The Physics of Music

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Nature of sound waves

- What is a sound wave?
  - Nature of waves: vibrations that transfer energy
  - Sound is longitudinal: the motion of the wave is in the same direction as the energy transfer
  - In most mediums, the speed of sound is \(~343 \text{ m/s}\)
- Sound waves are also pressure waves
  - Compressions are high pressure areas, rarefactions are low pressure areas
  - Distance between successive compressions/rarefactions corresponds to wavelength
  - Changes in pressure are measured in the amplitude of the wave
The Anvil Story

- Believed the music of his time was harmonious enough
- According to a legend, Pythagoras passed a blacksmith who was pounding weights and was intrigued by the different pitches he heard
- Discovered ratios of frequencies
Strings

- Length
- Tension
- Material
Greek to Modern Harmony

- [http://members.cox.net/mathmistakes/greek.mid](http://members.cox.net/mathmistakes/greek.mid)
- Pythagoras discovered the five note scale and the ratios of string lengths
- Applied these ratios to each note in the scale and produced the 12 tone scale
Frequency and Pitch

- **Frequency:**
  - Rate of vibrations that pass a point over a certain period of time
  - Measured in Hertz

- **Human range of hearing**
  - ~20 to ~20,000 Hz
  - Below 20 Hz is infrasound and above 20,000 Hz is ultrasound
  - Most humans can detect differences starting at around 7 Hz

- **Pitch:**
  - Refers to different notes in music
  - Corresponds to frequency (high frequency=high pitch, low frequency=low pitch)
Consonance

- When notes are played simultaneously, their sound waves interfere.
  - Sound waves with frequencies of integer ratios are consonant, or sound good together
  - These notes form musical intervals
- Examples of ratios:
  - Octaves 1:2
  - Fifths 3:2
  - Fourths 4:3
  - Thirds 5:4
Harmonics: The Basics

- Harmonics are key to not only understanding what harmonics are but the functioning of musical instruments.
- Example: the saxophone
- A sound that comes out of an instrument is a mixture of many frequencies which are called harmonics.
- As we know, frequency depends on the pitch of the note being played.
- A higher note has a different set of harmonics than a lower note.
- Harmonics are well mixed so that when one plays a note one does not hear the separate harmonics, but one sound.
- In effect, harmonics add to sound quality.
Where do harmonics come from?

If I play a G on the saxophone using vibrato (a musical technique), I can create a vibrating air column. Once I have my vibrating air column, harmonics are produced in halves, thirds, and fourths. Remember all these harmonics occur at the same time to create a rich, complex sound!

Due to resonance, or the ability of a sound to vibrate at maximum amplitude at a particular frequency, overtones can be heard. Overtones are heard in the higher harmonics such as for the thirds and fourths.
Timbre and Tone

- **Timbre:**
  - The color or “tone” of an instrument
  - Timbre is determined by the materials and design of the instrument itself. This is what allows us to tell the difference between instruments, even when they’re playing the same note.

- Timbre has many descriptions including:
  - Clear
  - Brassy
  - Reedy
  - Harsh…etc.

- Unique timbres are created by the unique harmonic frequencies that occur when a note is played on an instrument. These harmonic frequencies (overtones) happen at multiples of the note’s main frequency due to resonance in the instrument.
Fundamental (13 Hz)

Micromachine Accelerometer:
0.02% Total Harmonic Distortion

Geophone:
0.09% Total Harmonic Distortion
Resonance is the tendency of a system to oscillate at maximum amplitude at certain frequencies.
- Increase of amplitude as damping decreases and frequency approaches resonance frequency.
Resonant phenomena occur with all types of vibrations or waves. Resonant systems can be used to generate vibrations of a specific frequency, or pick out specific frequencies from a vibration containing many frequencies. Resonance occurs widely in nature, and is exploited in many man-made devices. It is the mechanism by which virtually all sinusoidal waves and vibrations are generated. Light and other short wavelength electromagnetic radiation is produced by resonance on an atomic scale, such as electrons in atoms.
Example:

- Maximum amplitude
- Resonance frequency
Acoustics

- Acoustics is the science of sound
  - Includes its production, transmission, and effects
  - “The acoustics of a room are those qualities that together determine its character with respect to the perception of that sound.” (Glossary of Acoustical Terms)

- Some main reasons for acoustical sound:
  - Wave Interference
  - Doppler Effect
  - Decibels
Wave Interference

- The phenomenon which occurs when two waves meet while traveling along the same medium. They pass through each other without being disturbed.
- Destructive and constructive interference help to explain the differences in the wave interaction and how we as humans perceive them (i.e. acoustics).

The Doppler Effect:

- The Doppler Effect is the shift in frequency and wavelength of waves which results from a source moving with respect to the medium, a receiver moving with respect to the medium, or even a moving medium.
- Change in the observed frequency (or wavelength) of waves due to relative motion between the wave source and the observer.
Decibels

- How do we measure sound?
  - Decibel: “A dimensionless unit which denotes the ratio between two quantities that are proportional to power, energy or intensity.” (Glossary of Acoustical Terms)
  - The decibel is commonly used in acoustics to quantify sound levels relative to some 0 dB (decibel) reference.
  - The reference level is typically set at the threshold of perception of an average human and there are common comparisons used to illustrate different levels of sound pressure.

- Decibels provide a relative measure of sound intensity.
  - The unit is based on powers of 10 to give a manageable range of numbers to encompass the wide range of the human hearing response.
Decibels at work
Possible exam questions

1. How do simultaneous sound waves form musical intervals?
2. What is a total possible number of nodes and antinodes in a third harmonic?
   A. 5
   B. 6
   C. 7
   D. 8
   E. 8.5
3. Timbre is caused by...
   A. How loud the instrument is played
   B. The specific note that is played
   C. The harmonic frequencies that are caused by the instrument’s design and material
   D. The skill of the player