OSHER LIFELONG LEARNING INSTITUTE

An Ear for Music

Session 6
Pipe Instruments; Timbre

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
5. Musical Notation; String Instruments
6. **Pipe Instruments and Timbre**
7. Human Voice and Singing
8. Harmony and Dissonance; Chords

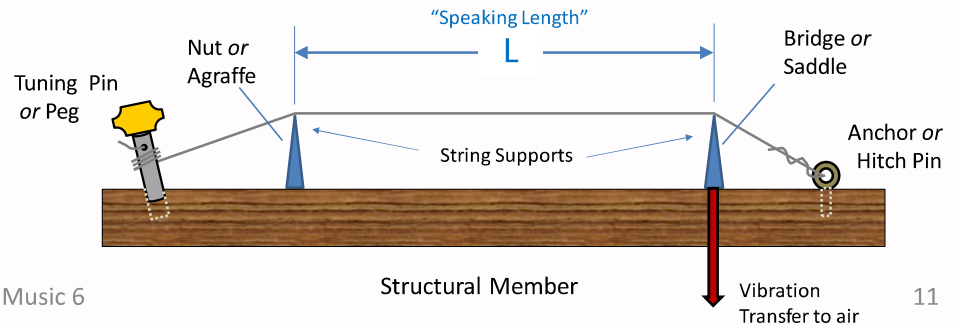
Frets

Strings

Demo

E2	82.4 Hz
A2	110.0
D3	146.8
G3	196.0
B3	246.9
E4	329.6 Hz

16 14 12 11 10 9 8 7 6 5 4 3 2 1 0 (nut)



Piano	MIDI	f	Chromatic Scale	Note	
45	**65**	**349.2**		F 4	
44	**64**	**329.6**		E 4	**E4**
43	**63**	**311.1**		D#/E♭ 4	
42	**62**	**293.7**		D 4	
41	**61**	**277.2**		C#/D♭ 4	
40	**60**	**261.6**		**C 4**	
39	59	246.9		B 3	**B3**
38	58	233.1		A#/B♭ 3	
37	57	220		A 3	
36	56	207.7		G#/A♭ 3	
35	55	196.0		G 3	**G3**
34	54	185.0		F#/G♭ 3	
33	53	174.6		F 3	
32	52	164.8		E 3	
31	51	155.6		D#/E♭ 3	
30	50	146.8		D 3	**D3**
29	49	138.6		C#/D♭ 3	
28	48	130.8		C 3	
27	47	123.5		B 2	
26	46	116.5		A#/B♭ 2	
25	45	110		A 2	**A2**
24	44	103.8		G#/A♭ 2	
23	43	98.0		G 2	
22	42	92.5		F#/G♭ 2	
21	41	87.3		F 2	
20	40	82.4		E 2	**E2**
19	39	77.8		D#/E♭ 2	

5 steps

4 steps

5 steps

5 steps

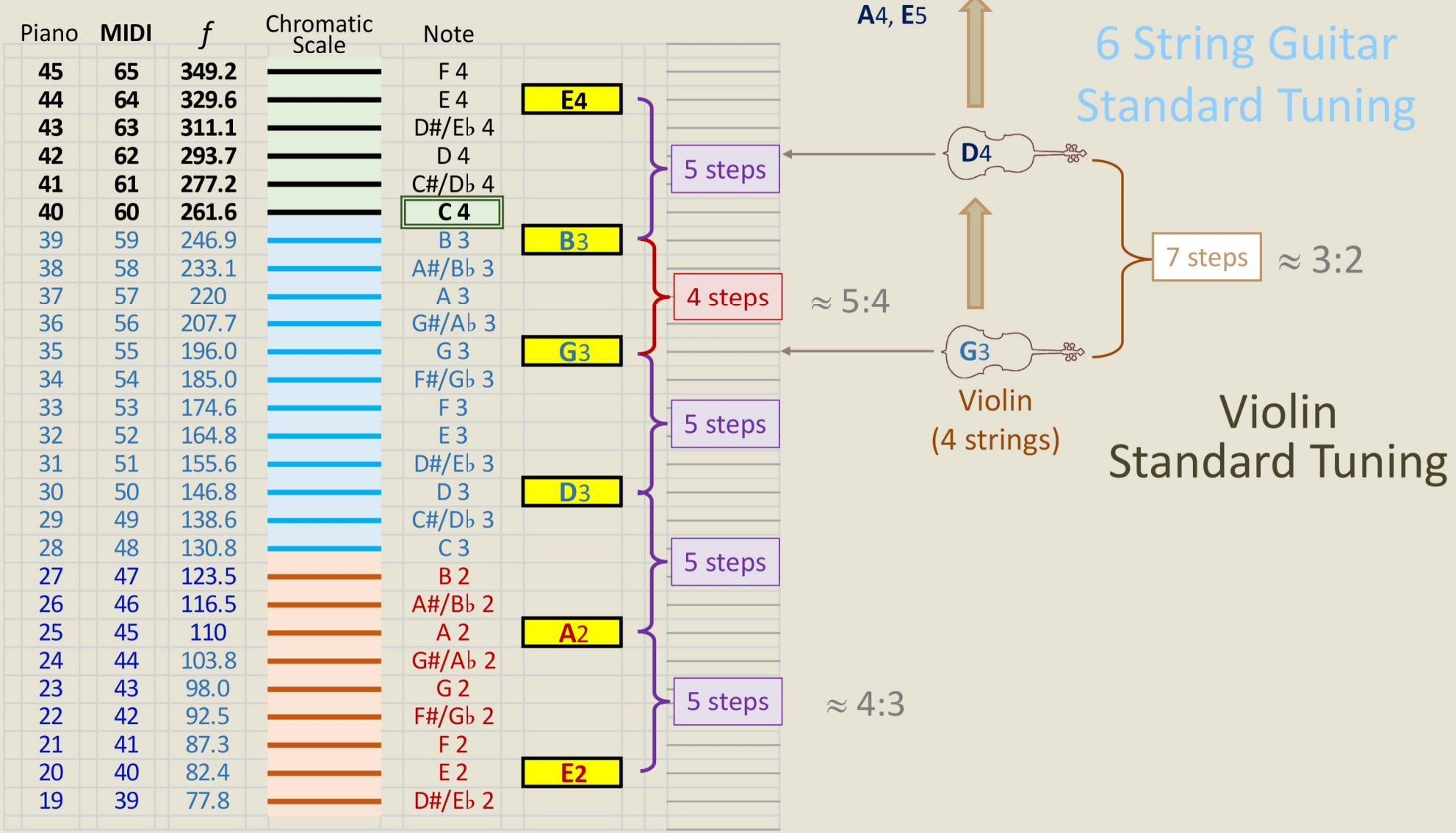
5 steps

≈ 5:4

≈ 4:3

6 String Guitar Standard Tuning

Open Strings


Piano
MIDI
f
Chromatic Scale
Note
45 65 349.2 F 4
44 64 329.6 E 4
43 63 311.1 D#/Eb 4
42 62 293.7 D 4
41 61 277.2 C#/Db 4
40 60 261.6 C 4
39 59 246.9 B 3
38 58 233.1 A#/Bb 3
37 57 220 A 3
36 56 207.7 G#/Ab 3
35 55 196.0 G 3
34 54 185.0 F#/Gb 3
33 53 174.6 F 3
32 52 164.8 E 3
31 51 155.6 D#/Eb 3
30 50 146.8 D 3
29 49 138.6 C#/Db 3
28 48 130.8 C 3
27 47 123.5 B 2
26 46 116.5 A#/Bb 2
25 45 110 A 2
24 44 103.8 G#/Ab 2
23 43 98.0 G 2
22 42 92.5 F#/Gb 2
21 41 87.3 F 2
20 40 82.4 E 2
19 39 77.8 D#/Eb 2
E4
B3
G3
D3
A2
E2
5 steps
4 steps
5 steps
5 steps
5 steps
≈ 5:4
≈ 4:3
A4, E5
6 String Guitar
Standard Tuning
D4
G3
7 steps
≈ 3:2
Violin
(4 strings)
Violin
Standard Tuning

6 String Guitar Standard Tuning

Piano	MIDI	f	Chromatic Scale	Note	Guitar Strings
45	**65**	**349.2**		F 4	
44	**64**	**329.6**		E 4	**E4**
43	**63**	**311.1**		D#/E♭ 4	
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21	41	87.3		F 2	
20	40	82.4		E 2	**E2**
19	39	77.8		D#/E♭ 2	

All 6 belong to *two* of the Pentatonic Scales

They also belong to 6 Diatonic Scales:

C Major	A minor
D Major	B minor
G Major	E minor

G Major Root Chord

G Major

E minor

Strings

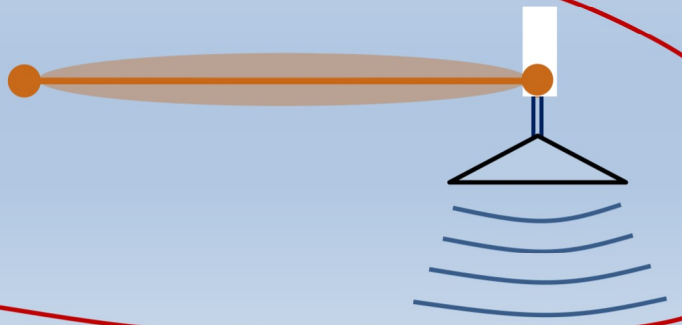
String Instruments

Three main problems:

1. Excitation EASY
   - How to get the string vibrating

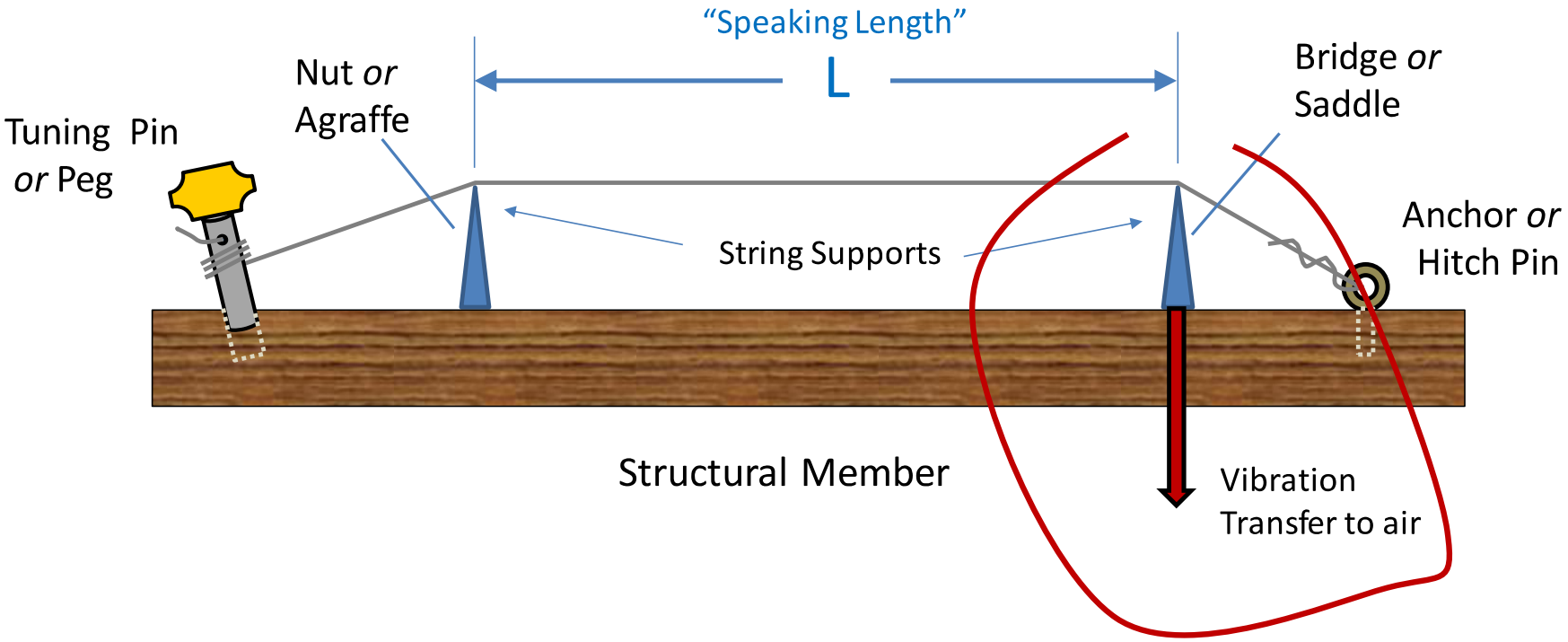
2. Frequency Control EASY
   - Playing desired notes

3. Getting Sound Out HARD
   - Coupling string vibrations to sound waves



Strings

Generic String:
Transferring String Vibrations into the Air

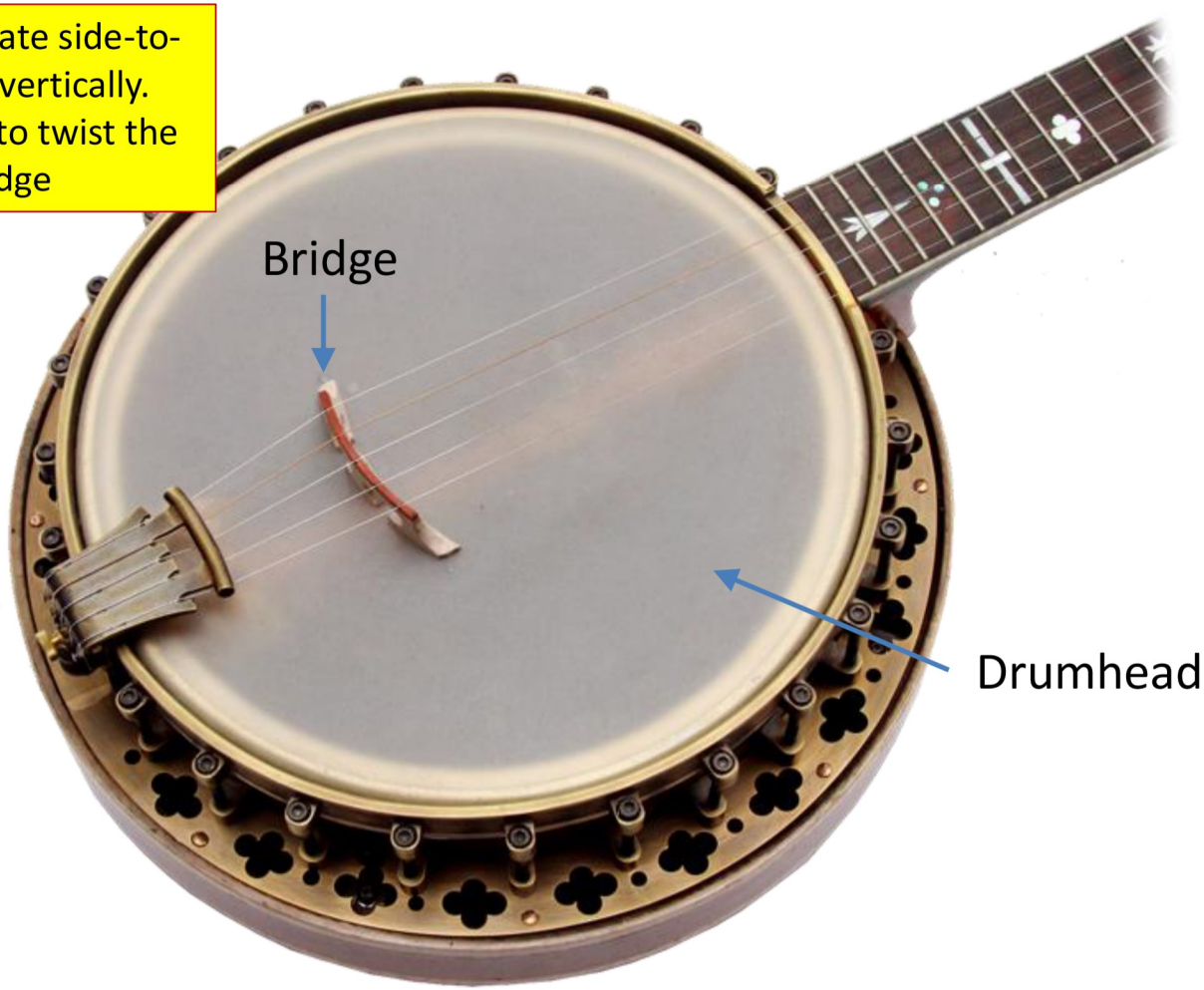


Strings

Banjo: Transferring String Vibrations into the Air

Strings vibrate side-to-side, not vertically. This tends to twist the Bridge

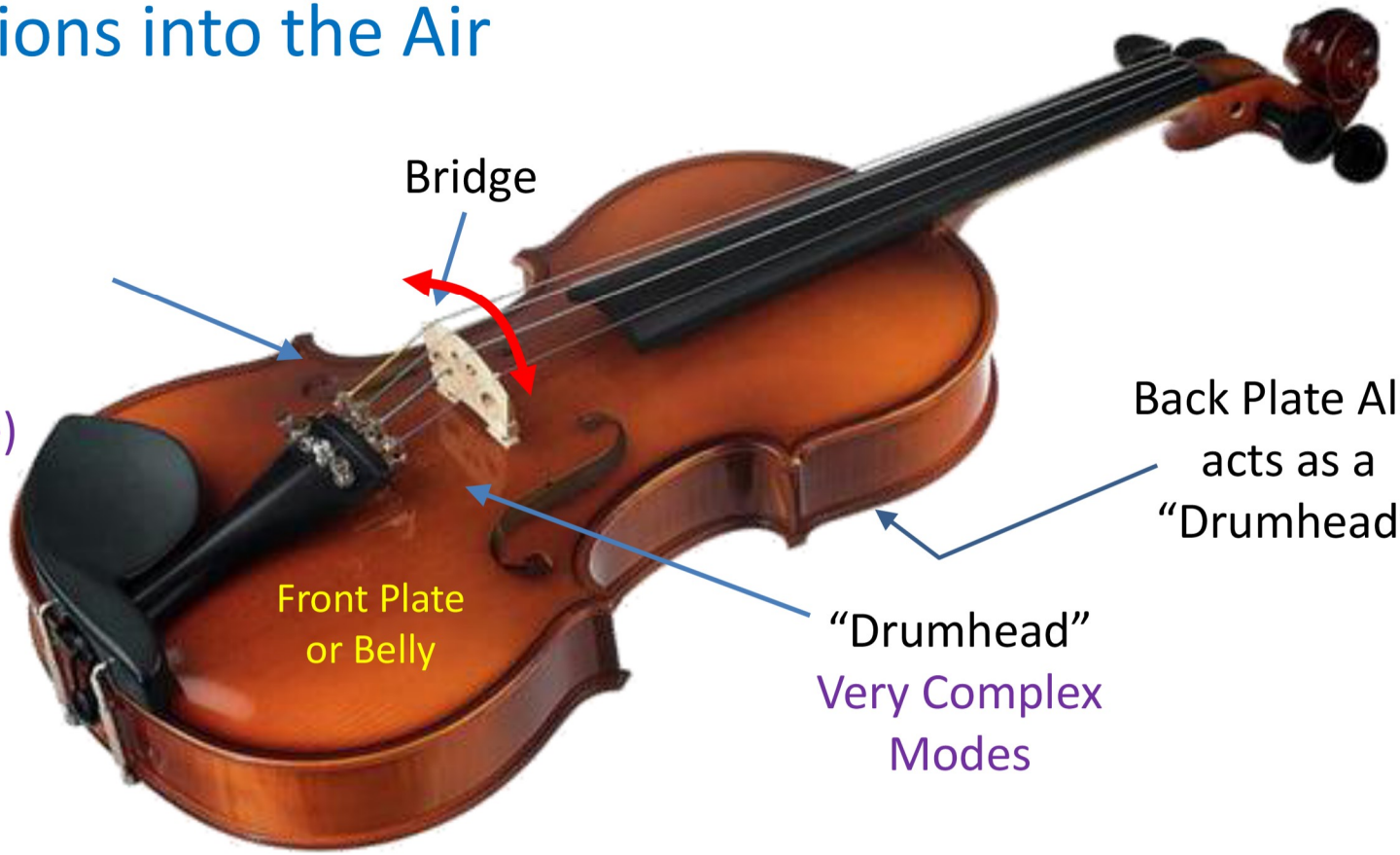
Closed Back Banjo



Strings

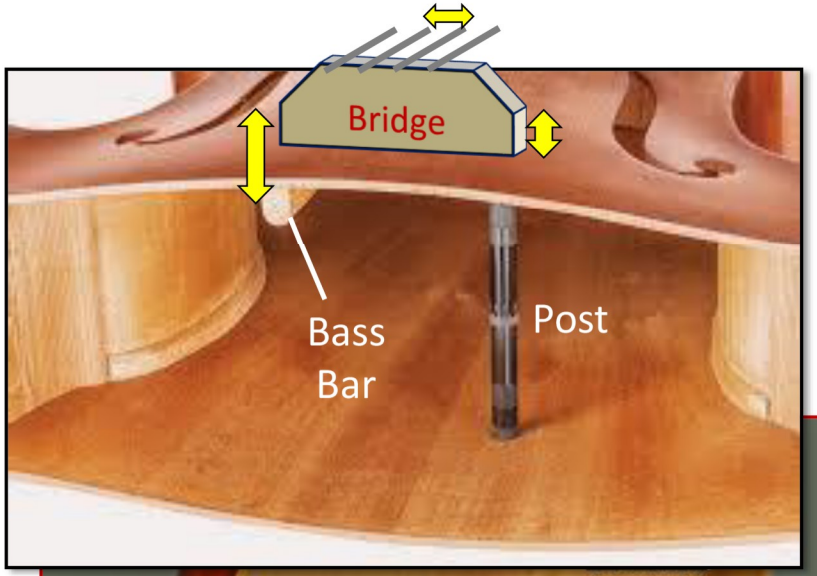
Violin: Transferring String Vibrations into the Air

Again, Strings vibrate side-to-side, not vertically.



Strings

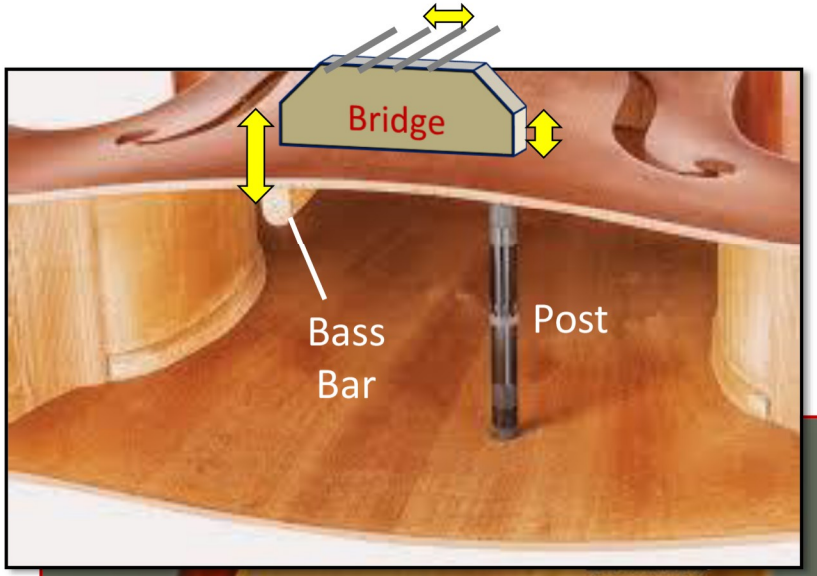
Violin: Transferring String Vibrations into the Air



Strings

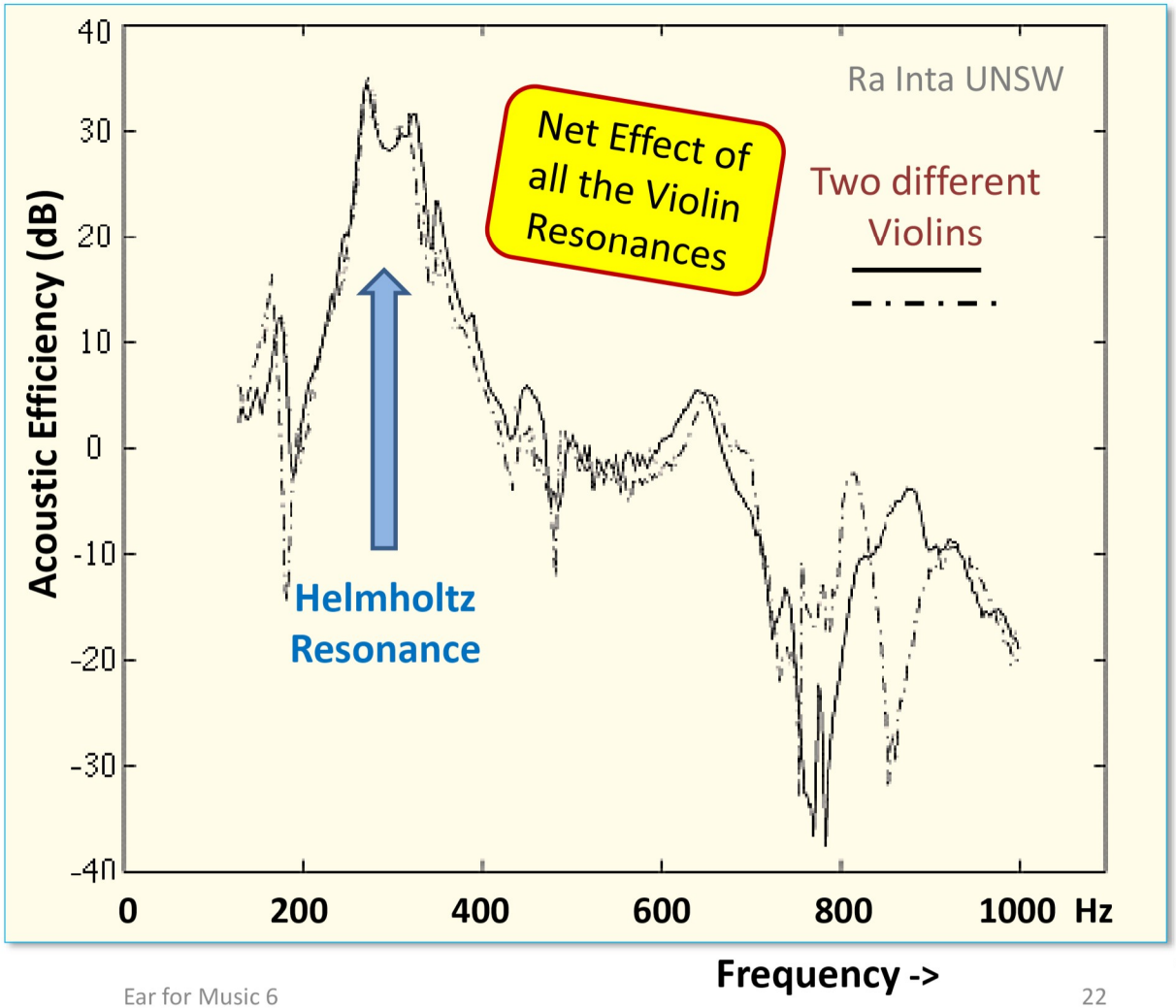
Violin: Transferring String Vibrations into the Air

