Why do musical instruments sound different from each other?

First of all, here's a challenge ...

See if you can identify the following instruments:

#1

#2

#3

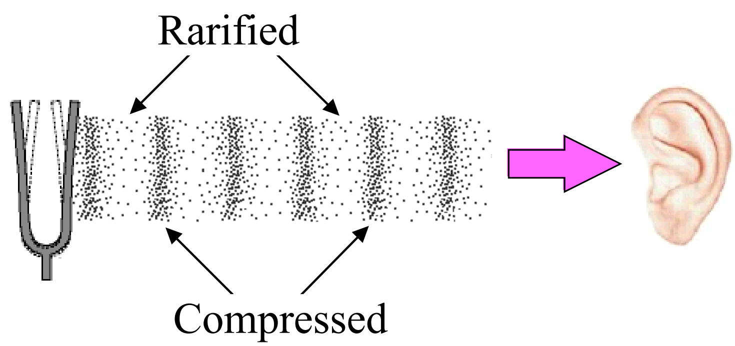
#4

#5

Why do they sound so very different?

In order to answer that question:

- ♫ First of all, what is sound?
- ♫ What are pure tones?
- ♫ Complex waveforms.
- ♫ Harmonics and waveforms from tubes
    - open tubes (flute, recorder penny whistle)
    - closed tubes (reed instruments, trumpet)
- ♫ Harmonics and waveforms from a stretched string
    - guitar
    - violin

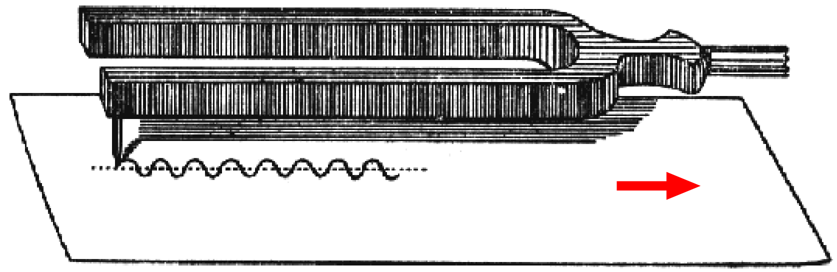


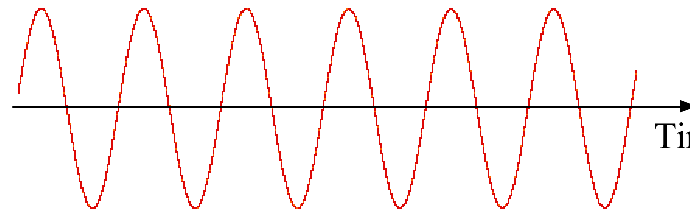
When a tuning fork is struck the prongs oscillate back-and-forth at a constant, single frequency. The oscillating prongs cause the air molecules to vibrate with the same frequency as the prongs. The air becomes alternately rarified and compressed producing a sound wave. The wave propagates to your ear. The oscillating air molecules cause your eardrum to vibrate at the same frequency.

Sound waves are longitudinal waves, which means the direction of oscillation is the same as the direction of propagation. However, as this animation shows, the air molecules only oscillate back-and-forth; *they do not travel from the source of sound into your ear, even though it might look like it!*

Watch the red dots in this animation.

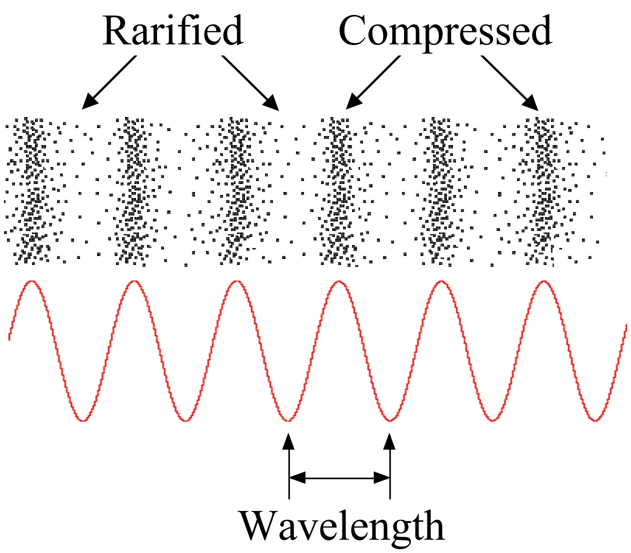
http://www.acs.psu.edu/drussell/demos/waves/wavemotion.html





A tuning fork produces a pure tone, i.e., a single frequency that can be represented by a simple *sine-wave*. The frequencies of tuning forks for:

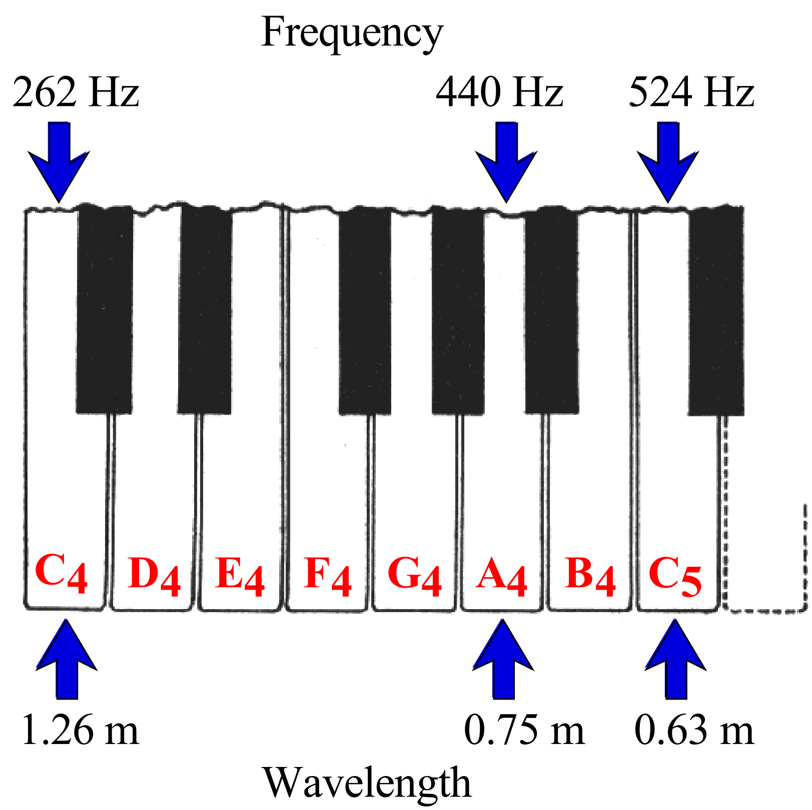
- Middle C (C_4) is 262 Hz.
- A_4 (above C_4) is 440 Hz.
- C_5 (an octave above C_4) is 524 Hz.

