Physics of Music / Physics of Musical Instruments

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UIUC

Saturday
Physics
Honors
Program

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What is Sound?

Describes two different physical phenomena:

• Sound = An auditory sensation in one's ear(s)/in one's brain…

• What is this exactly?

• Sound = A disturbance in a physical medium (gas/liquid/solid) which propagates in that medium. What is this exactly? How does this happen?

• Humans (& many other animal species) have developed the ability to hear sounds - because sound(s) exist in the natural environment.

• All of our senses are a direct consequence of the existence of stimuli in the environment - eyes/light, ears/sound, tongue/taste, nose/smells, touch/sensations, balance/gravity, migratorial navigation/earth's magnetic field.

• Why do we have two ears? Two ears are the minimum requirement for spatial location of a sound.

• Ability to locate a sound is very beneficial - e.g. for locating food & also for avoiding becoming food….

Acoustics

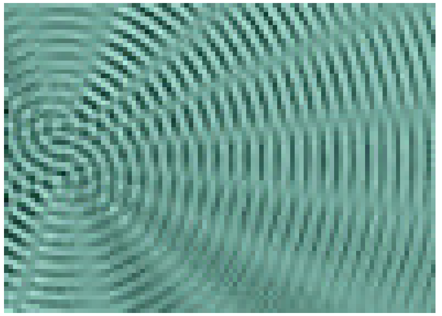
• Scientific study of sound

• Broad interdisciplinary field - involving physics, engineering, psychology, speech, music, physiology, neuroscience, architecture, etc….

•Different branches of acoustics:

- Physical Acoustics
- Musical Acoustics
- Psycho-Acoustics
- Physiological Acoustics
- Architectural Acoustics
- Etc...

Sound Waves



Sound propagates in a physical medium (gas/liquid/solid) as a wave, or as a sound pulse (= a collection/superposition of traveling waves)

• An acoustical disturbance propagates as a collective excitation (i.e. vibration) of a group of atoms and/or molecules making up the physical medium.

• Acoustical disturbance, e.g. sound wave carries energy, E and momentum, P

• For a homogeneous (i.e. uniform) medium, disturbance propagates with a constant speed, v

• See demos of longitudinal & transverse wave propagation….

• Longitudinal waves - atoms in medium are displaced longitudinally from their equilibrium positions by acoustic disturbance - i.e. along/parallel to direction of propagation of wave.

• Transverse waves - atoms in medium are displaced transversely from their equilibrium positions by acoustic disturbance - i.e. perpendicular to direction of propagation of wave.

• Speed of sound in air: $v_{air} = \sqrt{(B_{air}/\rho_{air})}$ ~ 344 m/s (~ 1000 ft/sec) at sea level, 20 degrees Celsius.

• Speed of sound in metal, e.g. aluminum: $v_{Al} = \sqrt{(Y_{Al}/\rho_{Al})}$ ~ 1080 m/s.

• Speed of transverse waves on a stretched string: $v_{string} = \sqrt{(T_{string}/\mu_{string})}$ where mass per unit length of string, $\mu_{string} = M_{string}/L_{string}$

Standing Waves on a Stretched String

Standing wave = superposition of left- and right-going traveling waves

• Left & right-going traveling waves reflect off of end supports

• Polarity flip occurs at fixed end supports. No polarity flip for free ends.

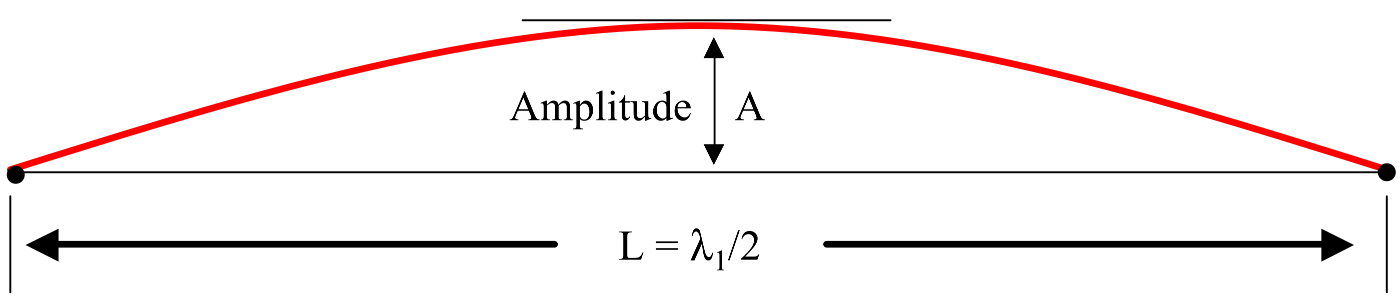
• Different modes of string vibrations - resonances occur!

• For string of length L with fixed ends, the lowest mode of vibration has frequency $f_1 = v/2L$ ($v = f_1\lambda_1$) (f in cycles per second, or Hertz (Hz))

• Frequency of vibration, $f = 1/\tau$, where τ = period = time to complete 1 cycle

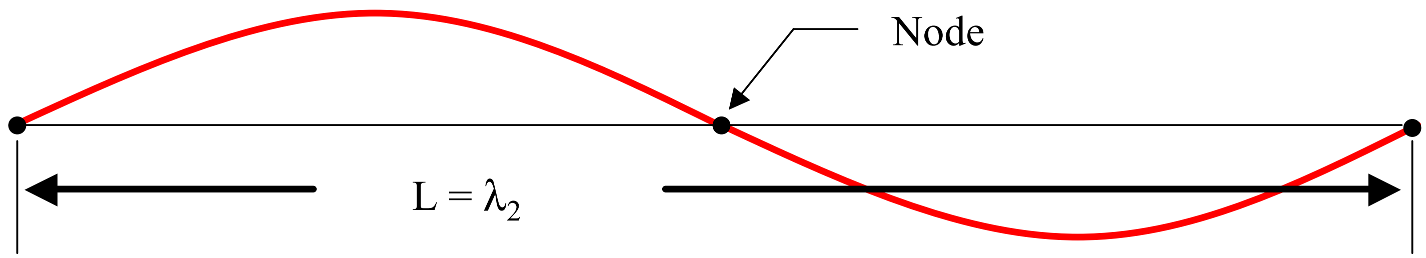
• Wavelength, λ_1 of lowest mode of vibration has $\lambda_1 = 2L$ (in meters)

• Amplitude of wave (maximum displacement from equilibrium) is A - see figure below - snapshot of standing wave at one instant of time, t:

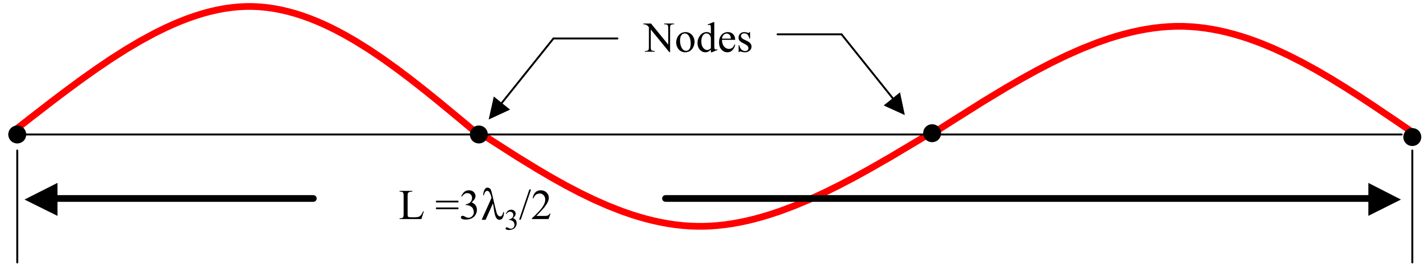


String can also vibrate with higher modes:

• Second mode of vibration of standing wave has $f_2 = 2v/2L = v/L$ with $\lambda_2 = 2L/2 = L$



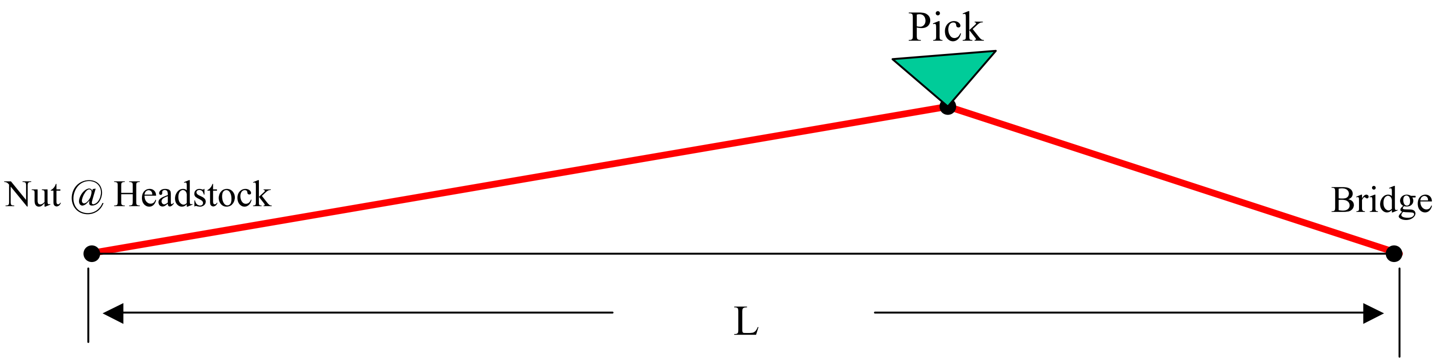
• Third mode of vibration of standing wave has $f_3 = 3v/2L$ with $\lambda_3 = 2L/3$



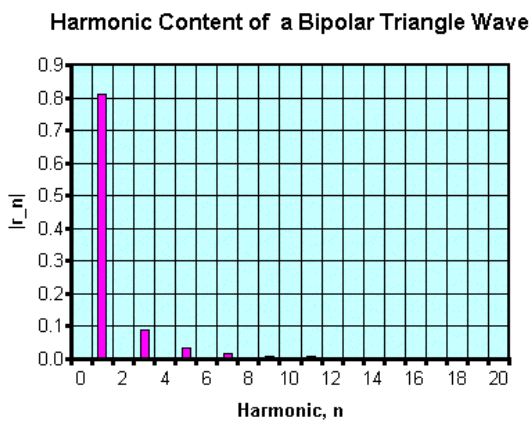
• The n^{th} mode of vibration of standing wave on a string, where n = integer = 1,2,3,4,5,…. has frequency $f_n = n(v/2L) = n\, f_1$, since $v = f_n\lambda_n$ and thus the n^{th} mode of vibration has a wavelength of $\lambda_n = (2L)/n = \lambda_1/n$

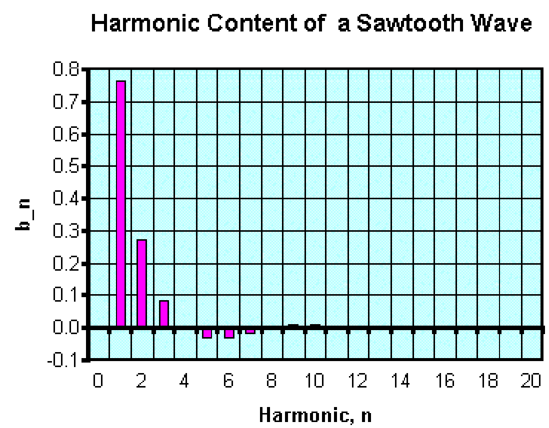
• See driven rope standing wave demo...

When we e.g. pick (i.e. pluck) the string of a guitar, initial waveform is a triangle wave:



The geometrical shape of the string (a triangle) at the instant the pick releases the string can be shown mathematically (using Fourier Analysis) to be due to a linear superposition of standing waves consisting of the fundamental plus higher harmonics of the fundamental! Depending on where pick along string, harmonic content changes. Pick near the middle, mellower (lower harmonics); pick near the bridge - brighter - higher harmonics emphasized!





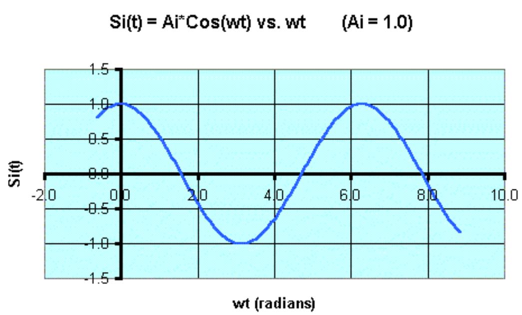
See electric guitar demos...

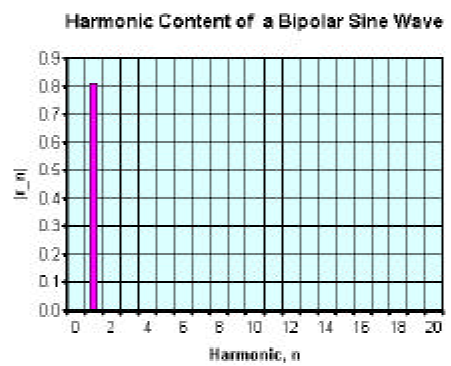
Harmonic Content of Complex WaveForms

In fact, geometrical/mathematical shape of any *periodic* waveform can be shown to be due to linear combination of fundamental & higher harmonics!

