OSHER LIFELONG LEARNING INSTITUTE

Sound of Music

How It Works

Session 2
Resonance: Building Musical Sounds

The Most Unusual Musical Instruments of the World
PerdoscopeTV (YouTube 2016)

OLLI at Illinois

Spring 2020

D. H. Tracy

OSHER LIFELONG LEARNING INSTITUTE

An Ear for Music

Session 2
Resonance and Building Complex Sounds

OLLI at Illinois

Spring 2024

D. H. Tracy

Course Outline

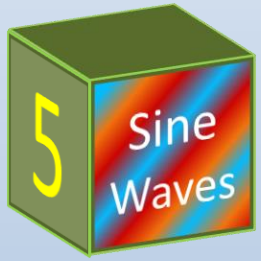
1. Building Blocks: Some basic concepts
2. **Resonance: Building Complex Sounds**
3. Hearing and the Ear
4. Musical Scales and Musical Notation
5. Musical Instruments: Strings and Others
6. Musical Instruments: Pipes
7. Human Voice and Singing
8. Harmony and Dissonance; Chords

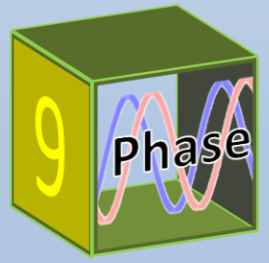
Question Times

- Zoomland
- In Person

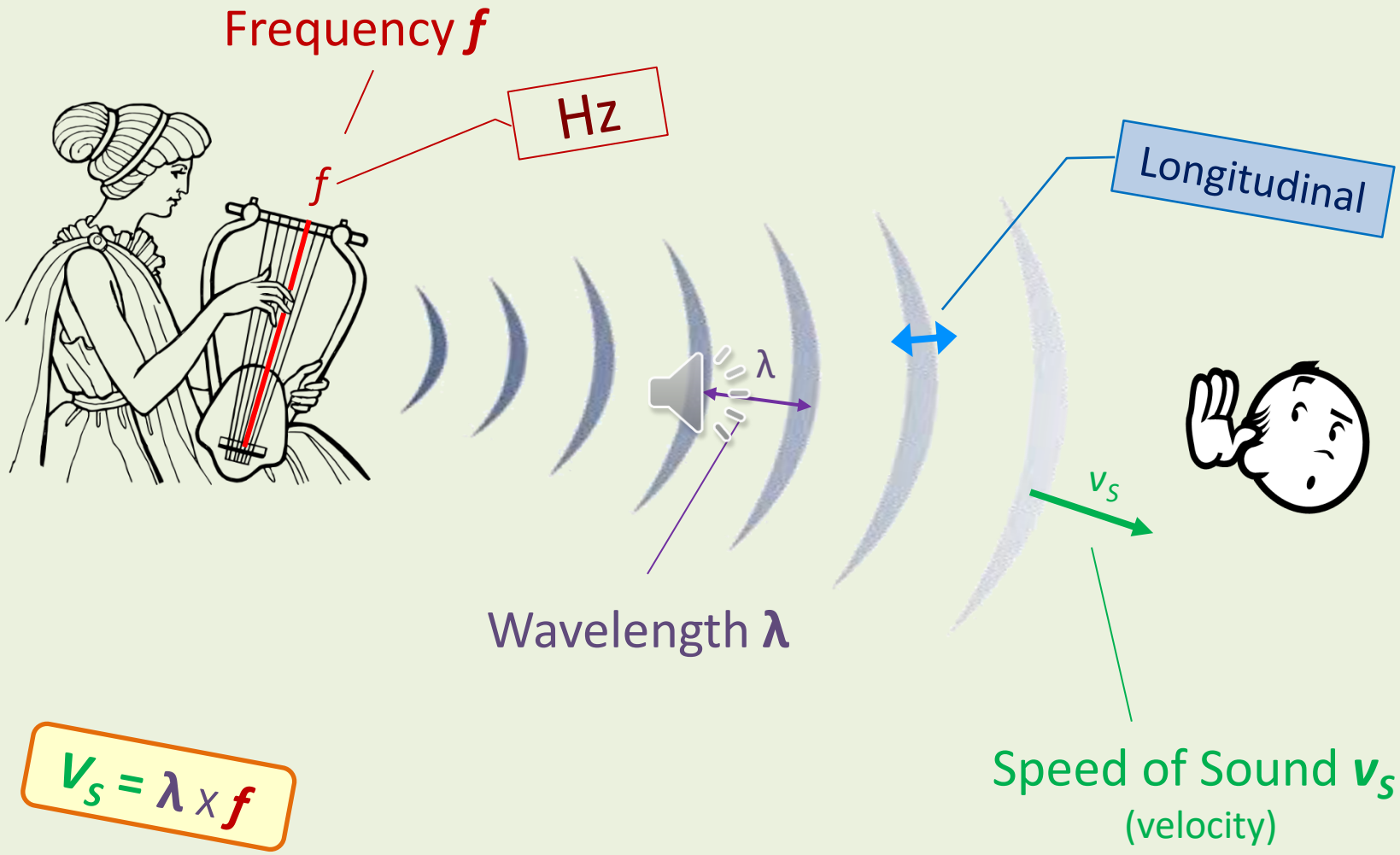
- Halfway Through
- At the End

Session 1 Outline: Building Blocks

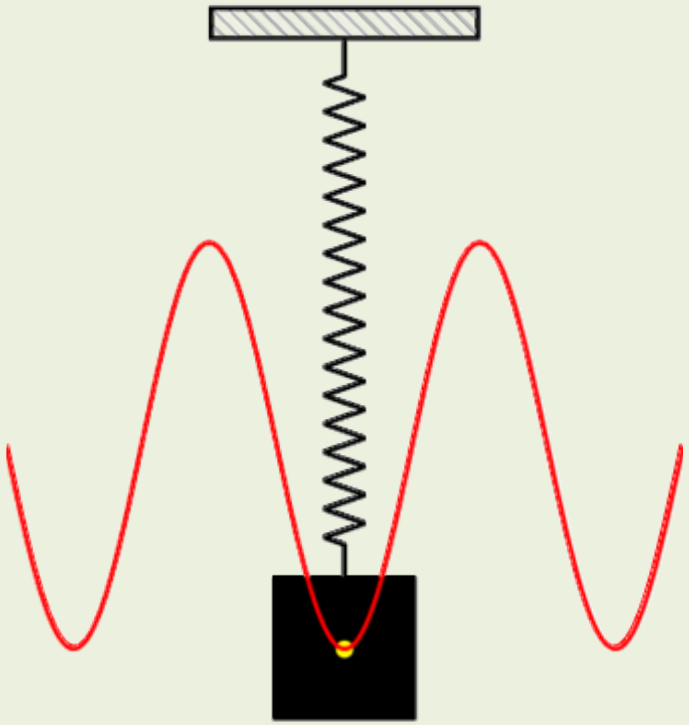




Sound As Compression Waves



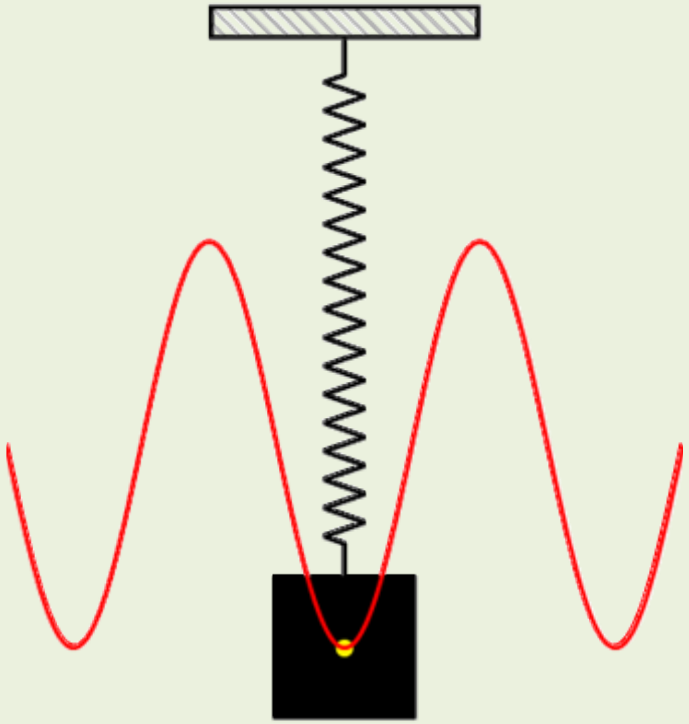
Simple Harmonic Oscillator



Imgur.com

James Dodd: You-Tube

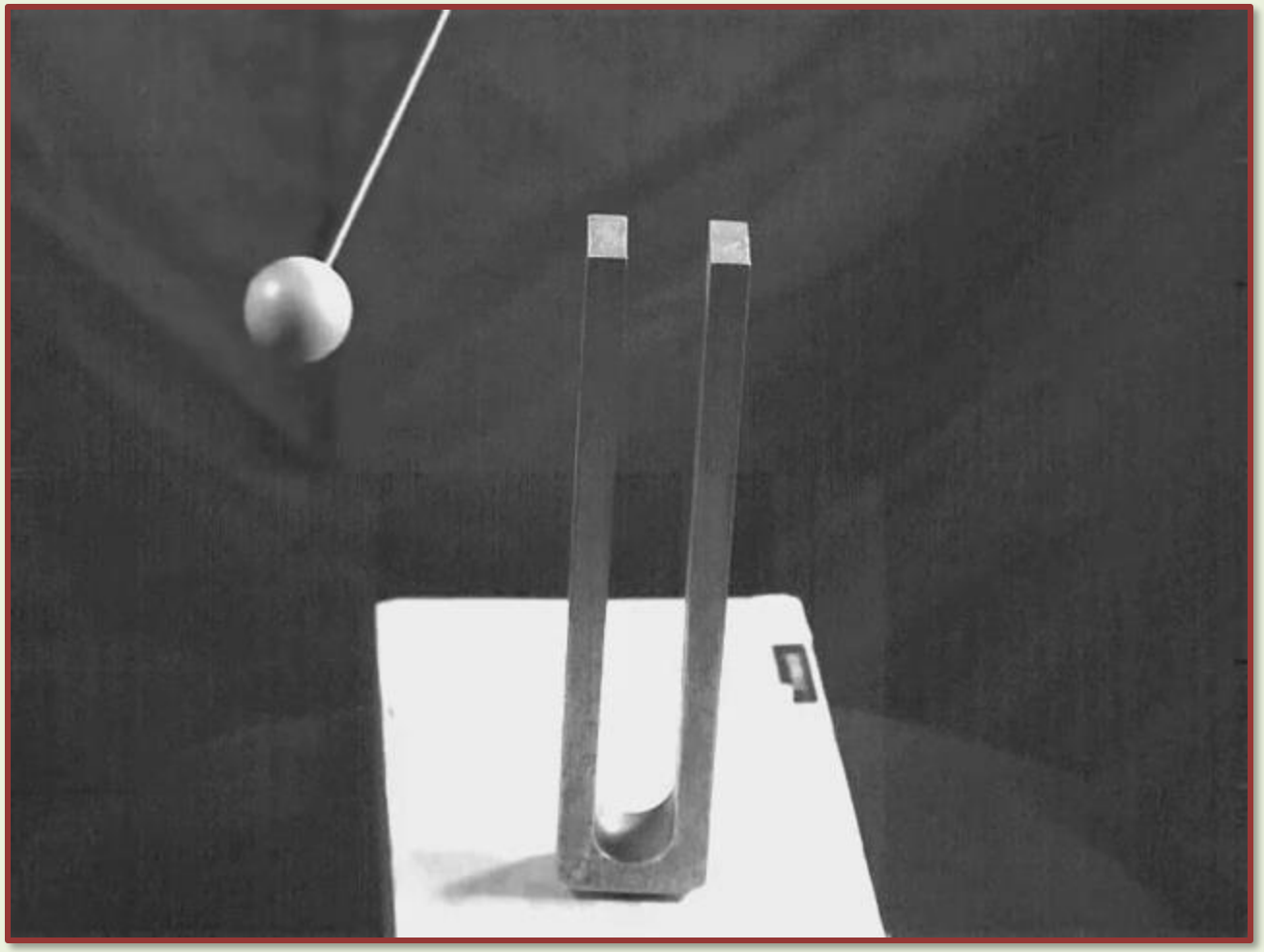
Simple Harmonic Oscillator



Imgur.com

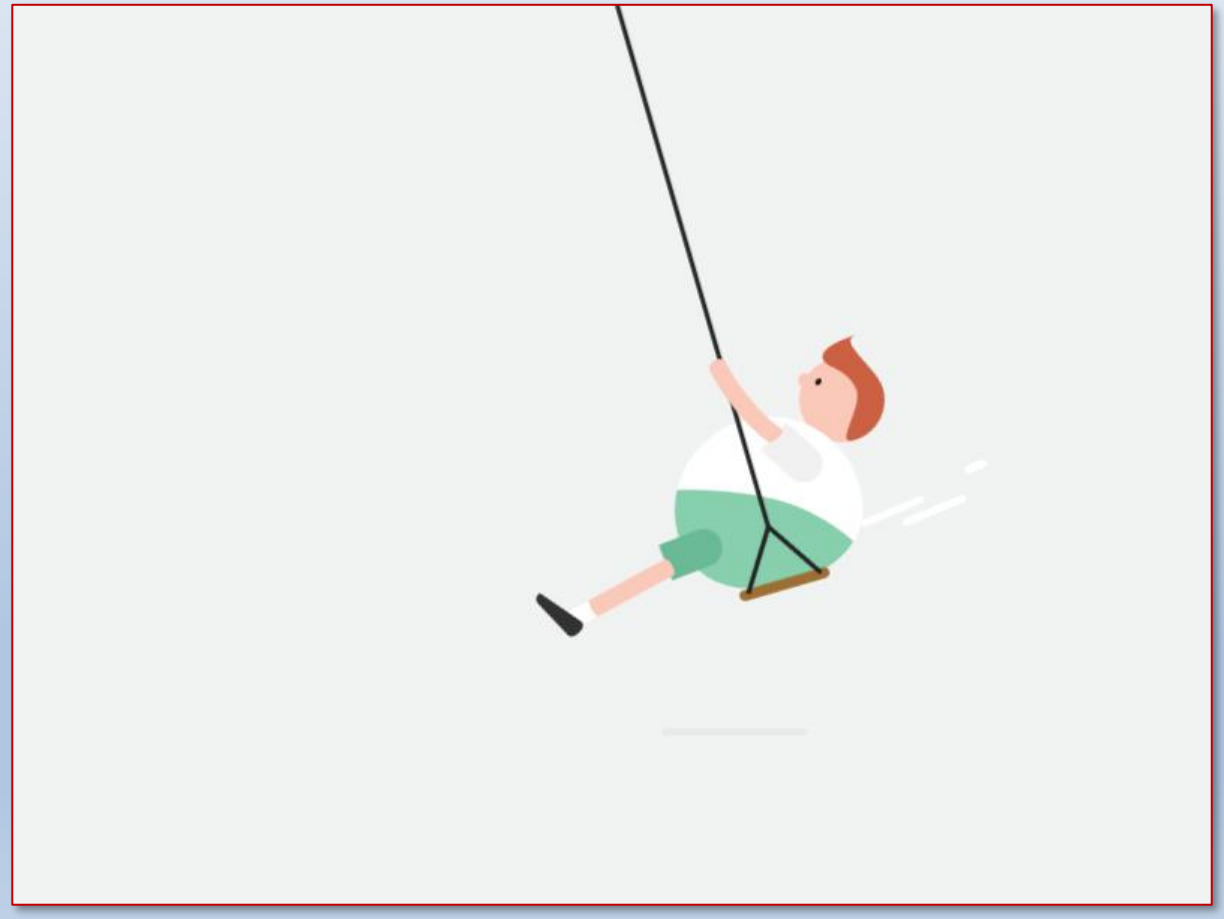
James Dodd: You-Tube

Tuning Fork



Michigan Tech
YouTube
9/11/2014

Resonators can be excited by well-timed nudges



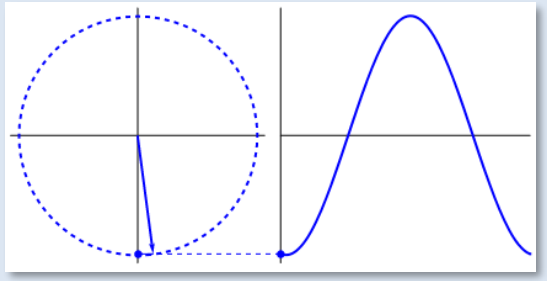
How can we make Sine Waves?

- Simple Harmonic Oscillators do it

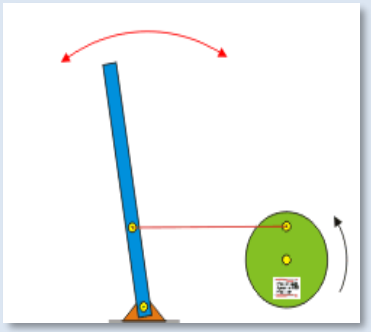
Simple Pendulum

Mass on Spring

e.g. Tuning Fork



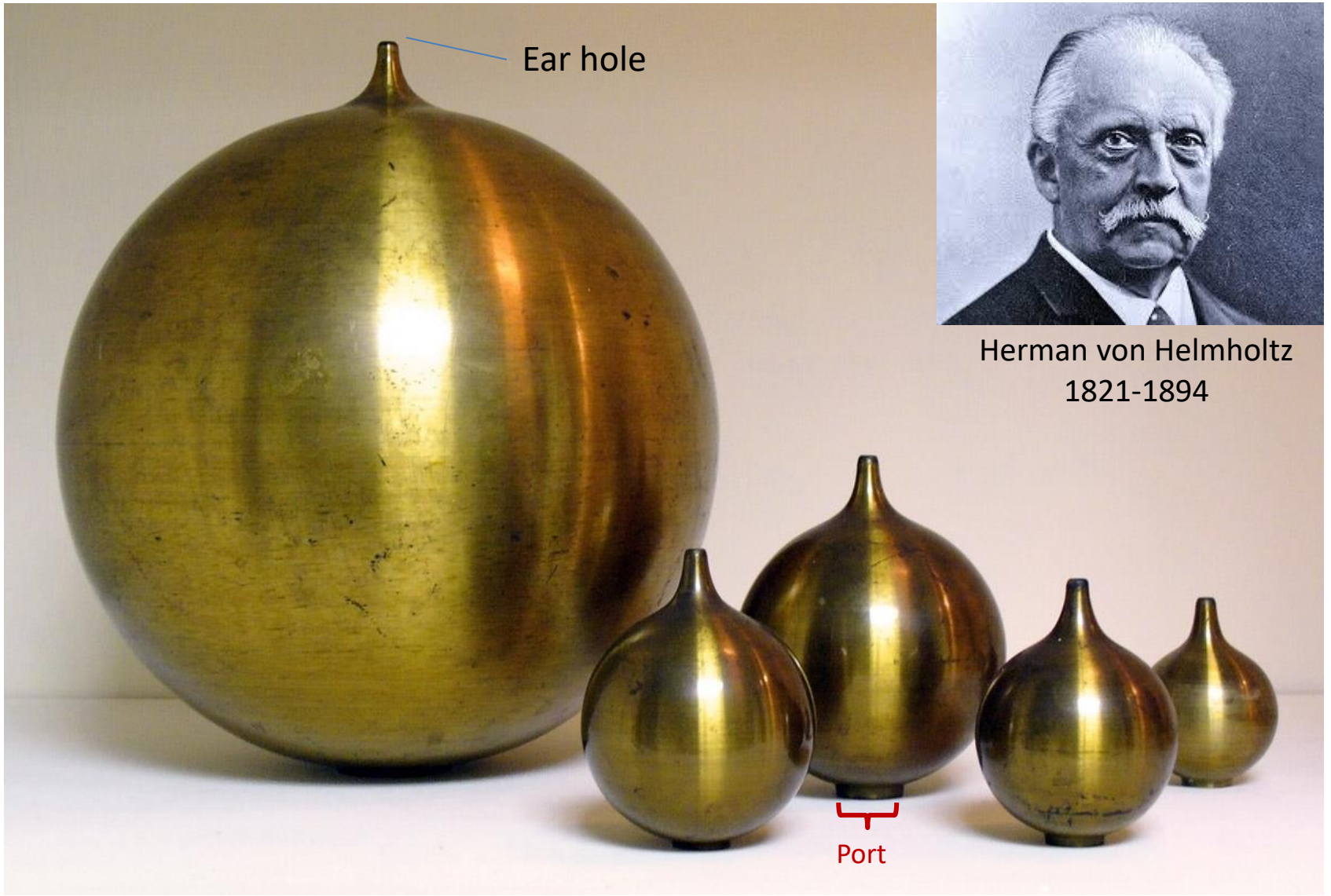
Circular Projection



e.g. Rotational Crank Mechanism

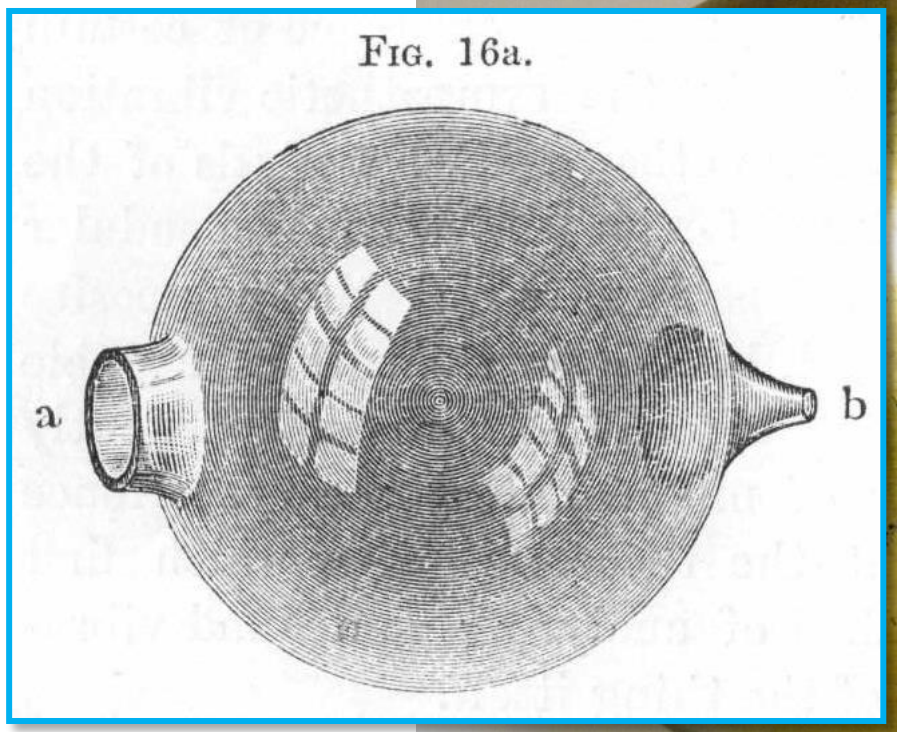
- Electronics can also do it

Helmholtz Resonators



Herman von Helmholtz
1821-1894

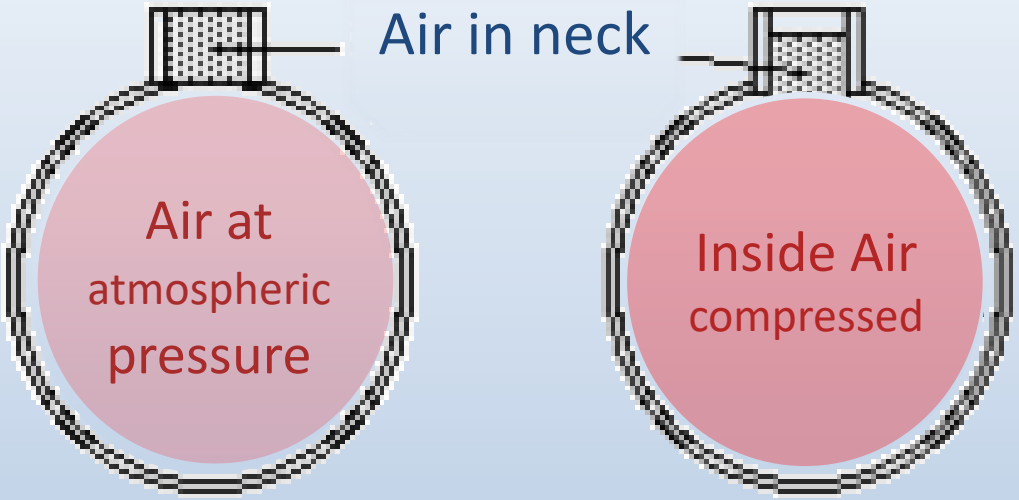
Helmholtz Resonators



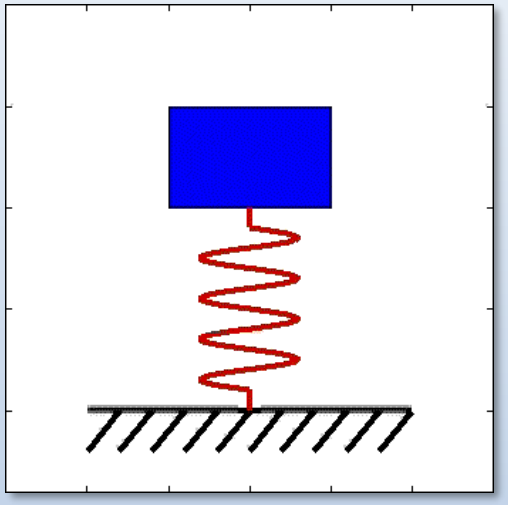
Herman von Helmholtz
1821-1894

Smithsonian National Museum of American History (2012)

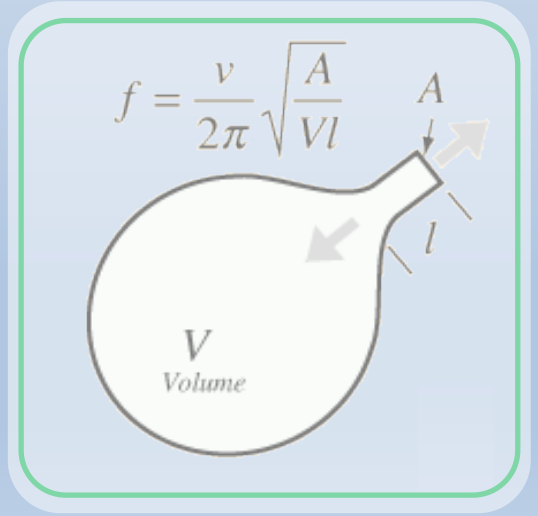
Helmholtz Resonators



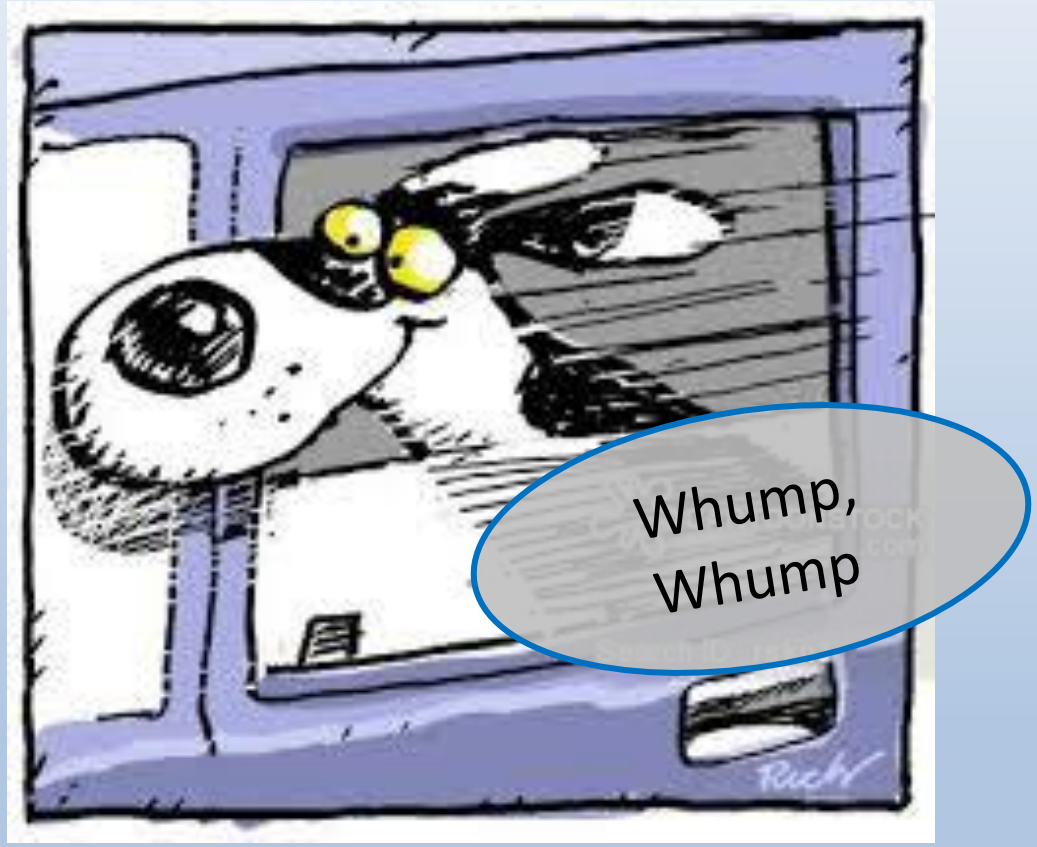
Simple Harmonic Oscillator



- The air is the Neck is the Mass
- The air in the volume acts as the spring



Ever experience a Whump-Whump in your car when a rear window is cracked open?