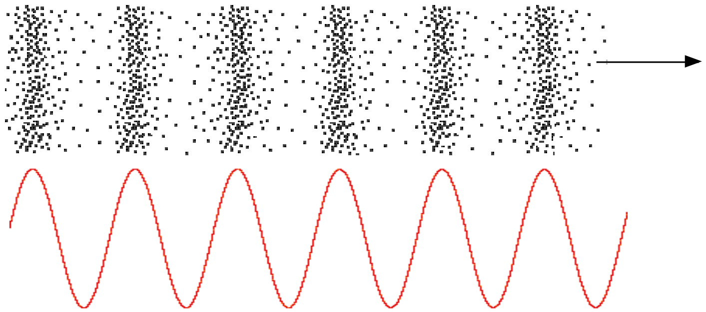


There is a simple relationship between the frequency of the tuning fork and the wavelength of the wave.

Higher frequency	⇔	Shorter wavelength
Lower frequency	⇔	Longer wavelength

Double/halve frequency ⇔ Halve/double wavelength





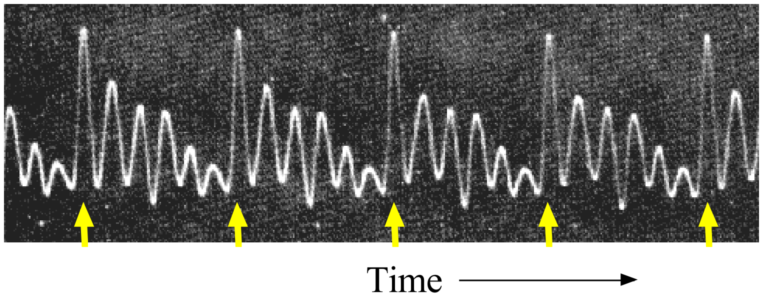
The speed of sound depends on the density of the gas it is traveling in. For example, in air the speed is about 340 m/s, i.e., about 760 mi/h; in helium, the speed is about 950 m/s; in argon the speed is about 319 m/s. For a given wavelength, the frequency of the sound depends on the speed; a greater speed means a higher frequency (pitch), which is why your voice is "squeaky" after your inhale helium!

What would happen to the sound of your voice if you inhaled argon?

If all musical instruments produced only pure tones, we wouldn't be able to tell the difference between different instruments! In fact, very few sounds are pure tones; most have a very complex waveform. How can we make a picture of the waveform?

We can connect a microphone to an oscilloscope. The microphone converts oscillations in the air into electrical signals, which can be displayed on an oscilloscope.

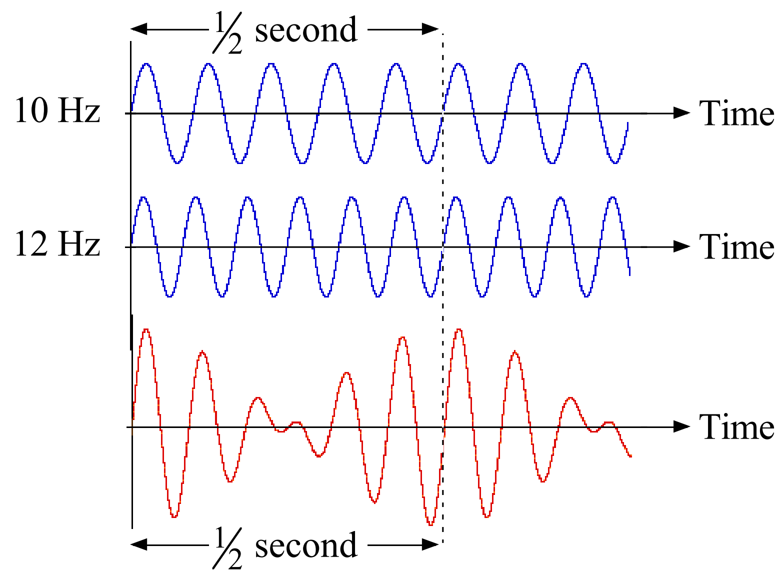
Here is an example of a waveform on an oscilloscope.



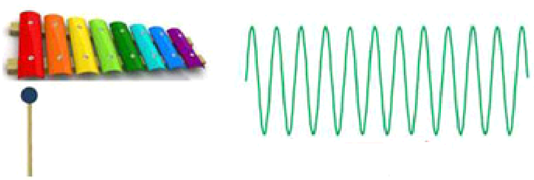
It is the waveform produced by a bass singing ***ah*** (as in f***a***ther) at a pitch of F_3 (about 174 Hz). Although the pattern looks complicated, it does repeat every 0·006s, which corresponds to a frequency of 174 Hz.

How are complex waveforms produced?

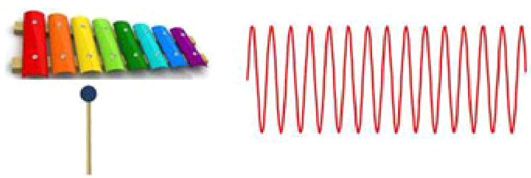
Answer: when waves of different frequencies are combined. The frequencies can be *unrelated*:



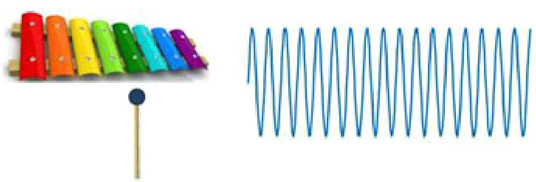
As an example, think of a chord made up of three notes ... middle C, middle E and middle G:



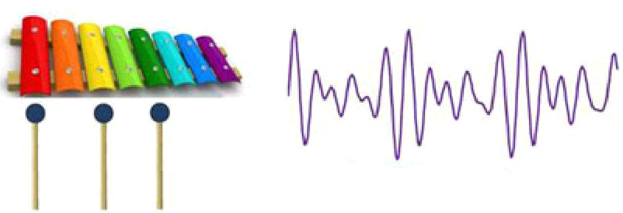
Middle C (262 Hz)



Middle E (330 Hz)

