Physics 5B

Lecture 11, February 6, 2012

Chapter 16, Sound and Music

Speed of a Pressure Wave

$$v = \sqrt{\frac{B}{\rho}}$$

$$\frac{\Delta V}{V} = -\frac{1}{B}\Delta P \qquad \text{Bulk Modulus}$$

For an ideal gas, B and ρ depend on pressure in the same way, such that the pressure dependence cancels in the ratio (see Section 19-9 on adiabatic compression and expansion of an ideal gas).

That leaves, for an ideal gas, only a dependence on temperature:

$$v \approx (331 + 0.60 \cdot T) \text{ m/s} \quad (\text{with } T \text{ in } {}^\circ C)$$

Sound travels about 4 times faster in water than in air because

A. Water is far more dense than air.

B. Water is far less compressible than air.

C. Water is colder than air.

Factor of ~1000 in density, but a factor of ~20,000 in bulk modulus!

TABLE 16–1 Speed of Sound in Various Materials (20°C and 1 atm)

Material	Speed (m/s)
Air	343
Air (0°C)	331
Helium	1005
Hydrogen	1300
Water	1440
Sea water	1560
Iron and steel	≈ 5000
Glass	≈ 4500
Aluminum	≈ 5100
Hardwood	≈ 4000
Concrete	≈ 3000

Sound Intensity

TABLE 16–2
Intensity of Various Sounds

| Source of the Sound	Sound Level (dB)	Intensity (W/m²)
Jet plane at 30 m	140	100
Threshold of pain	120	1
Loud rock concert	120	1
Siren at 30 m	100	1×10^{-2}
Truck traffic	90	1×10^{-3}
Busy street traffic	80	1×10^{-4}
Noisy restaurant	70	1×10^{-5}
Talk, at 50 cm	65	3×10^{-6}
Quiet radio	40	1×10^{-8}
Whisper	30	1×10^{-9}
Rustle of leaves	10	1×10^{-11}
Threshold of hearing	0	1×10^{-12} ← I_0

$$\beta = 10 \log \frac{I}{I_0}$$

Decibels

- If the sound intensity increases by a factor of 1000, what is the corresponding increase in the intensity level, in dB?

    A. 20 dB

    B. 30 dB

    C. 60 dB

    D. 100 dB

   E. 1000 dB

Problem 16-27
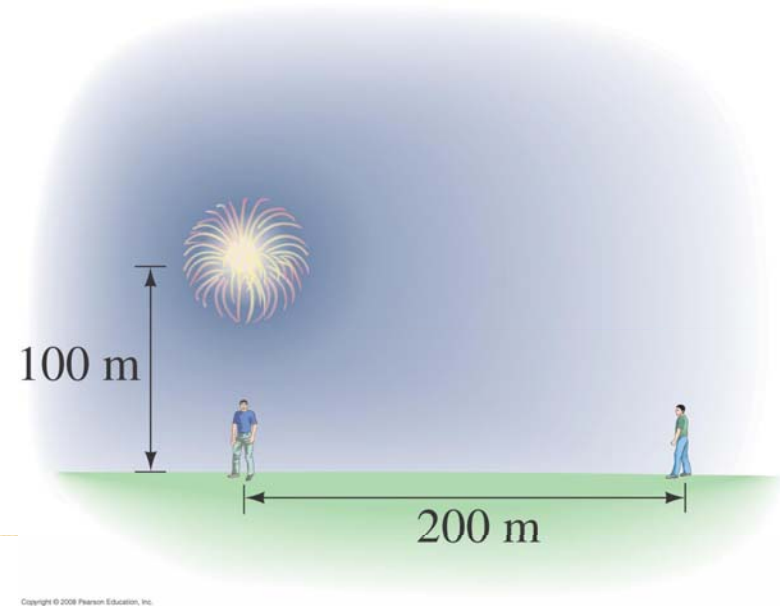
A fireworks shell explodes 100 m above the ground. How much greater is the sound level of the explosion for a person standing at a point directly below the explosion than for a person a horizontal distance of 200 m away?

