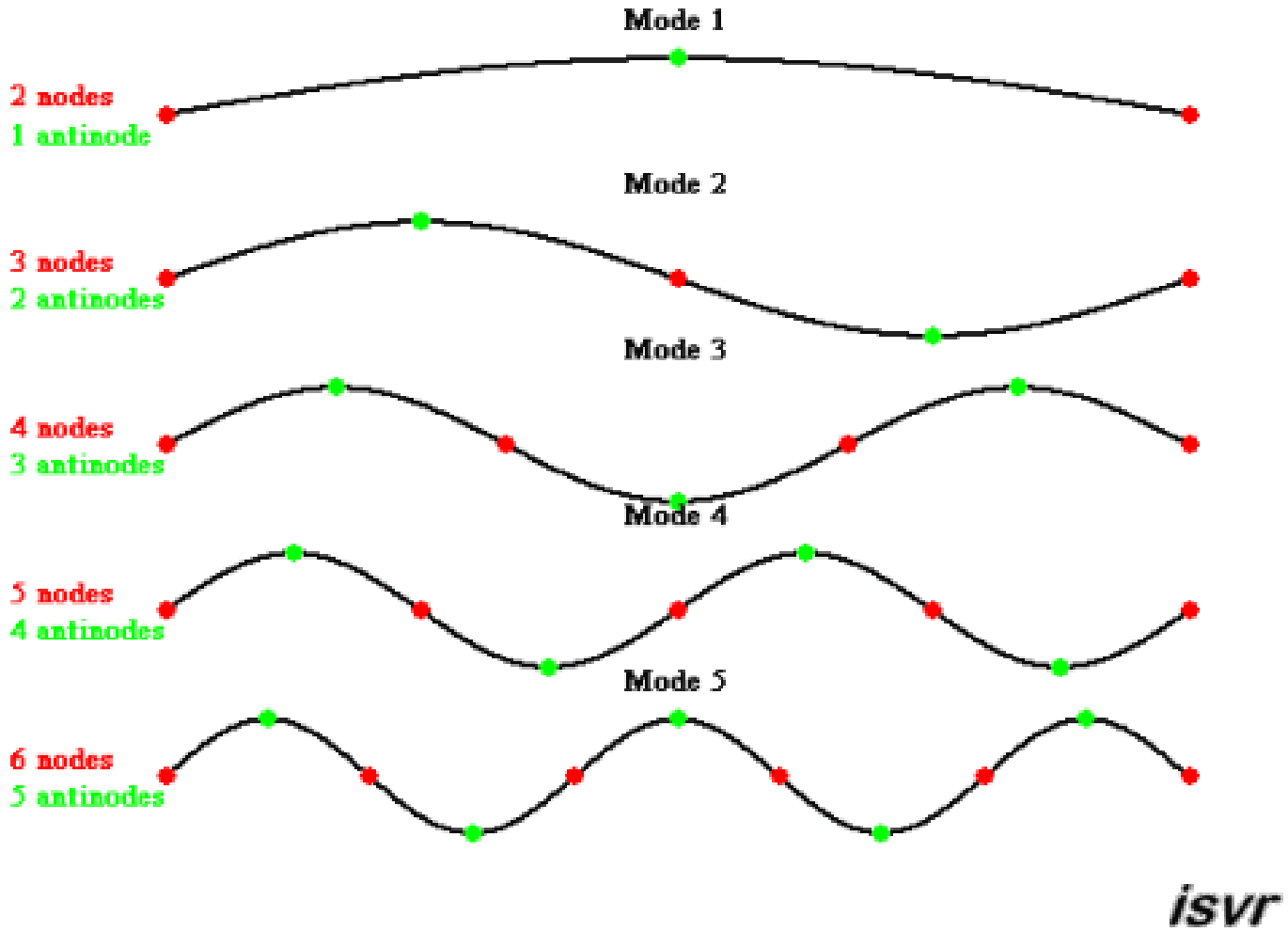
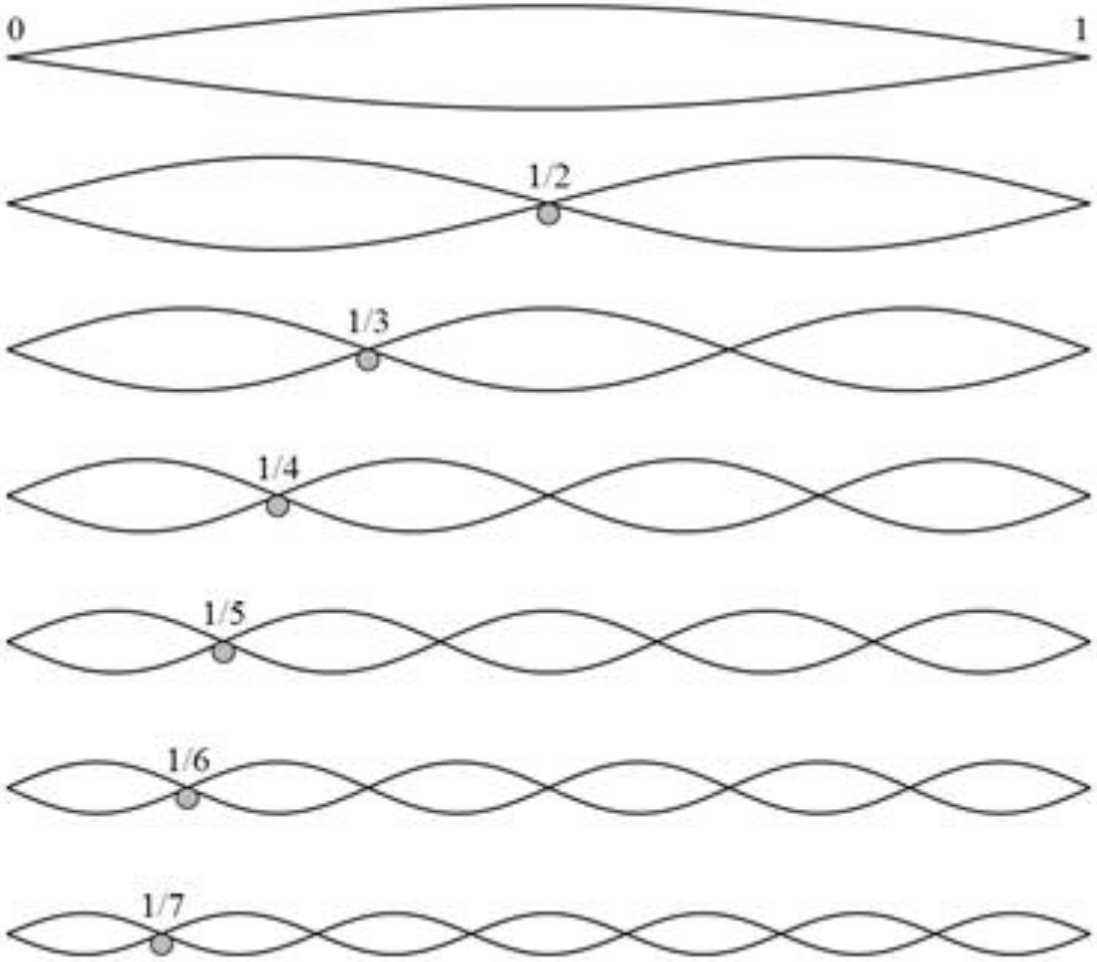


Can an object have more than one natural frequency?

Demo!



Natural Frequencies of a Vibrating String



Fundamental

2nd Harmonic

3rd Harmonic

4th Harmonic

5th Harmonic

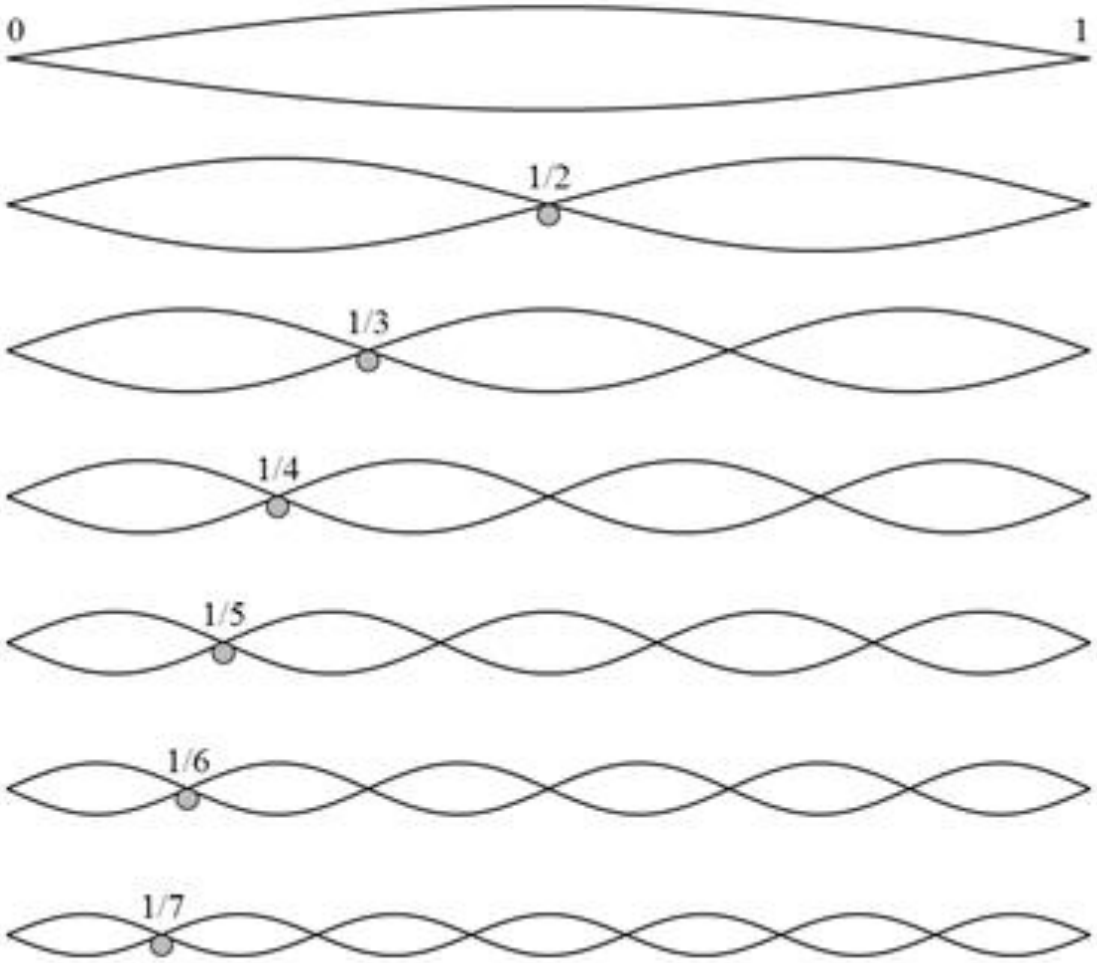
6th Harmonic

7th Harmonic

How does the size of the wave change as the harmonic gets bigger?

$$\text{Wavelength of Harmonic} = \frac{\text{Wavelength of Fundamental}}{n}$$

Natural Frequencies of a Vibrating String



Fundamental $n = 1$

2nd Harmonic $n = 2$

3rd Harmonic $n = 3$

4th Harmonic $n = 4$

5th Harmonic

6th Harmonic

7th Harmonic

$$\text{Wavelength of Harmonic} = \frac{\text{Wavelength of Fundamental}}{n}$$

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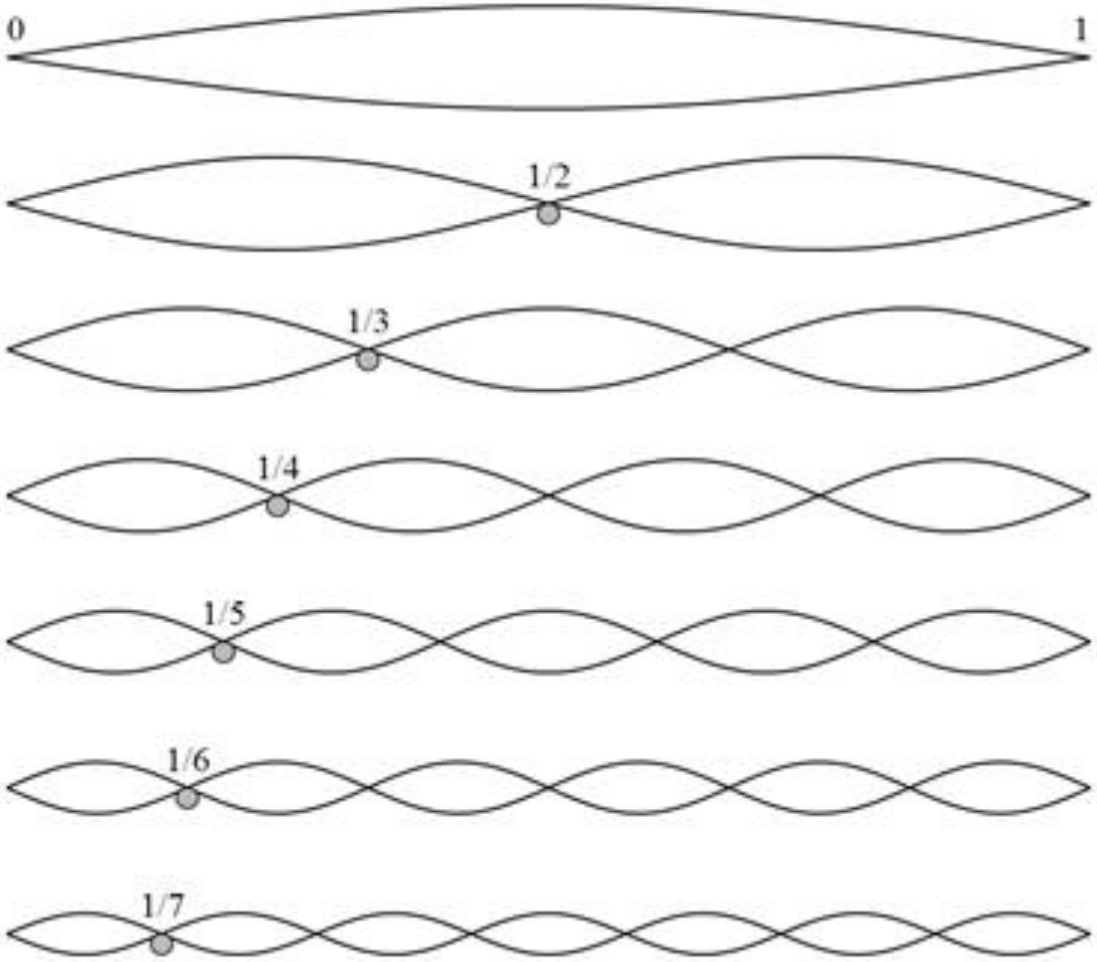
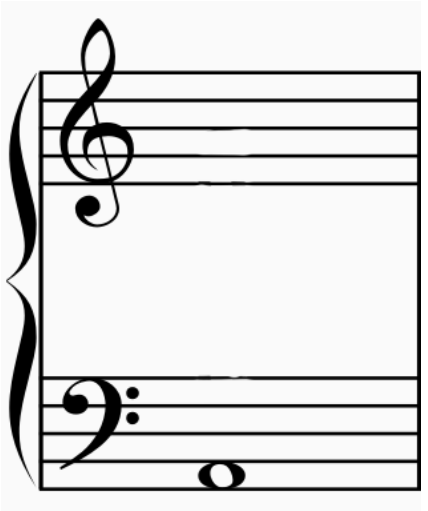