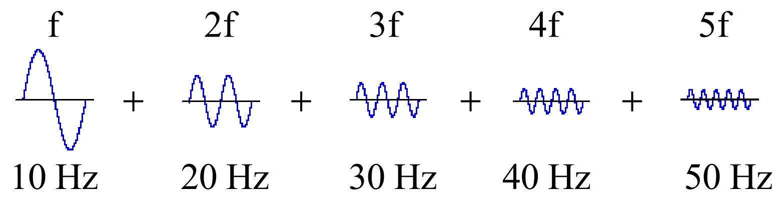


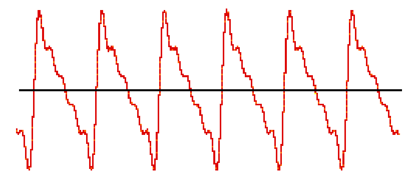
Middle G (392 Hz)



Chord: C + E + G

However, the frequencies can be related, for example, a series of ***harmonics***:





In this example, the *fundamental* frequency is 10 Hz. The additional frequencies are multiples of the fundamental and are called *harmonics*.

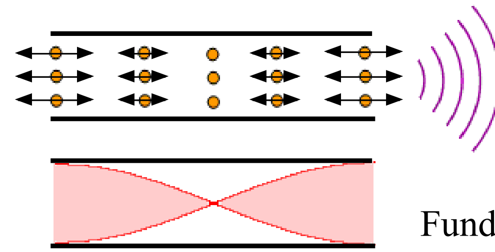
Here's what a trumpet and a violin sound like playing B_4 (494 Hz).

Here's what a trumpet and a violin sound like playing B_4 (494 Hz) when the higher frequencies (i.e., the harmonics 2f [988 Hz] , 3f [1482 Hz], 4f, [1976 Hz] etc.) are filtered out.

Now, they sound the same! It is the higher harmonics that give musical instruments their characteristic sounds.

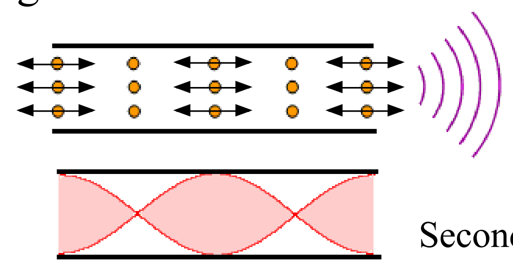
Let's look at how harmonics are produced ....

The harmonics of an open tube (roughly similar to a flute, recorder, penny whistle):

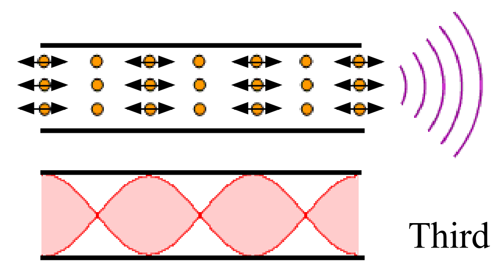


Fundamental (f)

The fundamental frequency (f) depends on the length of the tube.

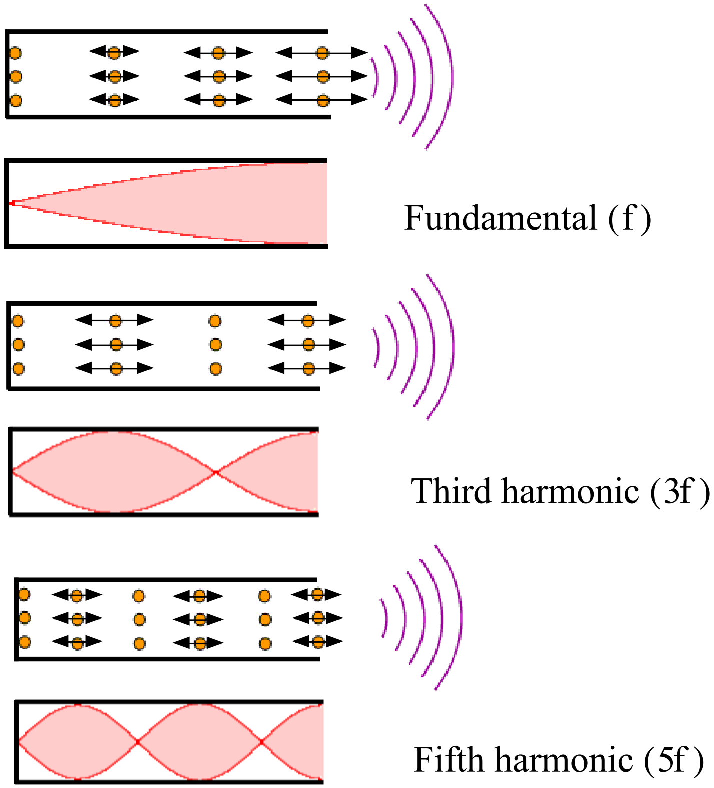


Second harmonic (2f)

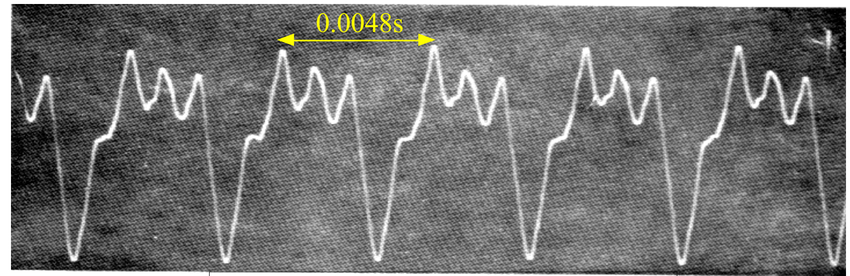


Third harmonic (3f)

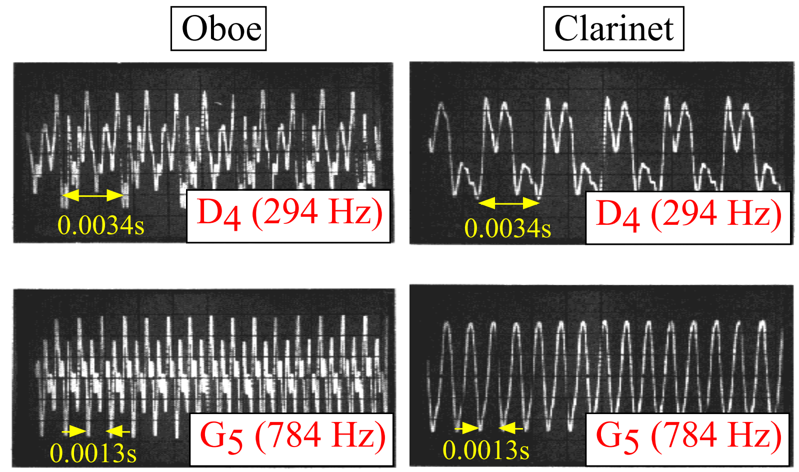
The harmonics of an closed tube (roughly similar to a clarinet [and other reed instruments], trumpet, trombone):



The odd harmonics tend to dominate in these types of instruments.