(Assume that the sound waves expand outward uniformly in all directions, and ignore the possibility that some sound reflects from the ground.)

Reflection at a Pipe End

It is obvious why a sound wave reflects from the closed end of a pipe: the pressure wave pushes on the rigid end, and it pushes back.

But a sounds wave will also (partially) reflect from an open end. Inside the pipe the sound is confined and propagates differently from outside, where it spreads out in all directions. When a pressure maximum reaches an open end, it spreads out, sucking some air out of the tube and sending a pressure minimum back down the tube.
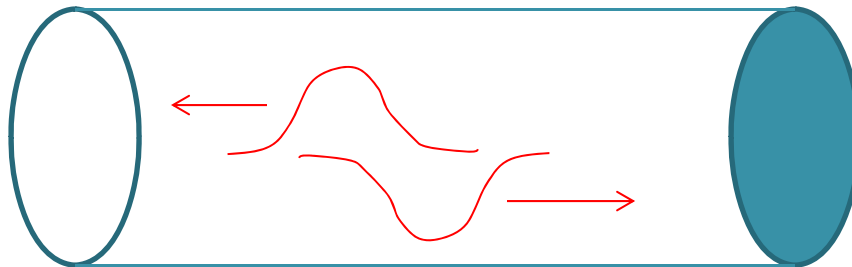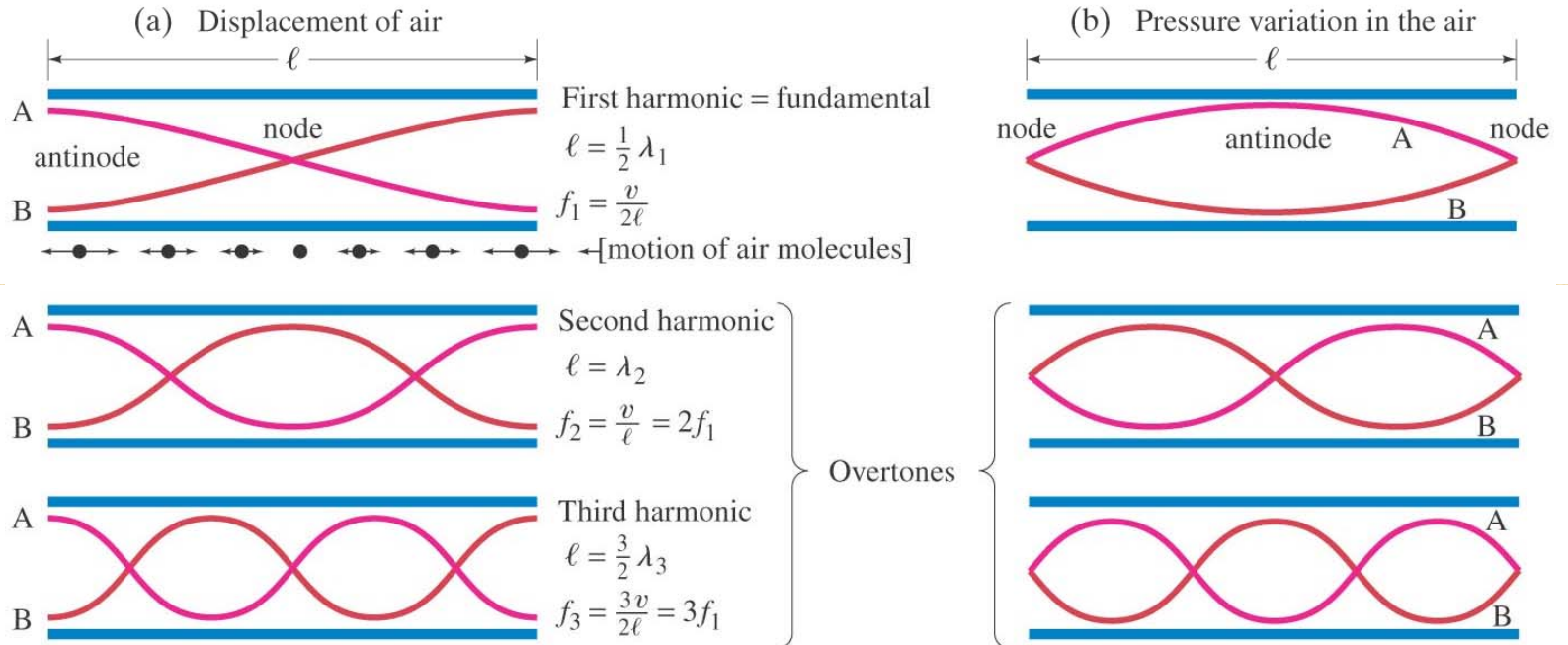

