Physics of Music

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Sound

- Sound refers to the physical sensation that stimulates our ears
- The source of a sound always starts with a vibrating object
- The vibrating source gives off energy in the form of longitudinal waves
- These sound waves travel in the air, and the vibrations in the air force our eardrums to vibrate and that’s how we get sound

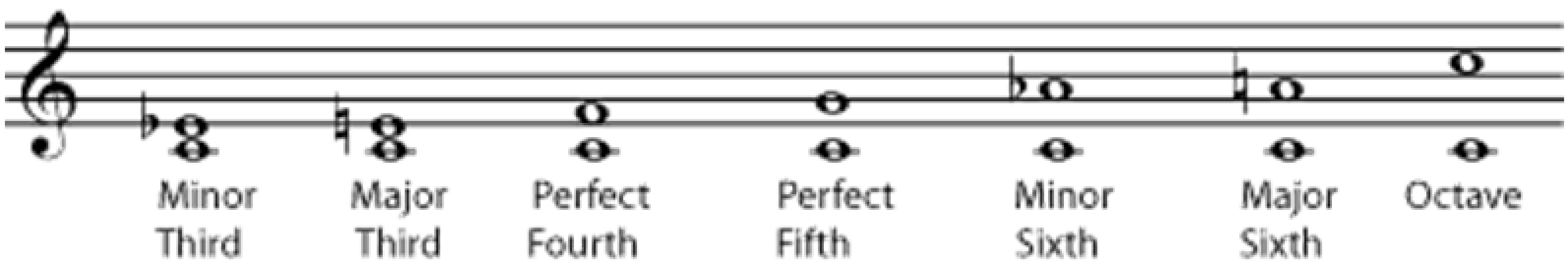
Harmony and Overtones

Consonance and Dissonance: Why Music Sounds Good

- First of all, to say what sounds “good” or “bad” is largely subjective
- But within Western culture, there has developed a sort of standardization of “good” and bad”
  - Development of scales
  - “Rules” in music
- Since we’re all probably most familiar with the Western music system, for the sake of this lecture, we’ll just consider the differences between the **12 notes** in that system
  - In case you forgot, the notes are: A,B,C,D,E,F,G
  - …and their flats/sharps, which makes the complete scale: A, Ab/B#, B, C, Cb/D#, D, Db/E#, E, F, Fb/G#, G, Gb/A#
  - So, in theory, I could play any two of those notes at the same time and, depending on their distance apart from each other on the scale, some notes would sound better together than others.
  - <u>Consonance</u> is when they sound good
  - <u>Dissonance</u> is when they sound bad

Traditional Intervals

- An interval is the amount of "space" between two notes on a scale
- Here are the consonant intervals:



Traditional Intervals

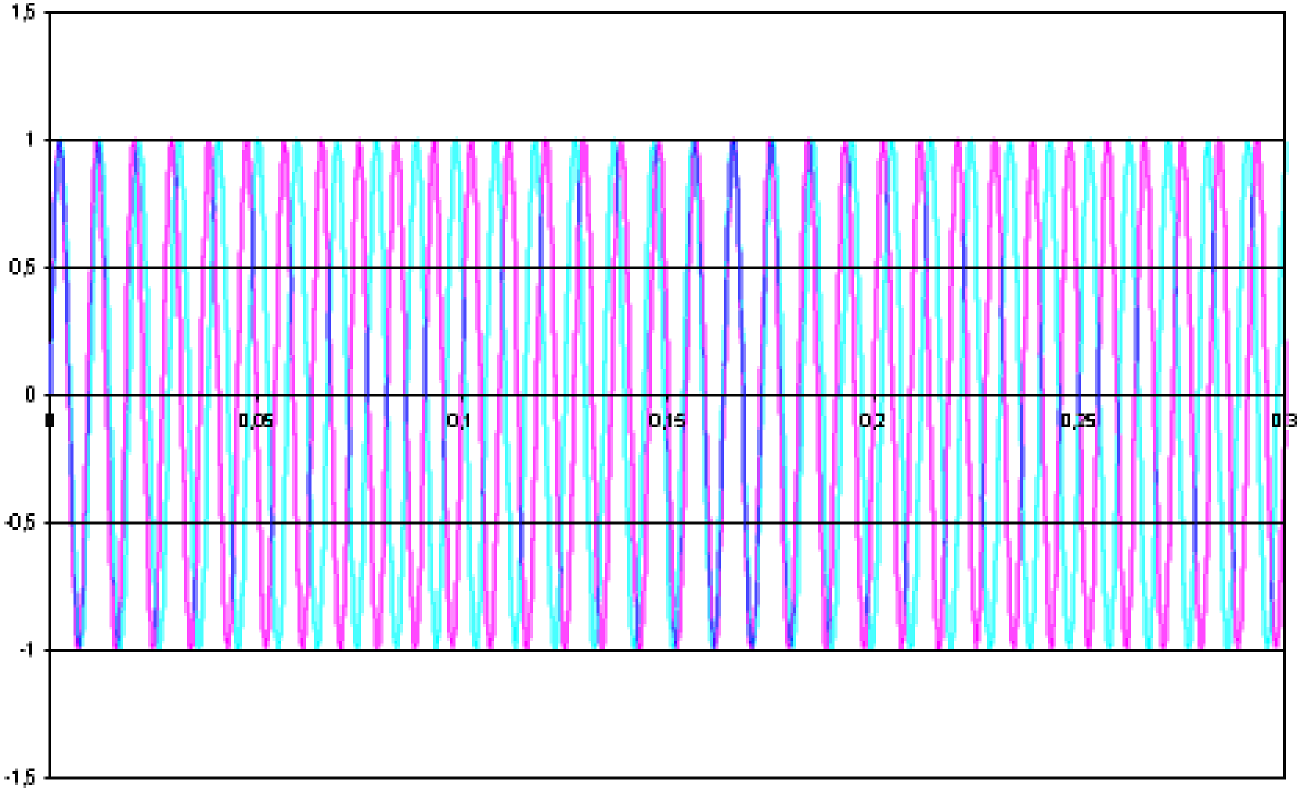
- And here are the dissonant intervals:

- Notice how the first two dissonant intervals are *really* close together?

Dissonant Tones

- We get different pitches for sound by altering its wavelength.
- (Shorter wavelength = higher frequency = higher pitch)
- So, when two similar, but not quite matching tones are played simultaneously, you get interesting destructive and constructive patterns of interference.

Dissonant Tones

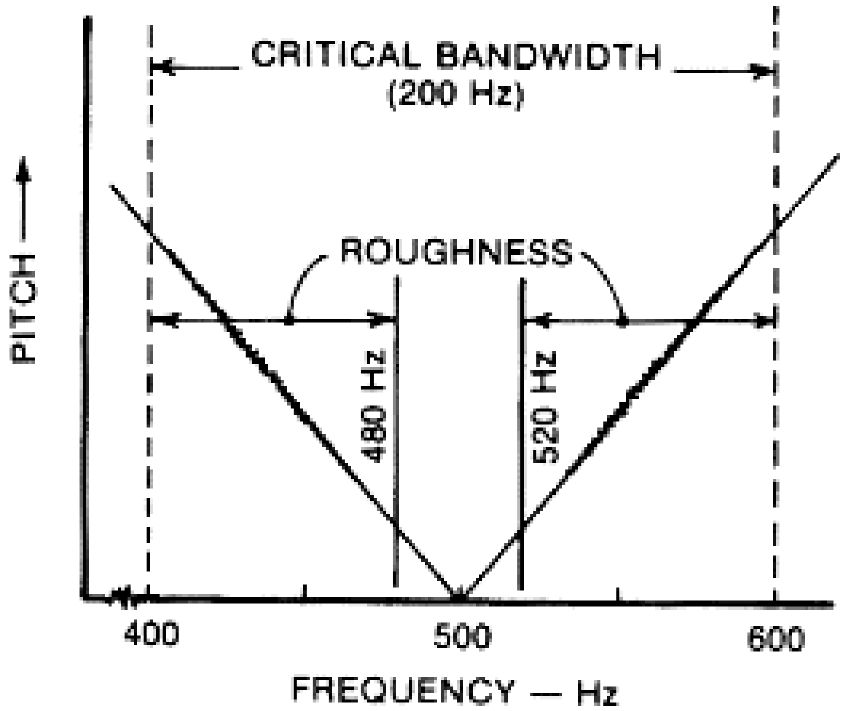


Dissonant Tones

- There are areas where the two tones line up perfectly (represented in blue) as well as areas where they come *close*, but don't exactly line up (represented in pink and teal)
- You'll know what these sound like when you hear them. It's a phenomenon known as "beating."
- The tiny little deviations from symmetry, depending on both the size of the deviation, and *your* particular sensitivity to different tones are what traditionally constitutes dissonance in music.