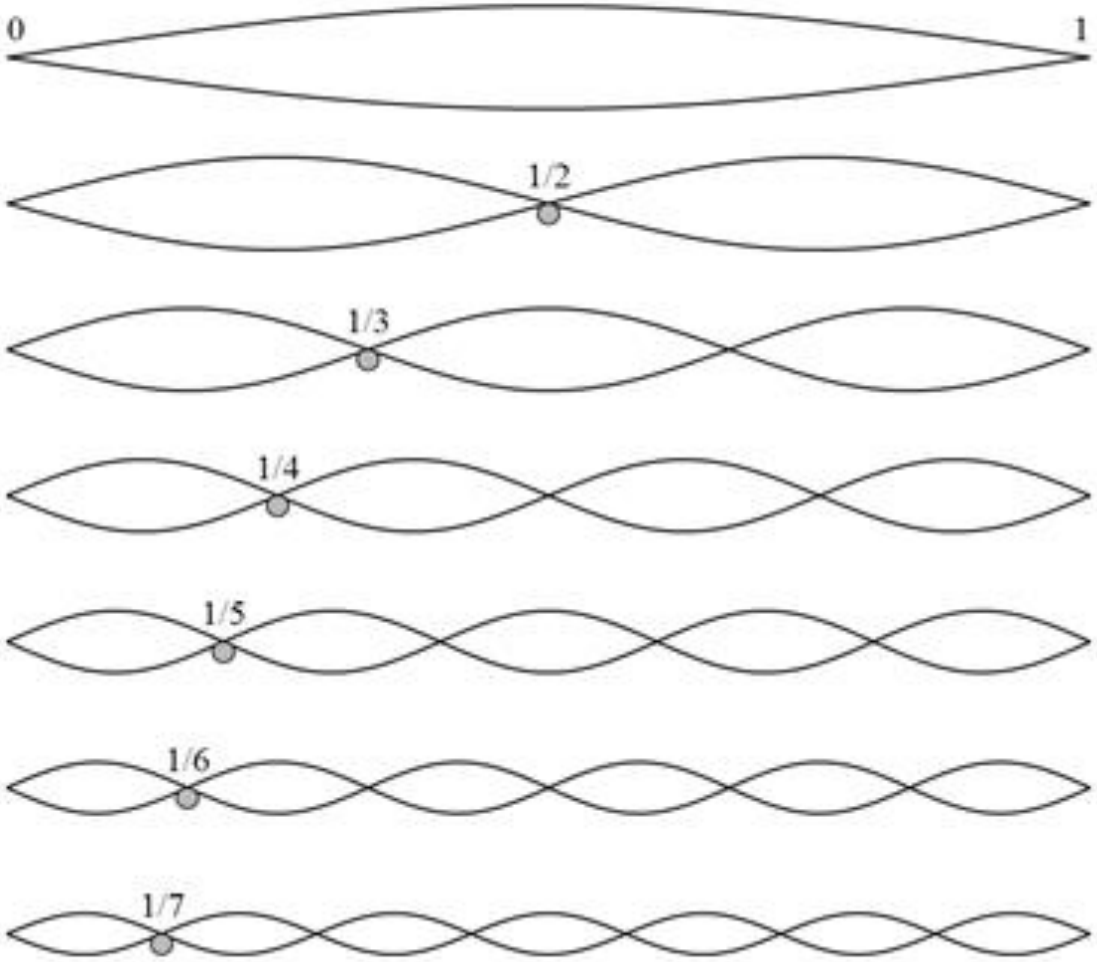
Frequency
(Musical Pitch)

Fundamental	$n = 1$	220 Hz
2nd Harmonic	$n = 2$	
3rd Harmonic	$n = 3$	
4th Harmonic	$n = 4$	
5th Harmonic	⋮	
6th Harmonic		
7th Harmonic		

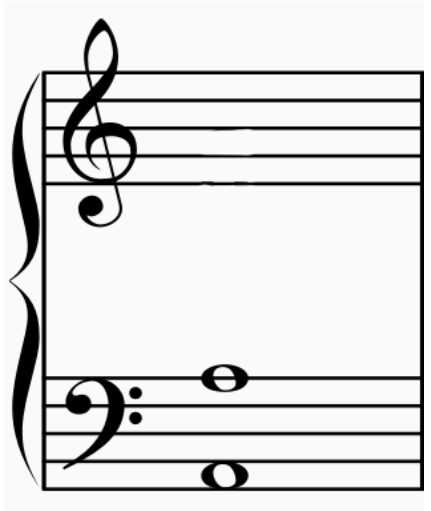


$$\text{Frequency of Harmonic} = n \times \text{Frequency of Fundamental}$$

Natural Frequencies of a Vibrating String



		Frequency (Musical Pitch)
Fundamental	$n = 1$	220 Hz
2nd Harmonic	$n = 2$	440 Hz
3rd Harmonic	$n = 3$	
4th Harmonic	$n = 4$	
5th Harmonic	⋮	
6th Harmonic		
7th Harmonic		



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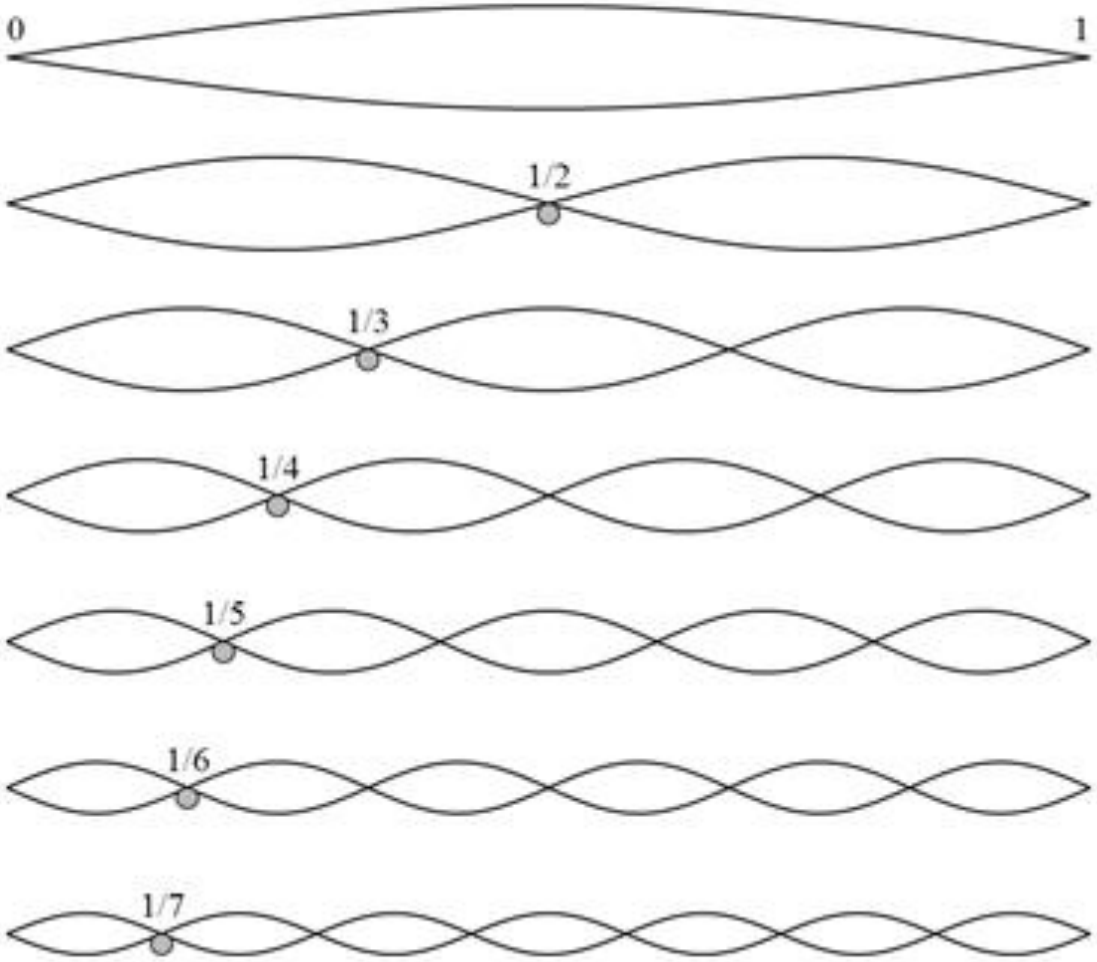
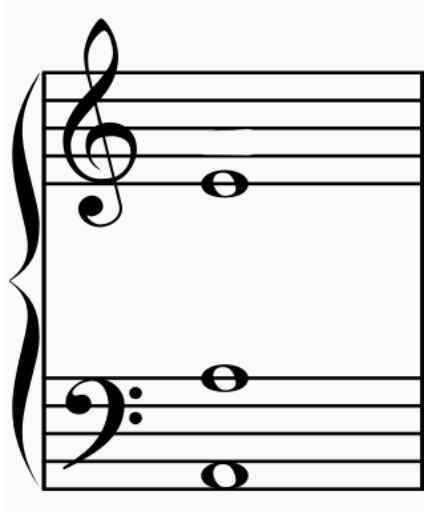
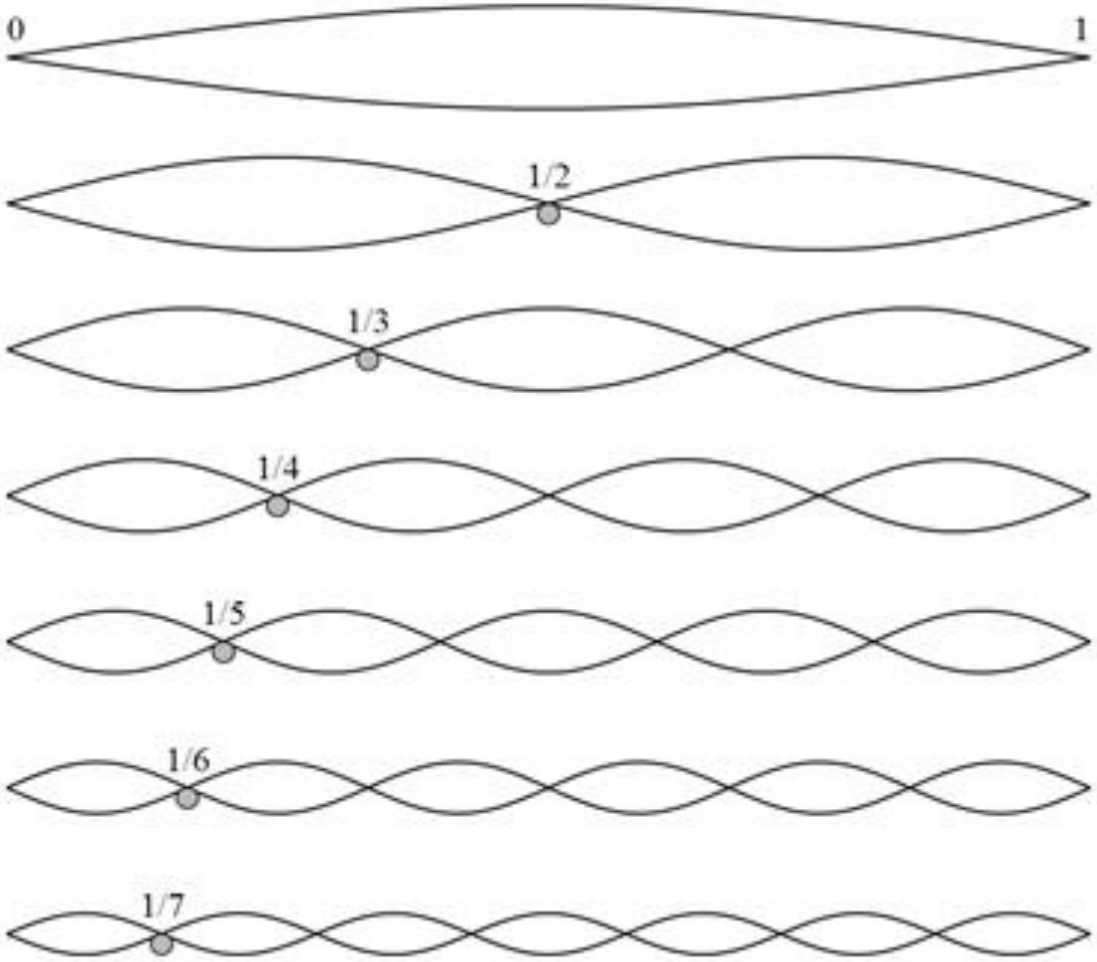


		Frequency (Musical Pitch)
Fundamental	$n = 1$	220 Hz
2nd Harmonic	$n = 2$	440 Hz
3rd Harmonic	$n = 3$	660 Hz
4th Harmonic	$n = 4$	
5th Harmonic	⋮	
6th Harmonic		
7th Harmonic		

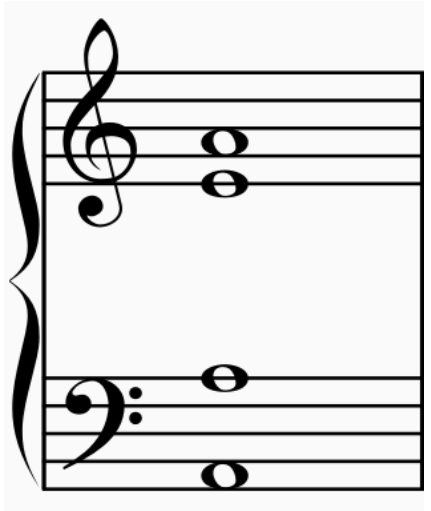


$$\text{Frequency of Harmonic} = n \times \text{Frequency of Fundamental}$$

Natural Frequencies of a Vibrating String

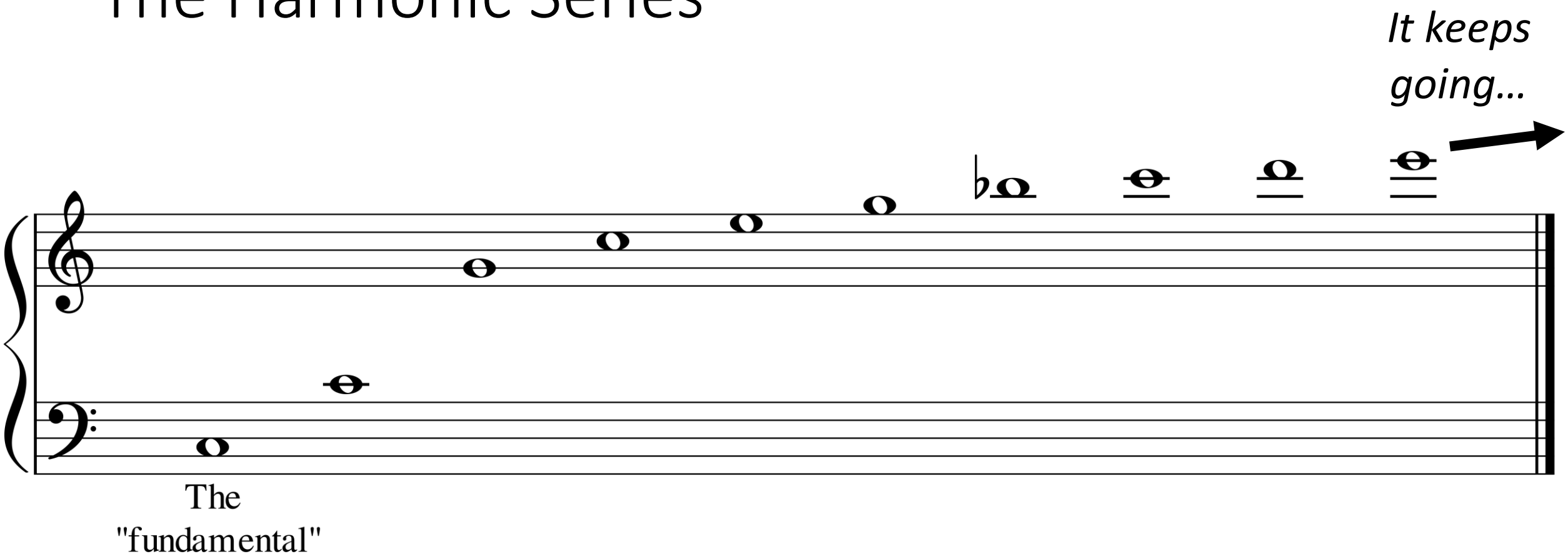


		Frequency (Musical Pitch)
Fundamental	$n = 1$	220 Hz
2nd Harmonic	$n = 2$	440 Hz
3rd Harmonic	$n = 3$	660 Hz
4th Harmonic	$n = 4$	880 Hz
5th Harmonic	⋮	⋮
6th Harmonic		
7th Harmonic		



$$\text{Frequency of Harmonic} = n \times \text{Frequency of Fundamental}$$

The Harmonic Series



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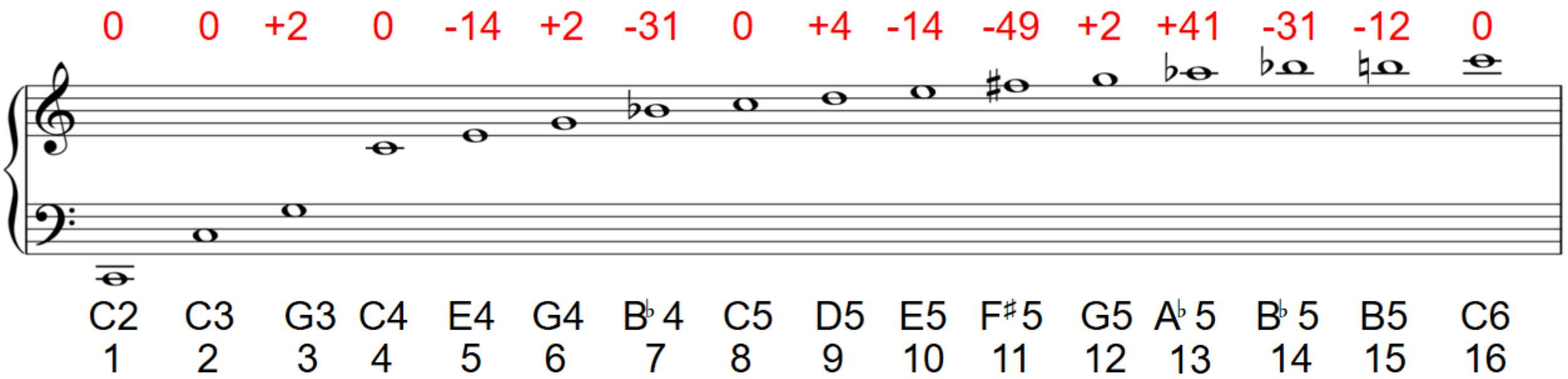


Figure 1.20 from [Müller, FMP, Springer 2015]

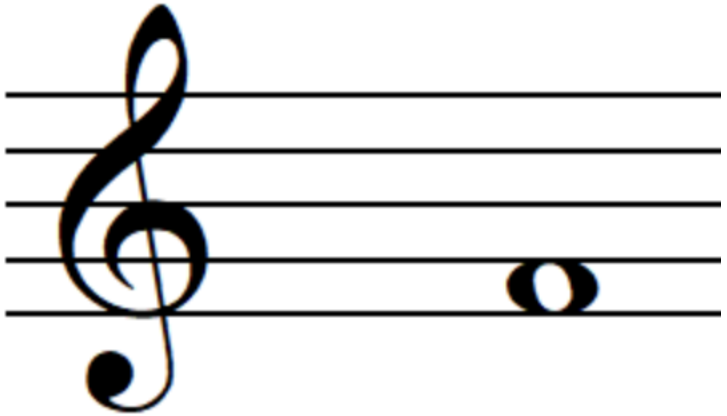
Which frequency do we actually hear?