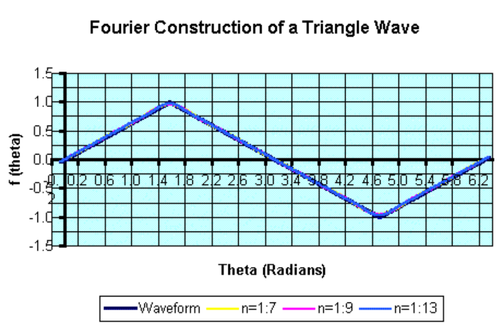
Sound Tonal Quality - *Timbre* - harmonic content of sound wave

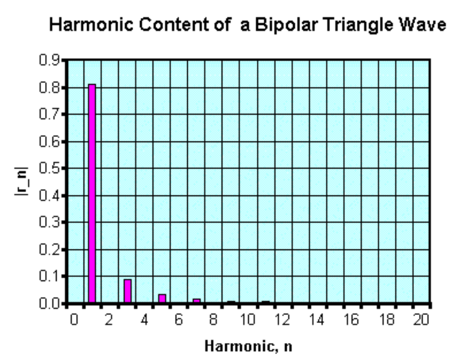
Sine/Cosine Wave: Mellow Sounding – fundamental, no higher harmonics



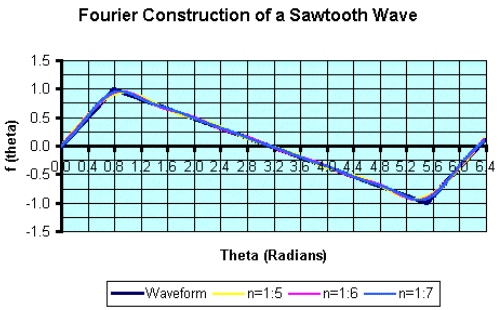


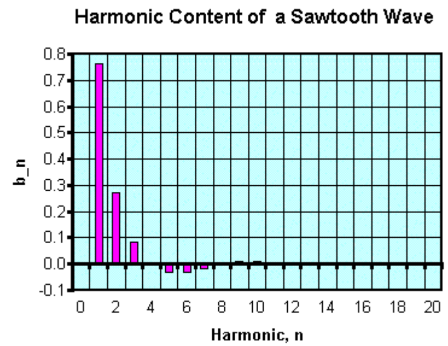
Triangle Wave: A Bit Brighter Sounding – has higher harmonics!



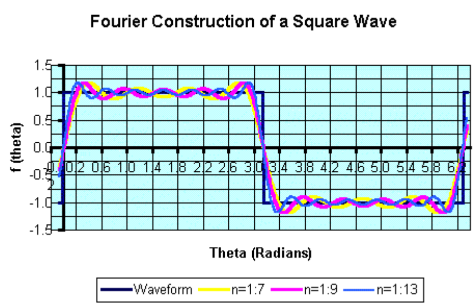


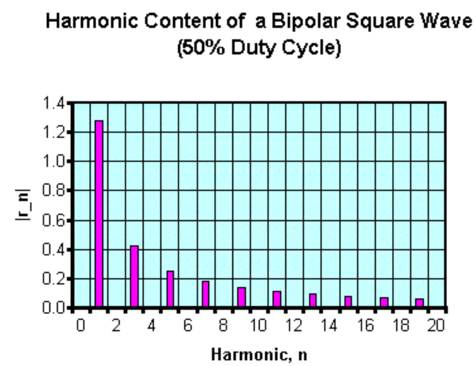
Asymmetrical Sawtooth Wave: Even Brighter Sounding – even more harmonics!





Square Wave: Brighter Sounding – has the most harmonics!





• See/hear demo of sine/triangle/square wave signals...

What *is* Music?

• An aesthetically pleasing sequence of tones?

• *Why* is music pleasurable to humans?

• Music has always been part of human culture, as far back as we can tell

• Music important to human evolution?

• Music shown to *stimulate* human brain

• Music facilitates brain development in young children and in learning

• Music is also important to other living creatures - birds, whales, frogs, etc.

• Many kinds of animals utilize sound to communicate with each other

• What is it about music that does all of the above ???

Human Development of Musical Instruments

• Emulate/mimic human voice (some instruments much more so than others)!

• Sounds from musical instruments can evoke powerful emotional responses - happiness, joy, sadness, sorrow, shivers down your spine, raise the hair on back of neck, etc.

Musical Instruments

- Each musical instrument has its own characteristic sounds - quite complex!
- Any note played on an instrument has fundamental + harmonics of fundamental.
- Higher harmonics - brighter sound
- Less harmonics - mellower sound
- Harmonic content of note can/does change with time:
    - Takes time for harmonics to develop - "attack" (leading edge of sound)
    - Harmonics don't decay away at same rate (trailing edge of sound)
    - Higher harmonics tend to decay more quickly
- Sound output of musical instrument is not uniform with frequency
    - Details of construction, choice of materials, finish, etc. determine *resonant structure* (formants) associated with instrument - mechanical vibrations!
- See harmonic content of guitar, violin, recorder, singing saw, drum, cymbals, etc.
- See laser interferogram pix of vibrations of guitar, violin, handbells, cymbals, etc.

