OSHER LIFELONG LEARNING INSTITUTE

Sound of Music

How It Works

Session 5

Musical Instruments: Pipes

"Throat Singing" YouTube Medley

OLLI at Illinois

Spring 2020

D. H. Tracy

OSHER LIFELONG LEARNING INSTITUTE

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How It Works

Session 6

Musical Instruments: Pipes

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Course Outline

1. Building Blocks: Some basic concepts
2. Resonance: Building Sounds
3. Hearing and the Ear
4. Musical Scales
5. Musical Instruments
6. More Musical Instruments
7. Singing; Notation
8. Harmony and Dissonance

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

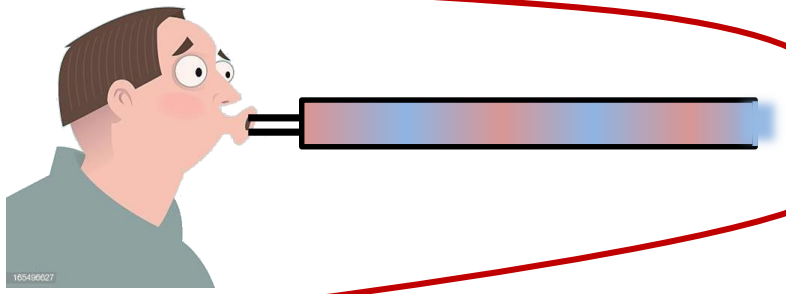
- Jiahu Flutes
- Henan Province, China
- Discovered 1999
- ~ 9000 BP
- Ulna bone of red-crowned crane
- Still playable

Pipes

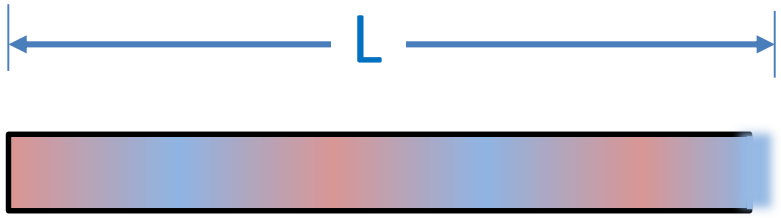
Aerophone Instruments

Three main problems:

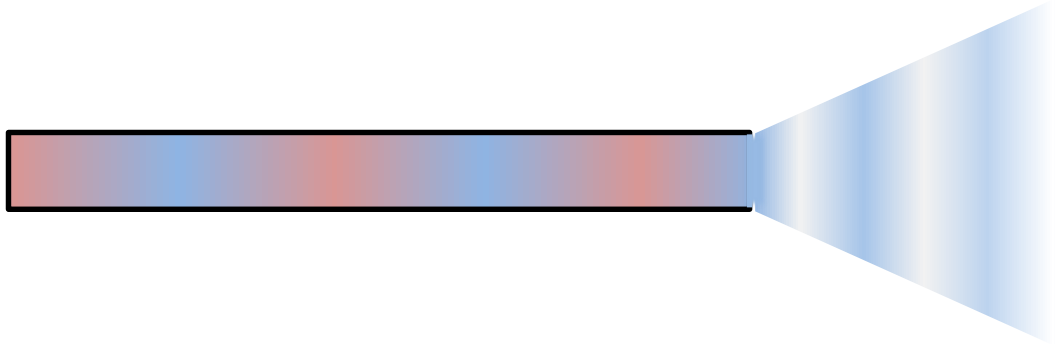
1. Excitation HARD
   - How to get the pipe resonating



2. Frequency Control MEDIUM
   - Playing desired notes



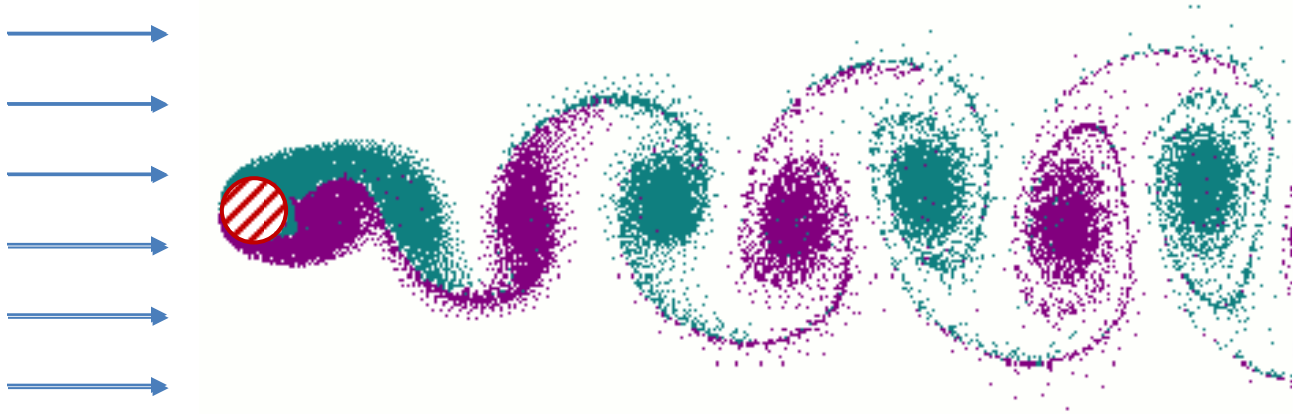
3. Getting Sound Out EASY
   - Resonances are *already* sound waves



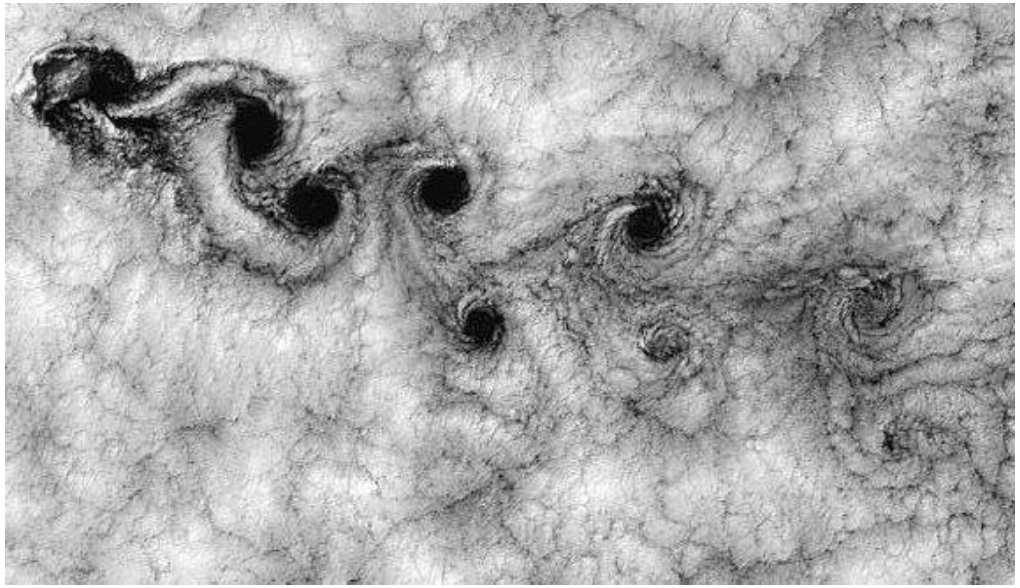
3 Basic Kinds of Excitation of Pipes

- Edge Tones
- Untuned Reeds
- Vibrating Human Lips

Air hitting cylinder barrier creates “Vortex Street”

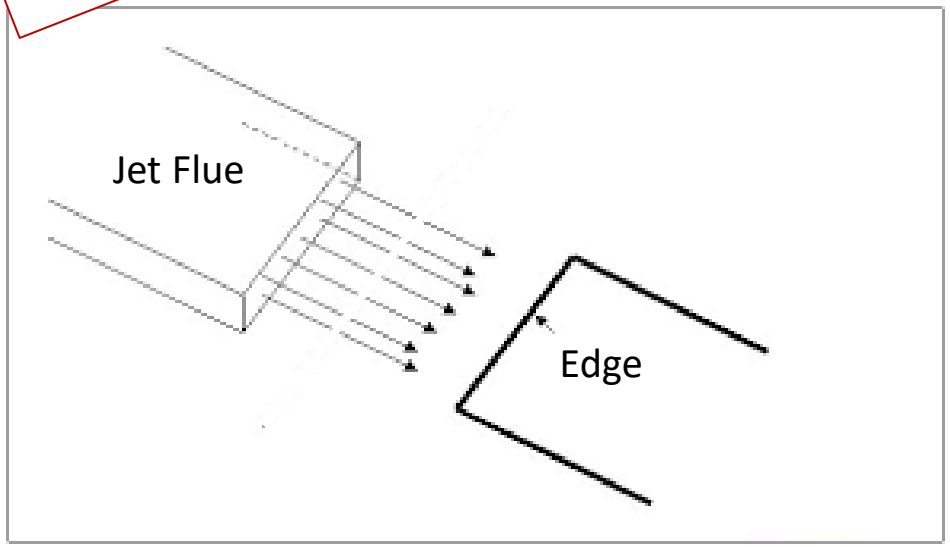


Mountain
Vortex Street
in Atmosphere
(from space)