Let’s see what happens when we add the harmonics together…

https://phet.colorado.edu/sims/html/fourier-making-waves/latest/fourier-making-waves_en.html

Alternative Simulator: https://meettechniek.info/additional/additive-synthesis.html#google_vignette

Timbre



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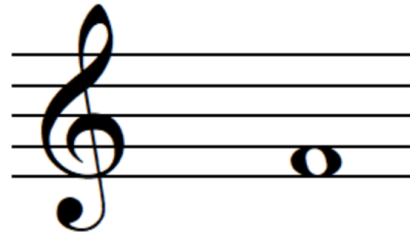


Trombone

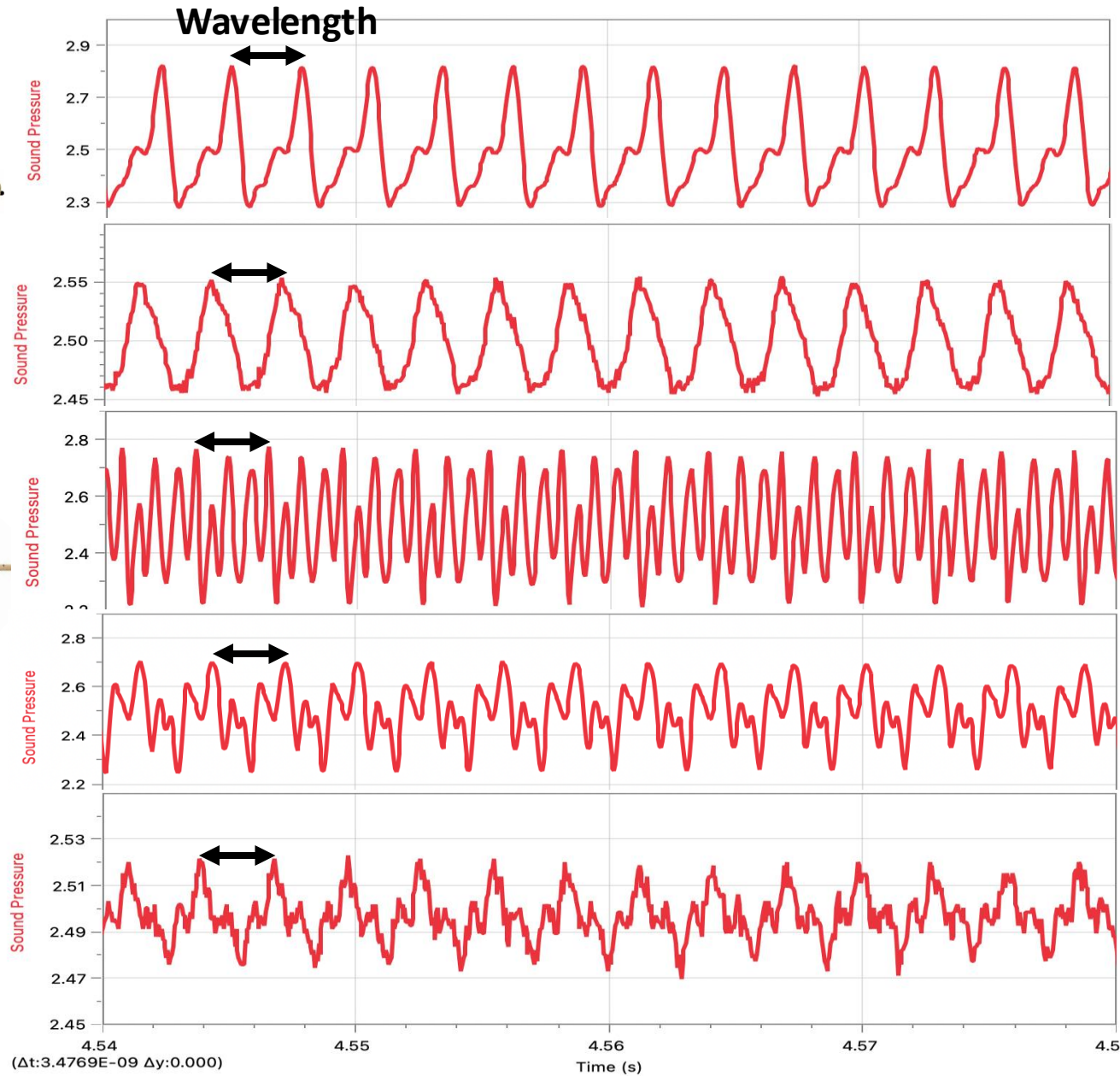
Recorder

Oboe

Clarinet

Guitar

Fundamental Frequency = 350 Hz



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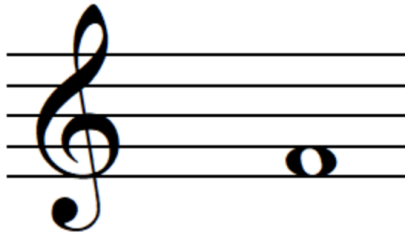
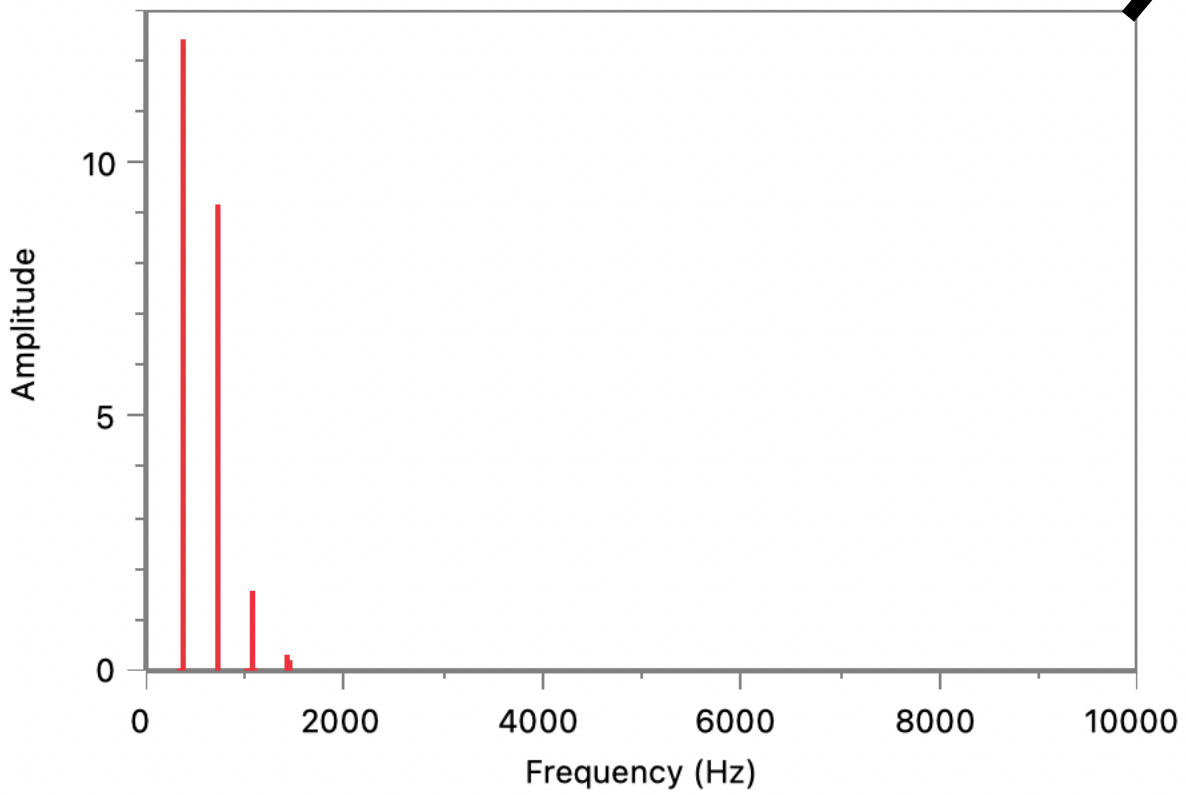
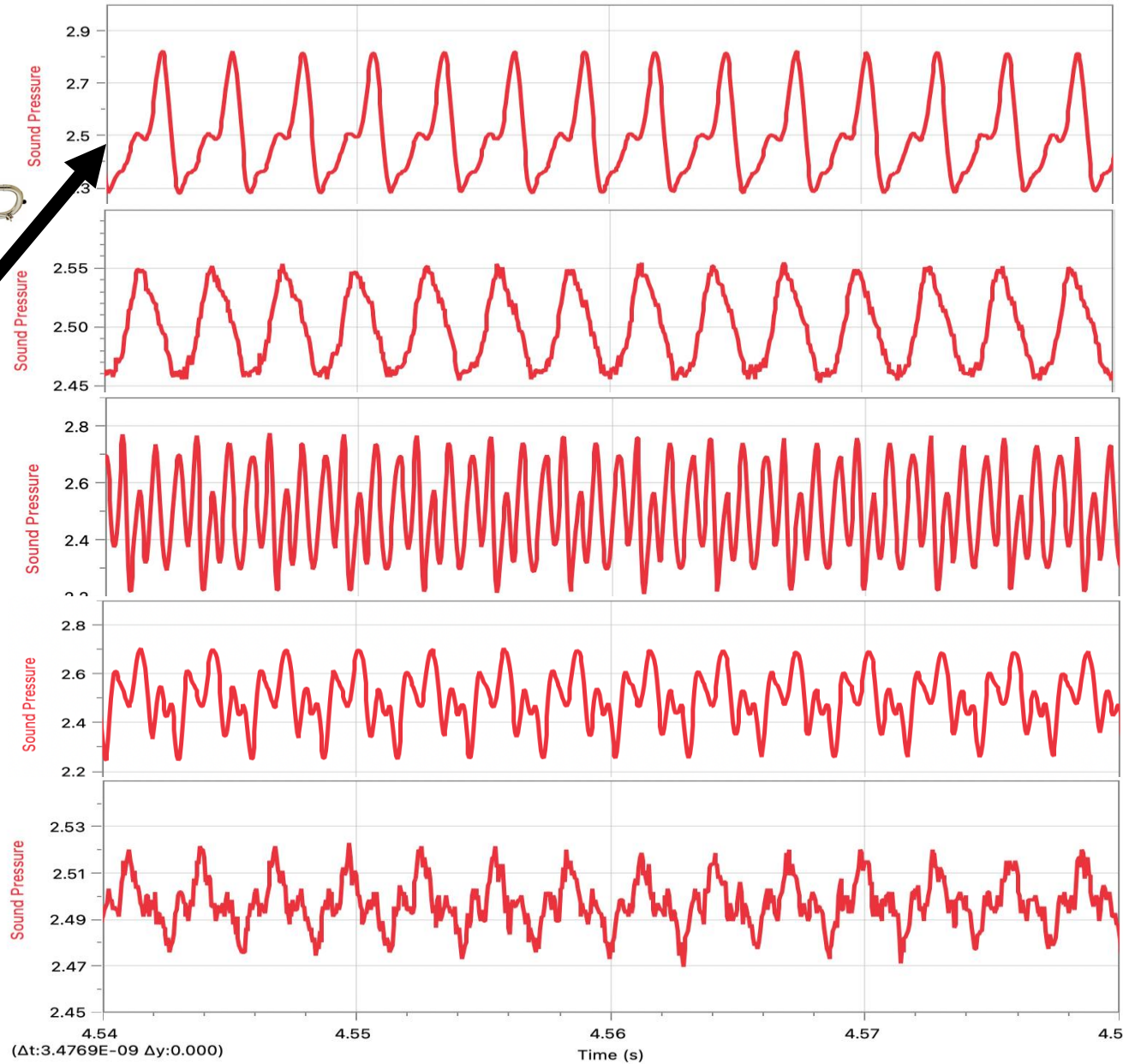


Trombone

FFT



Fundamental Frequency = 350 Hz



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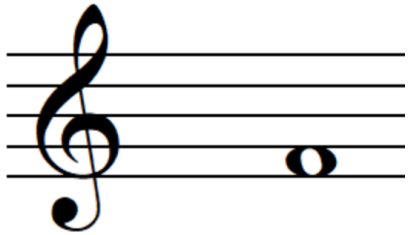

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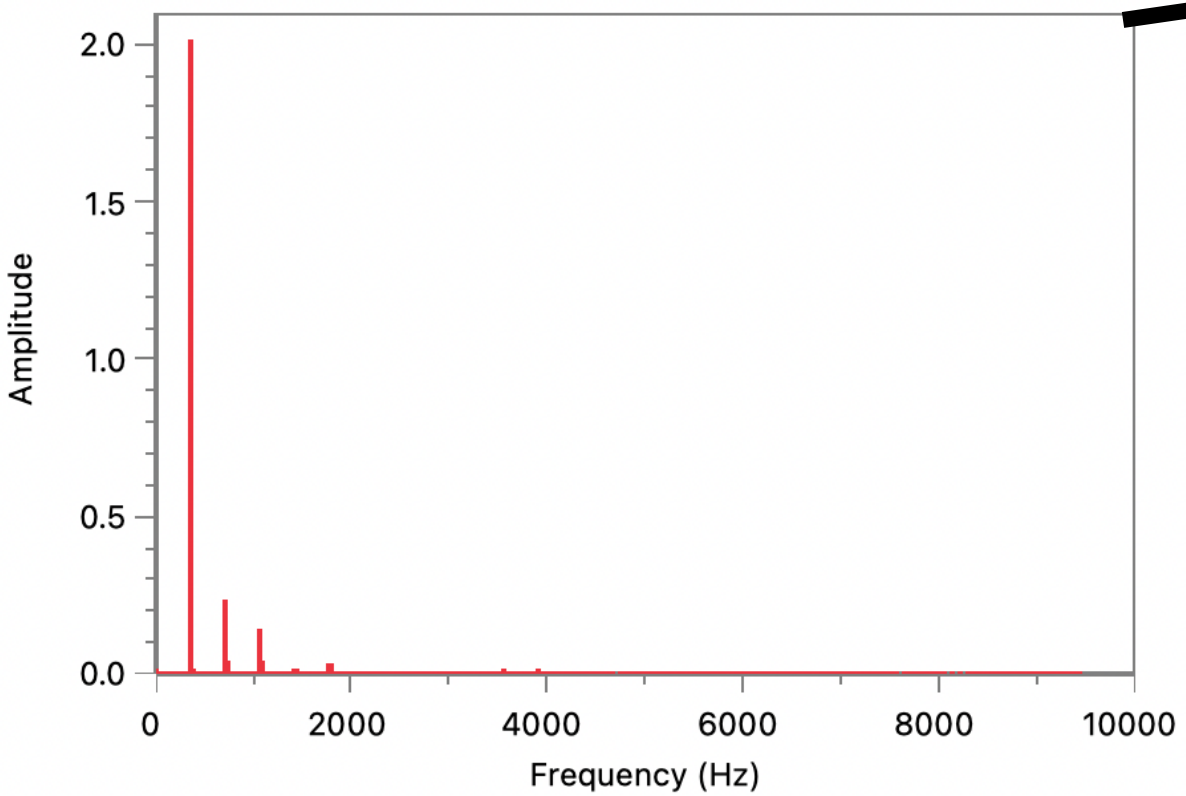