Vibrational Modes of an Acoustic Guitar

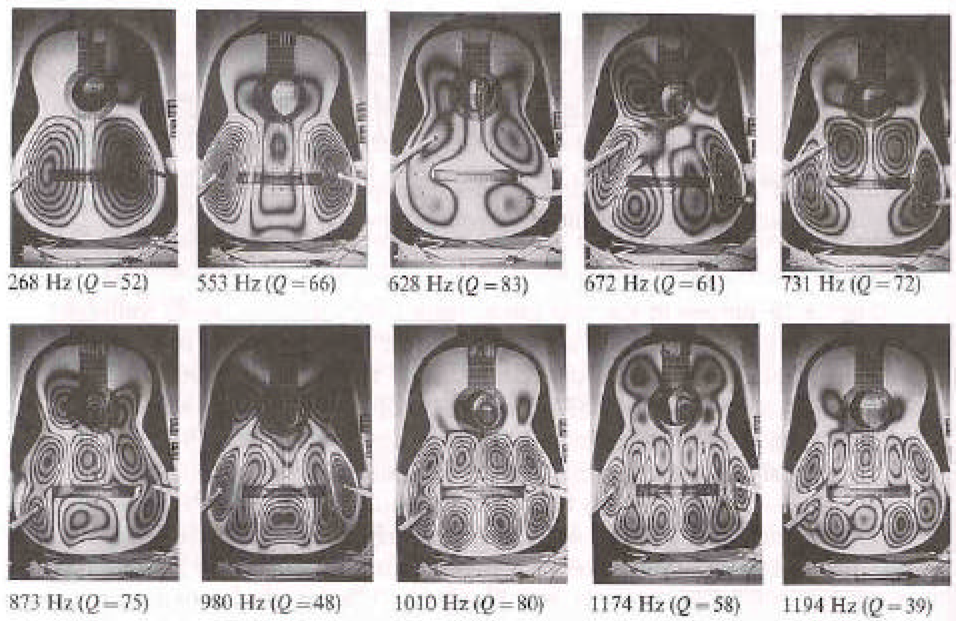


FIGURE 9.16. Time-averaged holographic interferograms of top-plate modes of a guitar (Guitar BR11). The resonant frequencies and Q values of each mode are shown below the interferograms (Richardson and Roberts, 1985).

Resonances of an Acoustic Guitar

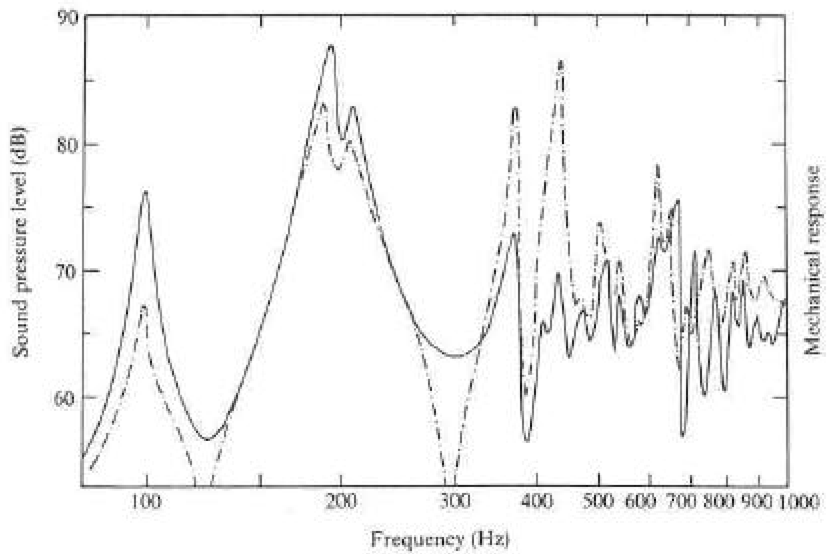


FIGURE 9.20. Mechanical frequency response and sound spectrum 1 m in front of a Martin D-28 folk guitar driven by a sinusoidal force of 0.15 N applied to the treble side of the bridge. Solid curve, sound spectrum; dashed curves, acceleration level at the driving point.

Vibrational Modes of a Violin

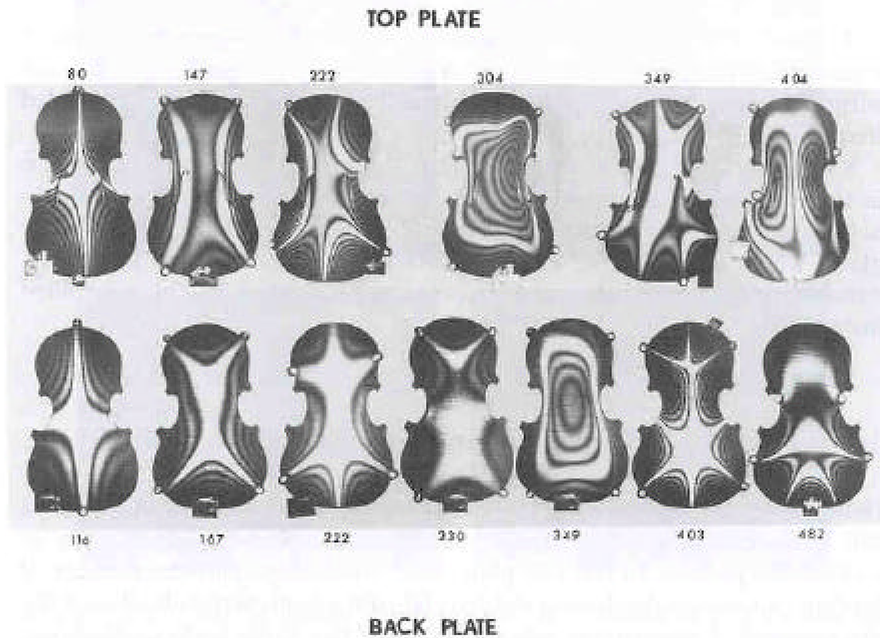


FIGURE 10.14. Time-average holographic interferograms of a free violin top plate and back plate (Hutchins et al., 1971).

Vibrational Modes of Handbells

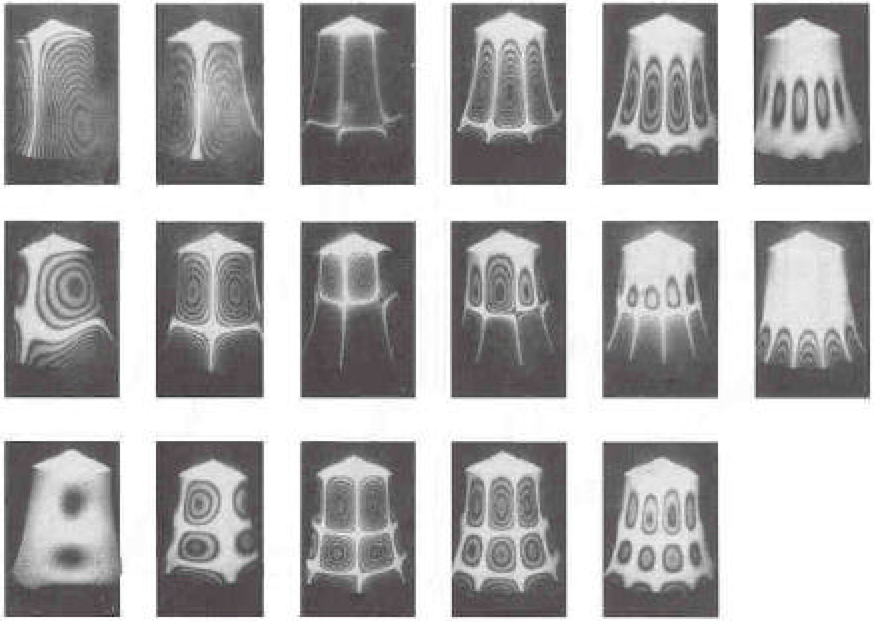


FIGURE 21.16. Time-average hologram interferograms of vibrational modes in a C_5 handbell (Rossing et al., 1984).