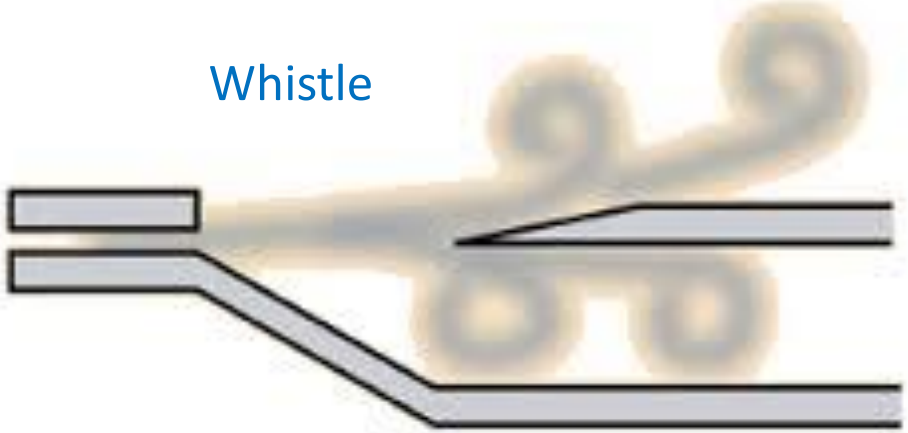


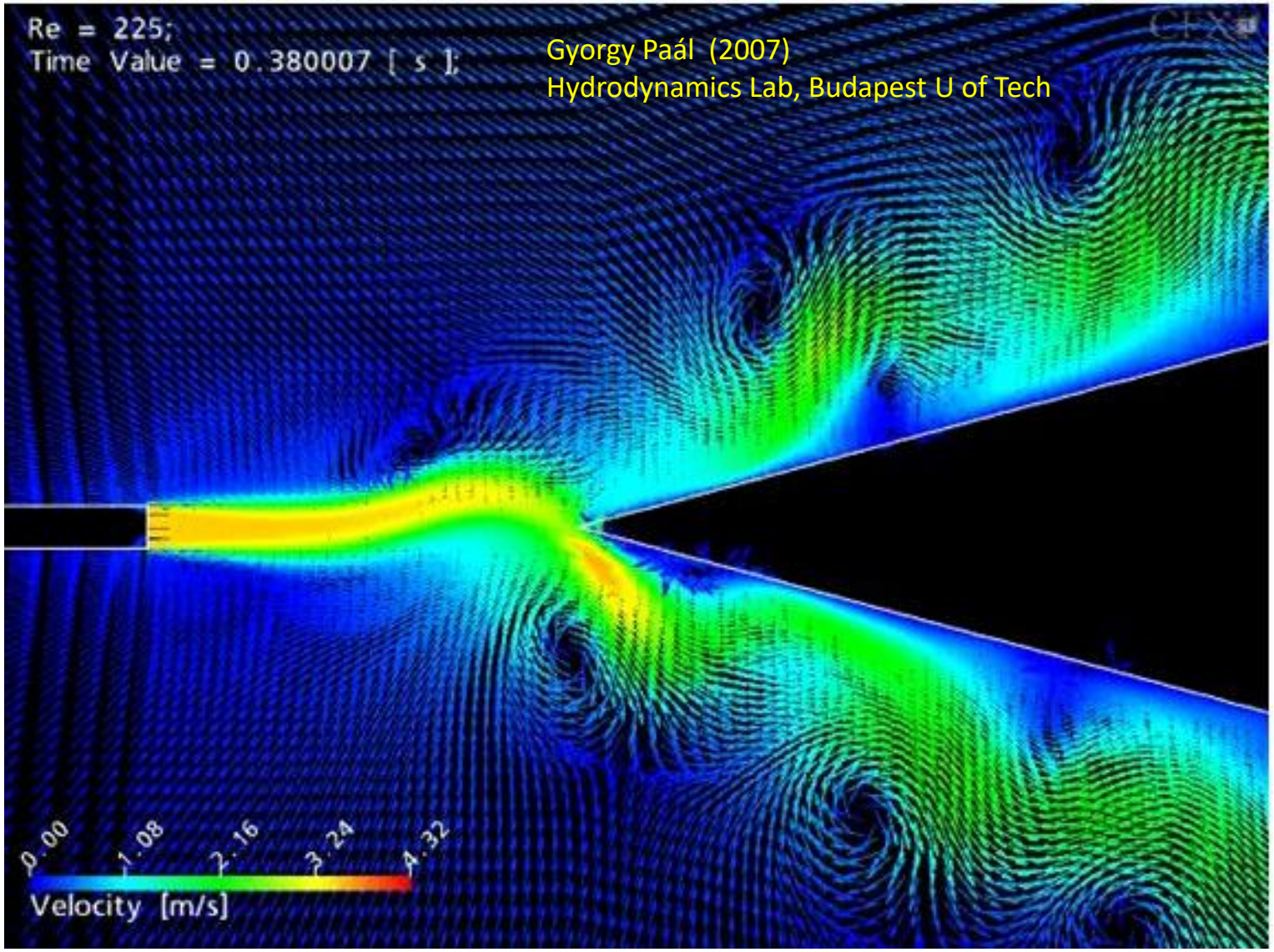
Pipes

Turbulent Flow: Edge Tones



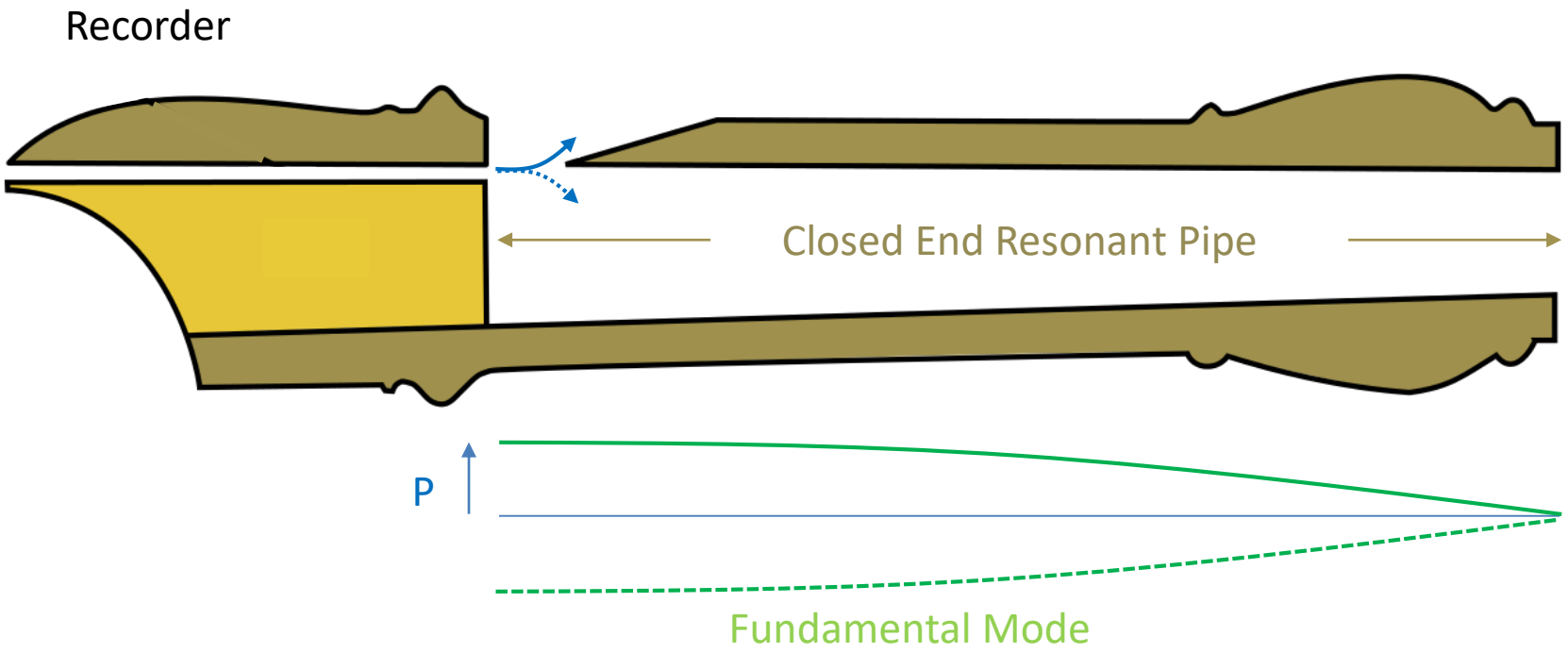
Whistle





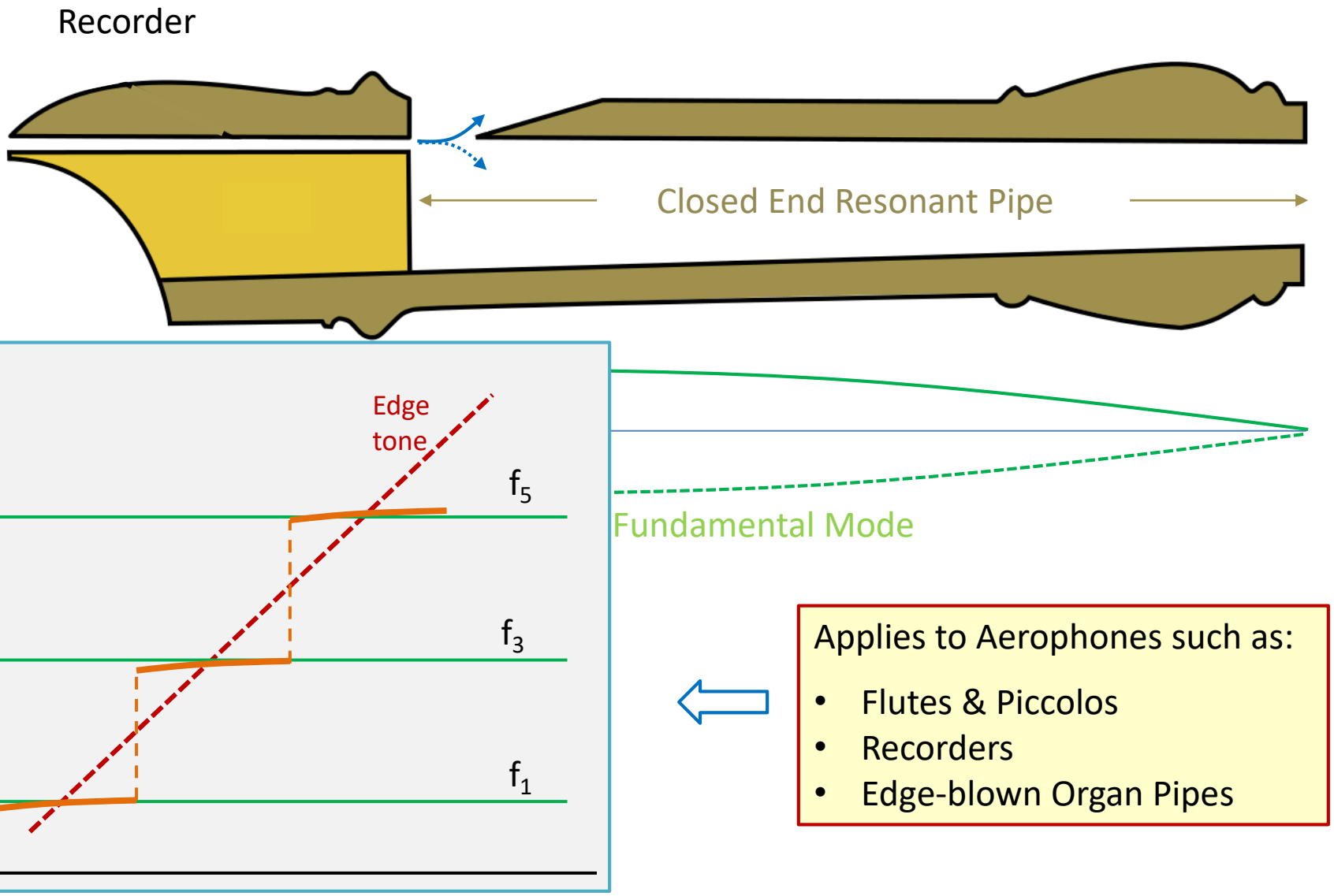
Pipes

Edge Tone + Resonant Pipe



Pipes

Edge Tone + Resonant Pipe



Applies to Aerophones such as:

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

Pipes

Edge-Blown Aerophones

Recorder

Flutes

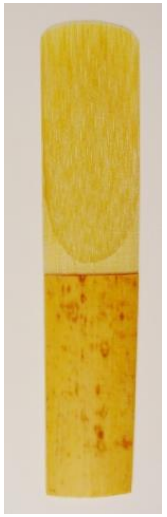
Piccolo

Organ Pipes

Pipes

Woodwind Reeds (Untuned – Stiff)

arundo donax (Giant Cane)



Sax Reed

Bassoon Double Reeds

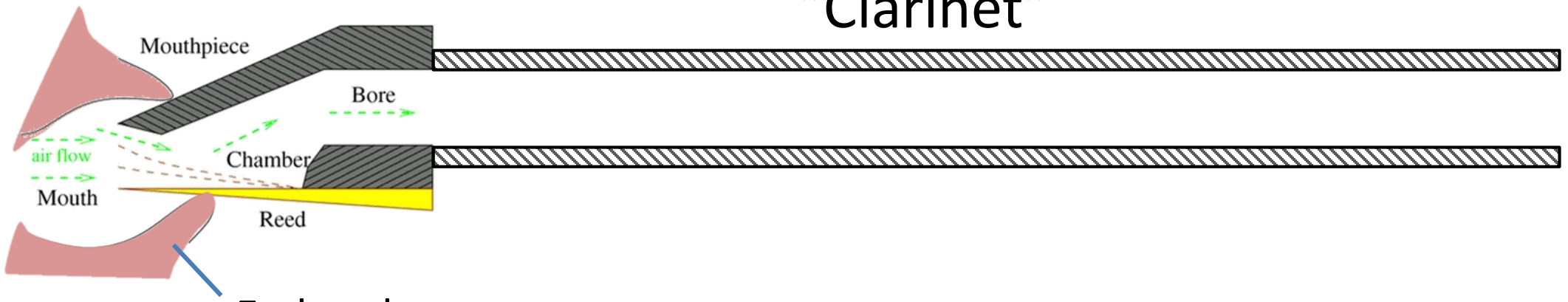
Single Reeds
(mounted *on* mouthpiece)
- Clarinets
- Saxophones
- Some Bagpipes

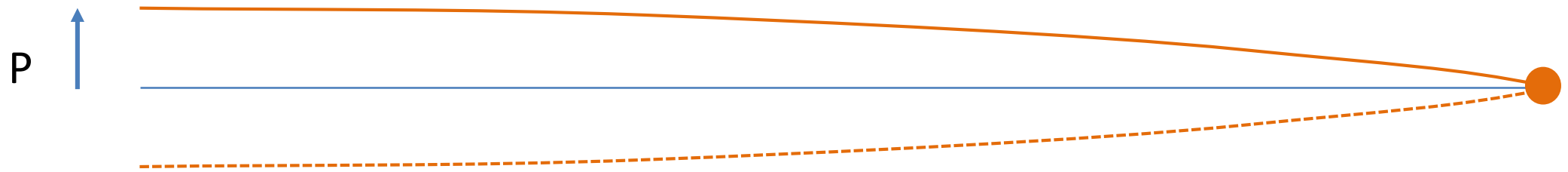
Double Reeds
(act *as* the mouthpiece)
- Oboe
- Bassoon
- English Horn

also
- Some Bagpipes

Pipes

Single Reed Aerophones: Excitation



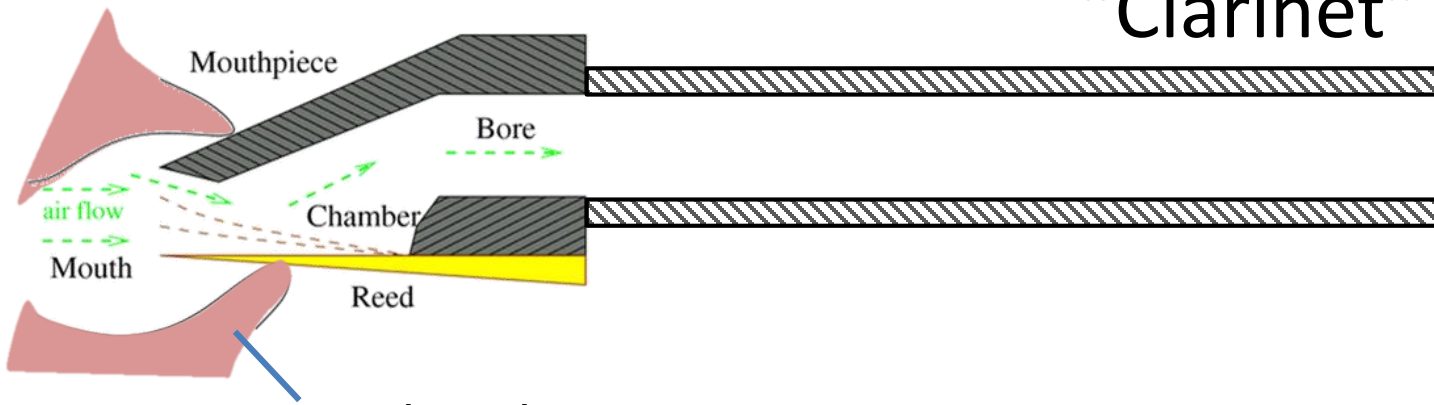


Reed is opened and closed by the pressure of the resonant mode, at its frequency

Pipes

Single Reed Aerophones: Excitation

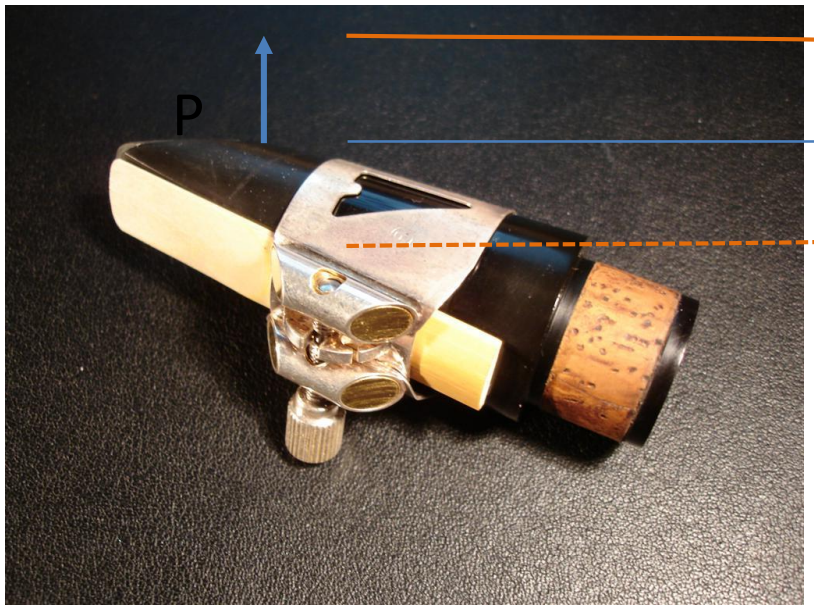
"Clarinet"



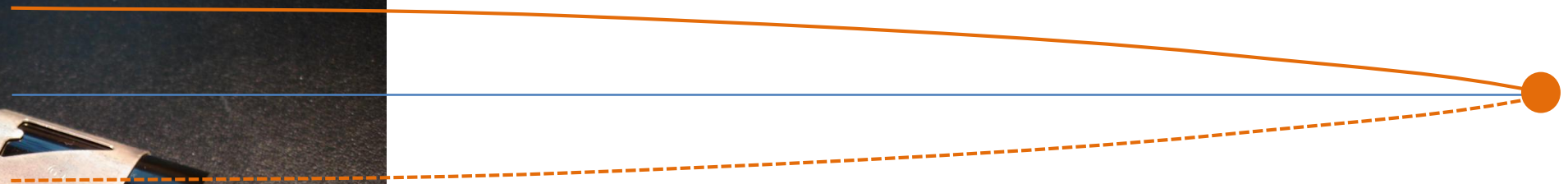
Embrochure

Other Single Reed Instruments:

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



Fundamental Mode



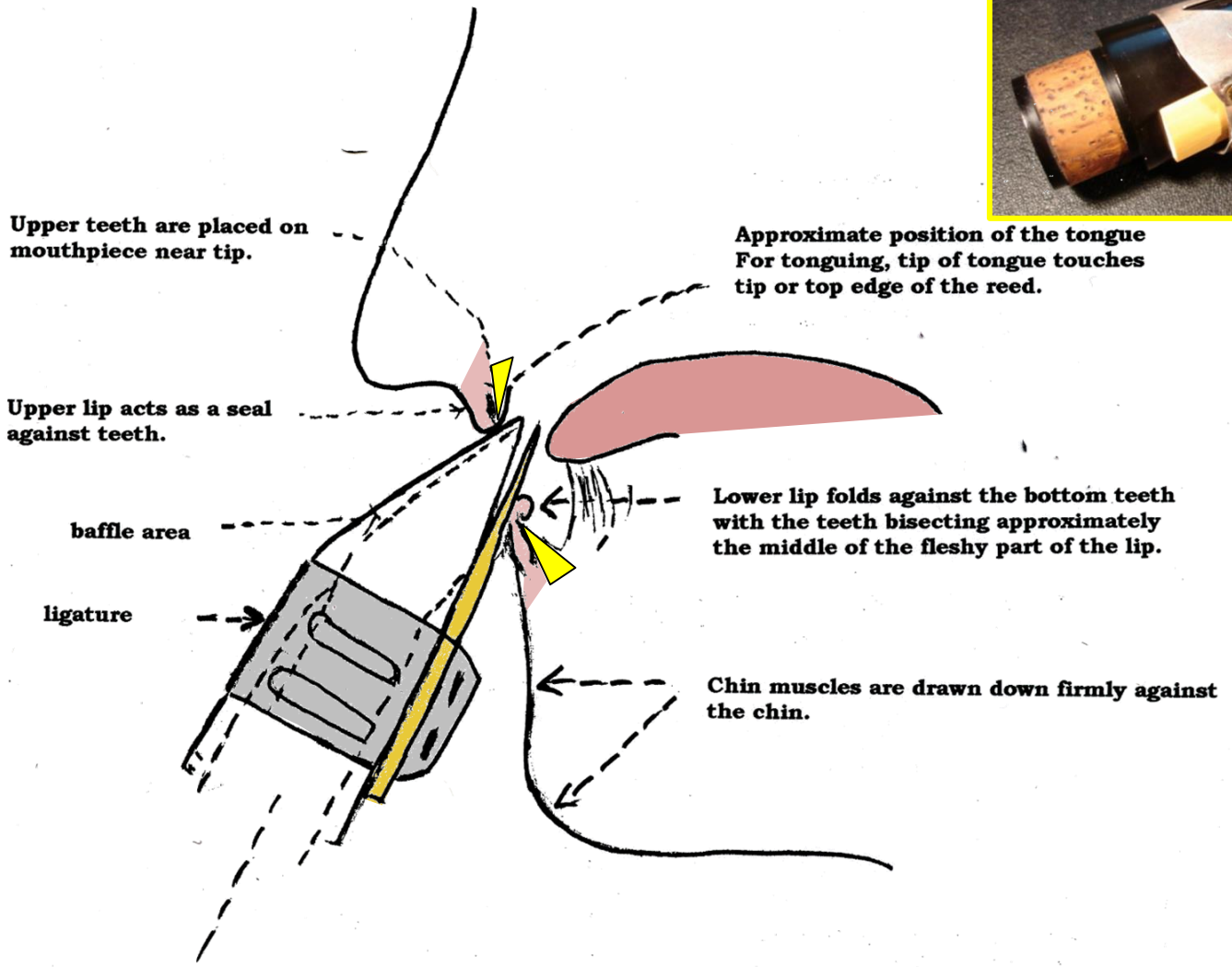
Reed is opened and closed by the pressure of the resonant mode, at its frequency

Pipes

Clarinet Embouchure

Pipes

Clarinet Embouchure

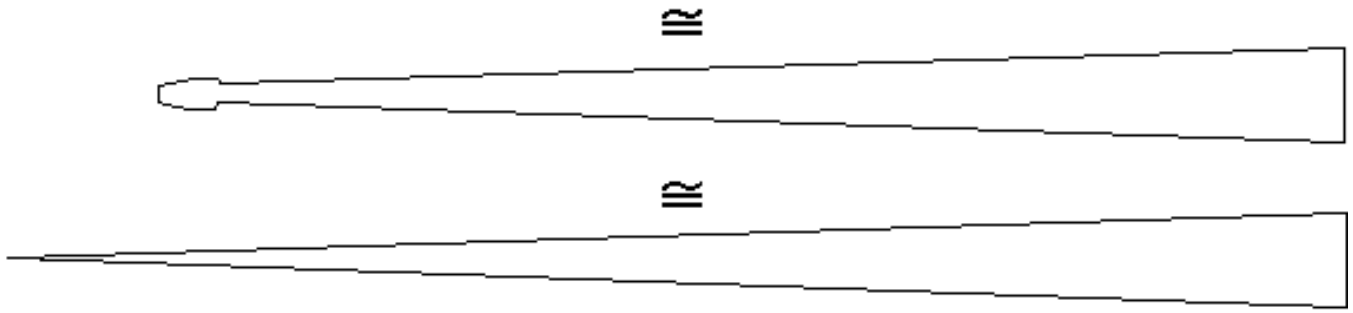


Pipes

Oboe Demo

Pipes

Sax, Oboe, Bassoon: Conical Case



Sax cavity approximates a cone

$\lambda/2$

Invented June 1846
by Adolphe Sax

Tenor
Saxophone

Both Odd and Even Harmonics

Pipes

Brasses Excited by Lip Vibrations
(Labrosones)