See the animation in the following link:

http://www.phys.unsw.edu.au/jw/flutes.v.clarinets.html

Standing Waves in Pipes

In reality, the pressure node is not exactly at the pipe end but is a little bit beyond

TUBE OPEN AT BOTH ENDS

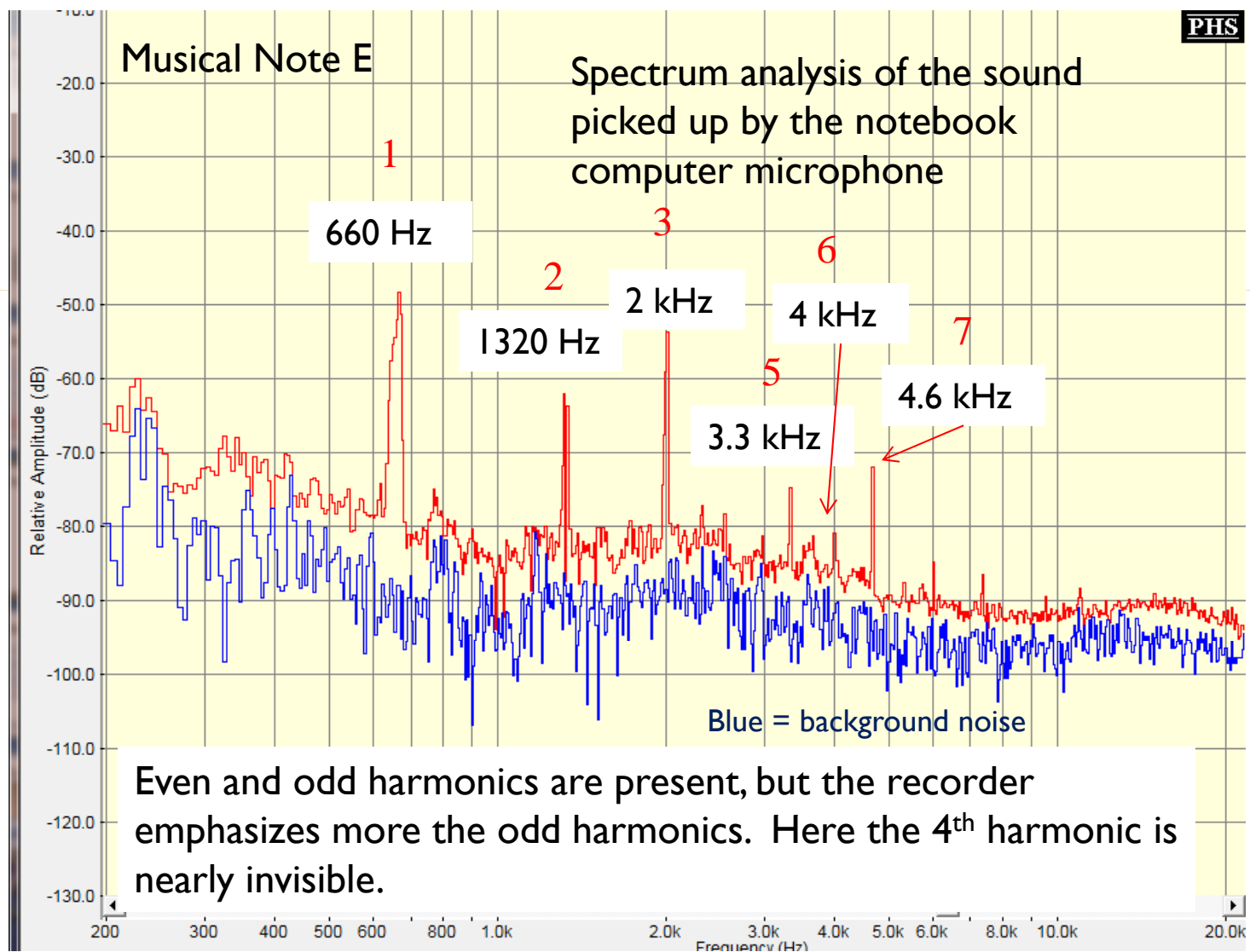(a) Displacement of air

ℓ

A

node

antinode

B

First harmonic = fundamental

$\ell = \frac{1}{2}\lambda_1$

$f_1 = \frac{v}{2\ell}$

←[motion of air molecules]

A

B

Second harmonic

$\ell = \lambda_2$

$f_2 = \frac{v}{\ell} = 2f_1$

A

B

Third harmonic

$\ell = \frac{3}{2}\lambda_3$

$f_3 = \frac{3v}{2\ell} = 3f_1$

Overtones

(b) Pressure variation in the air

ℓ

node

antinode

A

node

B

A

B

A

B

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Don't let the red graphs confuse you! The displacement is really along the direction of wave motion—the long dimension of the pipe.

Examples: open organ pipes and flutes

Example: the Recorder (flute)

Standing Waves in Pipes


TUBE CLOSED AT ONE END

(a) Displacement of air

A
B

First harmonic = fundamental
$\ell = \frac{1}{4}\lambda_1$
$f_1 = \frac{v}{4\ell}$