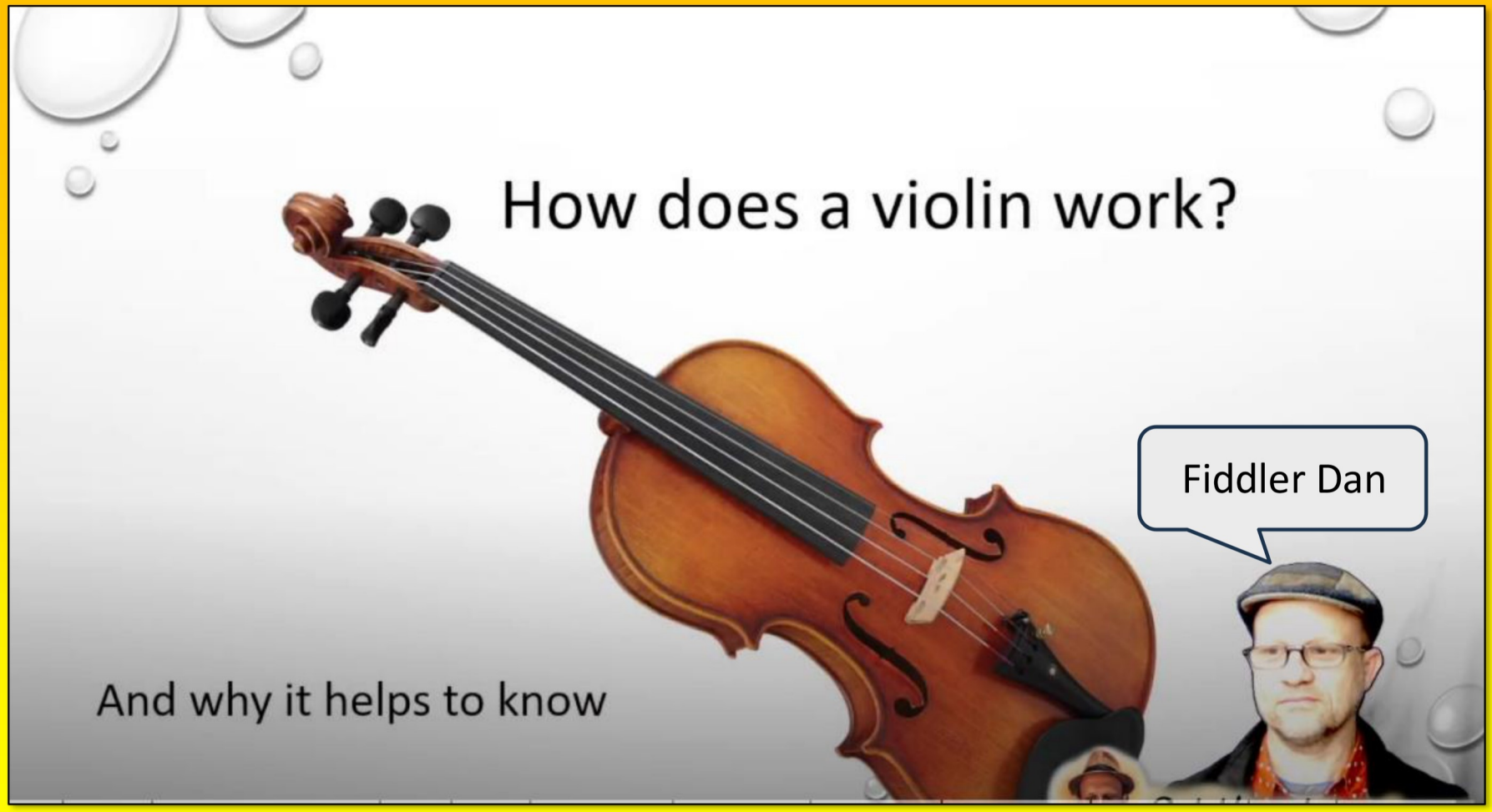
Loose powder on vibrating plate accumulates at nodal lines.
Different patterns like this for different modes (frequencies).



Strings

Violin: How Efficiently String Vibrations are Converted to Sound in the Air





[How does a violin make a sound? Violin Physics why it matters (youtube.com)] *[18 min]*

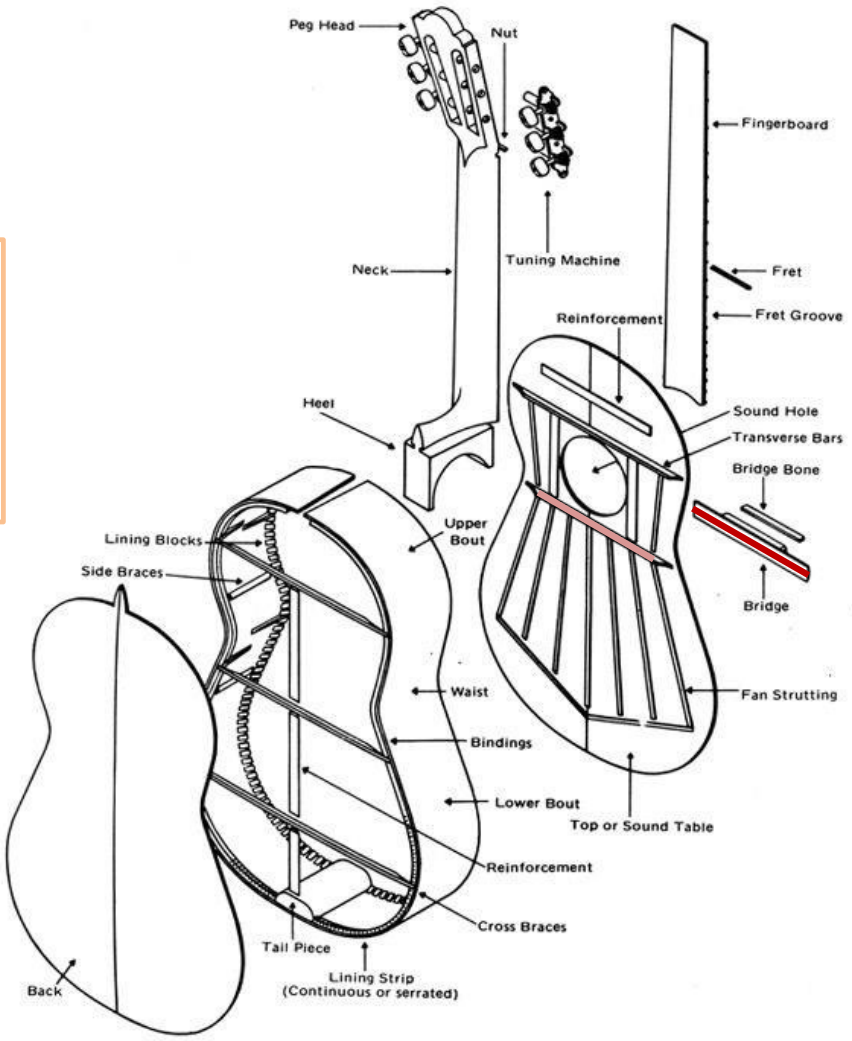
Strings

Guitar Internal Structure

String vibrations excite:

- Drumhead-like modes in top & bottom
- Helmholtz Resonator (body + hole)

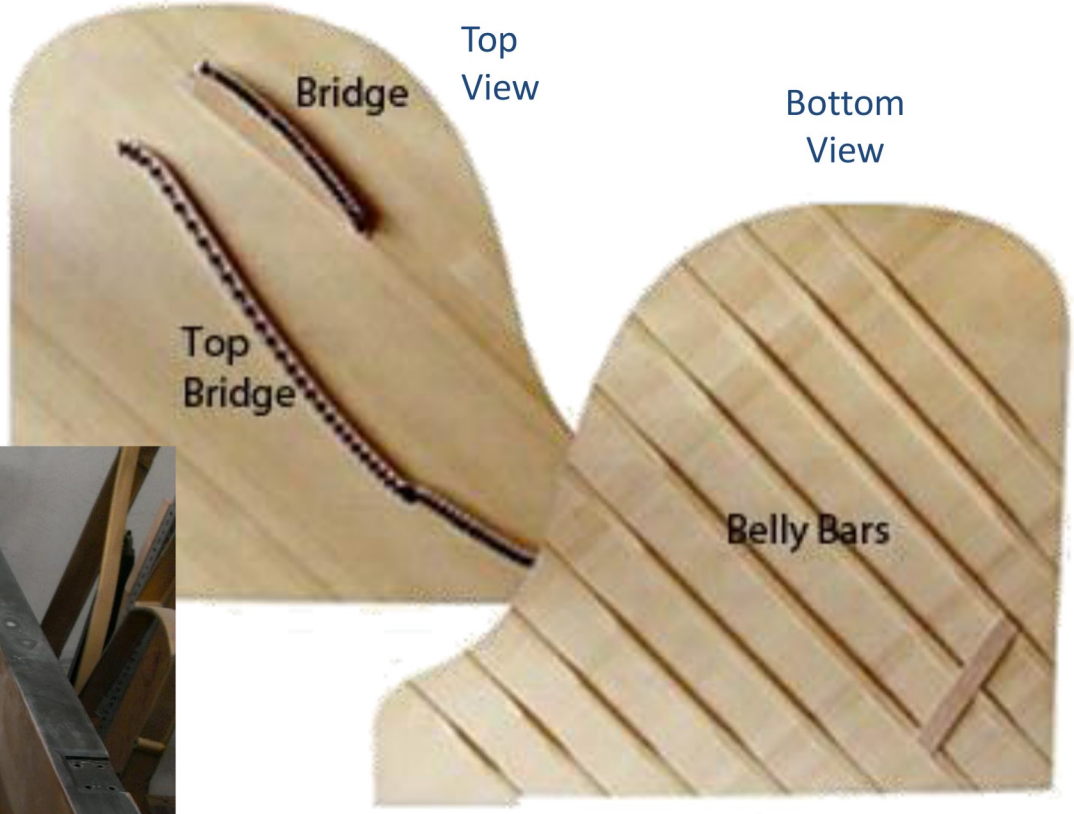
Usually, no Post. However, Posts are sometimes used in guitars.



Strings

Piano Sounding Board

- Sitka spruce
- Thickness varies ¼ to 3/8 “
- Crowned upward for strength
- Has carefully controlled membrane resonances



For Piano, Strings vibrate vertically, directly driving the Bridge into the Sounding Board.

Question Time

- String Sound Output

- Zoomland
- In Person

Pipes?

Oldest Musical Instrument?

- **Divje Babe** “Flute”
- Cave Bear femur
- Discovered 1995 near Cerkno, Slovenia
- Age ~ 43,000 BP (Neanderthal)
- Origin and purpose of holes controversial

Pipes

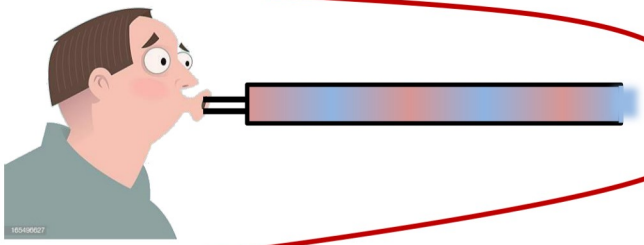
Playable Neolithic Chinese Flutes

- Jiahu Flutes
- Henan Province, China
- Discovered 1999
- ~ 9000 BP
- Ulna bone of red-crowned crane
- Still playable

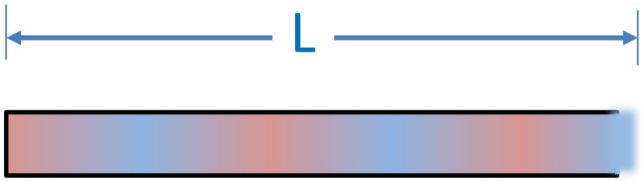
Pipes

Aerophone Instruments

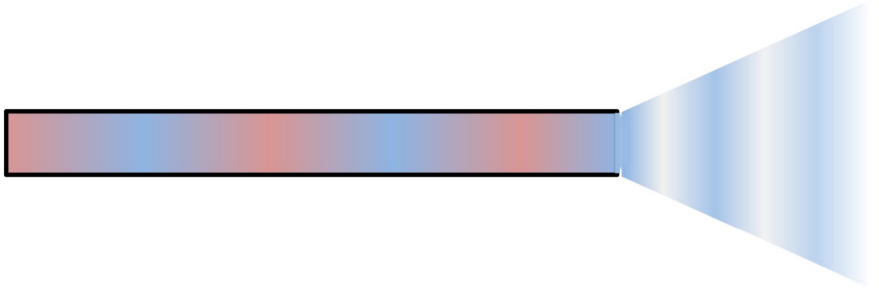
Three main problems:



1. Excitation HARD
   - How to get the pipe resonating
2. Frequency Control MEDIUM
   - Playing desired notes

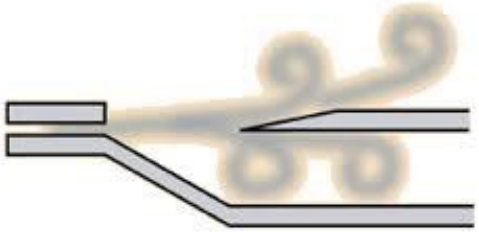


3. Getting Sound Out EASY
   - Resonances are *already* sound waves

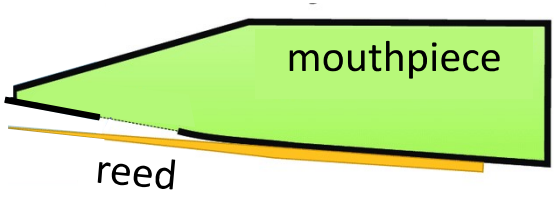


3 Basic Kinds of Excitation of Pipes

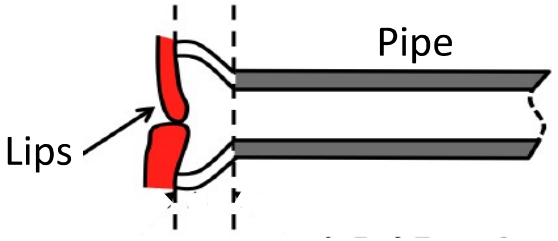
- Edge Tones



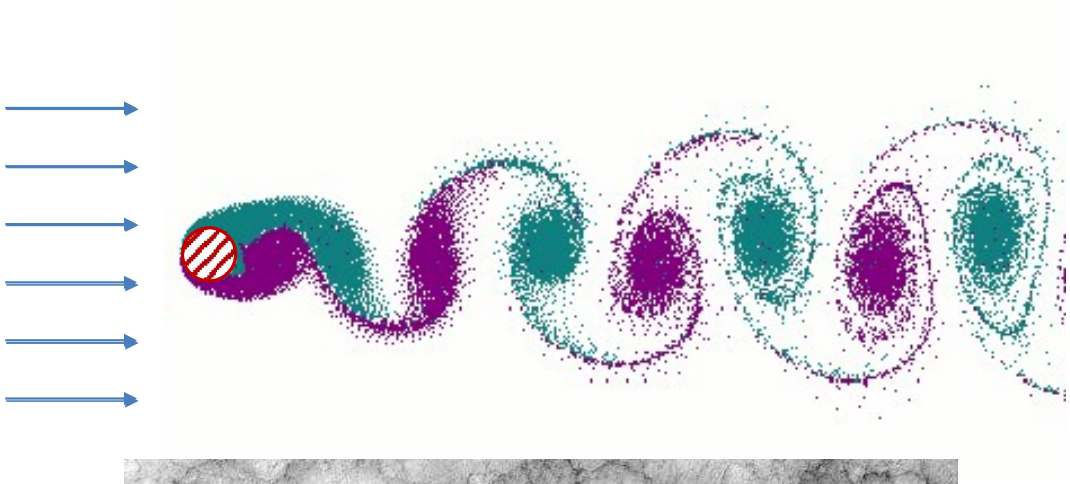
- Untuned Reeds



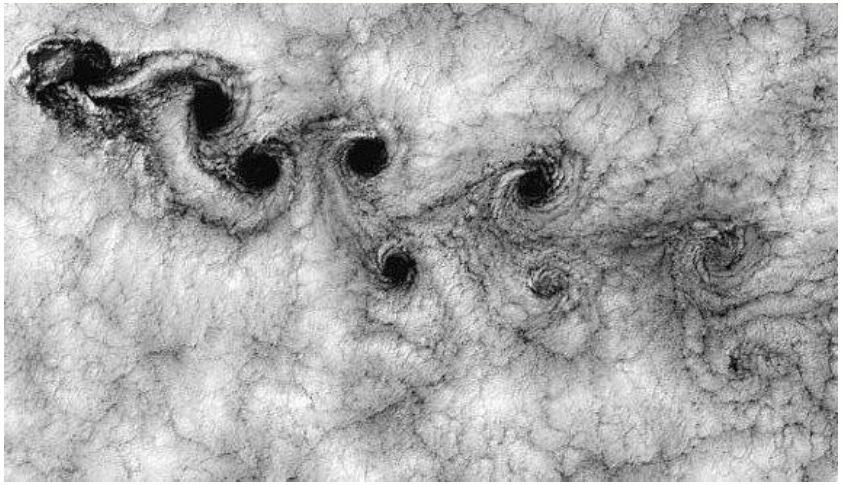
- Vibrating Human Lips



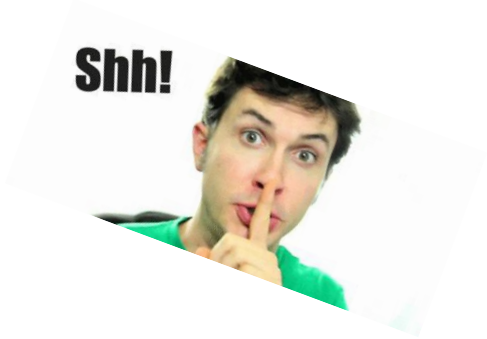
Air hitting cylinder barrier creates “Vortex Street”



Mountain
Vortex Street
in Atmosphere
(from space)



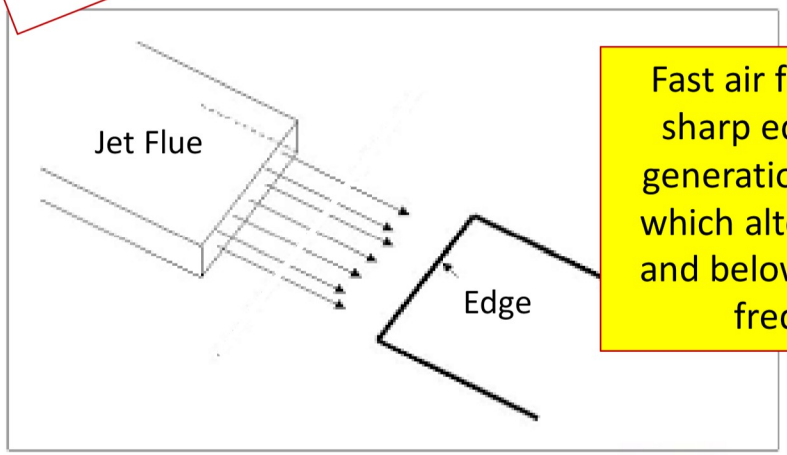
Turbulent Air Flow → Noise



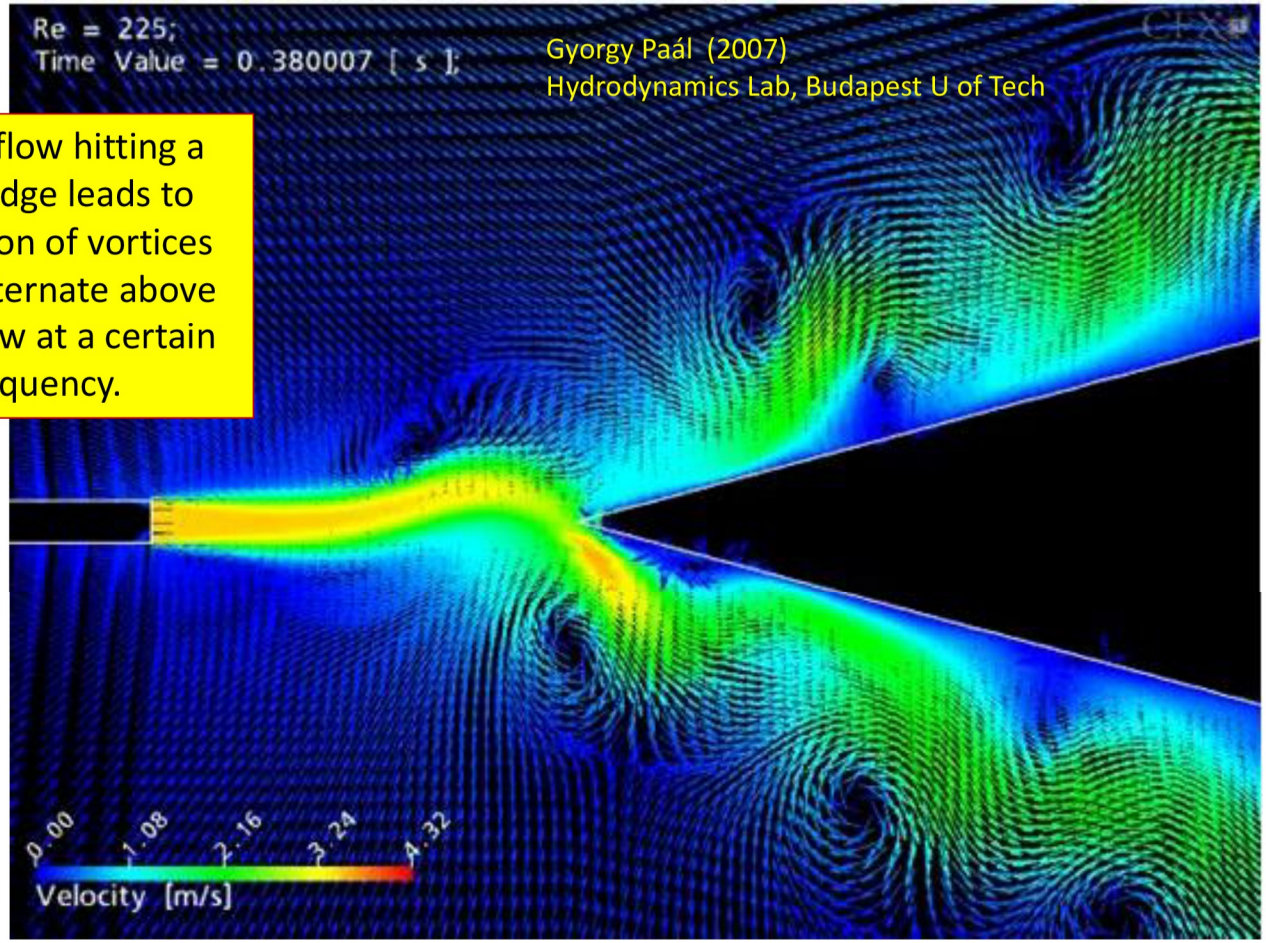
Most commonly, turbulent flow just makes broadband noise. But in certain cases, it can generate single frequencies….

Pipes

Turbulent Flow: Edge Tones



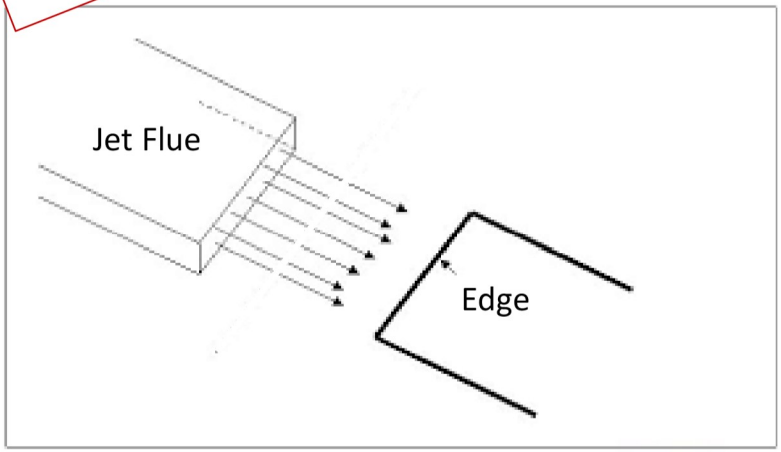
Fast air flow hitting a sharp edge leads to generation of vortices which alternate above and below at a certain frequency.