Trumpet

Alto Horn

Tuba*

Didgeridoo/Yidaki

French Horn

Euphonium*

Cornet

Trombone

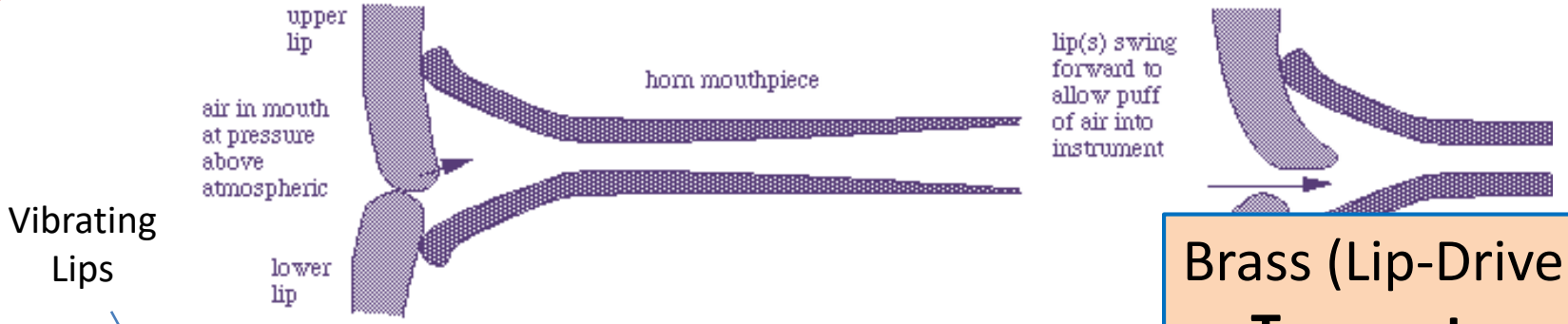
Pipes

Generic Brass: Lip-Driven (Labrosones)

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

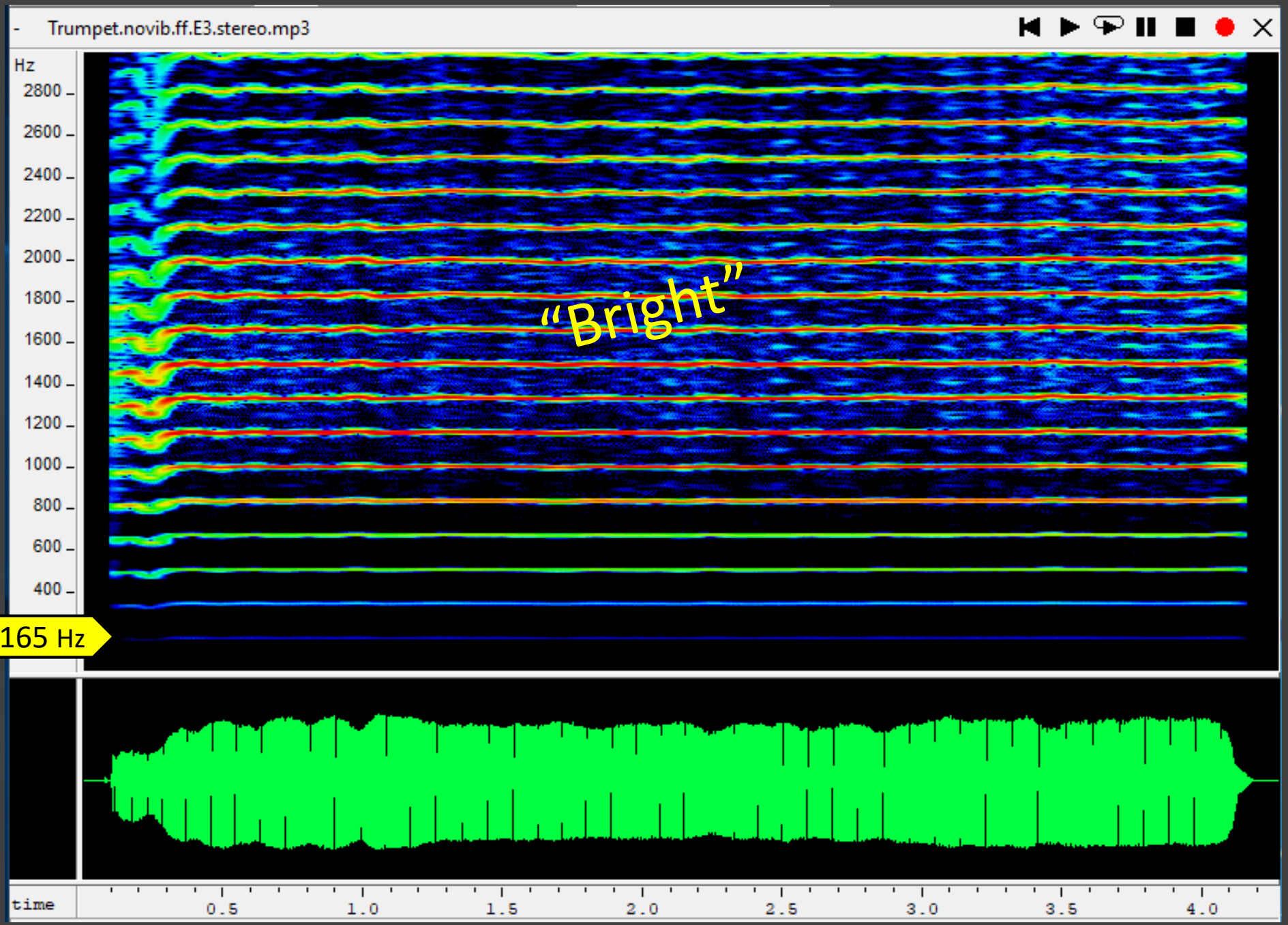
Brass (Lip-Driven) Instruments:

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

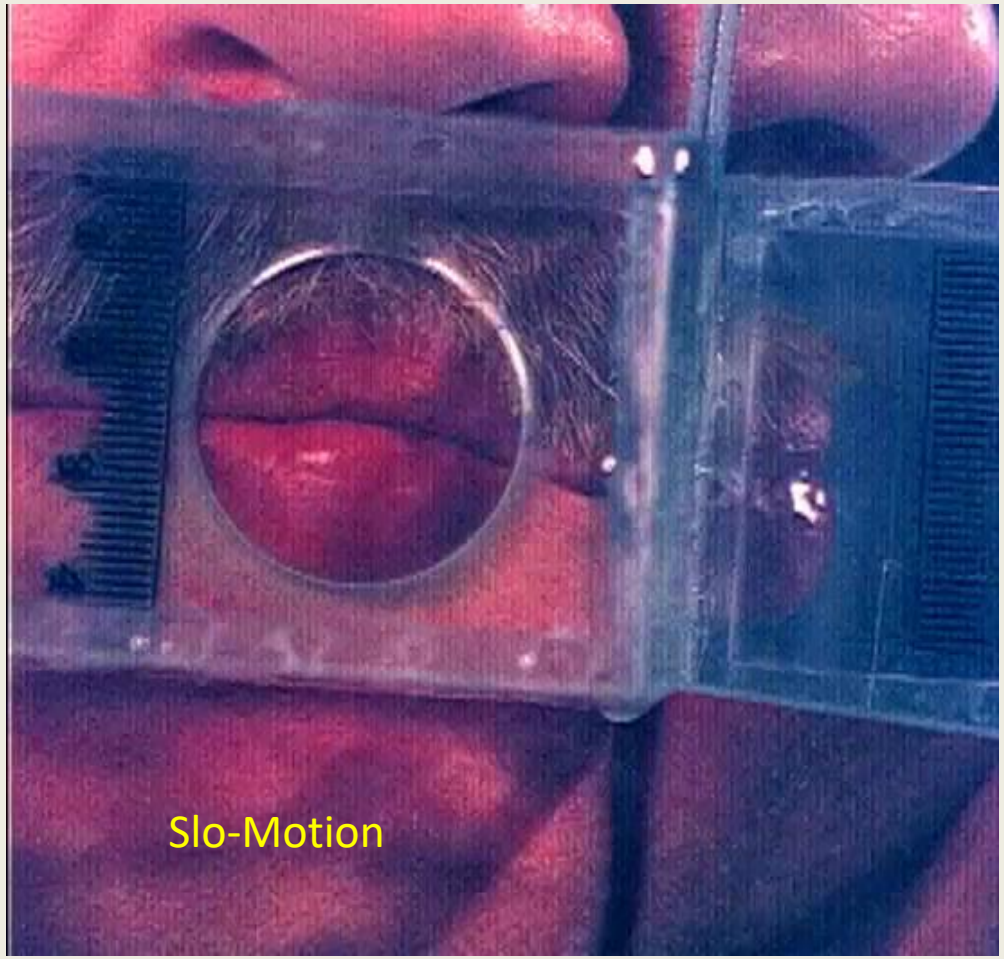
Pedal Notes

…Trombone also

Fundamental virtually missing, but we hear the implied pitch



Lip Vibrations: Glass Didgeridoo



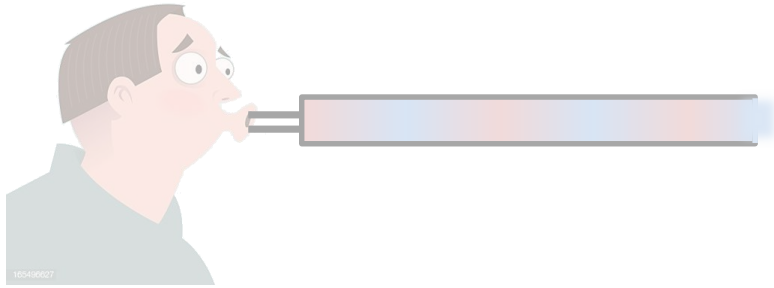
newt.phys.unsw.edu.au/jw/didjeridu.html

Pipes

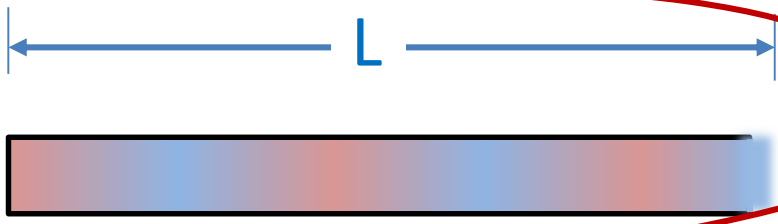
Aerophone Instruments

Three main problems:

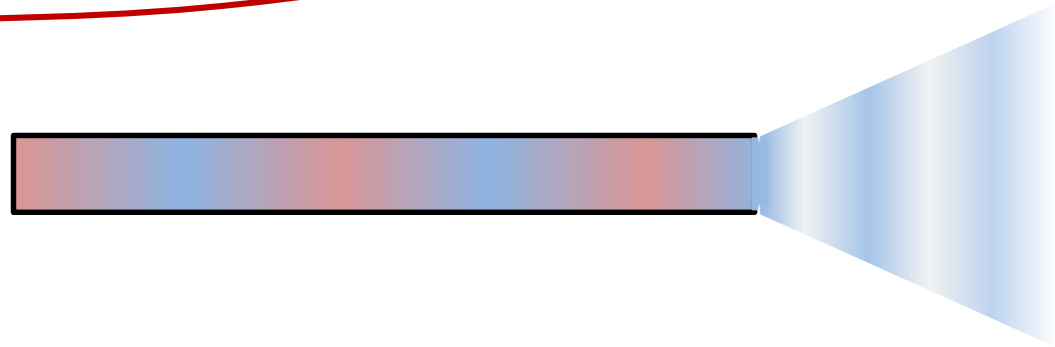
1. Excitation HARD
   - How to get the pipe resonating



2. Frequency Control MEDIUM
   - Playing desired notes



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



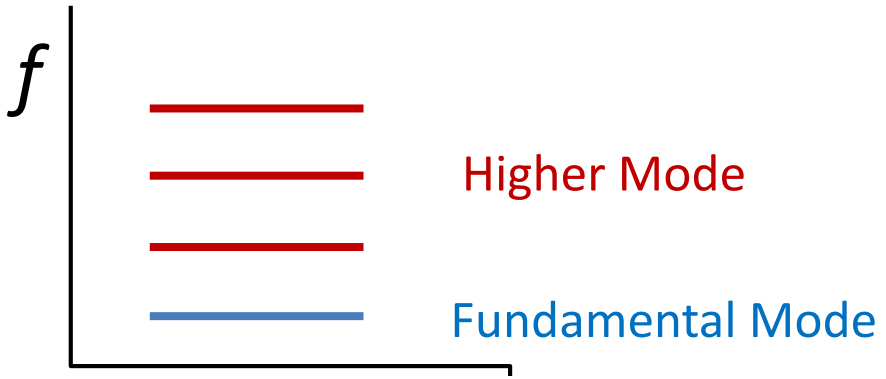
Pipes

Frequency Control

- Two Basic Strategies

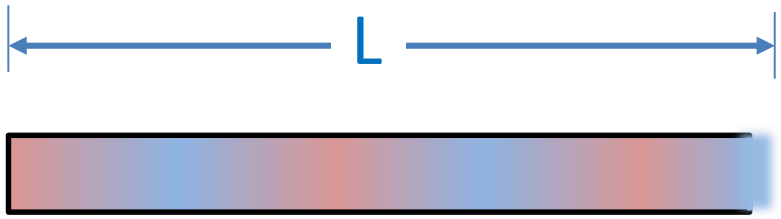
1. Employ Different
   Resonant Modes (Partials)

Course Control



2. Vary the effective pipe length L

Fine Control



Pipes

Frequency Control by Mode Selection (Register)

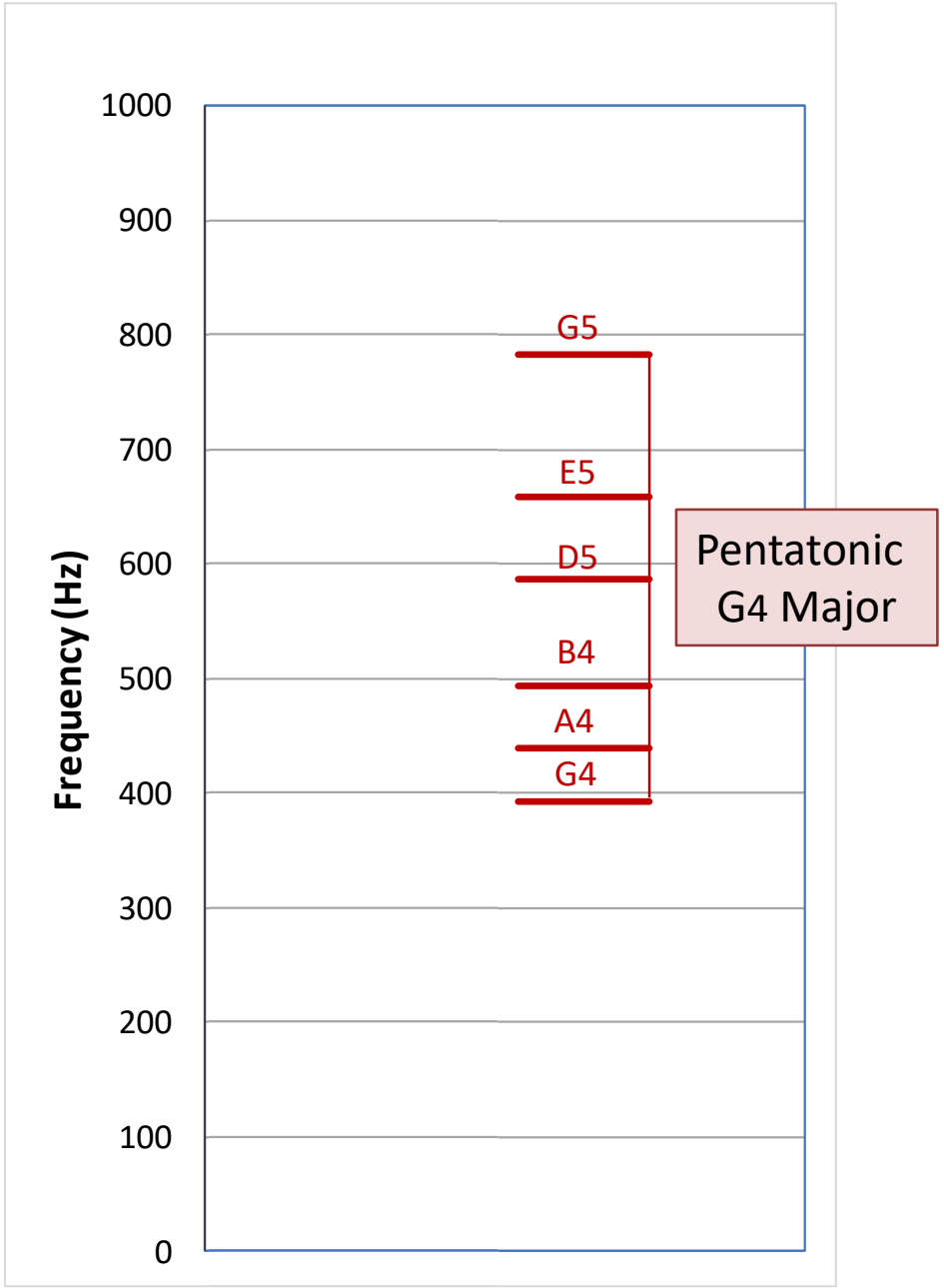
"Natural Horns" have no Valves

Length is Fixed

Baroque Horn
ca 18th Century

Conical

Let's say we want to play a tune that uses the Pentatonic G4 Major scale



Pipes

Frequency Control by Mode Selection (Register)