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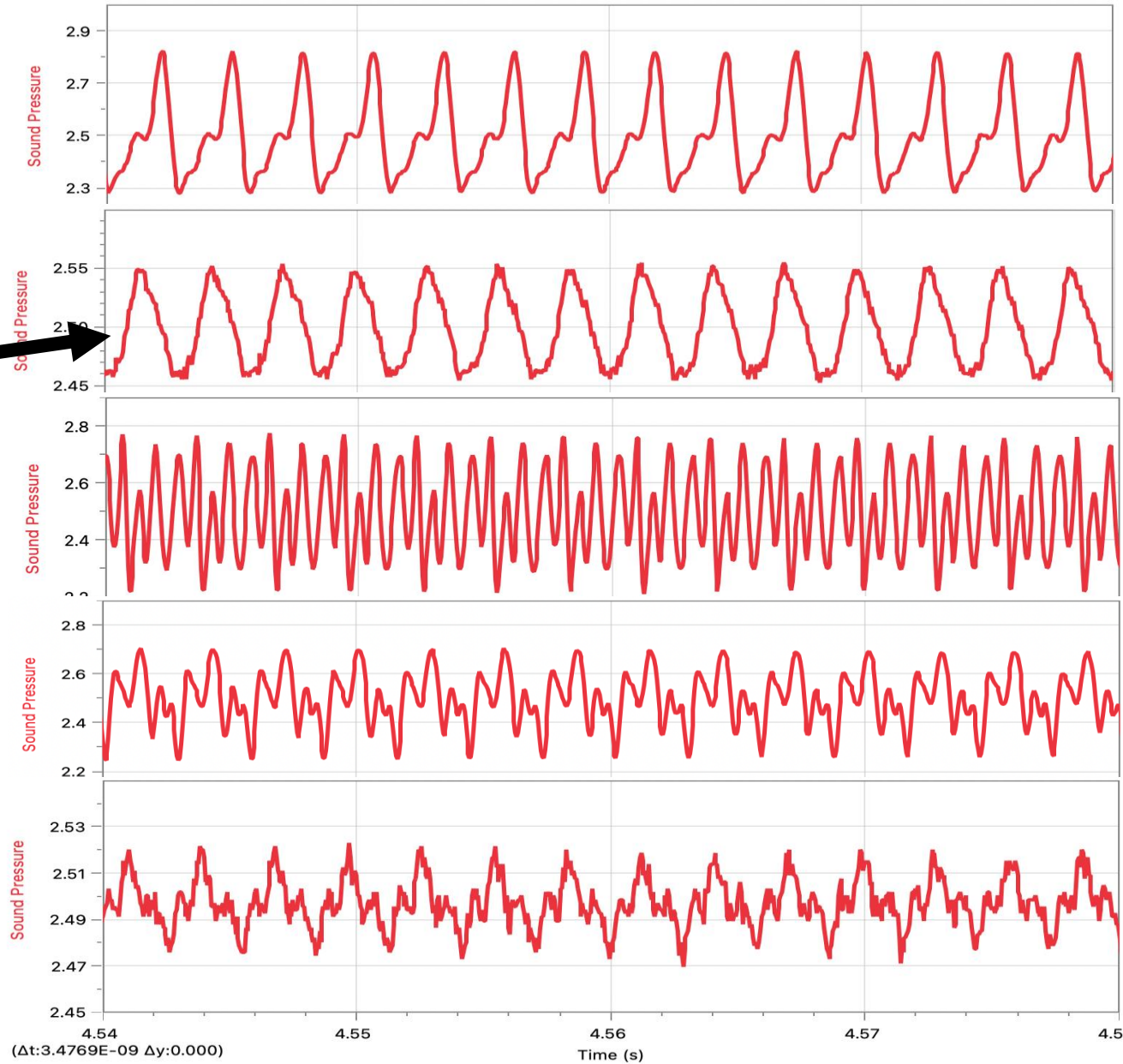

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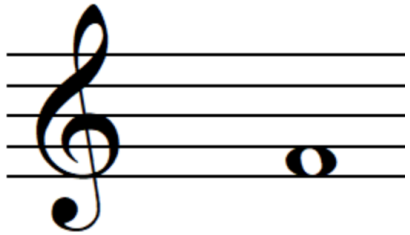

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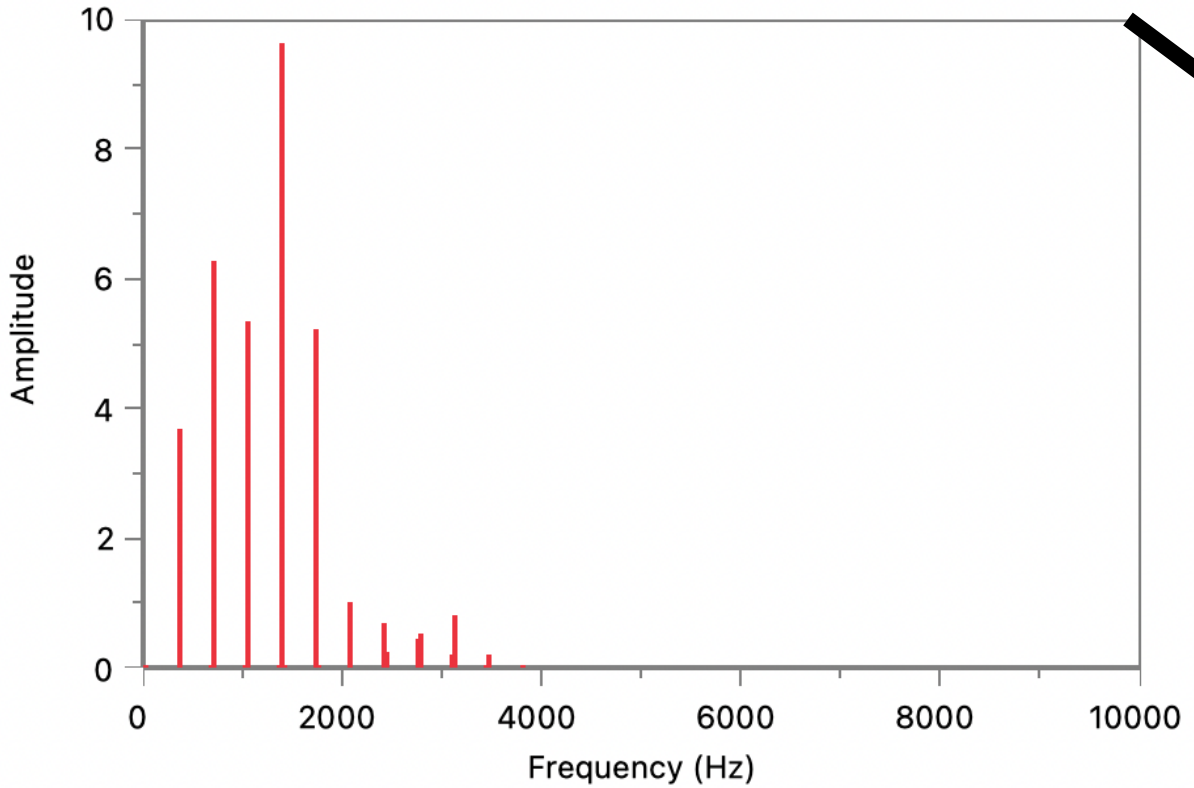
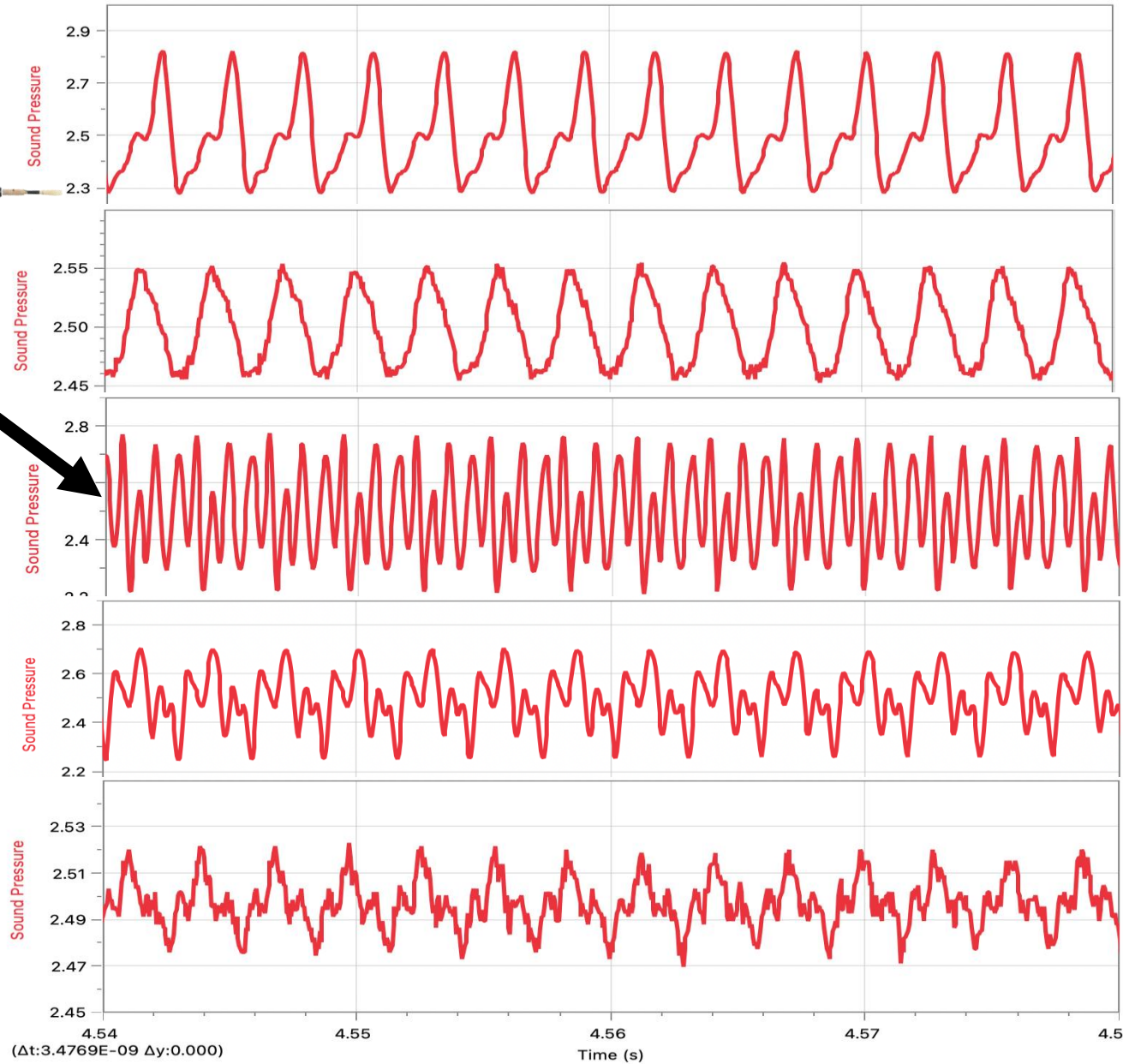
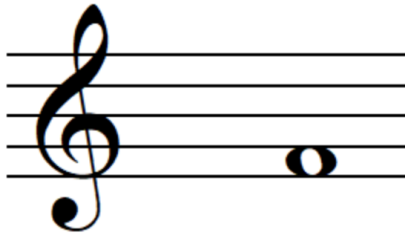