Critical Bandwidth

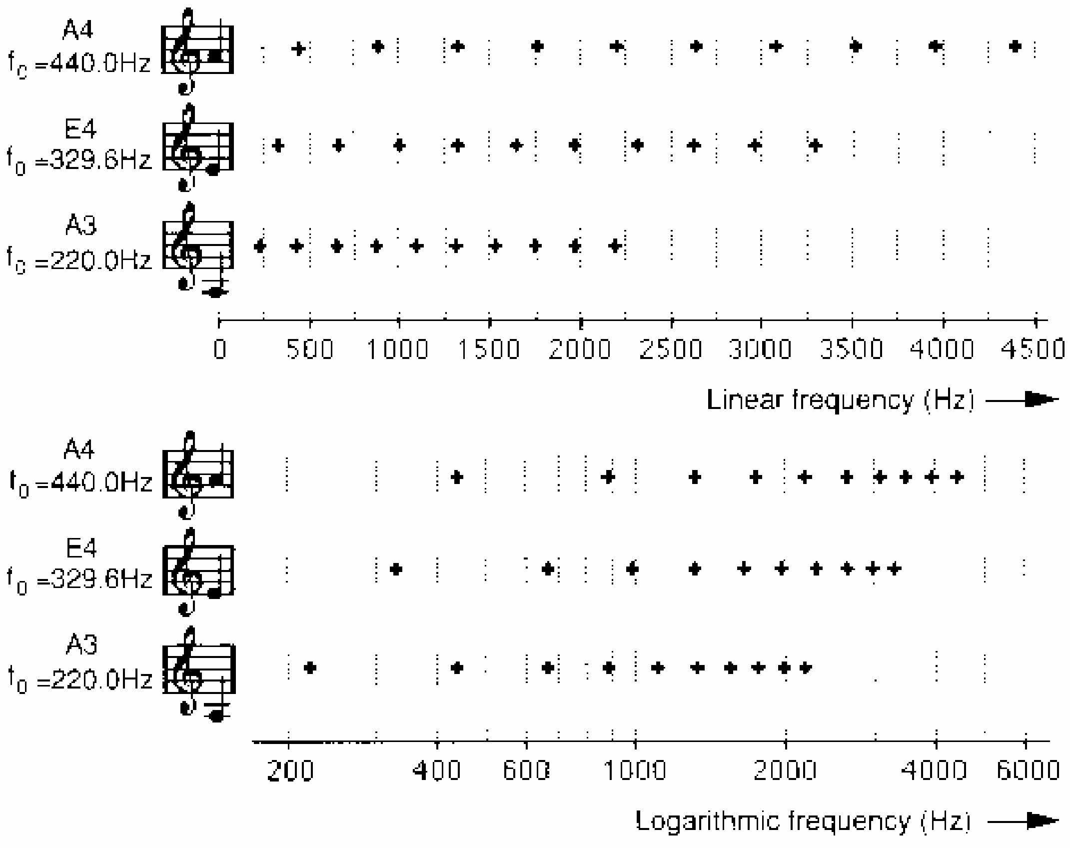
- This is known as the Critical Bandwidth:



Consonance

- So why do certain notes sound good together?
- Because sometimes two different wavelengths will interfere constructively in all or many of the right places:

Consonance



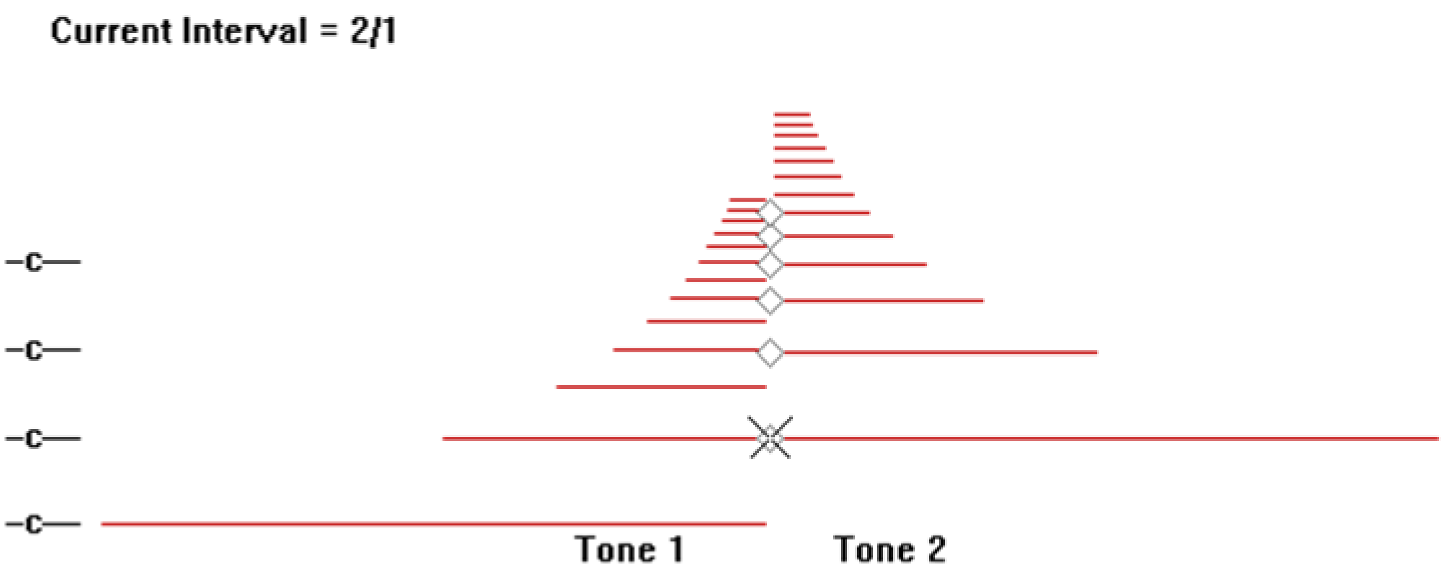
A4
f0 =440.0Hz
E4
f0 =329.6Hz
A3
f0 =220.0Hz
0 500 1000 1500 2000 2500 3000 3500 4000 4500
Linear frequency (Hz)
A4
f0 =440.0Hz
E4
f0 =329.6Hz
A3
f0 =220.0Hz
200 400 600 1000 2000 4000 6000
Logarithmic frequency (Hz)

Two Different A’s?!