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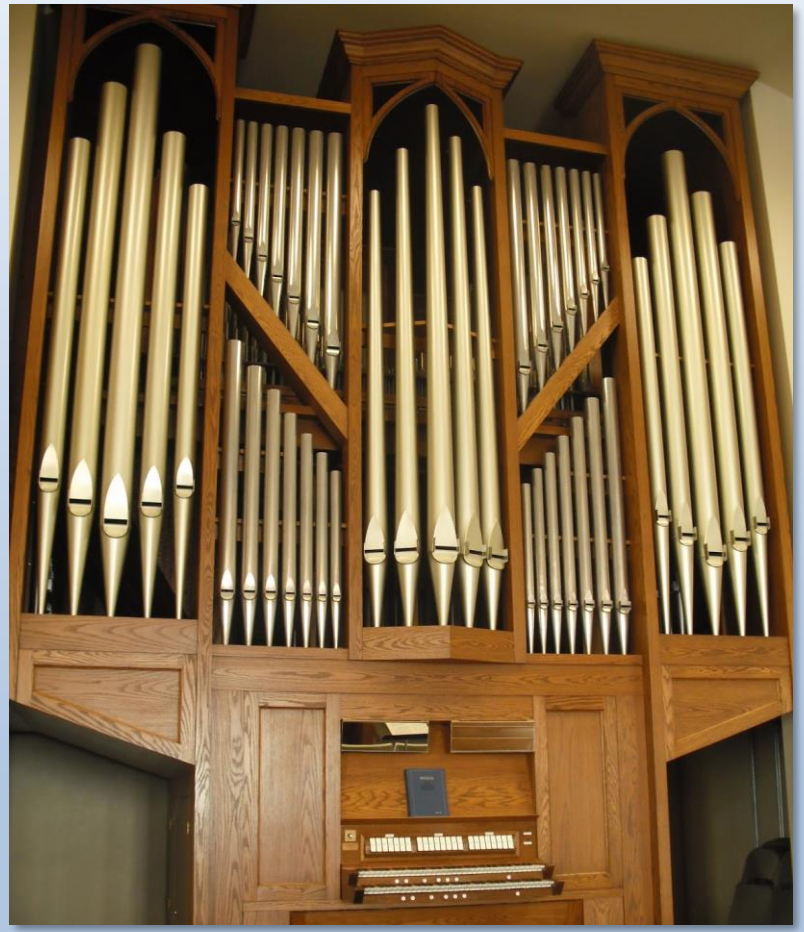
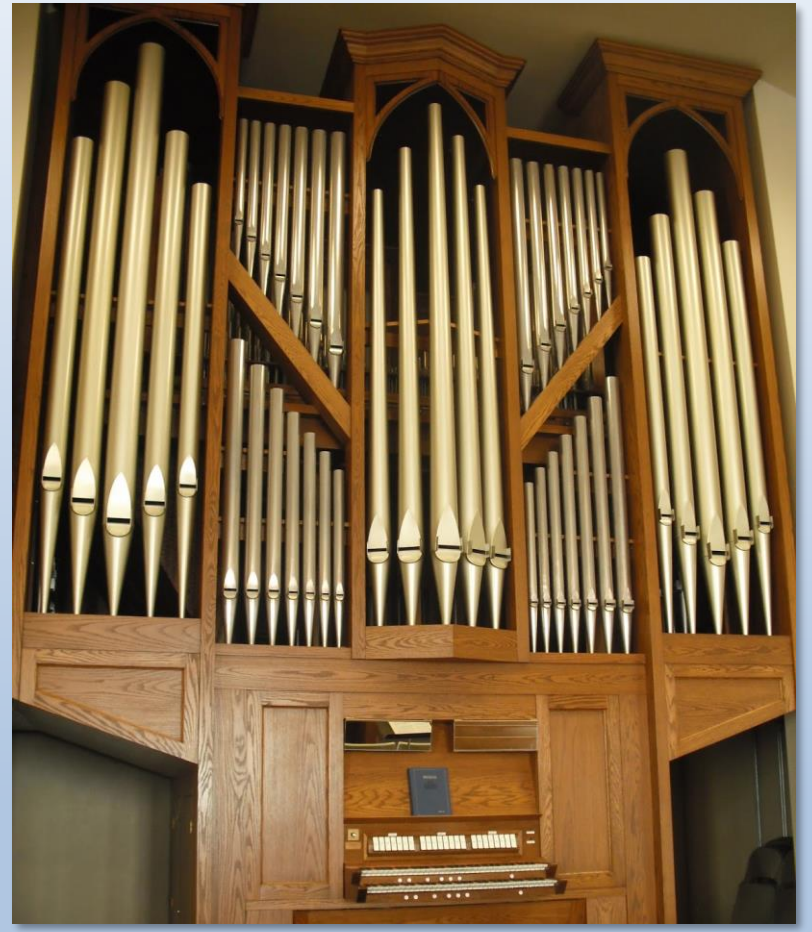
Resonators Using Strings and Pipes



Resonators Using Strings and Pipes

Anne Sullivan playing Siciliana (Respighi)



Resonators Using Strings and Pipes

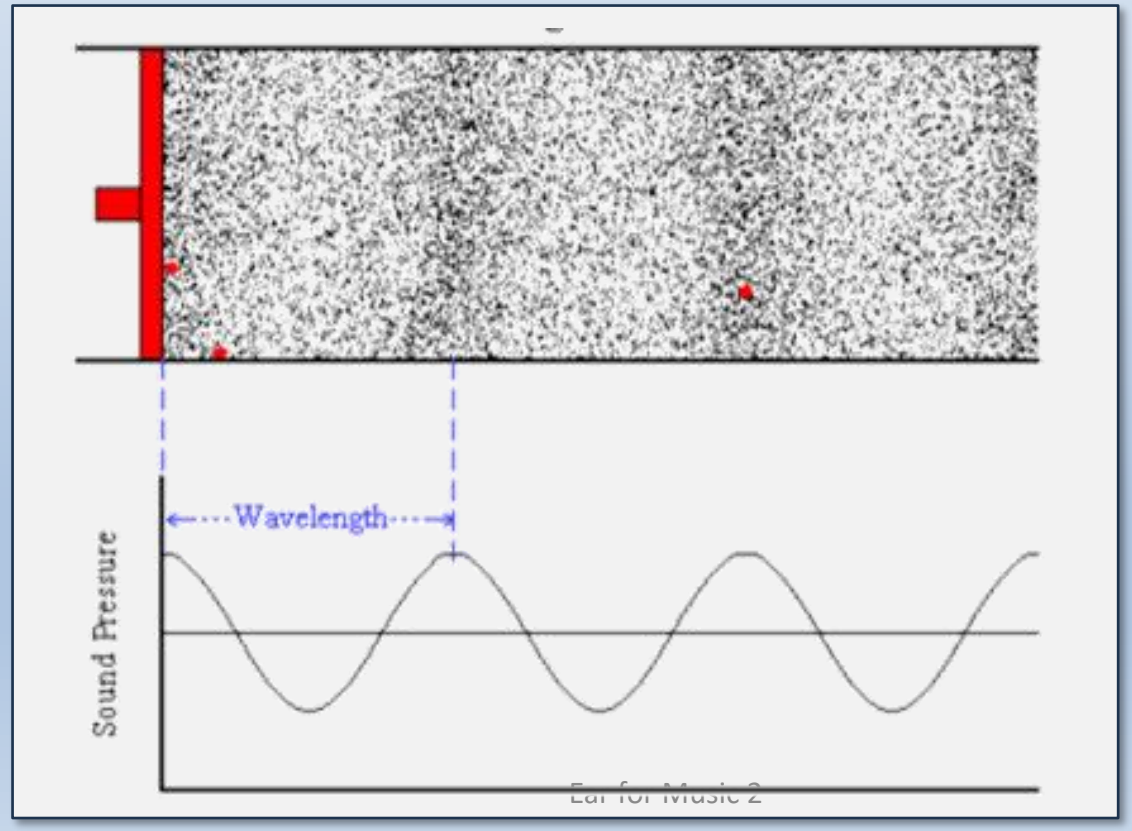
Prelude in C Major (Bach): Brian of the LDS [Liahona.net]

Resonators Using Strings and Pipes

Easiest way to understand these is via the concept of "Standing Waves"

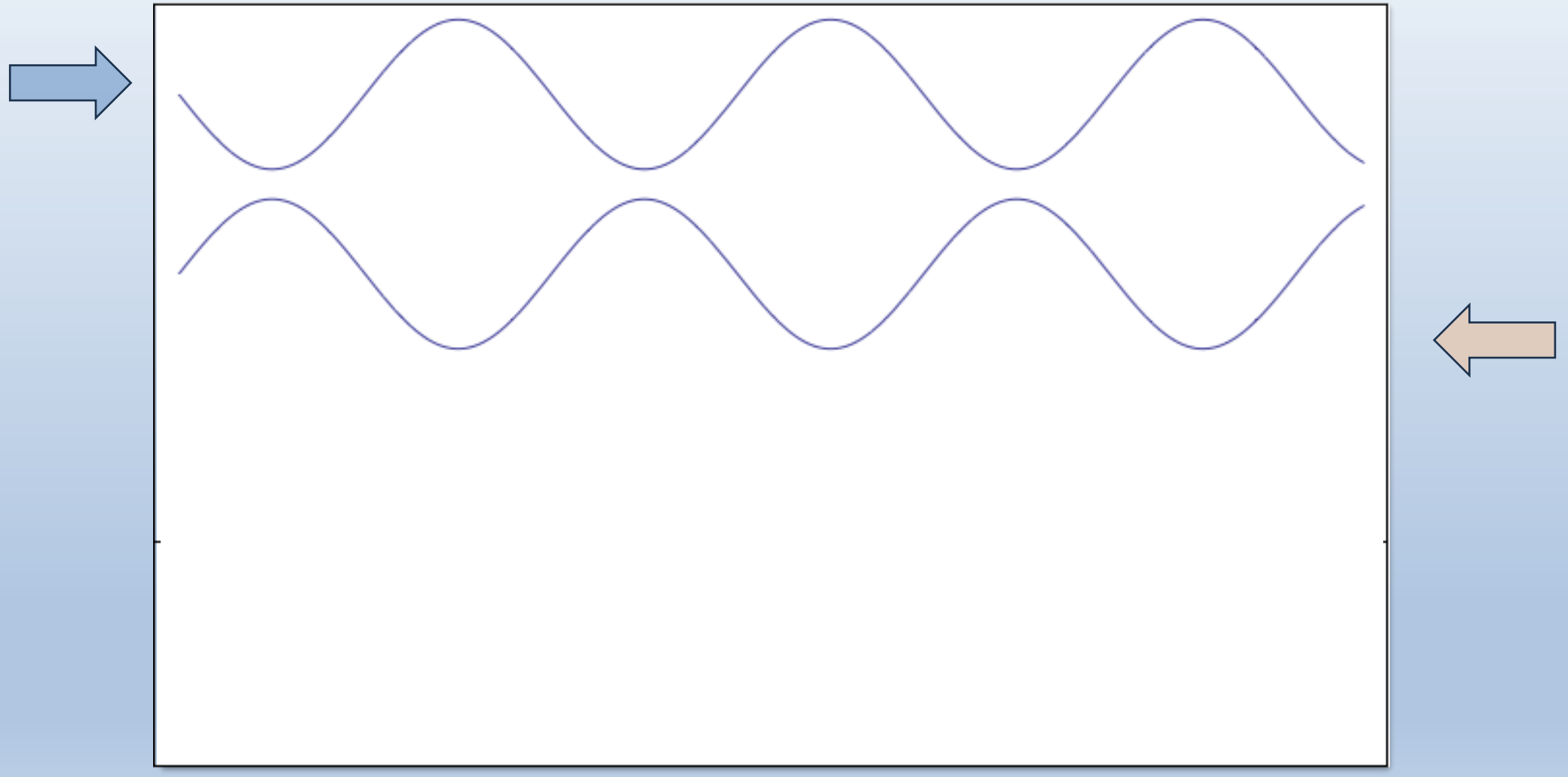
Traveling Waves

Transverse Waves
on a Rope or String



Longitudinal
Sound Waves

2 **Traveling** Waves Combine… To Form a **Standing** Wave



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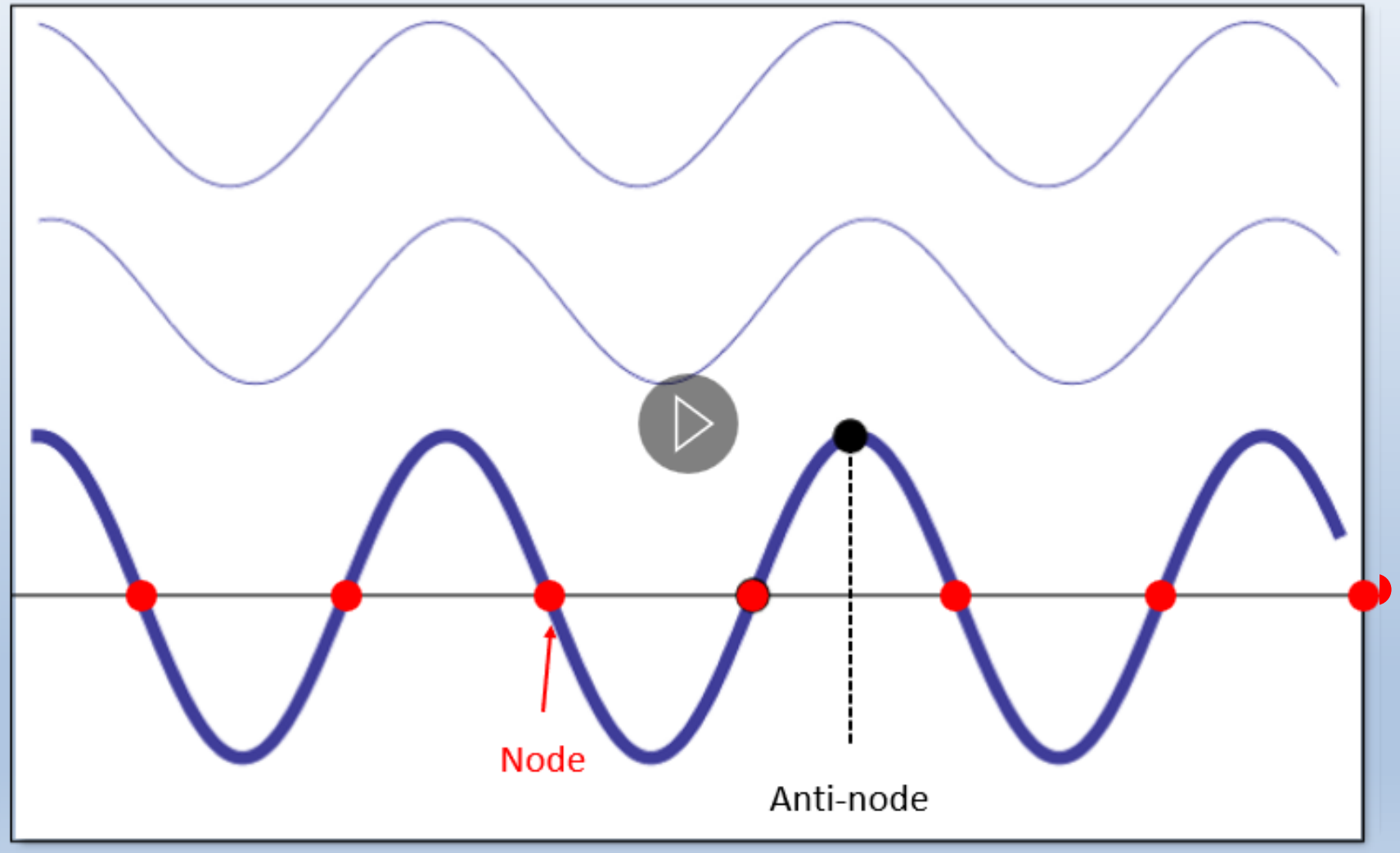

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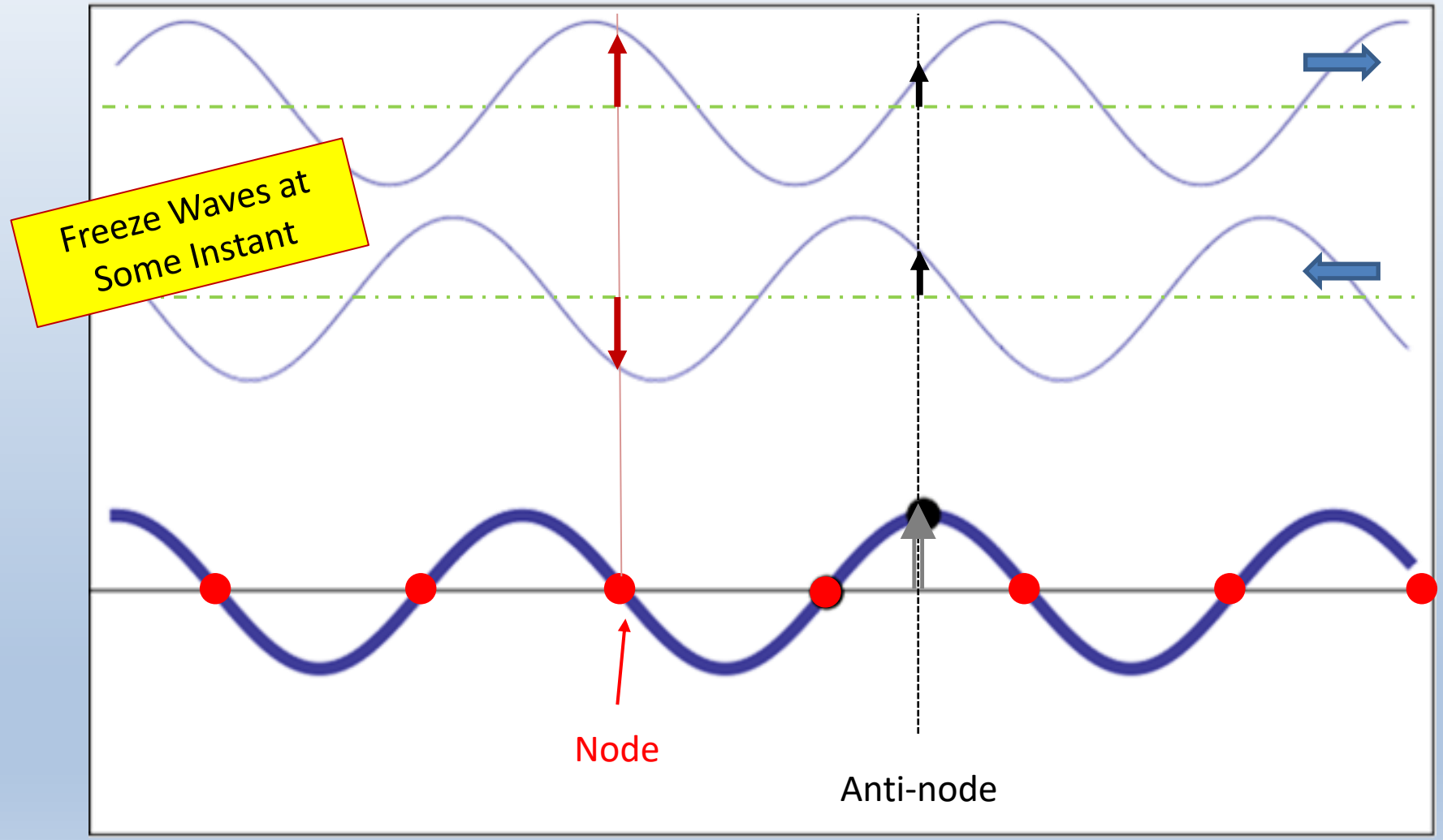
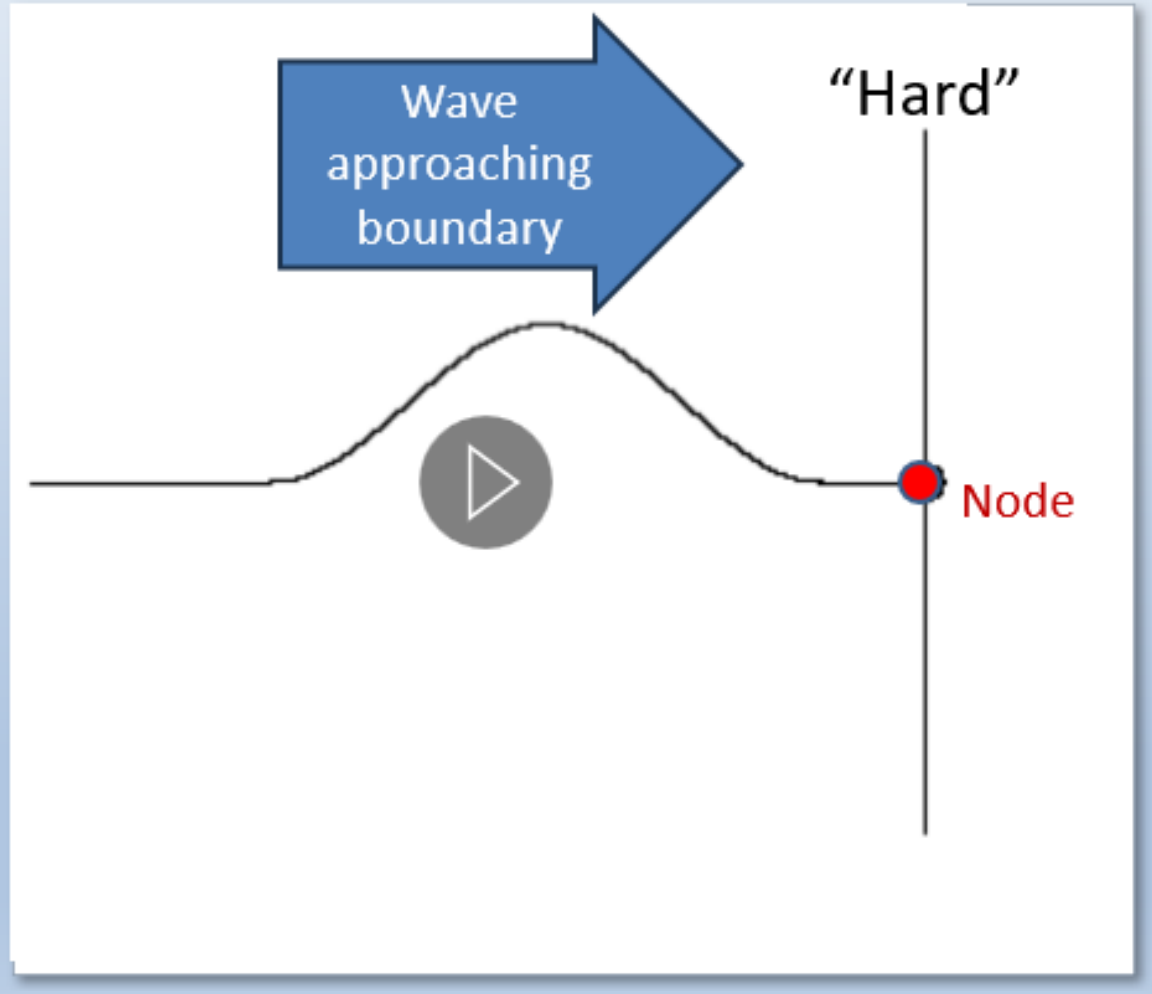


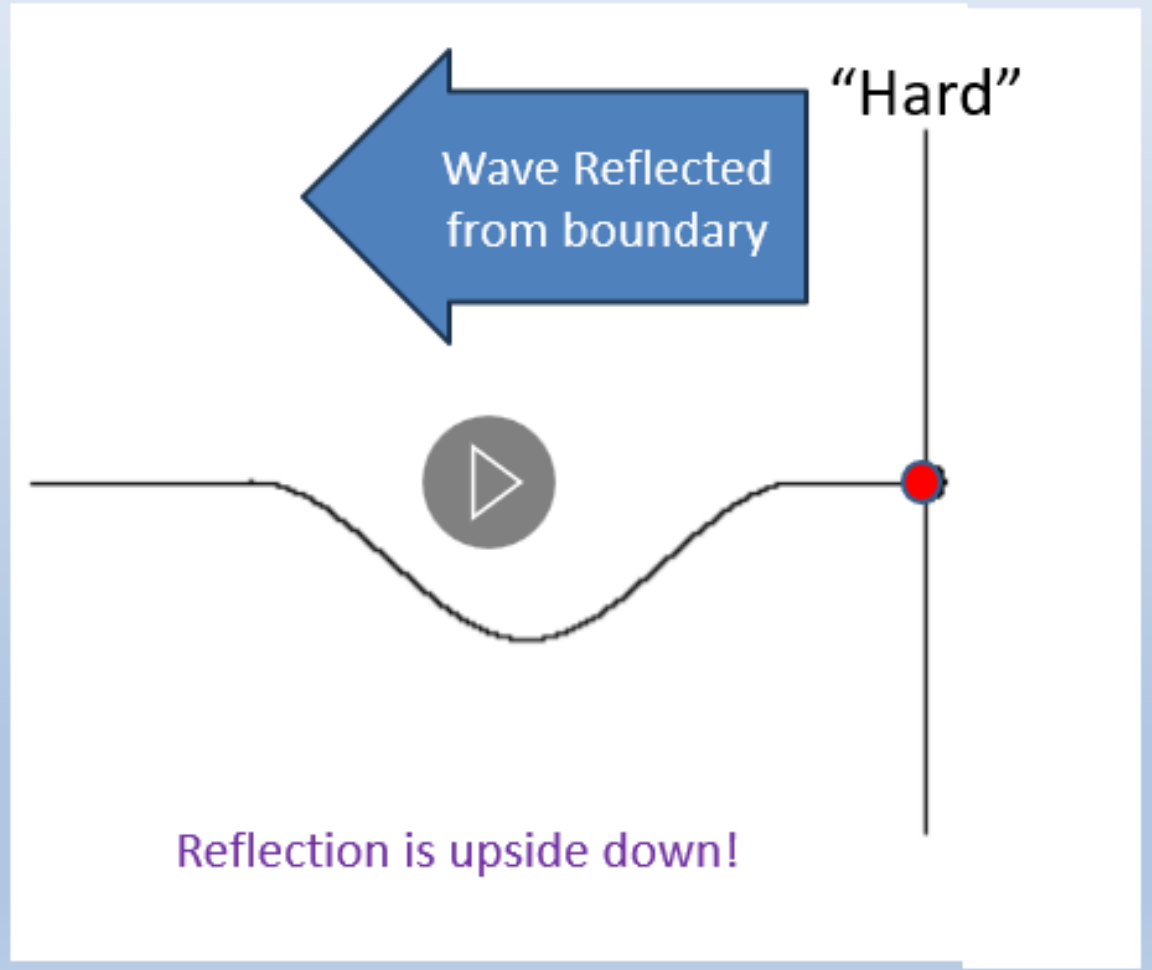
Standing Waves in Air

A Demo We could do (but didn't)

Q: How Do We Make Standing Waves?