Fundamental Frequency = 350 Hz

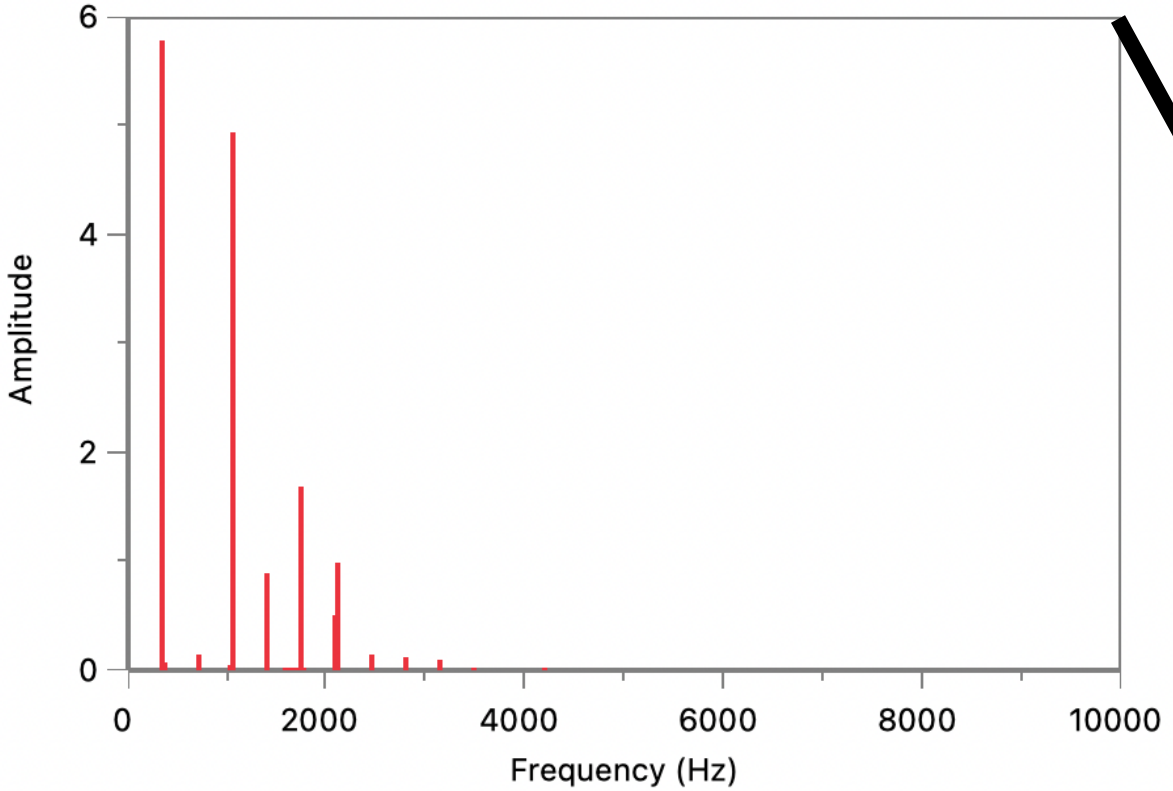


Timbre

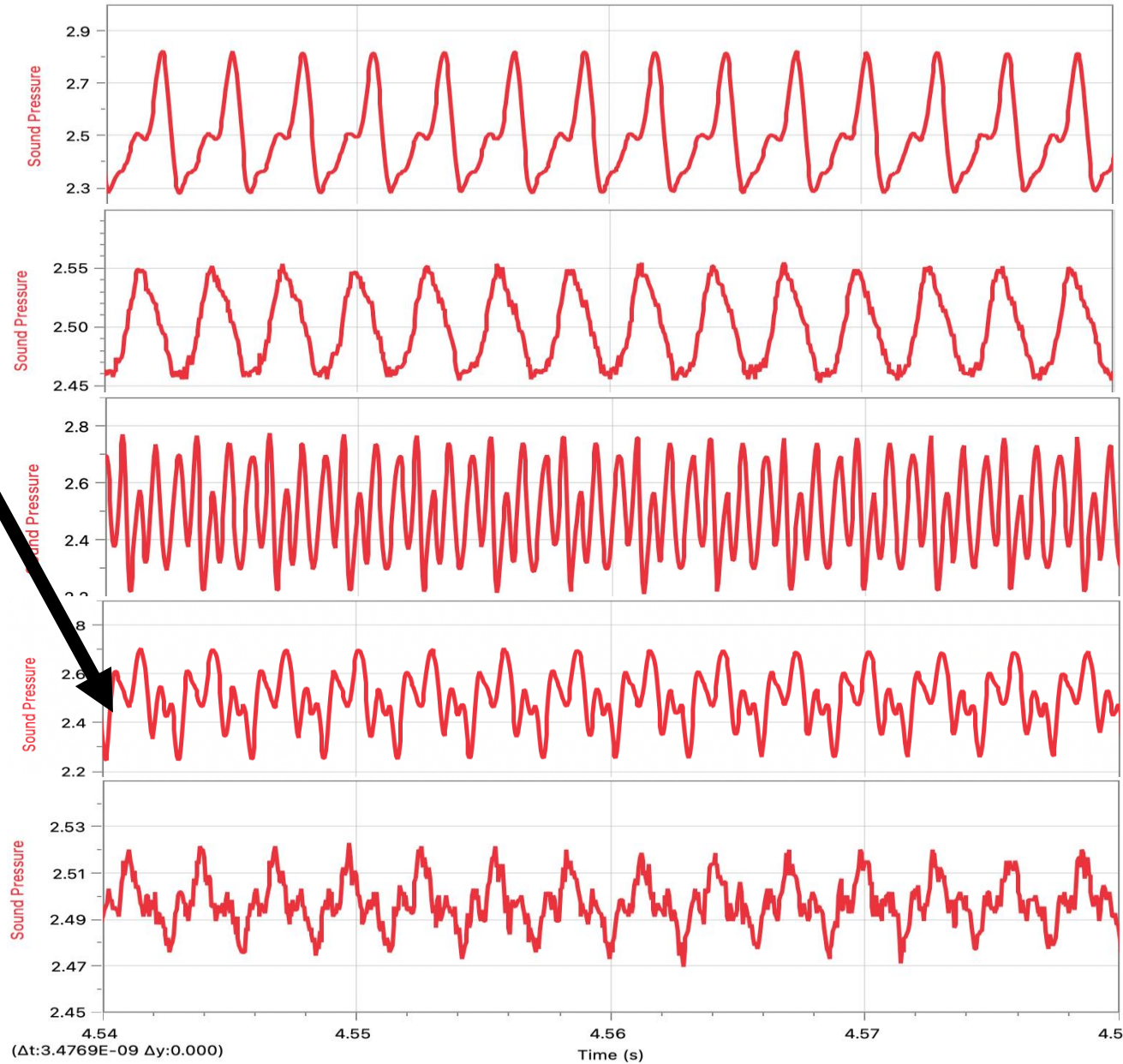


Clarinet

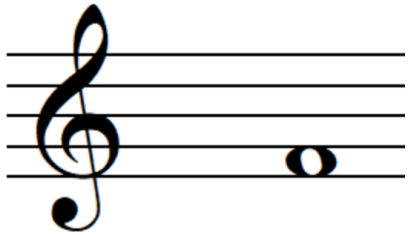
FFT



Fundamental Frequency = 350 Hz

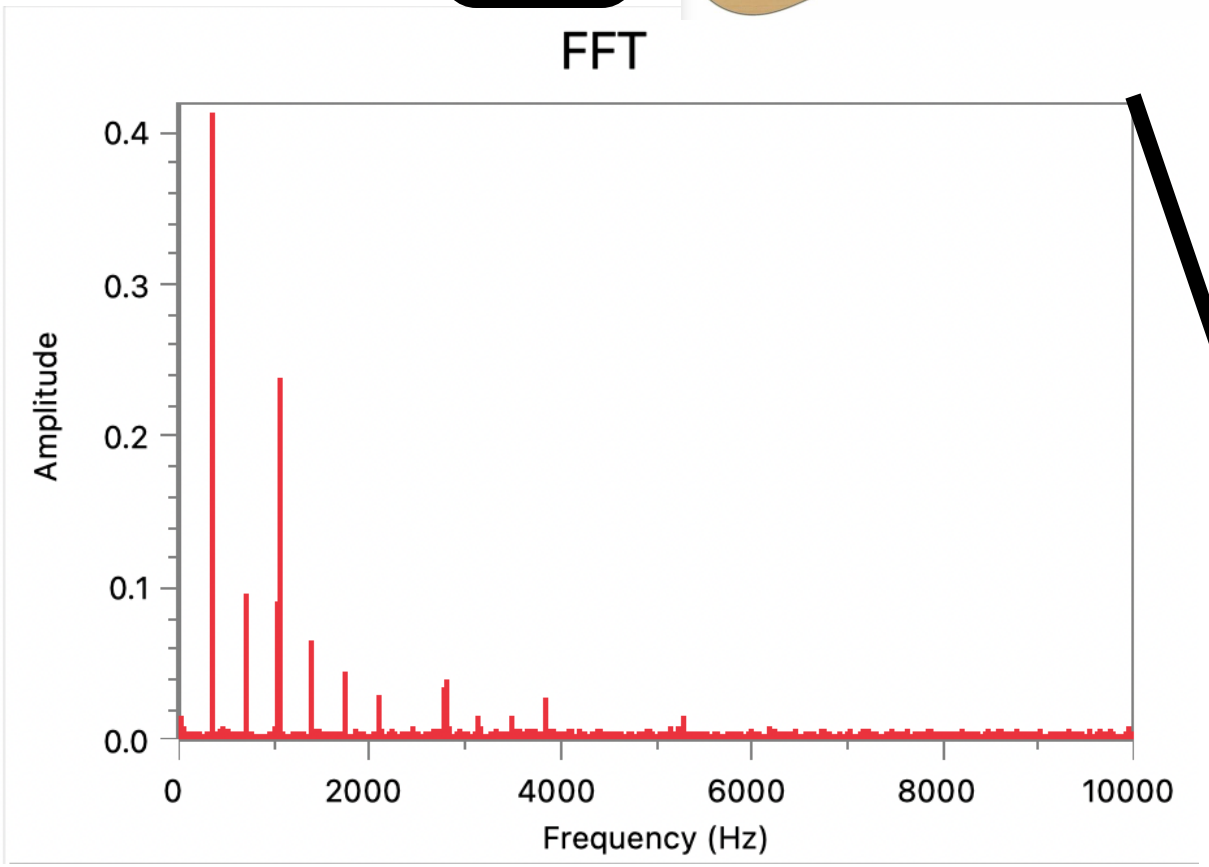


Timbre

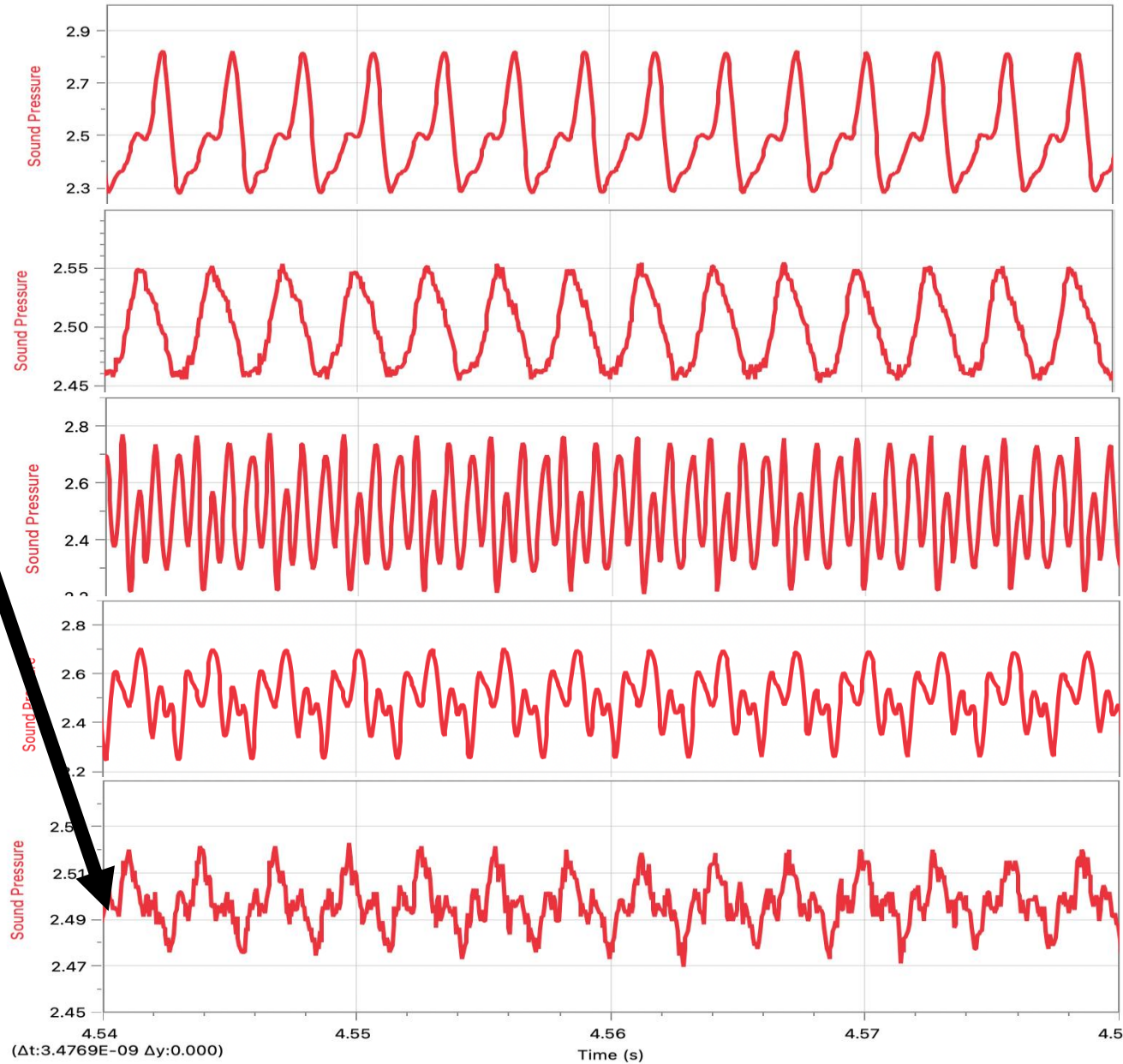


Guitar

FFT

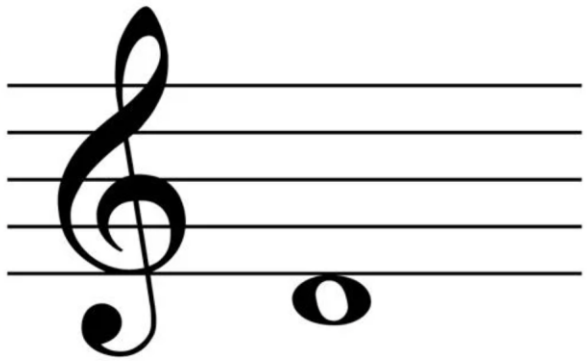


Fundamental Frequency = 350 Hz

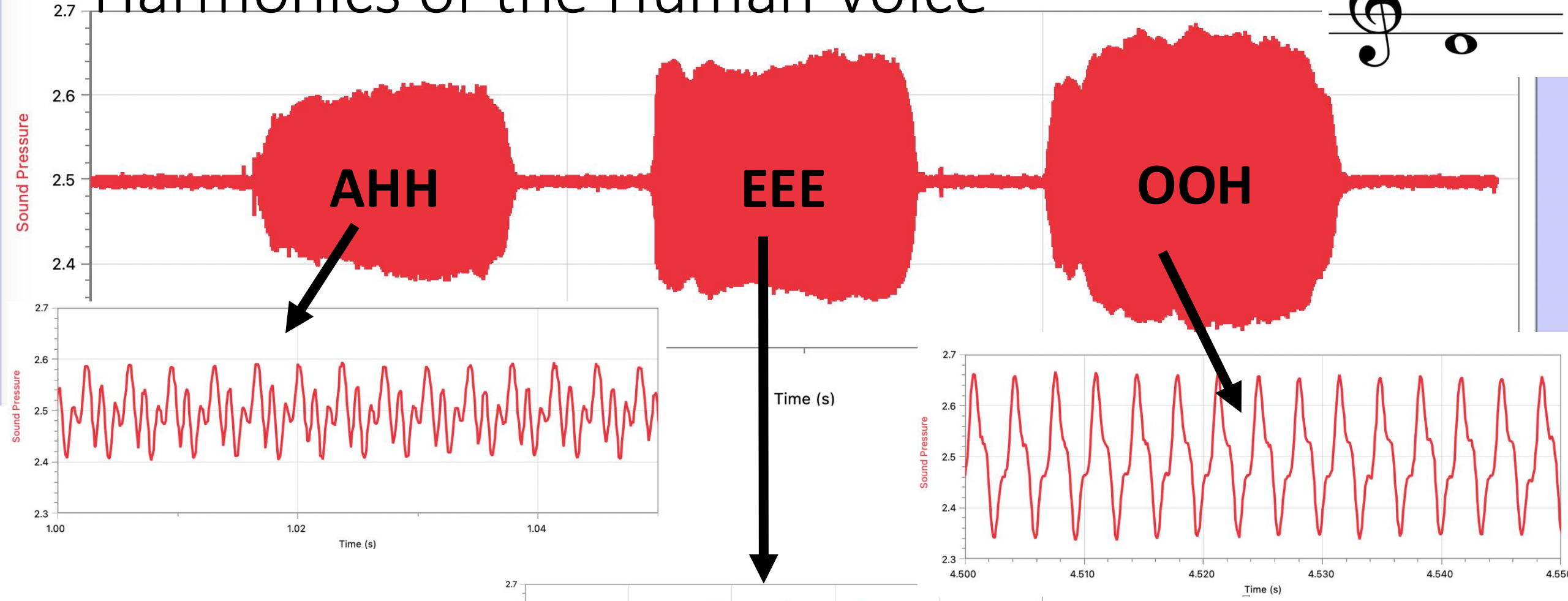


Vowel Sounds

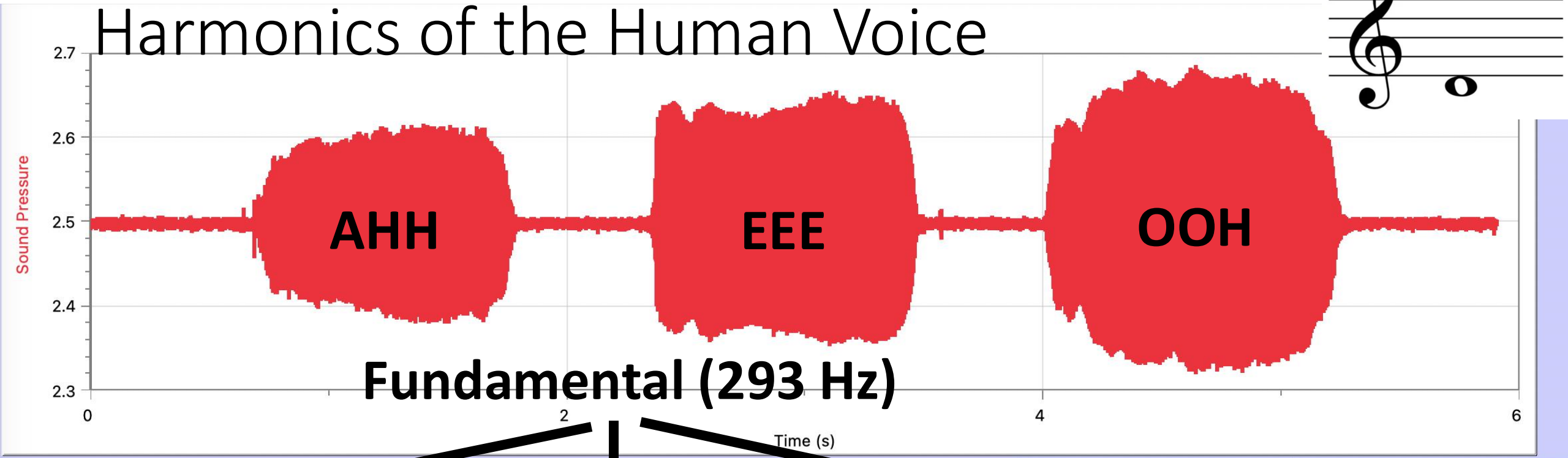