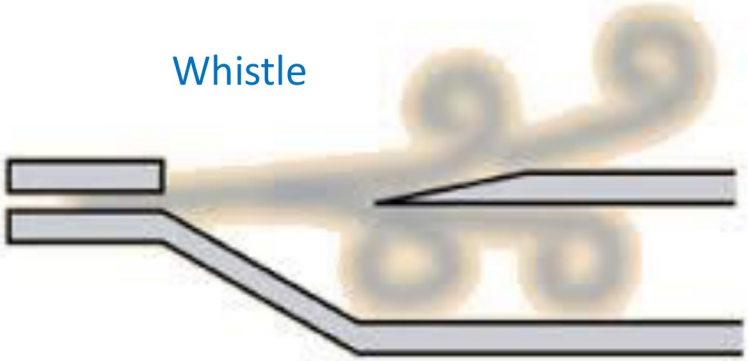
Whistle

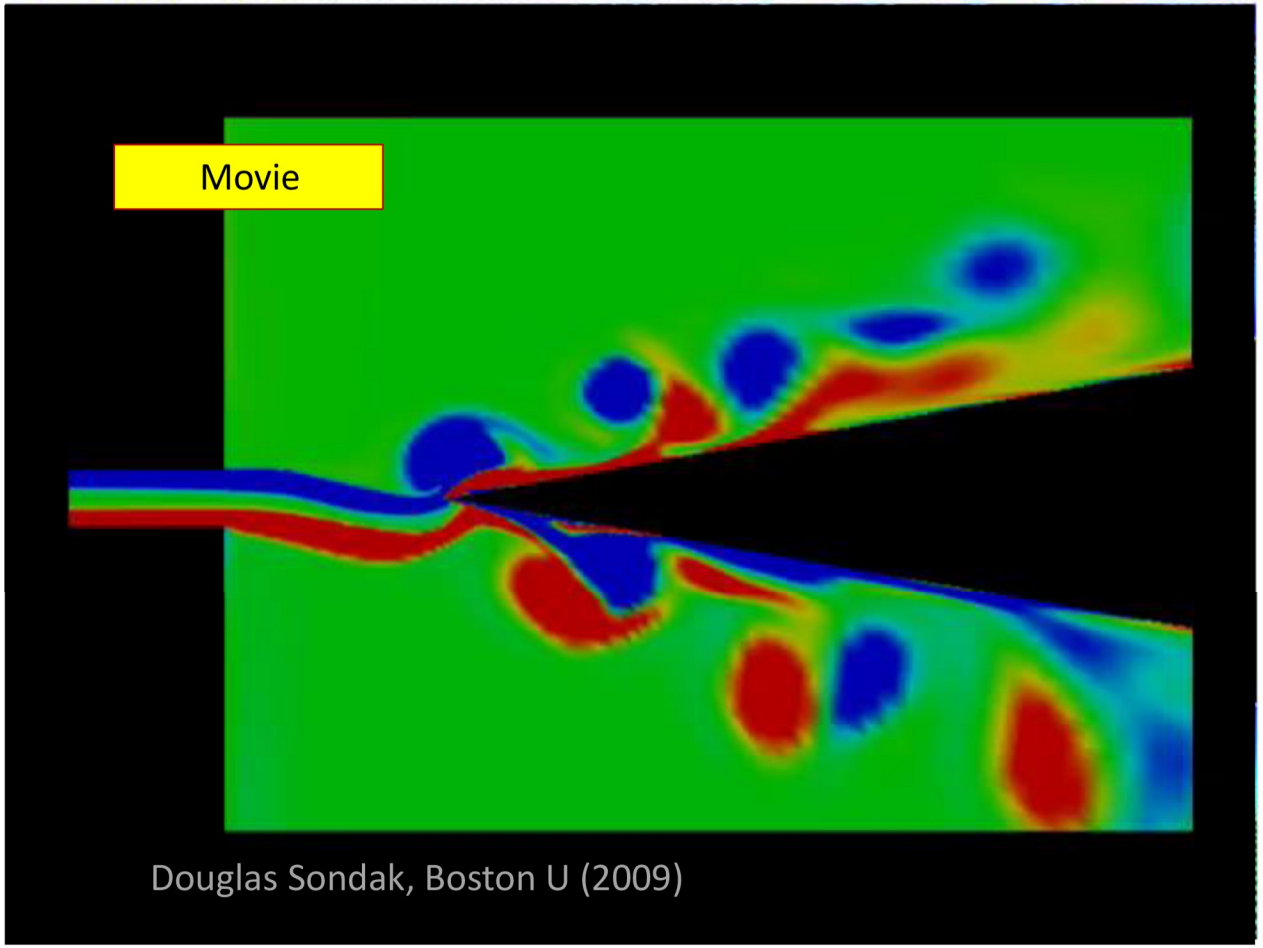
Pipes

Turbulent Flow: Edge Tones



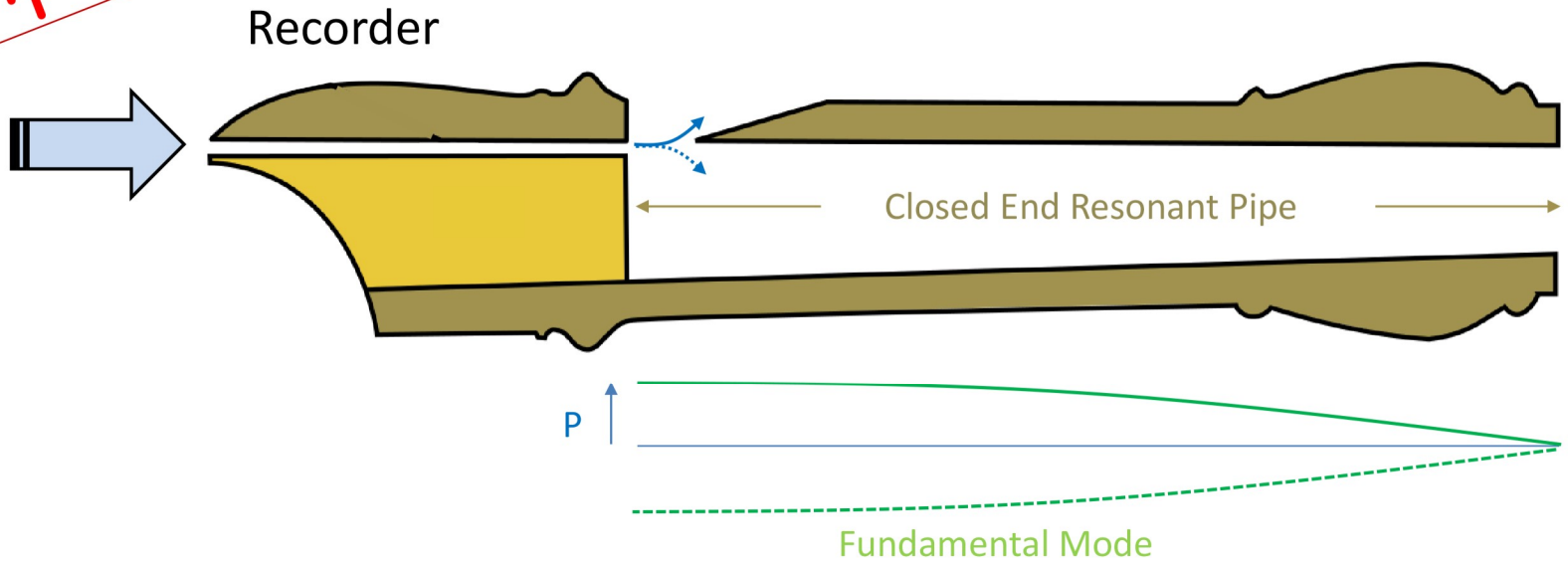
Whistle





Pipes

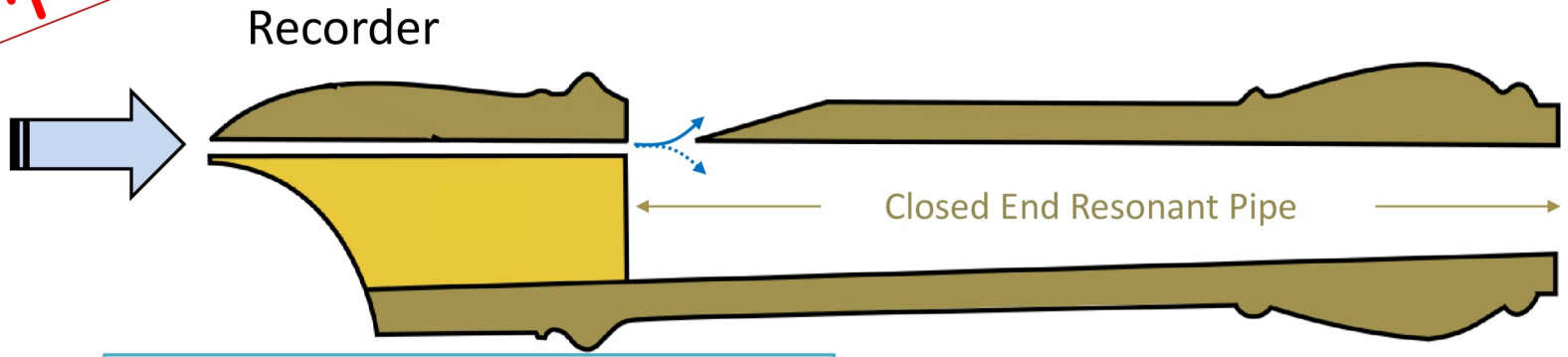
Edge Tone + Resonant Pipe

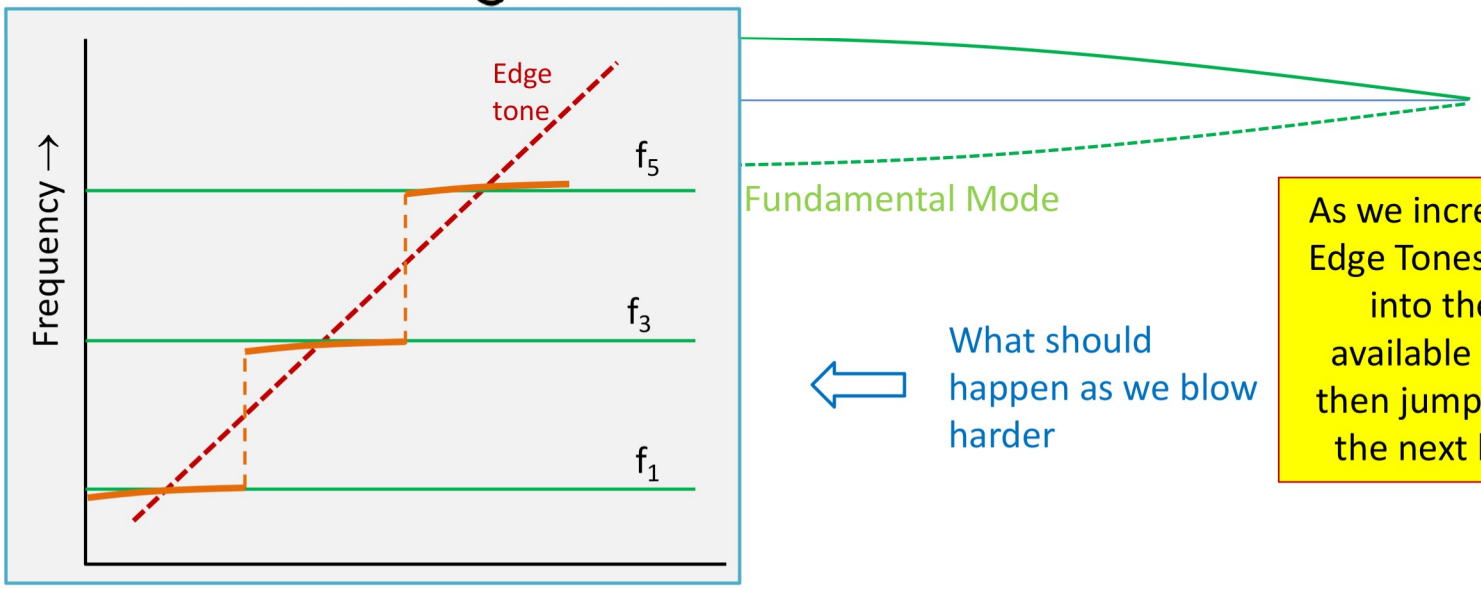


Closed Pipe Modes can be excited by pressure fluctuations due to the Edge Tones.
Edge tone frequency must approximately match the Mode frequency.

Pipes

Edge Tone + Resonant Pipe



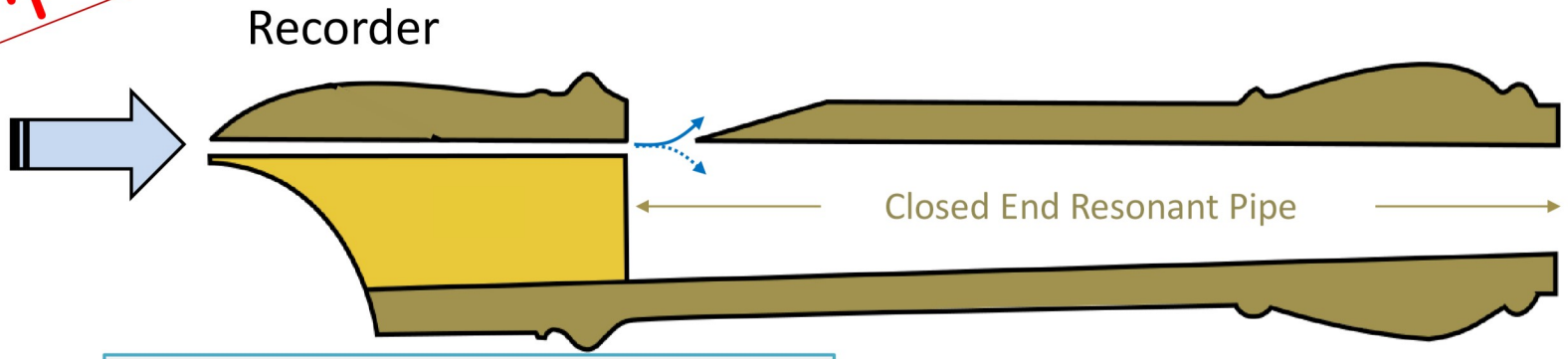


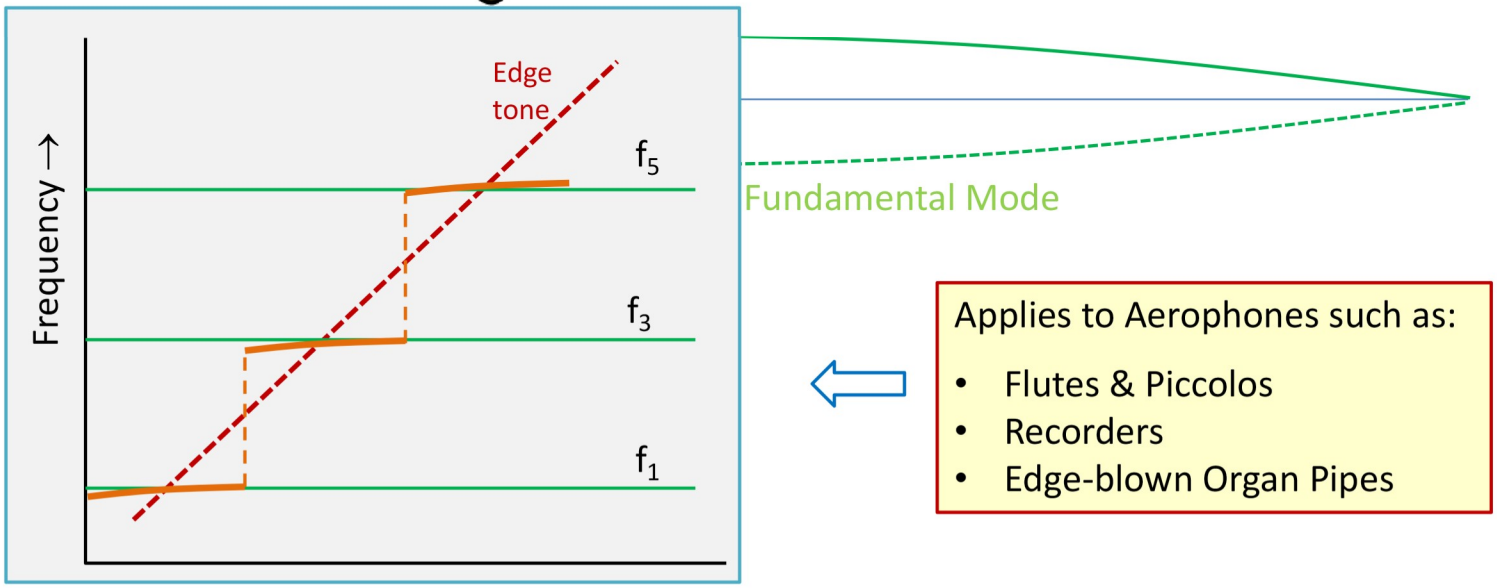
What should happen as we blow harder

As we increase velocity, Edge Tones tend to lock into the nearest available Pipe Mode, then jump suddenly to the next higher one.

Pipes

Edge Tone + Resonant Pipe





Applies to Aerophones such as:

- Flutes & Piccolos
- Recorders
- Edge-blown Organ Pipes

Pipes

Edge-Blown Aerophones

Recorder

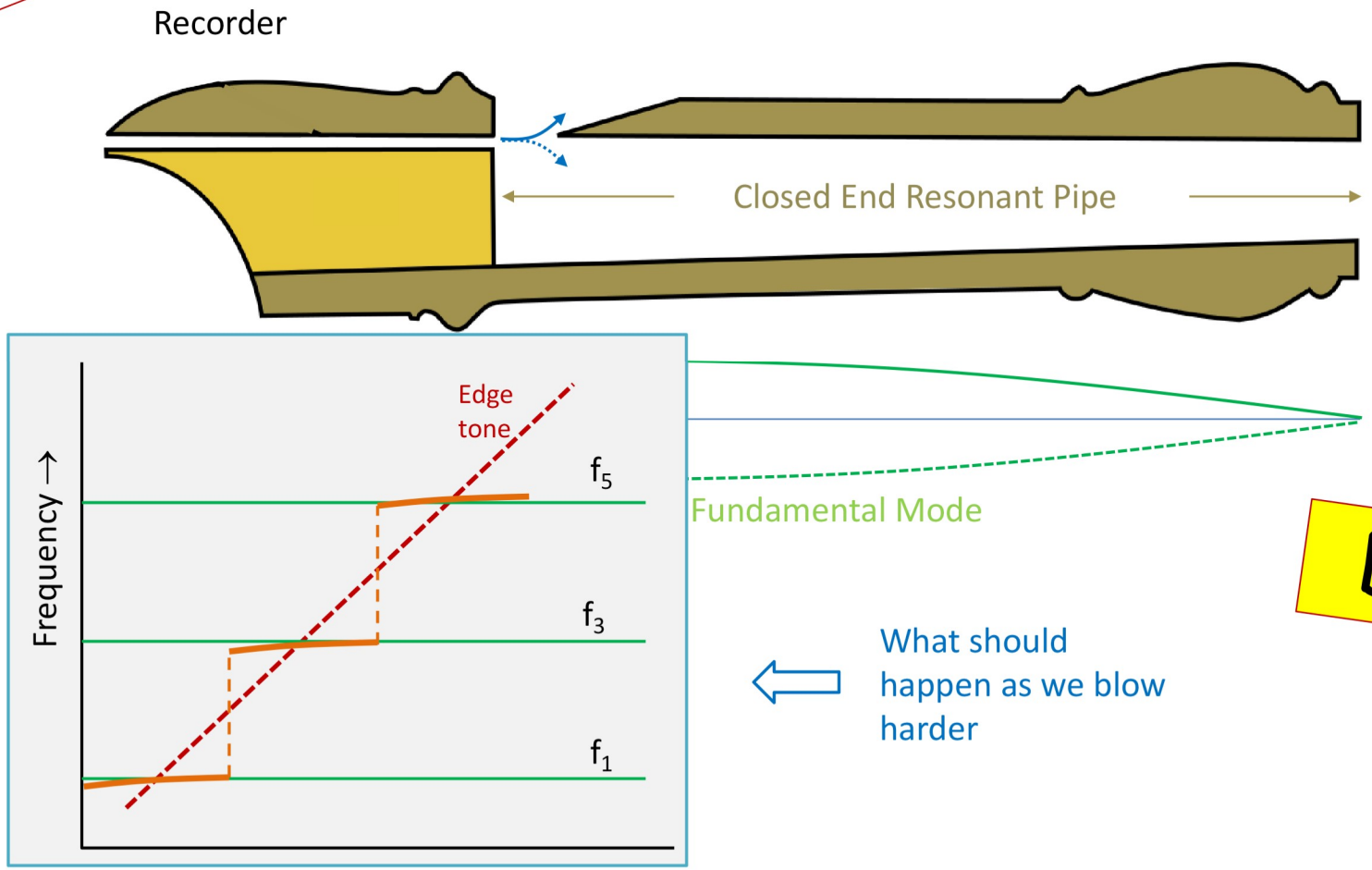
Flutes

Piccolo

Organ Pipes

Pipes

Edge Tone + Resonant Pipe



Demo

⇦ What should happen as we blow harder

Pipes

Woodwind Reeds (Untuned – Stiff)

arundo donax (Giant Cane)

Sax Reed ←

Bassoon Double Reeds ↓

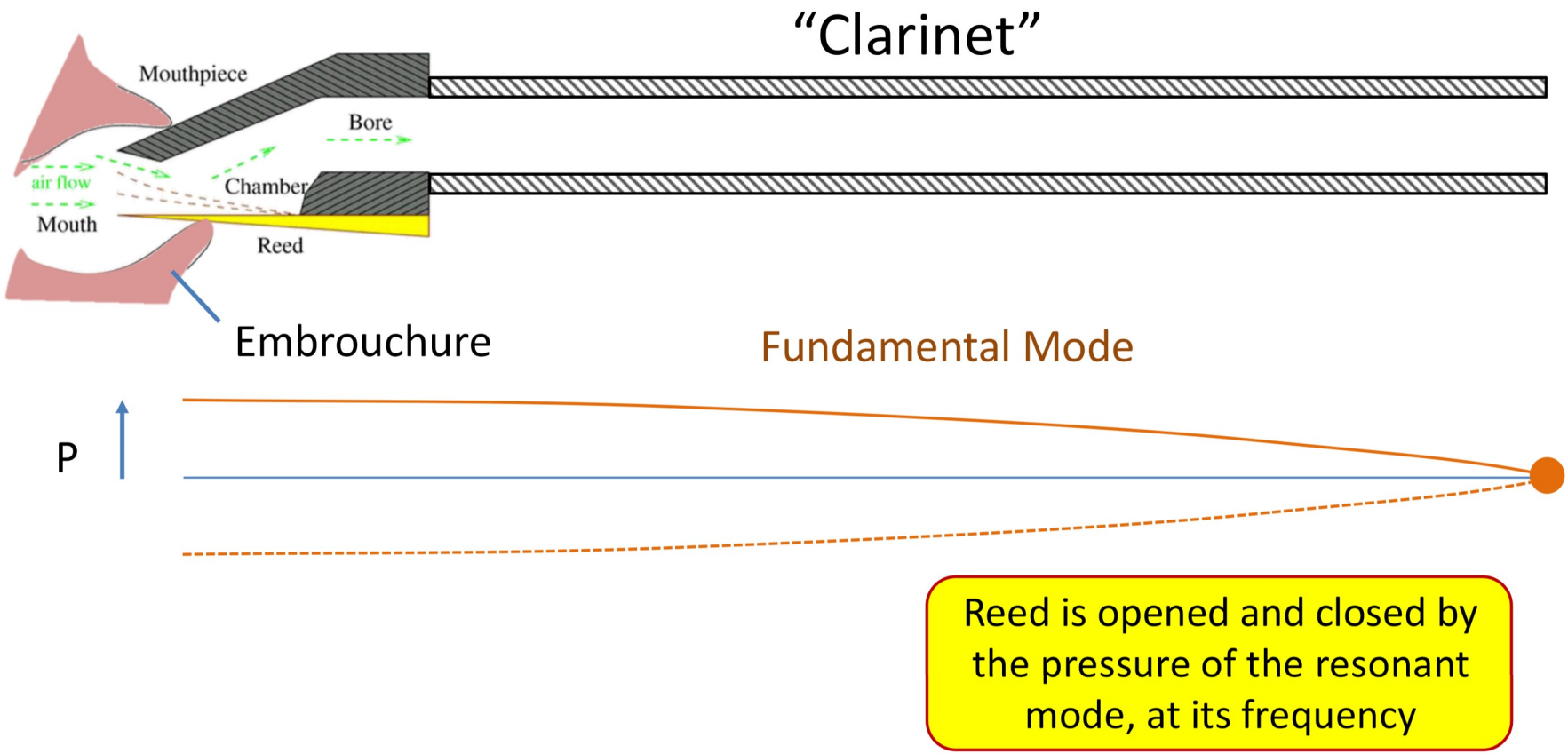
Single Reeds
(mounted *on* mouthpiece)
- Clarinets
- Saxophones
- Some Bagpipes

Double Reeds
(act *as* the mouthpiece)
- Oboe
- Bassoon
- English Horn

also
- Some Bagpipes

Pipes

Single Reed Aerophones: Excitation



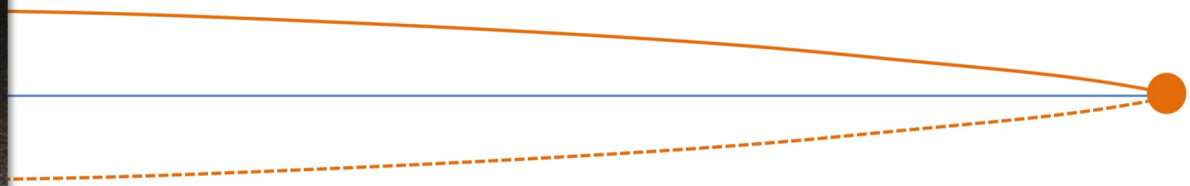
Reed is opened and closed by the pressure of the resonant mode, at its frequency

Pipes

Single Reed Aerophones: Excitation

Other Single Reed Instruments:

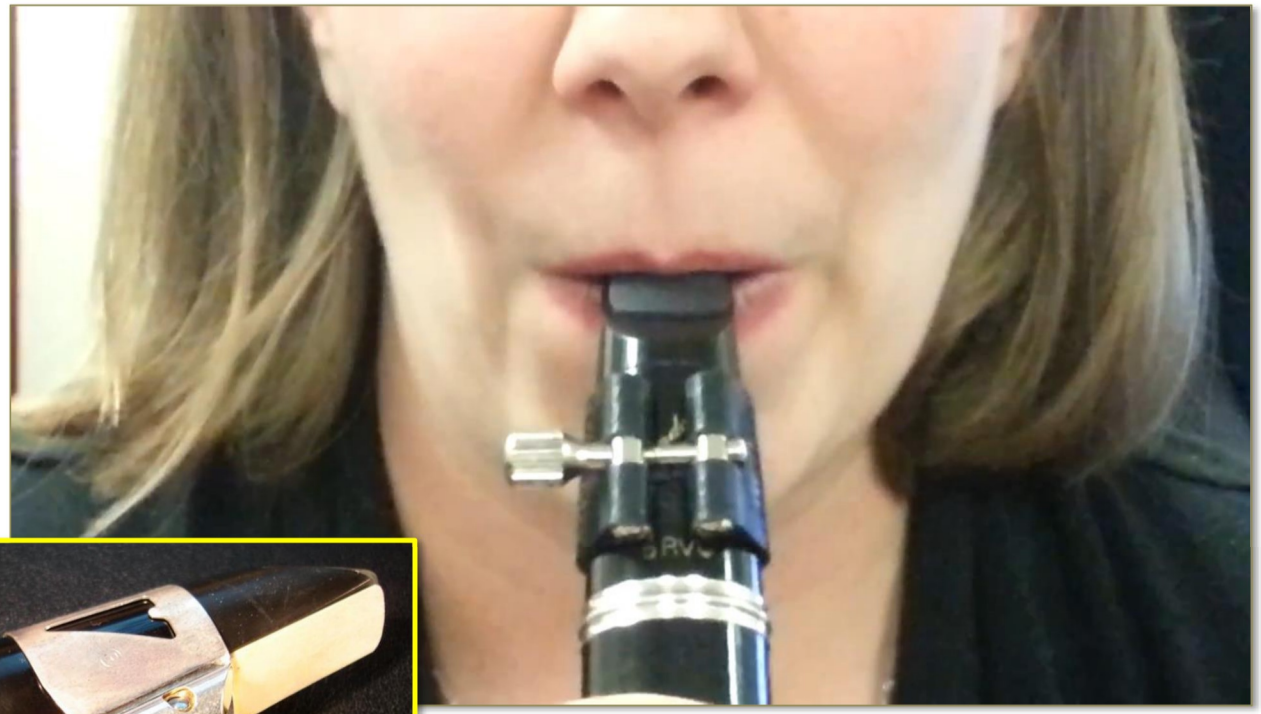
- **Saxophones**
- **Some Bagpipes**



Reed is opened and closed by the pressure of the resonant mode, at its frequency

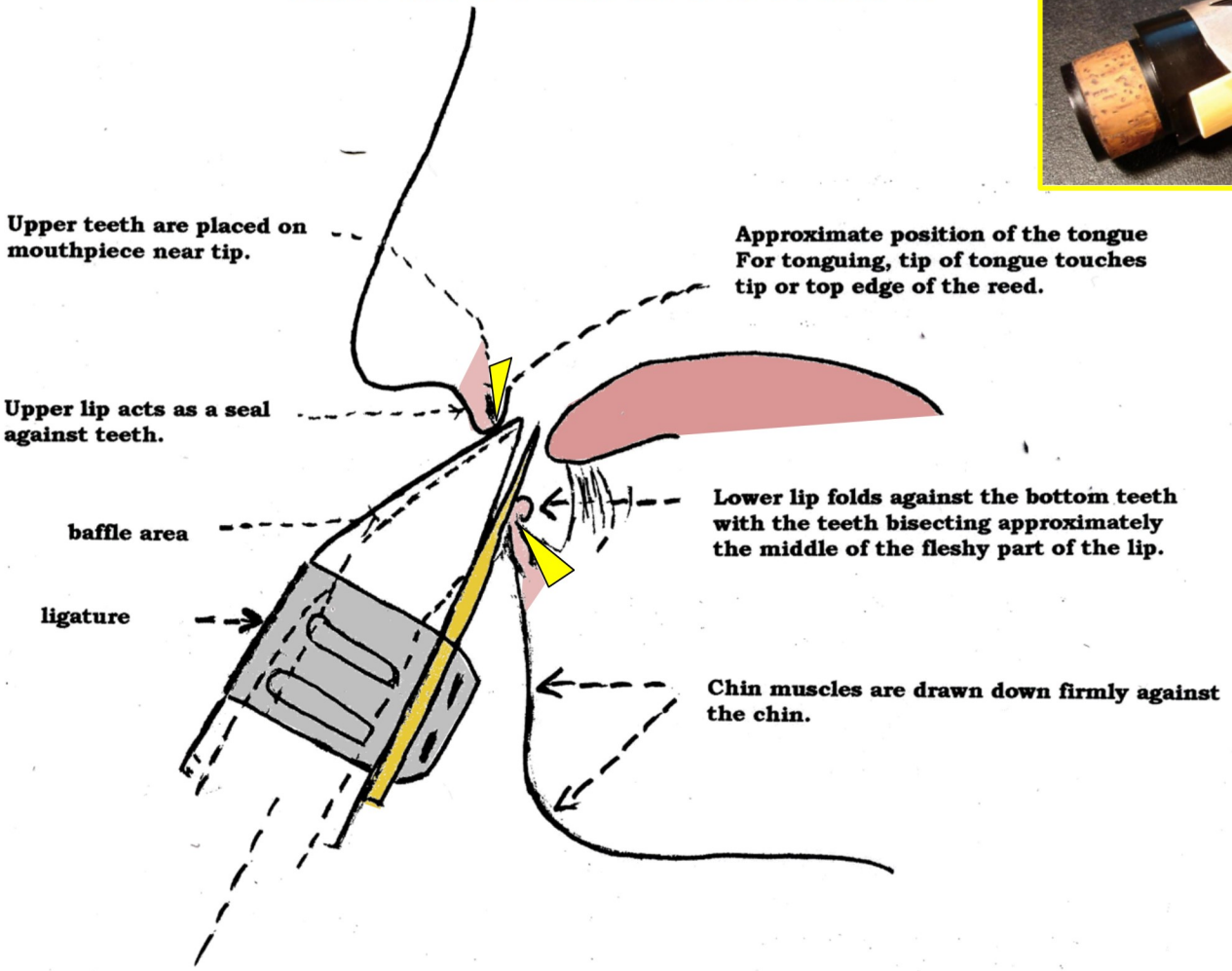
Pipes

Clarinet Embouchure



Pipes

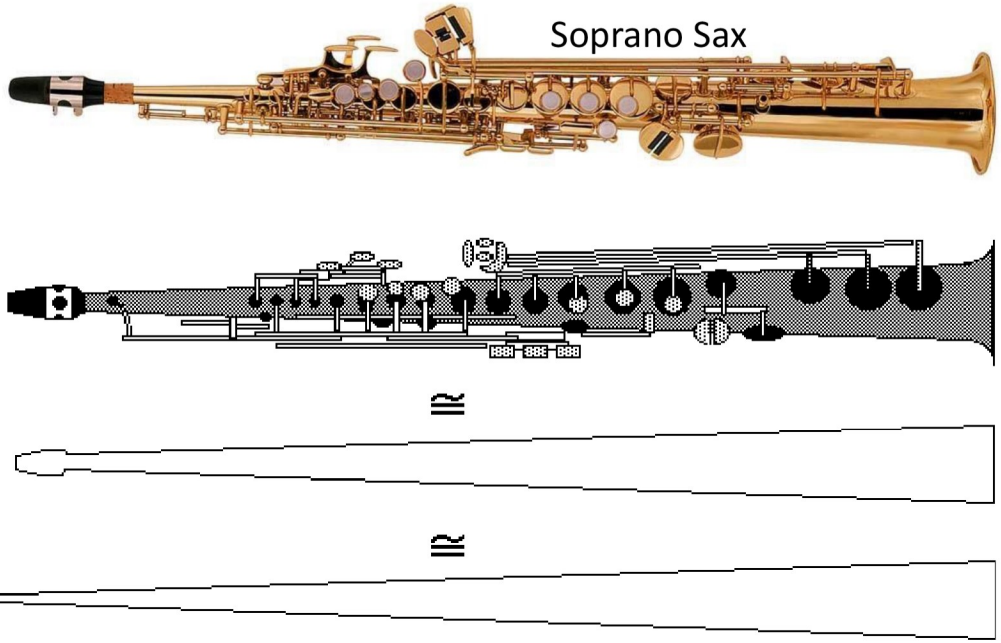
Clarinet Embouchure



Oboe Demo

Pipes

Sax, Oboe, Bassoon: Conical Case



Sax cavity approximates a cone

$\lambda/2$

Invented June 1846
by Adolphe Sax

Both Odd and Even Harmonics

Pipes

Brasses Excited by Lip Vibrations
(Labrosones)

Trumpet

Alto Horn

Tuba*

Didgeridoo/Yidaki

French Horn

Euphonium*

Cornet

Trombone

Pipes

Generic Brass: Lip-Driven (Labrosones)

Vibrating Lips

Cup

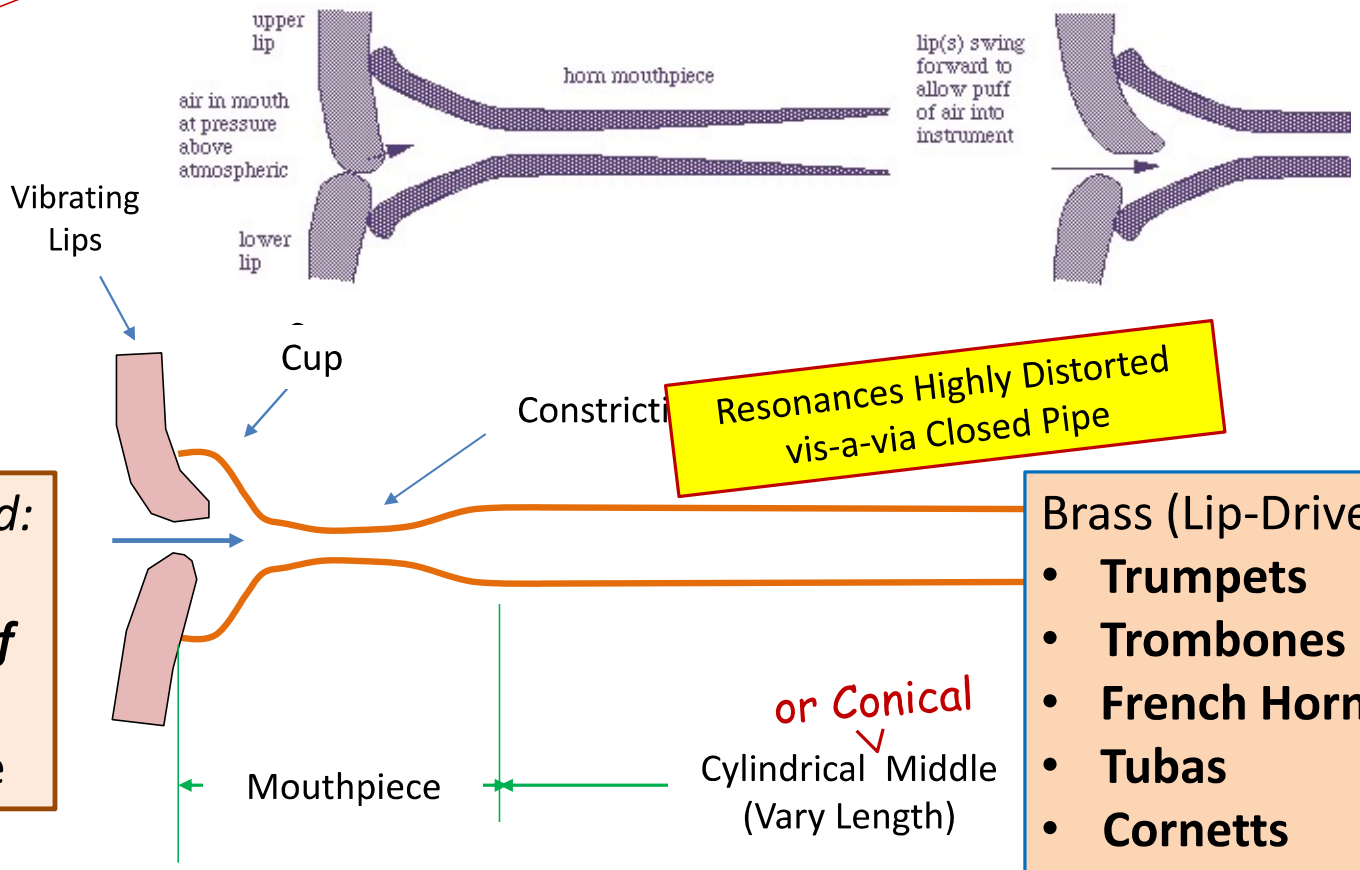
Constriction

Lips must be made to vibrate exactly at the desired frequency, ***and*** this ***f*** must match a mode of the pipe!

Skill Required: Lips lock to Resonance ***f*** only over a small range

Pipes

Generic Brass: Lip-Driven (Labrosones)



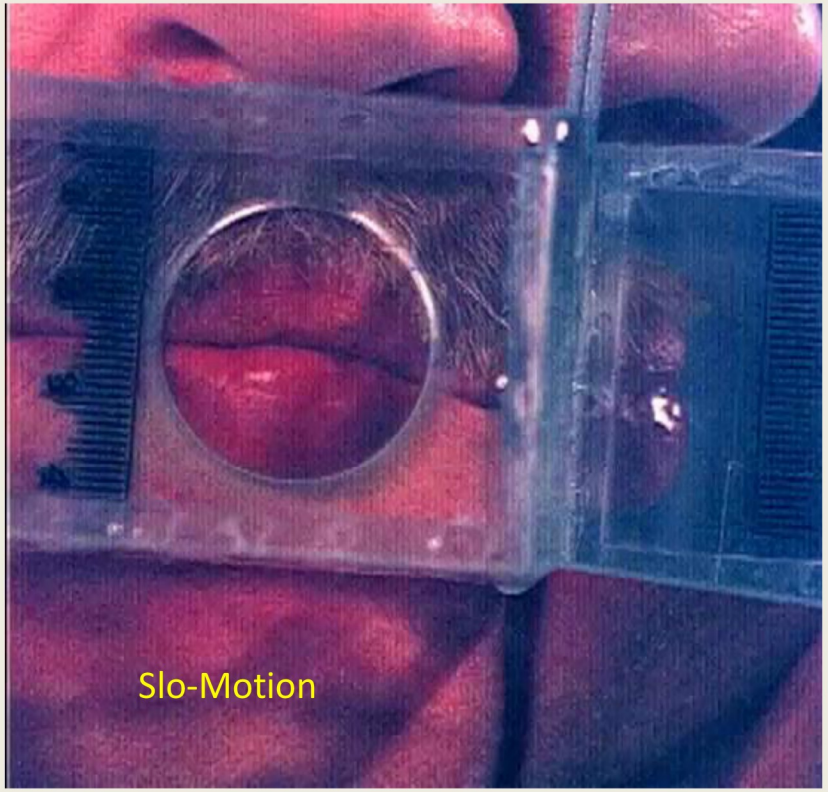
Skill Required: Lips lock to Resonance ***f*** only over a small range

Brass (Lip-Driven) Instruments:

- **Trumpets**
- **Trombones**
- **French Horns**
- **Tubas**
- **Cornetts**
- **Bugles**
- **Didgeradoos**


John Wright
Brass Embrouchure Basics
(YouTube 2022)

Lip Vibrations: Glass Didgeridoo

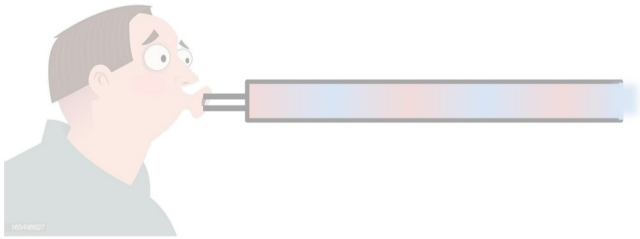


newt.phys.unsw.edu.au/jw/didjeridu.html

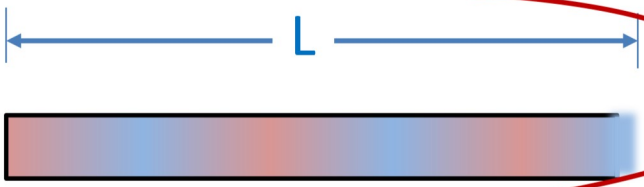
Pipes

Aerophone Instruments

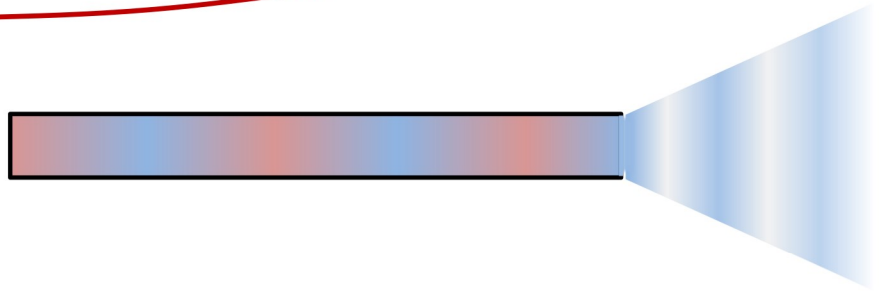
Three main problems:



1. Excitation HARD
   - How to get the pipe resonating
2. Frequency Control MEDIUM
   - Playing desired notes



3. Getting Sound Out EASY
   - Resonances are *already* sound waves

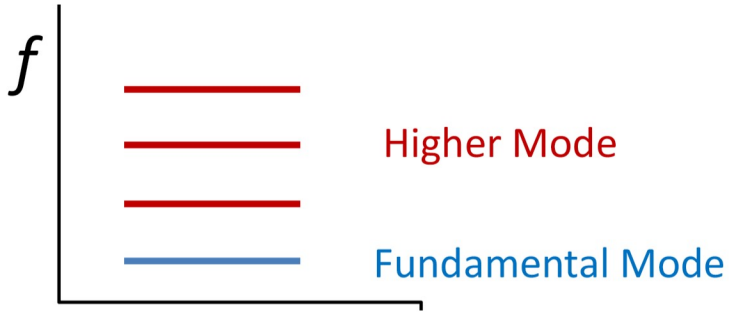


Pipes

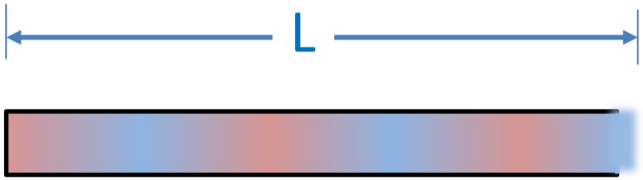
Frequency Control

- Two Basic Strategies

1. Employ Different
   Resonant Modes (Partials)



2. Vary the effective pipe length L



or Both!

Pipes

Frequency Control by Mode Selection (Register)

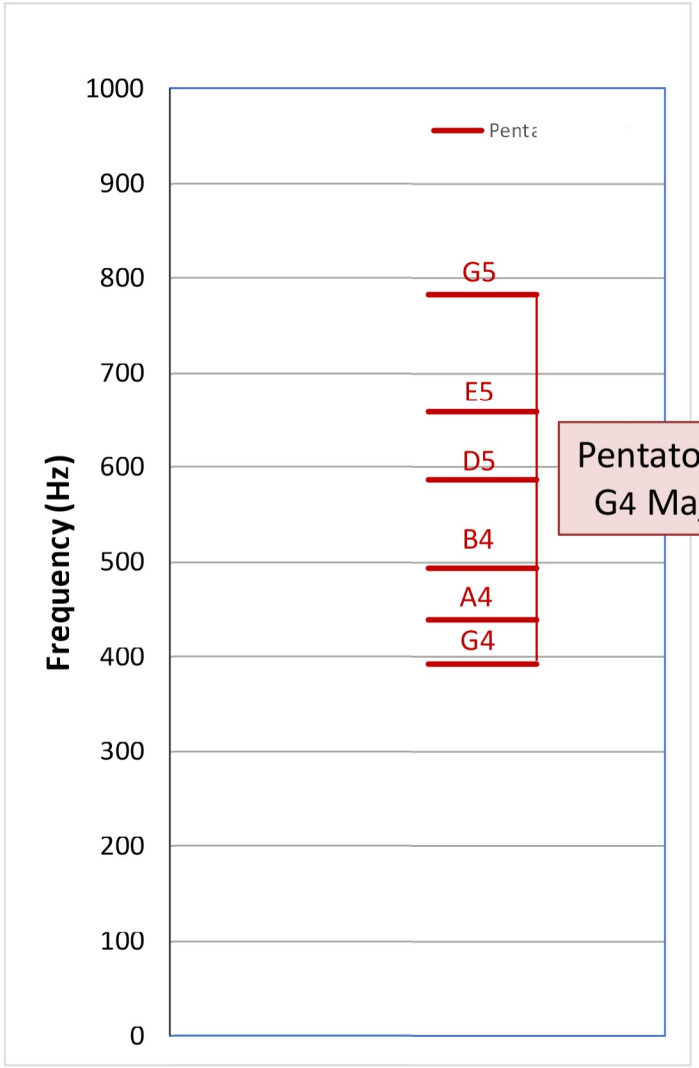
"Natural Horns" have no Valves

Length is Fixed

Baroque Horn
ca 18th Century

Conical

Say we want to play notes from the G Major scale. But we have a fixed length tube.



Pipes

Frequency Control by Mode Selection (Register)

"Natural Horns" have no Valves

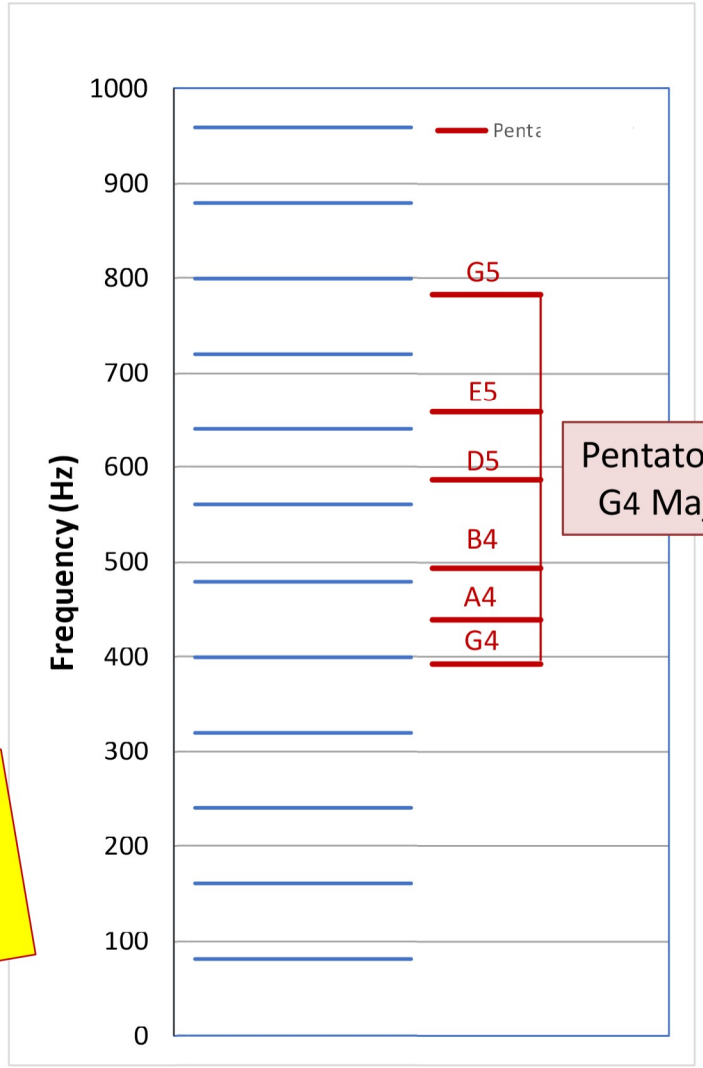
Length is Fixed

Baroque Horn
ca 18th Century

Conical

Try L ≈ 40 inches
$f_1 \approx$ **80** Hz

No luck! No available resonance modes of this tube match the notes we want.



Pipes

Frequency Control by Mode Selection (Register)

"Natural Horns" have no Valves

Length is Fixed

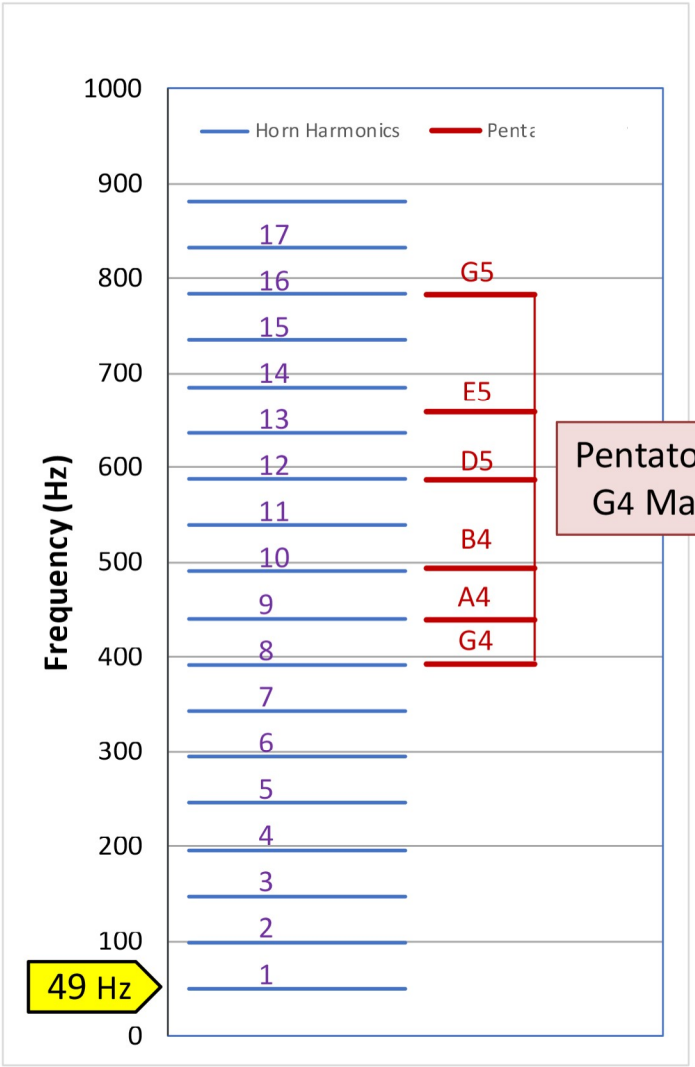
Baroque Horn
ca 18th Century

Conical

~~Try L ≈ 40 inches~~
~~$f_1 \approx$ **80** Hz~~

Try L ≈ 65 inches
$f_1 \approx$ **49** Hz

This is better. We can access all but E5, if we can control our lip frequency well enough.