A
B

Third harmonic
$\ell = \frac{3}{4}\lambda_3$
$f_3 = \frac{3v}{4\ell} = 3f_1$

A
B

Fifth harmonic
$\ell = \frac{5}{4}\lambda_5$
$f_5 = \frac{5v}{4\ell} = 5f_1$

Overtones

(b) Pressure variation in the air

A
B

A
B

A
B
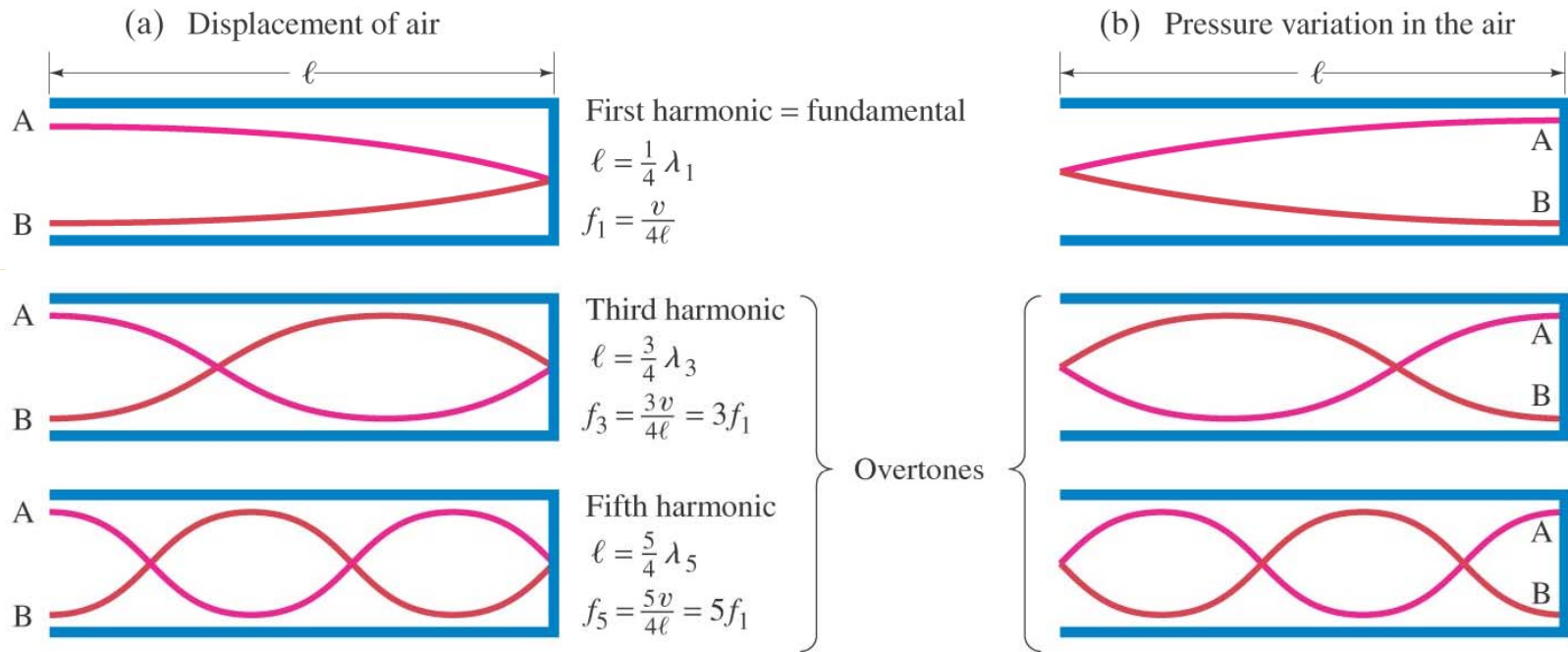
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Example: closed organ pipes

Note: the case with a tube closed at both ends is not very interesting for music, because we want the sound to escape and be heard.