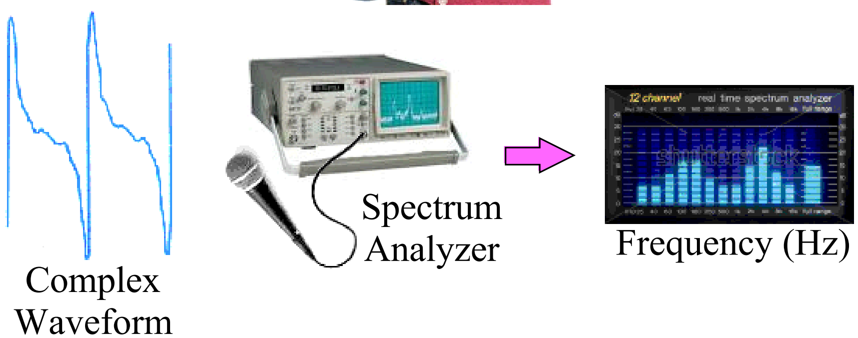


Waveform for a saxophone playing G# (208 Hz)



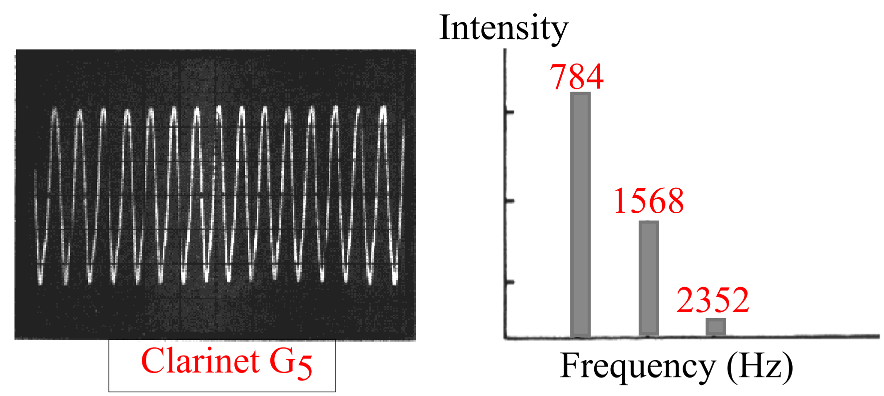
The waveforms for three different instruments. Note that even though the notes played by the oboe and clarinet are the same, the waveforms are very different. That's why they sound different.

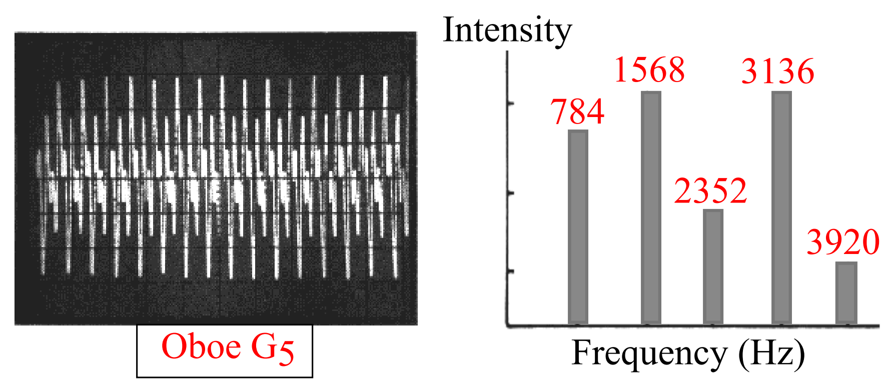
How do we find the components of a complex waveform? We use a *spectrum analyzer*.



A spectrum analyzer determines not only what frequencies are present but the amount of each of the components.

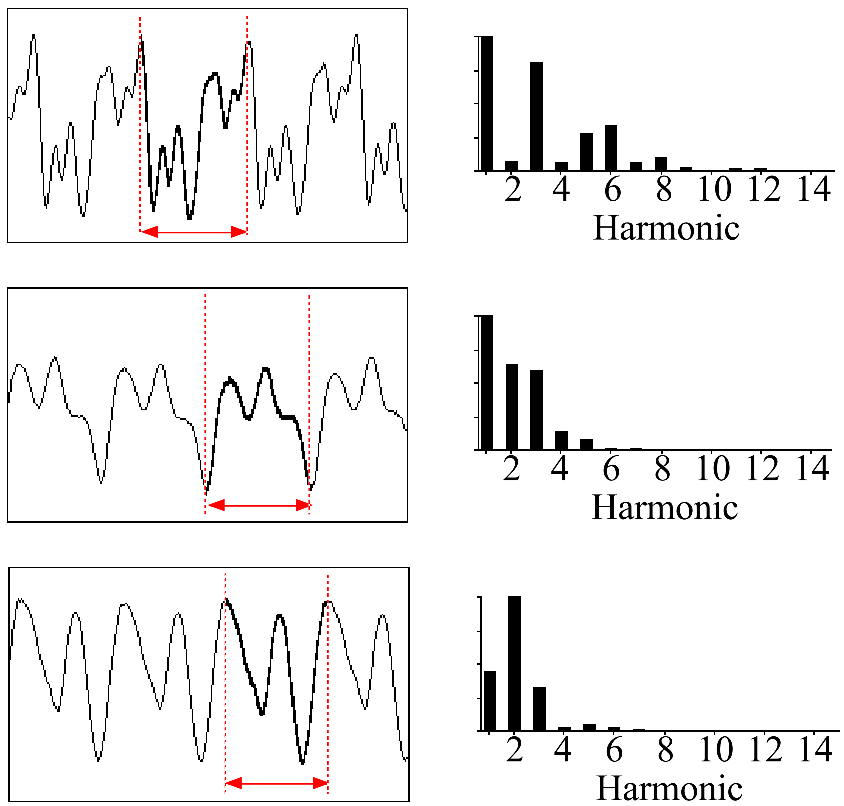
The components of the waveforms from a clarinet and an oboe playing the same note G_5 (784 Hz).



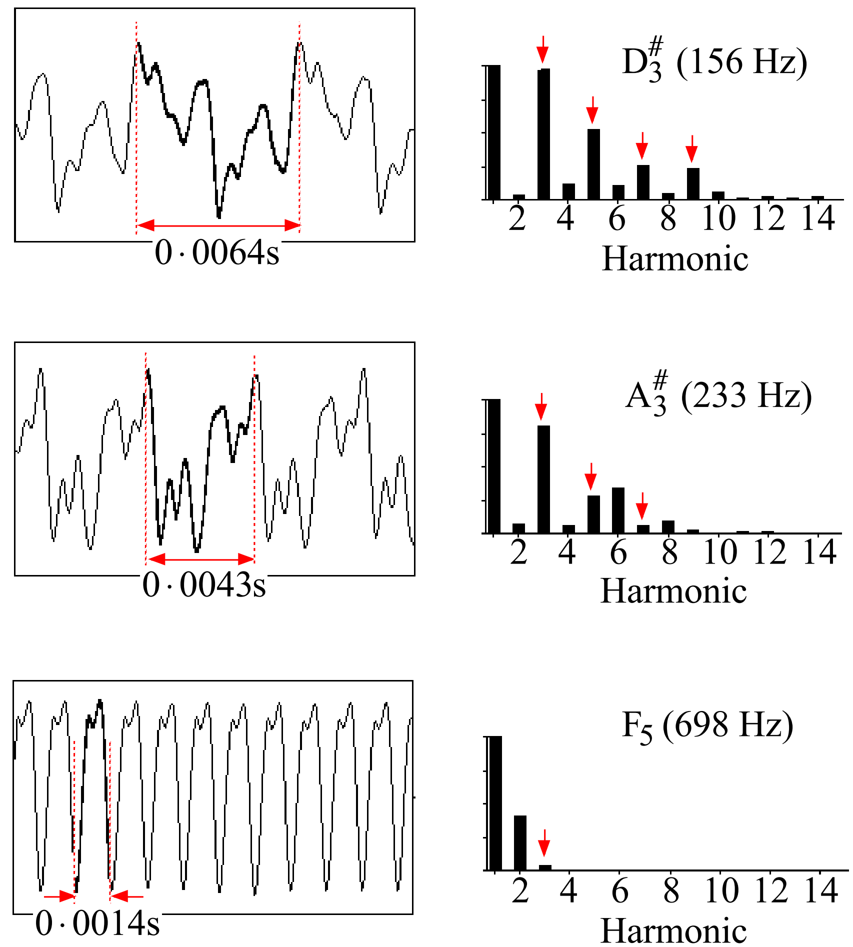


Although the waveforms are very different the frequency sequence in both cases consists of *harmonics*, i.e., f, 2f, 3f, etc.

Clarinet, flute and bassoon playing the same note B_3 (247 Hz). Although the waveforms are very different the frequency sequence is the same in all cases is *harmonic*, i.e., f, 2f, 3f, 4f, etc.

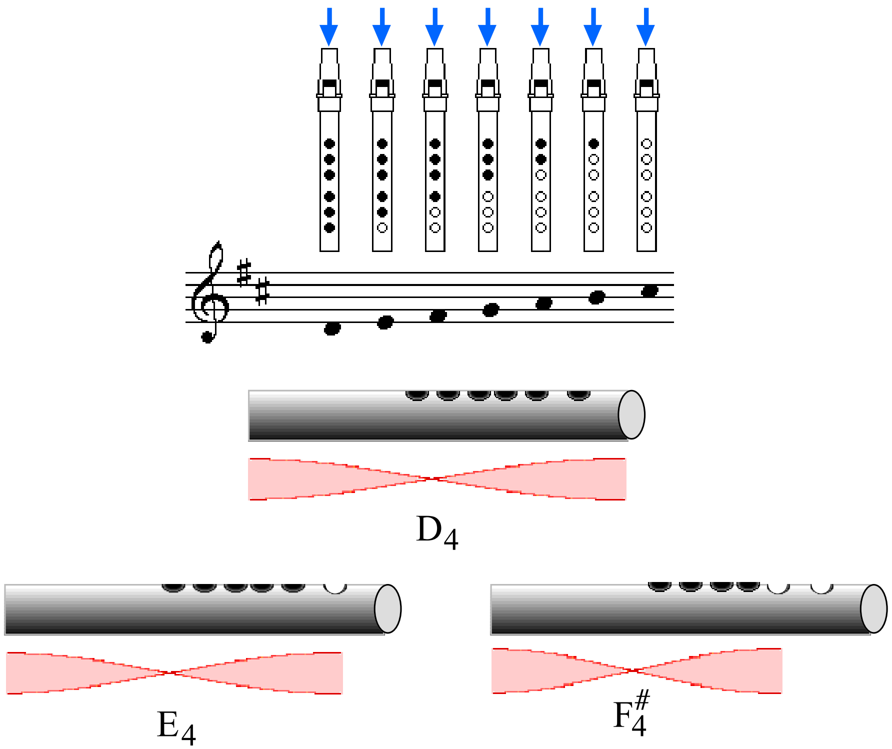


Clarinet playing three different notes. The odd harmonics are enhanced at the lower frequencies:



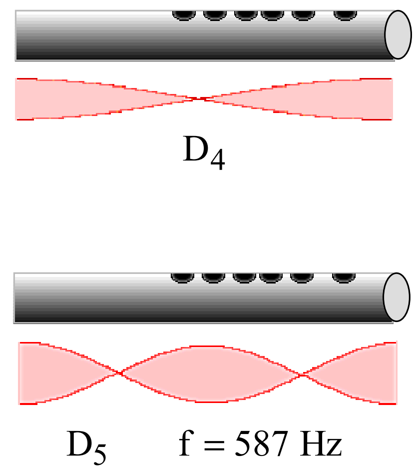
How to get different notes:

Example: a penny whistle



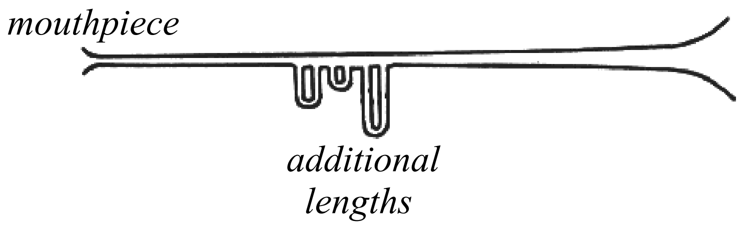
The fundamental frequency (f) depends on the length of the tube; uncovering a hole shortens the length and increases the frequency.