A: Reflections at a Boundary





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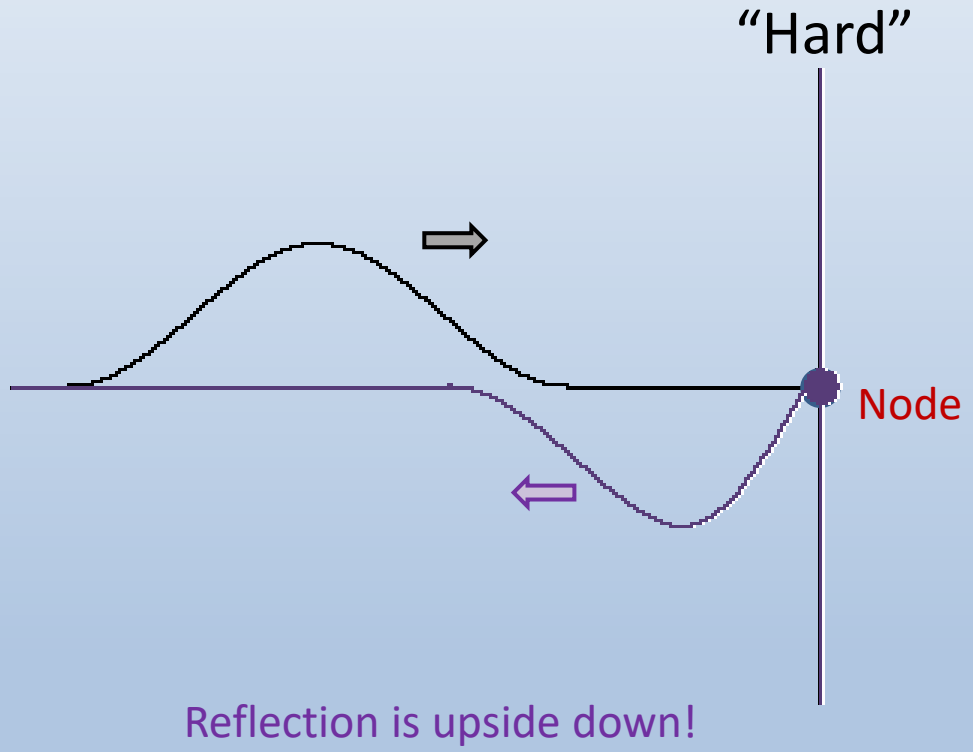

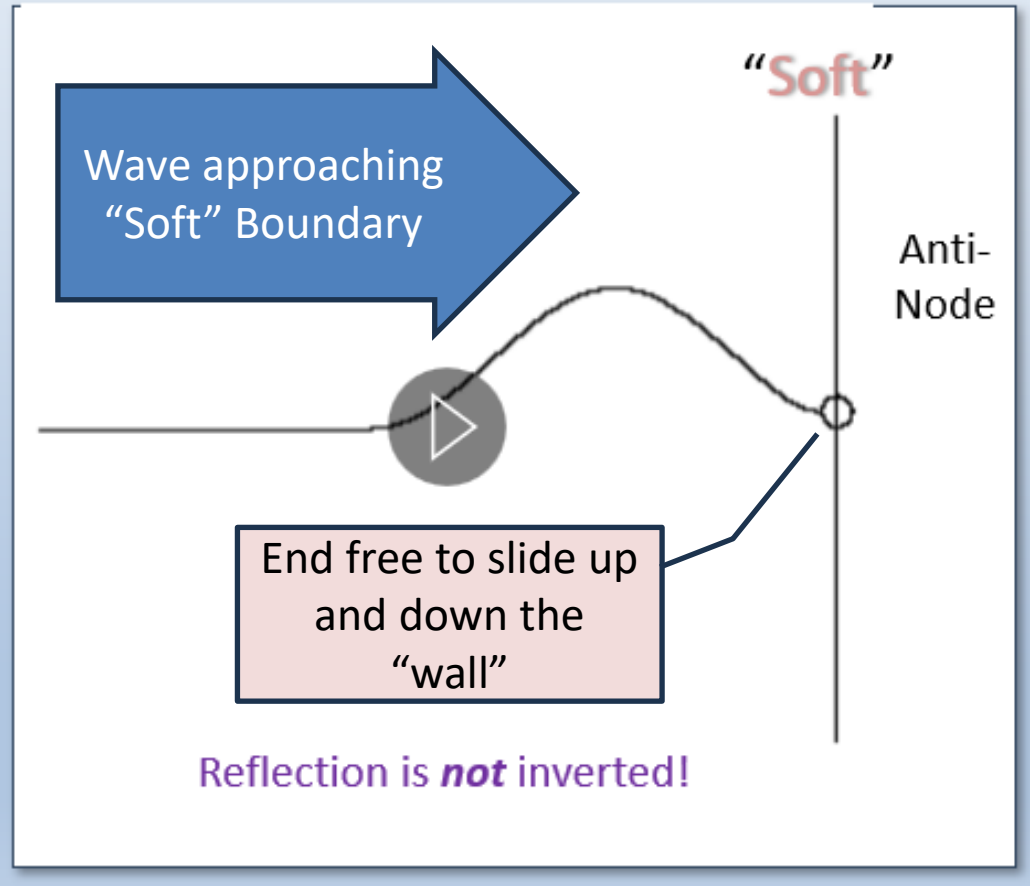

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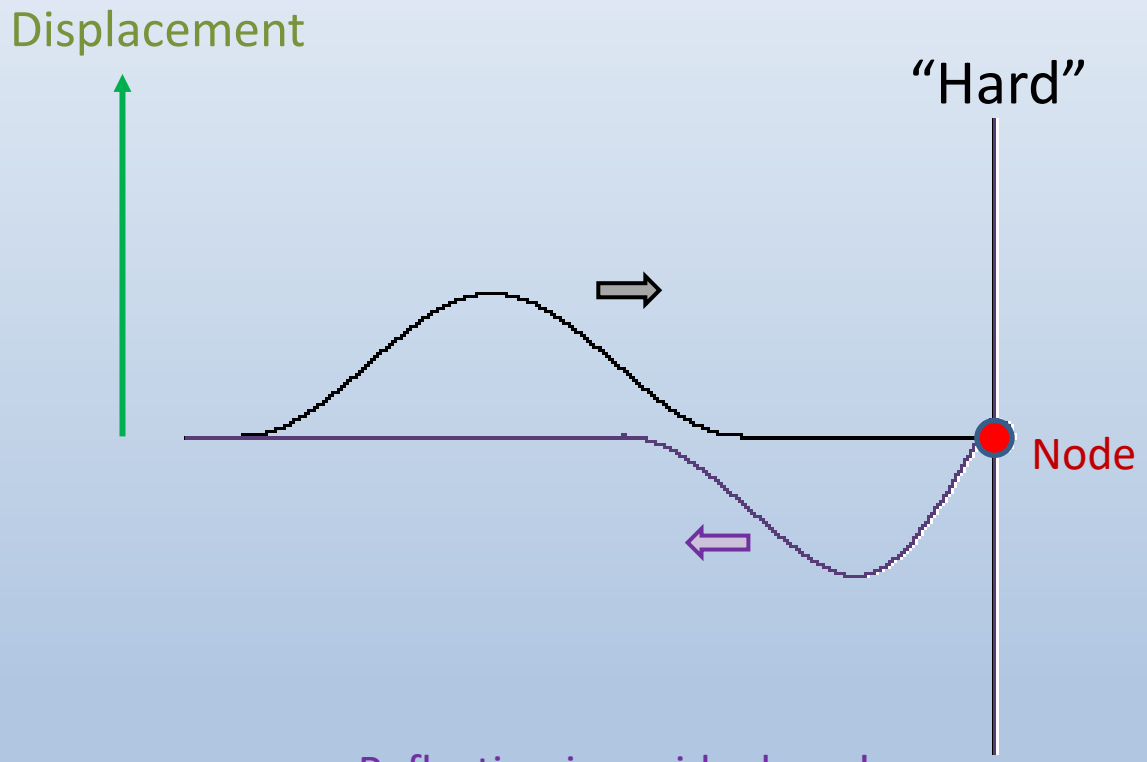
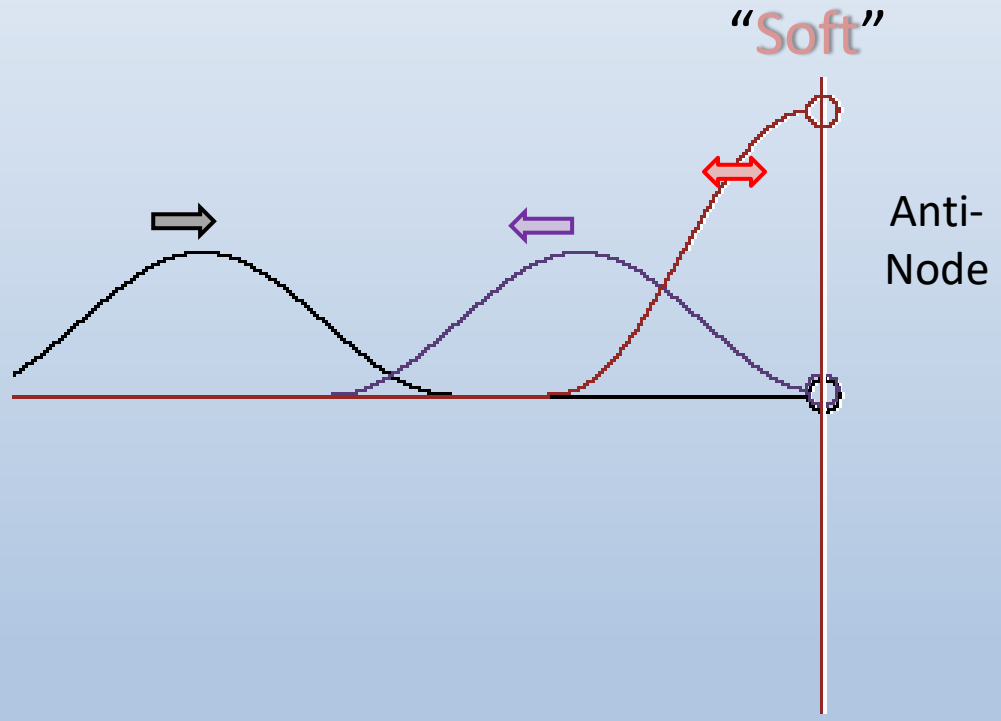


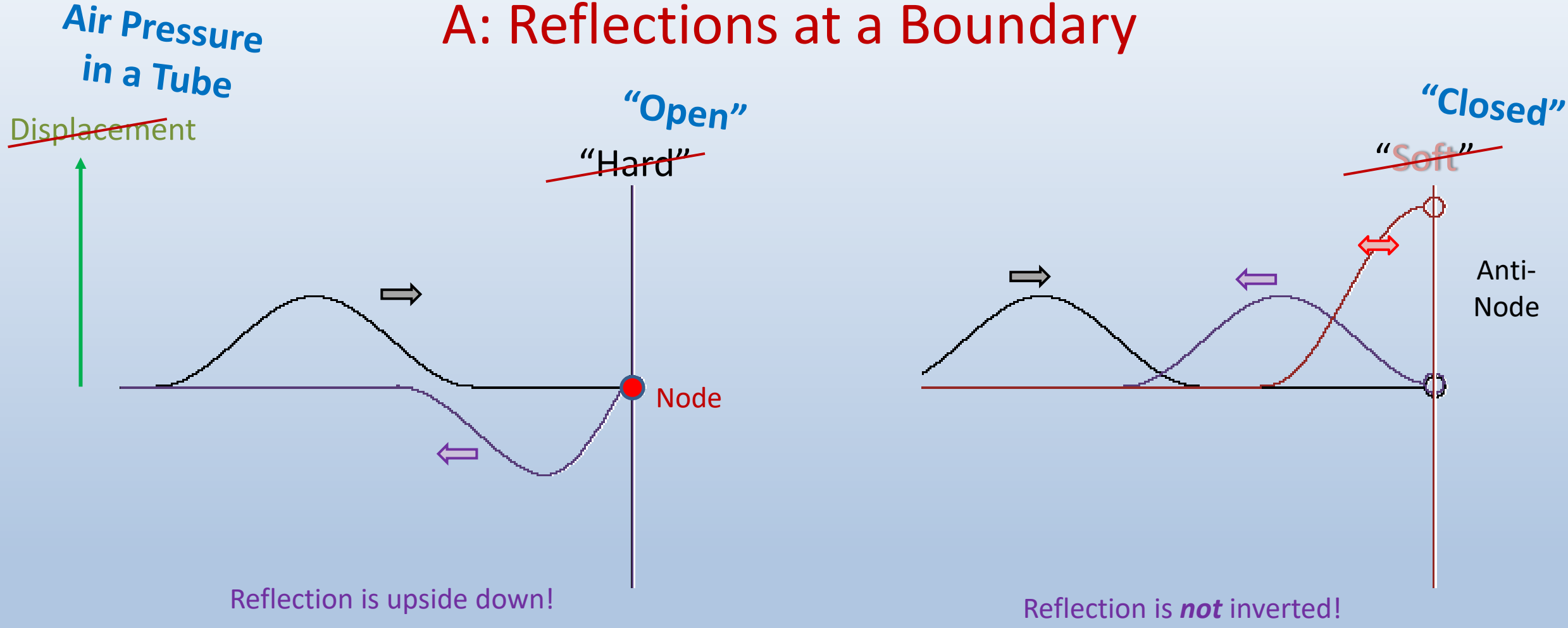
Reflection is upside down!



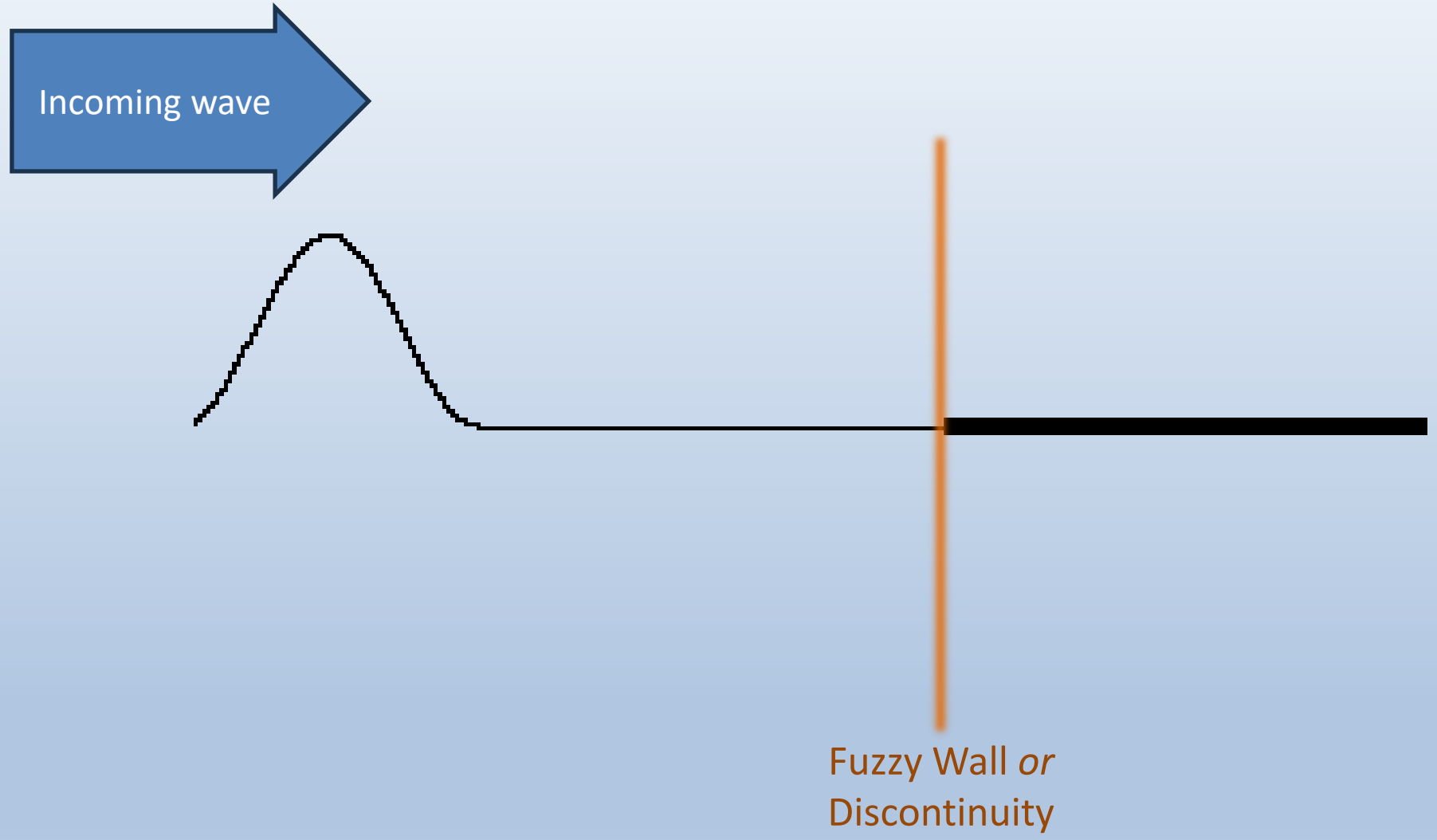
Reflection is ***not*** inverted!

Q: How Do We Make Standing Waves?

A: Reflections at a Boundary



Partial Reflection



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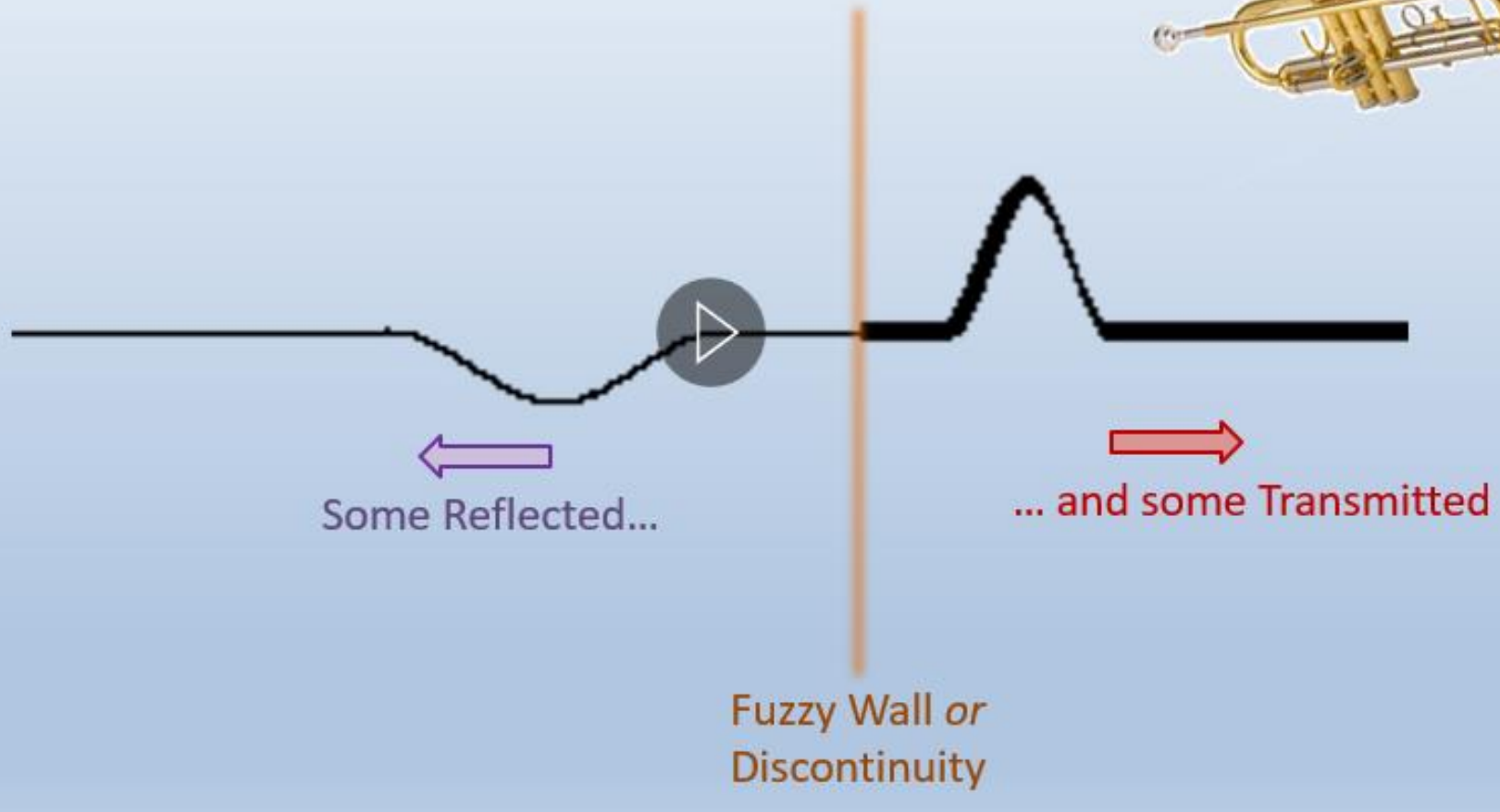