Sound Resonance in a Pipe
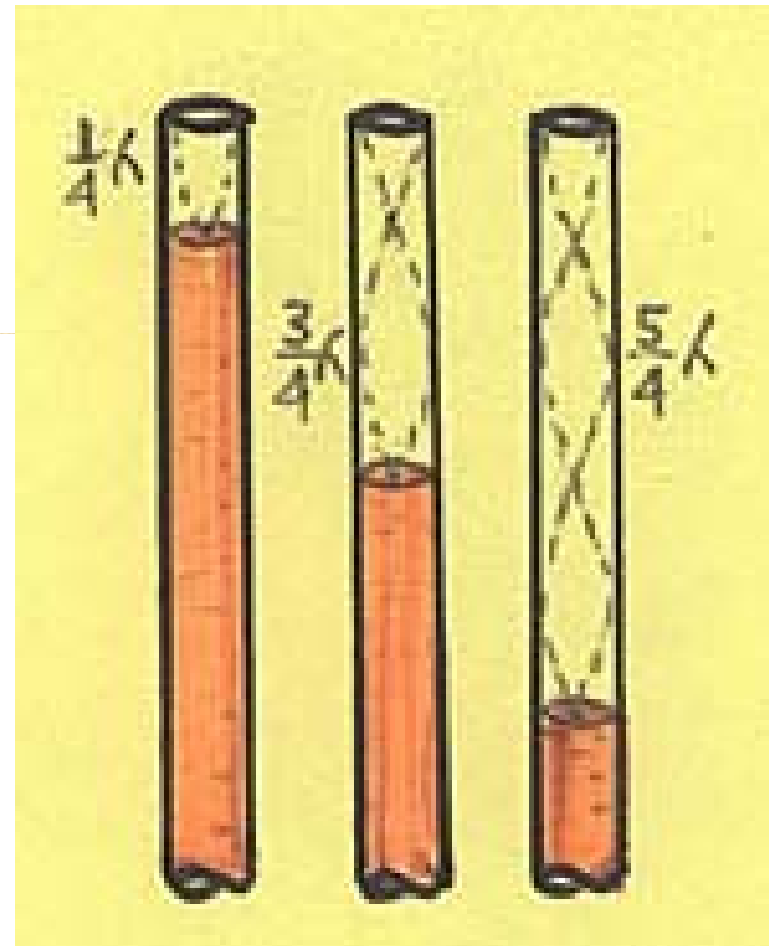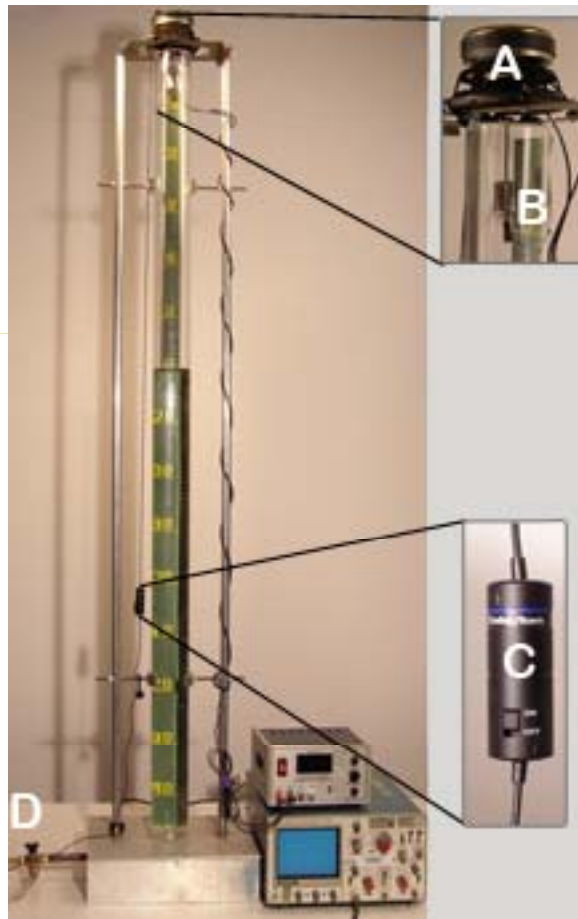
When a standing wave in the tube can oscillate at the same frequency as the speaker (resonance), the sound wave amplitude builds up constructively over many cycles, getting noticeably louder.

Warming up the Orchestra

A musician playing the clarinet warms up before a concert. As she blows warm air through the clarinet its temperature rises. What happens to the pitch of the sound from the instrument? (Assume that any change in size of the clarinet with temperature is negligible.)

A. It goes up slightly.

B. It is unchanged.

C. It goes down slightly

$$f = \frac{v}{\lambda} \quad \text{and } \lambda \text{ is set by the instrument's length}$$

Closed organ pipe

A middle C (262 Hz) is played on an organ pipe that is closed at one end. What is the frequency of the first overtone?

A. 393 Hz   (G)

B. 524 Hz   (C)

C. 786 Hz   (G)

D. 1048 Hz (C)

A pipe closed on one end plays only the odd harmonics.

Problem 16-89

The A string (440 Hz) of a violin is 32 cm long between fixed points and has a mass per unit length of 7.2×10^{-4} kg/m.

a) What are the wave speed and tension in the string?

b) What is the length of the tube of a simple wind instrument closed at one end whose fundamental is also 440 Hz if the speed of sound is 343 m/s in air?

c) What is the frequency of the first overtone of each instrument?