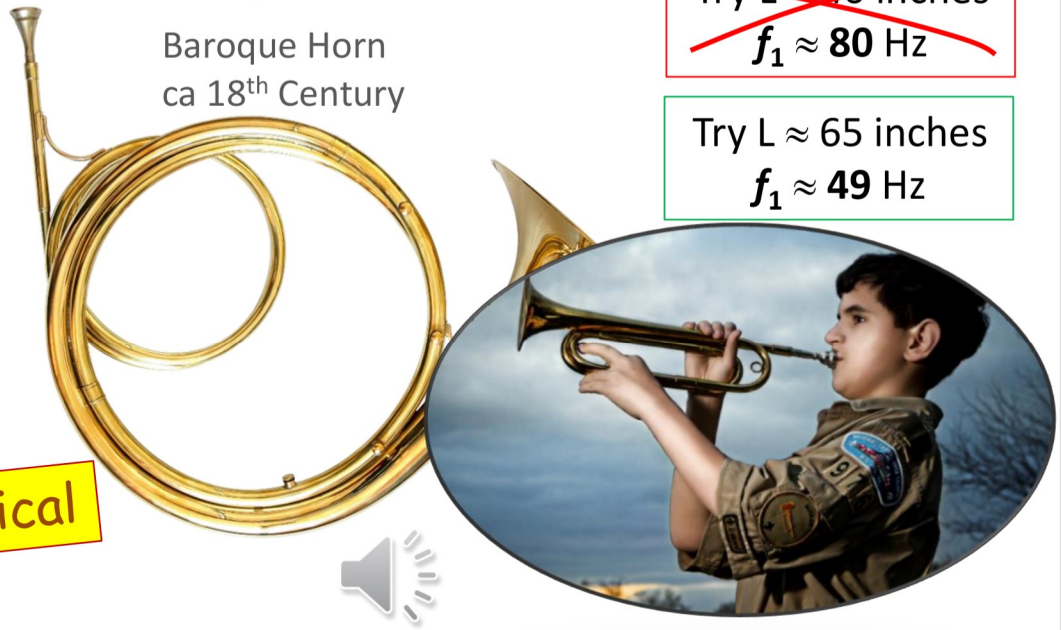
Pipes

Frequency Control by Mode Selection (Register)

"Natural Horns" have no Valves

Length is Fixed

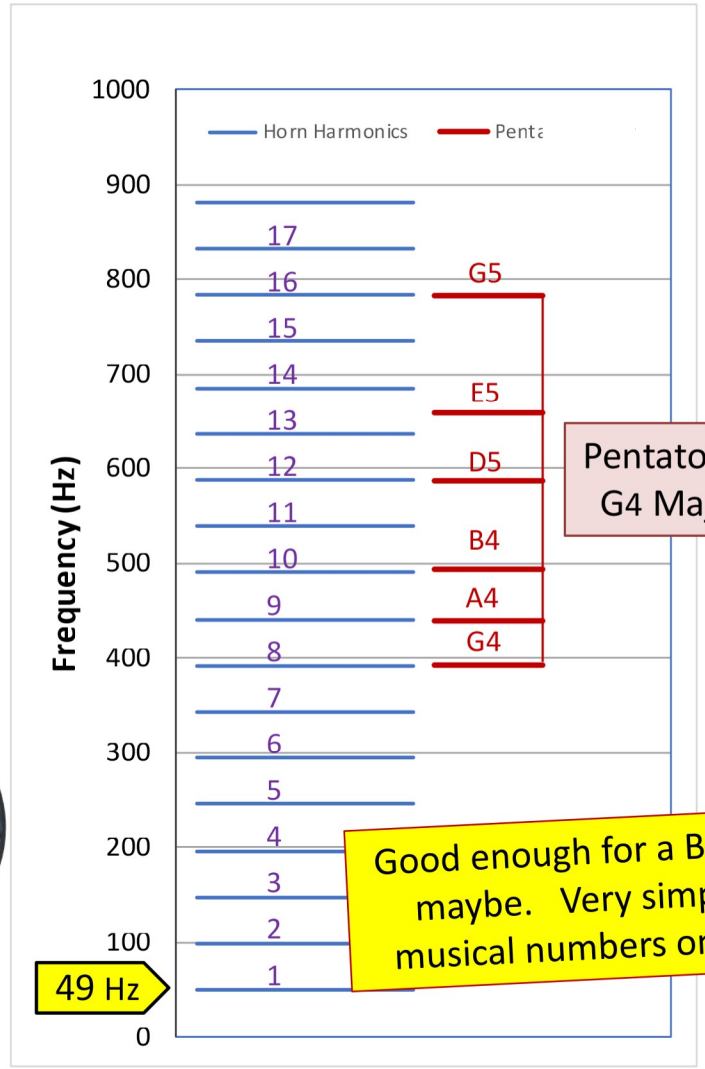
Baroque Horn
ca 18th Century



Conical

~~Try L ≈ 40 inches~~
~~$f_1 \approx$ **80** Hz~~

Try L ≈ 65 inches
$f_1 \approx$ **49** Hz



Pipes

Frequency Control by Mode Selection (Register)

"Natural Horns" have no Valves

Length is Fixed

Baroque Horn
ca 18th Century

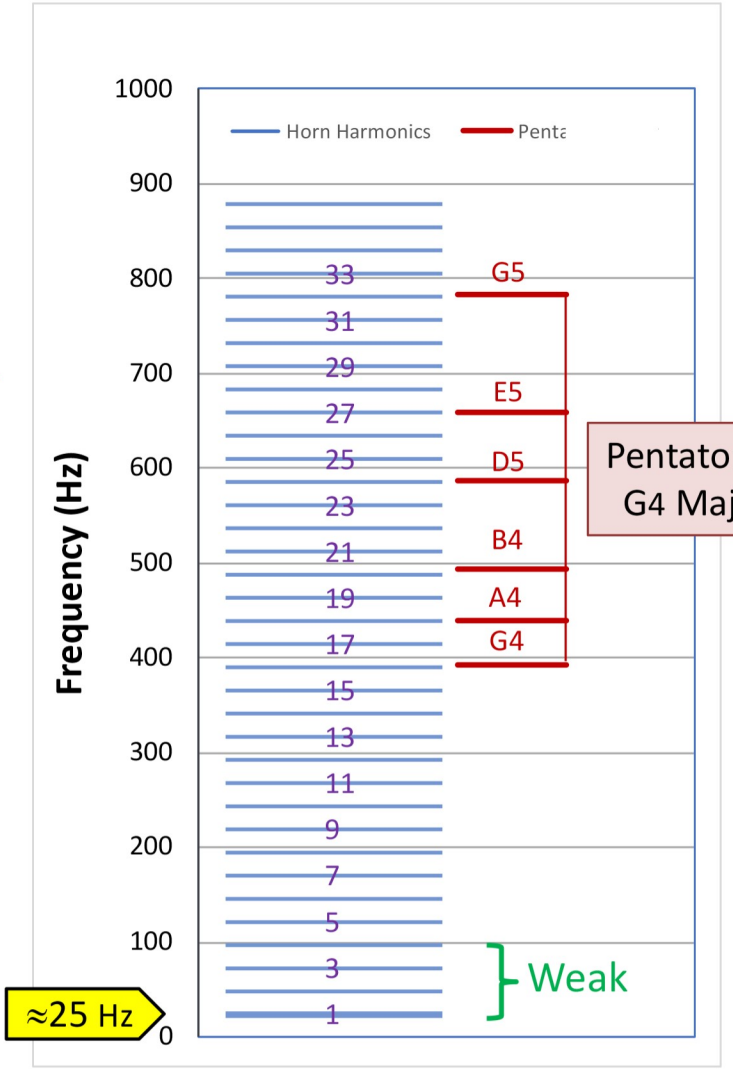
Conical

~~Try L ≈ 40 inches~~
~~$f_1 \approx$ **80** Hz~~

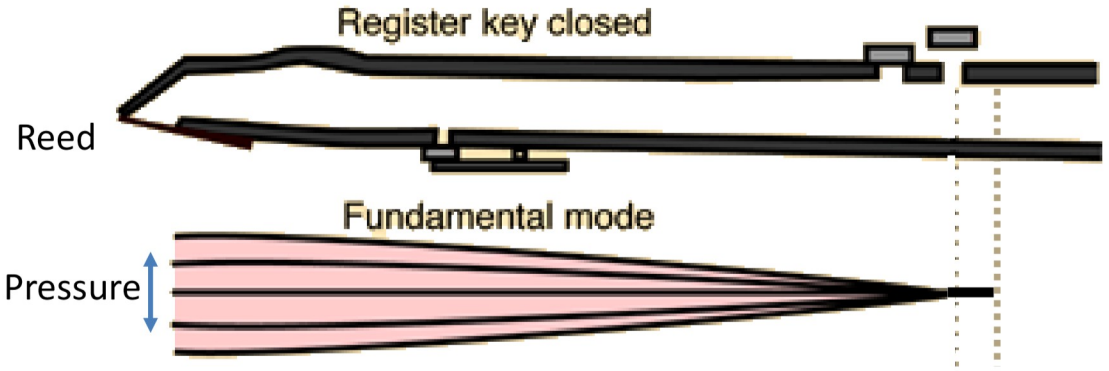
~~Try L ≈ 65 inches~~
~~$f_1 \approx$ **49** Hz~~

Try L ≈ 130 inches
$f_1 \approx$ **25** Hz

Now we have a length big enough to provide resonances closely matching all the notes we need. This L is typical of Baroque Horns and French Horns.



Changing Register in a Clarinet



Low Note

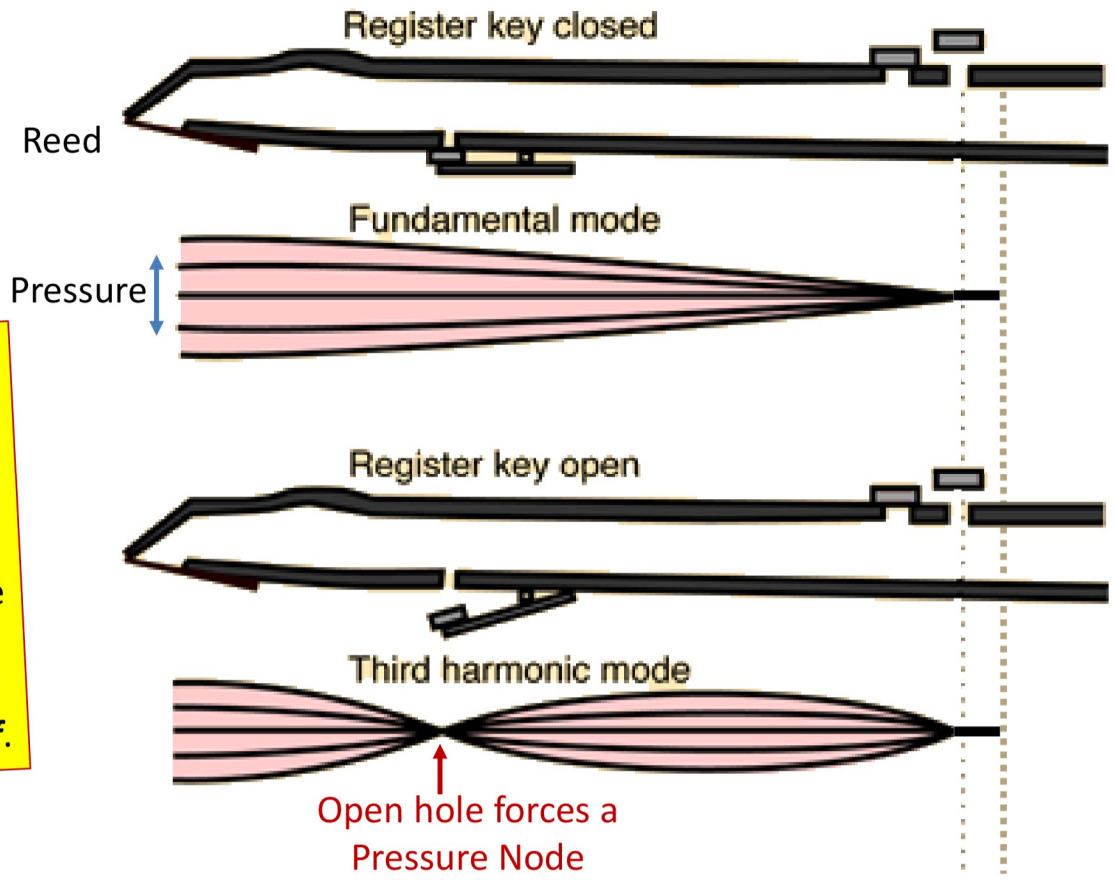
Now we change to the Length shifting approach. Opening side holes effectively shortens the Pipe Length, increasing f.

3x Higher Note

Hyperphysics
Georgia State U

Pipes

Changing Register in a Clarinet



Opening the Register Hole kills the Fundamental mode (pressure there forced to zero), but allowed the 3rd Harmonic which has a pressure Node at that location. Thus musician can blow the 3rd harmonic, a much higher ***f***.

Low Note

3x Higher Note

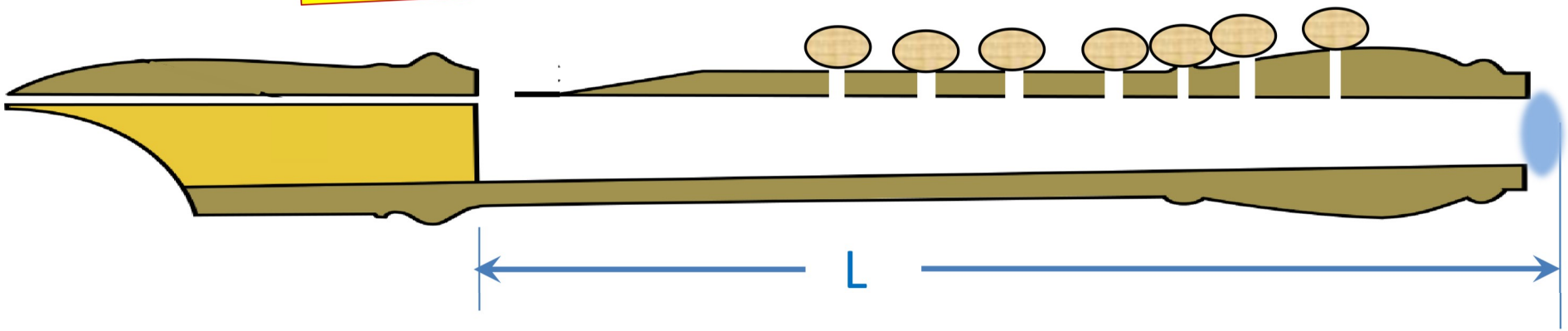
Hyperphysics
Georgia State U

Pipes

Reducing Length by Opening Holes

Recorder

All closed holes means L= full length of pipe.

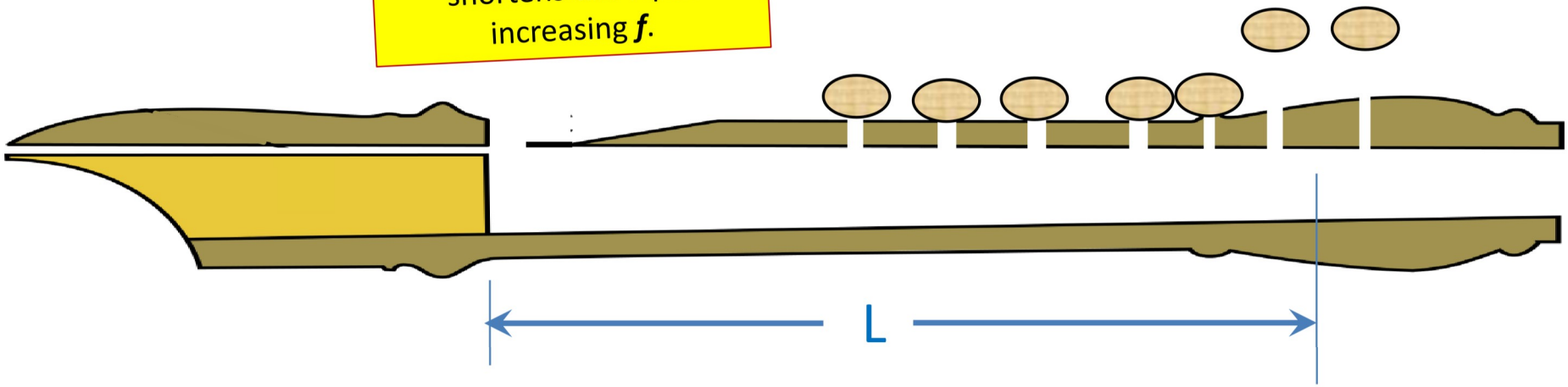


Pipes

Reducing Length by Opening Holes

Recorder

Opening some holes shortens the Pipe. increasing ***f***.



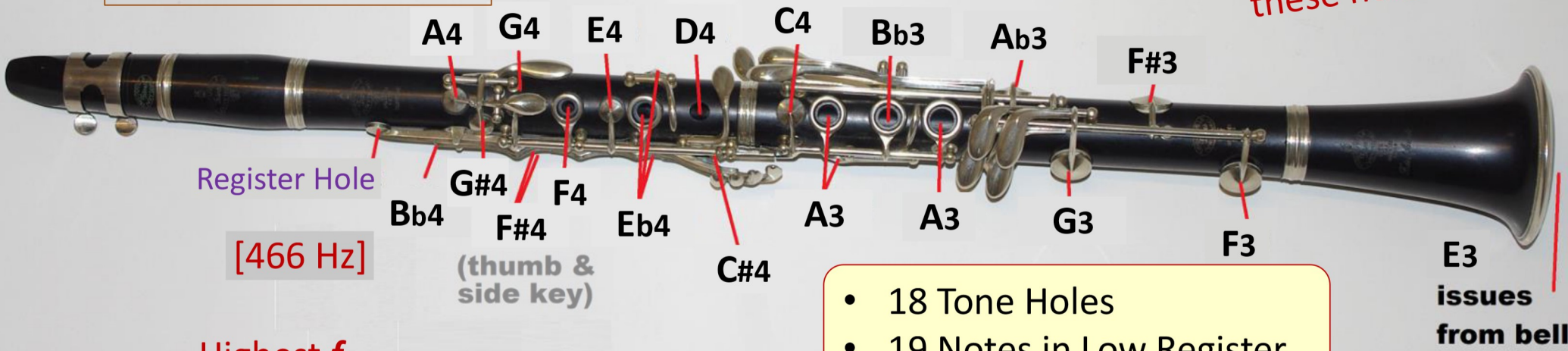
Pipes

Reducing Length by Opening Holes

B flat Clarinet

Note Assignments are for the Low (Fundamental) Register

Sound comes out mostly through these holes!



[466 Hz]

Highest *f*

- 18 Tone Holes
- 19 Notes in Low Register

[165 Hz]

Lowest *f*

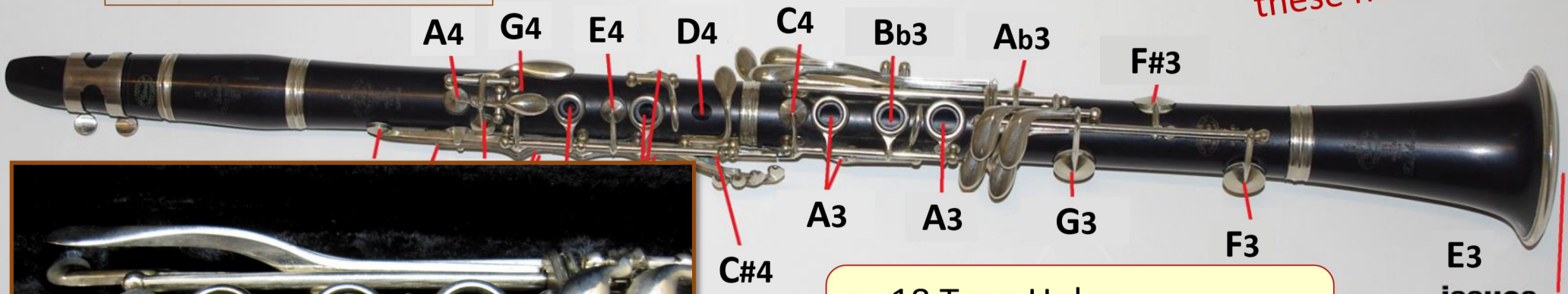
Pipes

Reducing Length by Opening Holes

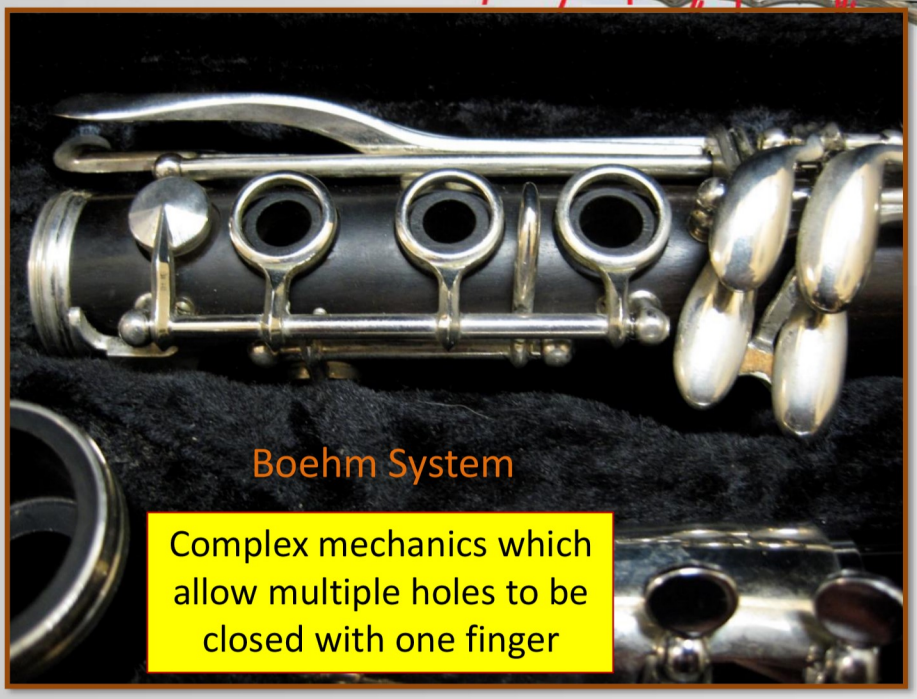
B flat Clarinet

Note Assignments are for the Low (Fundamental) Register

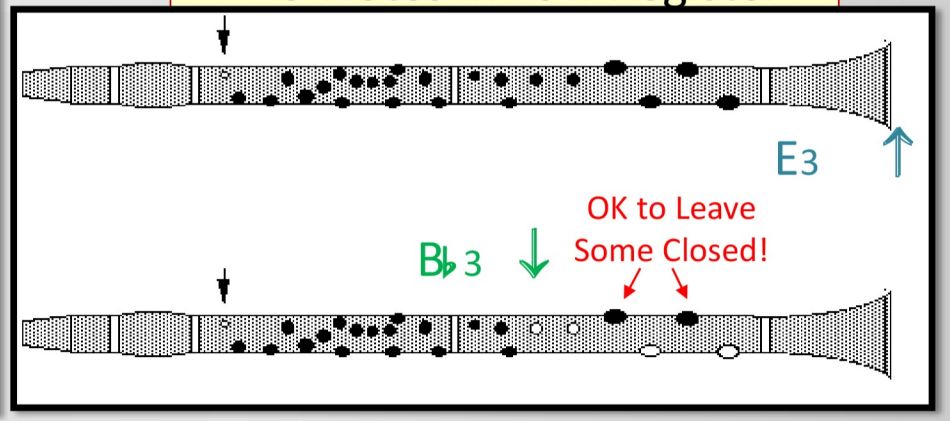
Sound comes out mostly through these holes!



[165 Hz]



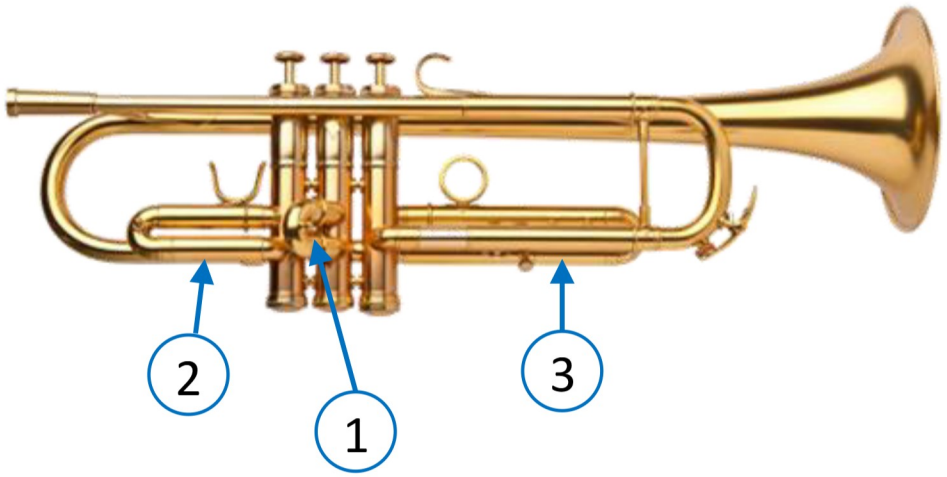
- 18 Tone Holes
- 19 Notes in Low Register



Pipes

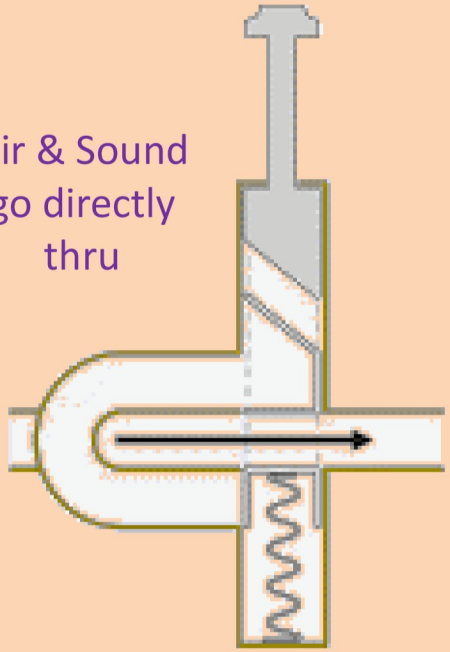
Frequency Control by Valves (Length Change)

B♭ Trumpet
has 3 Valves



OPEN

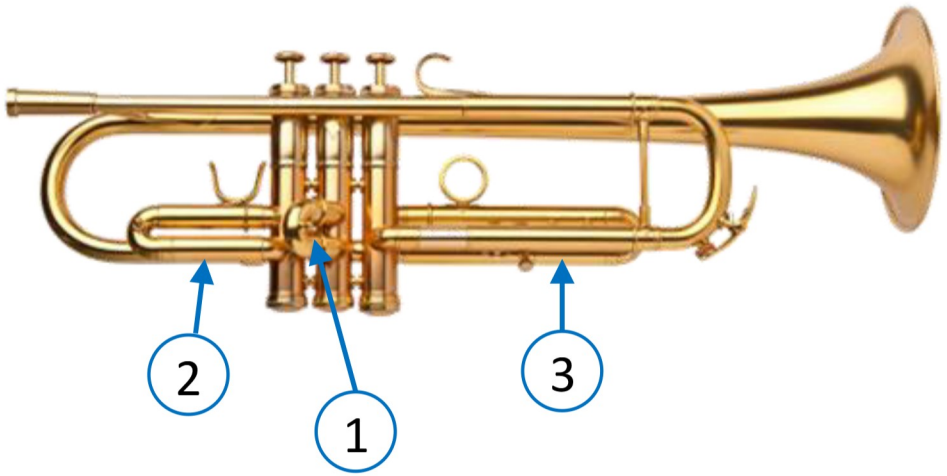
Air & Sound go directly thru

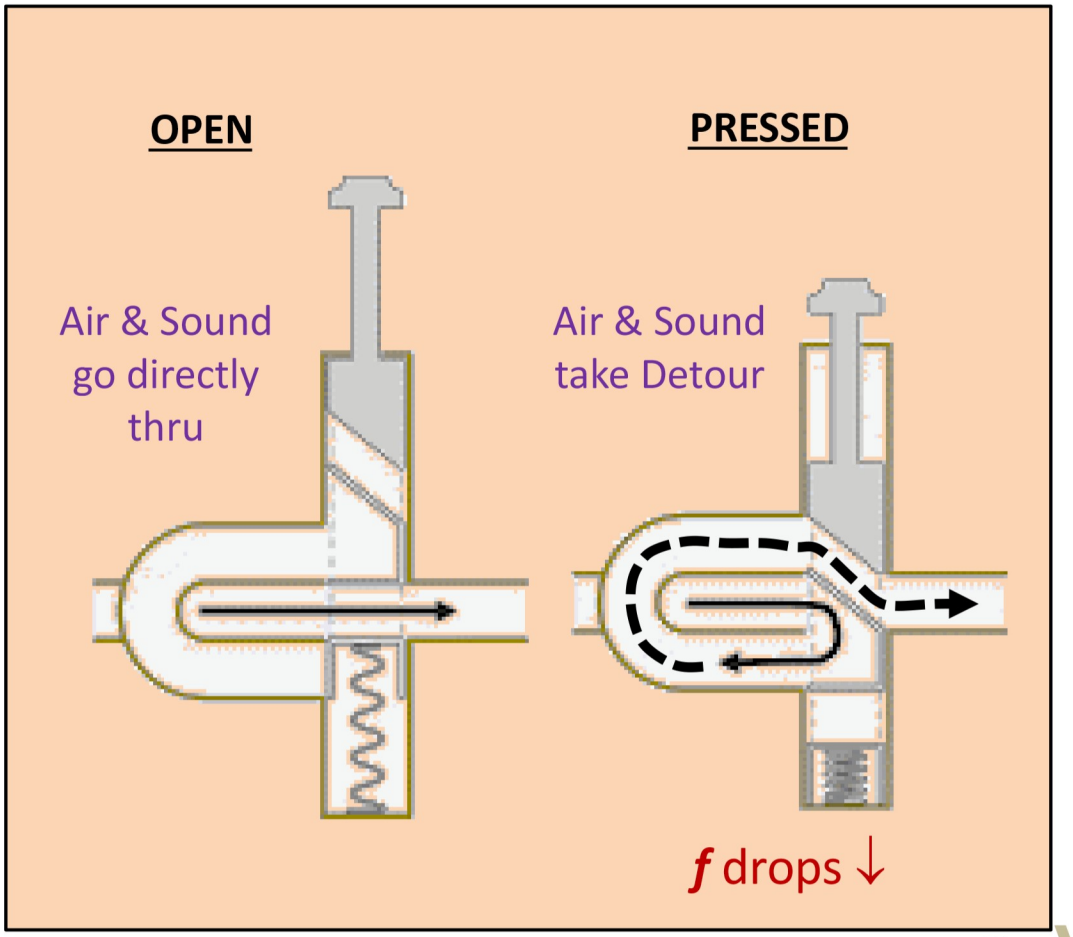


Pipes

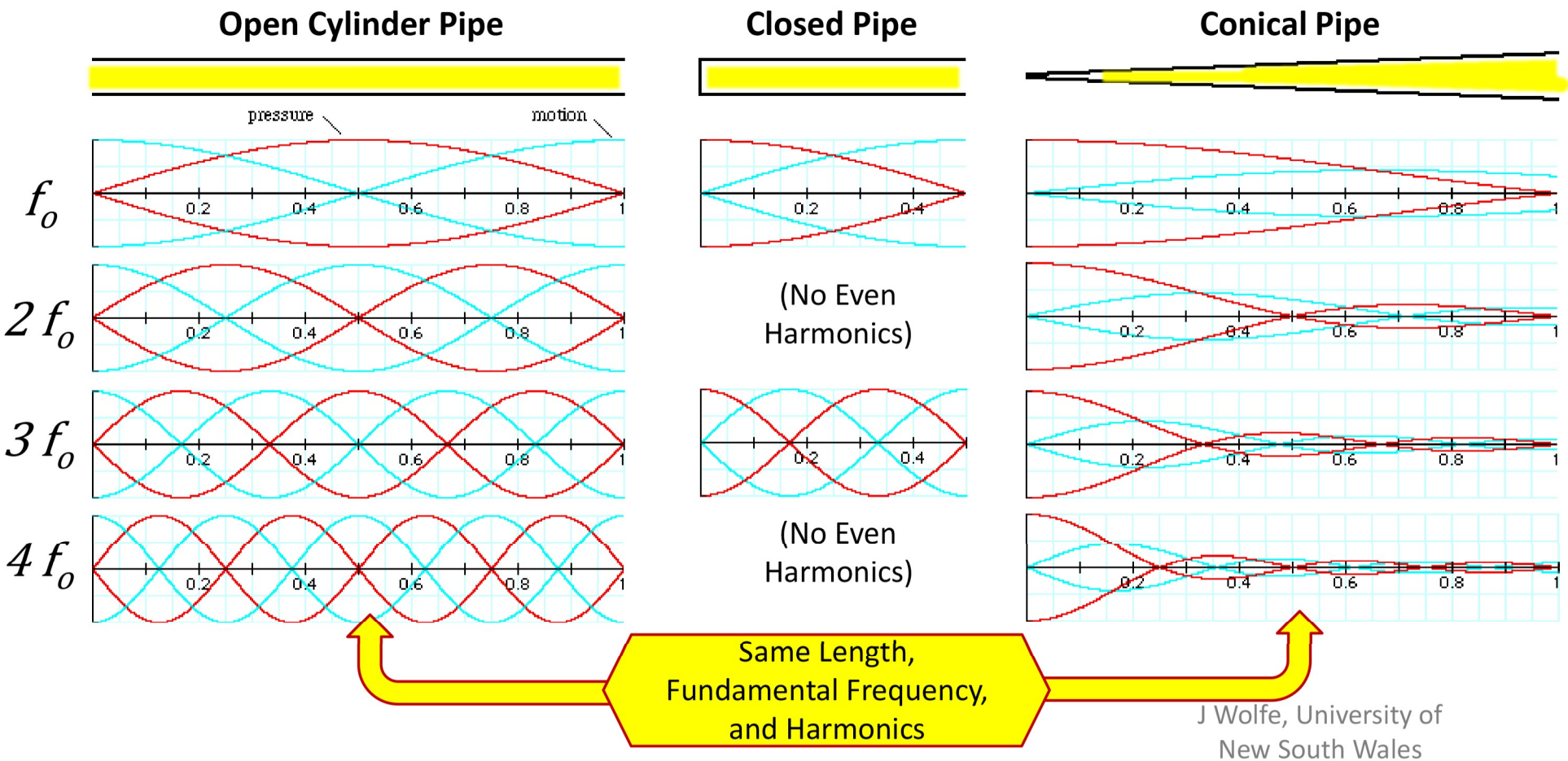
Frequency Control by Valves (Length Change)

B♭ Trumpet has 3 Valves



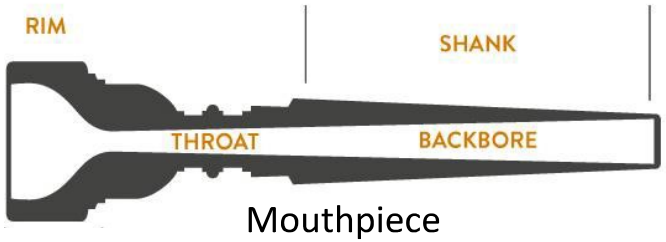


Comparison of Standing Wave Modes

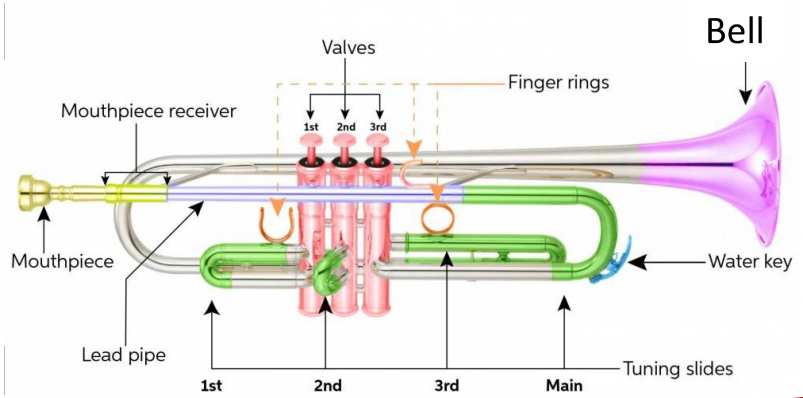


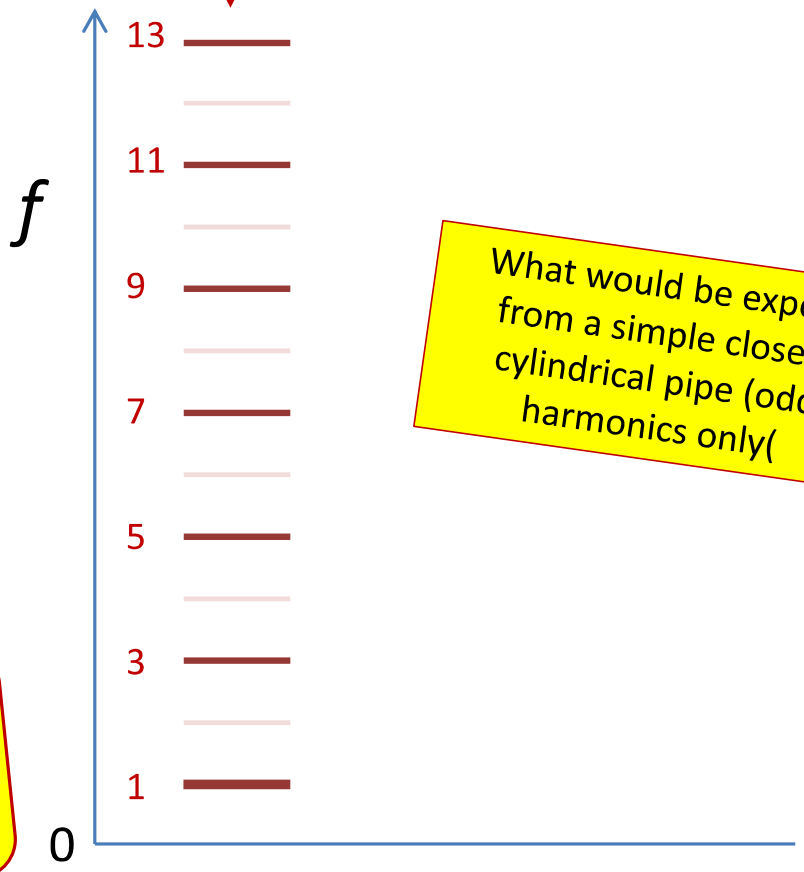
J Wolfe, University of New South Wales

Trumpet is neither a Simple Closed Pipe nor Conical



Mouthpiece

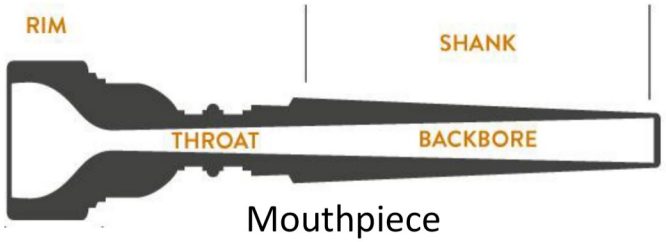




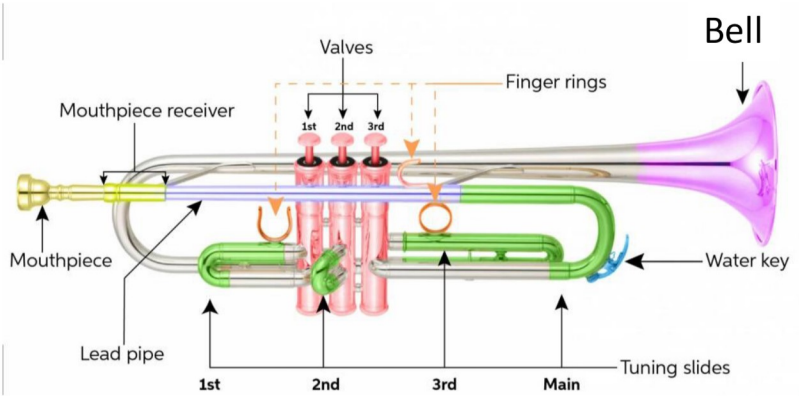
What would be expect from a simple closed cylindrical pipe (odd harmonics only(

Odd Harmonics Only!

Trumpet is neither a Simple Closed Pipe nor

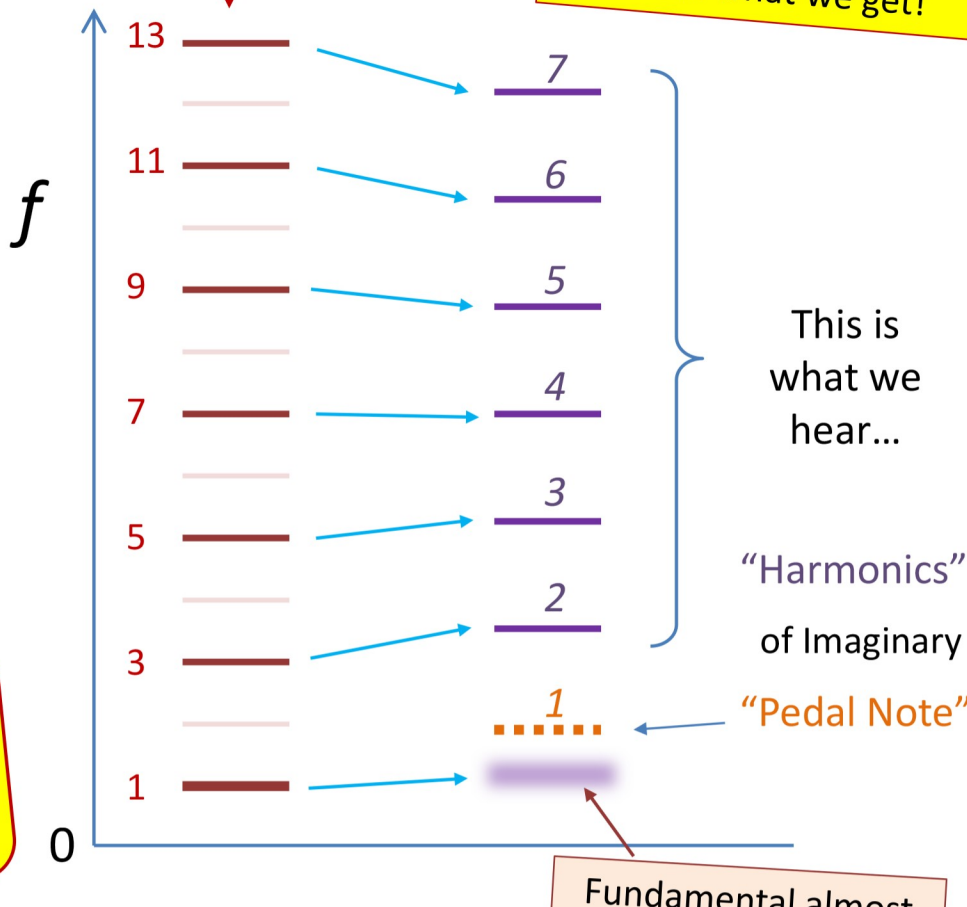


Mouthpiece



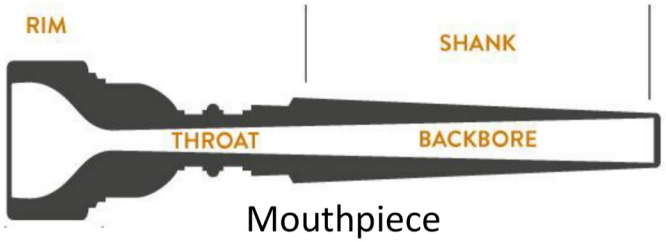
Odd Harmonics Only!

But due to complex shape of mouthpiece and bell, this is what we get!

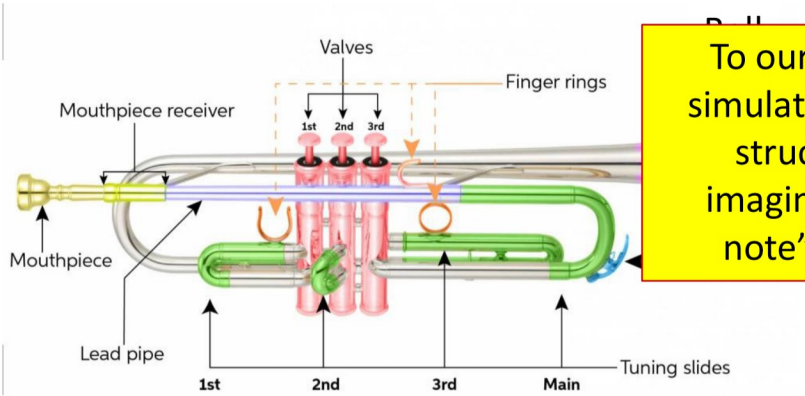


Trumpet is neither a Simple Closed Pipe nor

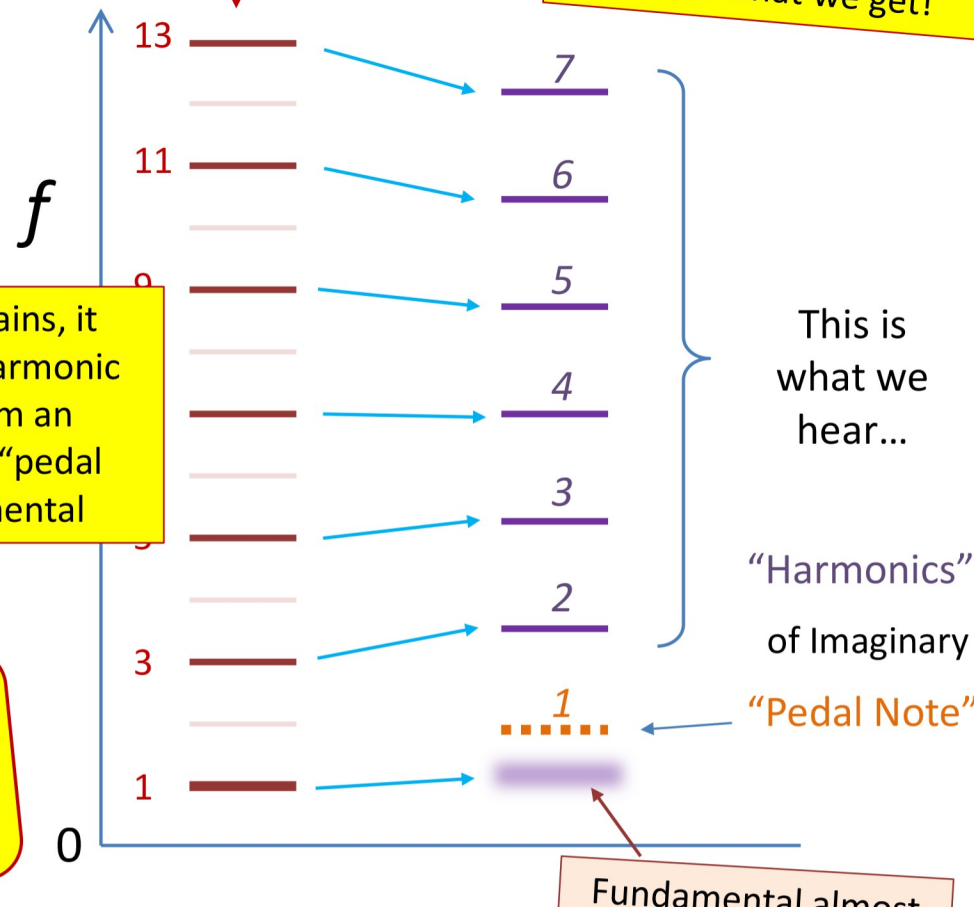
But due to complex shape of mouthpiece and bell, this is what we get!



Mouthpiece



To our ears/brains, it simulates the harmonic structure from an imaginary low "pedal note" fundamental



This is what we hear…

"Harmonics" of Imaginary "Pedal Note"

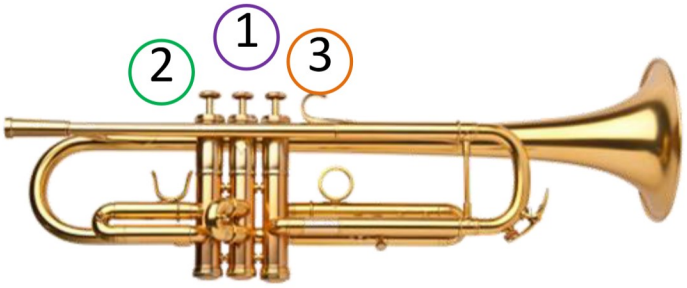
Odd Harmonics Only!

Fundamental almost disappears

Pipes

Frequency Control by Valves (Length Change)

B♭ Trumpet has 3 Valves



85	1108.7	C#/D♭ 6	8 (15h)
84	1046.5	C 6	
83	987.8	B 5	7 (13h)
82	932.3	A#/B♭ 5	
81	880	A 5	
80	830.6	G#/A♭ 5	6 (11h)
79	784.0	G 5	
78	740.0	F#/G♭ 5	
77	698.5	F 5	5 (9h)
76	659.3	E 5	
75	622.3	D#/E♭ 5	
74	587.3	D 5	
73	554.4	C#/D♭ 5	4 (7h)
72	523.3	C 5	
71	493.9	B 4	
70	466.2	A#/B♭ 4	
69	440	A 4	
68	415.3	G#/A♭ 4	3 (5h)
67	392.0	G 4	
66	370.0	F#/G♭ 4	
65	349.2	F 4	
64	329.6	E 4	
63	311.1	D#/E♭ 4	
62	293.7	D 4	
61	277.2	C#/D♭ 4	2 (3h)
60	261.6	C 4	
59	246.9	B 3	
58	233.1	A#/B♭ 3	
57	220	A 3	
56	207.7	G#/A♭ 3	
55	196.0	G 3	
54	185.0	F#/G♭ 3	
53	174.6	F 3	
52	164.8	E 3	
51	155.6	D#/E♭ 3	
50	146.8	D 3	
49	138.6	C#/D♭ 3	
48	130.8	C 3	
47	123.5	B 2	
46	116.5	A#/B♭ 2	
45	110	A 2	1

Chromatic Scale

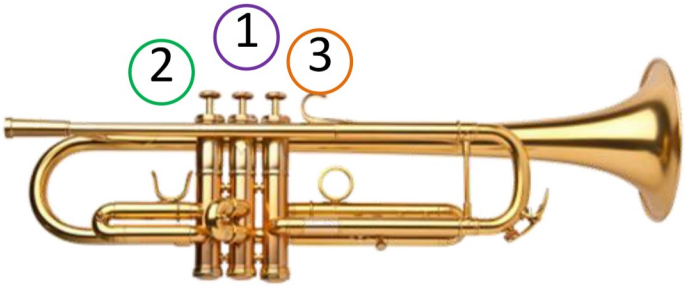
B♭ 5

Without pressing Valves, we have these distorted overtones available, which more or less match some of the notes of the chromatic scale, but with large gaps.
Vibrating lips at these frequencies directly accesses these few notes.

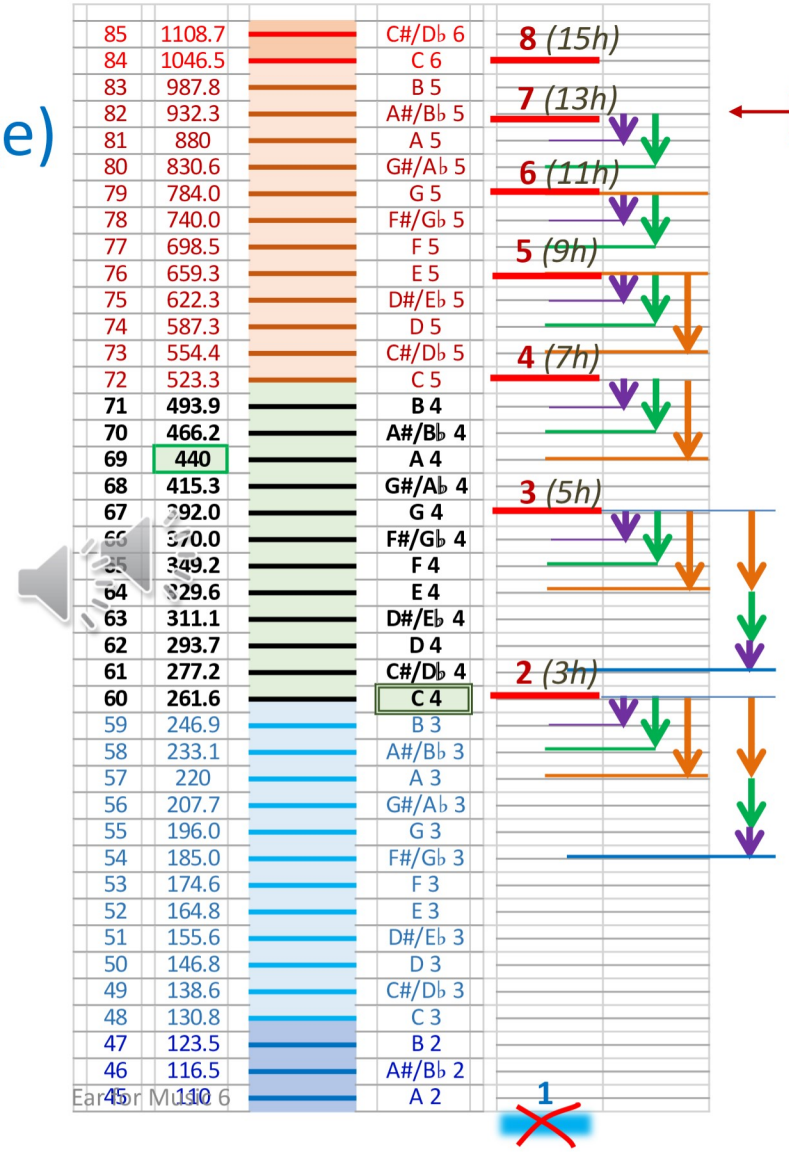
Pipes

Frequency Control by Valves (Length Change)

B♭ Trumpet has 3 Valves



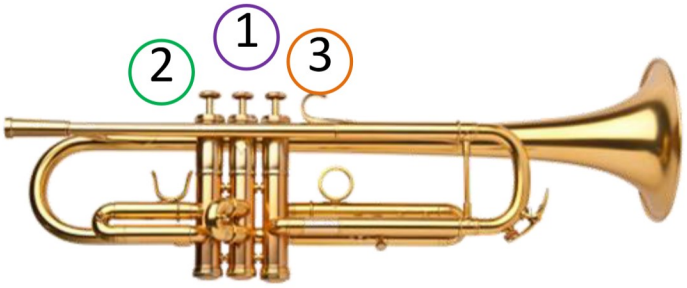
By lengthening the tube using Valves, these resonances are dropped down to allow us to access all the in-between notes.