The Monochord

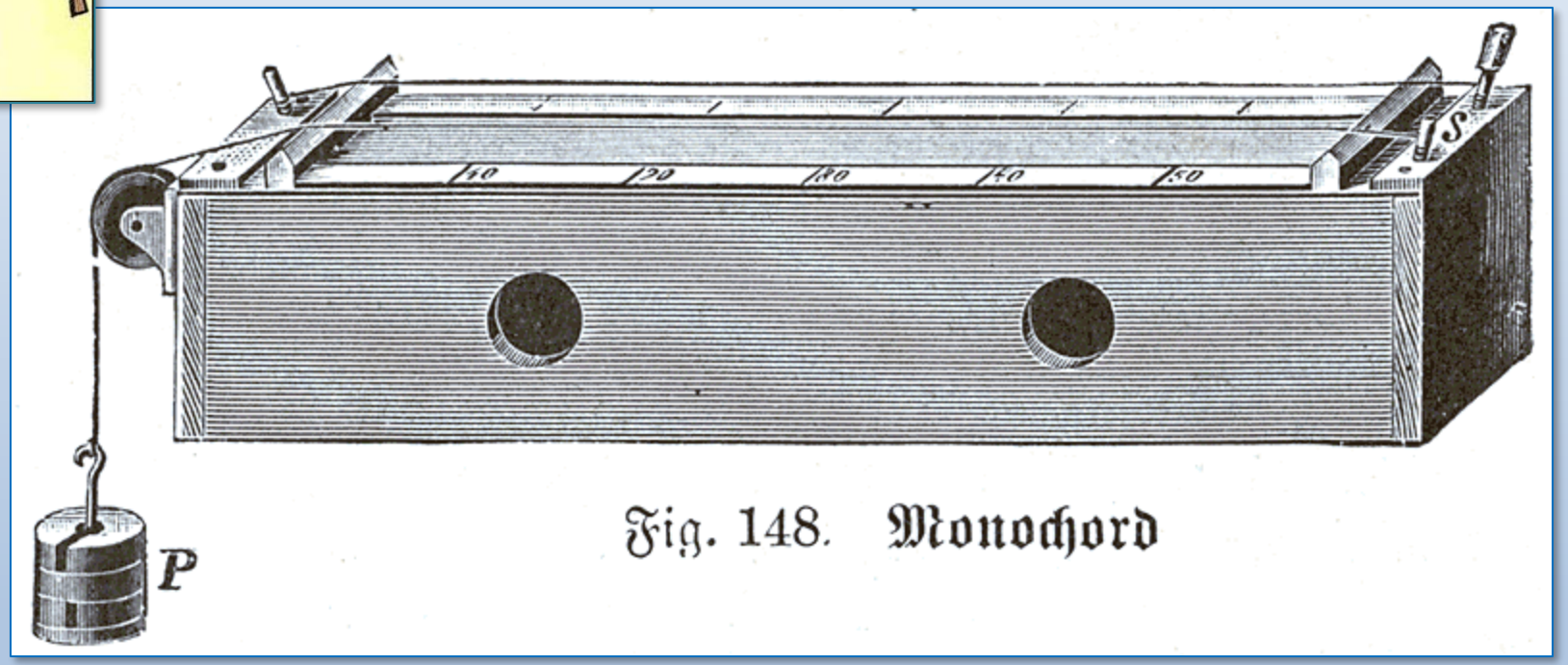
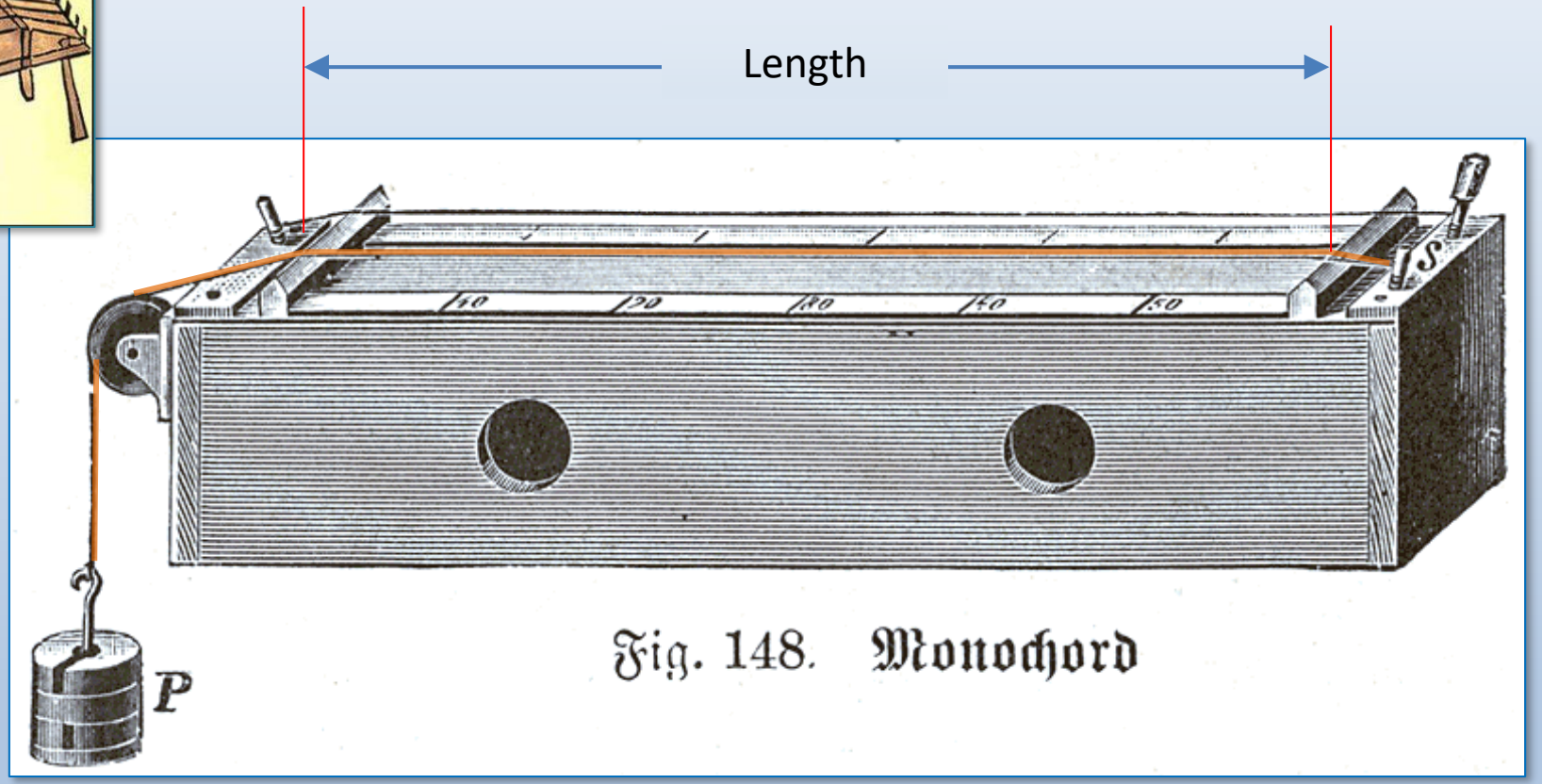


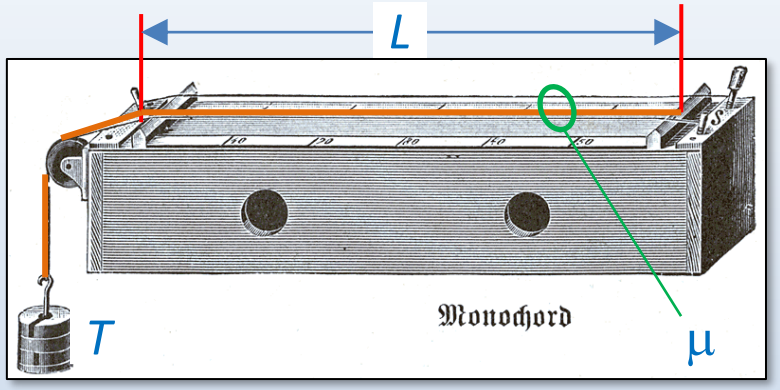
Fig. 148. Monochord

The Monochord



Mersenne's Laws of Strings

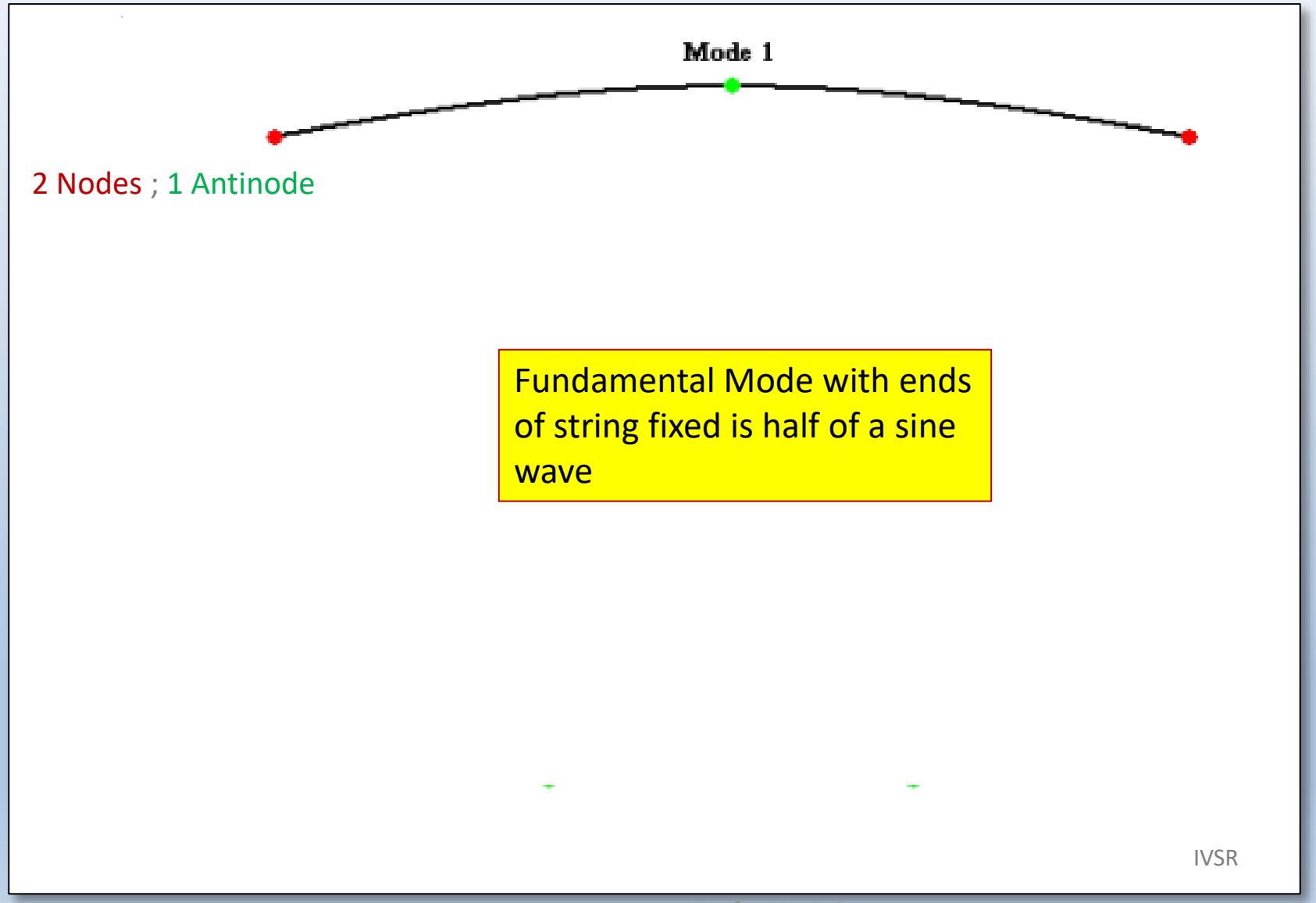
$$f_0 = \frac{1}{2L}\sqrt{T/\mu}$$



Frequency *f* depends on Length ***L***, Tension Force ***T***, and String Mass/length **μ**:

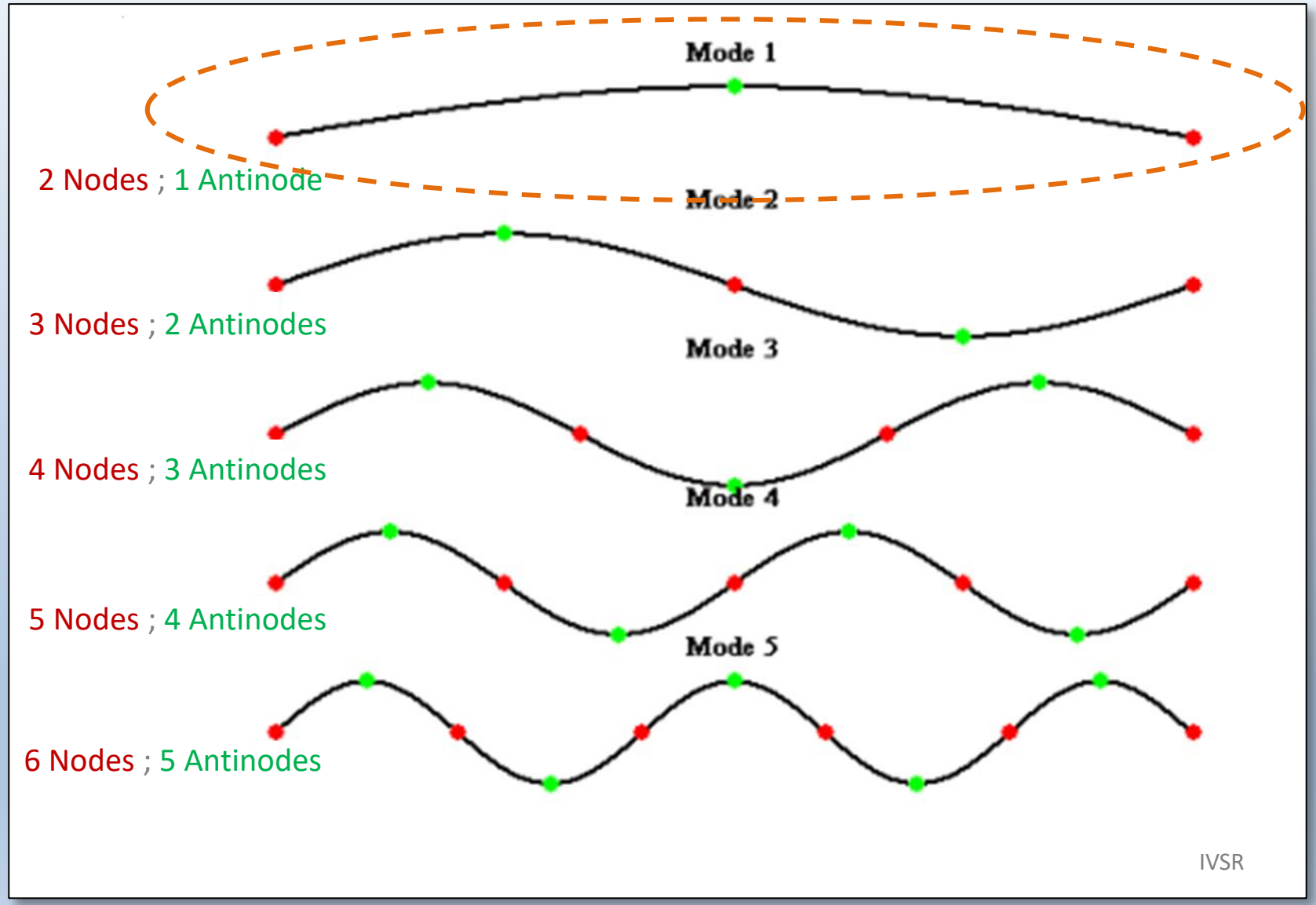
- $f_0 \propto 1 / L$ inversely proportional to <u>length</u>
- $f_0 \propto \sqrt{T}$ proportional to *square root* of <u>tension</u>
- $f_0 \propto 1 / \sqrt{\mu}$ inversely proportional to *square root* of <u>mass per unit length</u> ('fatness')

Possible Pure String Modes



f Fundamental

Possible Pure String Modes



f Fundamental

$2f$

$3f$

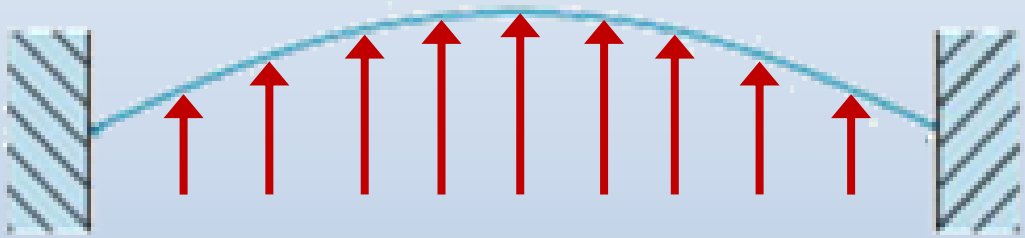
$4f$

$5f$

Harmonics

Try to Launch the Fundamental Mode:

Sine shape



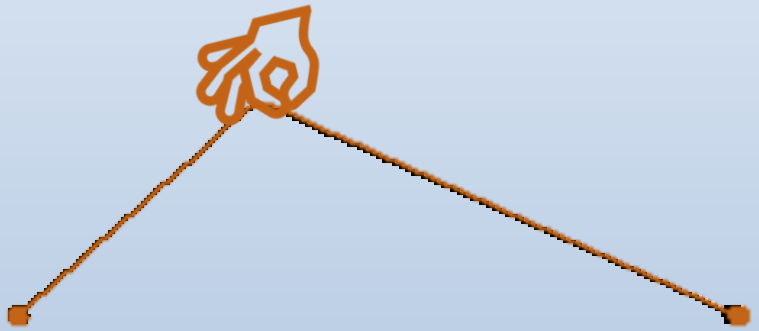
Carefully pull string up into a half-sine shape at many points…..

then let go to launch the fundamental mode

Try to Launch the Fundamental Mode:

Sine shape

But we actually pluck a triangle …

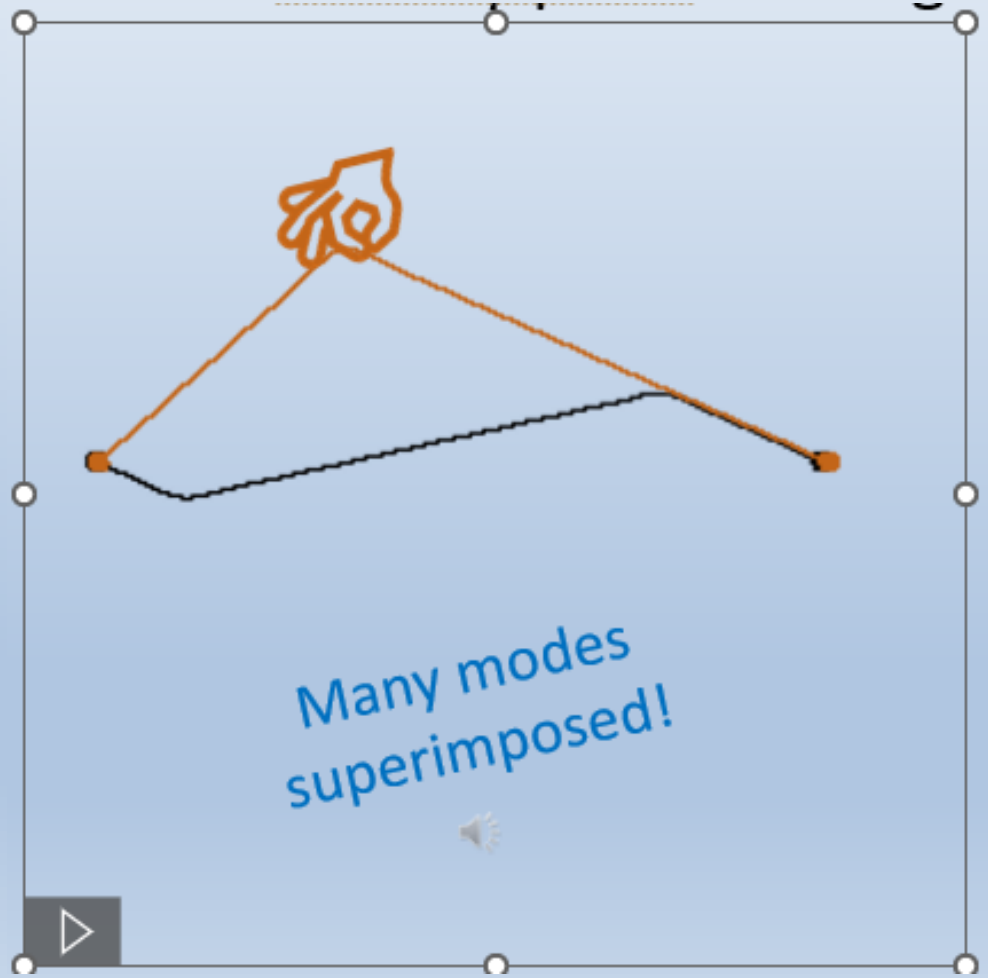


Many modes superimposed!

Try to Launch the Fundamental Mode:

Sine shape

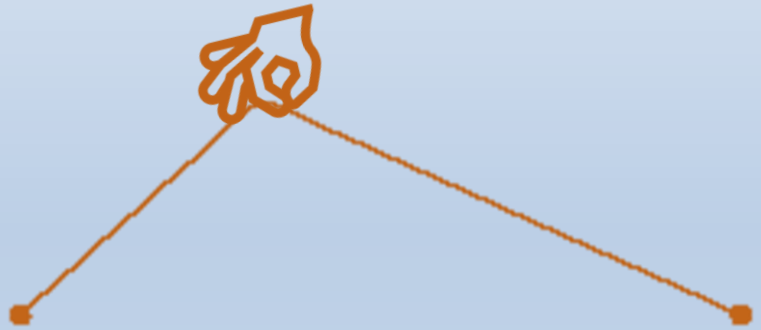
But we actually pluck a triangle …



Try to Launch the Fundamental Mode:

Plucked String in Slo-Mo

Dan Russell, Kettering/Penn State (2011)



Many modes superimposed!

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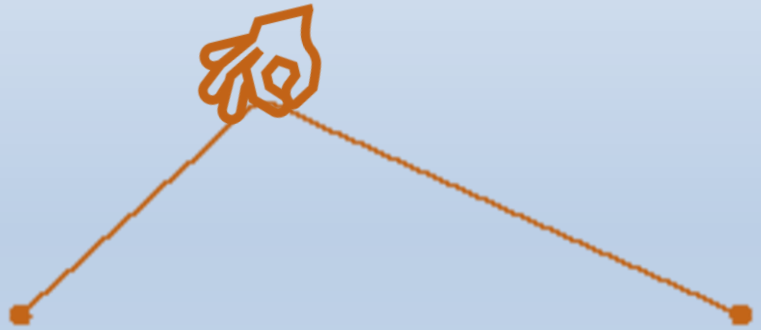
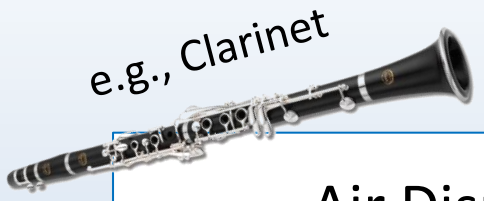


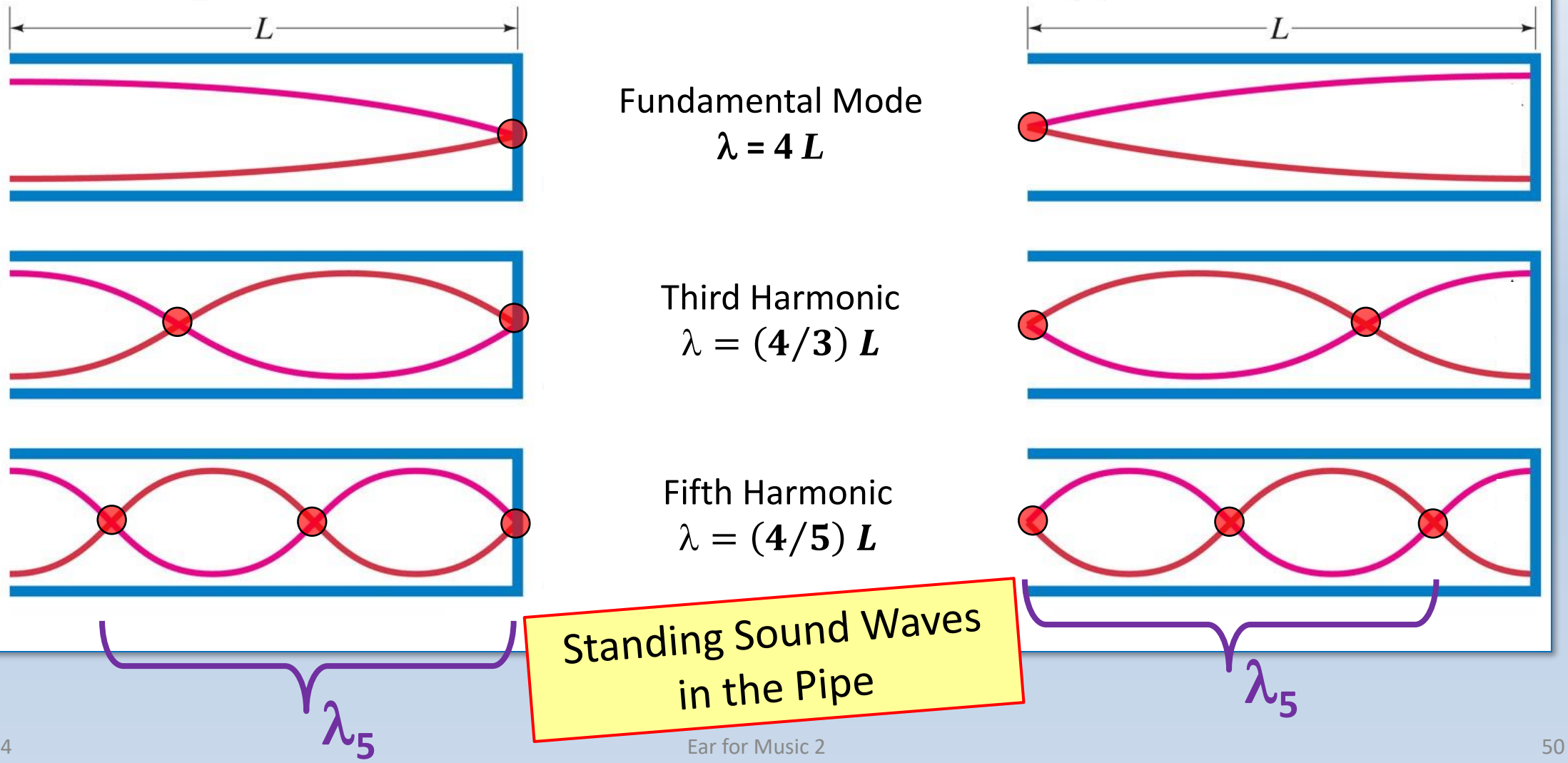
Many modes superimposed!