AHH **EEE** **OOH**



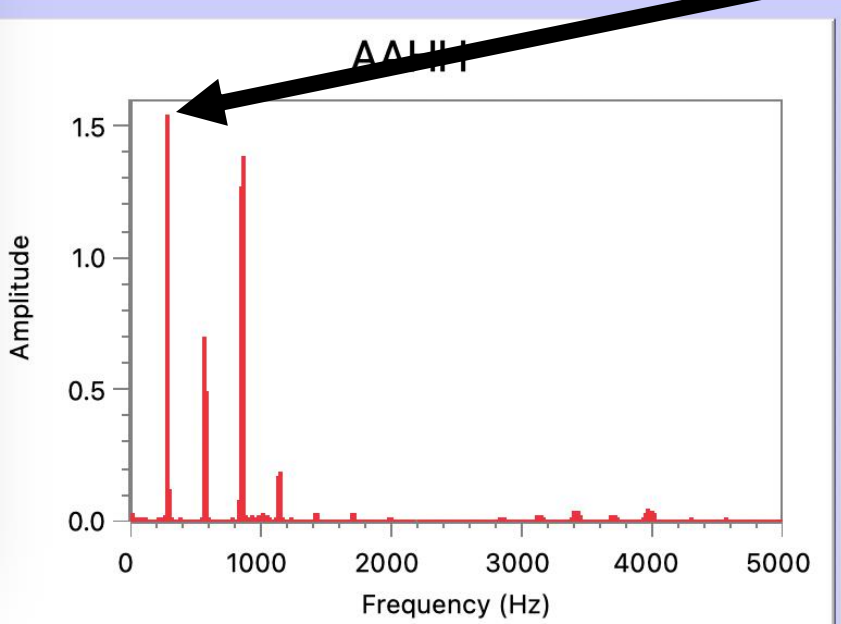
Harmonics of the Human Voice

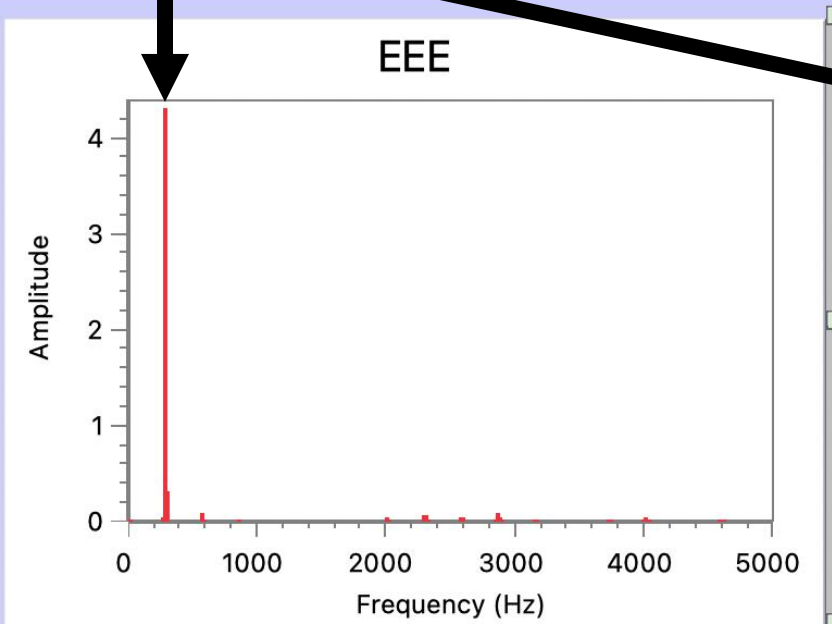


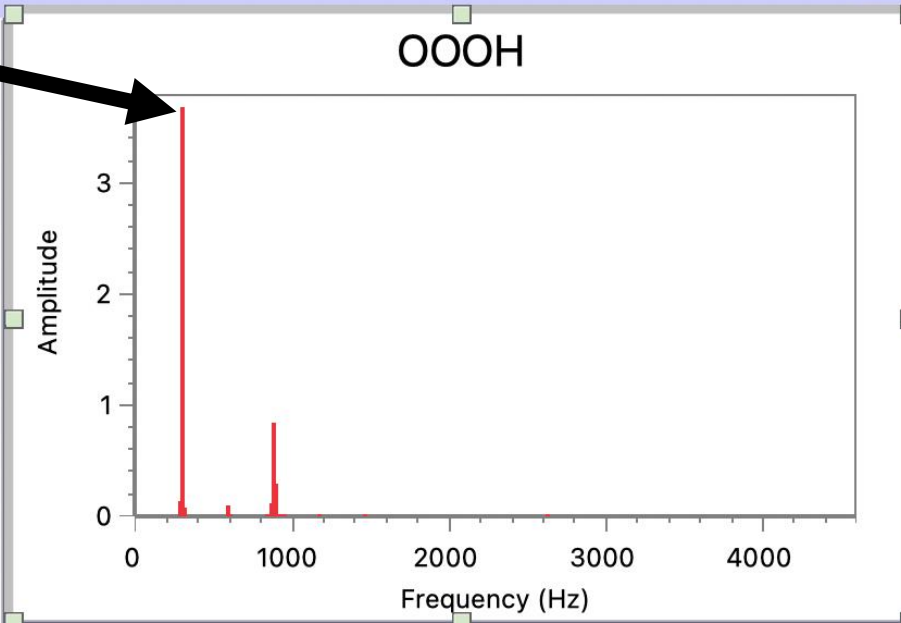
Harmonics of the Human Voice



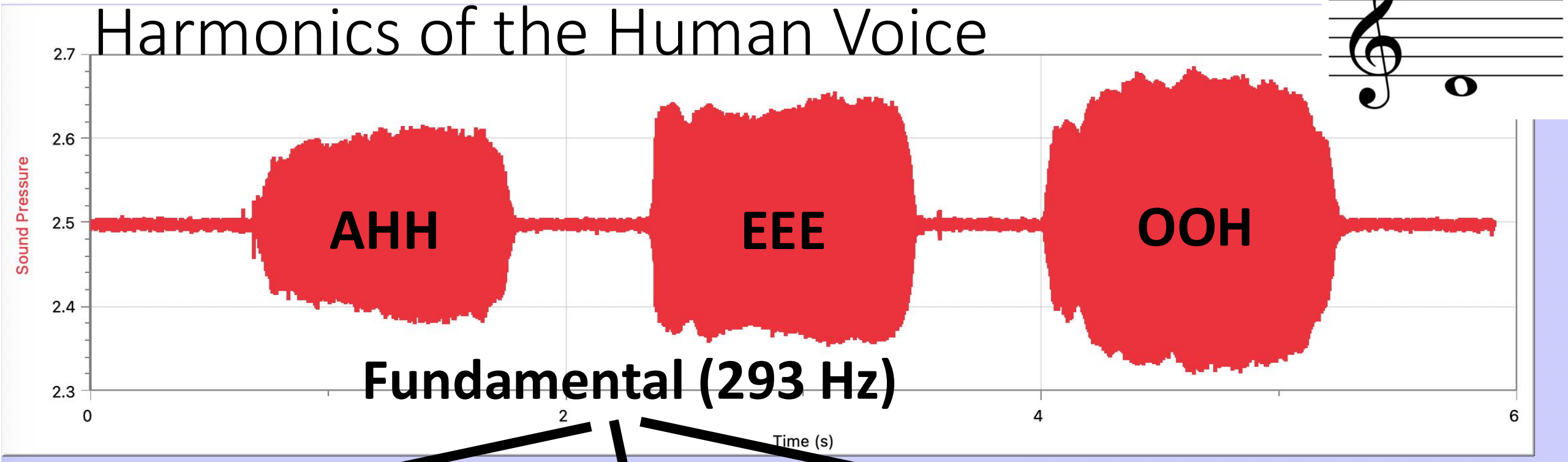
Fundamental (293 Hz)



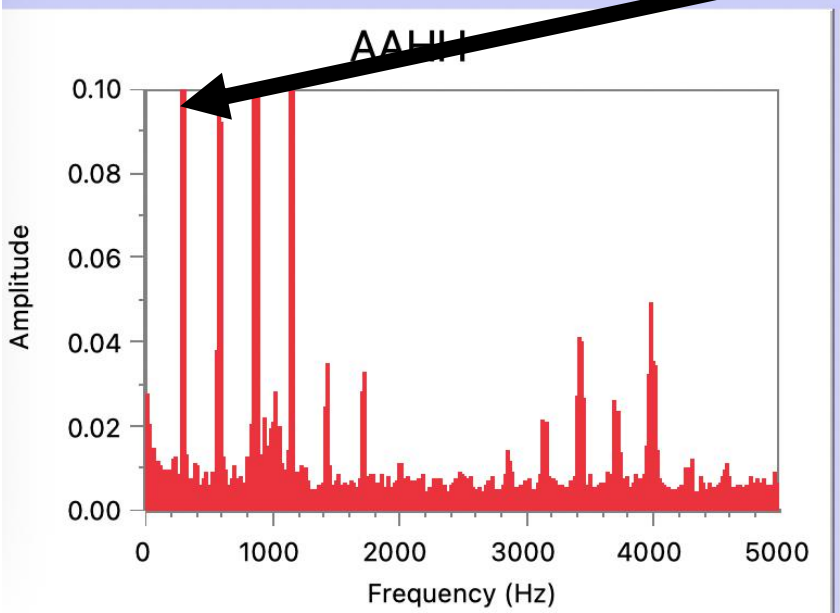


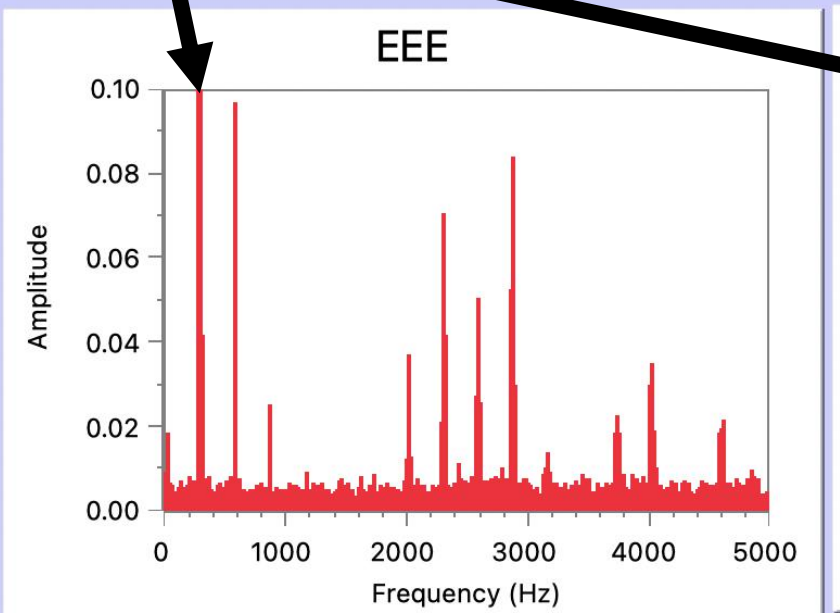


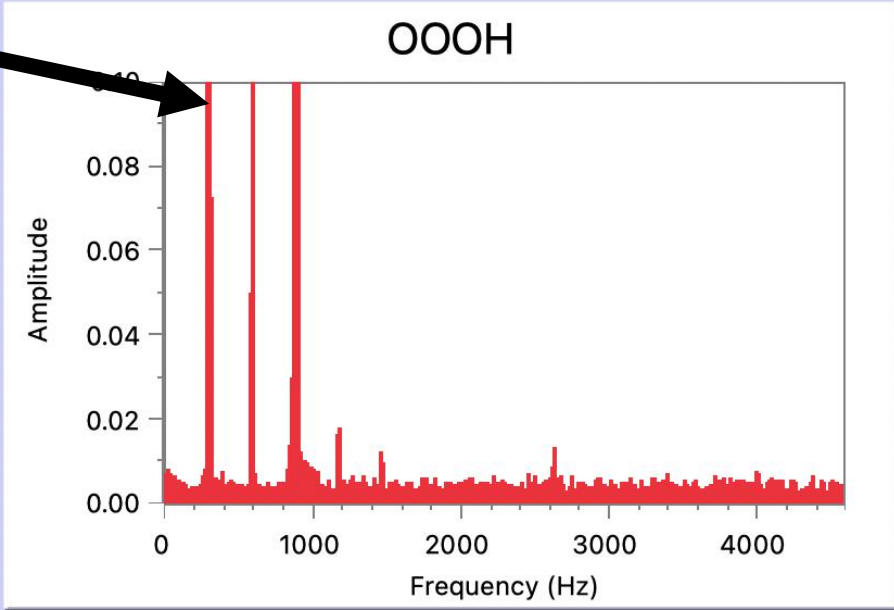
Harmonics of the Human Voice



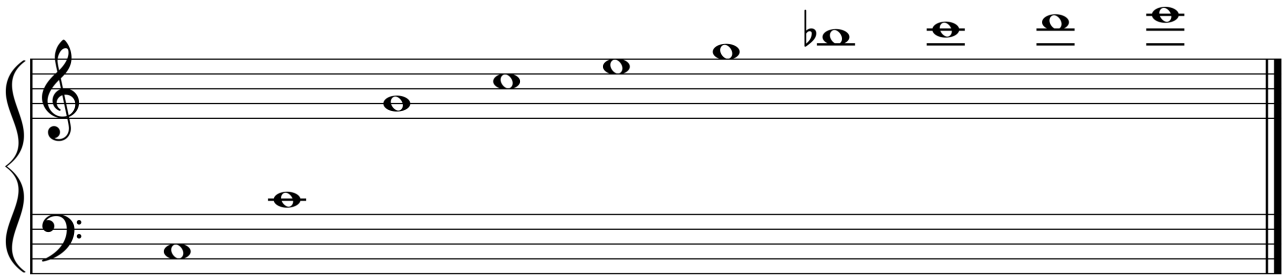
Fundamental (293 Hz)