"Natural Horns" have no Valves

Length is Fixed

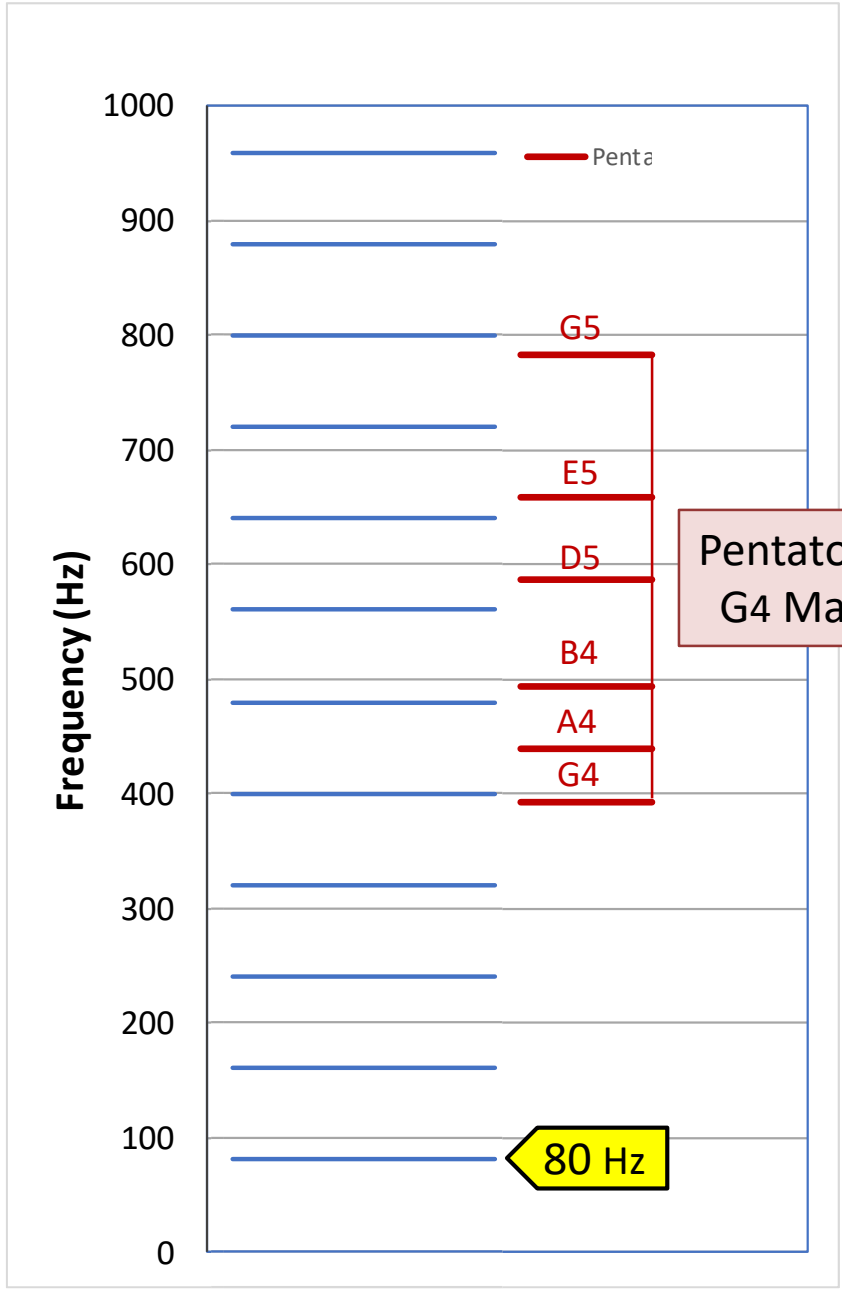
Try L ≈ 40 inches

$f_1 \approx$ **80** Hz

Baroque Horn
ca 18th Century

Conical

So we try a natural horn 40 inches long, giving a fundamental frequency of ~80 Hz



Pipes

Frequency Control by Mode Selection (Register)

"Natural Horns" have no Valves

Length is Fixed

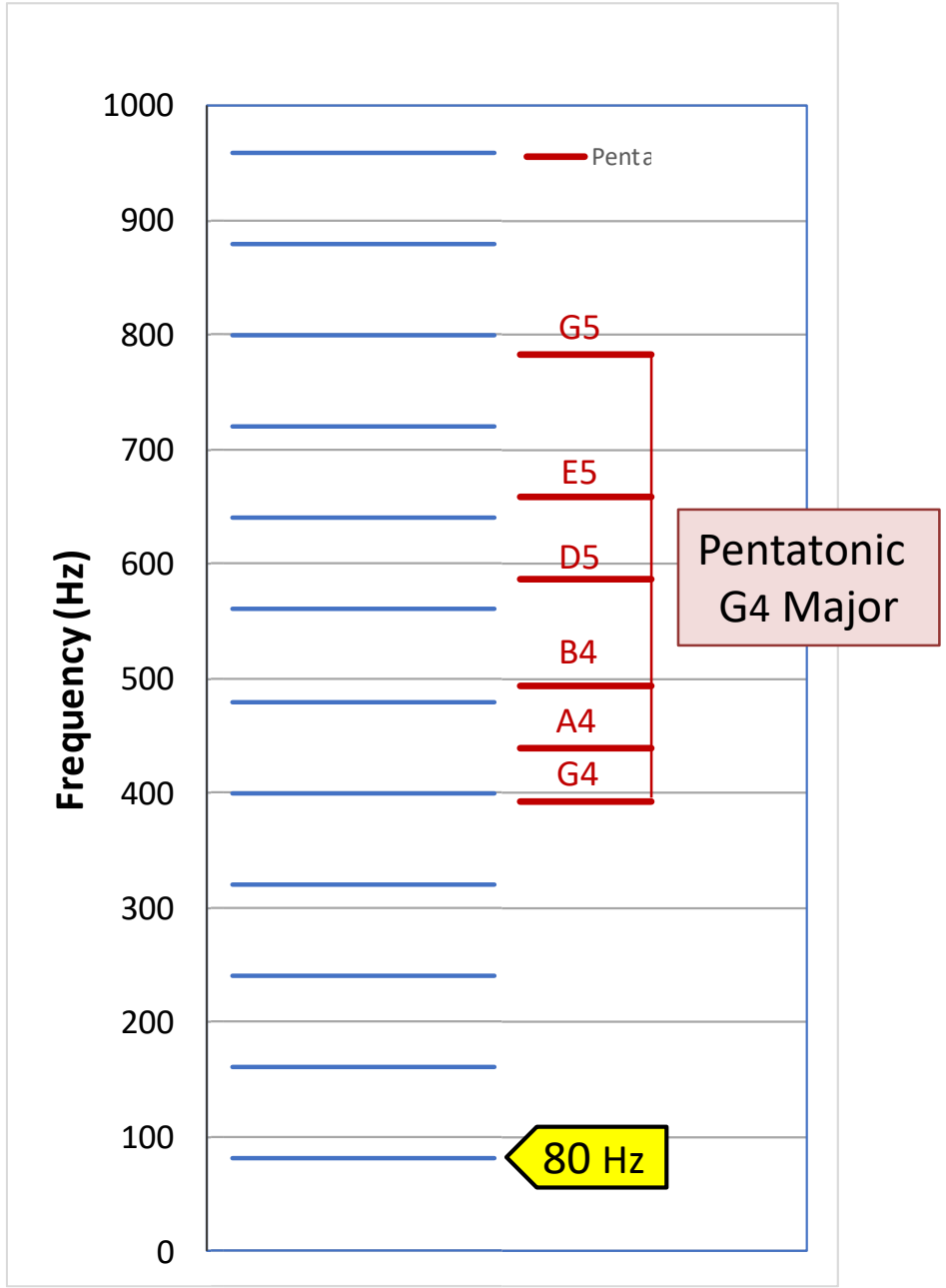
Try L ≈ 40 inches

$f_1 \approx$ **80** Hz

Baroque Horn
ca 18th Century

Conical

But none of its modes match up with the G4 Major notes we need, so it fails – we can't hit these notes.



Pipes

Frequency Control by Mode Selection (Register)

"Natural Horns" have no Valves

Length is Fixed

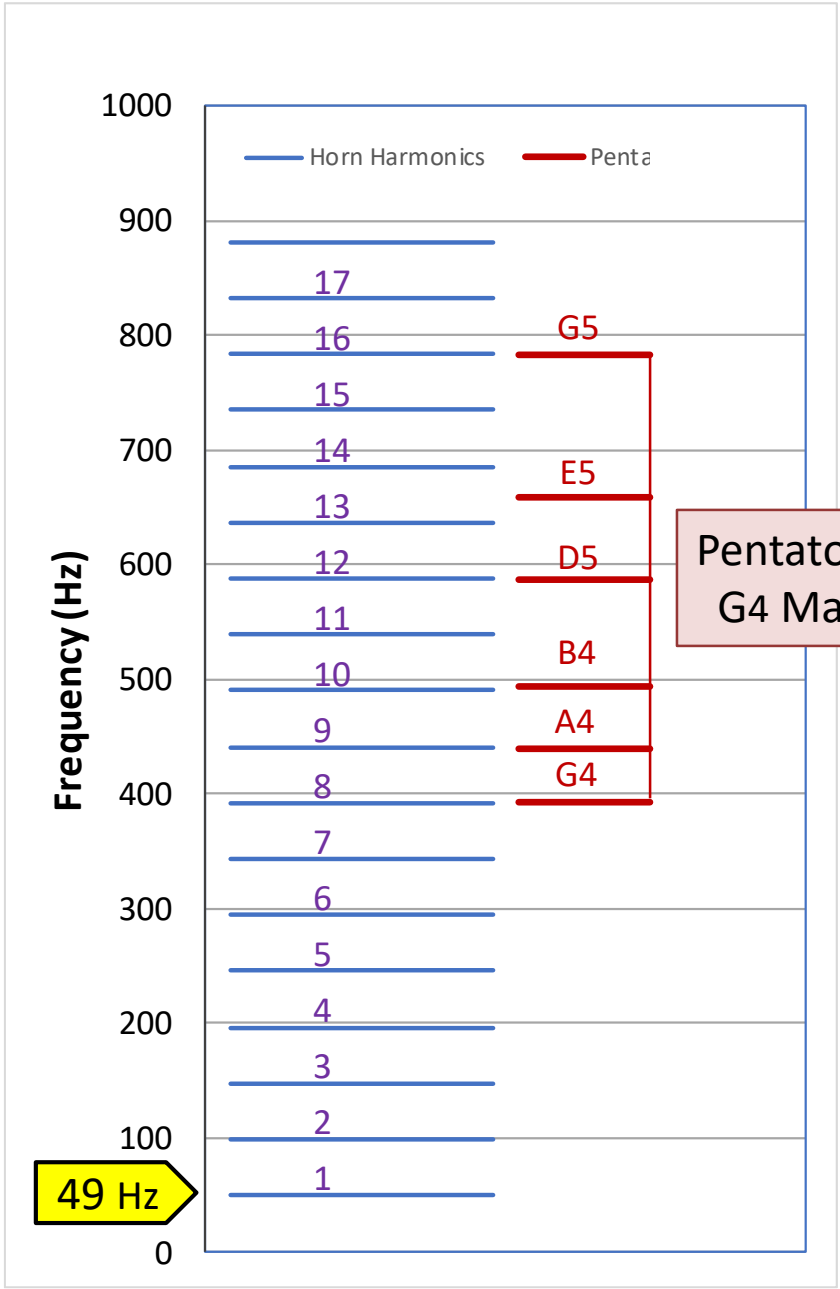
Baroque Horn
ca 18th Century

Conical

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

Try L ≈ 65 inches
$f_1 \approx 49$ Hz

So we try other lengths. With L=65 inches we are in luck. 5 of the harmonics line up with desired notes, more or less



Pipes

Frequency Control by Mode Selection (Register)