To get a higher octaves on a *penny whistle* ...

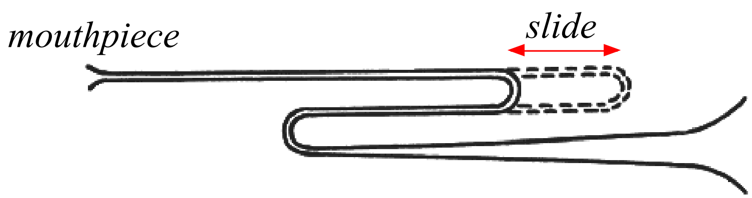


... blowing harder excites the second harmonic, one octave above the fundamental.

There are two main methods for varying the length of a horn to change the fundamental frequency.



[1] The length of the air column can be changed in finite steps by adding in different lengths of tube using valves (trumpet, French horn).

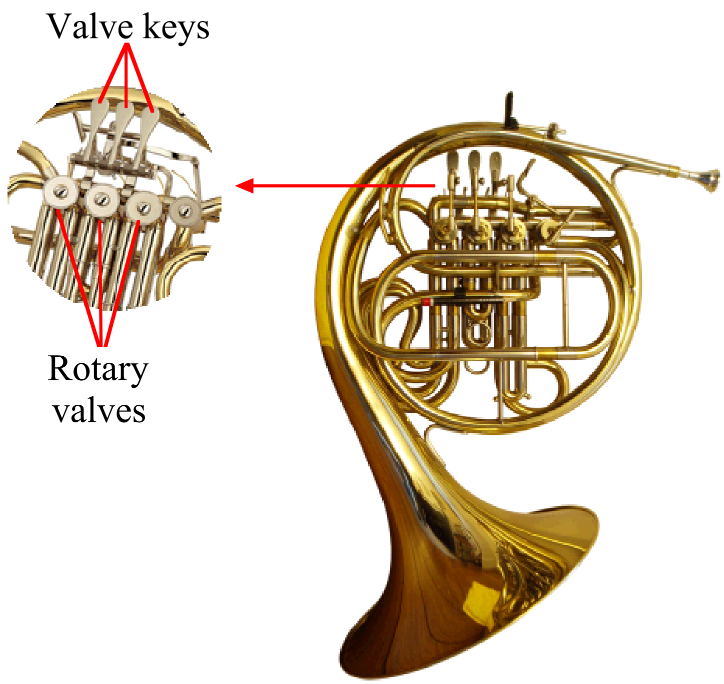


[2] The length of the air column can be changed continuously by a 'telescopic' slide (trombone).

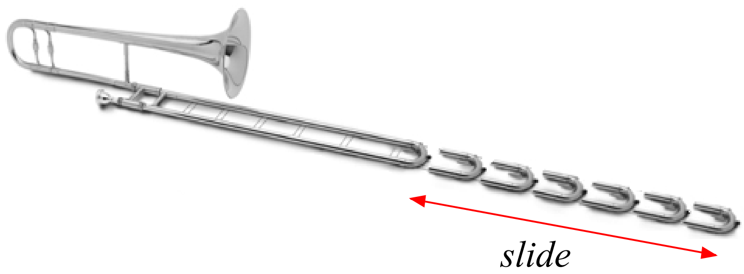
○○○ ○○● ○●○ ●○○

○●● ●○● ●●○ ●●●

The three piston valves on a typical trumpet enable a total of eight different lengths to be obtained. The overall tube length is roughly 6 ft. A typical instrument covers 3 octaves (E_3 to B_5); the higher octaves are achieved by altering the "blow".

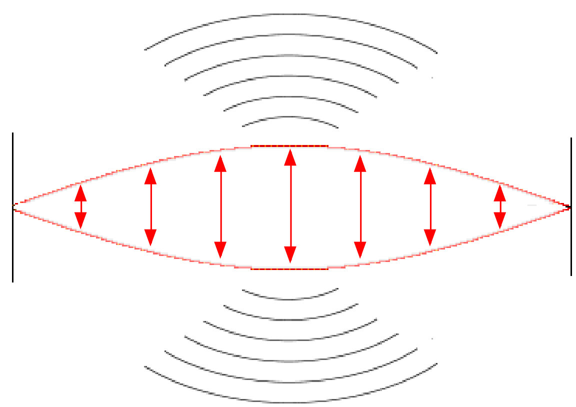


A French horn has either three or four rotary valves; three for beginners and four for expert players. The overall tube length of a typical French horn is about 12 ft. The valves provide up to eight (fourteen) different lengths to cover three octaves (B_1 to F_5).



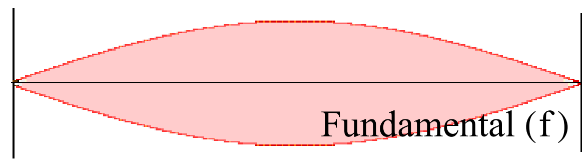
The overall tube length of a typical trombone is roughly 9 ft. Moving the slide outward, lowers the pitch of the fundamental frequency and the sliding action means the frequency can be changed continuously. A typical instrument covers two-and-a-half octaves (E_2 to B_4).

When a string is plucked or bowed a transverse standing wave is created. The string causes the air to vibrate also. However, the sound intensity produced by the string alone is very low. The sound has to be "amplified" by a sound box, i.e., the body of the instrument, which is designed to increase and enhance the sound.