Tone of a Musical Instrument
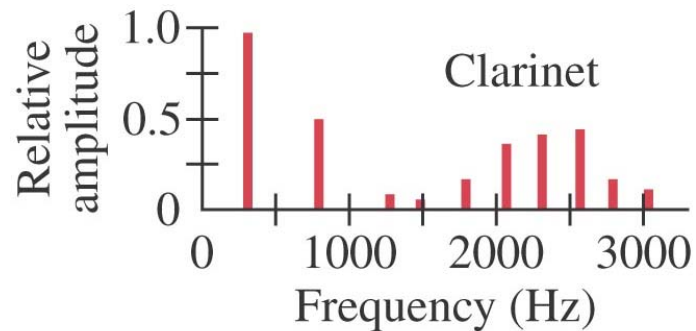
We hear a superposition of harmonics, each with a different amplitude depending on the instrument. This gives the instrument a characteristic "tone color" or "timbre".
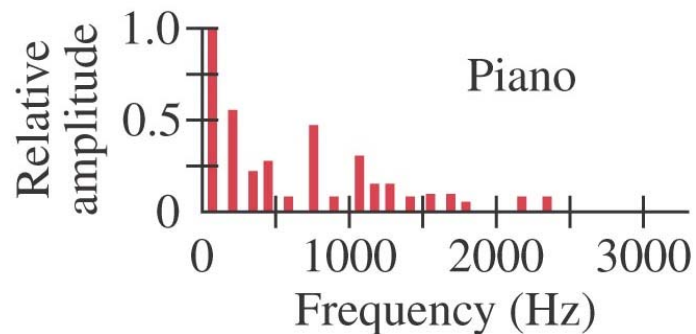
The overall sound experience, however, is much more complex, as it depends strongly on how the sound starts up ("attack") and how the different harmonics fade away with time ("sustain" and "decay").
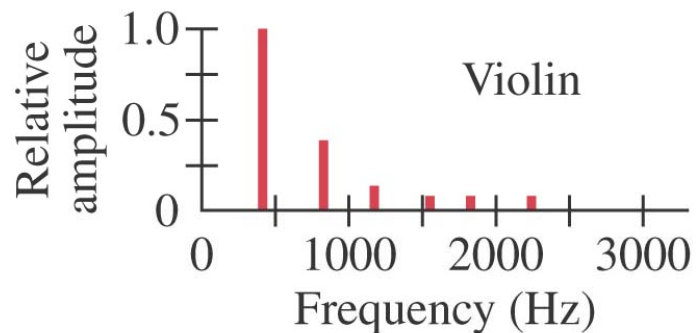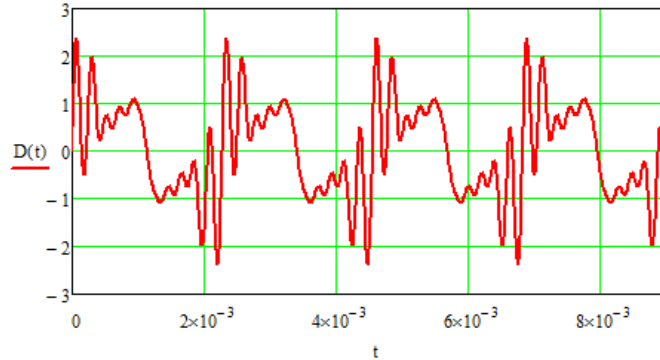
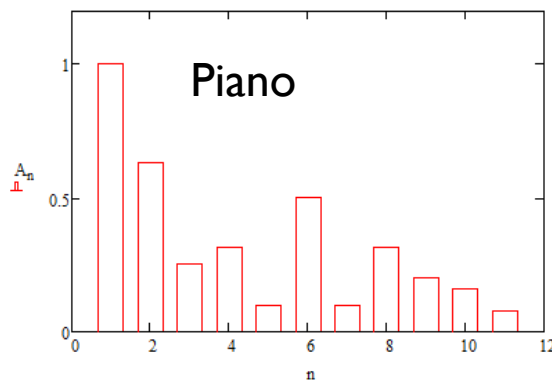# Adding the Harmonics with MathCad