"Natural Horns" have no Valves

Length is Fixed

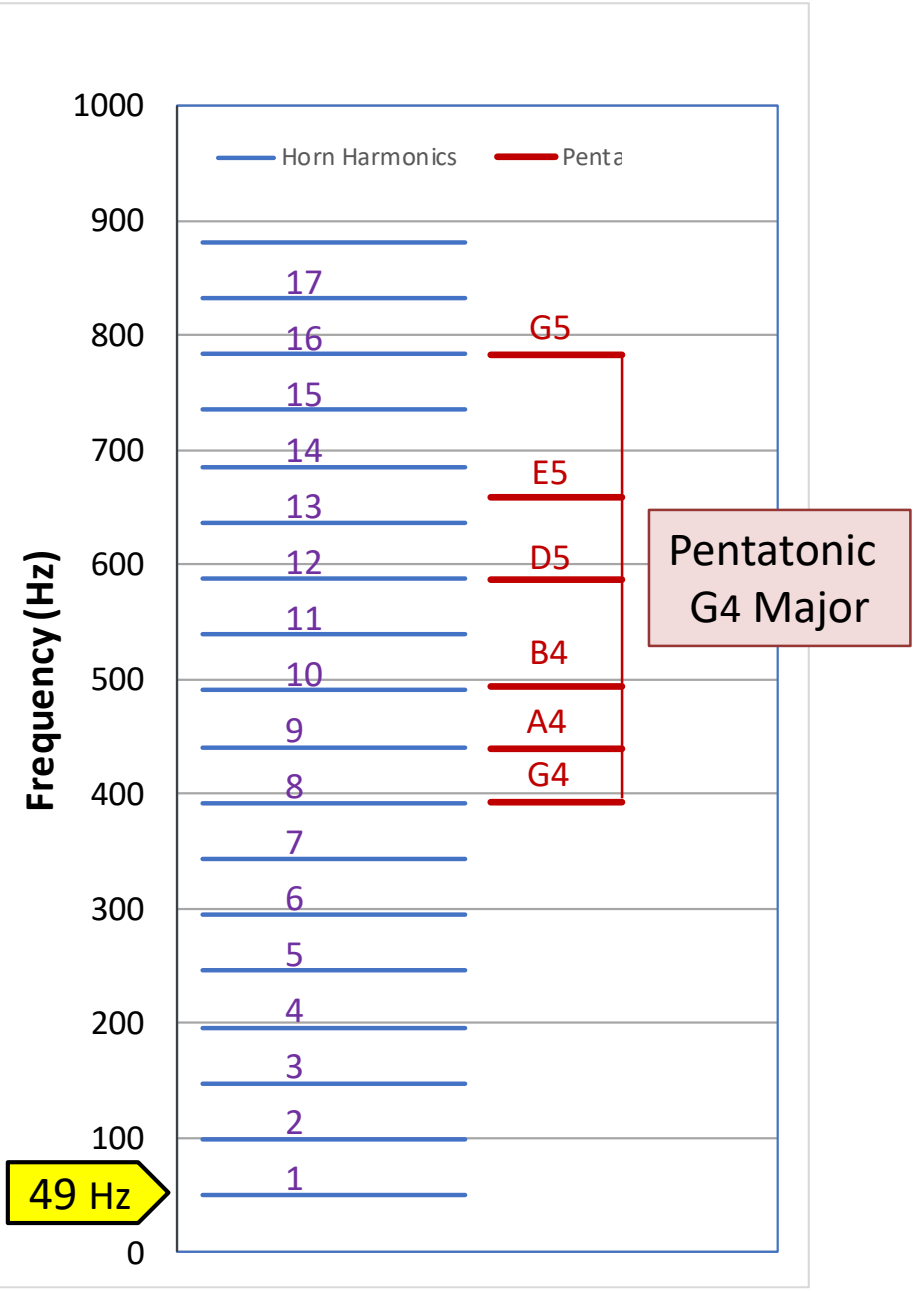
Baroque Horn
ca 18th Century

Conical

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

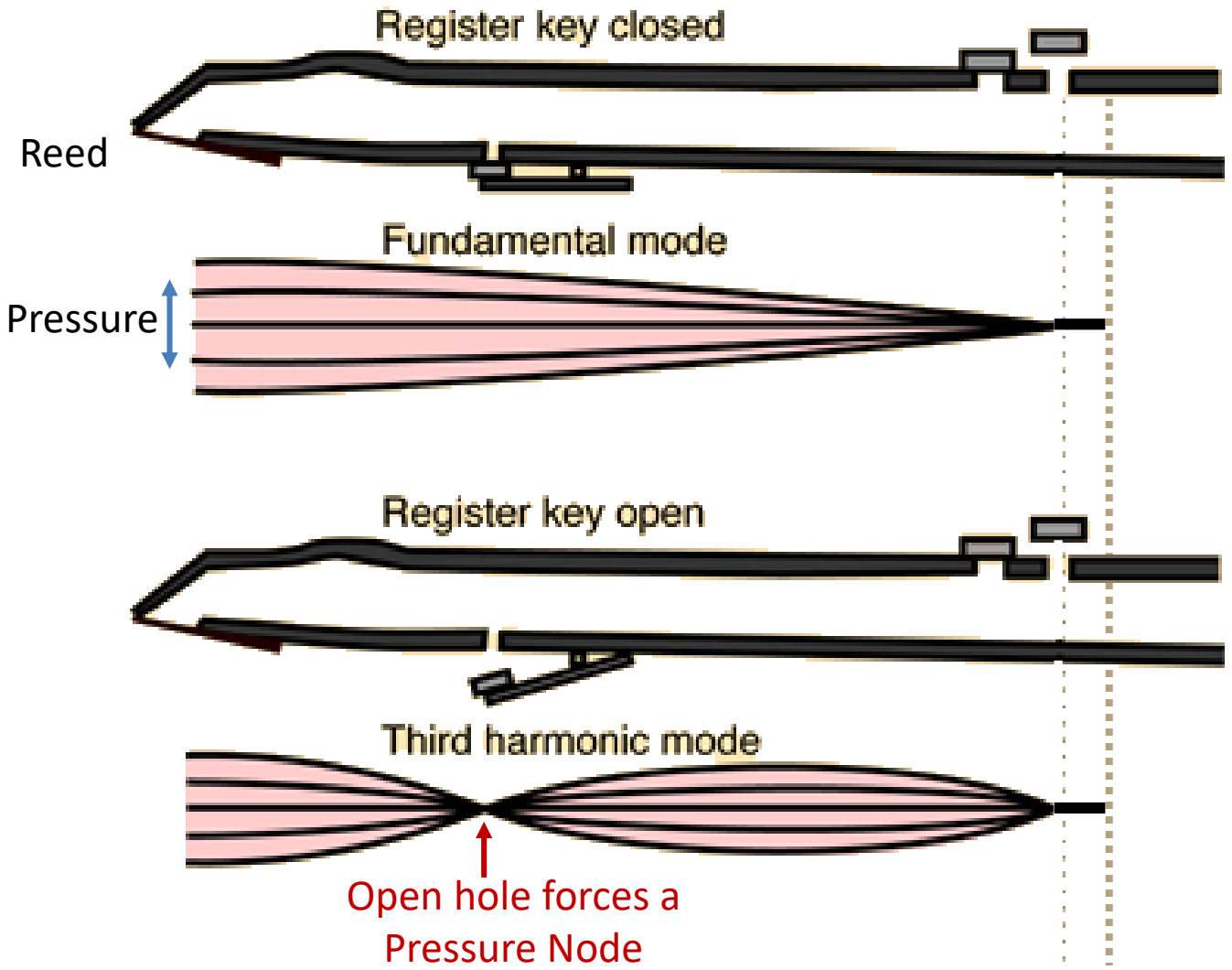
Try L ≈ 65 inches
$f_1 \approx 49$ Hz

Bugle plays a recognizable tune using this technique.



Pipes

Changing Register in a Clarinet



Opening the Register Key hole kills the fundamental mode

Low Note

3x Higher Note

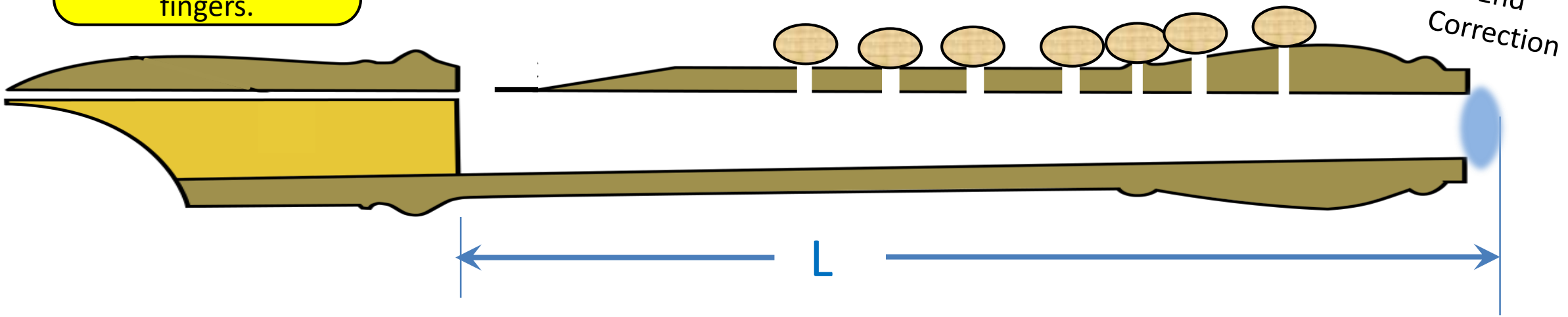
Hyperphysics
Georgia State U

Pipes

Reducing Length by Opening Holes

Recorder

Greatest length, lowest note when all holes covered by fingers.

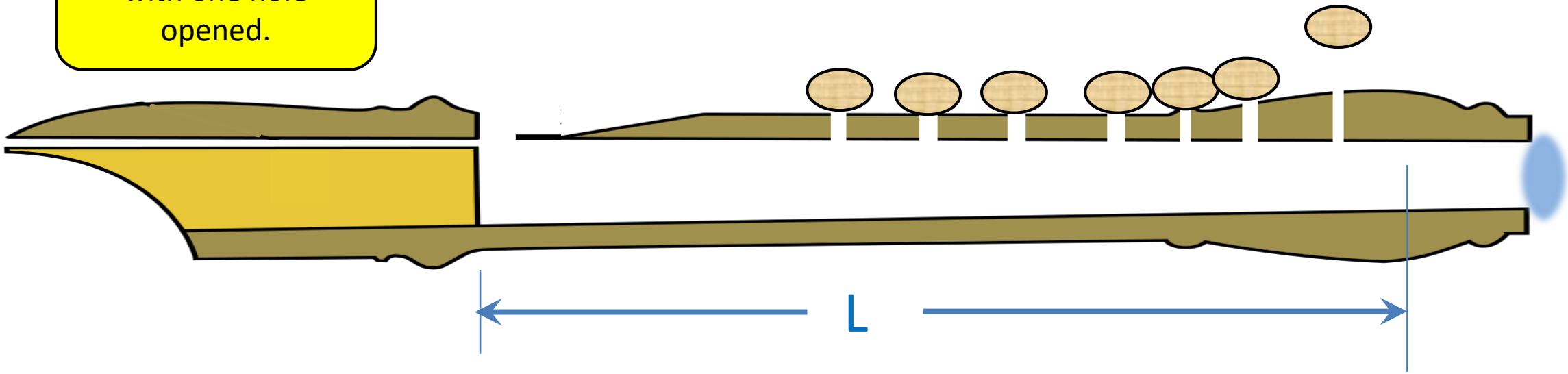


Pipes

Reducing Length by Opening Holes

Recorder

Next higher note with one hole opened.

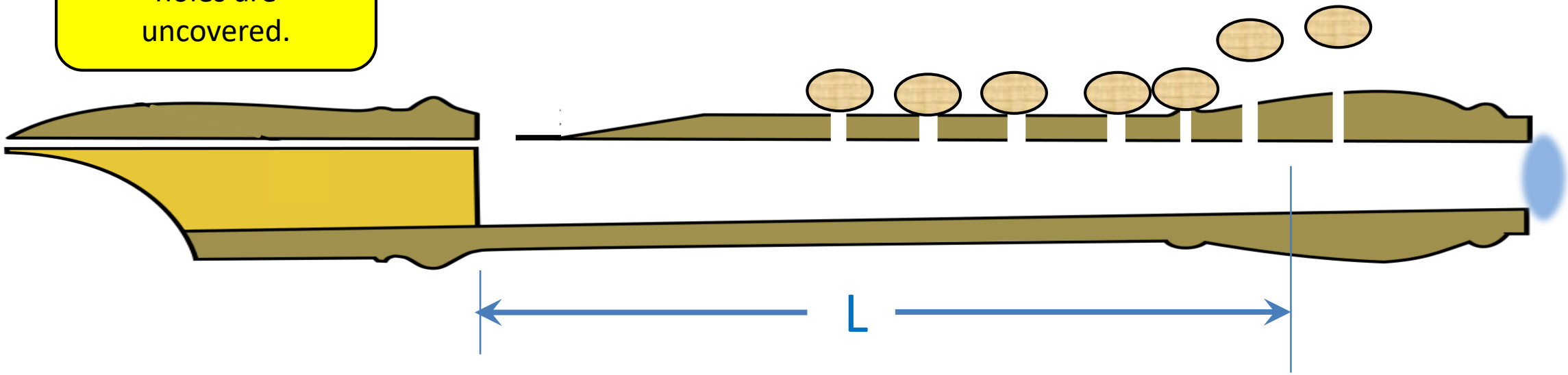


Pipes

Reducing Length by Opening Holes

Recorder

And so on as more holes are uncovered.

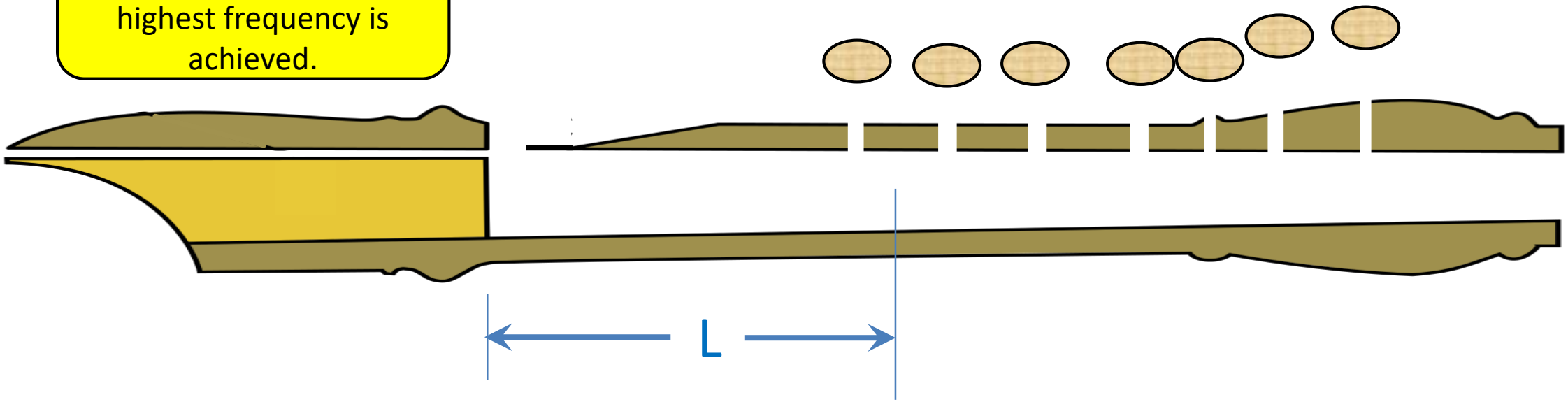


Pipes

Reducing Length by Opening Holes

Recorder

With all holes open, the shortest Length and highest frequency is achieved.



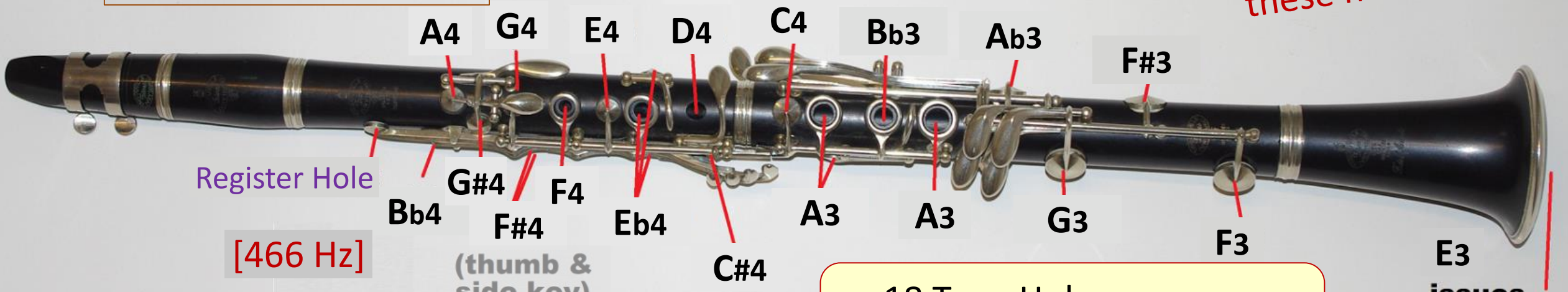
Pipes

Reducing Length by Opening Holes

B flat Clarinet

Note Assignments are for the Low (Fundamental) Register

Sound comes out mostly through these holes!



- 18 Tone Holes
- 19 Notes in Low Register

Opening a hole as marked (plus most of the holes to the right) shortens the Clarinet so as to emit that note, mostly through that hole.

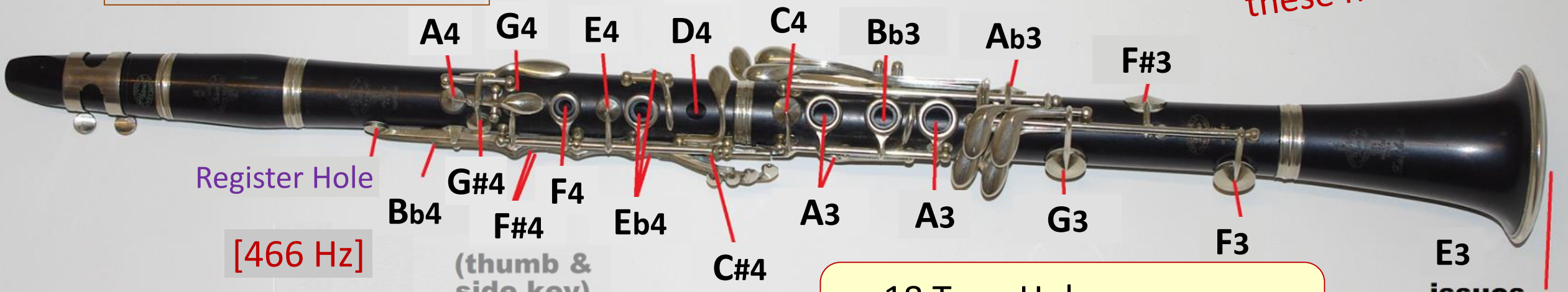
Pipes

Reducing Length by Opening Holes

B flat Clarinet

Note Assignments are for the Low (Fundamental) Register

Sound comes out mostly through these holes!