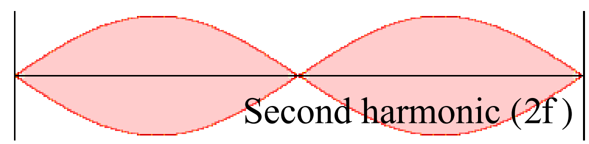


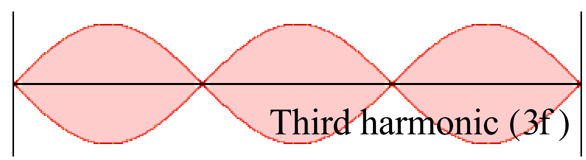
Harmonics are produced by plucking or bowing the string at different positions along its length

The harmonics of a stretched string:

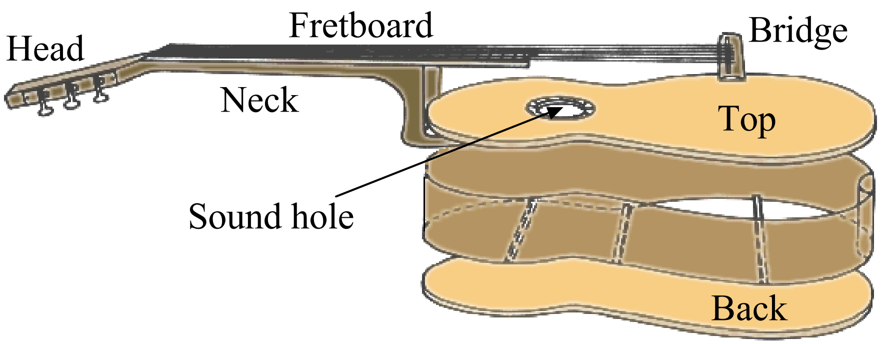


The fundamental frequency (f) depends on the type and length of the string and the tension.

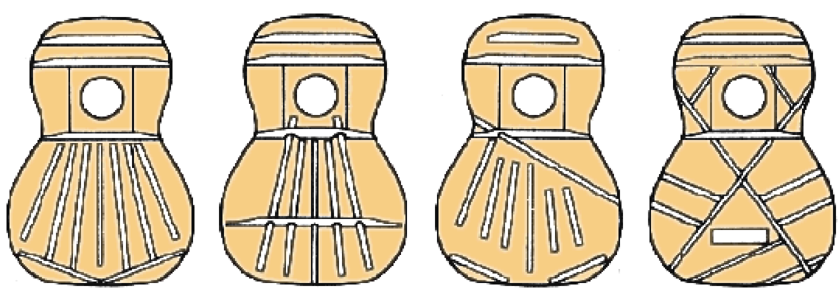




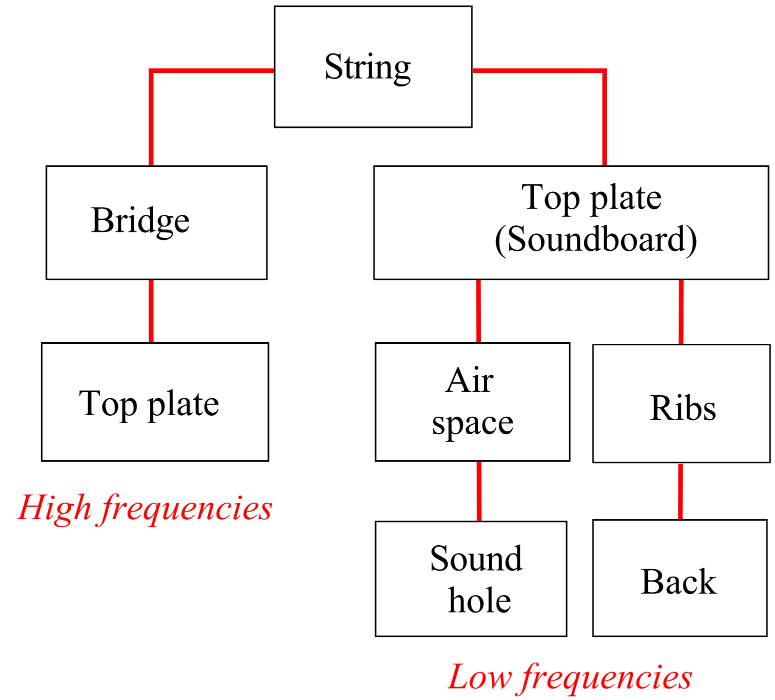
Note: all harmonics (f, 2f, 3f, 4f, etc) are allowed.



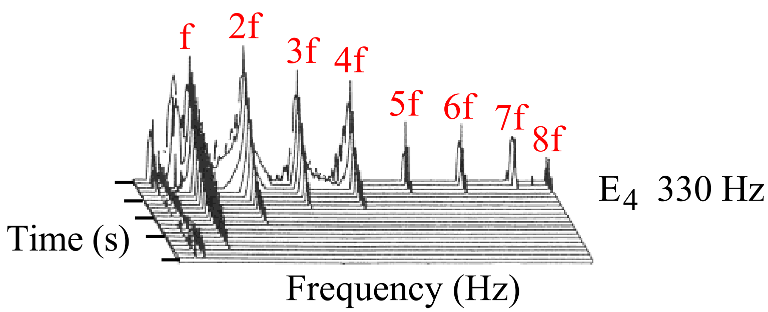
Exploded view of an acoustic guitar. The top, sides and back act as a sound box. The amplified sound emerges through the sound hole.

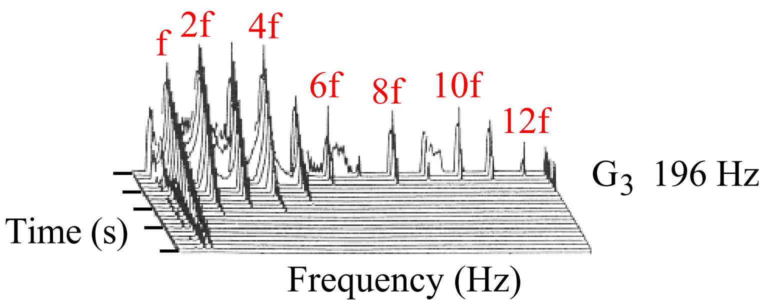


Various designs for bracing the guitar soundboard (i.e., the top) are shown above.

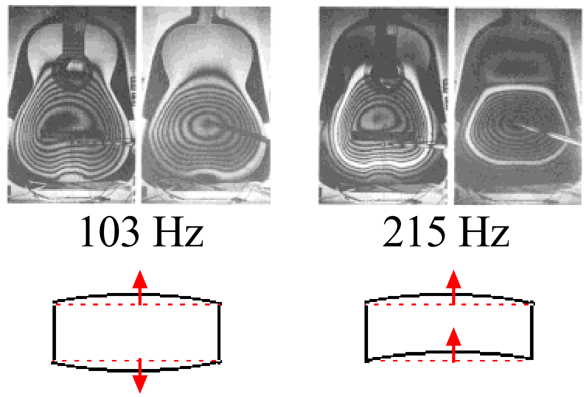


At *high frequencies*, most of the sound of a guitar is radiated by the top plate. At *low frequencies*, sound is radiated by the top and back plates and the sound hole.