Vibrational Modes of Membranes and Plates

(Drums and Cymbals)

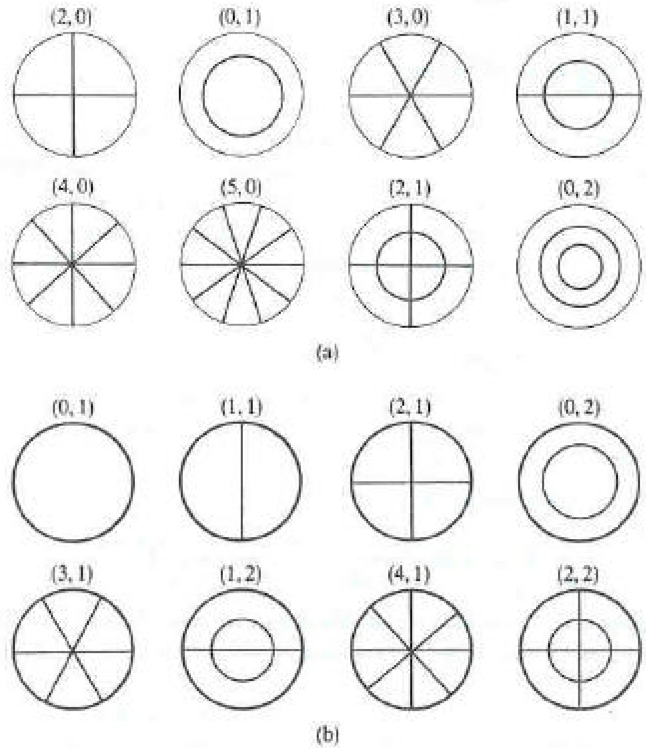
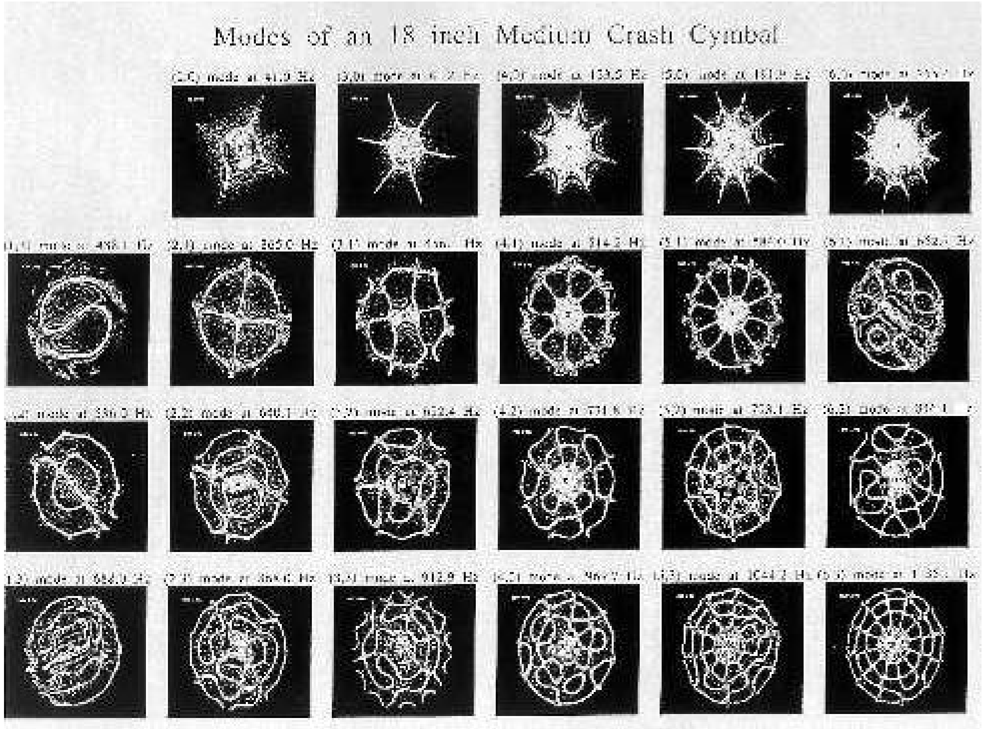


FIGURE 3.8. Vibrational modes of circular plates: (a) free edge and (b) clamped or simply supported edge. The mode number (n, m) gives the number of nodal diameters and circles, respectively.

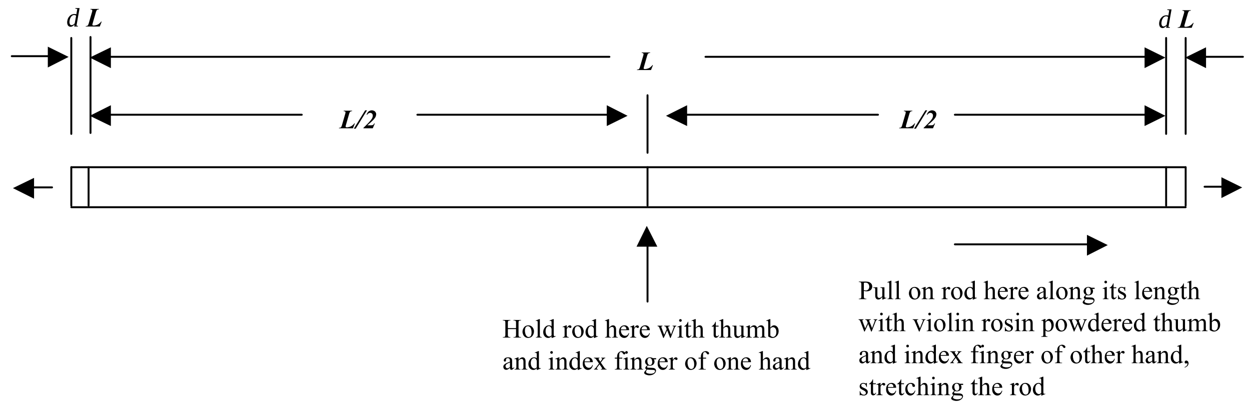
See drum strobe-light demo...

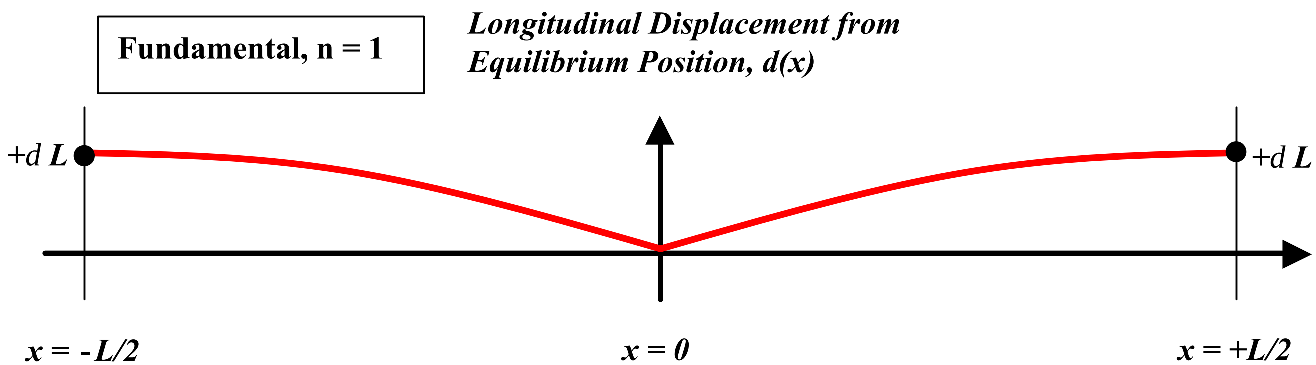
Vibrational Modes of Cymbals



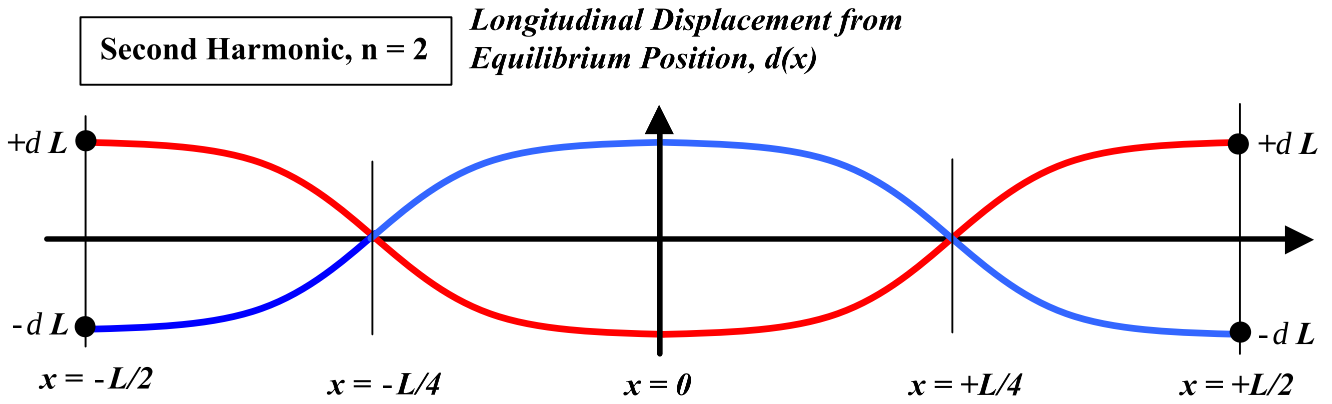
Modal Vibrations of a "Singing" Rod

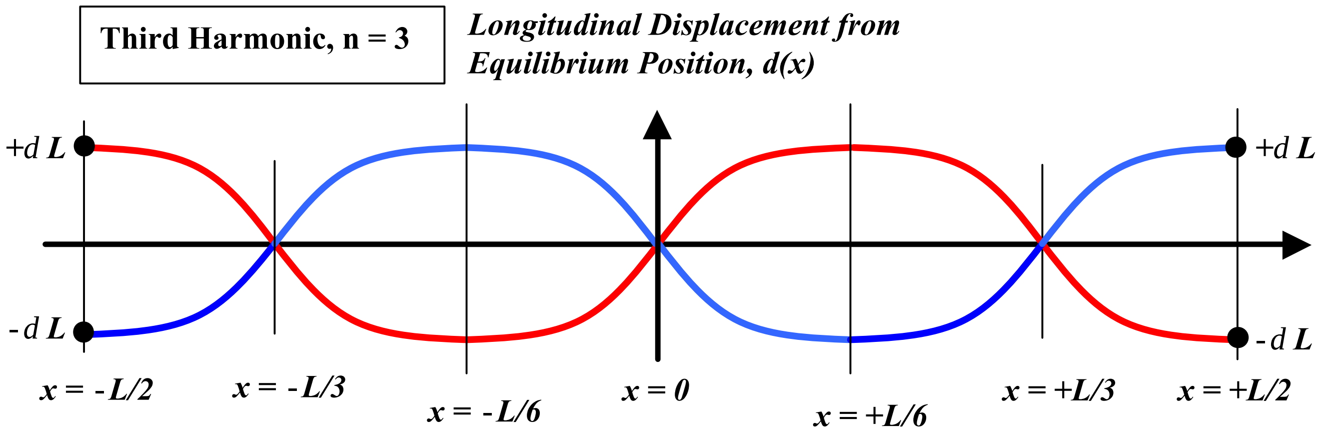
A metal rod (e.g. aluminum rod) a few feet in length can be made to vibrate along its length – make it "sing" at a characteristic, resonance frequency by holding it precisely at its mid-point with thumb and index finger of one hand, and then pulling the rod along its length, toward one of its ends with the thumb and index finger of the other hand, which have been dusted with crushed violin rosin, so as to obtain a good grip on the rod as it is pulled.