Amplitude of Each Harmonic
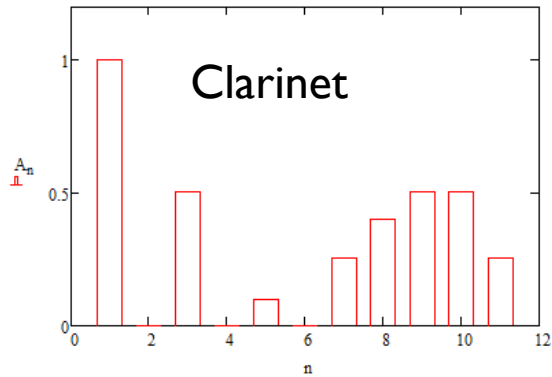
Clarinet

Piano

Violin

Displacement versus Time (4 periods)

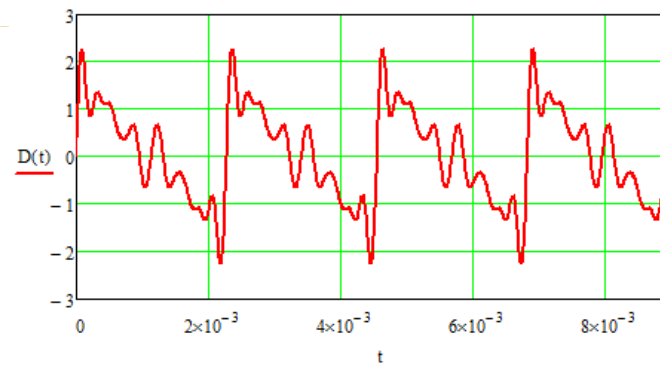PureTone440.wav

ClarinetTone.wav

Click to play the tone
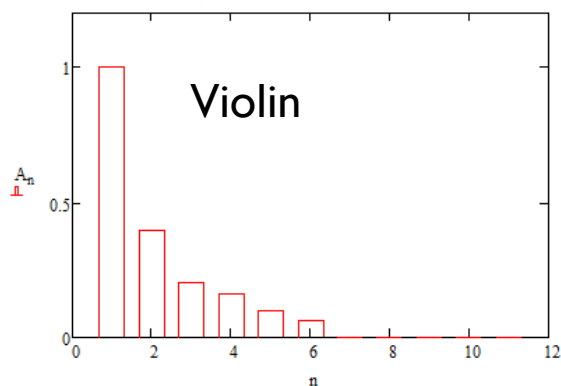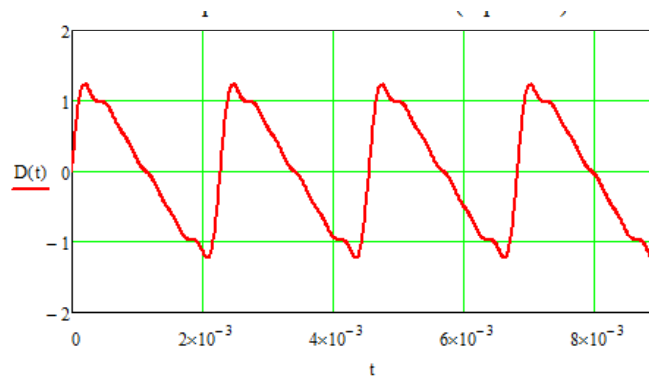
PianoTone.wav

All tones are 440 Hz fundamental (A)
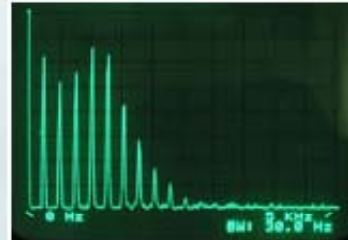
ViolinTone.wav

Example Spectra of Musical Instruments

Harmonic spectrum of a xylophone.

Harmonic spectrum of a guitar.

Harmonic spectrum of a trumpet.

Harmonic spectrum of a harmonica.

More Examples:

Again, all are recorded with a 440 Hz fundamental frequency.

- A square wave

http://scipp.ucsc.edu/~johnson/phys5b/SquareWave.wav

- A triangle wave

http://scipp.ucsc.edu/~johnson/phys5b/Triangle.wav

- White noise (all frequencies with equal amplitudes; the most random sound possible)

http://scipp.ucsc.edu/~johnson/phys5b/WhiteNoise.wav