- 18 Tone Holes
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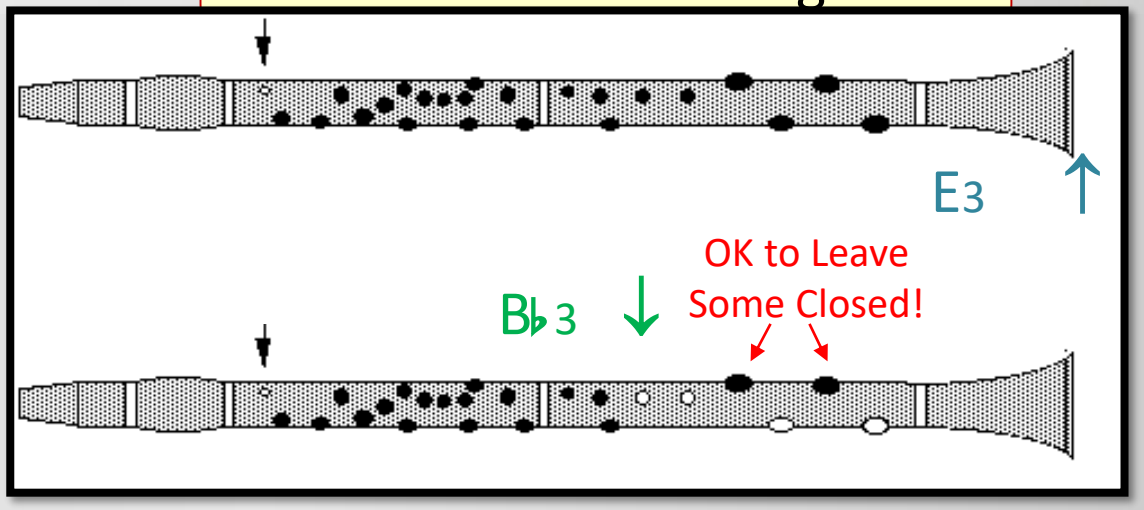


But not all the orphan holes to the right of the note-determining hole need to be open to work OK.
Black dots=closed, white circles=open

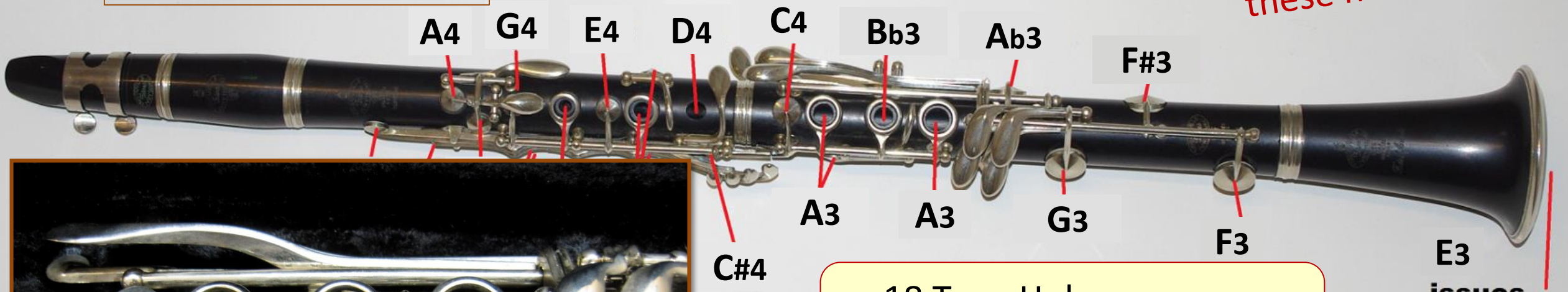
Pipes

Reducing Length by Opening Holes

B flat Clarinet

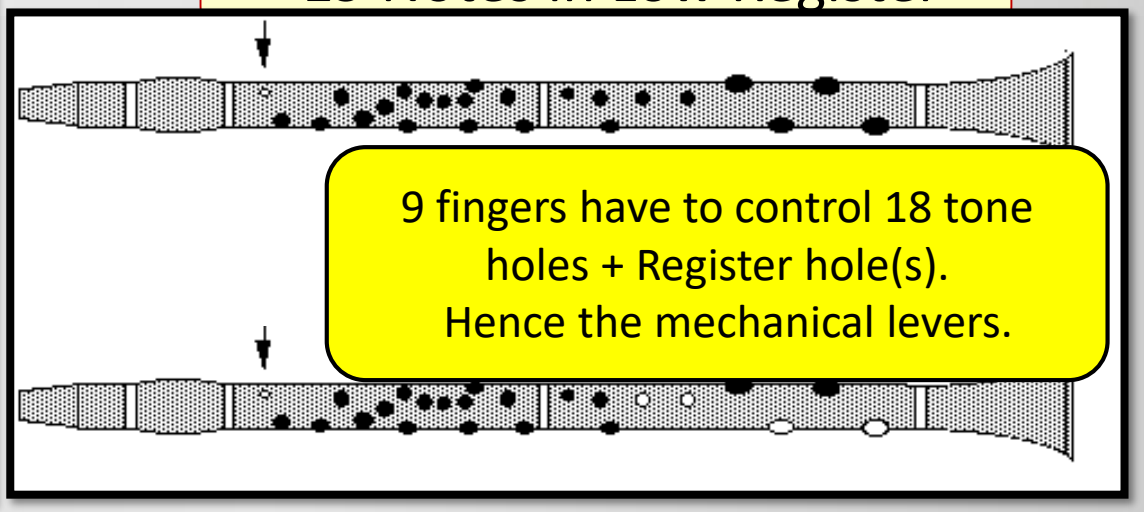
Note Assignments are for the Low (Fundamental) Register

Sound comes out mostly through these holes!



- 18 Tone Holes
- 19 Notes in Low Register

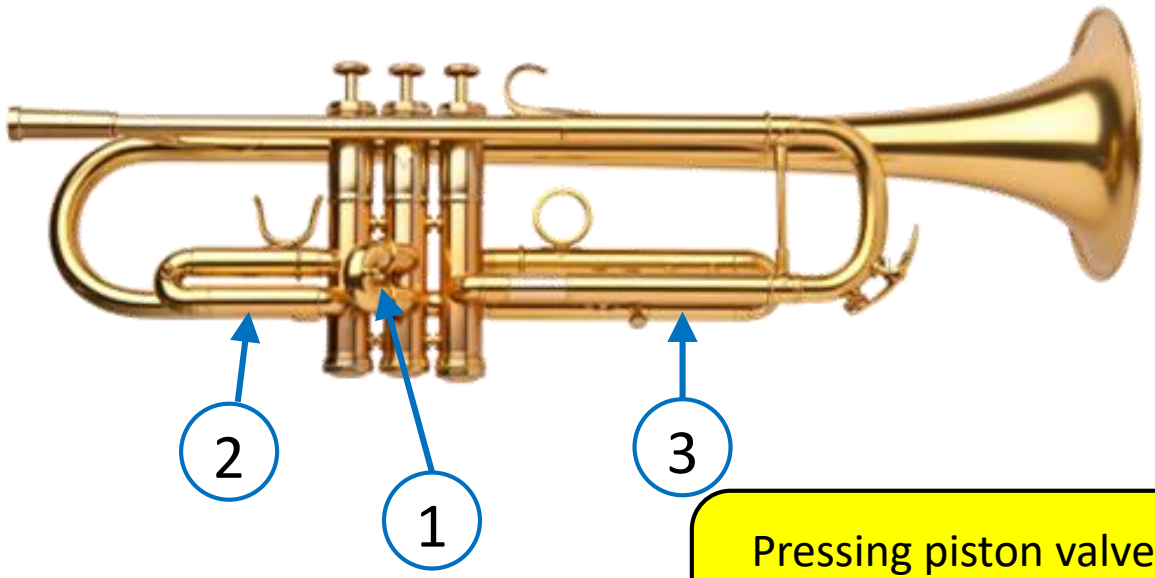
[165 Hz]

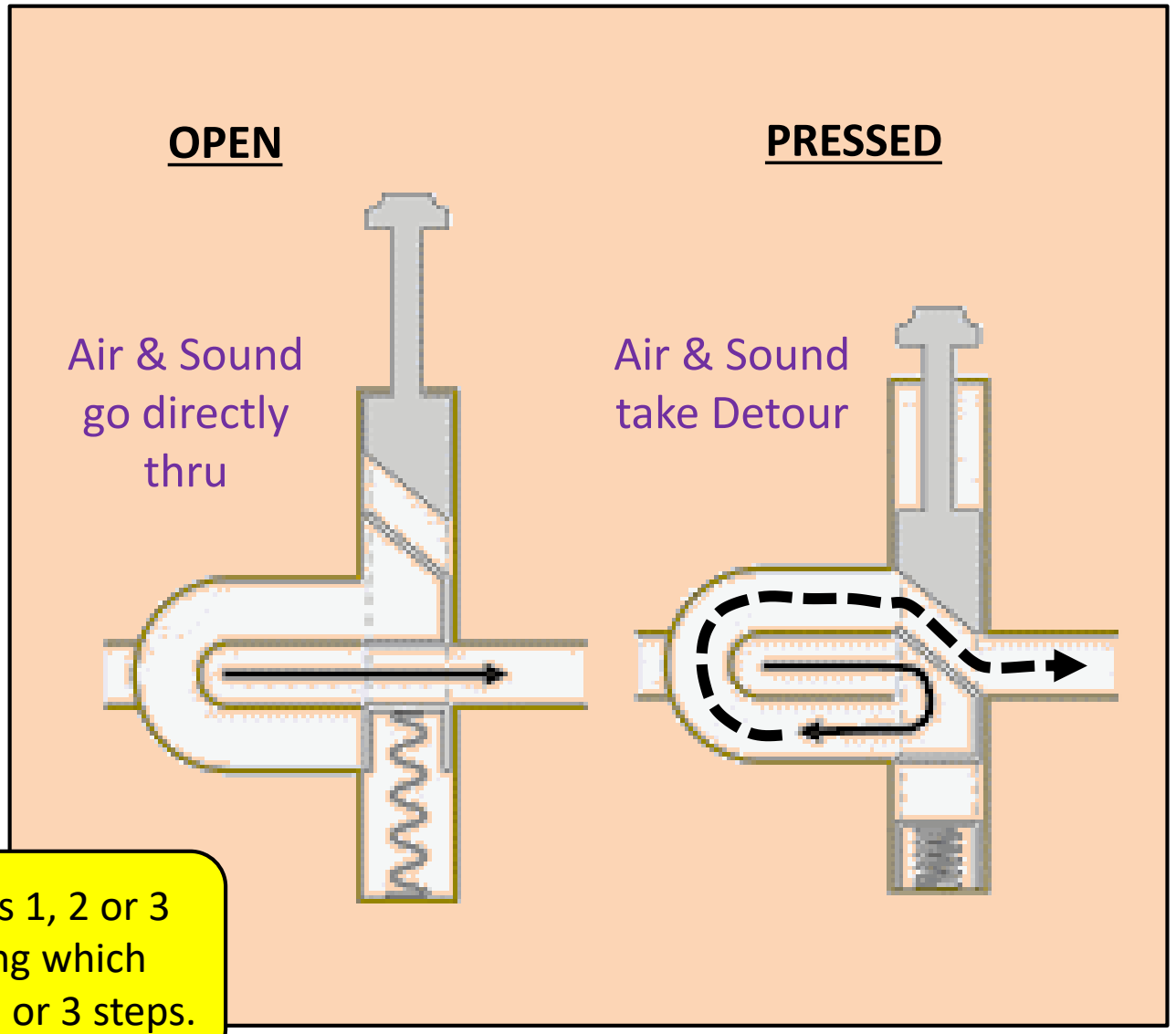


Pipes

Frequency Control by Valves (Length Change)

B♭ Trumpet has 3 Valves



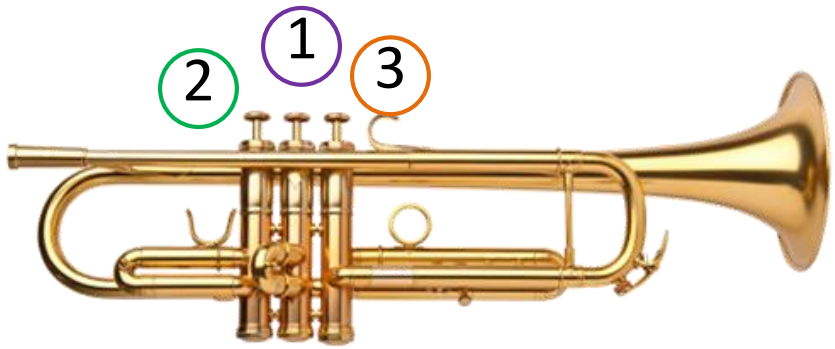


Pressing piston valves 1, 2 or 3 add lengths of tubing which lower the pitch by 1, 2 or 3 steps.

Pipes

Frequency Control by Valves (Length Change)

B♭ Trumpet has 3 Valves



With Valves not Pressed, various overtones modes are available, allowing us to play C4, G4, C5, E5, G5, Bb5, C6, but no notes in between.
The fundamental cannot be played due to the small tubing diameter.

85	1108.7	C#/D♭ 6	8
84	1046.5	C 6	
83	987.8	B 5	7
82	932.3	A#/B♭ 5	
81	880	A 5	
80	830.6	G#/A♭ 5	6
79	784.0	G 5	
78	740.0	F#/G♭ 5	
77	698.5	F 5	5
76	659.3	E 5	
75	622.3	D#/E♭ 5	
74	587.3	D 5	
73	554.4	C#/D♭ 5	4
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
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
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

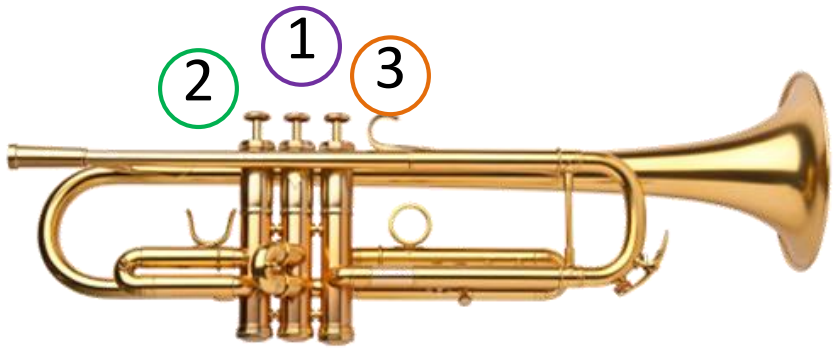
Chromatic Scale

B♭ 5

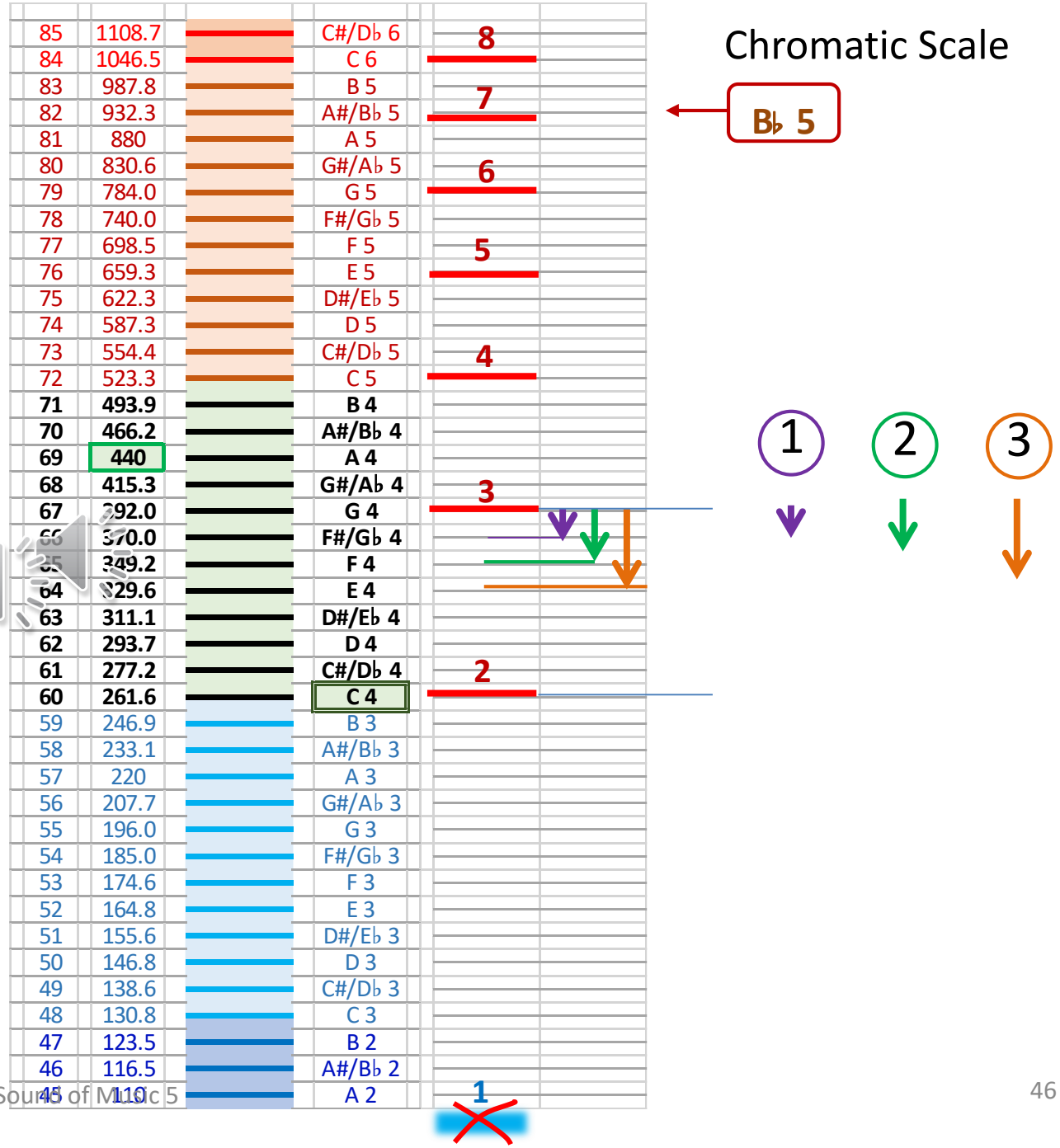
Pipes

Frequency Control by Valves (Length Change)

B♭ Trumpet has 3 Valves



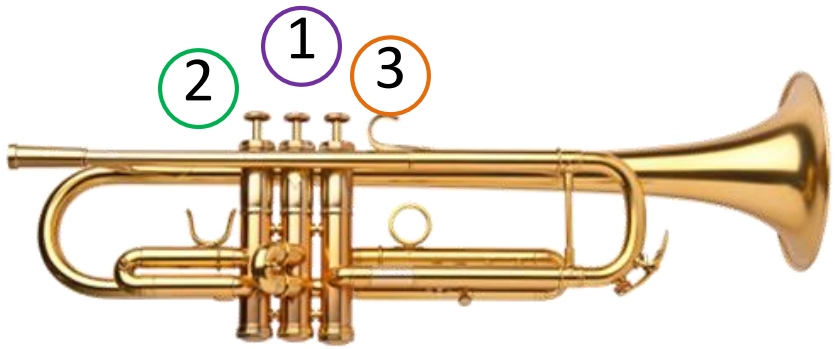
By pressing valves 1, 2 or 3 and blowing at the right frequencies, we can access Gb4, F4 and E4 in the 3rd harmonic register.



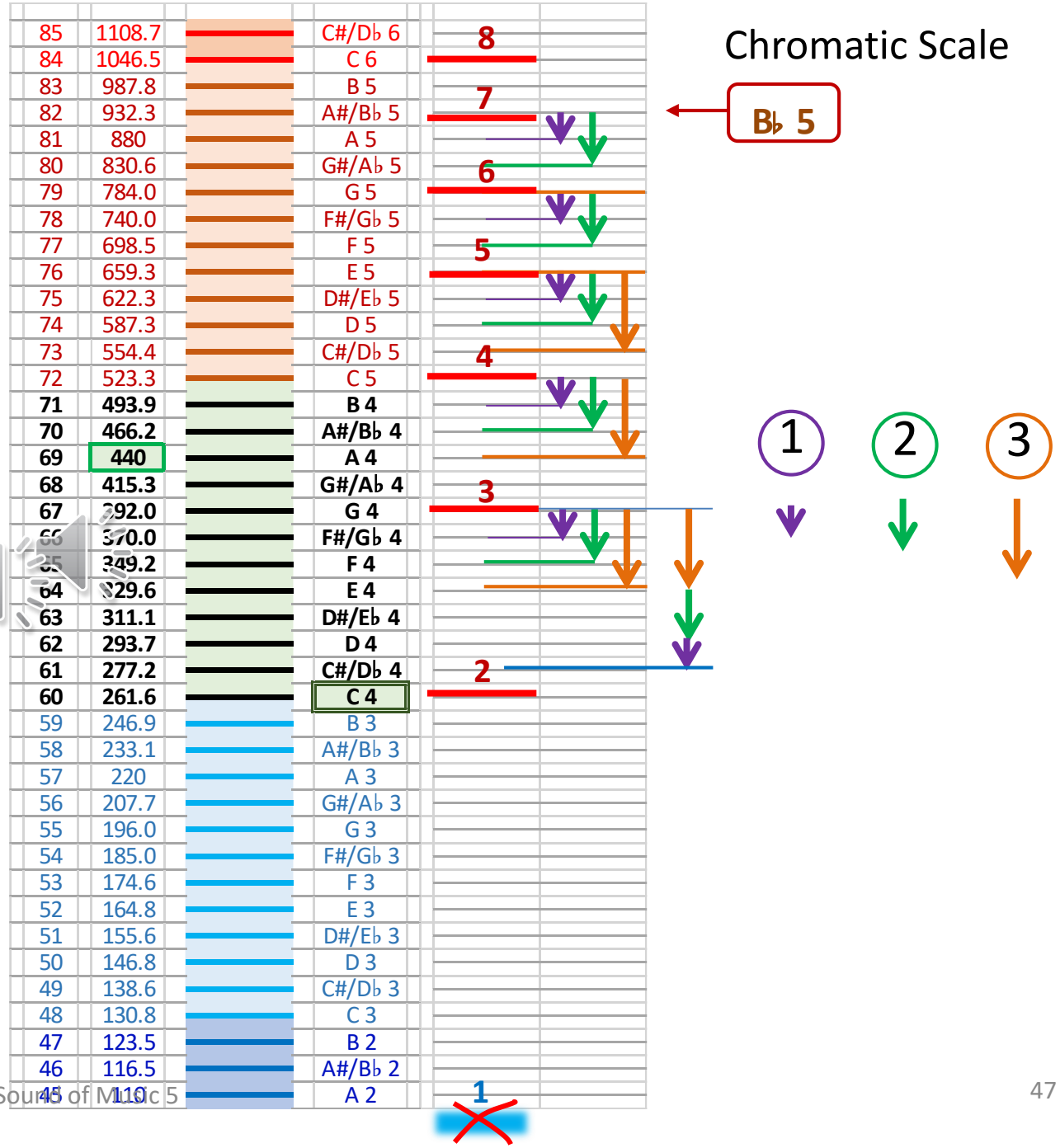
Pipes

Frequency Control by Valves (Length Change)

B♭ Trumpet has 3 Valves



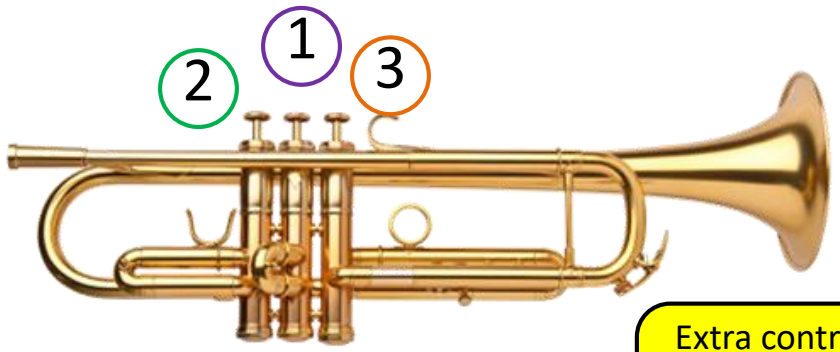
By pressing combinations of valves 1, 2 or 3 and blowing at the right frequencies, we can access Eb4, D4 and dB4 in 3rd[d] harmonic register.
Likewise we can fill in all the missing notes in the higher registers up to at least Bb5



Pipes

Frequency Control by Valves (Length Change)

B♭ Trumpet has 3 Valves



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
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66	370.0	F#/G♭ 4
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64	329.6	E 4
63	311.1	D#/E♭ 4
62	293.7	D 4
		C#/D♭ 4
		C 4
		B 3
		A#/B♭ 3
		A 3
		G#/A♭ 3
55	196.0	G 3
54	185.0	F#/G♭ 3
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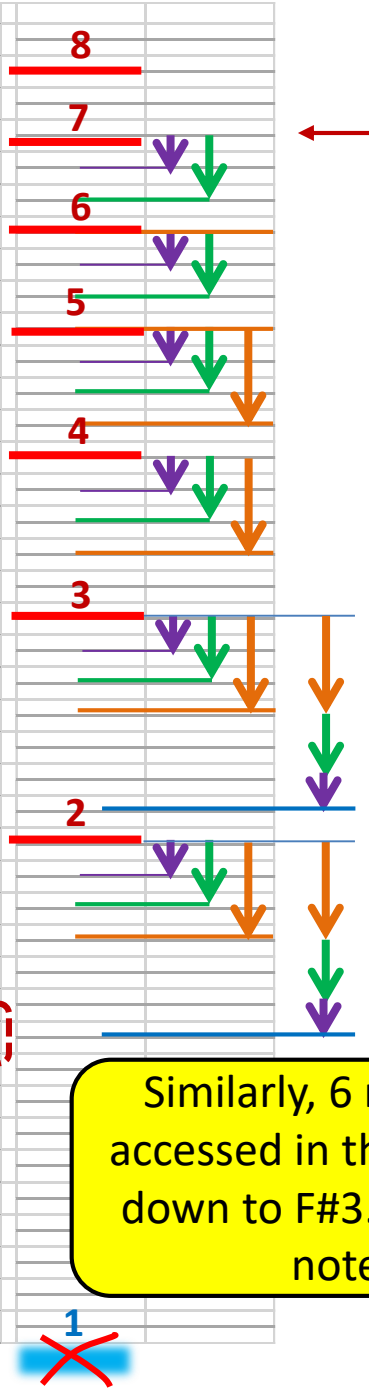
49	138.6	C#/D♭ 3
48	130.8	C 3
47	123.5	B 2
46	116.5	A#/B♭ 2
45	110	A 2



Chromatic Scale

B♭ 5

Extra controls tweak the effective pipe length to adjust for the fact that mathematically valve loop lengths do not quite add up to give correct note frequencies.

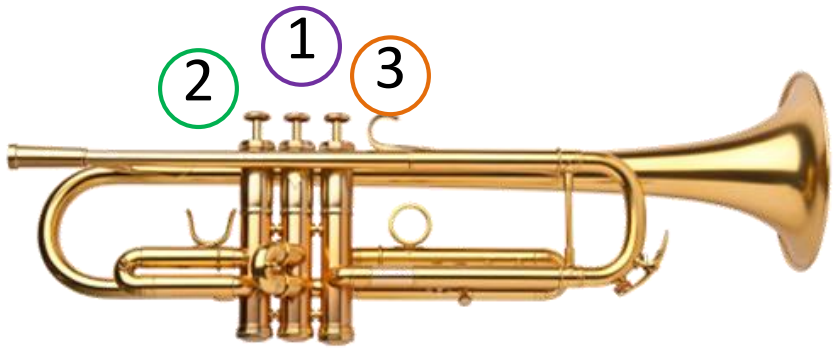
Lowest possible true note:
F#3 (185 Hz)

Similarly, 6 notes below C4 can be accessed in the 2nd harmonic register, down to F#3. Below this, only pedal notes can be used.

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
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52	164.8		E 3
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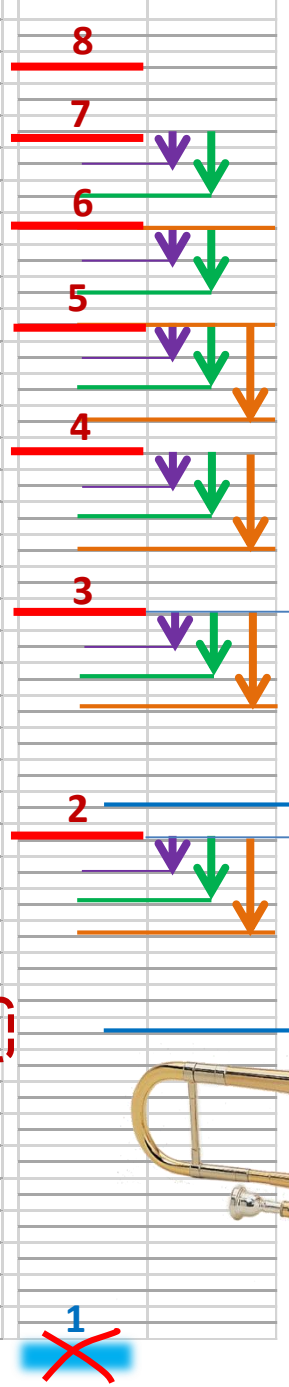
50	146.8		D 3
49	138.6		C#/D♭ 3
48	130.8		C 3
47	123.5		B 2
46	116.5		A#/B♭ 2
45	110		A 2



Chromatic Scale

B♭ 5

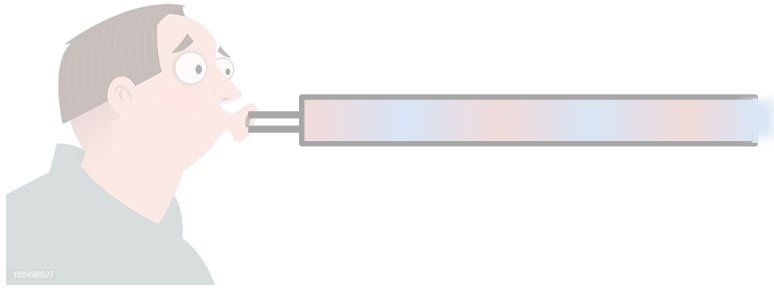
Trombone Needs ½ Octave Slide Range to fill in notes between 2nd and 3rd overtone registers.

Pipes

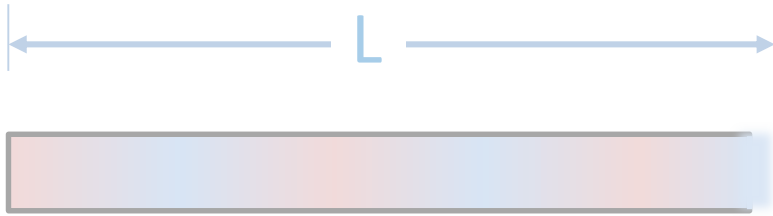
Aerophone Instruments

Three main problems:

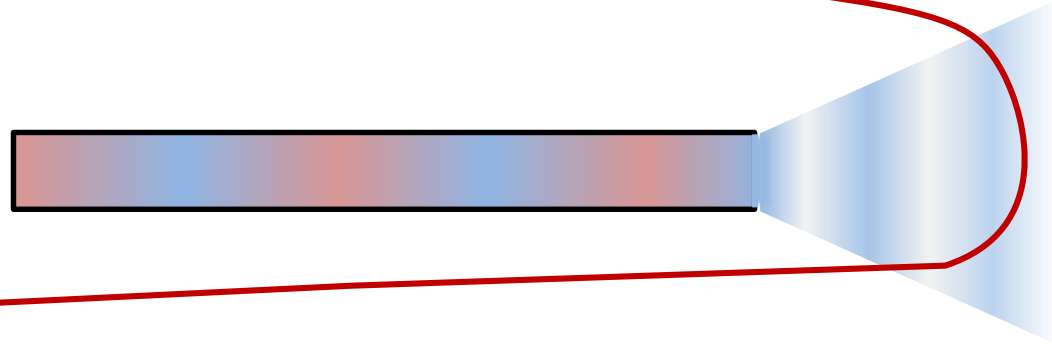
1. Excitation HARD
   - How to get the pipe resonating



2. Frequency Control MEDIUM
   - Playing desired notes



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



Pipes

Getting the Sound Out

French Horn

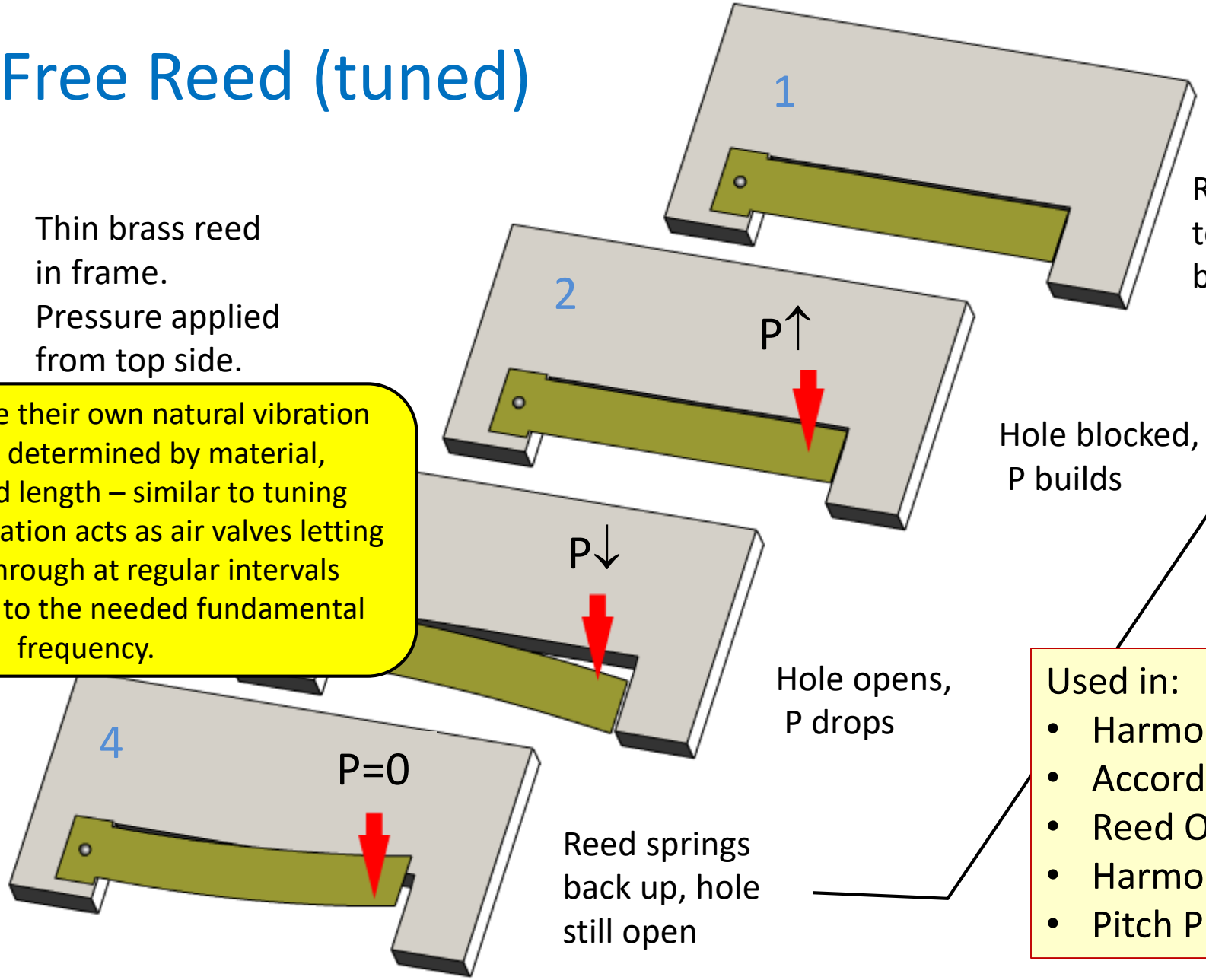
Brasses are somewhat Directional

Oboe

Woodwinds tend to be Omni- Directional

Free Reeds

Free Reed (tuned)



Thin brass reed in frame. Pressure applied from top side.

Free reeds have their own natural vibration frequencies determined by material, thickness, and length – similar to tuning forks. Their vibration acts as air valves letting puffs of air through at regular intervals corresponding to the needed fundamental frequency.

Reed returns to center, blocking hole

Hole blocked, P builds

Hole opens, P drops

Reed springs back up, hole still open

Used in:

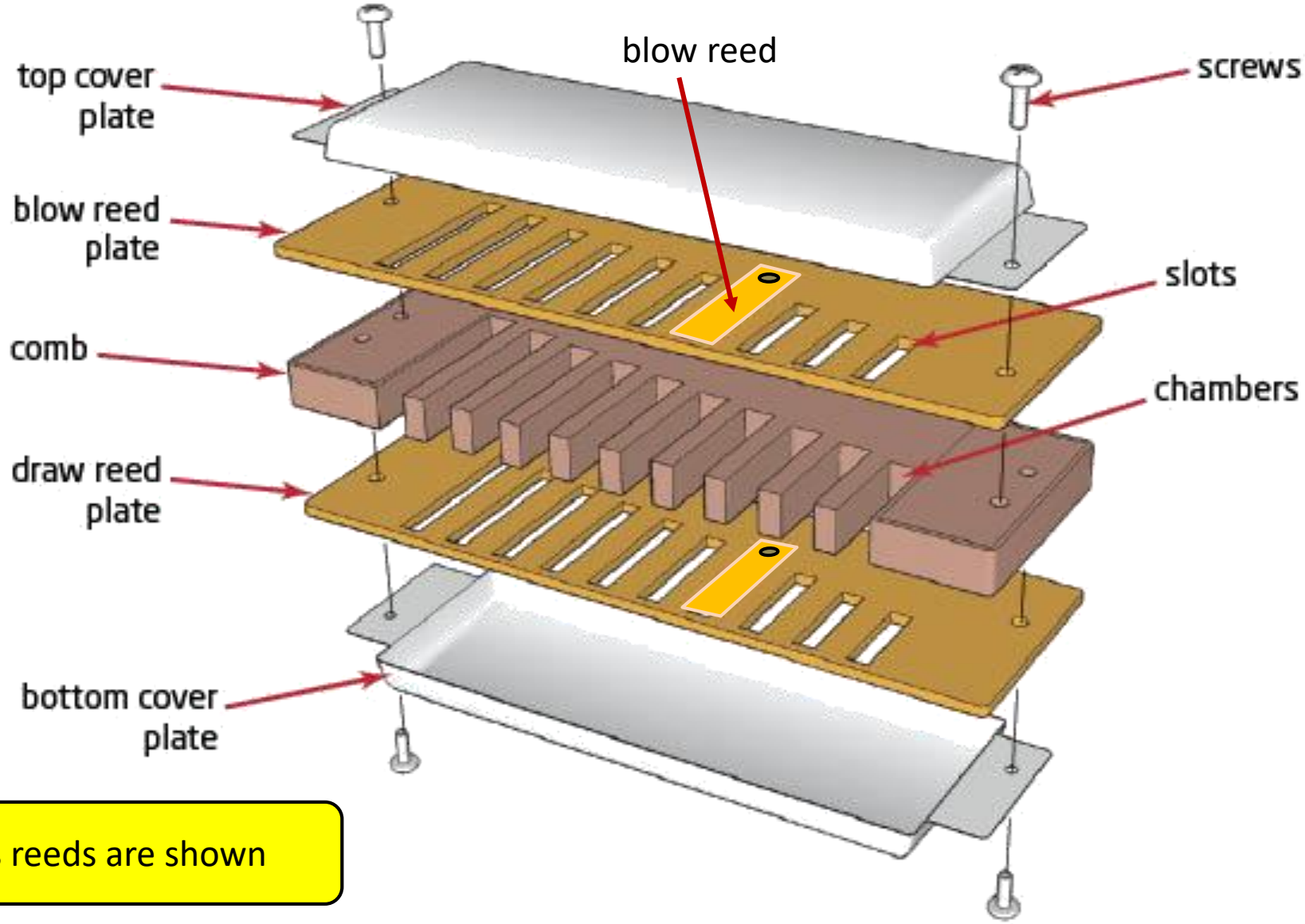
- Harmonicas
- Accordions
- Reed Organs
- Harmoniums
- Pitch Pipes

Free Reeds

Accordion

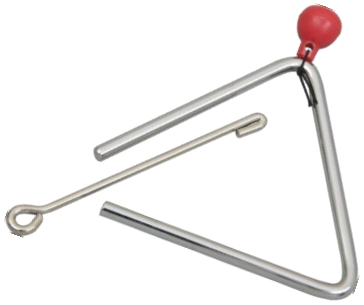
Free Reeds

Harmonica



Only 2 of 20 brass reeds are shown

Idiophones



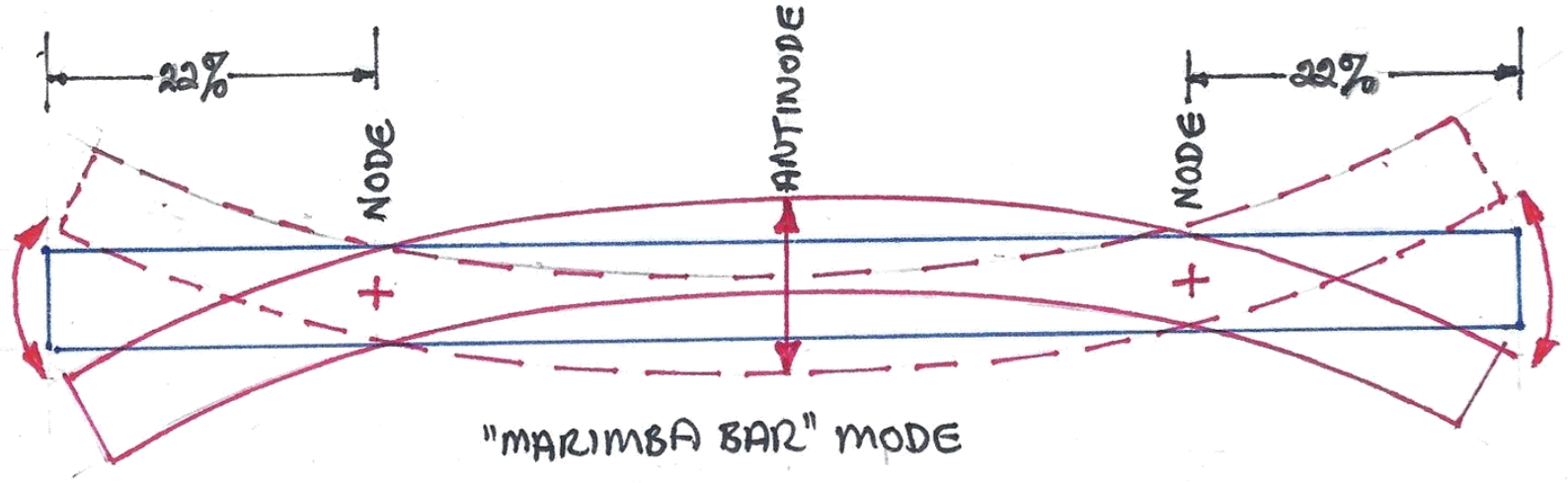
idiophone

ˈidēəˌfōn/

A musical instrument the whole of which vibrates to produce a sound when struck, shaken, or scraped, such as a bell, gong, xylophone.

Idiophones

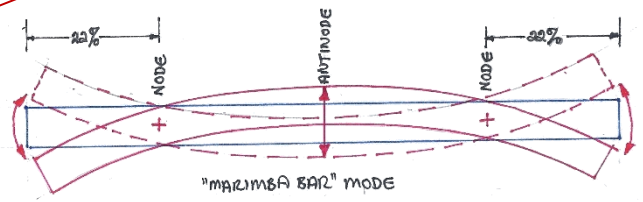
Vibrating Bars

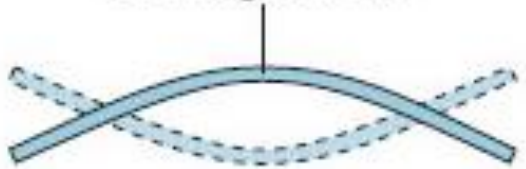


Simple case: Rectangular bar in Fundamental Transverse mode.

Idiophones

Vibrating Bars

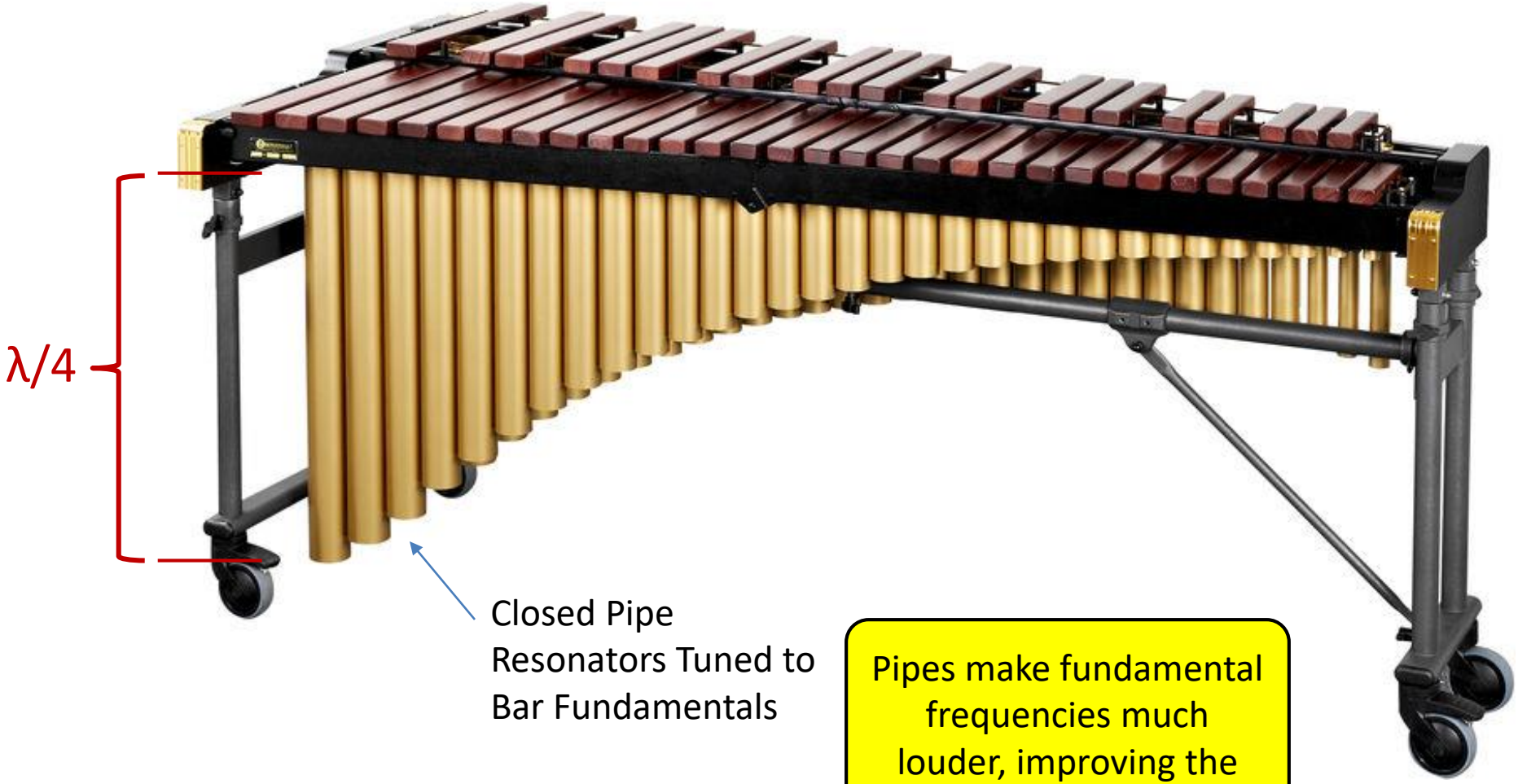


rectangular bar	mode	frequency
(a) 	first	f_1
(b) 	second	$2.76\,f_1$
(c) 	third	$5.40\,f_1$
(d) 	fourth	$8.93\,f_1$

The higher transverse vibration modes of the uniform bar are NOT harmonics of the fundamental.

Idiophones

Marimba

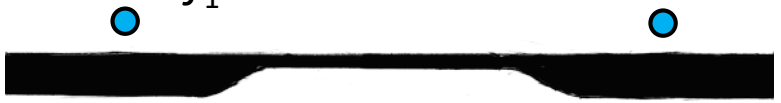


Pipes make fundamental frequencies much louder, improving the Timbre.

Idiophones

Marimba: Shaping the Bars

Fundamental f_1



2nd Mode $f_2 = \mathbf{4}\, f_1$

3nd Mode $f_3 = \mathbf{10}\, f_1$

Originally (late 1800's in meso-America), bars were rectangular. Later, esp. in professional instruments, bars were modified on the bottom to tune higher modes to integer multiples of f1. Namely, usually 4th and 10th harmonics.

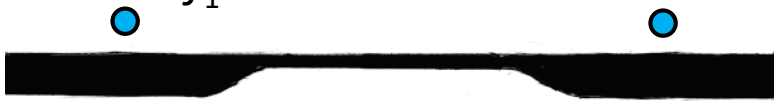
Torsional Modes f_T

Torsional (twist) modes are also used, and can be tuned to the 2nd harmonic of the fundamental.

Idiophones

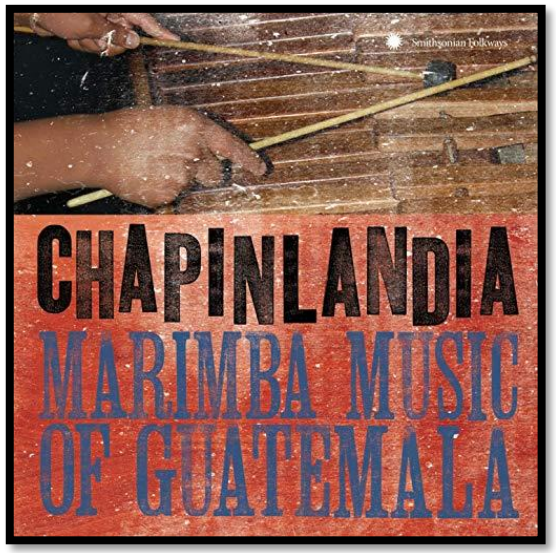
Marimba: Shaping the Bars

Fundamental f_1



2nd Mode $f_2 = \mathbf{4}\, f_1$

3nd Mode $f_3 = \mathbf{10}\, f_1$



Smithsonian Folkways Recordings

Cobán (2007)
Recorded in
Guatemala City

Torsional Modes f_T

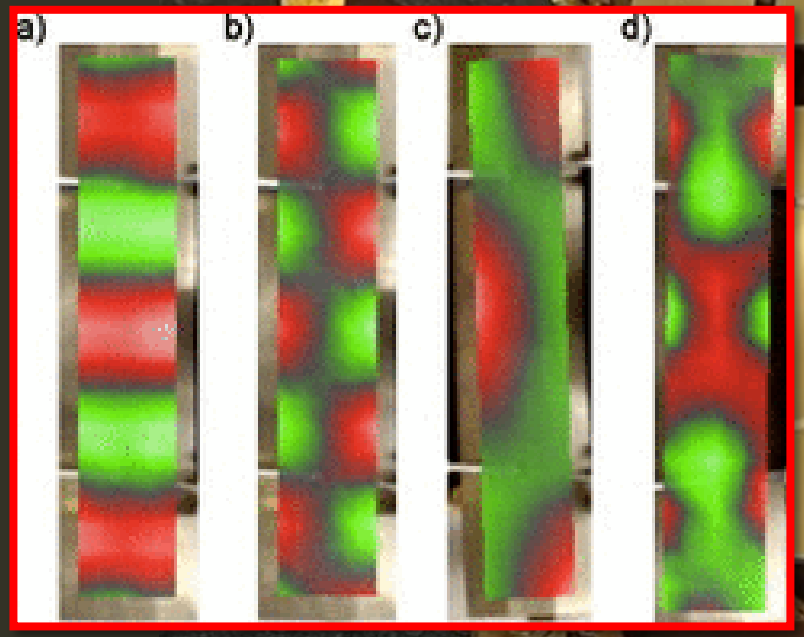
Balinese Gamelan Music

Gangsa
Metallophones

Bronze bars have trapezoidal cross-section, and are curved longitudinally. There is no attempt to control overtone frequencies, the pattern of which varies from bar to bar and instrument to instrument.

Balinese Gamelan Music

Gangsa Metallophones



Molly Jones et al, JASA 2010

Some examples of mode patterns of vibration measured on some bars similar to these, using laser velocimetry. Black lines are nodes, colored anti-nodes. *(a)* a high order transverse mode, *(b)* a torsional mode, *(c)* and *(d)* some weird unexplained modes.