Organ Pipe – One Closed End



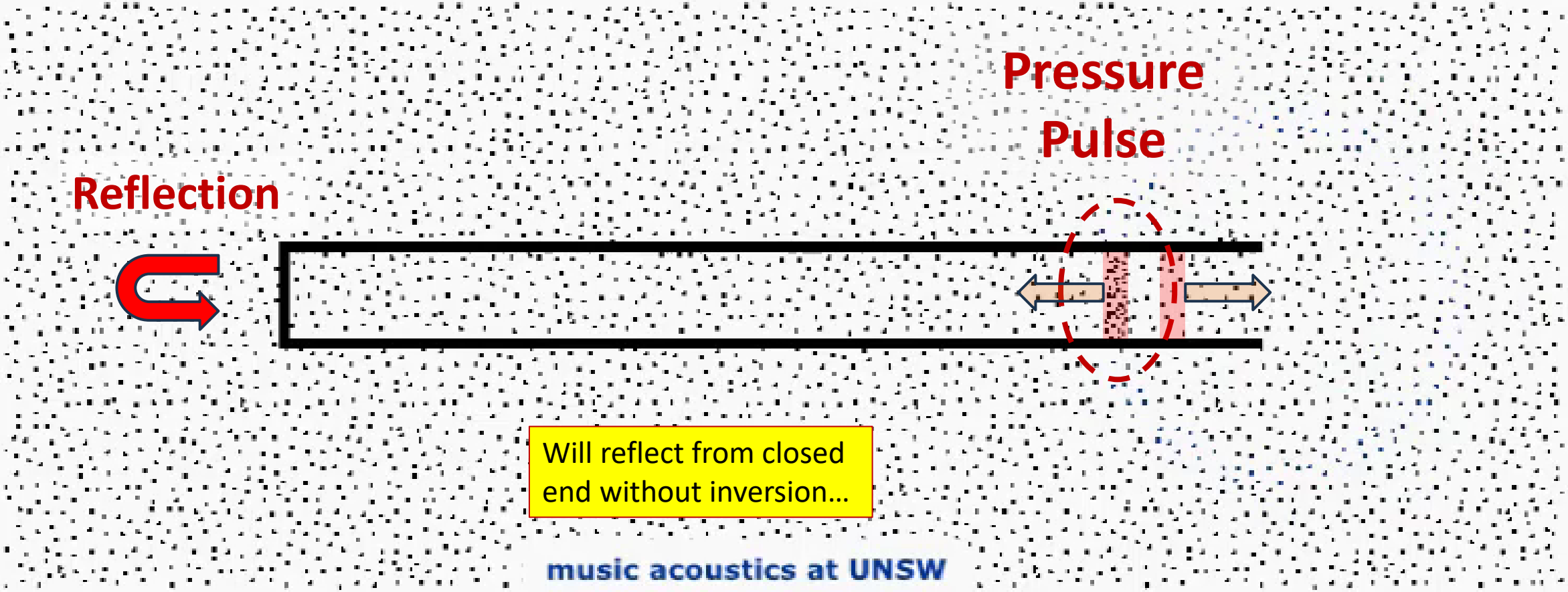
Air Displacement

Pressure



Standing Sound Waves in the Pipe

Illustration of Wave Reflections at Ends of Pipe



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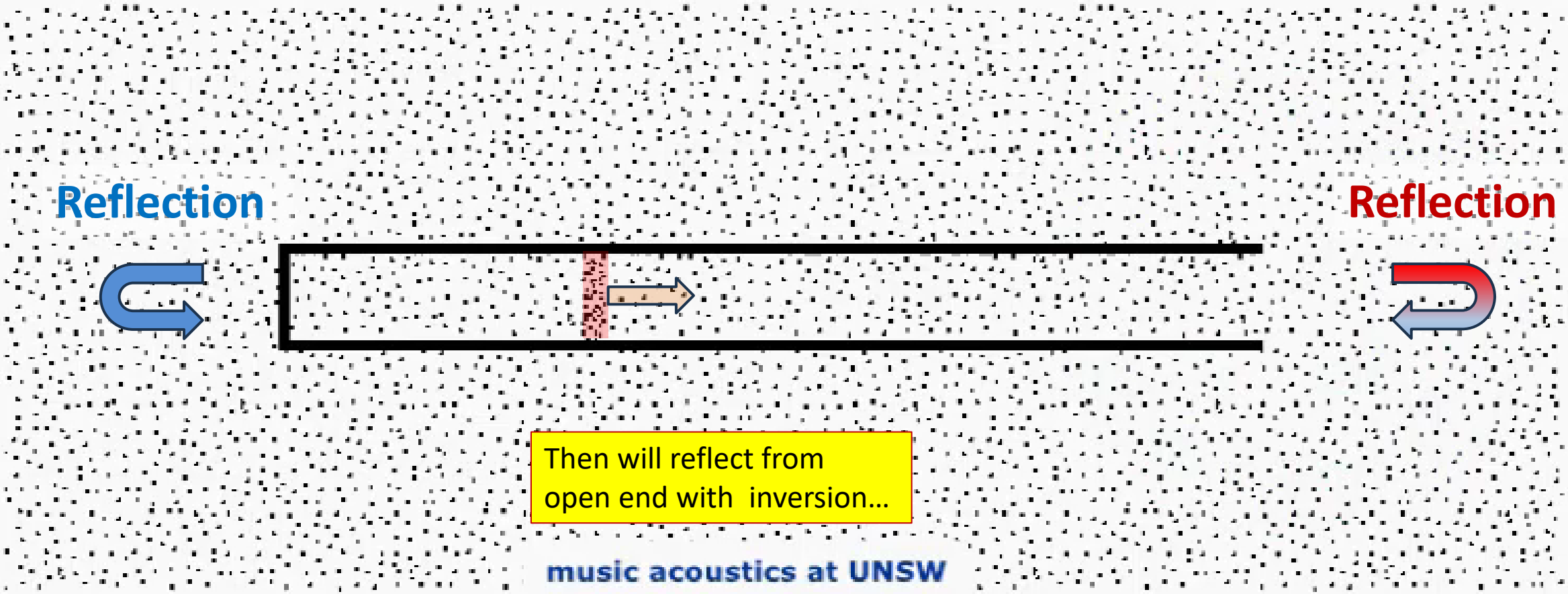

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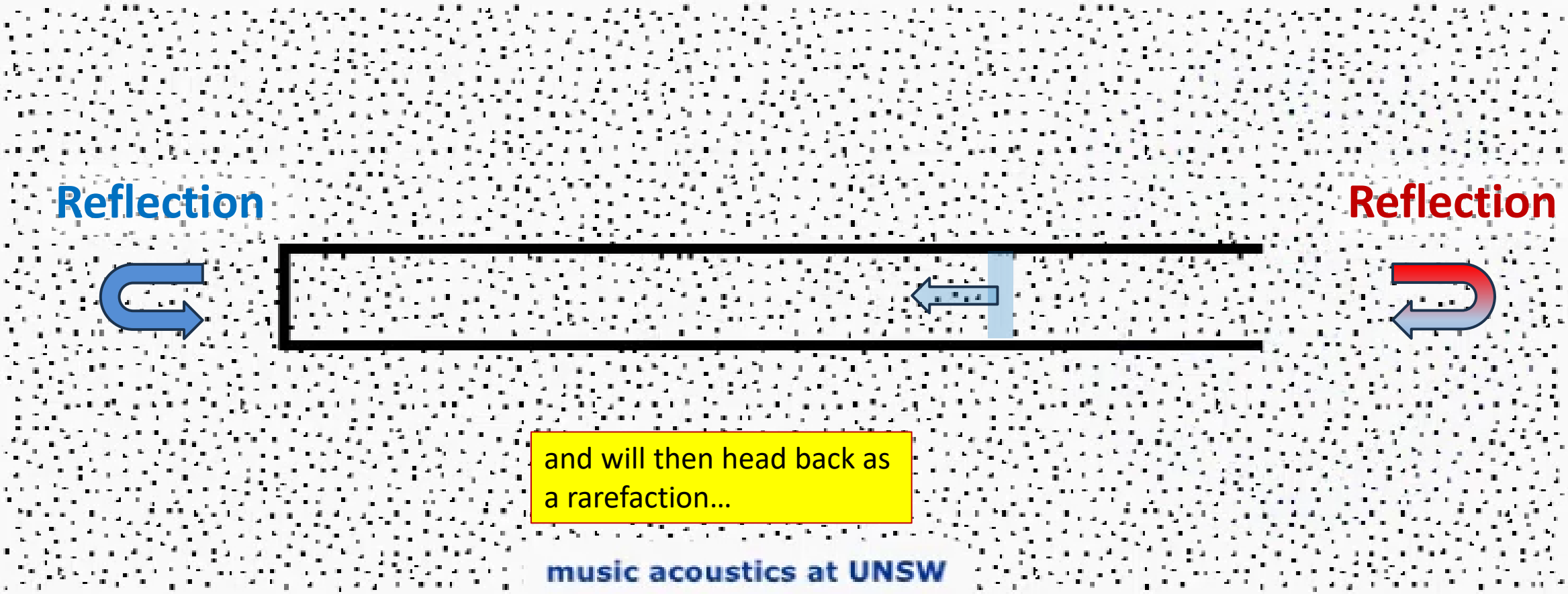
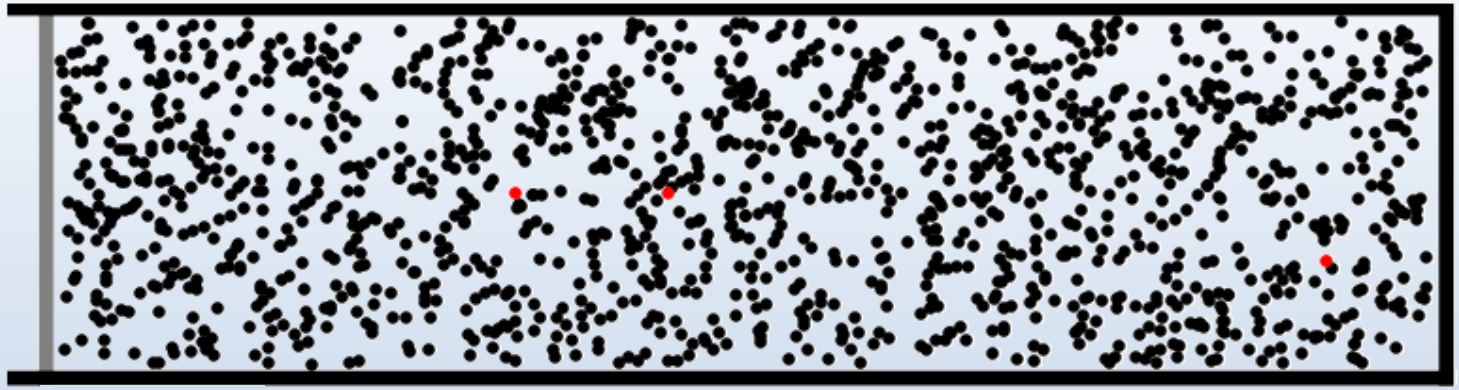


What's Actually Going On?

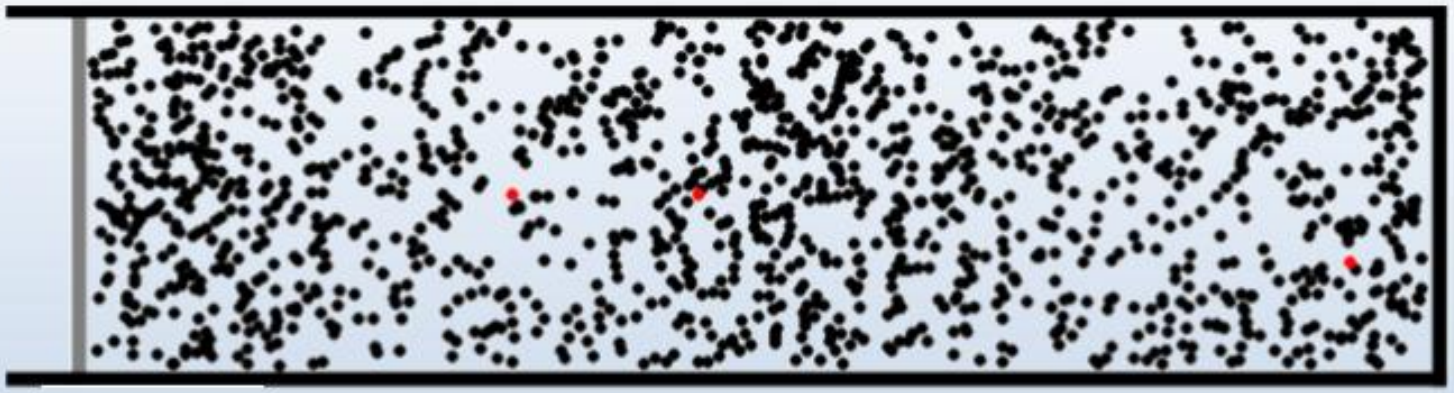
Open End of Pipe



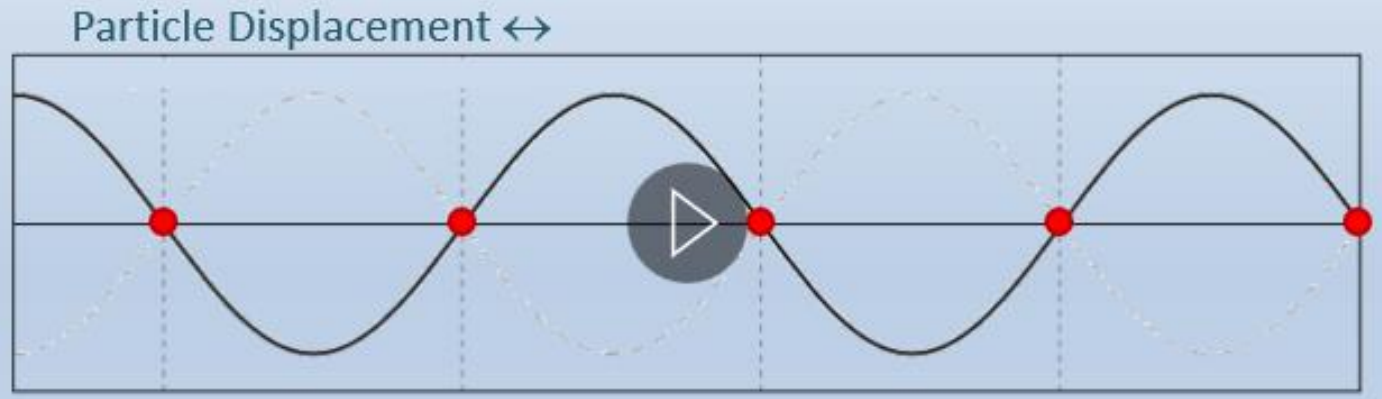
Open/Closed Organ Pipe: 9th Harmonic

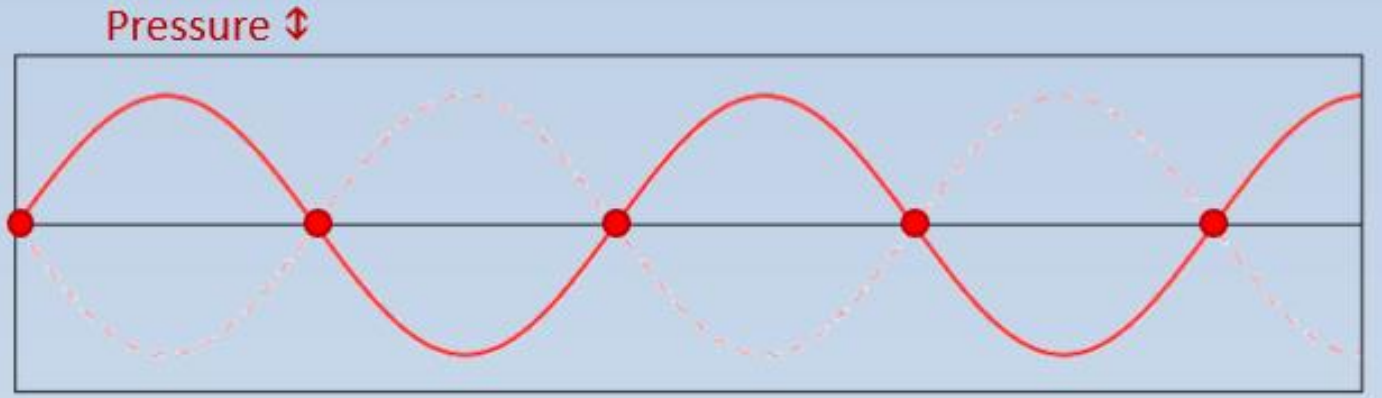
What's Actually Going On?

Open End of Pipe



Open/Closed Organ Pipe: 9th Harmonic

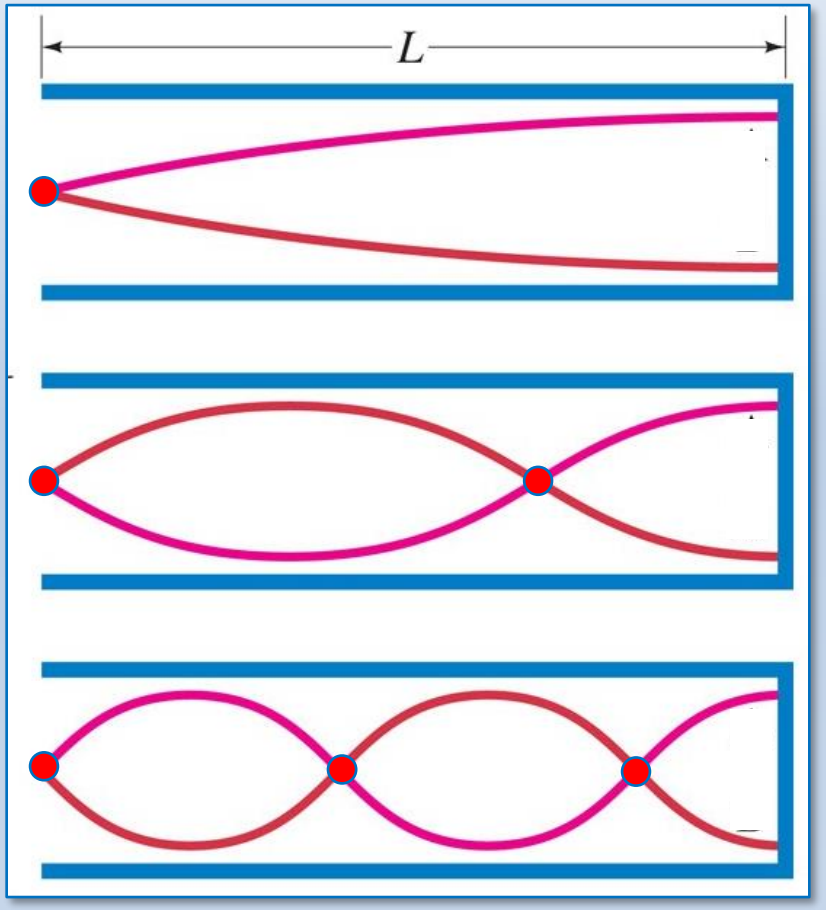




Closed vs. Open Pipe (*Pressure Modes*)

Closed One End

Clarinet , e.g.



f_c

$3f_c$

$5f_c$

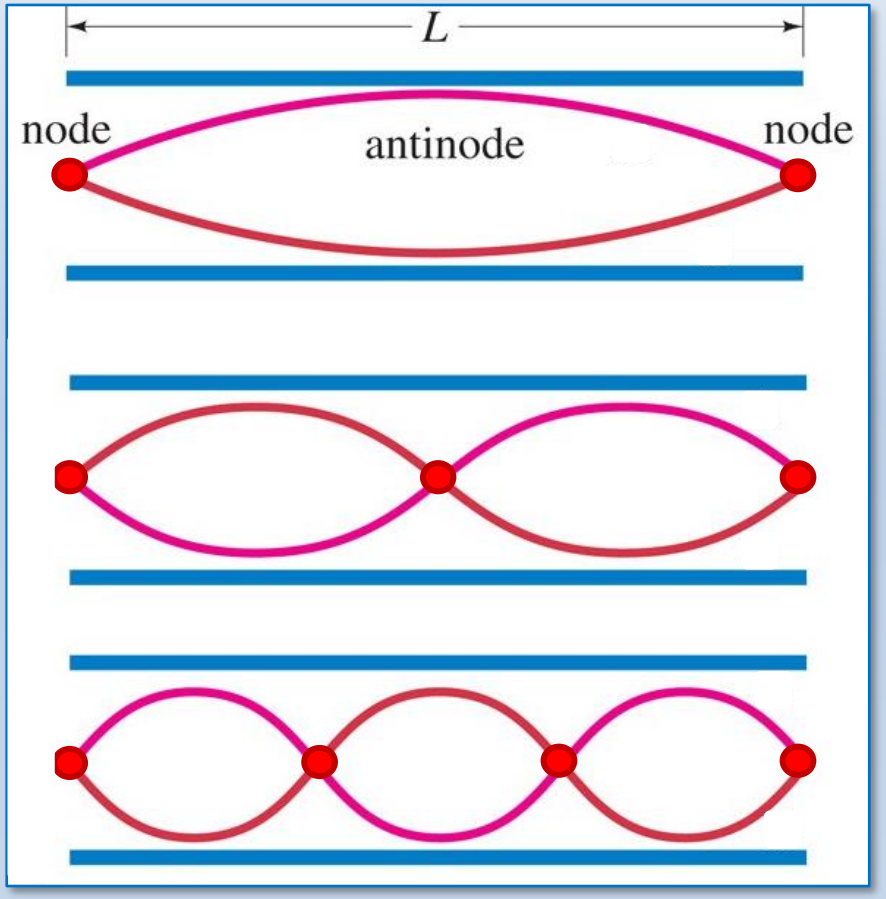
Open Both Ends

Flute, e.g.

$f_0 = 2f_c$

$2f_0$

$3f_0$



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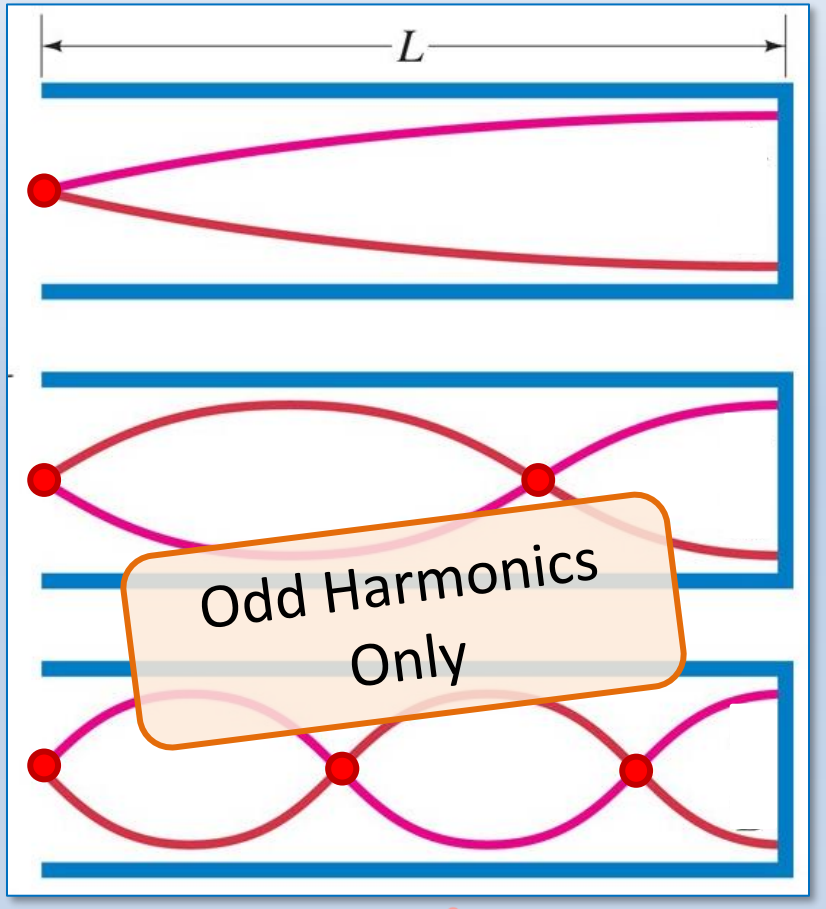
Closed One End

Clarinet , e.g.



f_c

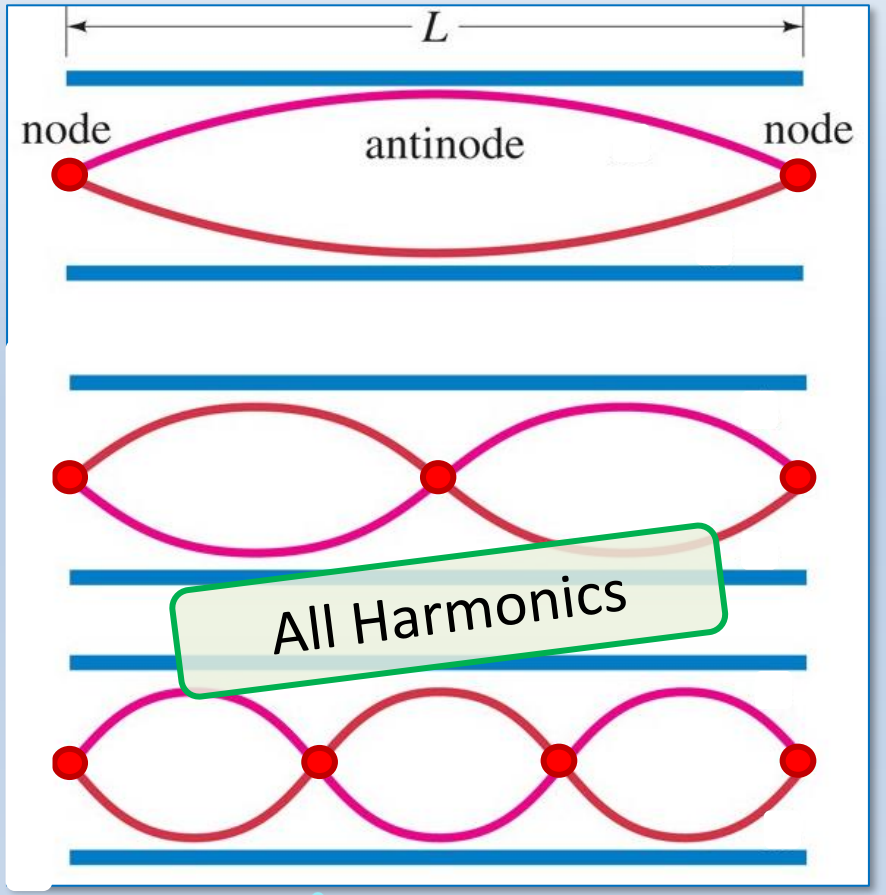
$3f_c$

$5f_c$

L= **25”**

Open Both Ends

Flute, e.g.