- Yes. Which brings us to the next interesting thing about music.
- You can have the same note represented in a number of different pitches. The only limitation is the range of your particular hearing.
- Did you notice the frequencies of the A3(220.0Hz) and the A4(440.0Hz) above?
  - One was exactly half of the other.
  - This is why, when I place my finger on the 12th fret of a guitar and pluck the same string, I produce the same note as when the string is plucked “open.”
  - The only difference is that the note from the 12th fret is higher pitched, because it’s double the frequency of the “open” note.
  - You’ll also notice that I’ve cut the guitar string *exactly* in half.

Converging Tones

- Like we said, sometimes two notes will have wavelengths that line up together nicely.



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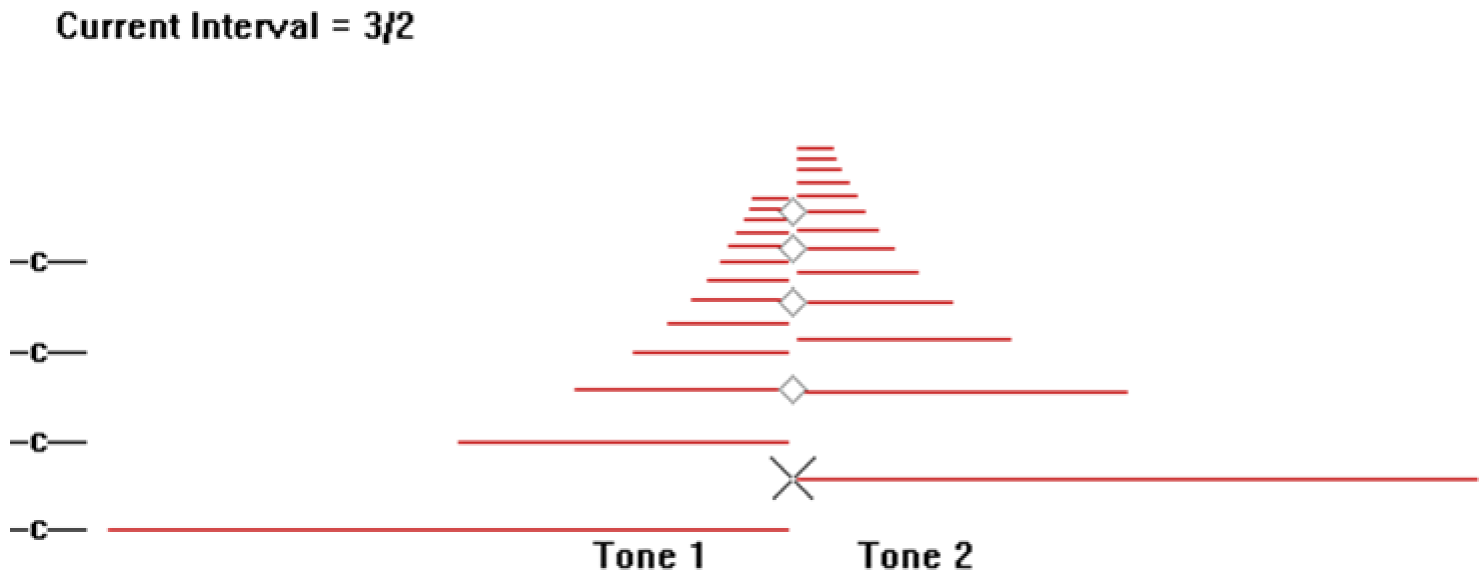

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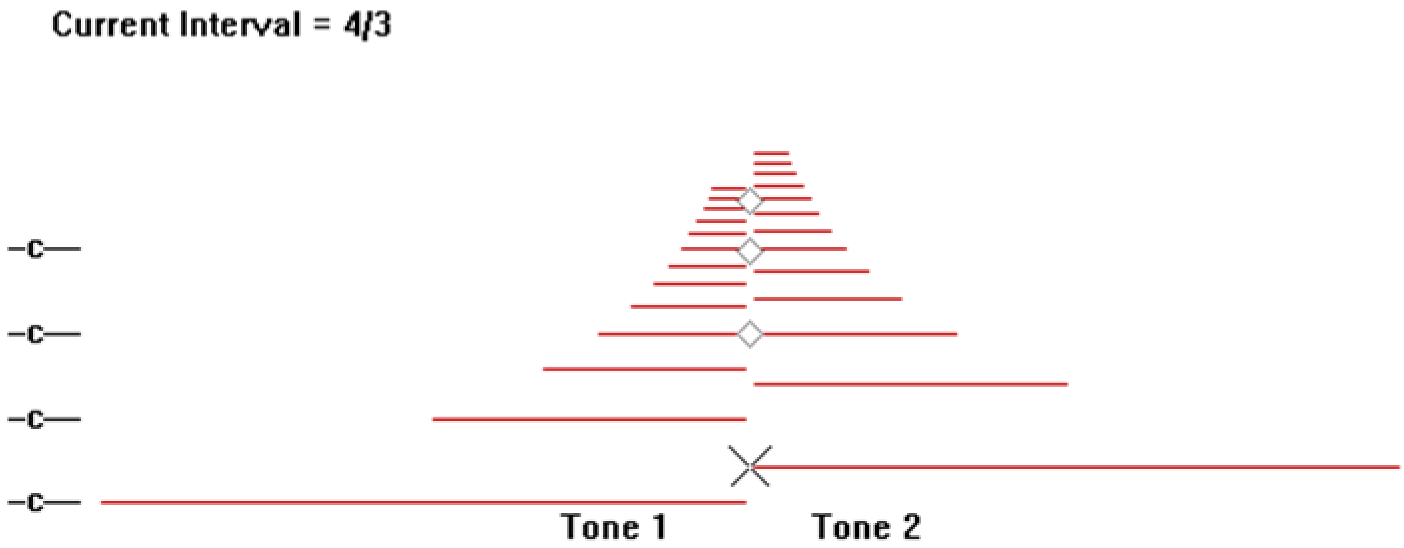

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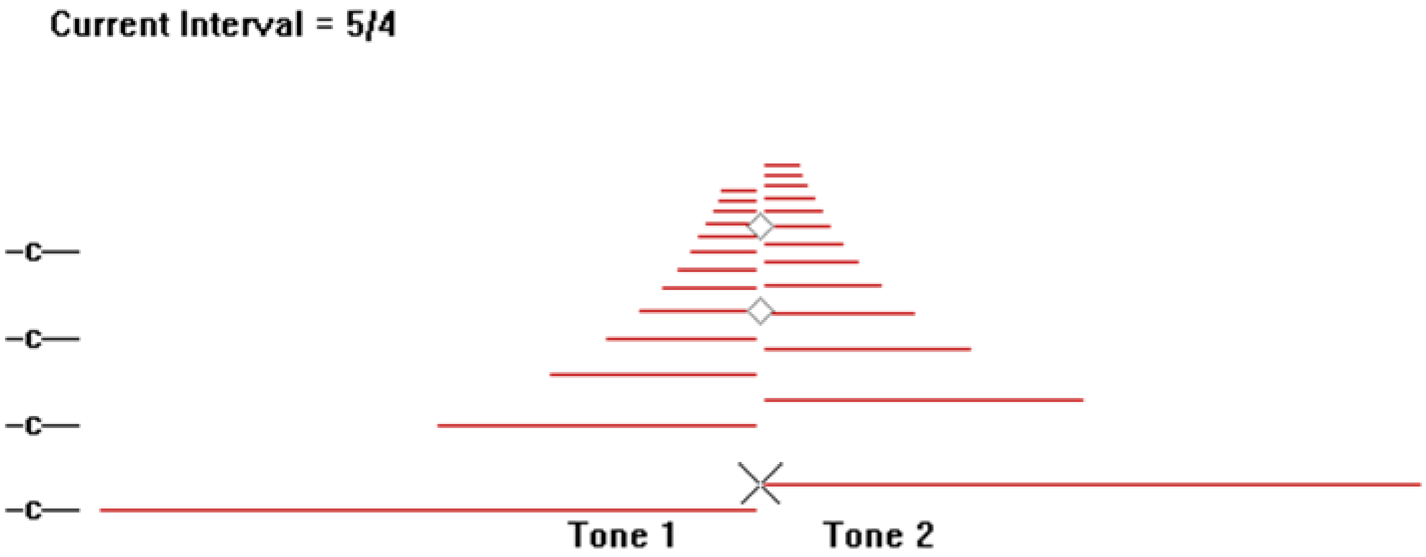

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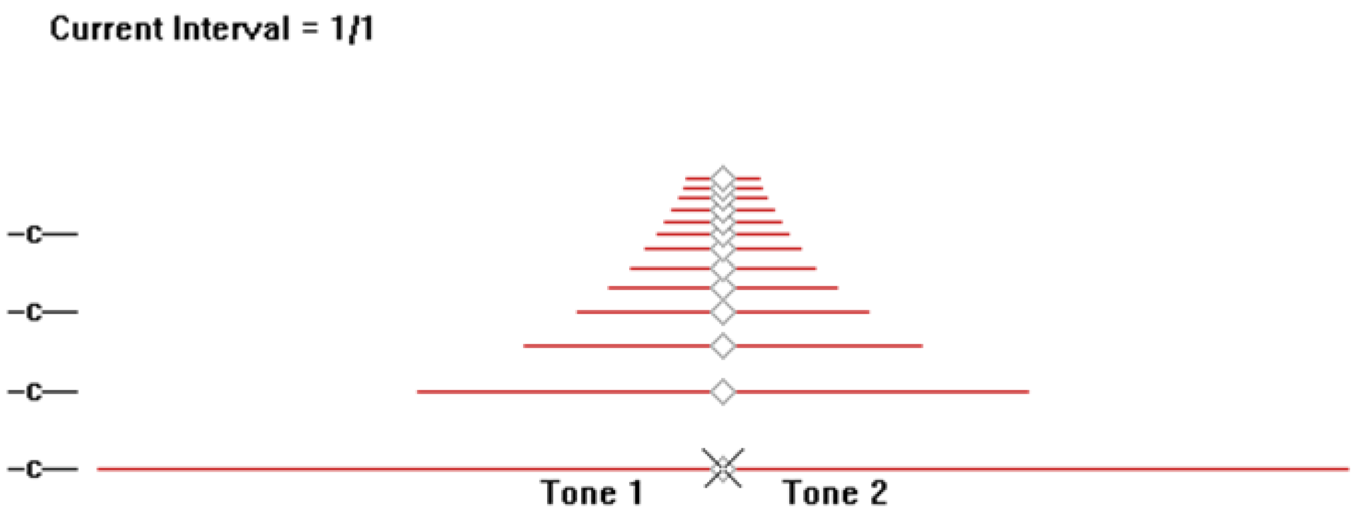

What about the SAME note on two DIFFERENT instruments?!

- The thing about sound that comes out of an instrument (except for flutes and tuning forks) is that you never get what's called a "pure tone."
- This is a pure tone:

- Most instruments do not make sounds like that, and the reason is because of their overtones

Overtones

- Essentially, overtones are frequencies at integer multiples of a fundamental tone.
- Remember the two different A's? They had different frequencies. A4(440 Hz) was an integer multiple of A3(220 Hz), because its frequency was exactly double, or a multiple of 2.
- Since "exactly double" is the first integer multiple you can get, in music this is known as the first harmonic

Anyway…

- All that stuff leads up to why the same note will sound distinct between two different instruments.
- The reason is, every instrument produces its own specific set of overtone frequencies. So, an acoustic guitar string, when plucked, might have a little more of the A4 frequency than the A3; but a piano, on the other hand, might have more A3 than A4. This, called <u>timbre</u> creates a different “voicing” of the same note.
- There are so many different ways to vary the overtones produced by an instrument

Anyway…

- For stringed instruments:
  - String thickness
  - Body composition
    - i.e. the type of wood used
    - or the overall size of its acoustic chamber
  - Where, on the string/along the body the note is produced
- For wind instruments:
  - Hollowness
  - Material composition
  - Reed composition
  - Size
- Basically, any physical aspect of an instrument is at least indirectly related to the sounds it can produce.
- So, exactly like with blackbody radiation, each instrument has its own **unique spectrum** of overtone frequencies.

Finally, just a little bit on progression

- Of course, we don’t always make music with just one note at time. For stringed instruments, like the guitar or piano, it’s possible to play several notes at once. These are called chords.
- Remember how it went A, B, C, D, E, F, G?
- To “build” a chord, all you have to do is skip over every other note.
- So, an A chord would look like this: A C E (G)
- And a C chord would look like this: C E G (B)
- Those two chords share a lot of the same notes.
- That means they share a lot of the same frequencies.
- That means, when I go from the A to the C, I won’t have a jarring change of frequencies, and the transition will sound pretty nice.

Harmonics, Overtones, and More on Timbre…because timbre is the spice of life!

- The reason is that every instrument produces a particular arrangement of *overtones* that give the instrument its characteristic tone color.
- Overtones are just what they say they are:
- "Tones" that sound "over" any given note, which is called the *fundamental.*
- Every note that is produced has a *fundamental* pitch, which is basically the longest wavelength we hear. It also happens to be the name of the note. However, our ears are not only picking up this fundamental frequency, but also a particular arrangement of higher frequencies/vibrations *above*, or *over* the note "C" (hence the term "overtones").
- So an overtone will always have a higher frequency than its fundamental. In fact, each overtone is always an integer multiple of the fundamental, *f,* and can be expressed like this: *f, 1f, 2f, 3f, 4f,* etc.

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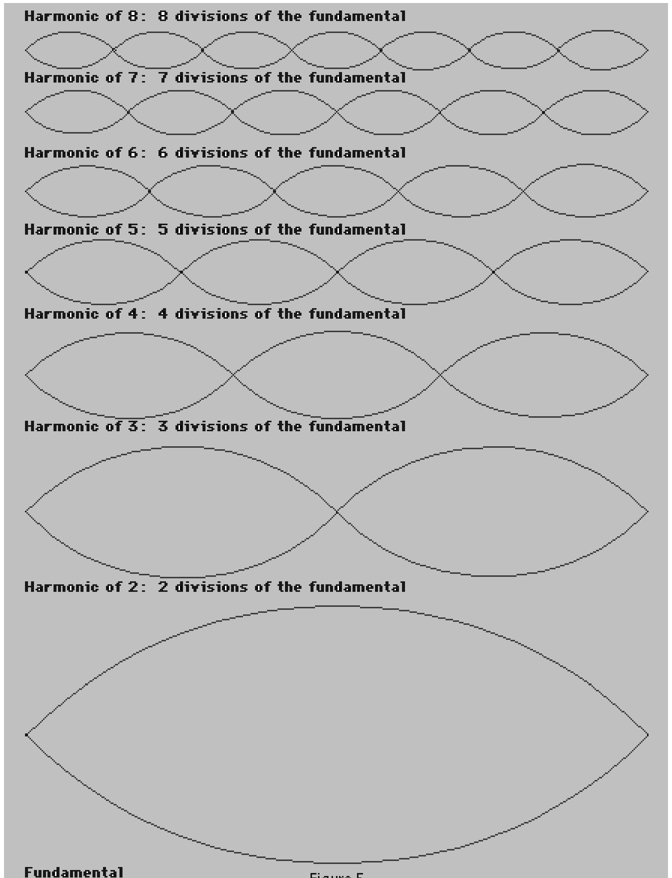

Figure 5
Wave Form of the Harmonic Series

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- Remember that the longest wavelength also corresponds to the lowest frequency, or lowest pitch. You can think of the fundamental as the open string of a violin, which is the lowest sounding note you can achieve on that particular string.
- Fun fact: Computer-generated instruments get their sounds from using the particular overtone pattern of the instrument they are mimicking. For example, a clarinet sound contains a LOT of the odd overtones (f, $3f$, $5f$, etc.) and hardly any of the even overtones, so a computer-generated clarinet sound would simply create a sound using those particular overtones.

Harmonics

- One way of getting very close to the sound of a pure tone is to use *harmonics.* Harmonics are notes that produce a lot <u>more</u> of their fundamental pitch and a lot <u>less</u> of all the overtones above the fundamental.
- On a stringed instrument, harmonics are created by lightly touching the string at a *node*. A node is a point on the string where the sound wave is at a minimum. It corresponds to the point along a standing wave where the amplitude would be close to zero.
- Jump Rope!!!

The Range of Human Hearing

- Quick Review: The number of vibrations produced per second is called frequency, which is measured in hertz (Hz). One hertz is equal to one vibration per second.
- Really low pitches have not only longer wavelengths (as mentioned earlier) but also lower frequencies.
- Likewise, really high pitches have shorter wavelengths and higher frequencies.
- The average healthy, young adult can hear from around 20 Hz – 20,000 Hz. This range becomes much narrower with age, and the higher end of the spectrum declines much more rapidly in men than women. (Go ladies!)

The Range of Human Hearing

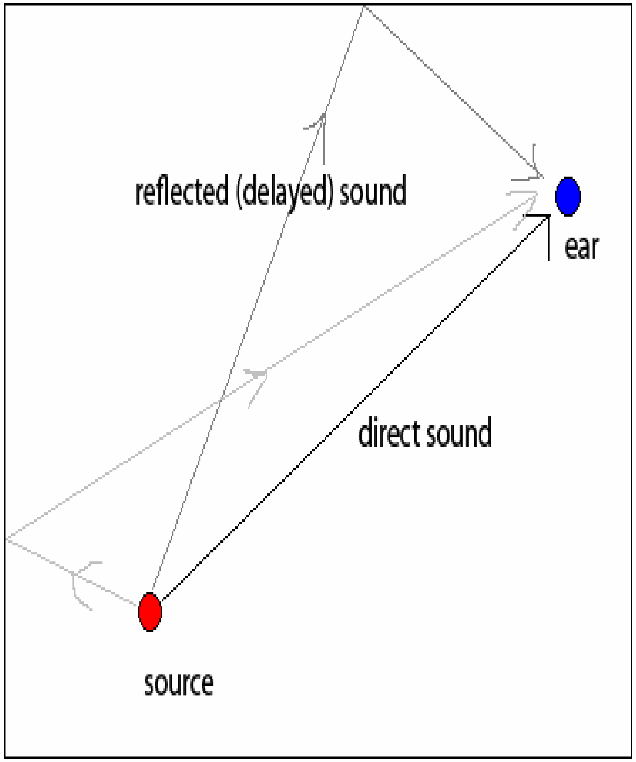
- Dog whistle = 20,000-22,000 Hz.
- Since it is too high for our hearing range, it is called *ultrasound.*
- When something is below the range of human hearing, we call it *infrasound.*
- Lowest "audible" note on a Tuba (low C)= 16 Hz!
- Even though the fundamental is below our range of hearing, all of the overtones above it are audible. Thus, our brain convinces us that we hear this low note on the tuba whereas we could never hear this pitch on a sound generator with no overtones – we would merely feel the vibrations.
- **…and finally…**

PHANTOM TONES!!! (don don don!)

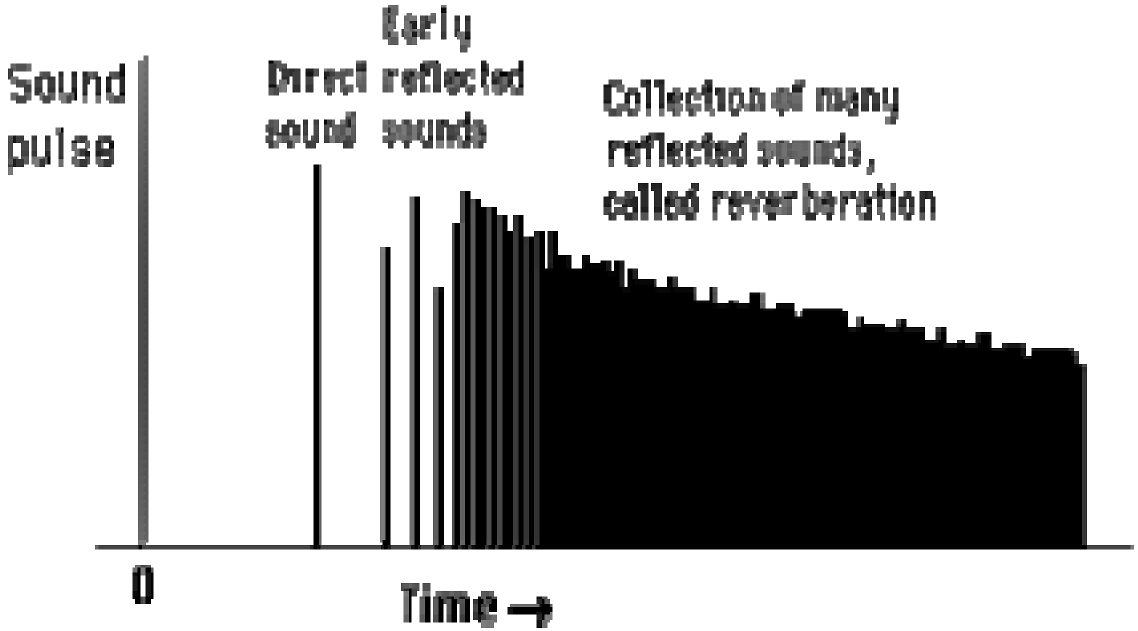
- Sound is a sensation in the brain created in response to small pressure fluctuations in the air.
- The entire sound does not even have to *exist* for us to be able to hear it…
- Studies have shown that if we hear three successive pure tones in the overtone series of any note, we will hear that note. So if we hear only *5f, 6f*, and *7f*, our brains still interpret the pitch of *f*. Our brains are effectively creating a phantom note for our ears to hear that doesn't actually exist!!

Musical Acoustics

- “The meeting place of music”
  - Physics of vibrating objects
  - Auditory Science
  - Architecture



- Constructive/Destructive Interference
- Acoustic Space
  - Conceptual
  - Emotional
  - Visual
  - Aural
- Reverberation



Reverberation

- The delay between direct sound and early reflected sounds
- The overall reverberation time

Criteria for Good Acoustics

- Achieve good projection of sound and retain clarity – overall reverberation time of 1.5-2.5 seconds
- Take into account subjective attributes such as “intimacy,” “liveliness,” and “warmth” – time between direct sound and early reflected sound of 30-50 milliseconds
- Achieve even dispersion of sound – echoes
- Overcome bass-loss problem

Concert Hall Acoustics

- When sound enters a new medium, it is reflected, transmitted, or absorbed.
- Sound can also be absorbed by different objects such as cork, rubber or acoustical tiles.
- In building concert halls, it is extremely important to take into consideration room acoustics because of the way sound moves.
- Concert halls acoustic designs have two basic properties: room acoustics and noise control.
- The design of the concert hall down to the furnishings, shaping and finishes are necessary to have that natural (unamplified) sound of musical instruments.
- Good acoustics in a concert hall means that there is a good sound distribution throughout the room as well as the freedom from acoustical disturbances (such as echoes or disturbing noises), natural sound diffusion and envelopment.

Concert Hall Acoustics

- Many concert halls generally play classical music, and symphony concerts have a special orchestral shell that is designed to put the orchestra in the same room with the audience.
- The orchestral shell eliminates soung energy loss and late arrival of sounds from the back of the stage.
- Noise control (the elimination of distracting sounds from the concert hall) is the other discipline in auditoriam acoustics.
- There are a number of typical disturbing noises such as within the concert hall or from outside sources or the buildings mechanical systems.
- First there is an “envelope” (also known as the room’s shape and volume) that is the interior of the auditorium; it has all the proper interior finishes and furnishings. Once that has been designed, only then can the floor, wall and ceiling structures to enclose the “envelope” are designed.

THEREMIN!

- One of earliest electronic musical instruments: not touched
- Invented by Leon Theremin in 1919 (Russia).
- Two metal antennas sense the position/motion of hands: “oscillators.” One hand is frequency, other is volume.
- Electric signals created, amplified, sent to a loudspeaker or amplifier.
- “The Day the Earth Stood Still,” “Mars Attacks!”, “The Lost Weekend,” as well as “The Thing.”
- **History**: Originally Russian government-sponsored project for proximity sensors. Theremin demonstrated his instrument and impressed Vladimir Lenin. Patented in the U.S. in 1928.
- Clara Rockmore (classical repertoire), Paul Robeson. Post-WWII American interest generated, later diminished.

THEREMIN!

- **Operating**: Heterodyne principle: to generate audio signals. Hands=grounding plates. Difference between frequencies of the two oscillators at each moment generates beat frequency in the audio frequency range, which create the audio signals, which are then sent to the loudspeaker or amplifier: any pitch throughout its entire range.
- Signals create vibrations, just like in all electronic instruments
- http://www.youtube.com/watch?v=Wph6wGwPn9M&feature=related
- http://www.youtube.com/watch?v=mW0B1sipLBI&feature=related