Pipes

Frequency Control by Valves (Length Change)

B♭ Trumpet has 3 Valves



Lowest possible true note:
F#3 (185 Hz)

85	1108.7	C#/D♭ 6	
84	1046.5	C 6	
83	987.8	B 5	
82	932.3	A#/B♭ 5	
81	880	A 5	
80	830.6	G#/A♭ 5	
79	784.0	G 5	
78	740.0	F#/G♭ 5	
77	698.5	F 5	
76	659.3	E 5	
75	622.3	D#/E♭ 5	
74	587.3	D 5	
73	554.4	C#/D♭ 5	
72	523.3	C 5	
71	493.9	B 4	
70	466.2	A#/B♭ 4	
69	440	A 4	
68	415.3	G#/A♭ 4	
67	392.0	G 4	
66	370.0	F#/G♭ 4	
65	349.2	F 4	
64	329.6	E 4	
63	311.1	D#/E♭ 4	
62	293.7	D 4	
61	277.2	C#/D♭ 4	
60	261.6	C 4	
59	246.9	B 3	
58	233.1	A#/B♭ 3	
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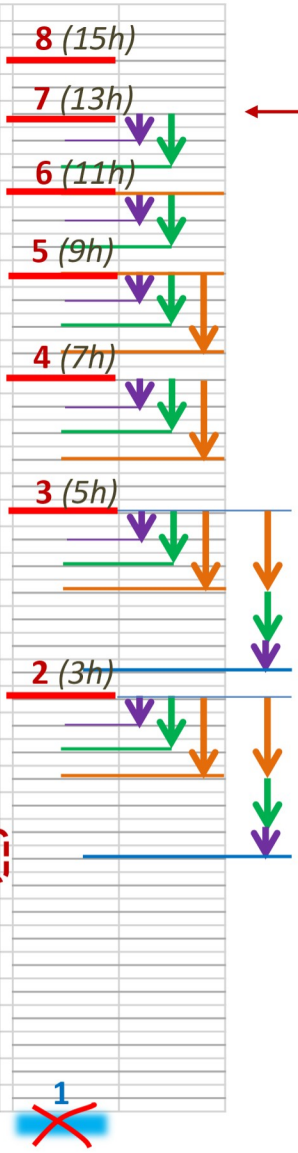
55	196.0	G 3	
54	185.0	F#/G♭ 3	
53	174.6	F 3	
52	164.8	E 3	
51	155.6	D#/E♭ 3	
50	146.8	D 3	
49	138.6	C#/D♭ 3	
48	130.8	C 3	
47	123.5	B 2	
46	116.5	A#/B♭ 2	
45	110	A 2	



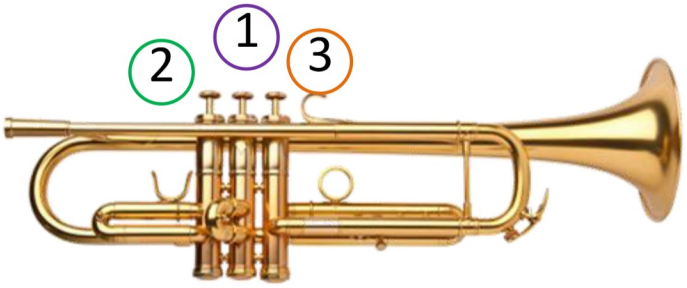
Chromatic Scale

B♭ 5

Pipes

Frequency Control by Valves (Length Change)

B♭ Trumpet has 3 Valves



85	1108.7	C#/D♭ 6	8 (15h)
84	1046.5	C 6	
83	987.8	B 5	7 (13h)
82	932.3	A#/B♭ 5	
81	880	A 5	
80	830.6	G#/A♭ 5	6 (11h)
79	784.0	G 5	
78	740.0	F#/G♭ 5	
77	698.5	F 5	5 (9h)
76	659.3	E 5	
75	622.3	D#/E♭ 5	
74	587.3	D 5	
73	554.4	C#/D♭ 5	4 (7h)
72	523.3	C 5	
71	493.9	B 4	
70	466.2	A#/B♭ 4	
69	440	A 4	
68	415.3	G#/A♭ 4	3 (5h)
67	392.0	G 4	
66	370.0	F#/G♭ 4	
65	349.2	F 4	
64	329.6	E 4	
63	311.1	D#/E♭ 4	
62	293.7	D 4	
61	277.2	C#/D♭ 4	2 (3h)
60	261.6	C 4	
59	246.9	B 3	
58	233.1	A#/B♭ 3	
57	220	A 3	
56	207.7	G#/A♭ 3	
55	196.0	G 3	
54	185.0	F#/G♭ 3	
53	174.6	F 3	
52	164.8	E 3	
51	155.6	D#/E♭ 3	
50	146.8	D 3	
49	138.6	C#/D♭ 3	
48	130.8	C 3	
47	123.5	B 2	
46	116.5	A#/B♭ 2	
45	110	A 2	

Chromatic Scale

B♭ 5

1 2 3

Lowest possible true note:
F#3 (185 Hz)

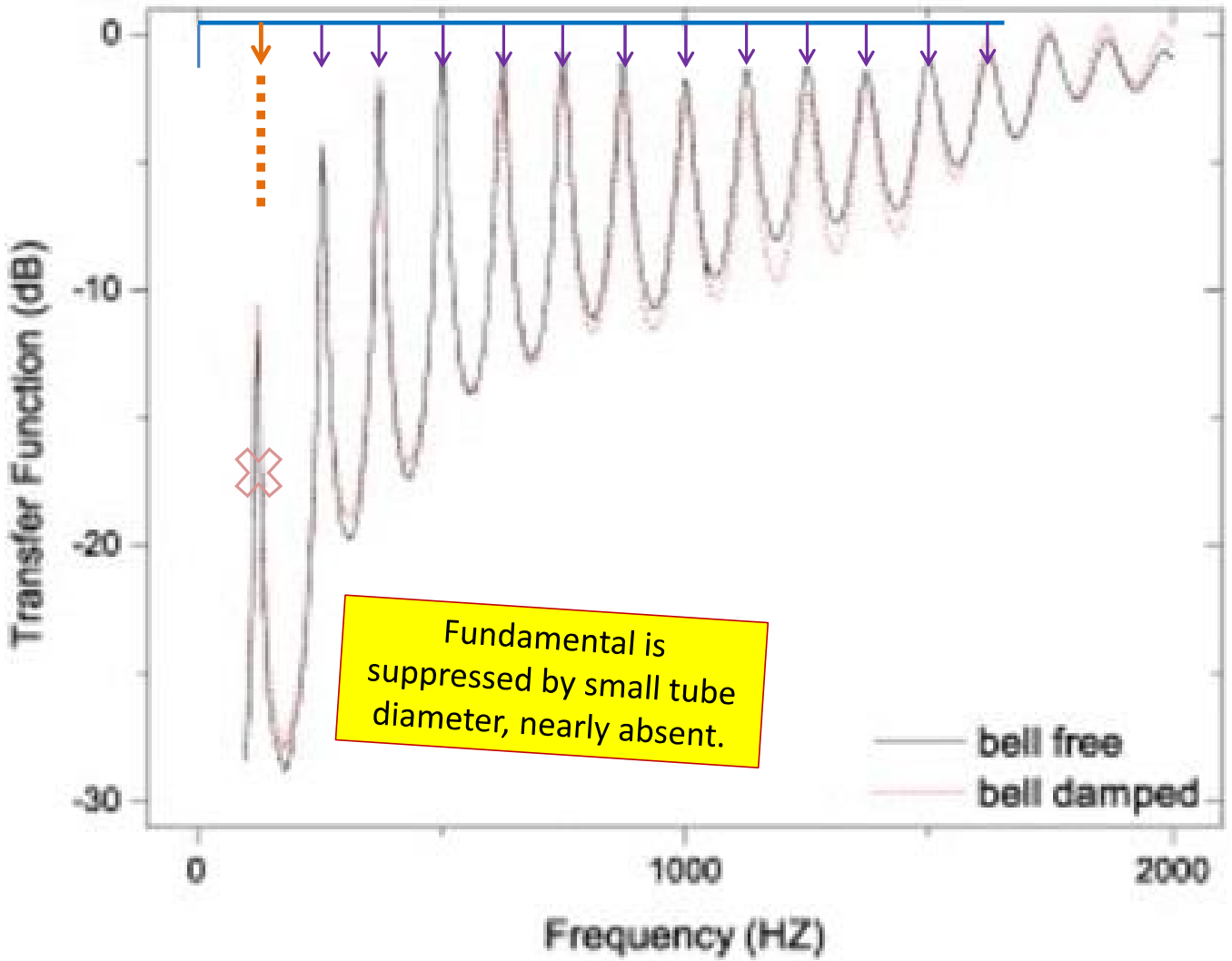
Need ½ Octave Slide Range

Trombone similar

1

Measured Trumpet Resonances

Kausel, Zietlow & Moore
J. Acoustical Soc. Am.
(2010)

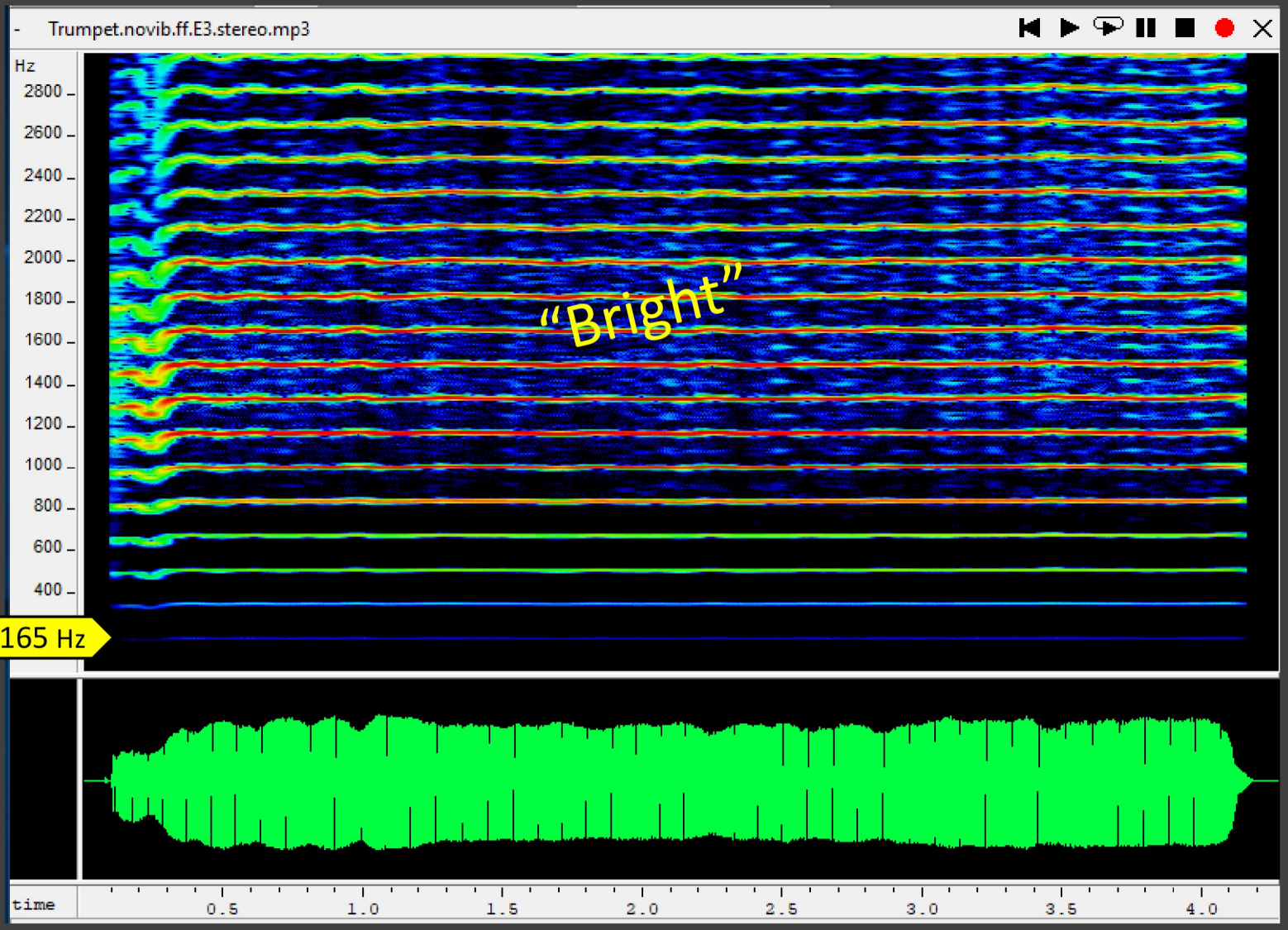


Pedal Notes

Trumpet playing
E3 (165 Hz)

…Trombone also

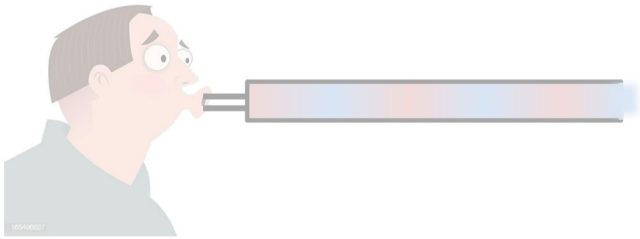
Fundamental virtually missing, but we hear the implied pitch



Pipes

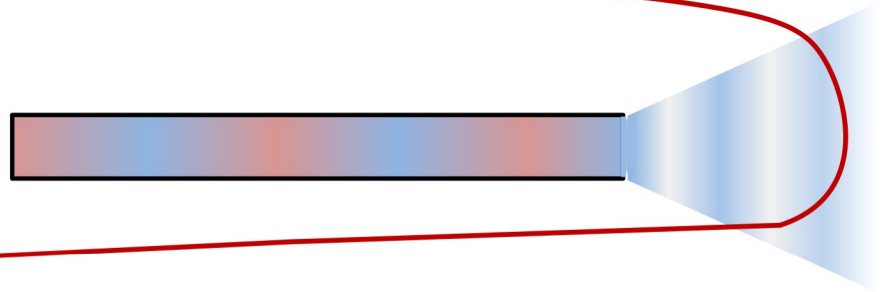
Aerophone Instruments

Three main problems:



1. Excitation HARD
   - How to get the pipe resonating

2. Frequency Control MEDIUM
   - Playing desired notes



3. Getting Sound Out EASY
   - Resonances are *already* sound waves

Pipes

Getting the Sound Out

French Horn

Brasses are Directional

Woodwinds tend to be Omni- Directional

Oboe

Sounds come out of first open hole

Question Time

- Aerophones

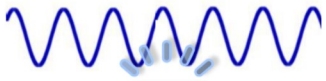
- Zoomland
- In Person

Timbre

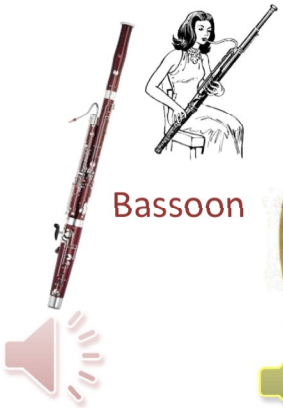
Soprano Sax

Clarinet (B♭)

Fundamental



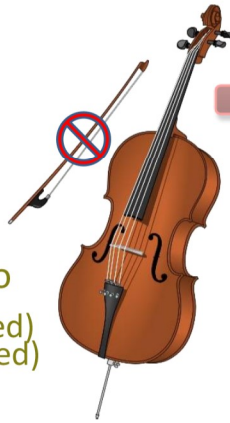
262 Hz (C4)



Bassoon

Trumpet

Oboe



Cello

(Bowed)
(Plucked)

Tuba

Tenor Trombone

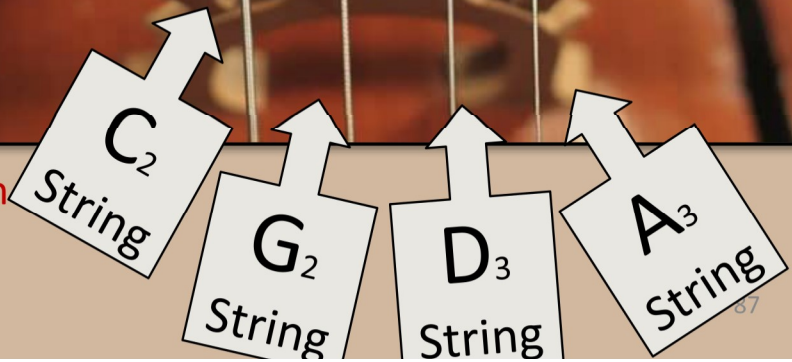
Violin
(Plucked)

Violin
(Bowed)

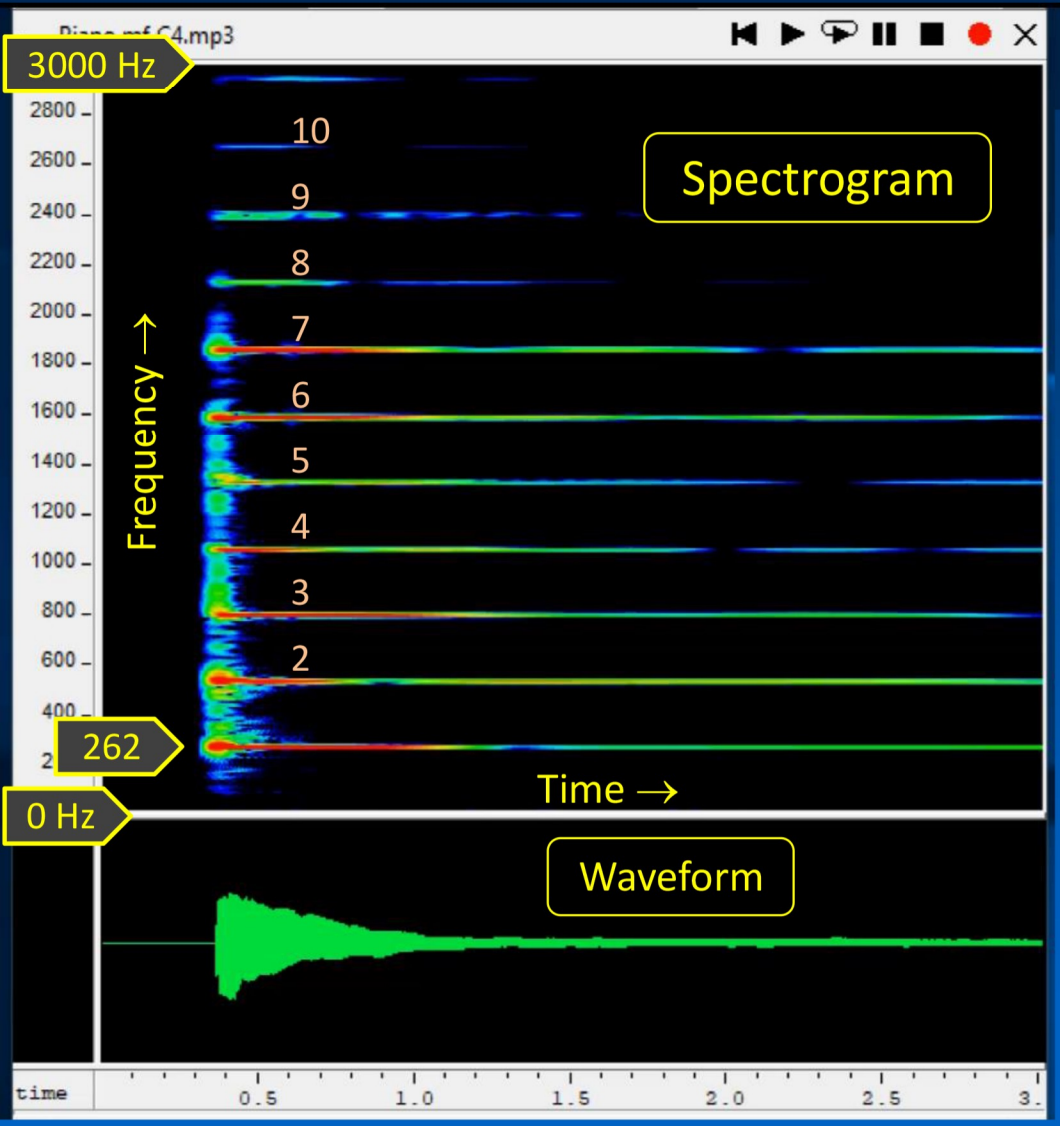
Timbre : Even for one instrument Timbre can vary

Cello

C4 (262 Hz) Played on Different Strings

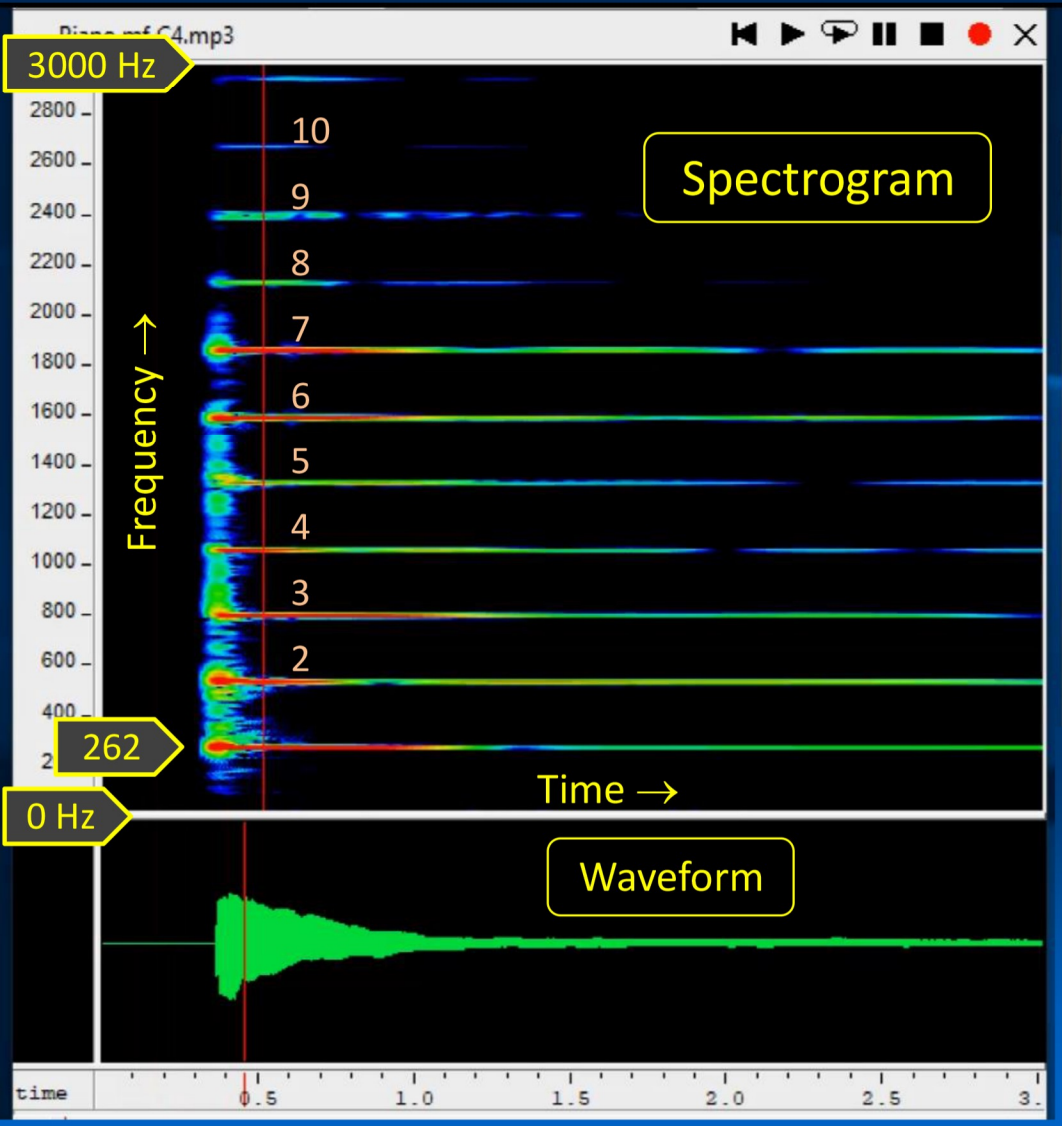


What’s going on here?