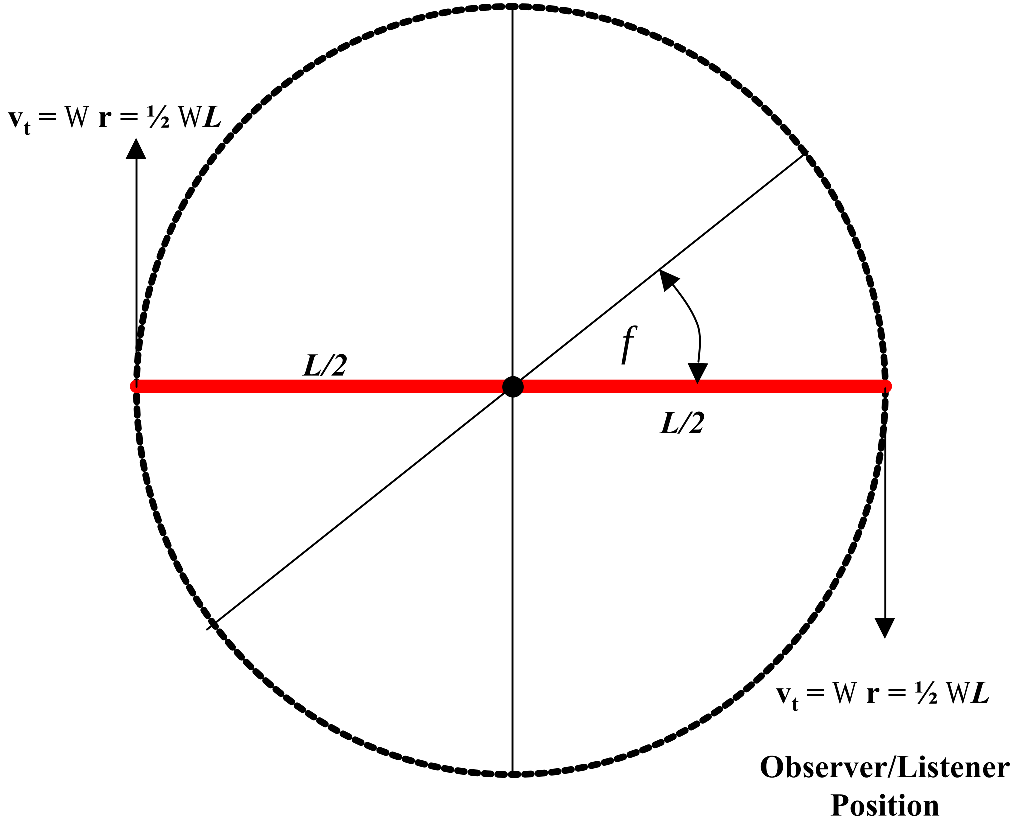
Of course, there also exist higher modes of vibration of the singing rod:





• See singing rod demo...

• If the singing rod is rotated - can hear Doppler effect & beats:

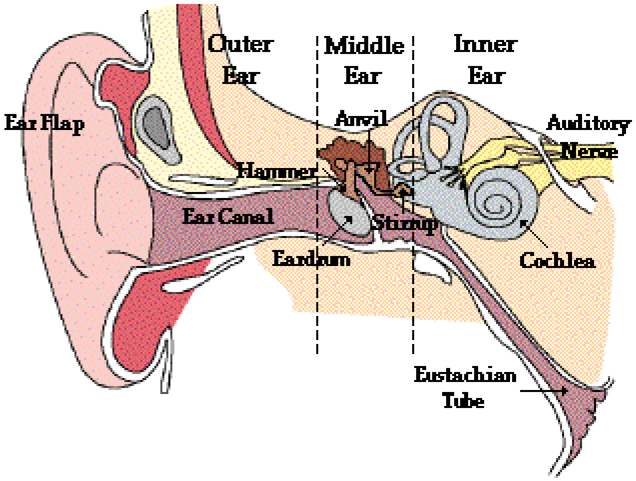


• Frequency of vibrations raised (lowered) if source moving toward (away from) listener, respectively

• Hear Doppler effect & beats of rotating "singing" rod...

• Would Mandi Patrick (UIUC Feature Twirler) be willing to lead the UI Singing Rod Marching Band at a half-time show ???

How Do Our Ears Work?



- Sound waves are focussed into the ear canal via the ear flap (aka pinna), and impinge on the ear drum.
- Ossicles in middle ear - hammer/anvil/stirrup - transfer vibrations to oval window - membrane on cochlea, in the inner ear.
- Cochlea is filled with perilymph fluid, which transfers sound vibrations into Cochlea.
- Cochlea contains basilar membrane which holds ~ 30,000 hair cells in Organ of Corti
- Sensitive hairs respond to the sound vibrations - send signals to brain via auditory nerve
- Brain processes audio signals from *both* ears - you *hear* the “sound”
- See/Hear demo of (your) hearing response vs. frequency...

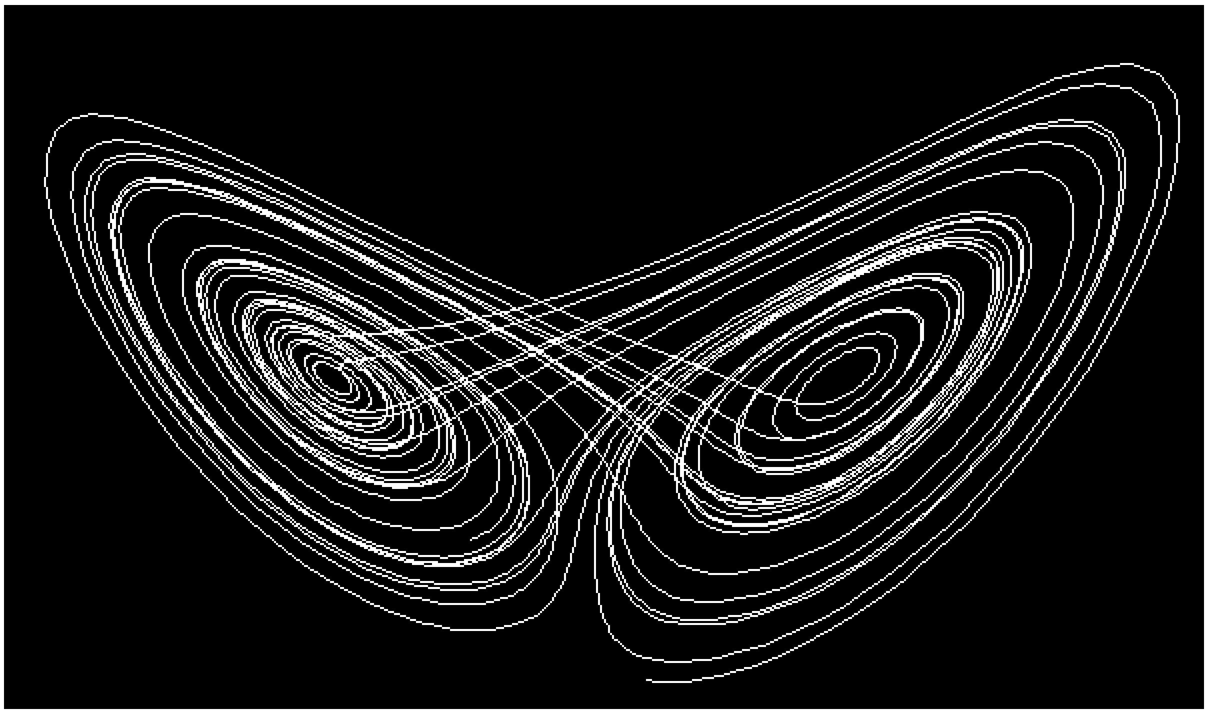
Consonance & Dissonance

Ancient Greeks - Aristotle and his followers - discovered using a *Monochord* that certain combinations of sound were pleasing to the human ear, for example:

- **Unison** - 2 sounds of *same* frequency, i.e. $f_2 = 1\ f_1 = f_1$ (= e.g. 300 Hz)
- **Minor Third** - 2 sounds with $f_2 = (6/5)\ f_1 = 1.20\ f_1$ (= e.g. 360 Hz)
- **Major Third** - 2 sounds with $f_2 = (5/4)\ f_1 = 1.25\ f_1$ (= e.g. 375 Hz)
- **Fourth** - 2 sounds with $f_2 = (4/3)\ f_1 = 1.333\ f_1$ (= e.g. 400 Hz)
- **Fifth** - 2 sounds with $f_2 = (3/2)\ f_1 = 1.50\ f_1$ (= e.g. 450 Hz)
- **Octave** - one sound is 2^{nd} harmonic of the first - i.e. $f_2 = (2/1)\ f_1 = 2\ f_1$ (= e.g. 600 Hz)
- See Monochord Demo….
- Also investigated/studied by Galileo Galilei, mathematicians Leibnitz, Euler, physicist Helmholtz, and many others - debate/study is still going on today...
- These 2-sound combinations are indeed very special!
- The resulting, overall waveform(s) are *time-independent* – they create standing waves on basilar membrane in cochlea of our inner ears!!!
- The human brain's signal processing for these special 2-sound consonant combinations is especially easy!!!
- See Consonance Demos...

Fractal Music

Lorentz's Butterfly - Strange Attractor



Iterative Equations:

$dx/dt = 10(y - x)$

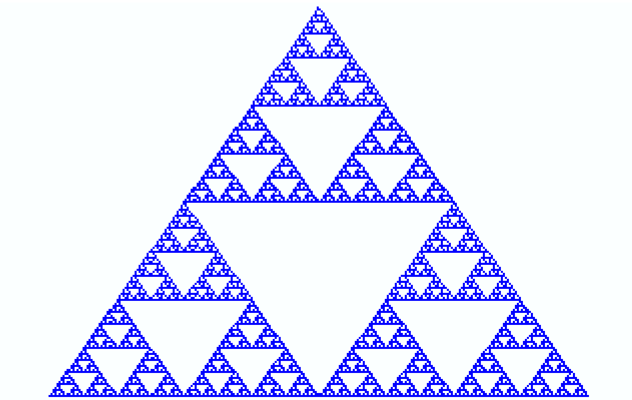
$dy/dt = x(28 - z) - y$

$dz/dt = xy - 8z/3.$

Initial Conditions:

Change of $t = 0.01$ and
the initial values
$x0 = 2$, $y0 = 3$ and $z0 = 5$

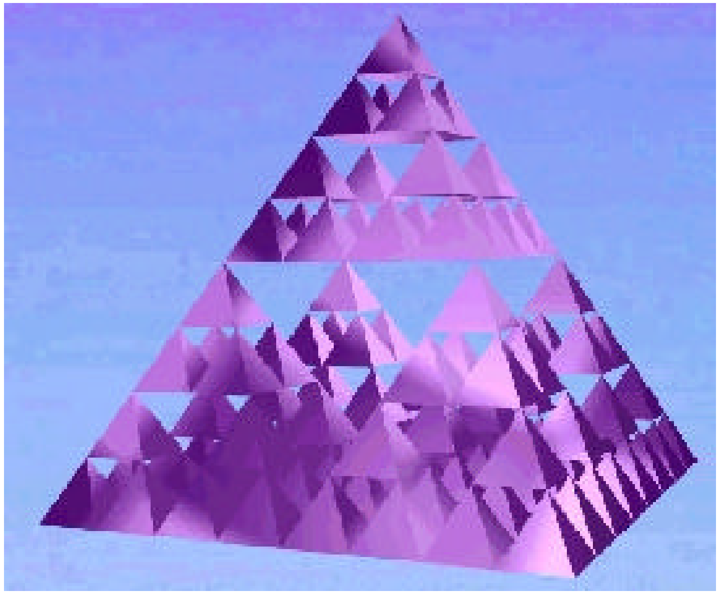
Fractal Music



The Sierpinski Triangle

is a fractal structure with fractal dimension 1.584.

The area of a Sierpinski Triangle is ZERO!



3-D Sierpinski Pyramid

Beethoven's Piano Sonata no. 15, op. 28, 3rd Movement (Scherzo) is a combination of binary and ternary units iterating on diminishing scales, similar to the Sierpinski Structure !!!

Natural Terrestrial/Earth Sounds

Sferics/Crackle

Tweeks

Dawn Chorus

Whistlers

Natural Sounds From Our Solar System

Sun

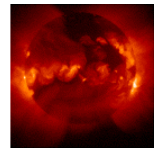
Jupiter

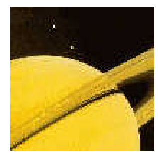
Saturn

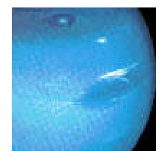
Neptune

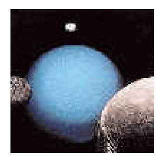
Uranus

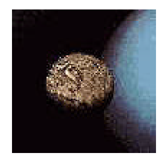
Miranda











Conclusions and Summary:

- Music is an intimate, very important part of human culture
- Music is deeply ingrained in our daily lives - it's everywhere!
- Music constantly evolves with our culture - affected by many things
- Future: Develop new kinds of music...
- Future: Develop new kinds of musical instruments...
- There's an immense amount of physics in music - much still to be learned !!!

MUSIC

Be a Part of It - Participate !!!

Enjoy It !!!

Support It !!!

Thanks to:

Nicole Drummer, Inga Karliner & Kevin Pitts

Special Thanks to:

Bernie Dick, Marion Evans, Gwendolyn Smith & Mark Tomory

For additional info on Physics of Music at UIUC - see e.g.

Physics 199 Physics of Music Web Page:

http://wug.physics.uiuc.edu/courses/phys199pom/

Physics 398 Physics of Electronic Musical Instruments Web Page:

http://wug.physics.uiuc.edu/courses/phys398emi/