$f_0 = 2f_c$

$2f_0$

$3f_0$

L= **25”**

L= **50”**

Open Pipe

$L \approx 2.7$ ft

$f = v_s / \lambda$

$v_s \approx 1100$ ft/s

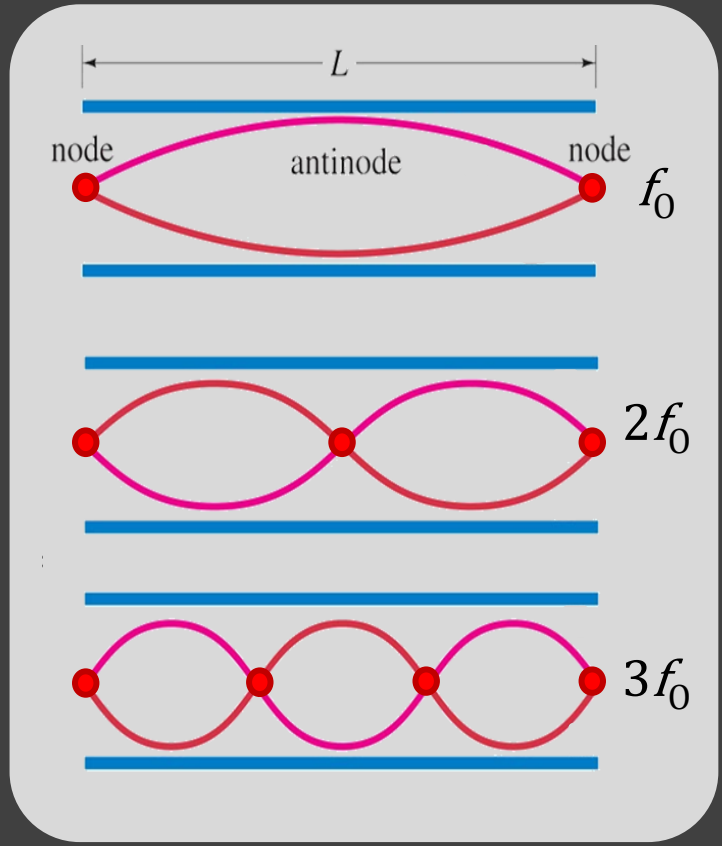
$\lambda_0 = 2L$ $\quad f_0 \approx 200$ Hz

$\lambda_1 = L$ $\quad f_1 \approx 400$ Hz

$\lambda_2 = (2/3)L$ $\quad f_2 \approx 600$ Hz

$\lambda_3 = (1/2)L$ $\quad f_2 \approx 800$ Hz

Demo
(failed)



Closed Pipe

≈2.7 ft

$f = v_s / \lambda$

$v_s \approx 1100$ ft/s

Demo

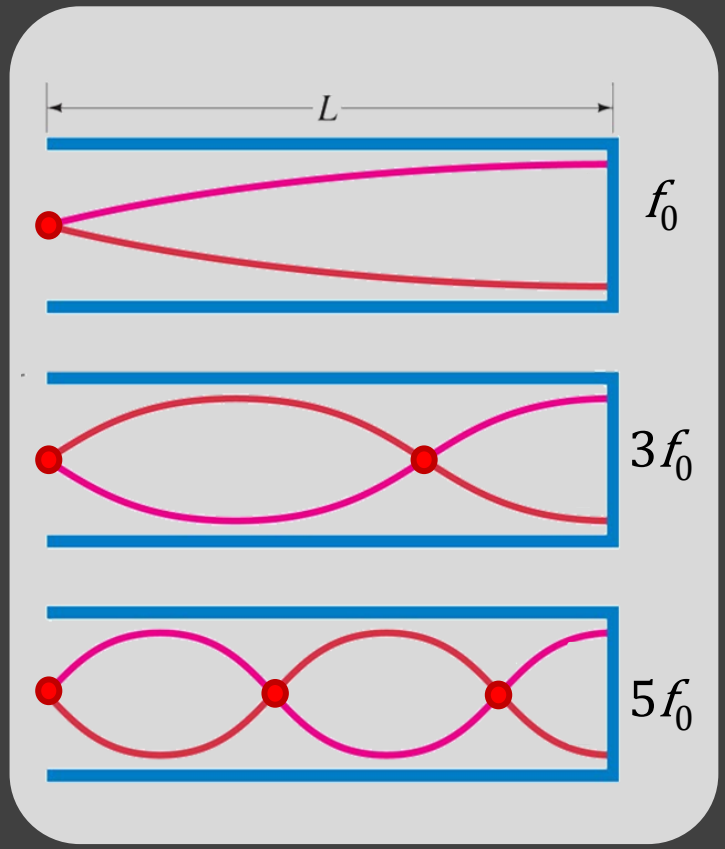
(failed)

$\lambda_1 = 4L$ $\quad f_1 \approx 100$ Hz

$\lambda_3 = (4/3)L$ $\quad f_3 \approx 300$ Hz

$\lambda_5 = (4/5)L$ $\quad f_5 \approx 500$ Hz

$\lambda_7 = (4/7)L$ $\quad f_7 \approx 700$ Hz

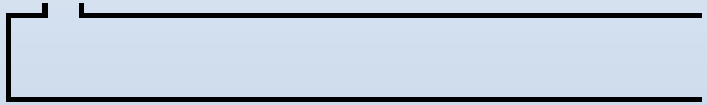


Question Time

- Helmholtz Resonators
- String Resonators
- Pipes

Air Column Instrument Examples

Open Cylinder

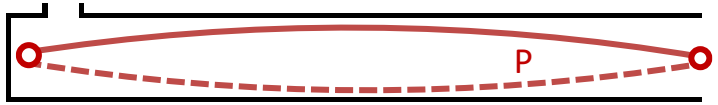


Flute

Air Column Instrument Examples

2 ft

Open Cylinder

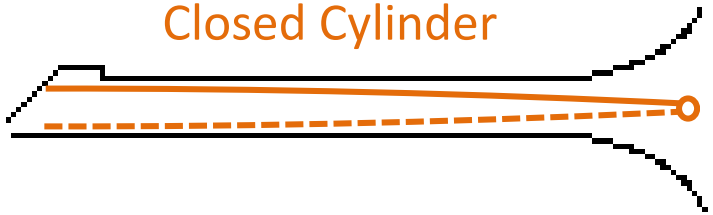


½ wave

Flute

$\lambda_o \approx 4$ ft

Closed Cylinder

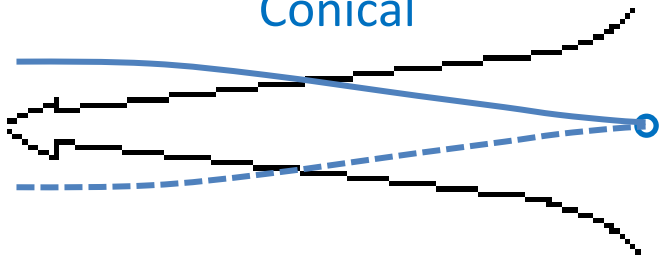


¼ wave

Clarinet

$\lambda_o \approx 8$ ft

Conical

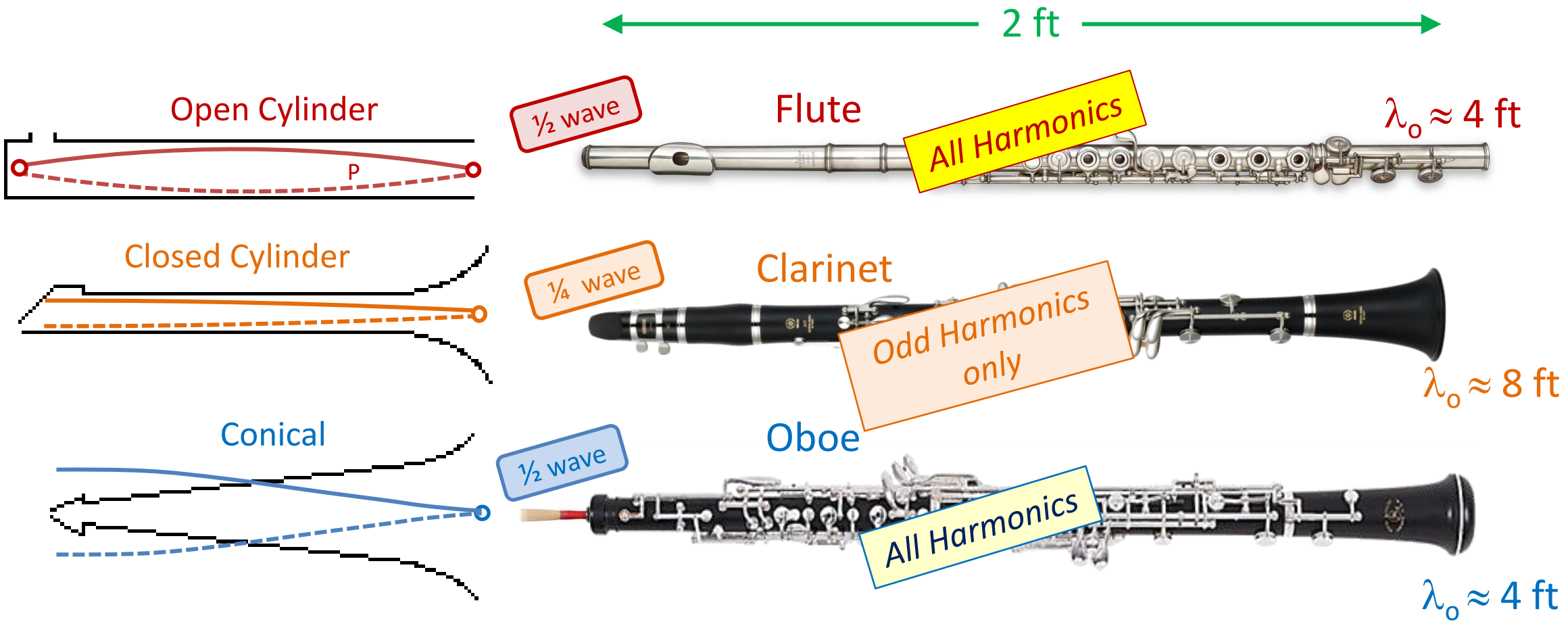


½ wave

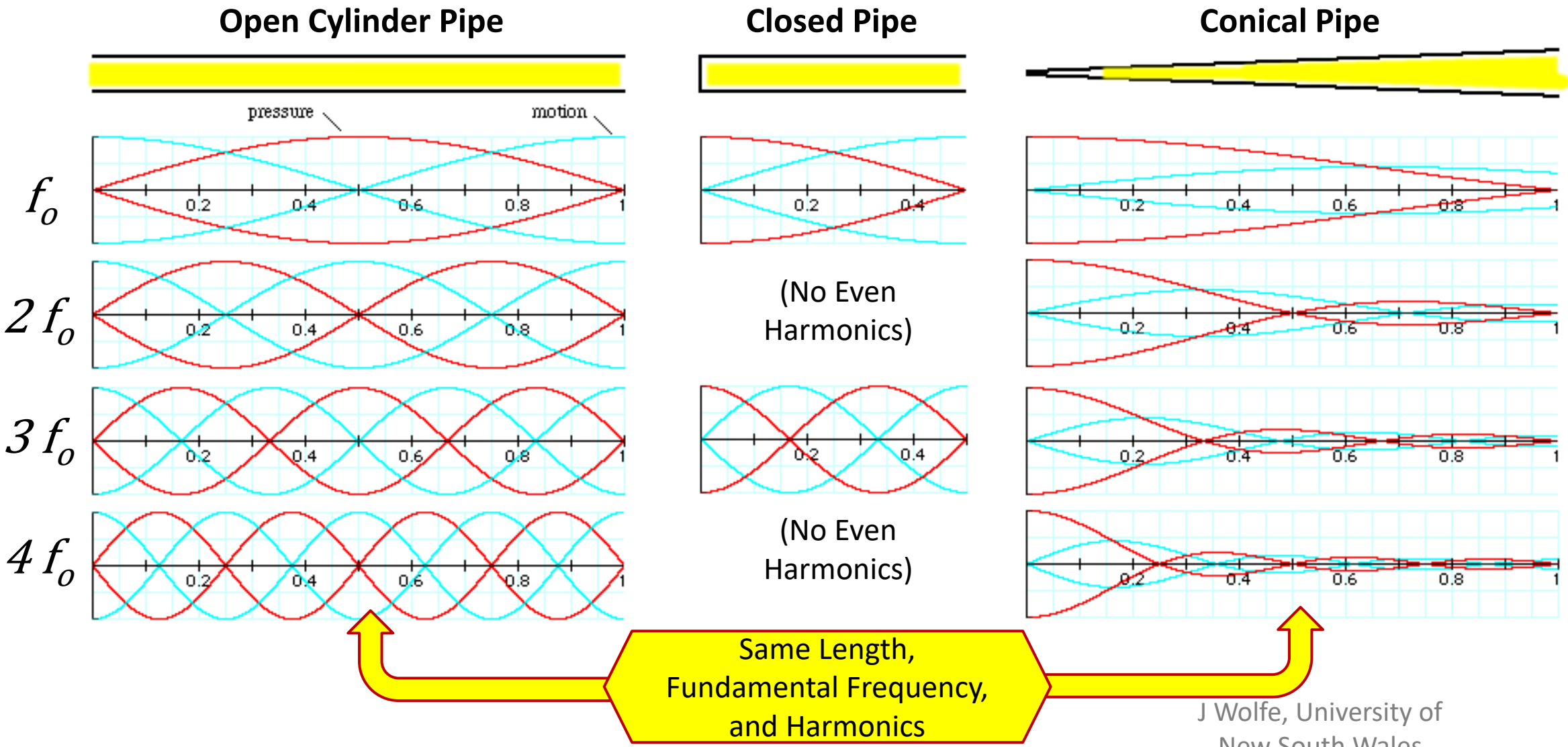
Oboe

$\lambda_o \approx 4$ ft

What About Timbre?



Comparison of Standing Wave Modes



J Wolfe, University of New South Wales

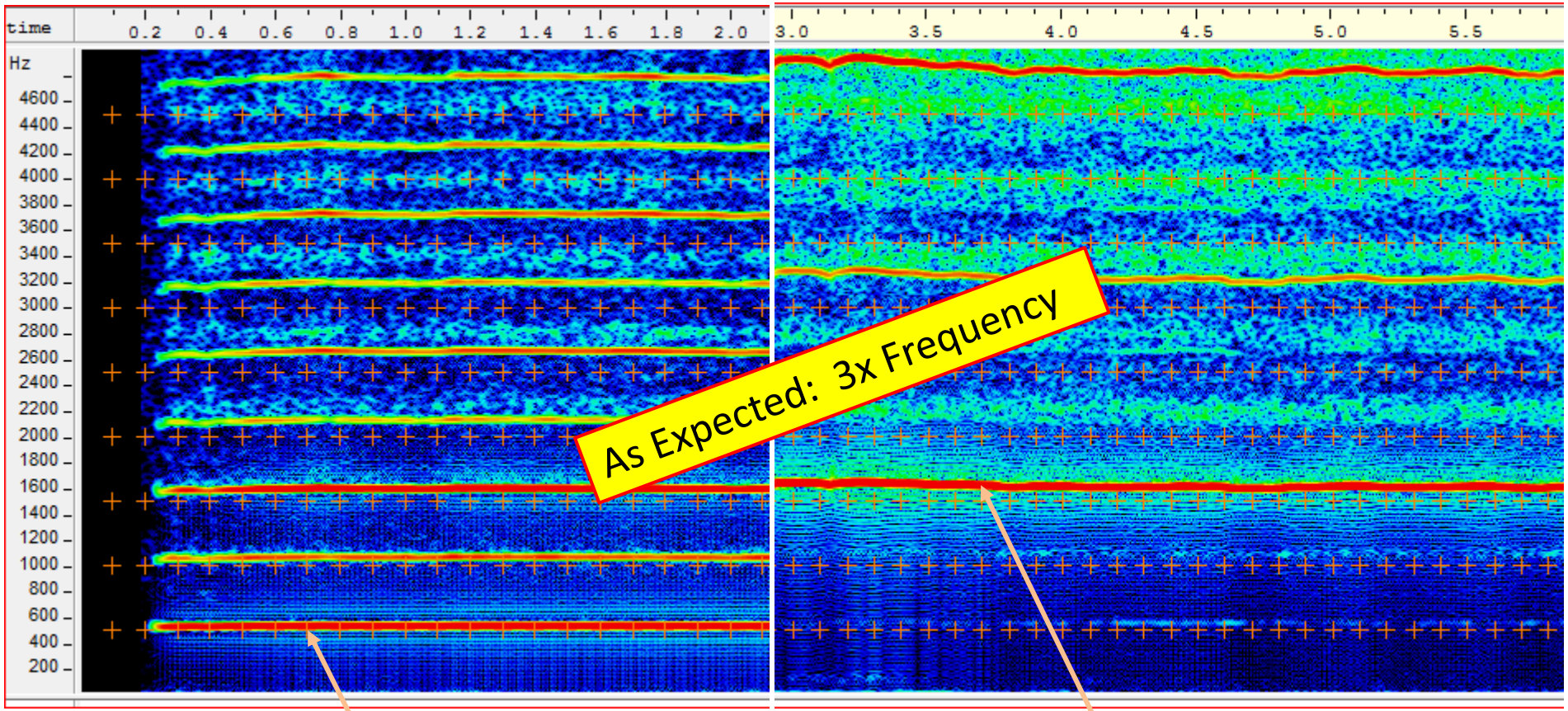
Recorder Pipe: Air *vs.* Helium

(All holes closed – base note)

Demo

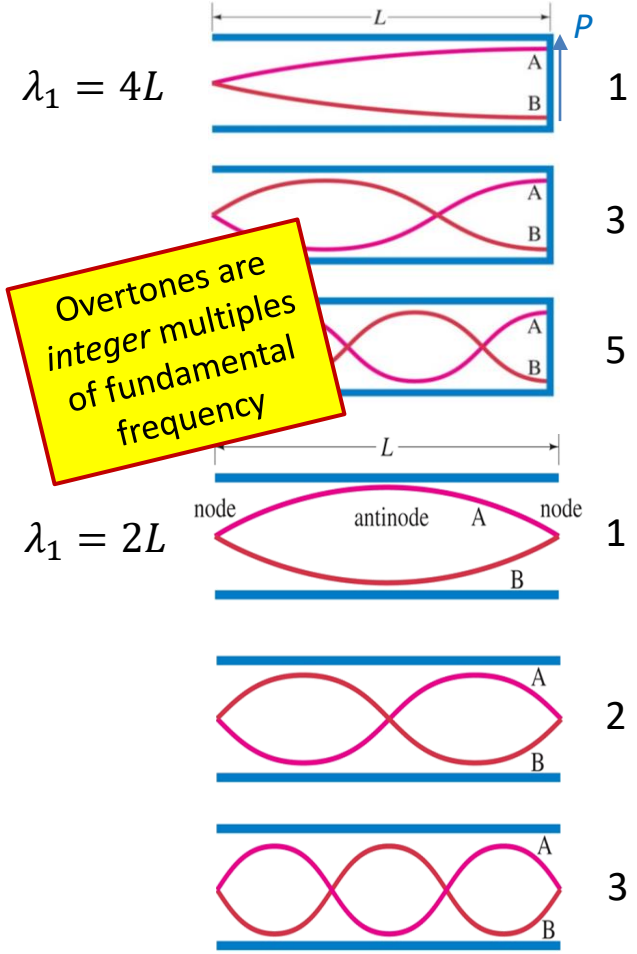
Air ($v_s \approx 1100$ ft/s)

Helium ($v_s \approx 3200$ ft/s)

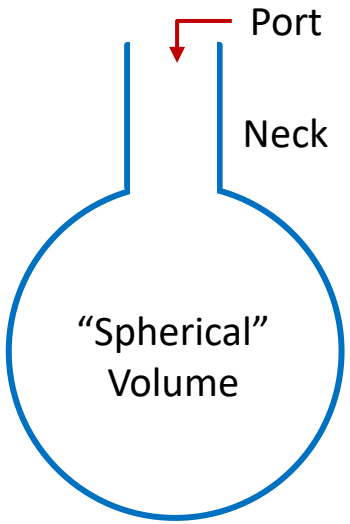


Resonant Cavities: Augmenting Sounds

Pipes

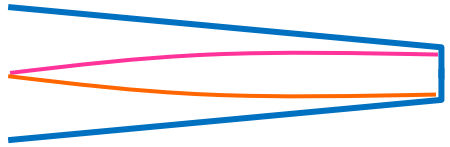


Helmholtz Resonators



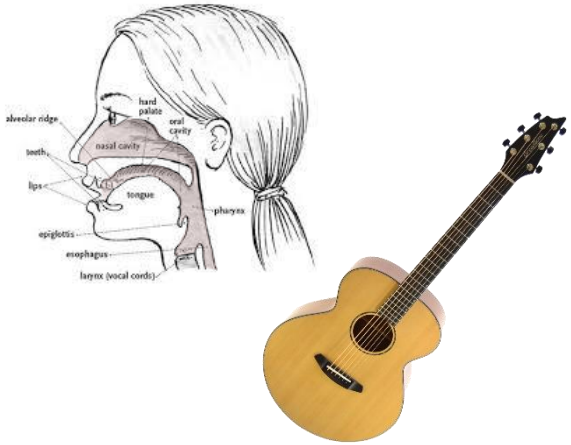
- Mainly has fundamental resonance
- Typically lower frequency than a pipe of similar length

Irregular Resonators

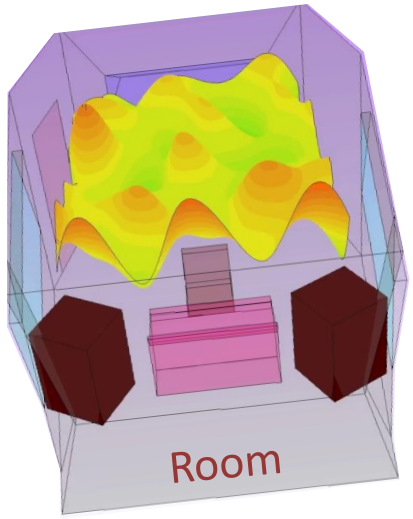


Non-uniform Pipe

- Overtones *may* be integer multiples (e.g. conical)
- *Example:* Saxophone



More Complex Resonators



Common Characteristic:
Modes are generally *not* harmonics of Fundamental

Singing Prayer Bowl

Resonant Vibrational Modes of a Wine Glass

Marty33 2009 YouTube
Wine Glass Resonance in Slow Motion

Resonant Vibrational Modes of a Wine Glass

Marty33 2009 YouTube
Wine Glass Resonance in Slow Motion

Benjamin Franklin's Glass Harmonica (1761)

Stick/Slip on rotating glass bowls

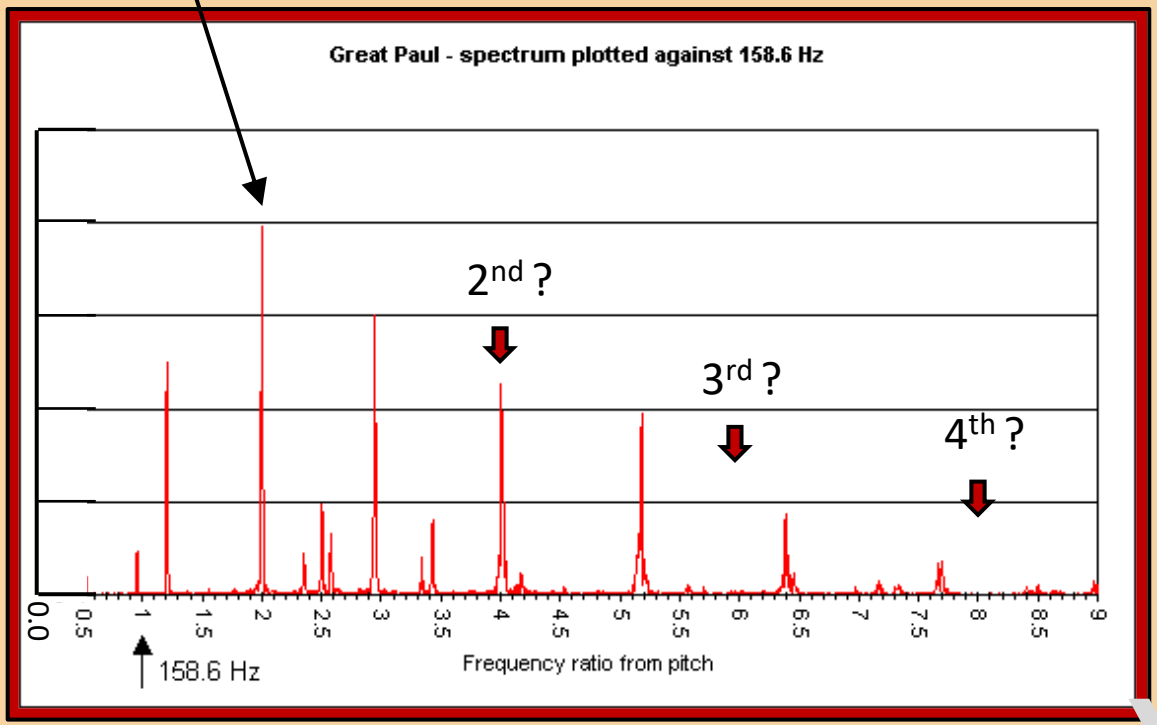
Thomas Bloch, Paris Music Museum 2007

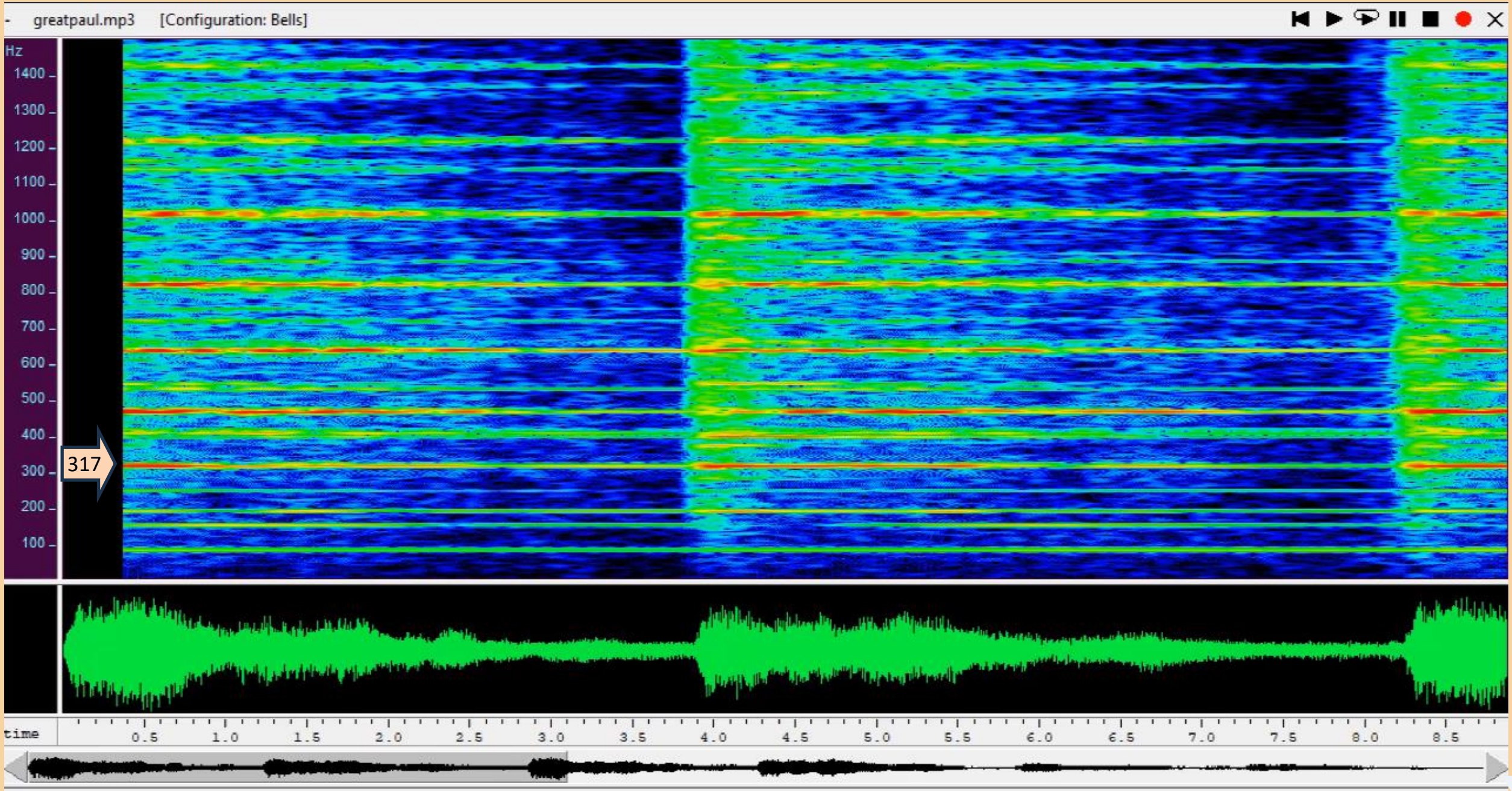
Great Paul Bell

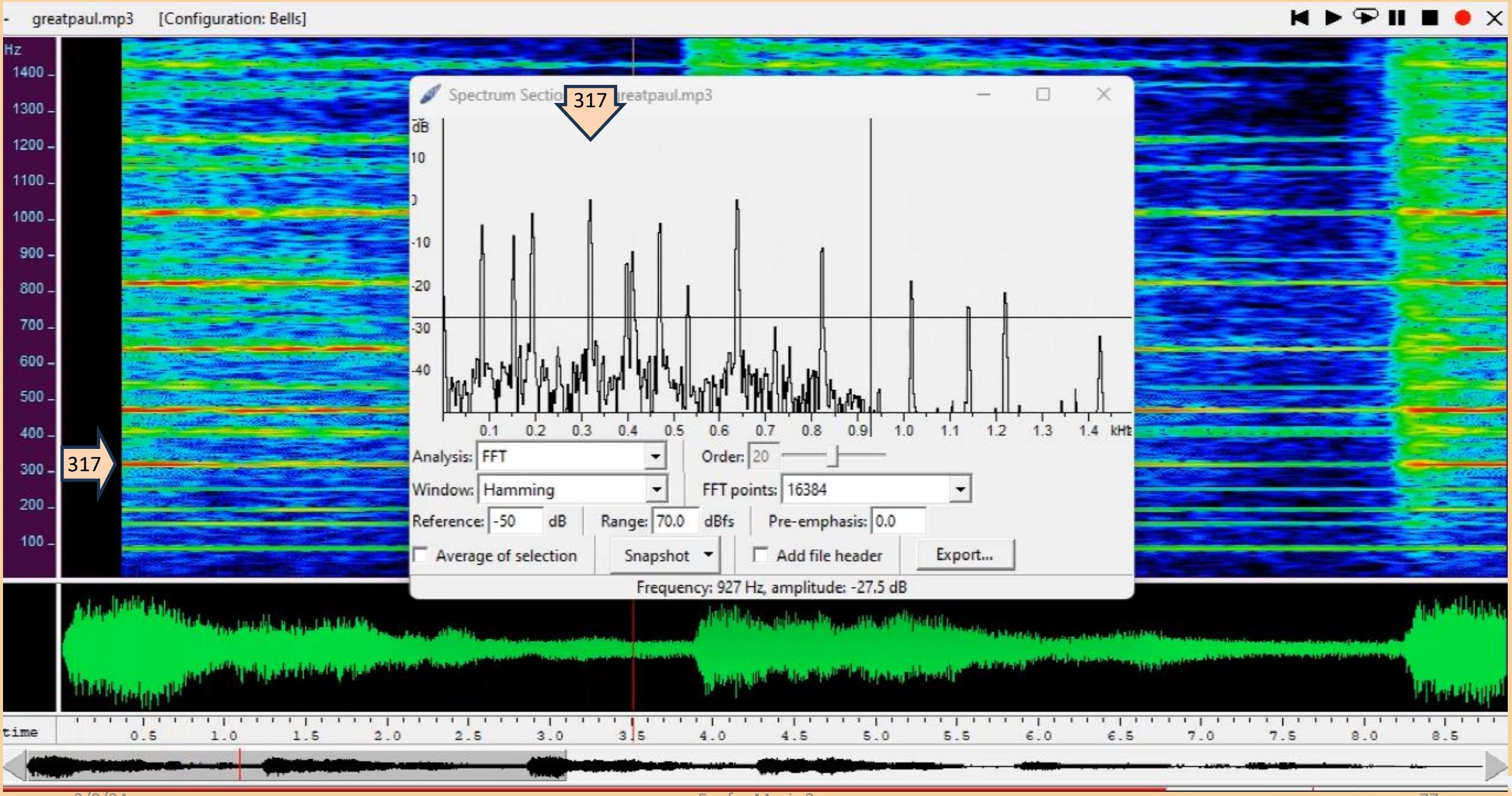
St. Paul's Cathedral

1882, 17 tons

Apparent Pitch:
317 Hz



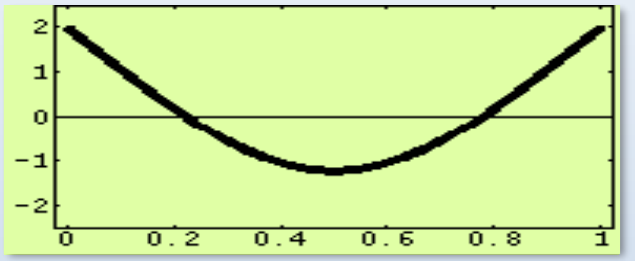

greatpaul.mp3
[Configuration: Bells]
Hz
1400
1300
1200
1100
1000
900
800
700
600
500
400
317
300
200
100
time
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5

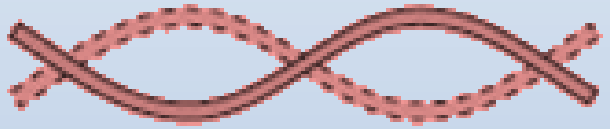

greatpaul.mp3 [Configuration: Bells]
Hz
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
317
Spectrum Sectio
317
greatpaul.mp3
dB
10
-10
-20
-30
-40
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 kHz
Analysis: FFT
Order: 20
Window: Hamming
FFT points: 16384
Reference: -50 dB
Range: 70.0 dBfs
Pre-emphasis: 0.0
Average of selection
Snapshot
Add file header
Export...
Frequency: 927 Hz, amplitude: -27.5 dB
time
0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5

Vibrating Bars

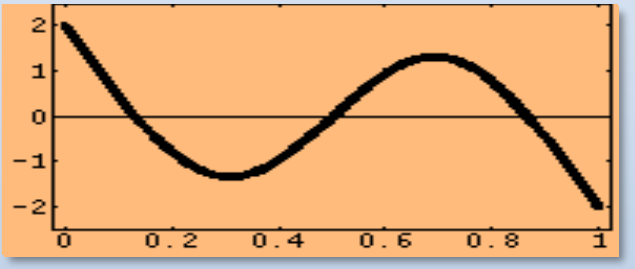
Xylophone
Rochdale Borough Council, UK
YouTube (~2020

f_0

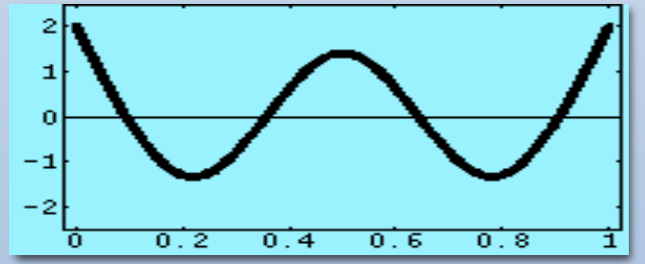


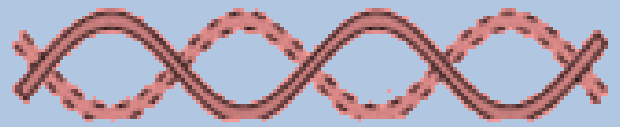


$2.76\ f_0$



$5.40\ f_0$





$8.93\ f_0$

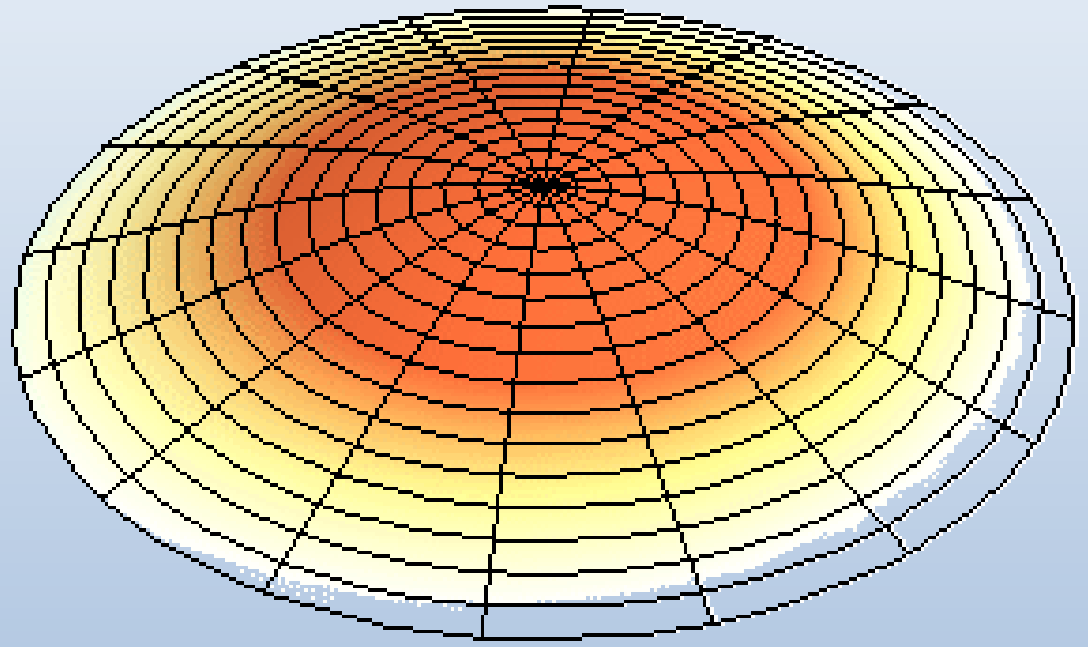
Dan Russell
(Penn State)

Open University [GB]

Not anywhere near harmonic!

Drumheads:
Two Dimensional Membranes

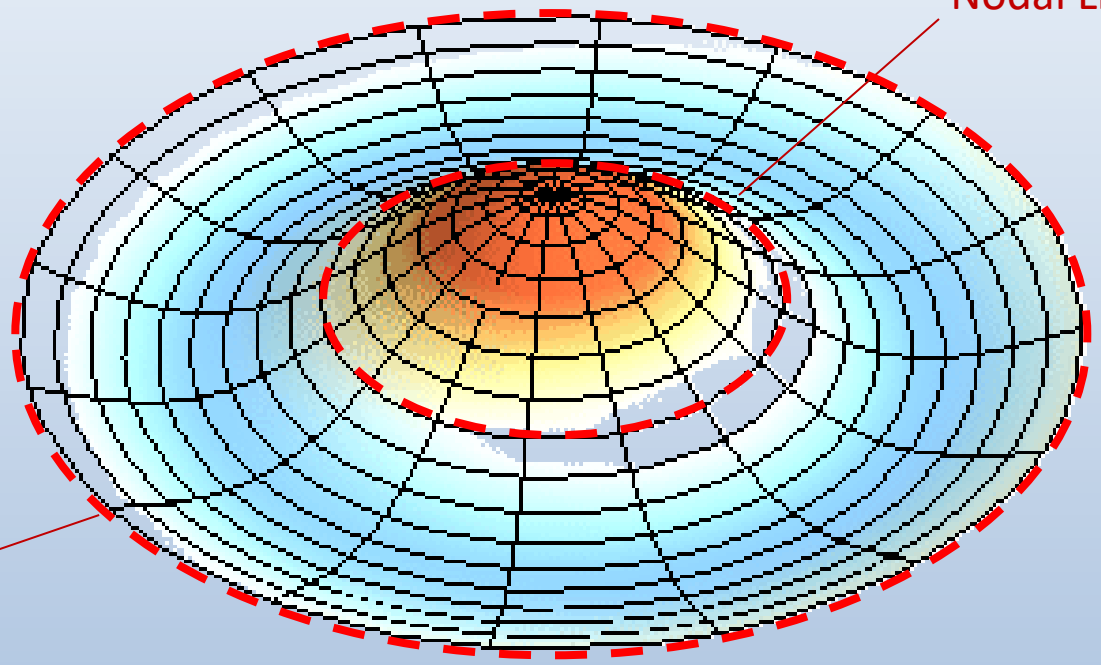
Fundamental Mode of a Drumhead (0,1)



$f = f_0$

D Russell Penn State

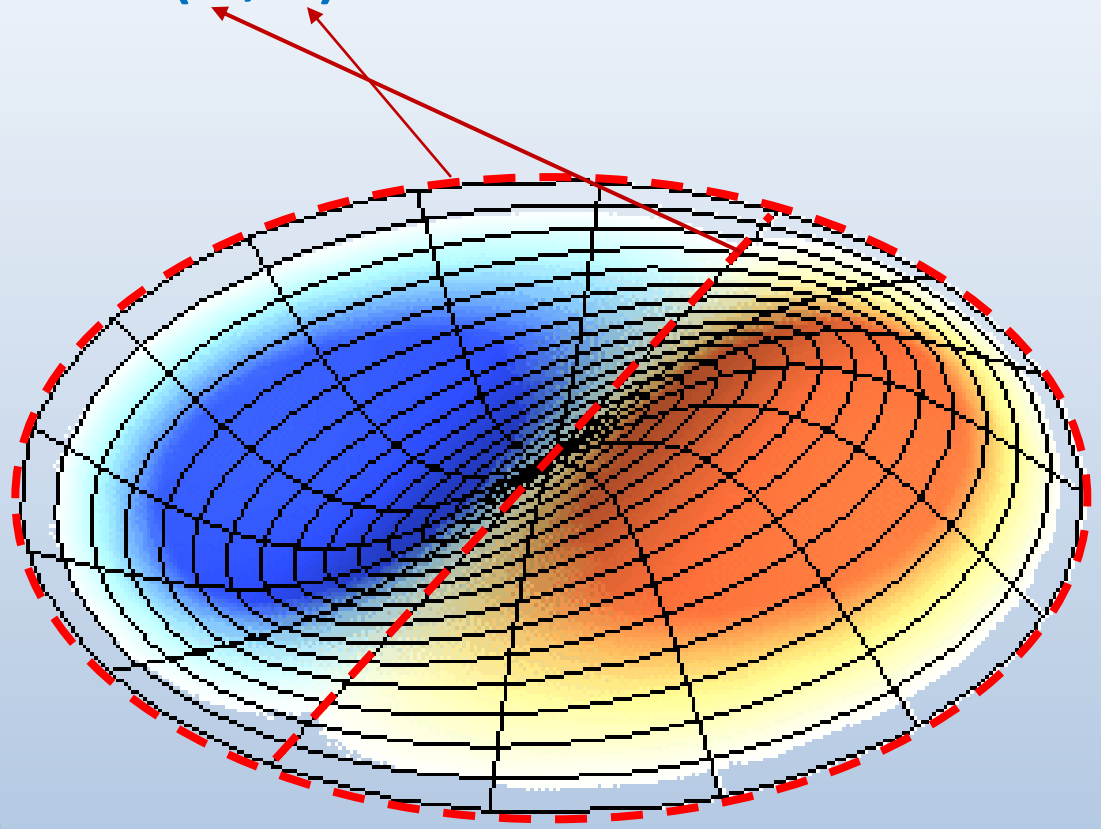
The (0,2) Drumhead Mode



$f = 2.295\, f_0$

D Russell Penn State

The (1,1) Drumhead Mode



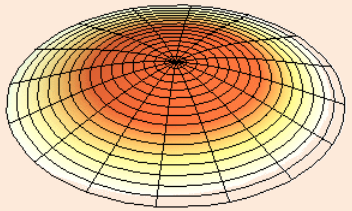
Symmetric:
No net air volume change under the drumhead

$f = 1.593\, f_0$

D Russell Penn State

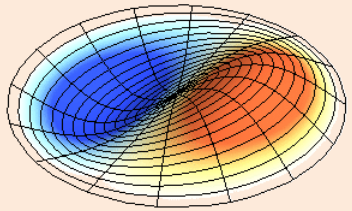
More Drumhead Modes

0,1



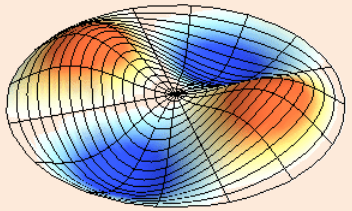
f_0

1,1



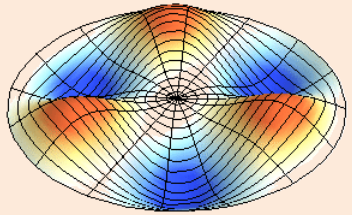
$1.593\ f_0$

2,1



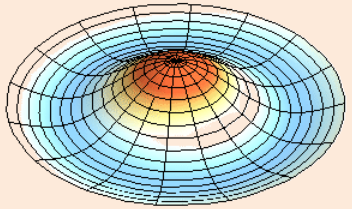
$2.135\ f_0$

3,1



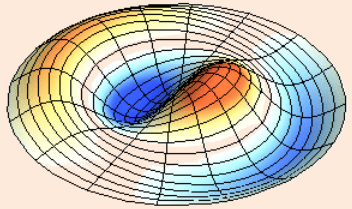
$2.653\ f_0$

0,2



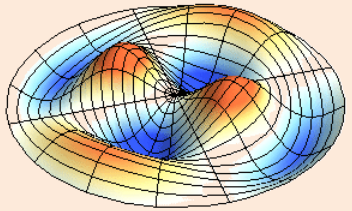
$2.296\ f_0$

1,2



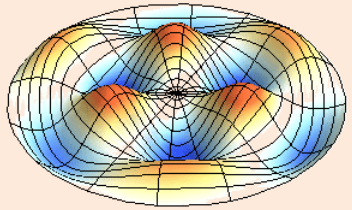
$2.918\ f_0$

2,2



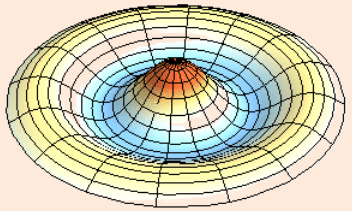
$3.501\ f_0$

3,2



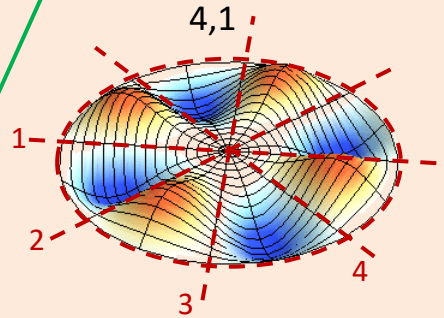
$4.060\ f_0$

0,3



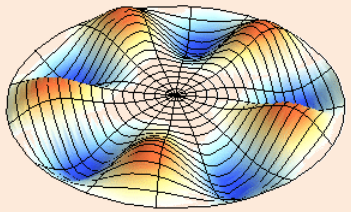
$3.600\ f_0$

4,1



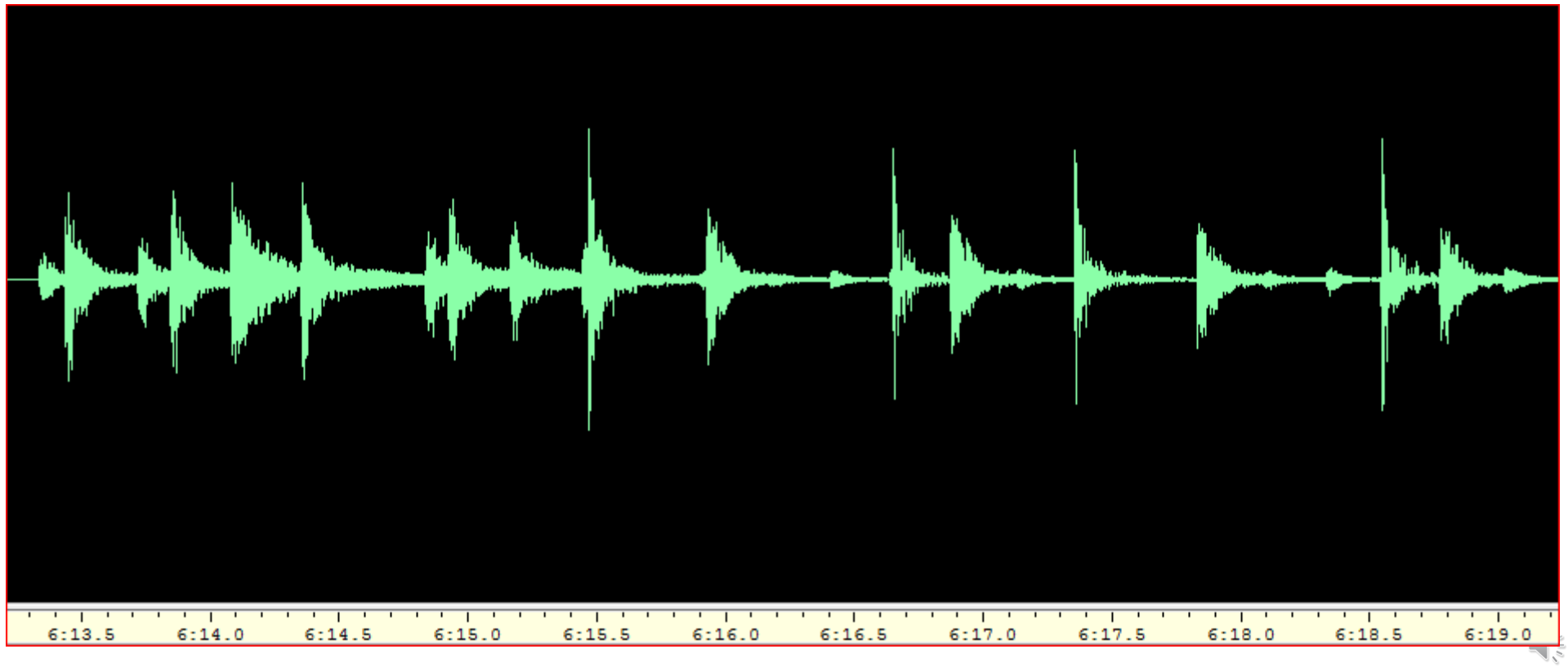
$3.156\ f_0$

5,1



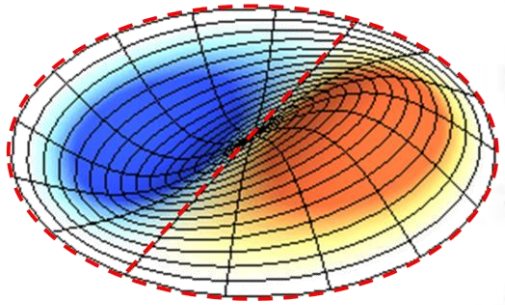
$3.652\ f_0$

What you're hearing…

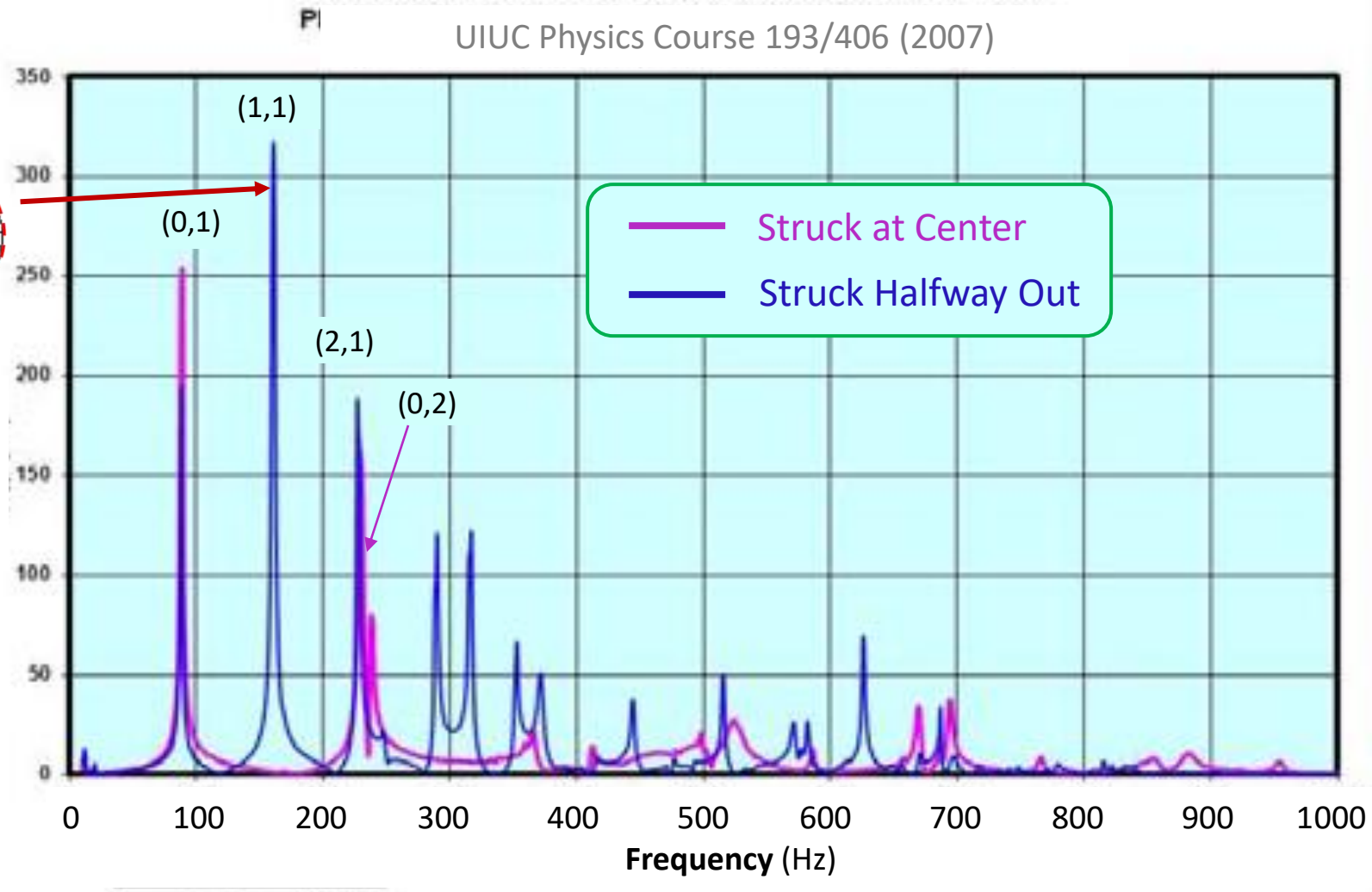


Measured Sound Spectrum of 12” Tom Drum

(1,1)