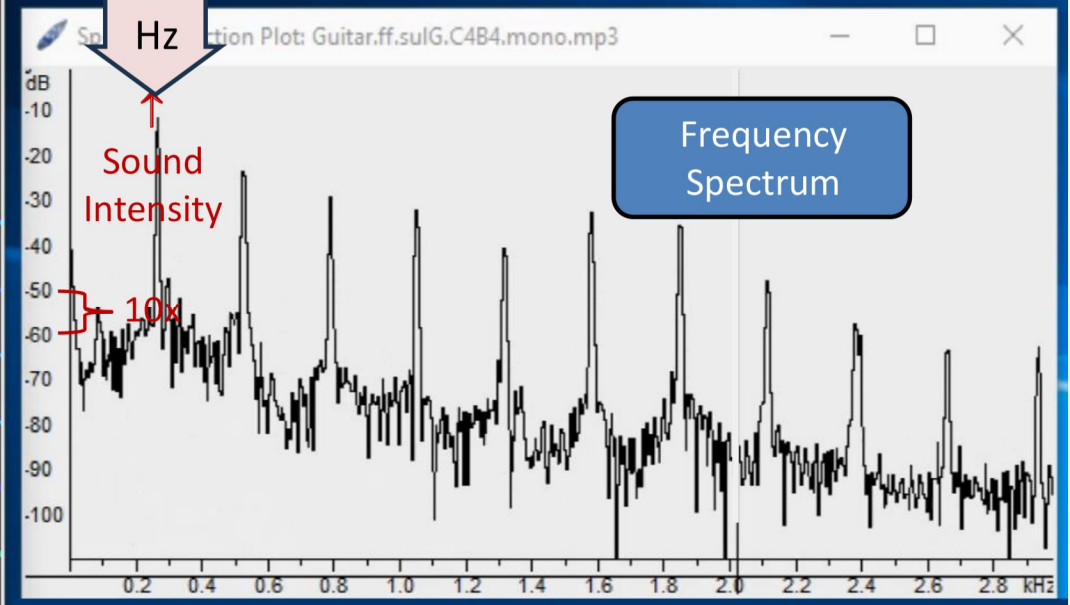


Piano C4 262 Hz

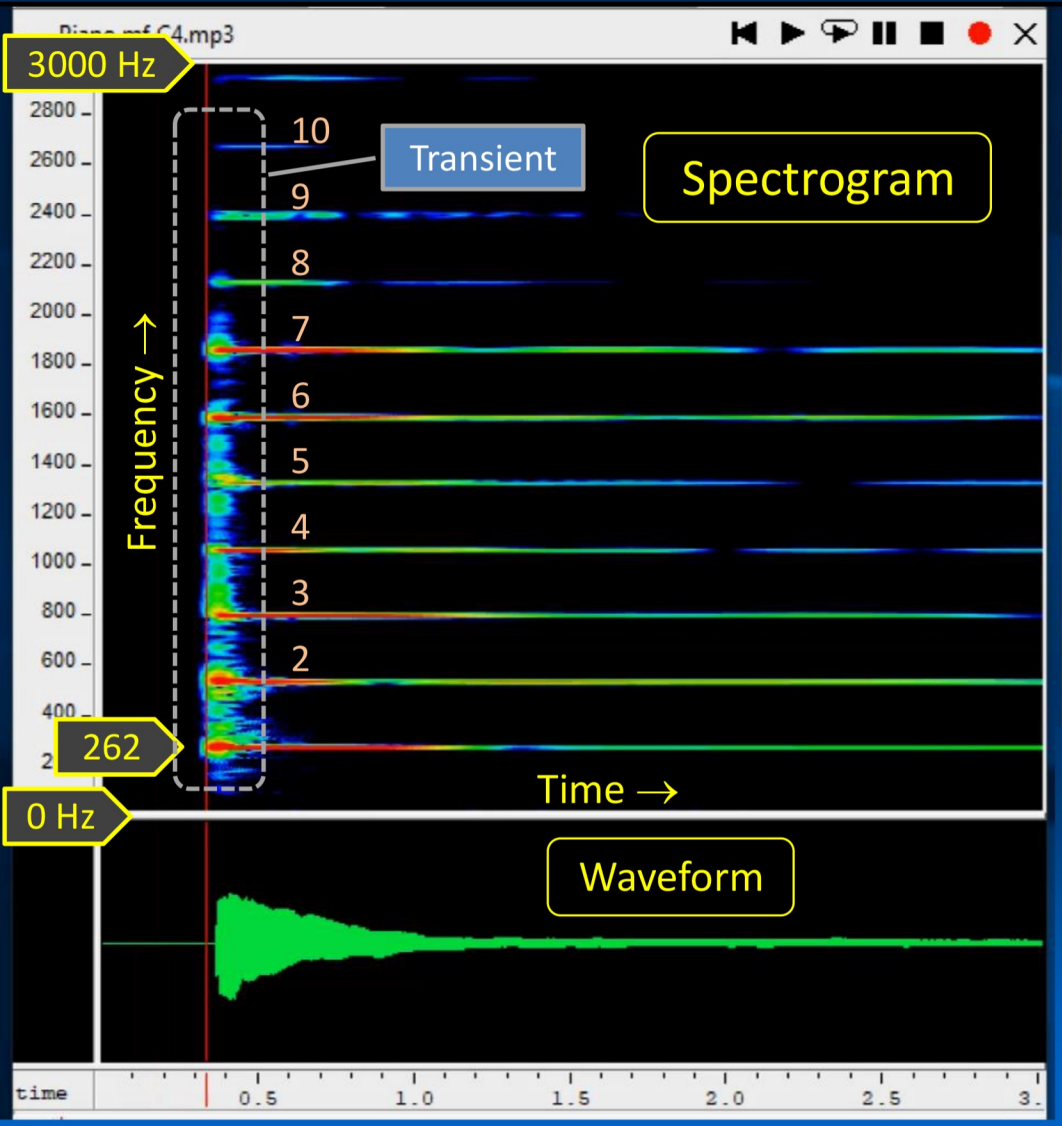
Visualizing a note
to understand Timbre



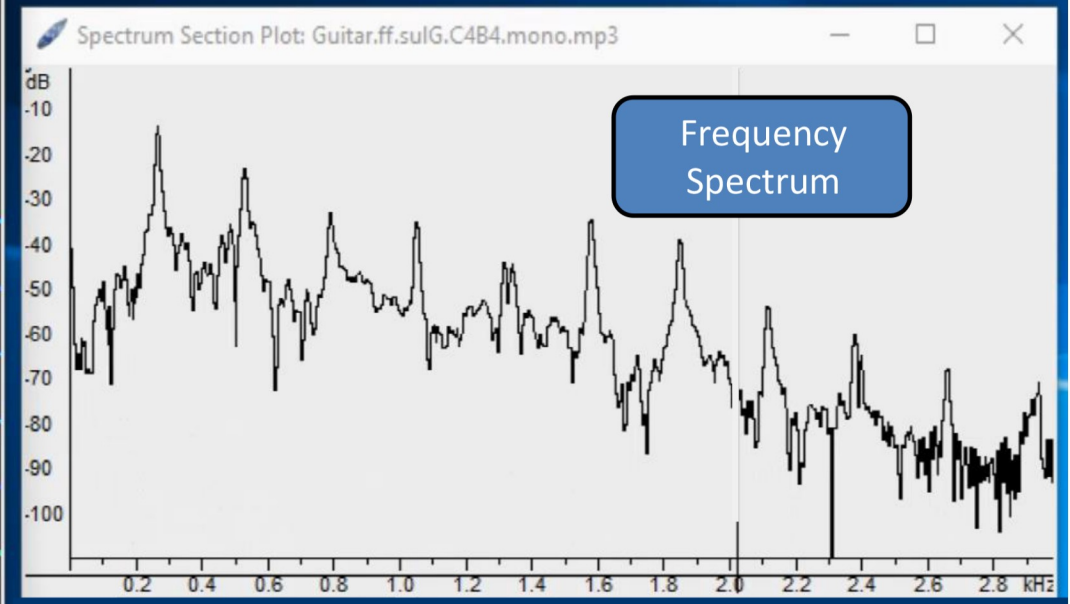
Piano C4 262 Hz



Visualizing a note
to understand Timbre

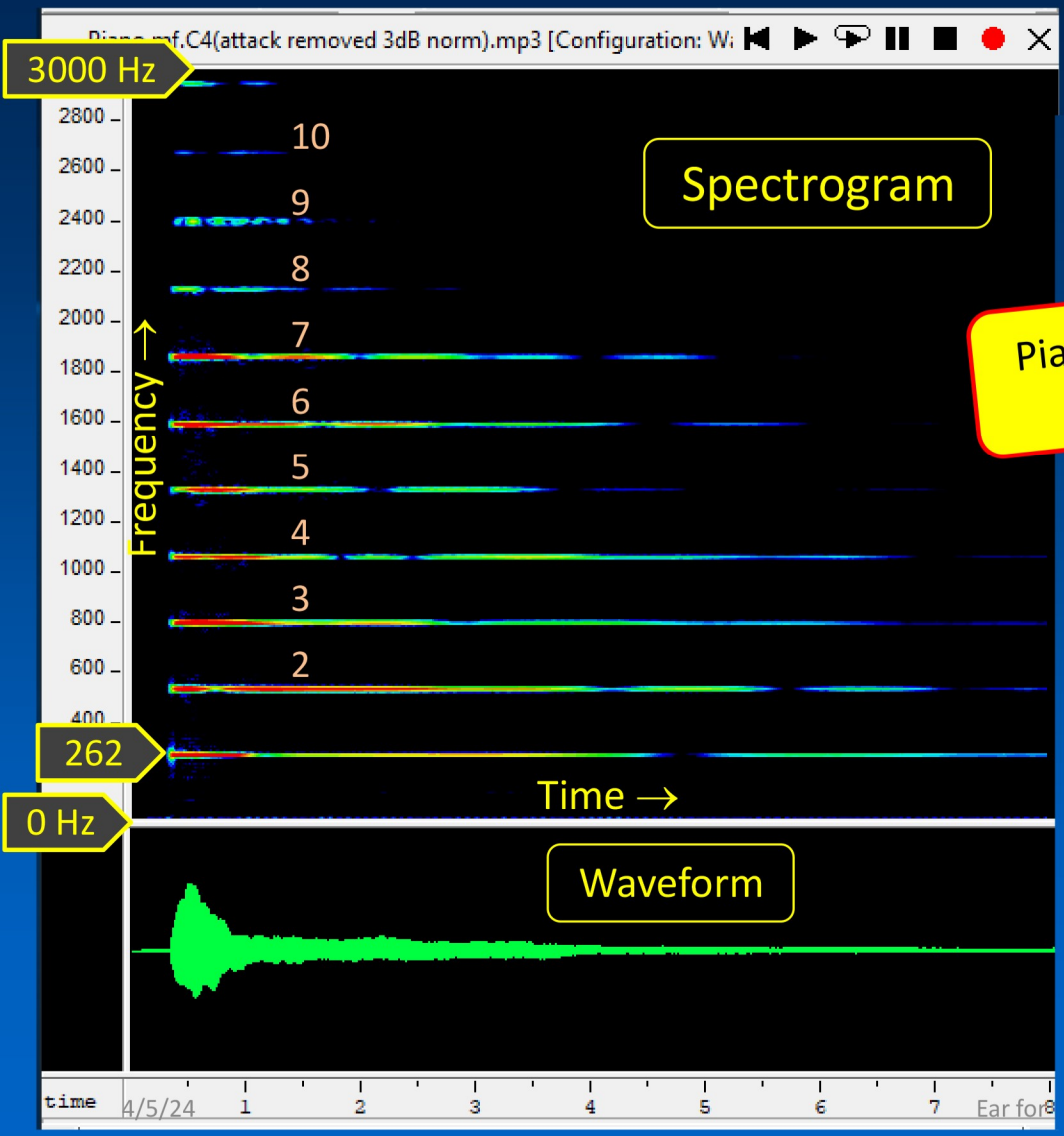


Piano C4 262 Hz



Frequency →

Visualizing a note
to understand Timbre:
The Attack

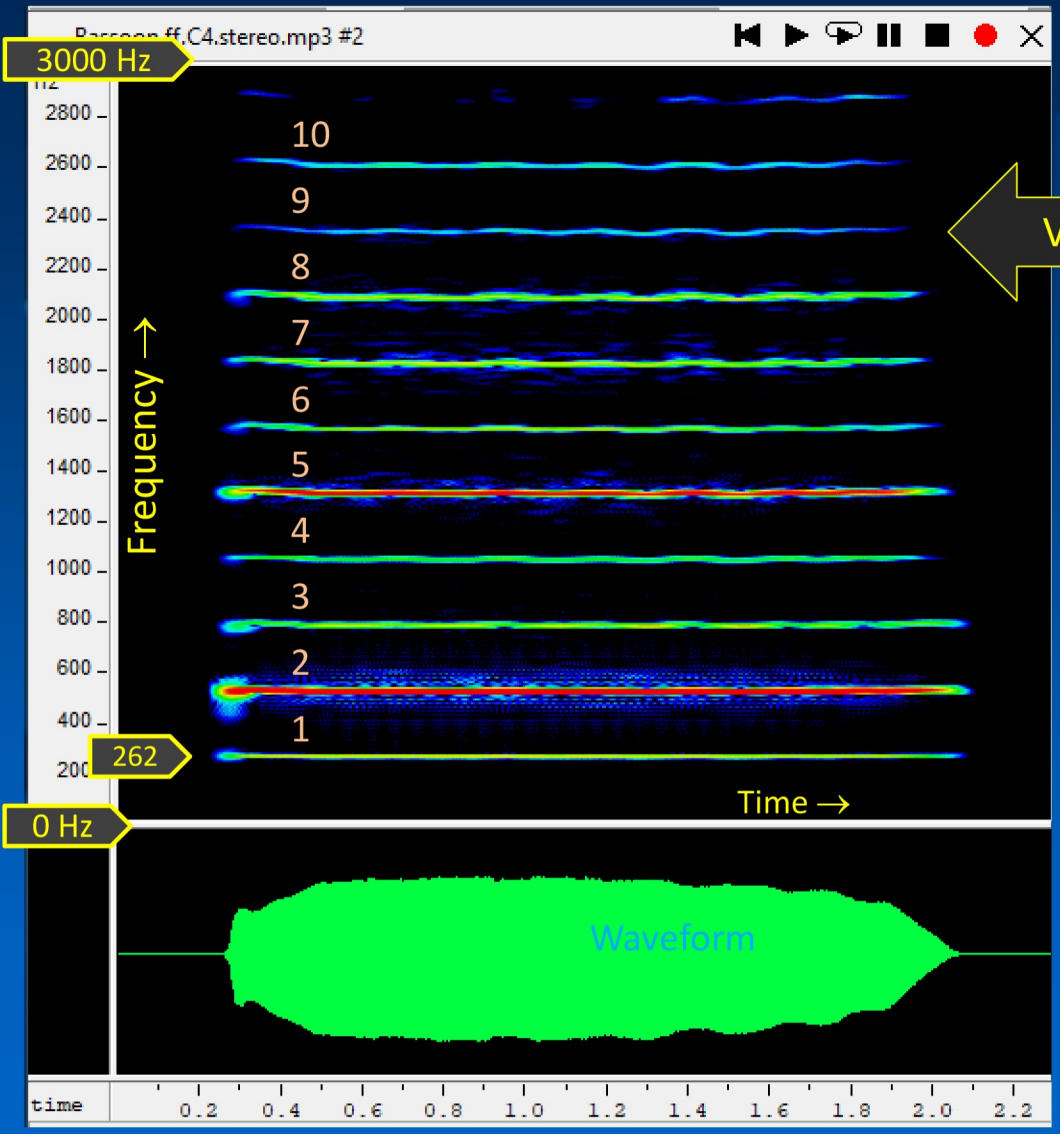


Piano C4 262 Hz

Piano C4 with "Hammer" Attack Removed

Visualizing a note to understand Timbre: The Attack removed

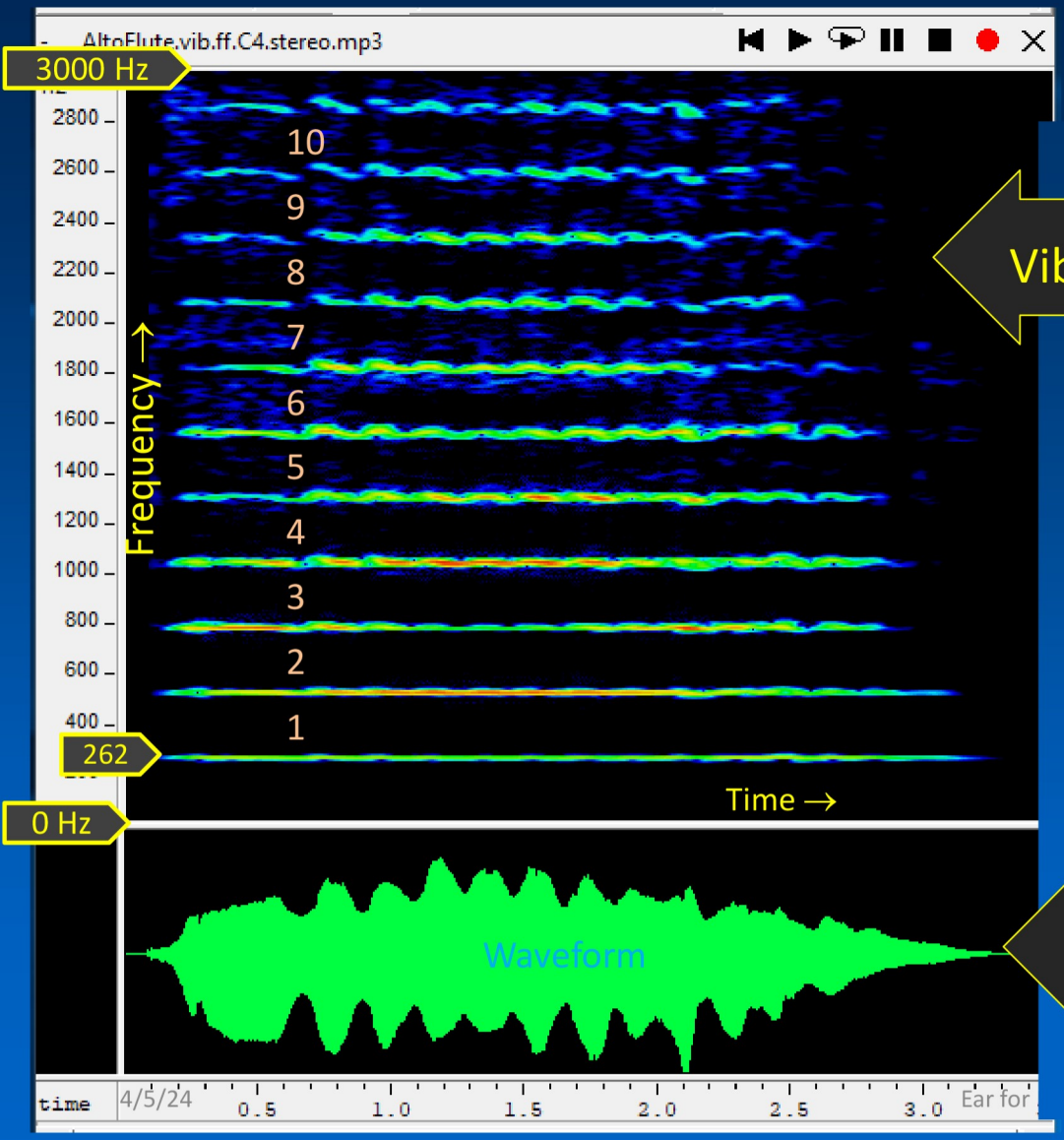
Sounds totally different!



Vibrato

Bassoon C4 262 Hz

Visualizing a note
to understand Timbre:
Steady Tone

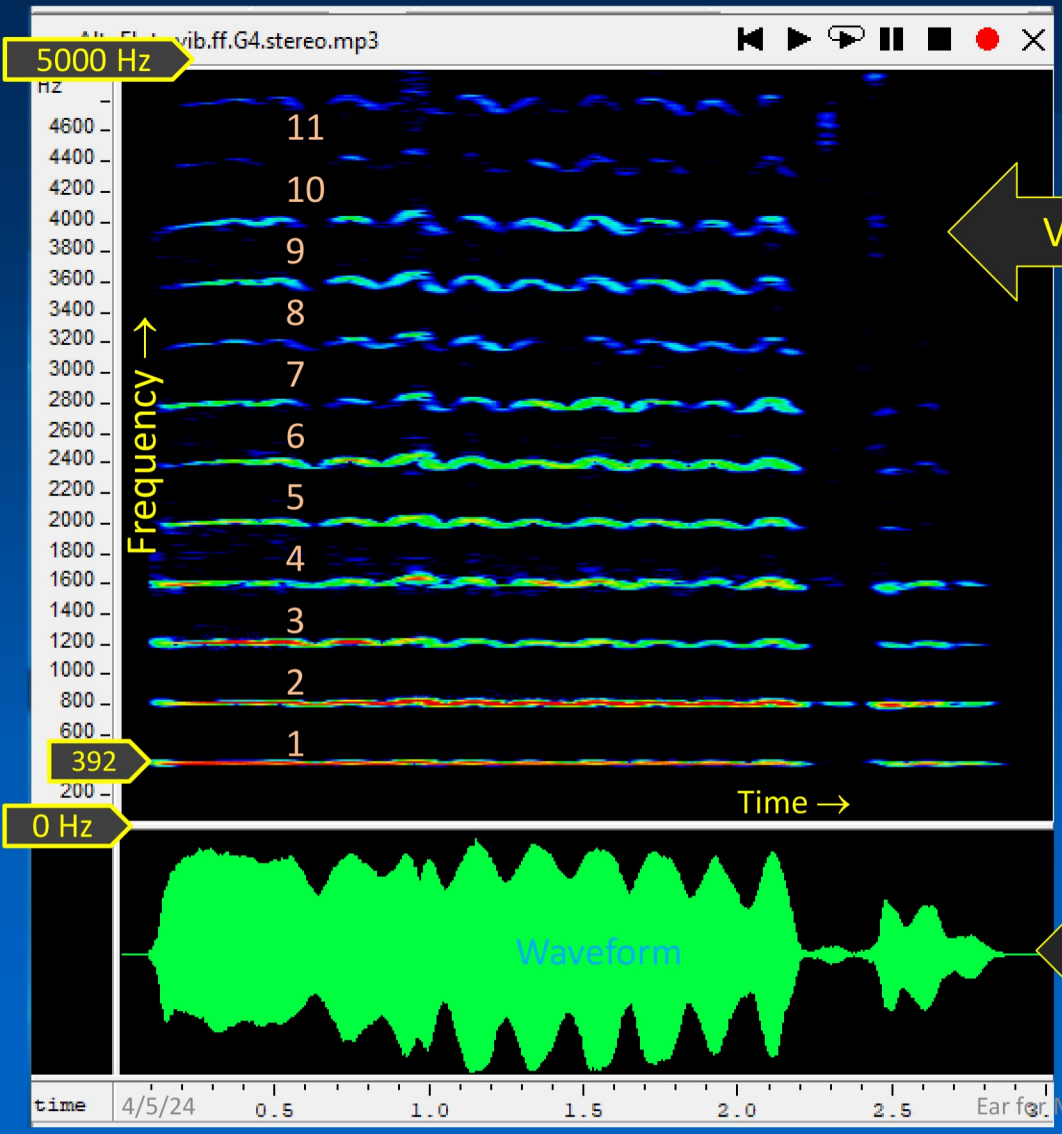


Alto Flute C4 262 Hz

Vibrato: f ↓↑

Tremolo: Loudness ↓↑

Visualizing a note
to understand Timbre:
Vibrato and Tremolo



Vibrato

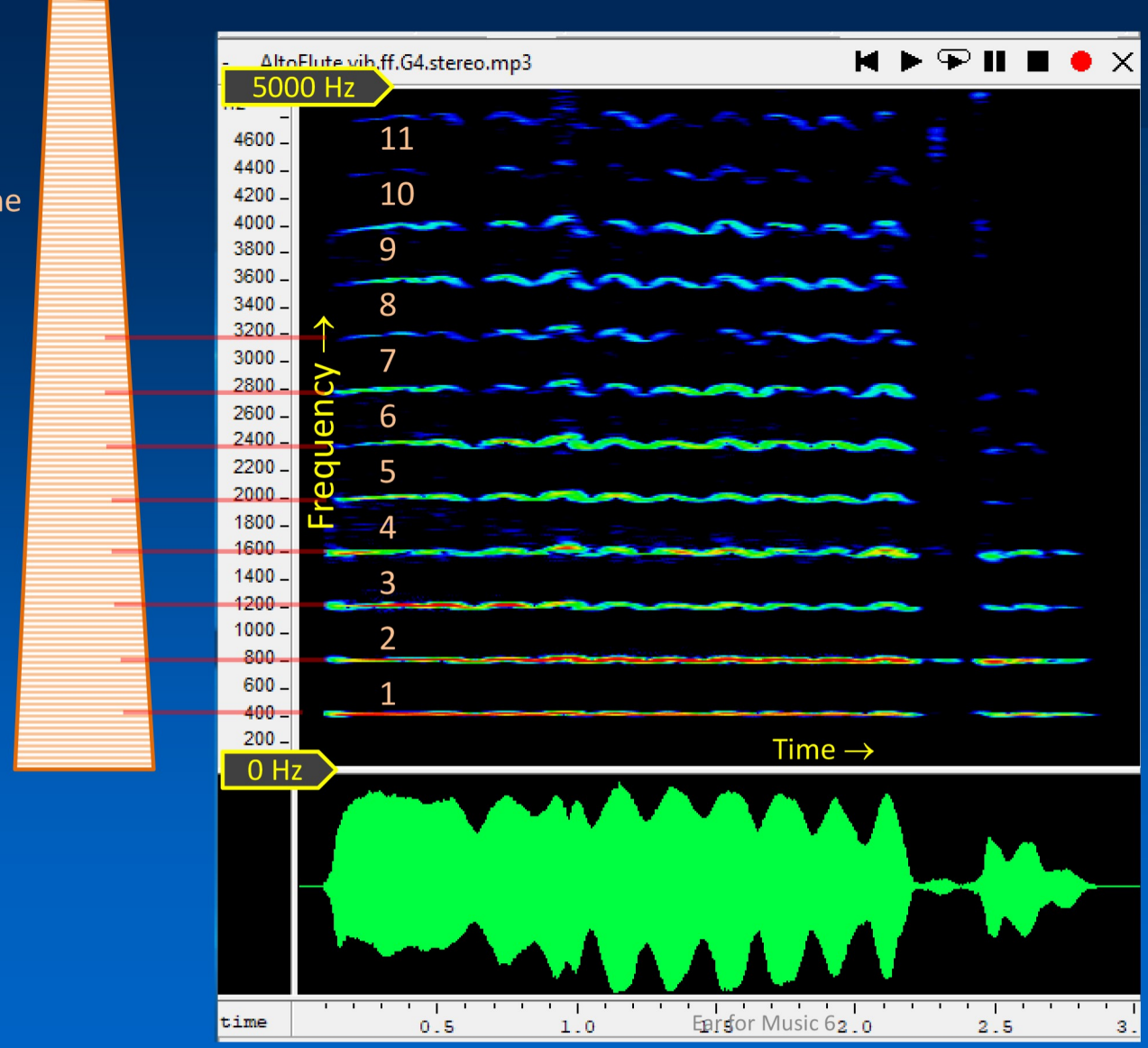
Tremolo

Alto Flute G4 392 Hz

Higher Note

Visualizing a note
to understand Timbre:
Vibrato and Tremolo

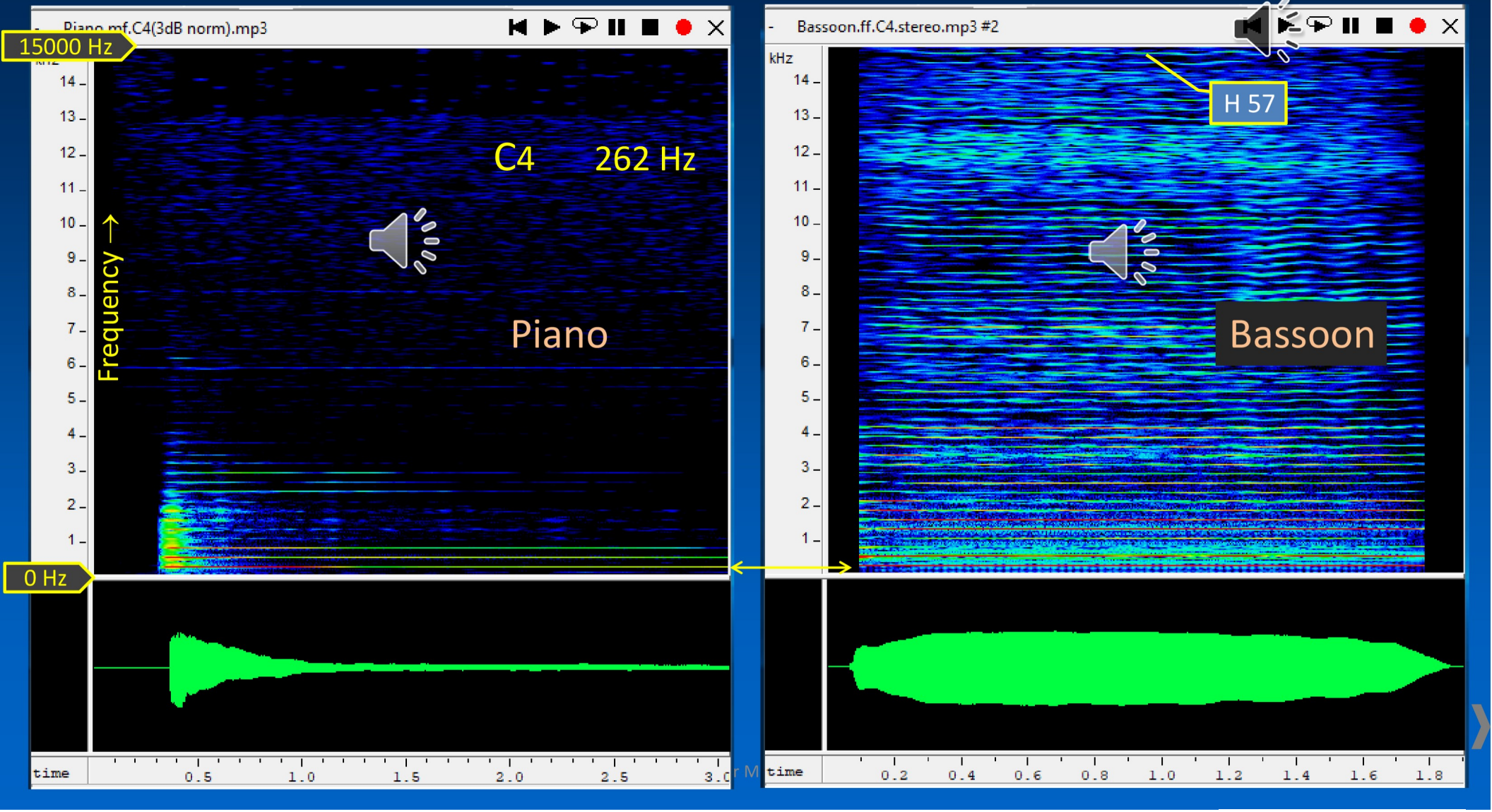
Alto Flute G4



In all cases, different harmonics fall on different parts of the Basilar Membrane…

but not always on different Critical Bands

Back to Piano *vs.* Bassoon (C4 262 Hz)


15000 Hz
C4
262 Hz
Frequency →
Piano
0 Hz
time
0.5
1.0
1.5
2.0
2.5
kHz
H 57
Bassoon
time
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8