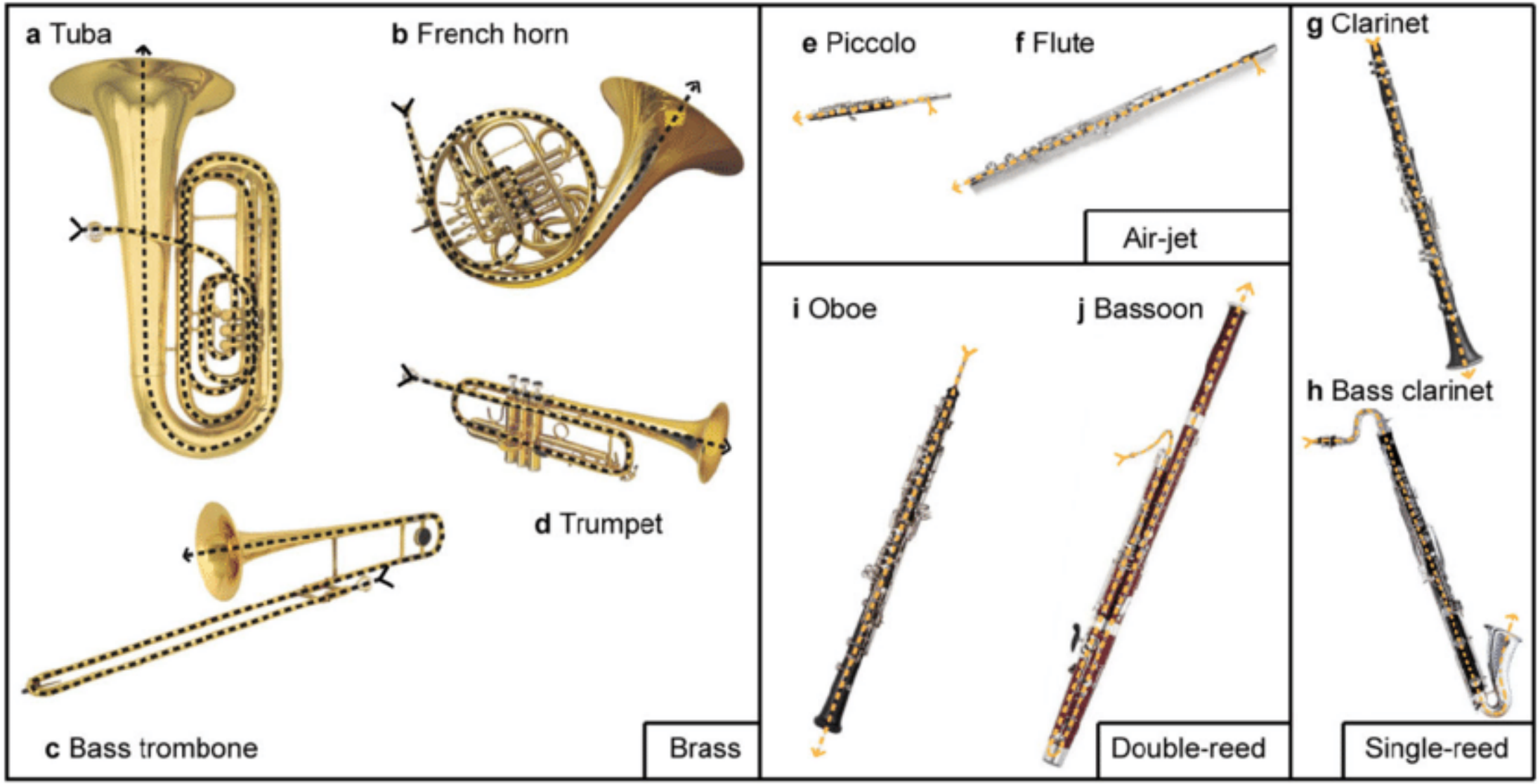




Wind Instrument Sound Production is based on Harmonics

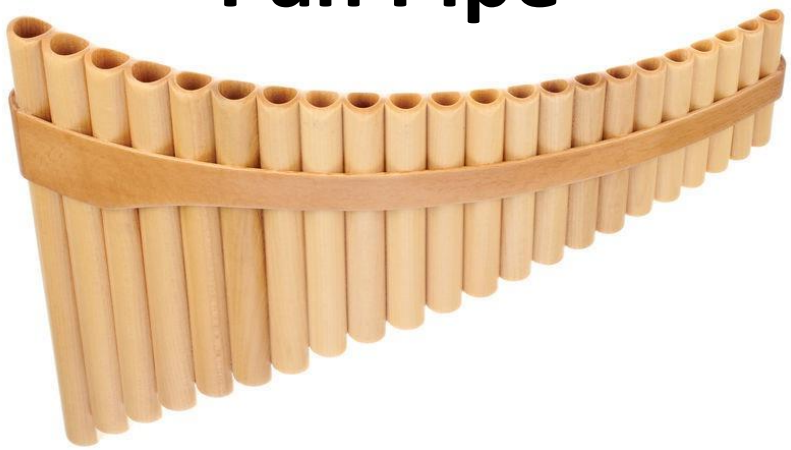


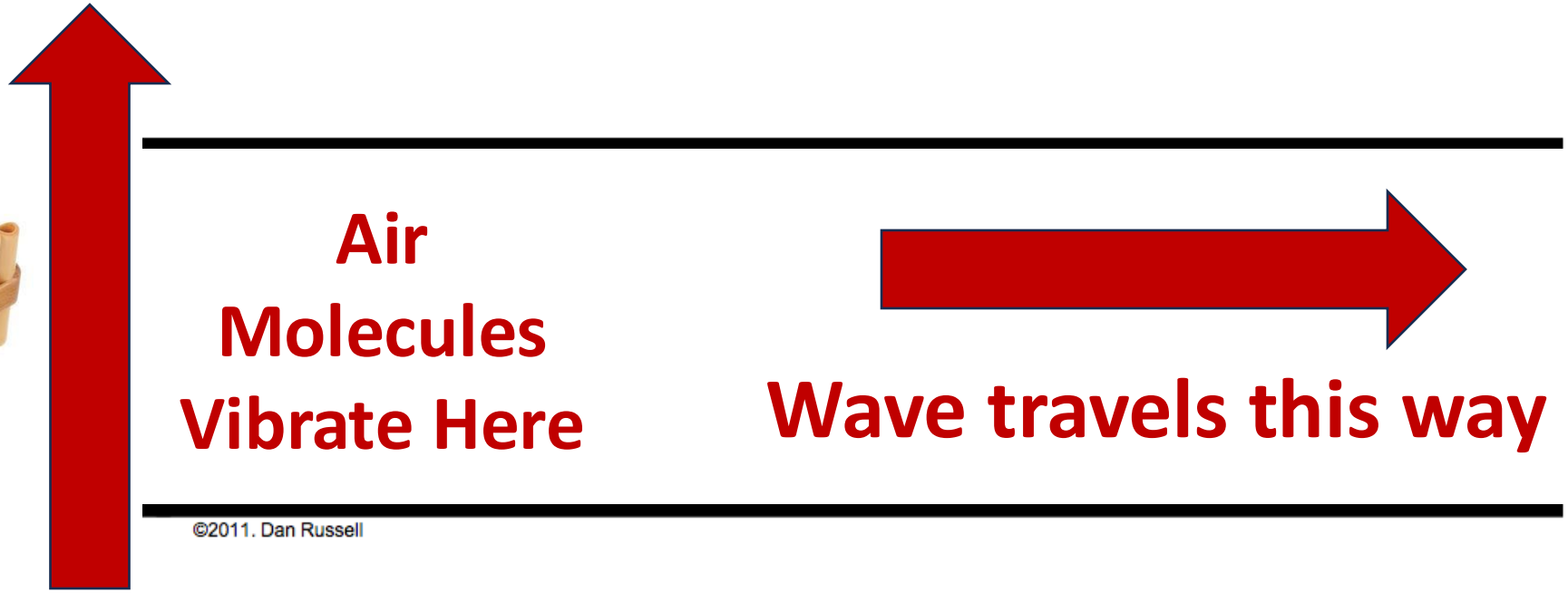
How long is the “pipe” in a wind instrument?



Air Pressure Waves inside Wind Instruments

Pan Pipe

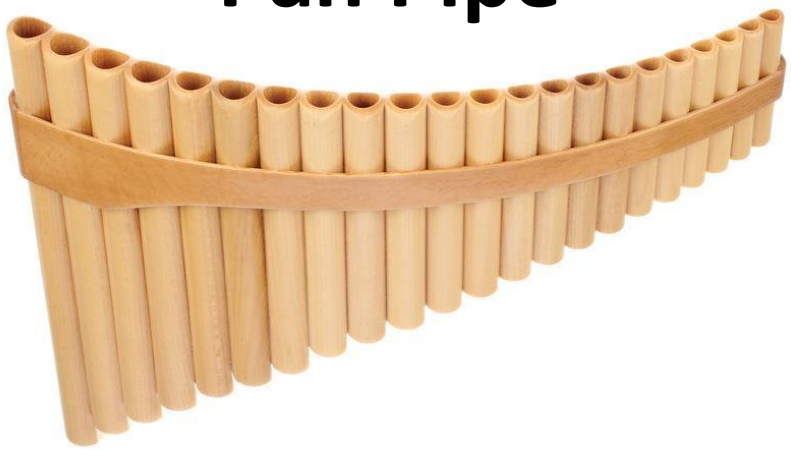


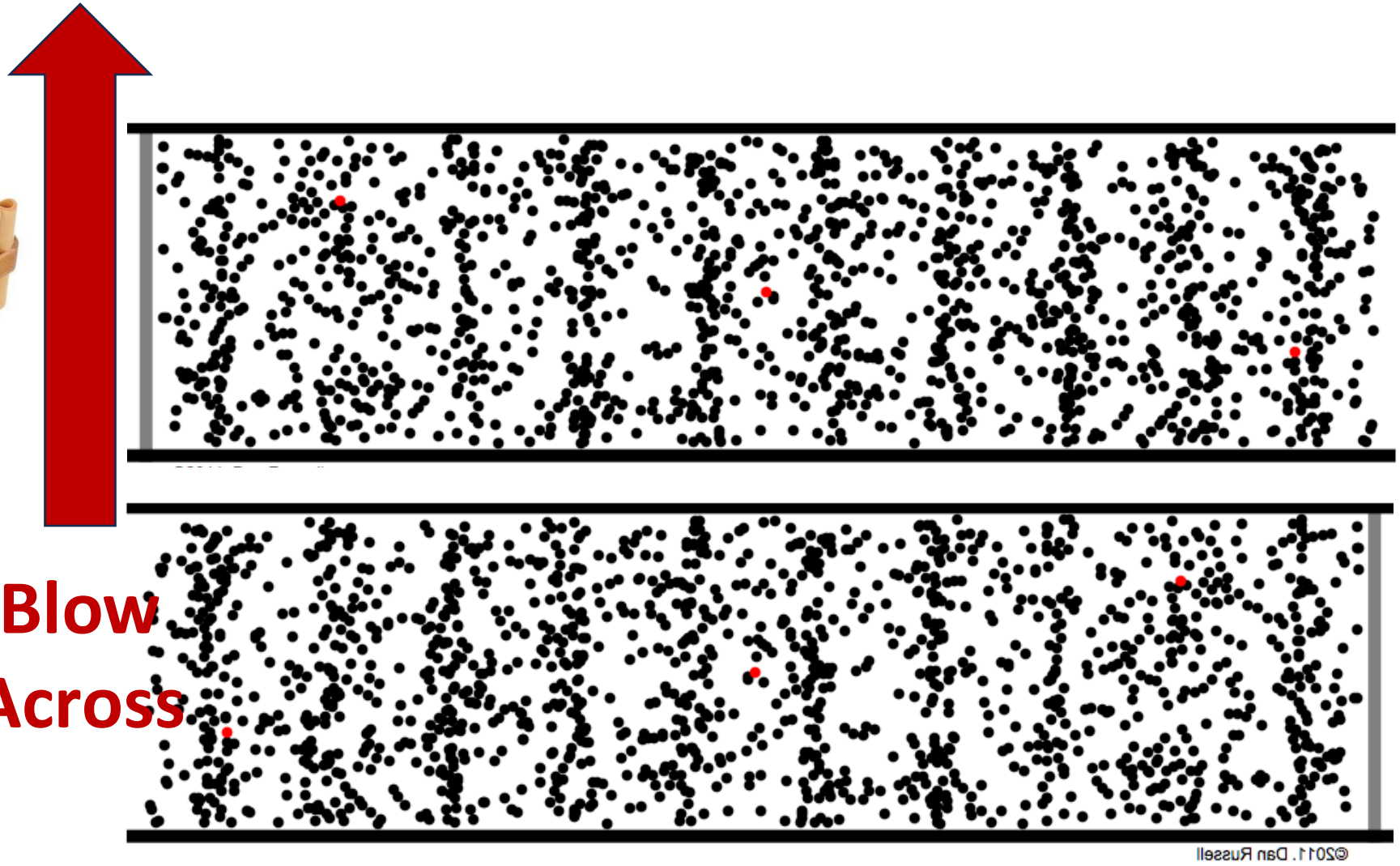


Blow Across

Air Pressure Waves inside Wind Instruments

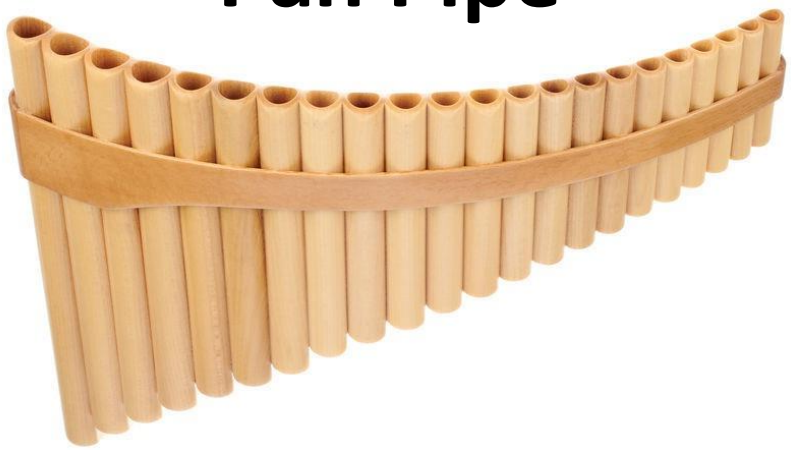
Pan Pipe

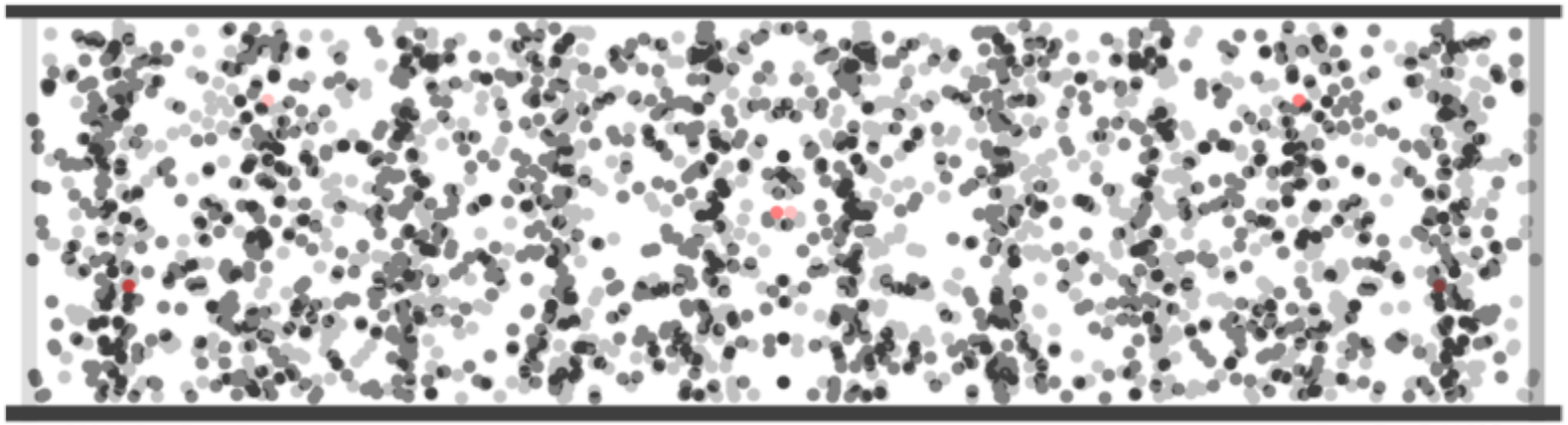




Air Pressure Waves inside Wind Instruments

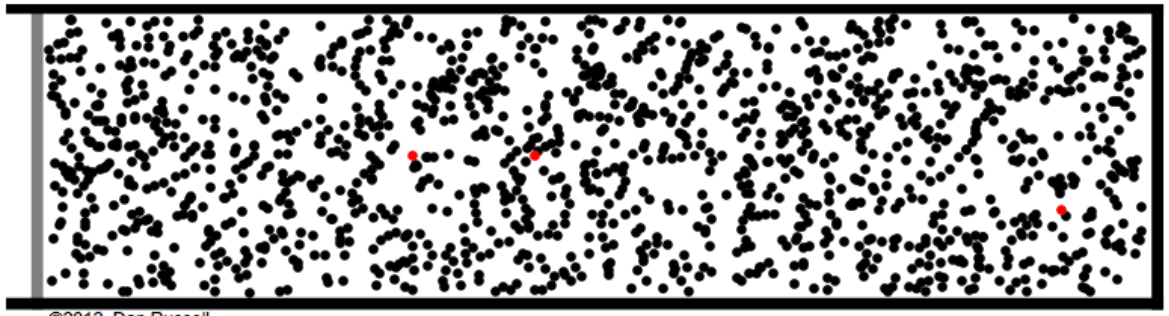
Pan Pipe





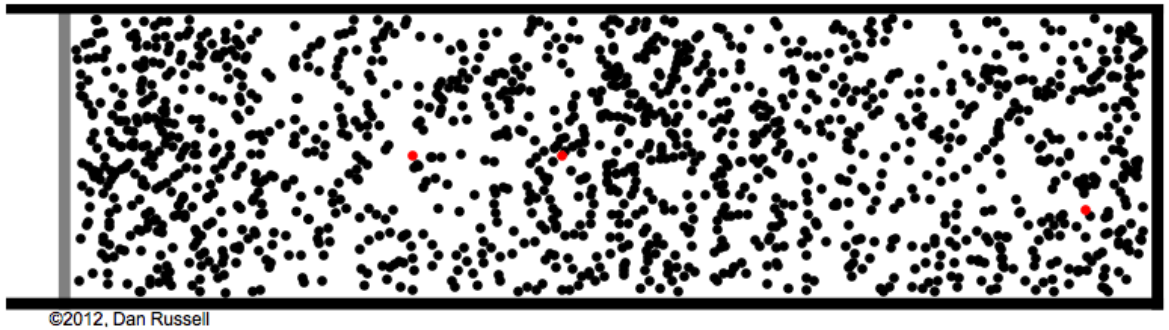
Air Pressure Waves inside Wind Instruments

Molecules:



Air Pressure Waves inside Wind Instruments

Molecules:

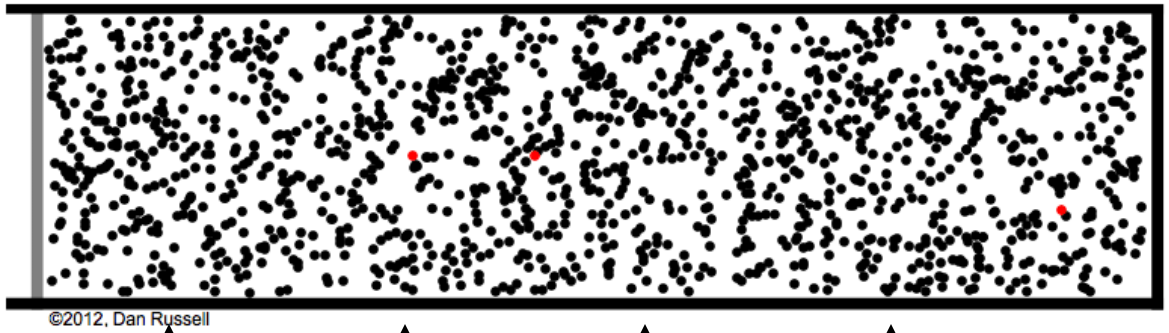


High Pressure

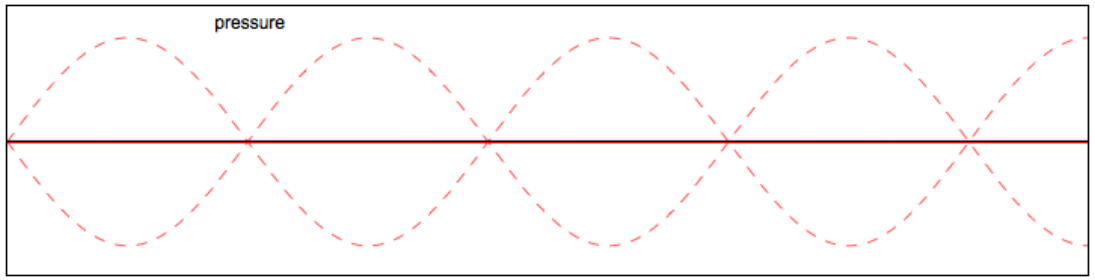
Low Pressure

Air Pressure Waves inside Wind Instruments

Air Molecules:



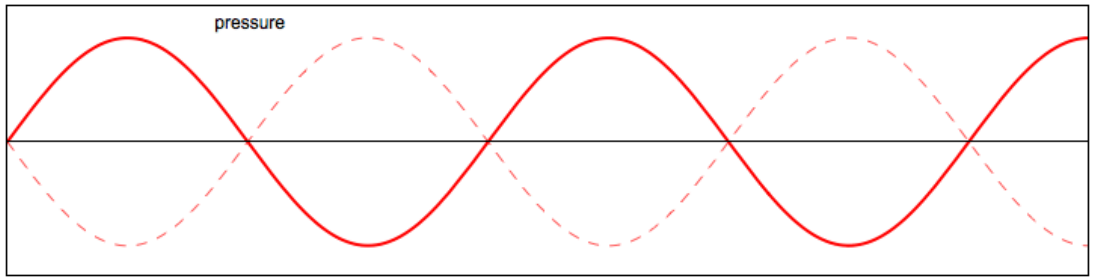
Pressure:



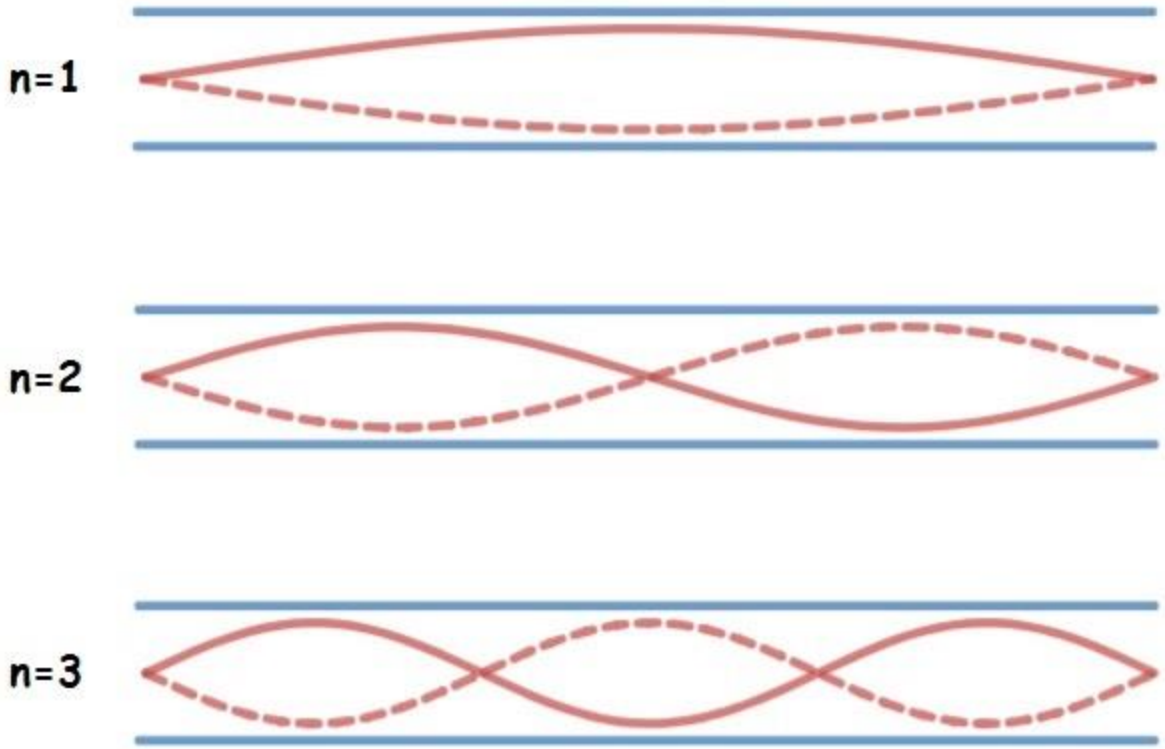
Air Pressure Waves inside Wind Instruments

Air Molecules:

Pressure:



Harmonics in Pipes



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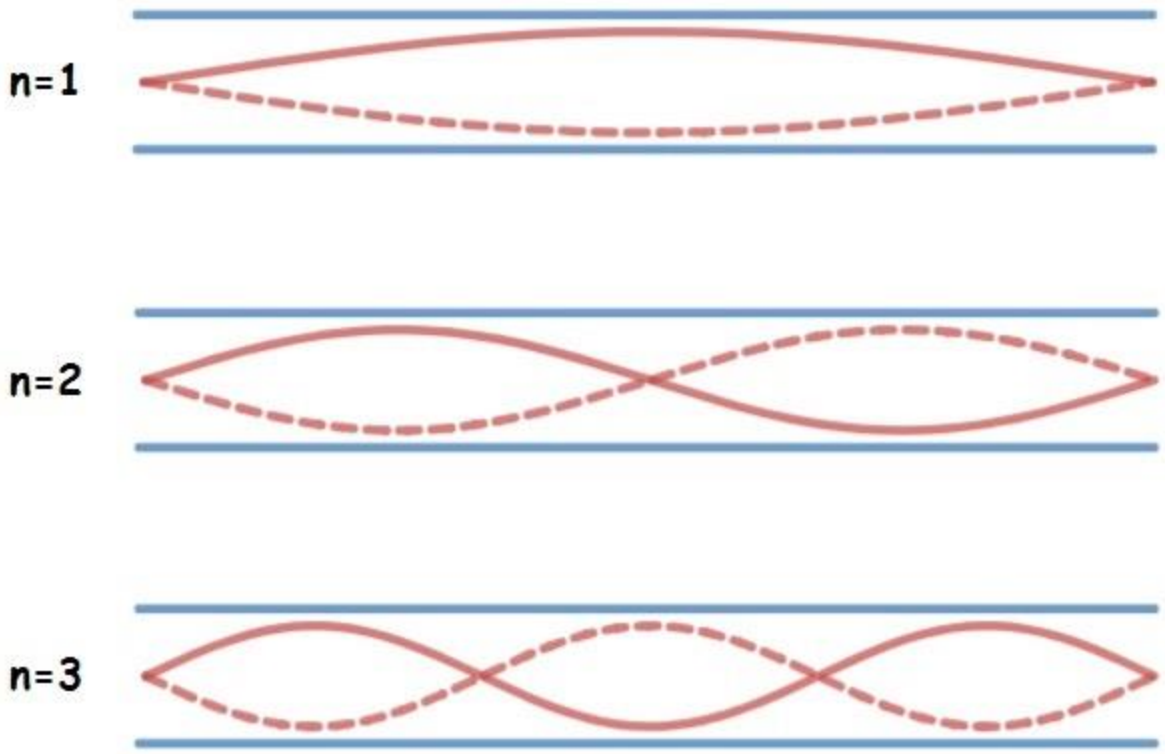
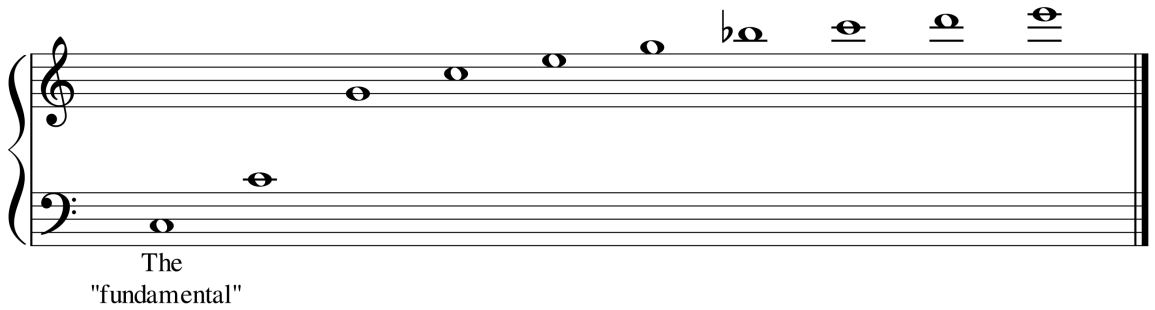
Harmonics in Pipes



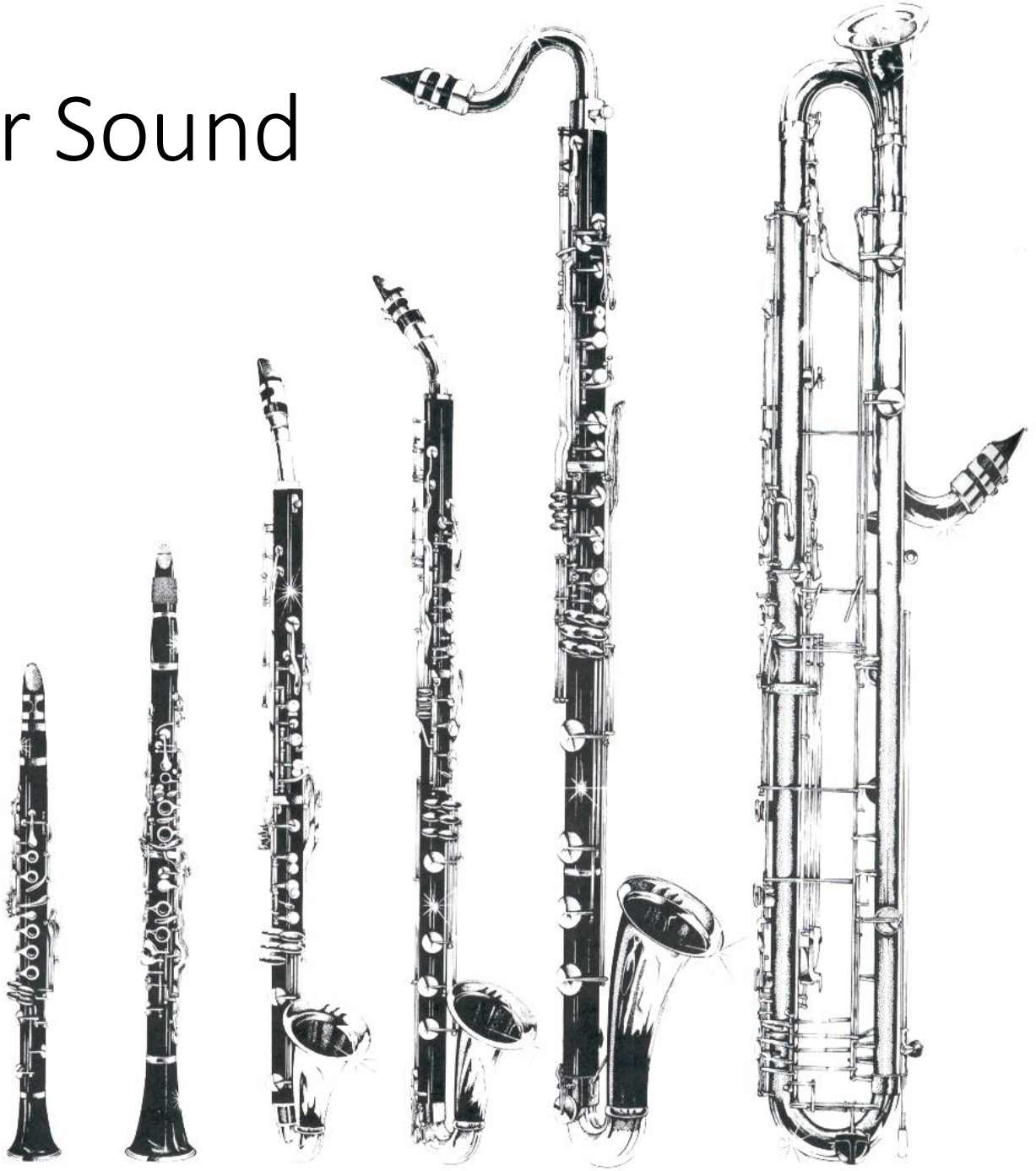


Larger Pipe = Lower Sound

Fundamental frequency:
(for an open-ended pipe)

$$f = \frac{v}{2L}$$

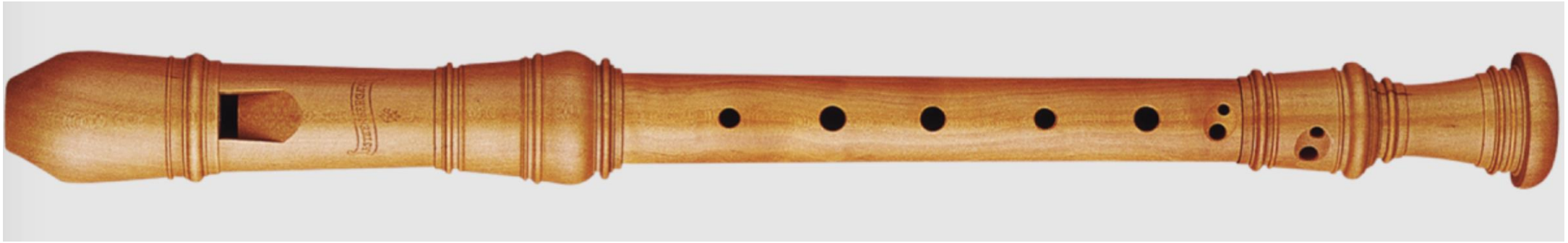
Larger Instrument = Lower Sound

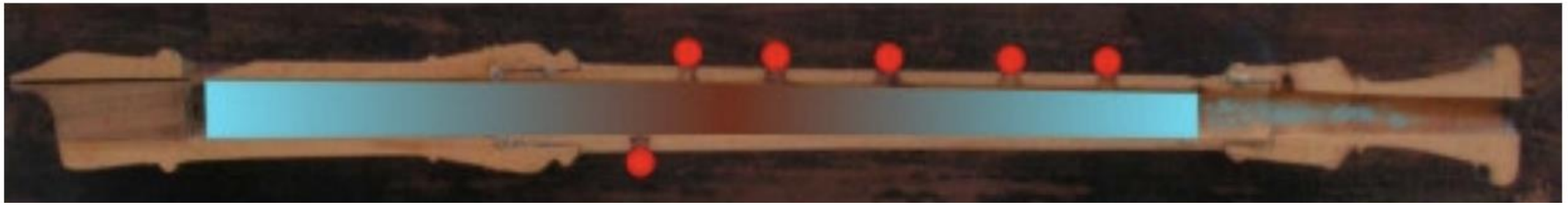


More fingers covering holes =

= longer “pipe”

= lower sound





OPEN **OPEN**

Tuning

This online applet shows how sound waves add together when instruments tune:

https://academo.org/demos/wave-interference-beat-frequency/

Tuning refers to matching the frequency produced by your instrument to a reference pitch.

FLEX Day Evaluation Link: