THE PRODUCTION AND NONLINEAR PROPAGATION OF SOUND IN MUSICAL INSTRUMENTS

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Outline

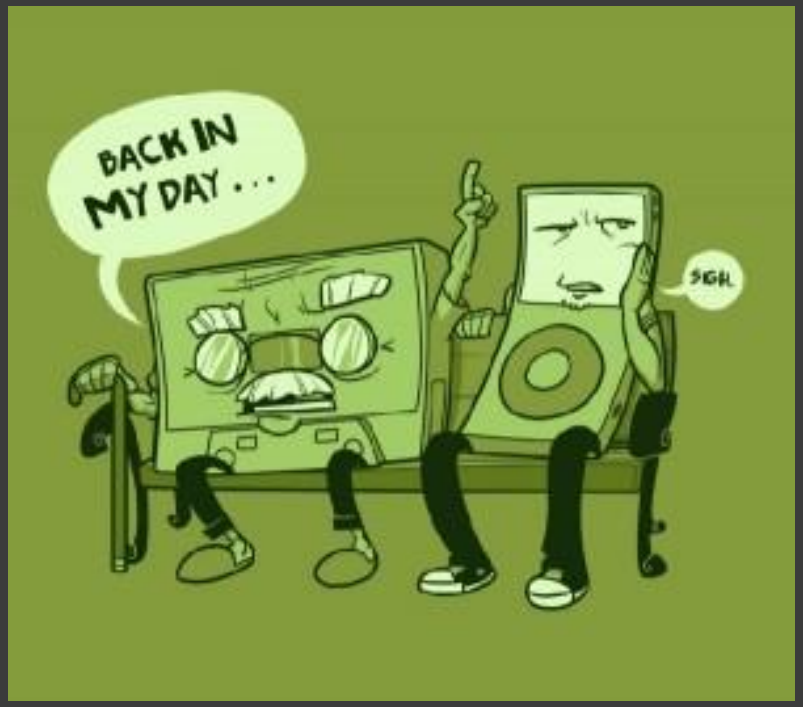
- What is music?
- What is sound?
- How is sound produced in musical instruments?
- Different types of wave propagation in musical instruments
- Experiments and simulations of the trumpet

What is Music?

Plato thought that harmony was considered a fundamental branch of physics, now known as musical acoustics.

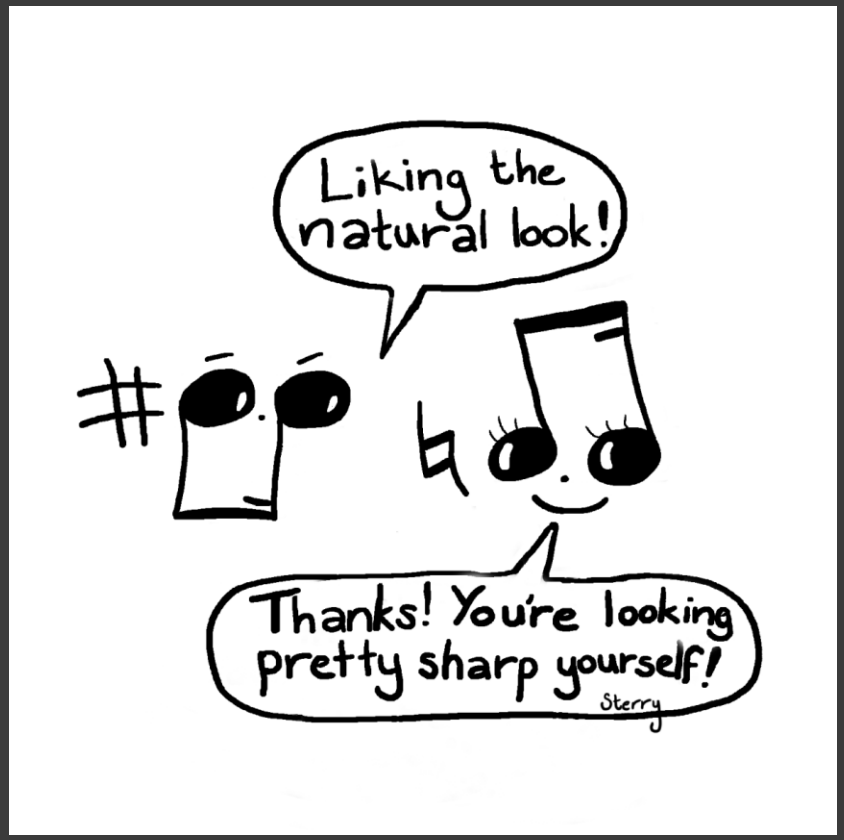
Traditional definitions:

Vocal or instrumental sounds (or both) combined in such a way as to produce beauty of form, harmony, and expression of emotion.



Is the art of producing pleasing, expressive combinations of tones.

It is all subjective...

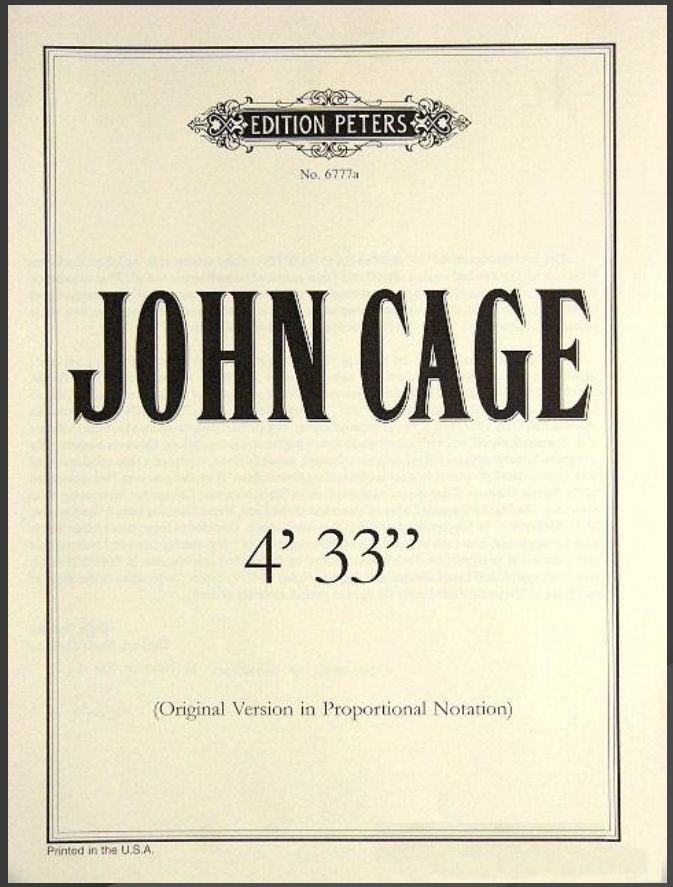


- What is beauty of form, harmony, and expression of emotion?
- *No sounds can be described as inherently unmusical, musicians in each culture have tended to restrict the range of sounds they will admit.*

#pleasantTone?

More modern definitions:

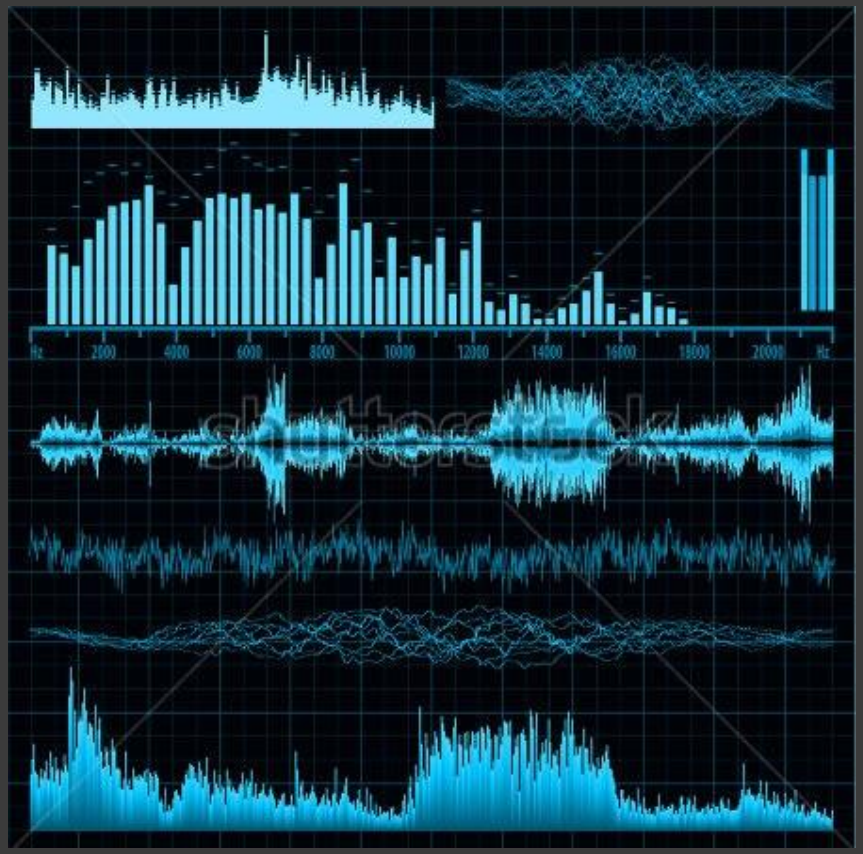
- organized sound
- noise is any undesired sound



Music...

What is sound?

is an art whose medium is sound.



Psychological characteristics of sound...

- Pitch
- Loudness
- Time
- Timbre

  - Vibrato
  - Beats
  - Consonance and dissonance
  - Rhythm

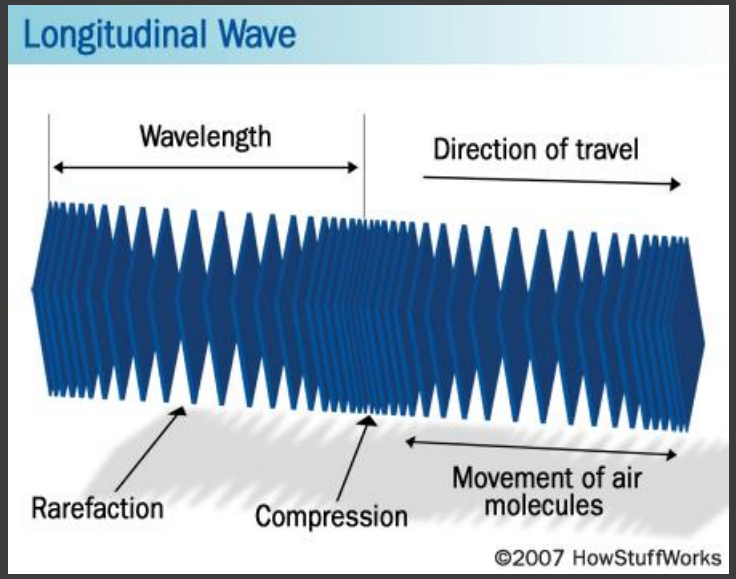
Physical properties of sound waves...

- Frequency
- Intensity
- Waveform
- Duration

Introduction to Sound

- Sound is vibrations in a medium
- In air when an object/system vibrates, there are waves of varying air pressure
- Longitudinal waves are produced
- Sound is represented by sinusoidal waves at multiple frequencies

Sound is a sequence of waves of varying air pressure that propagate through a medium.



Music => Sound => Math

Acoustics is the scientific study of sound

So sound is a complex phenomenon involving physics and perception and is created by vibrations in some sort of medium?

Sound propagation is influenced by…

- The interaction between density and pressure which is influenced by the temperature of the fluid
- The motion of the medium itself
- The viscosity of the medium

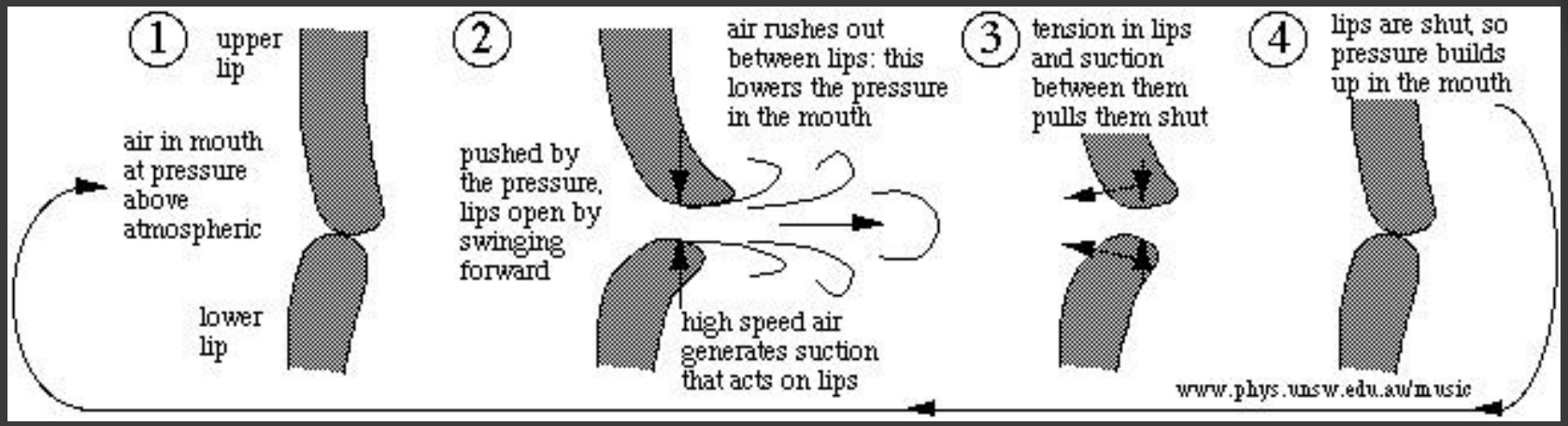
Woodwind vs. Brass Instruments

Clarinet mouthpiece

Trumpet and trombone mouthpiece

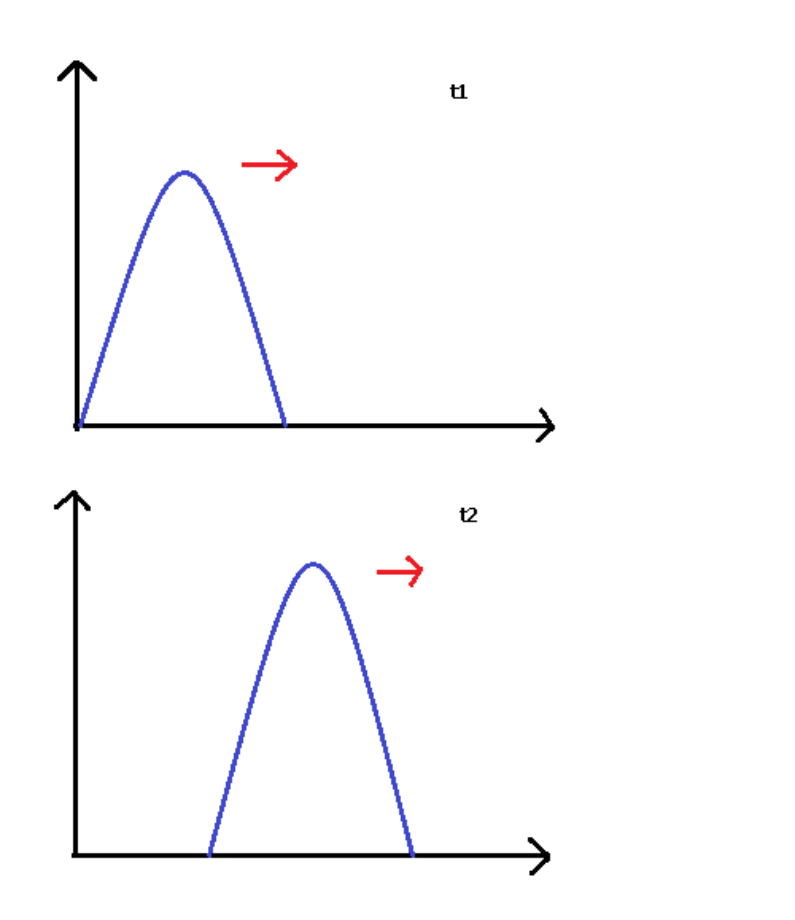
Sound in Brass Instruments

- Constant pressure input goes to the mouthpiece
- The lips coupled with the tube serve as a mechanical oscillator which creates fluctuating pressure output
- The fluctuating air pressure excites the air column inside the instrument and forces it to oscillate
- The pressure wave is reflected from the bell creating a standing wave
- These standing waves leak from the bell and this is when we hear sound

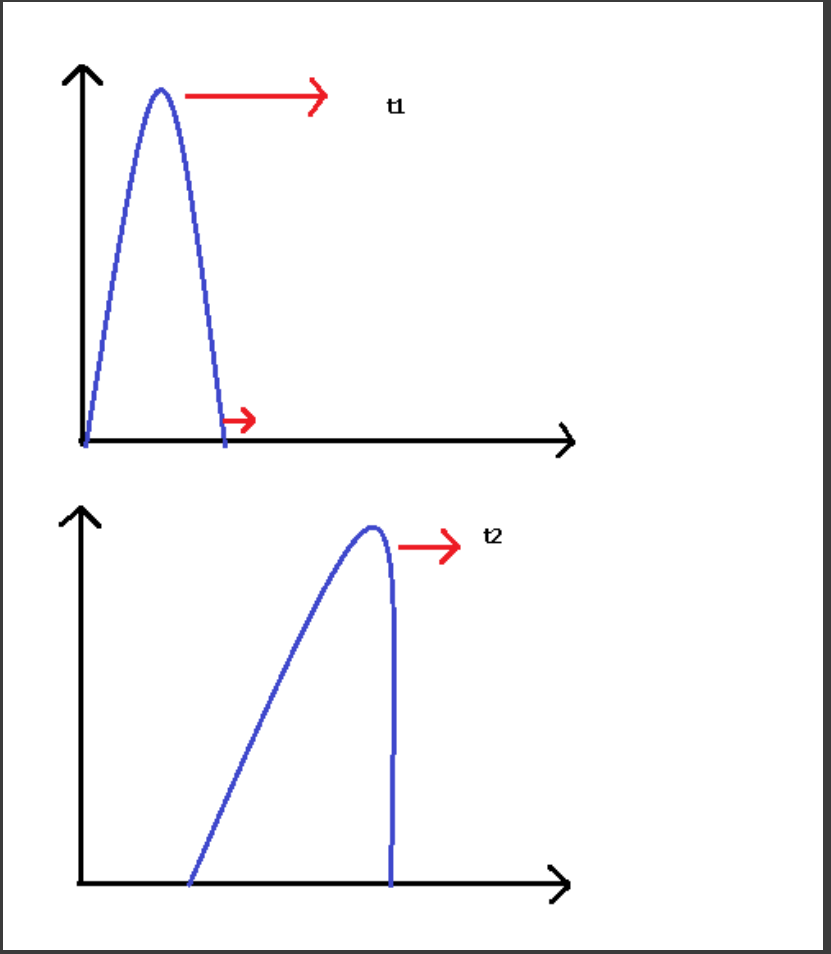

1
upper lip
air in mouth at pressure above atmospheric
lower lip
2
air rushes out between lips: this lowers the pressure in the mouth
pushed by the pressure, lips open by swinging forward
high speed air generates suction that acts on lips
3
tension in lips and suction between them pulls them shut
4
lips are shut, so pressure builds up in the mouth
www.phys.unsw.edu.au/music

Types of Wave Propagation

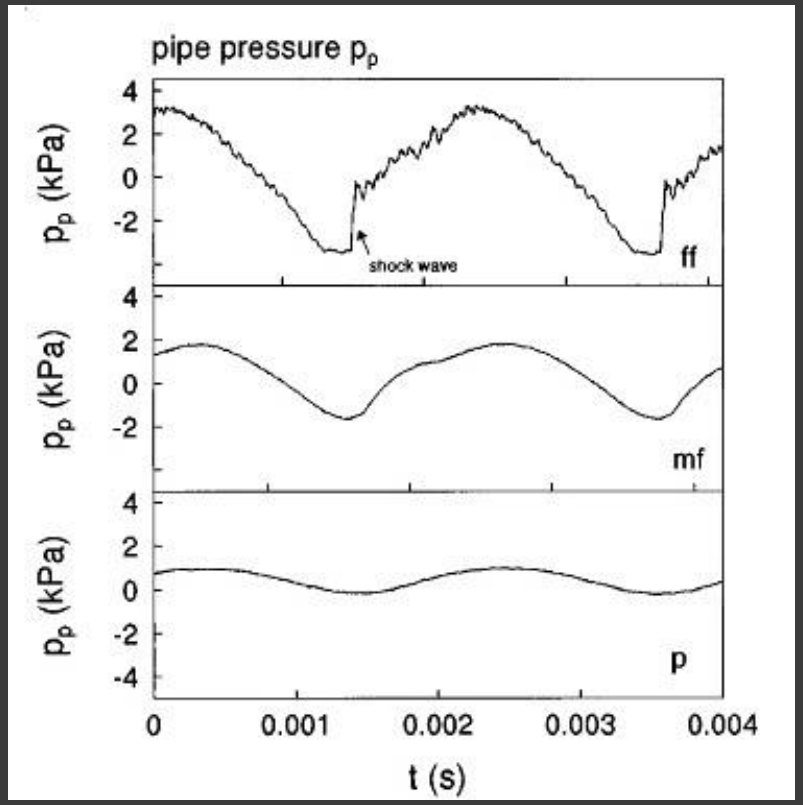
Linear Wave Propagation



Nonlinear Wave Propagation

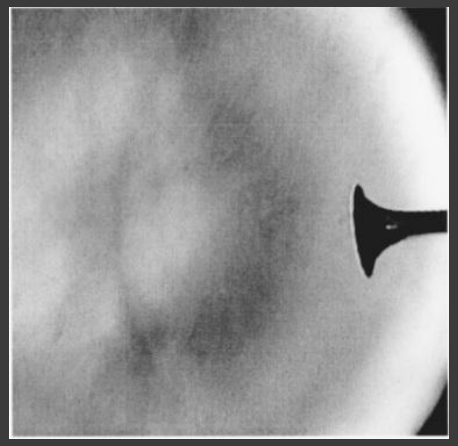


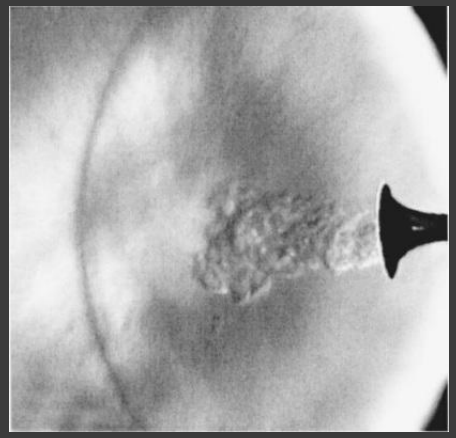
Pressure Measurements for a Trombone



Hirschberg, A. J., Gilbert, J., Msallam, R., and Wijnands, A. P. J. (**1995)**. `Shock waves in trombones,' J. Acoust. Soc. Am. 99, 1754-1758.

Shock Waves in a Trumpet





a) mf high G
b) f middle C
c) f high G

Pandya, B. H., Settles, G. S., and Miller, J. D. (**2003**), `Schlieren imaging of shock waves in a trumpet,' J. Acoust. Soc. Am. **114**, 3363-3367.

Acoustic Experiments

Experimental set up

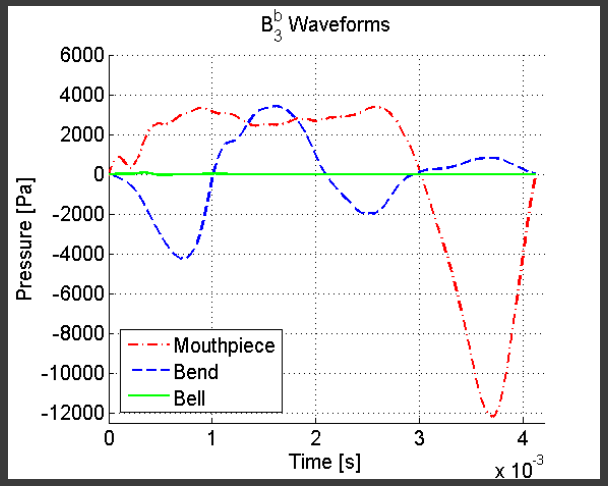
Microphone 1: (¼ inch) at mouthpiece
Microphone 2: (¼ inch) before first bend
Microphone 3: (½ inch) 16cm outside the bell

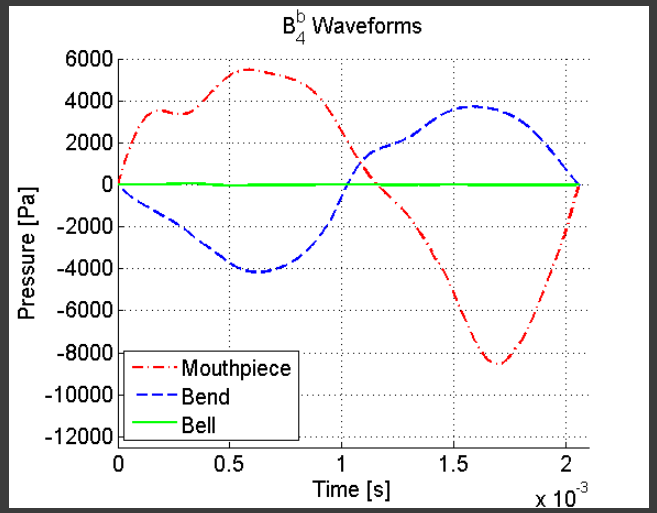
- Holes were cut into the trumpet for microphones 1 and 2 and then sealed with an o-ring
- Placed microphone 3 outside the bell
- Recorded B_3^b and B_4^b notes, both played *f*
- Microphones were connected to a four-input oscilloscope, and were recorded simultaneously

Resch, J., Krivodonova, L., and Vanderkooy, J. (**2014**), `A two-dimensional study of finite amplitude sound waves in a trumpet using the DG method,' J A Vol.22 No.3.

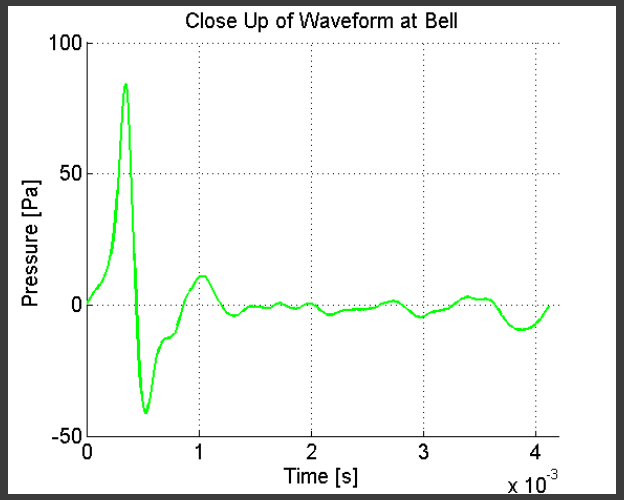
Microphone Measurements

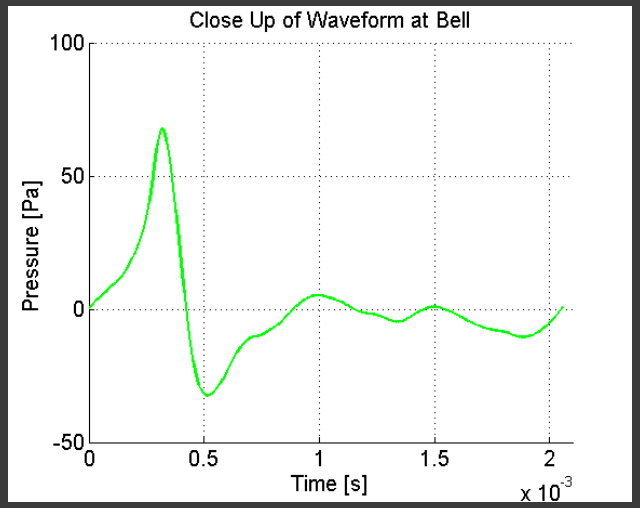
Waveforms measured at all three positions





Close up of waveforms outside bell





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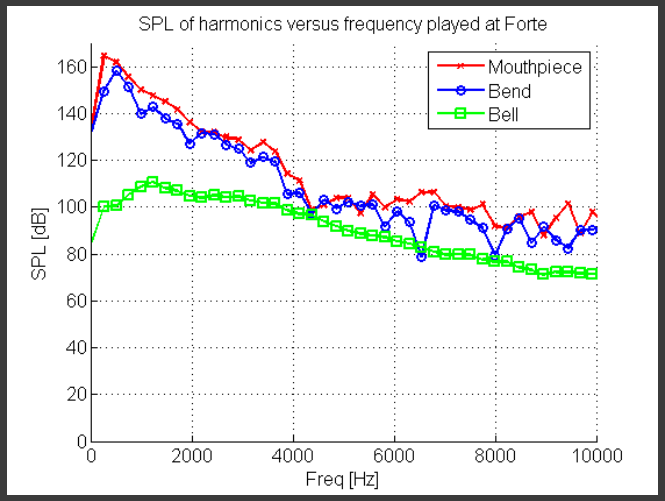
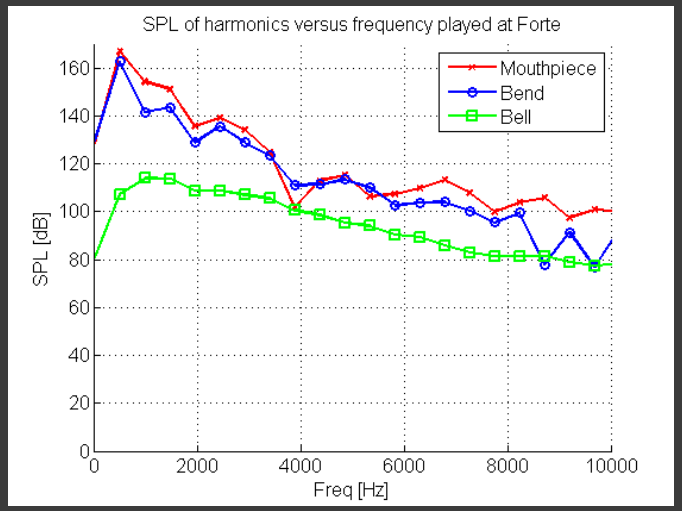
Frequency Spectra

B_3^b frequency spectra



B_4^b frequency spectra

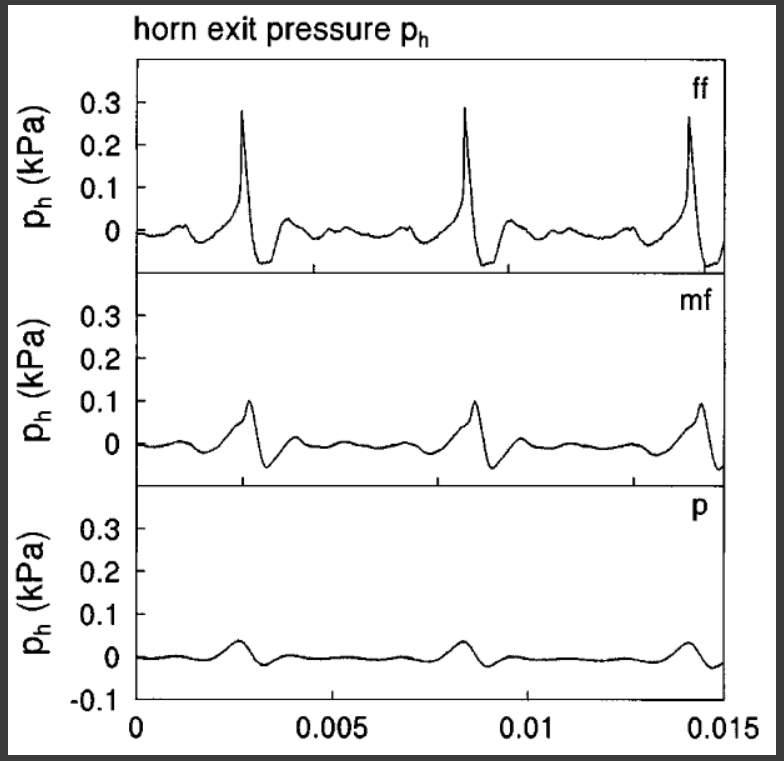


- In literature, wave steepening and shock waves are characterized by a transfer of energy from the lower harmonic components to the higher components
- May be seeing that in bell output since green line is flatter (could be ambient noise)

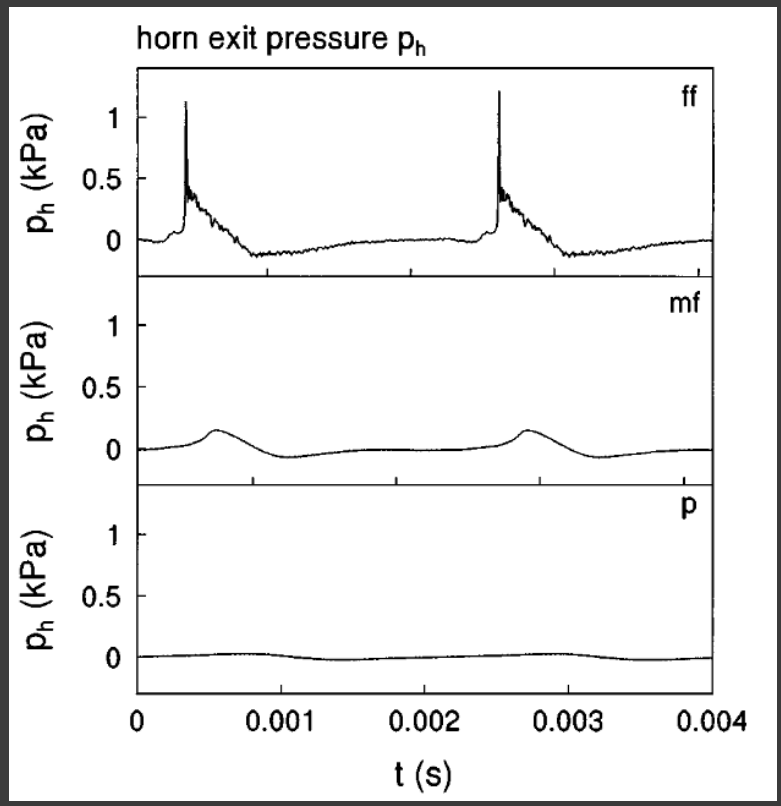
Resch, J., Krivodonova, L., and Vanderkooy, J. (**2014**), `A two-dimensional study of finite amplitude sound waves in a trumpet using the DG method,' J A Vol.22 No.3.

Comparison of other Pressure Measurement Results

Wave steepening



Shock wave



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Mathematical Description

Compressible Inviscid Euler Equations:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0,$$

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2 + p)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = 0,$$

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho v^2 + p)}{\partial y} + \frac{\partial(\rho vw + p)}{\partial z} = 0,$$

$$\frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho uw)}{\partial x} + \frac{\partial(\rho vw + p)}{\partial y} + \frac{\partial(\rho w^2 + p)}{\partial z} = 0,$$

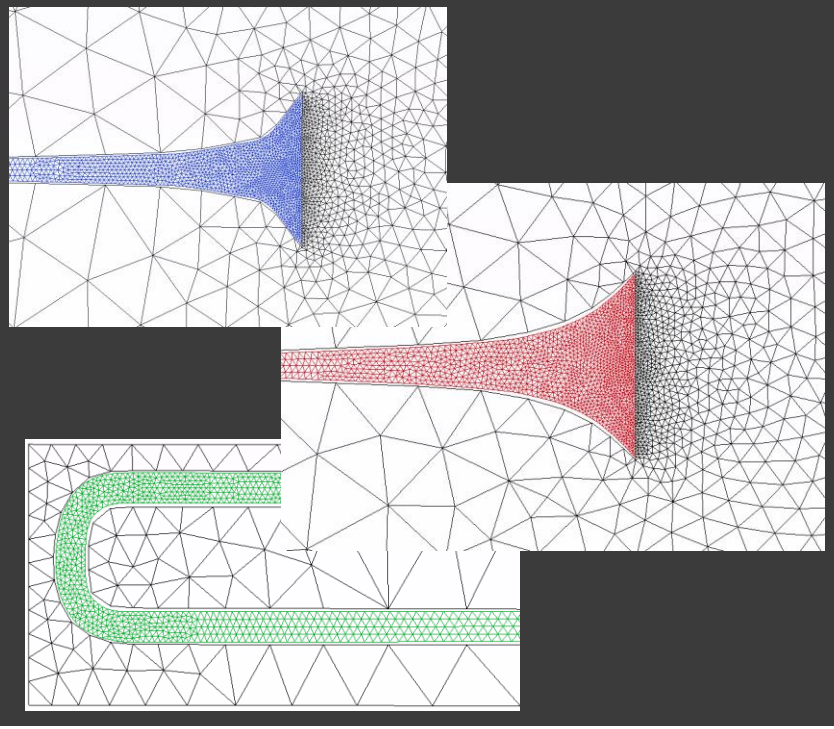
$$\frac{\partial E}{\partial t} + \frac{\partial(u(E + p))}{\partial x} + \frac{\partial(v(E + p))}{\partial u} + \frac{\partial(w(E + p))}{\partial z} = 0,$$

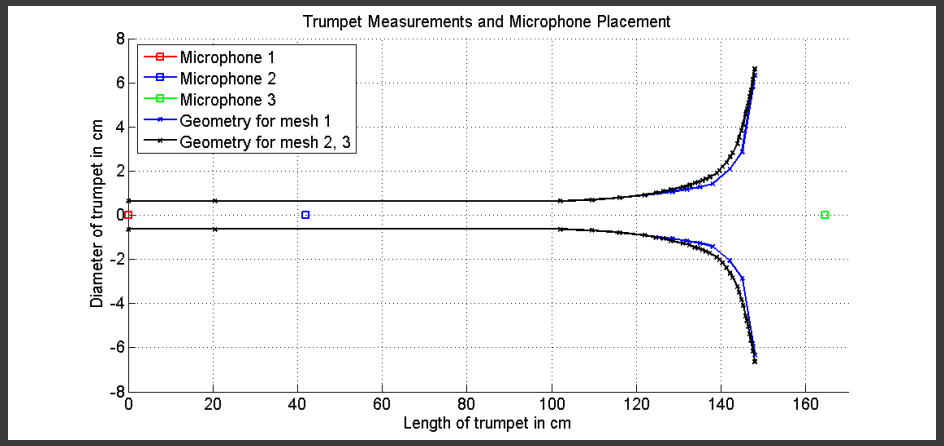
$$E = \frac{p}{\gamma - 1} + \frac{\rho}{2}(u^2 + v^2 + w^2).$$

Parameters:

- ρ is density of air,
- p is internal air pressure,
- (ρu, ρv, ρw) is the momenta in the (x, y, z) direction,
- E is the total energy,
- γ ~ 1.4 is the specific heat.

2D Computational Mesh





- Modeled a trumpet inside a box
- Cut out box around tubing parts to make simulations more efficient
- Elements inside the trumpet and around the bell (and bend) are smaller than the elements around the boundary
- We used reflective boundary conditions around the trumpet and pass through boundary conditions at the edge of the box (the boundary lines at the flare and bell have curved reflective boundary conditions)

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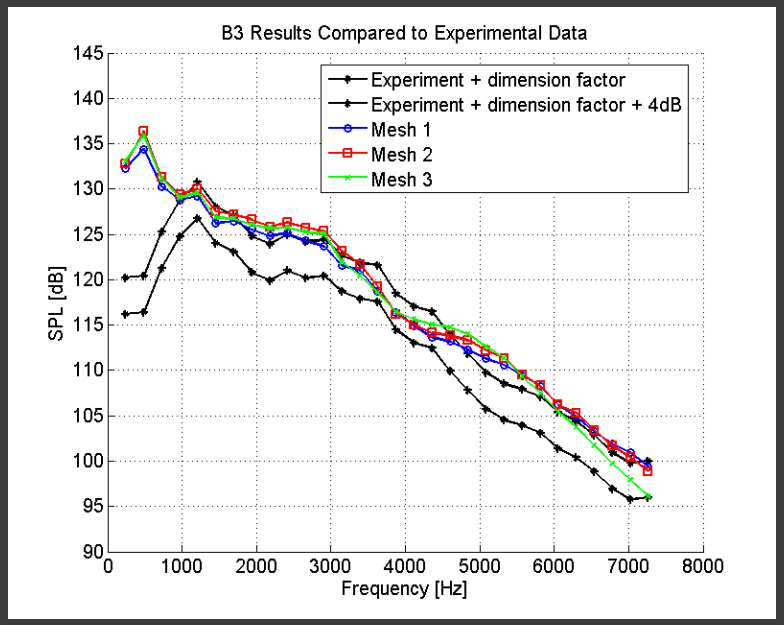
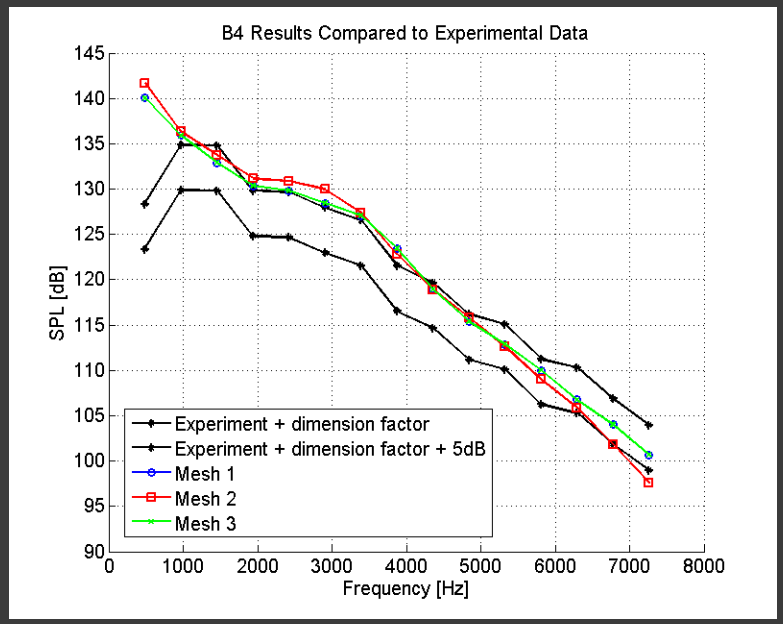
2D Simulated Results for B_3^b & B_4^b

Mesh 1: Machine shop bell, no bend
Mesh 2: Matlab drawn bell, no bend
Mesh 3: Matlab drawn bell, with bend





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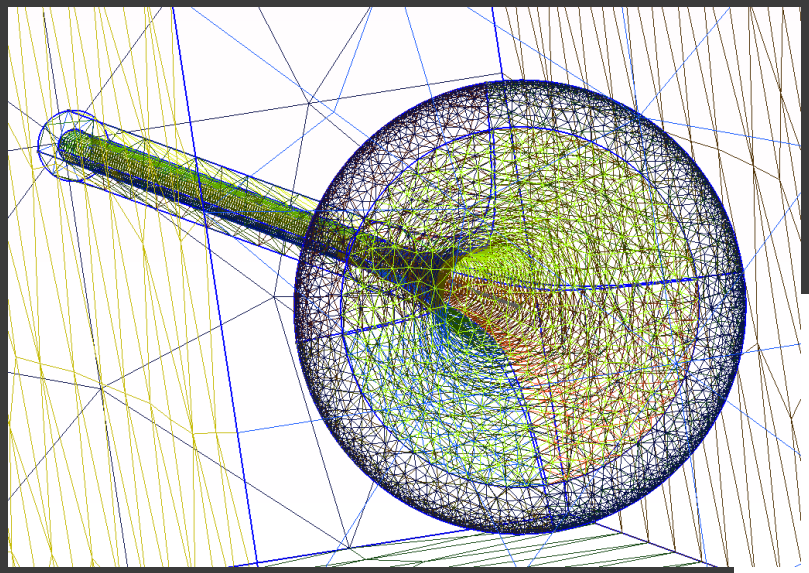
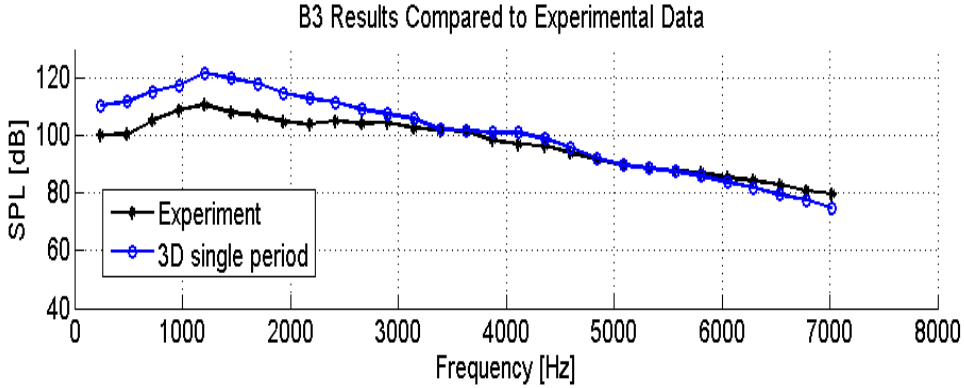
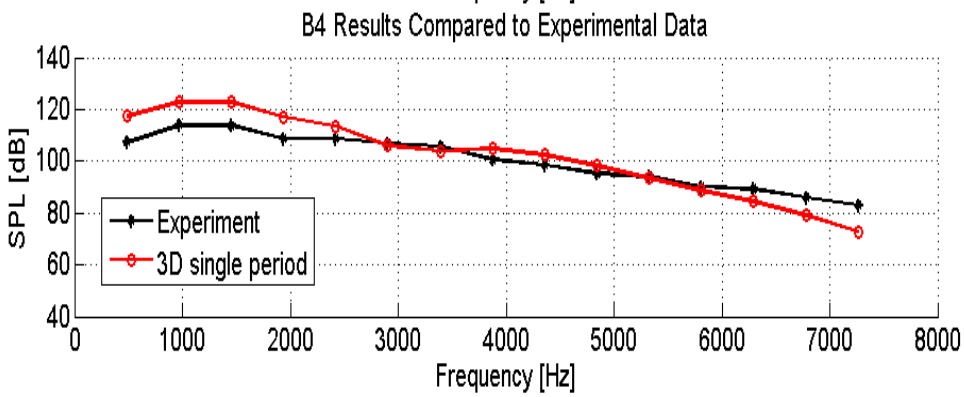
3D Simulated Results for B_3^b & B_4^b







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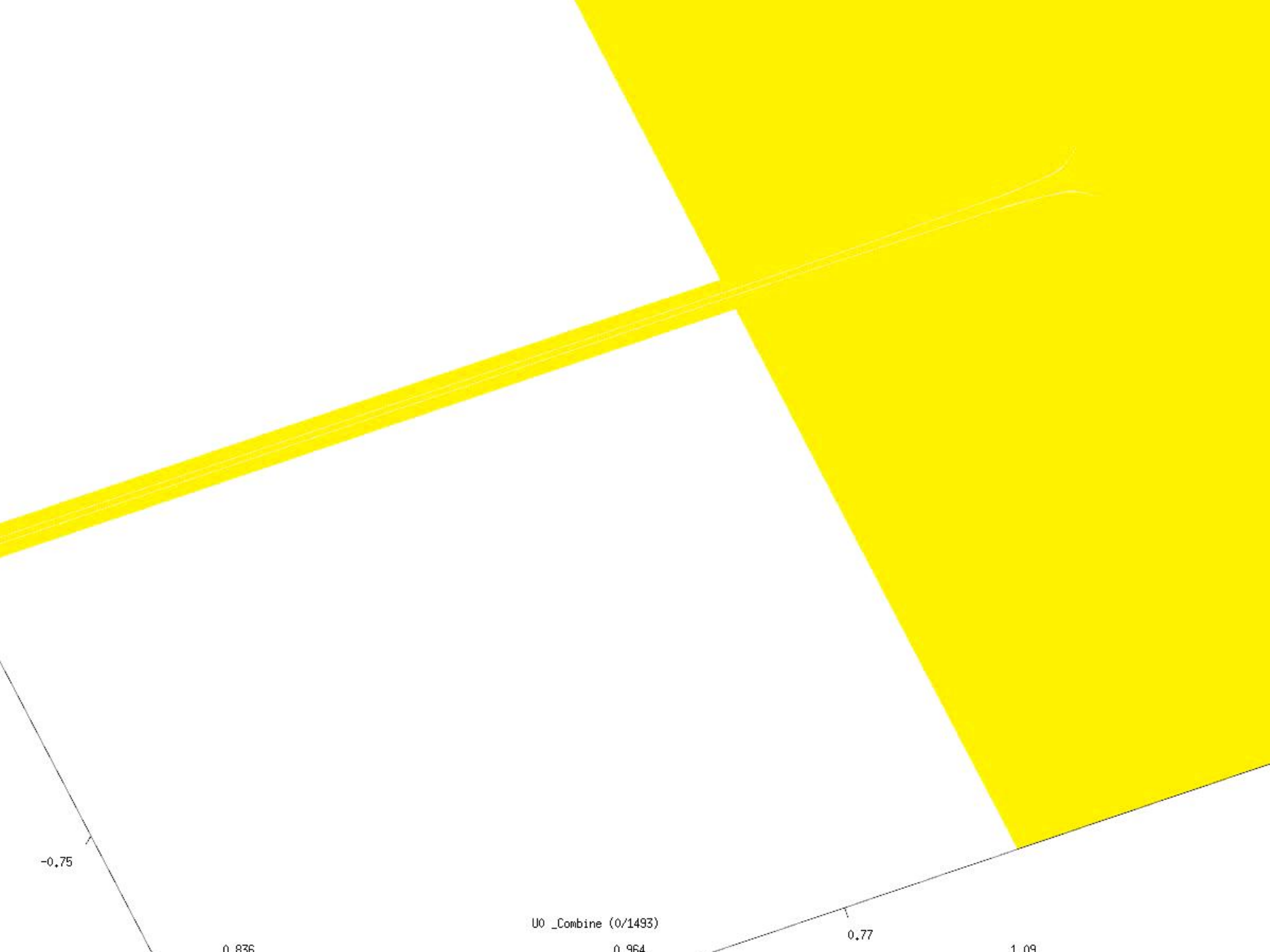
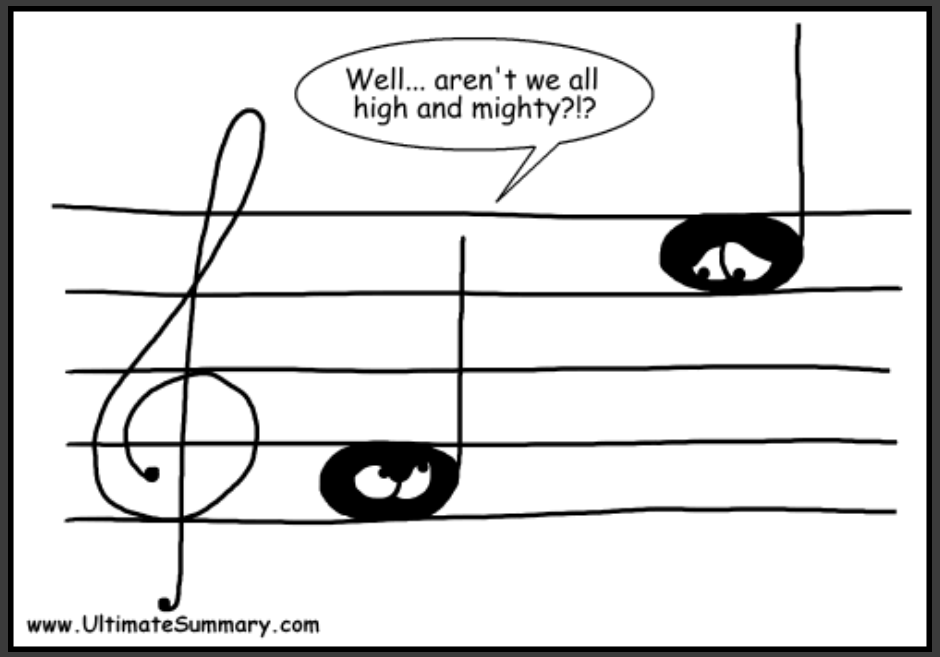

-0.75
U0 _Combine (0/1493)
0.77

Questions?

Thank you for your attention!



Important properties of sound

- Nondispersive wave motion refers to the motion of wave in which the wave disturbance does not change shape as it
- Dispersion occurs when waves of different wavelengths have different propagation velocities, so that a wave packet of mixed wavelengths tends to spread out in space