“Lug Tone”



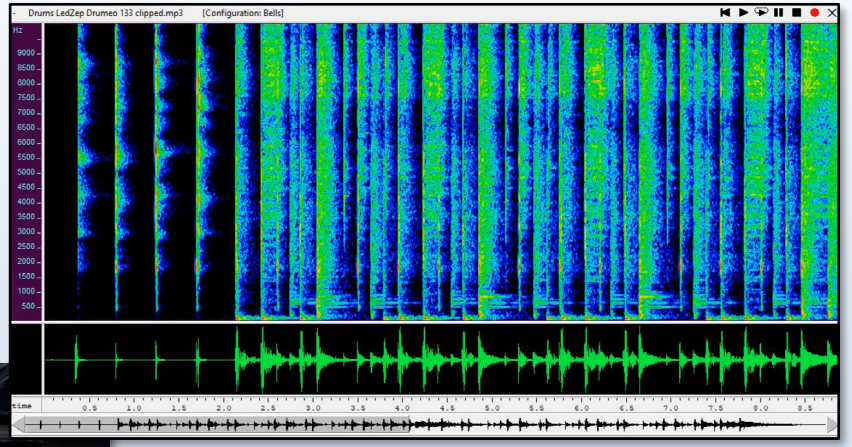
Groove from

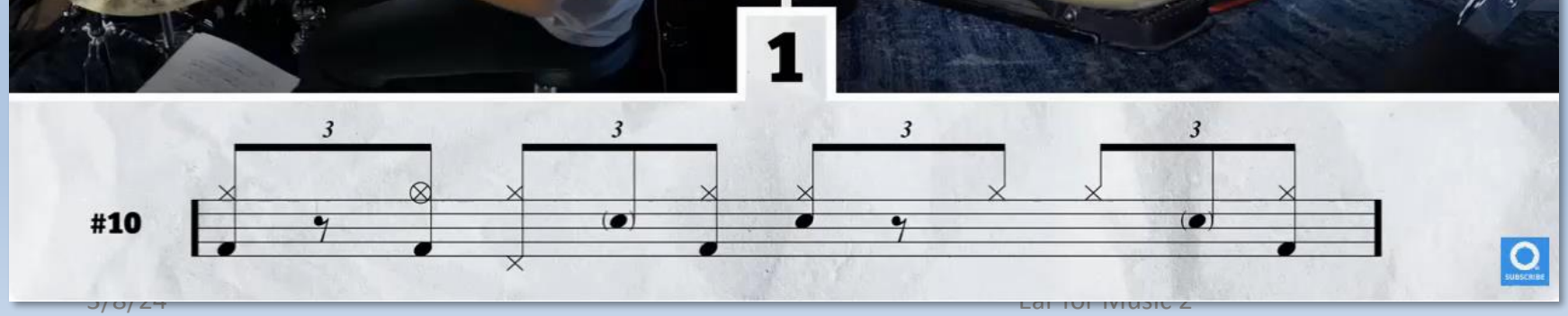
Led Zeppelin's

"Fool In the Rain"

Drumeo

YouTube ~2021





Groove from

Led Zeppelin's

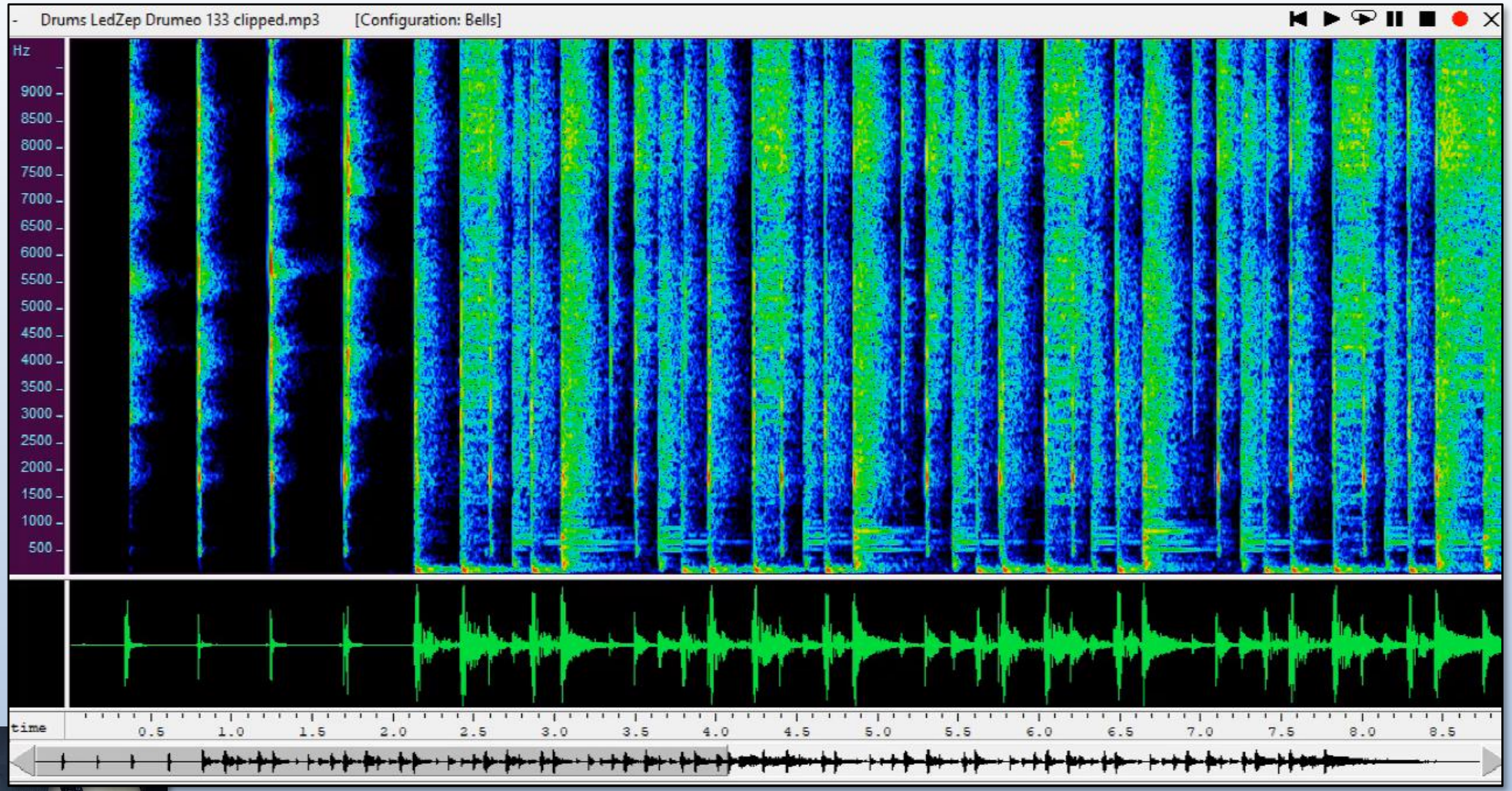
"Fool In the Rain"

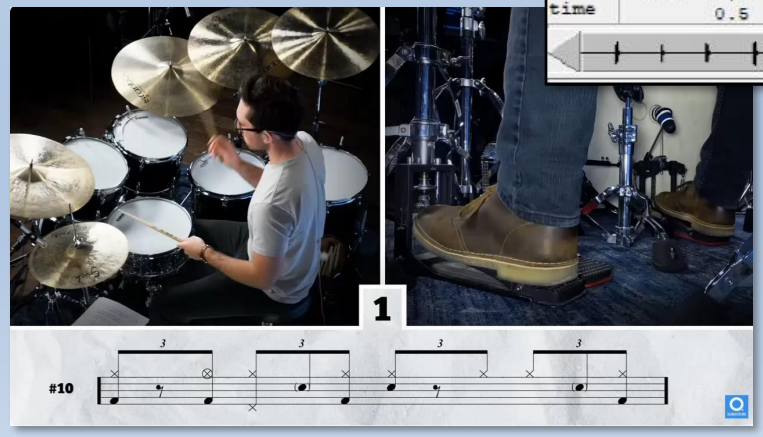
Drumeo

YouTube ~2021

10 kHz

0 Hz

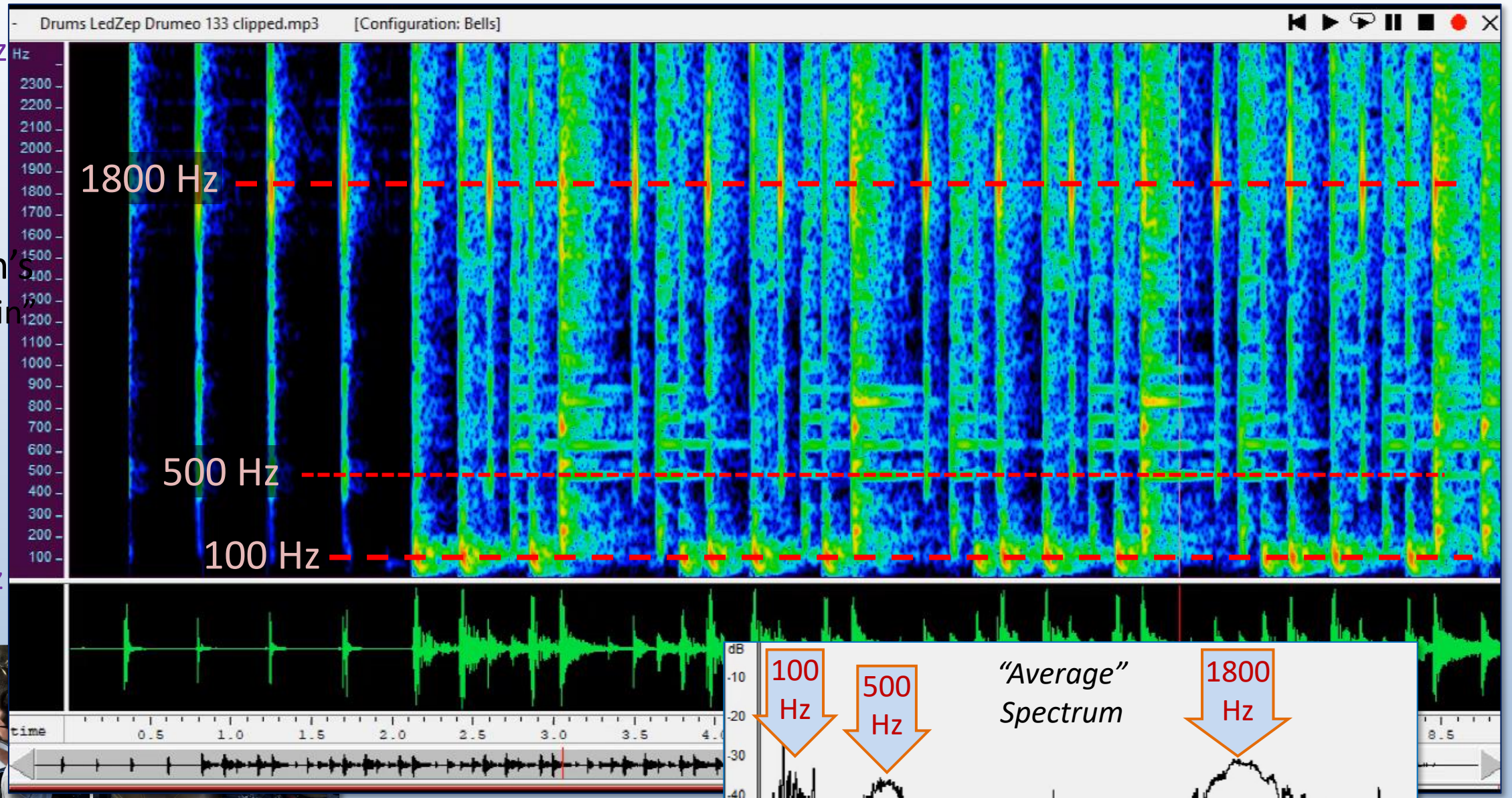




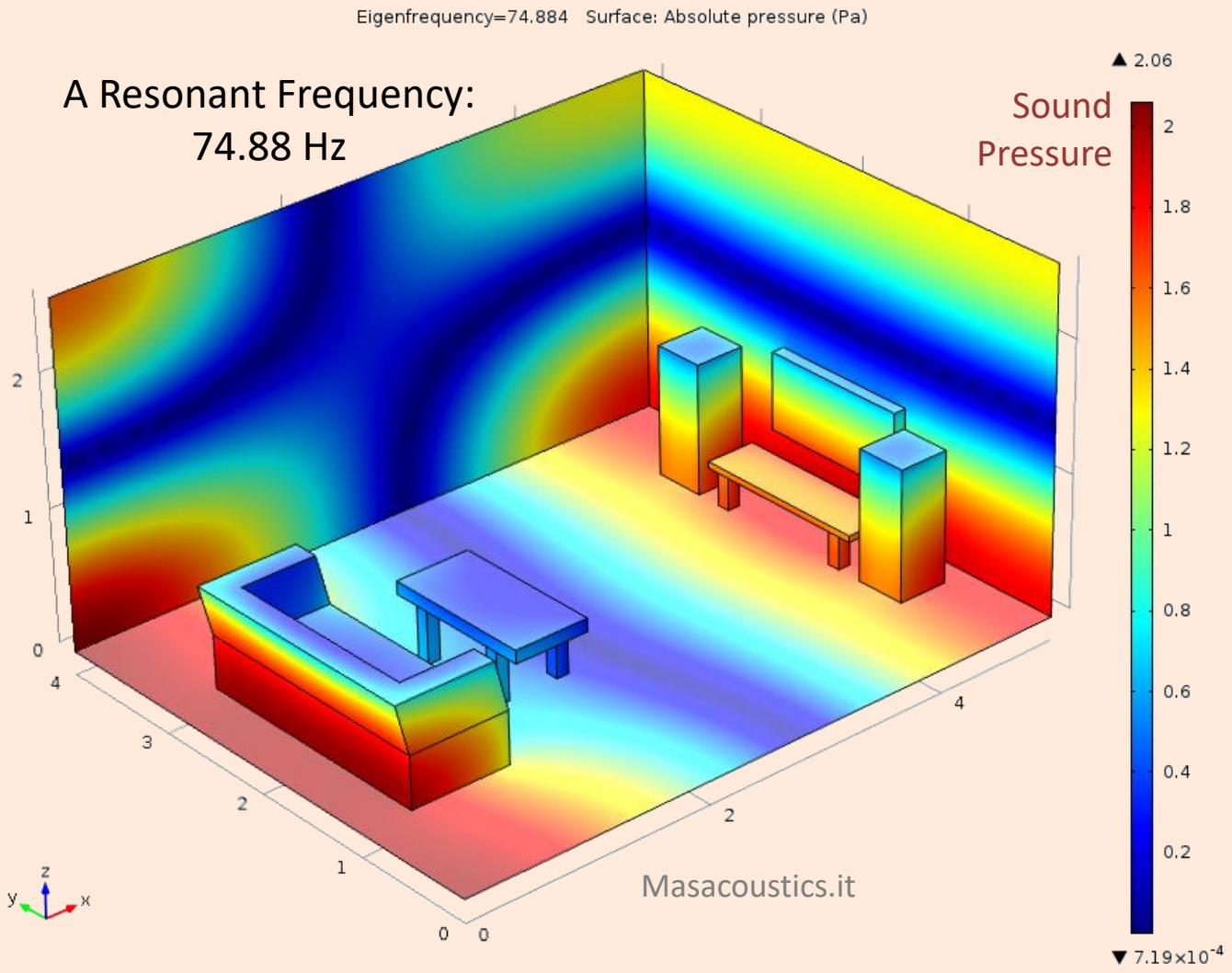
2.5 kHz

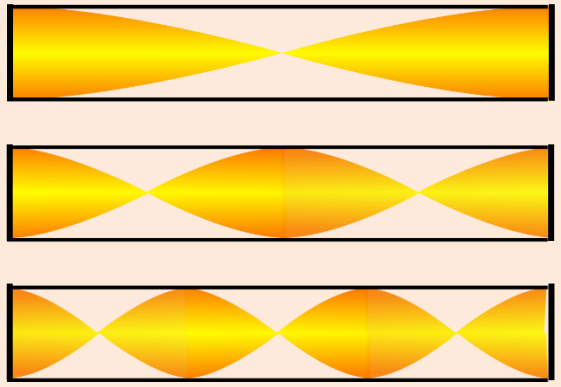
Groove from
ed Zeppelin's
ool In the Rain"
Drumeo
YouTube ~2021

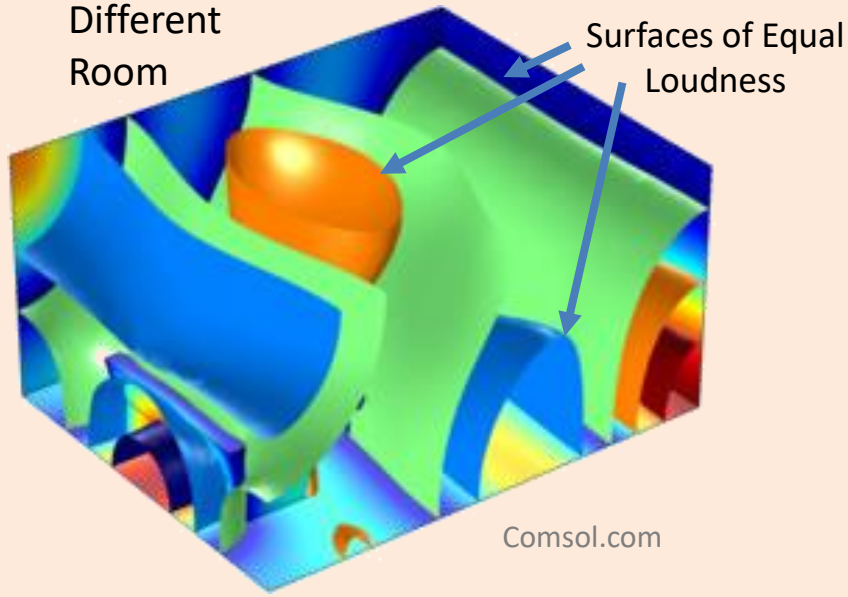
0 Hz



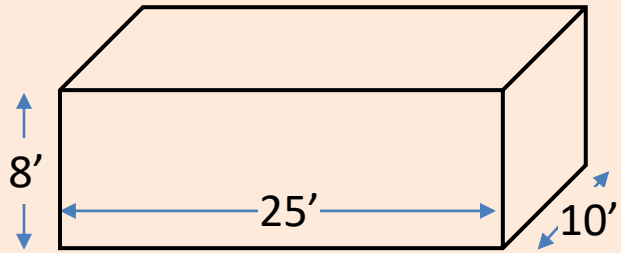
Room Modes

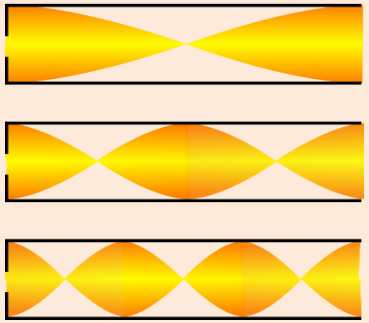

Eigenfrequency=74.884 Surface: Absolute pressure (Pa)
A Resonant Frequency:
74.88 Hz
Sound
Pressure
▲ 2.06
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
▼ 7.19×10^-4
Masacoustics.it



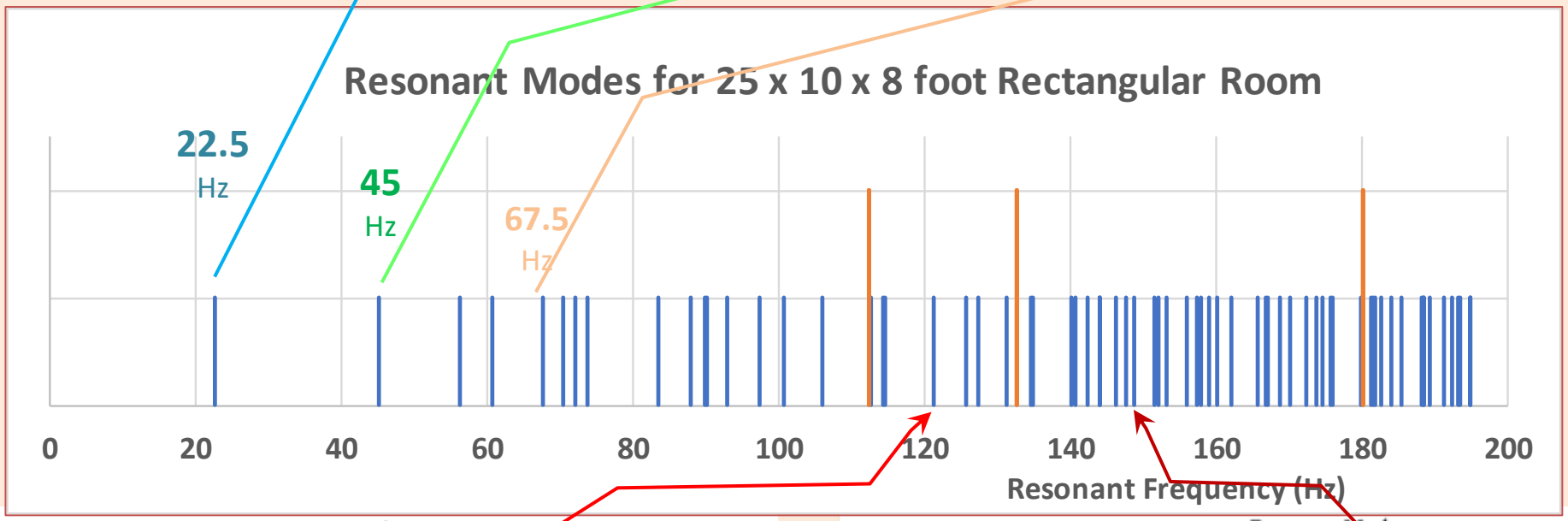

Different
Room
Surfaces of Equal
Loudness
Comsol.com

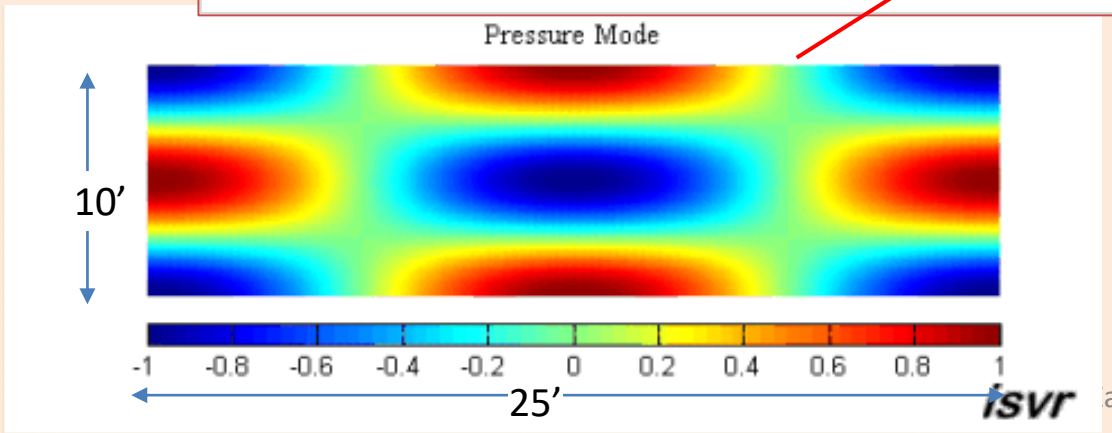
Room Modes

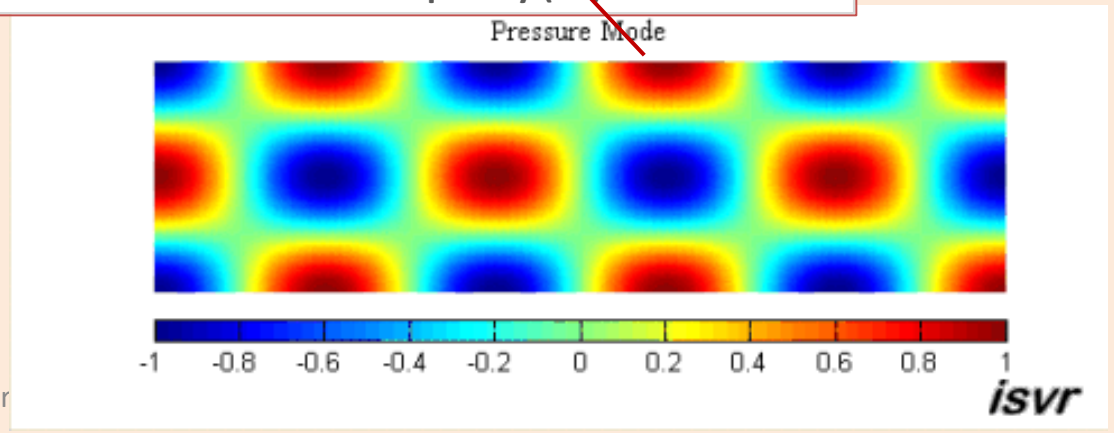




Longitudinal “Organ Pipe” modes







Question Time

- Pipe Instruments
- Non-harmonic resonators
- Drums
- Room Resonances

Course Outline

1. Building Blocks: Some basic concepts
2. **Resonance: Building Complex Sounds**
3. Hearing and the Ear
4. Musical Scales and Musical Notation
5. Musical Instruments: Strings and Others
6. Musical Instruments: Pipes
7. Human Voice and Singing
8. Harmony and Dissonance; Chords