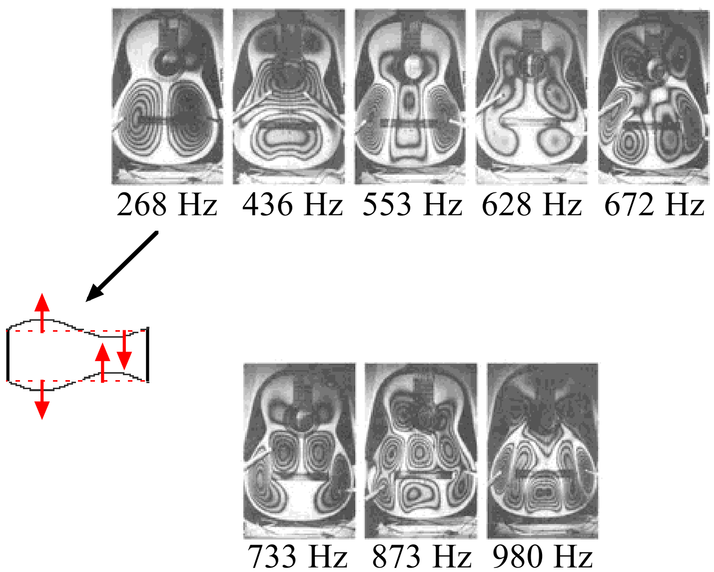


Sound spectra for two notes on a guitar (the first and third strings). The vertical axis shows the intensity of the harmonics, a second axis shows the frequencies present in the sound, and a third axis shows how these two quantities vary with time. All plucked instruments (piano, harp, harpsichord, etc.) show similar responses.

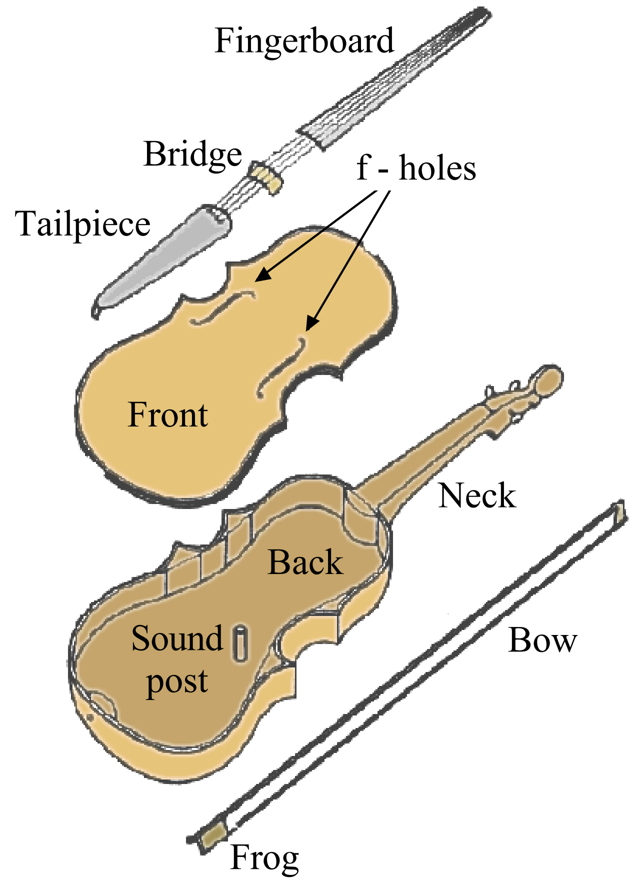


Two modes of vibration of a classical guitar. Both modes involve motion of the soundboard, the back plate and air in and out of the sound-hole. The patterns are like contours on a map and show the size of the deflection.

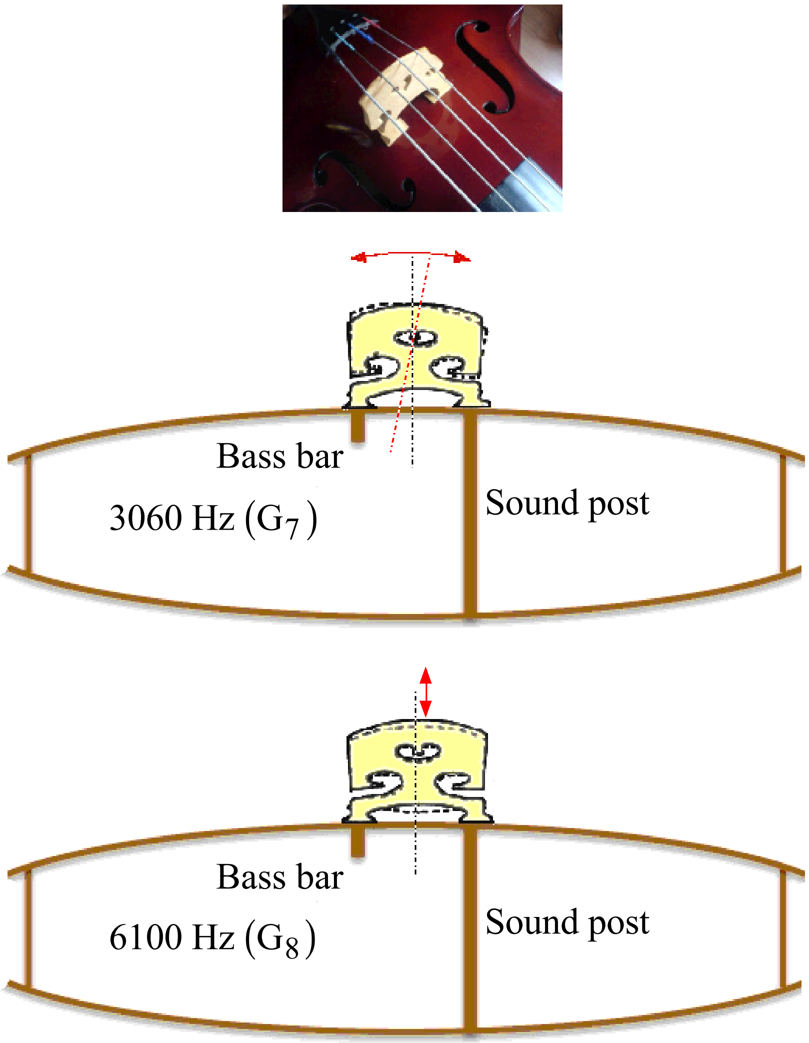
At 103 Hz, the soundboard and back plate oscillate in opposite directions. One octave higher, at 215 Hz, the two surface oscillate up-and-down together.



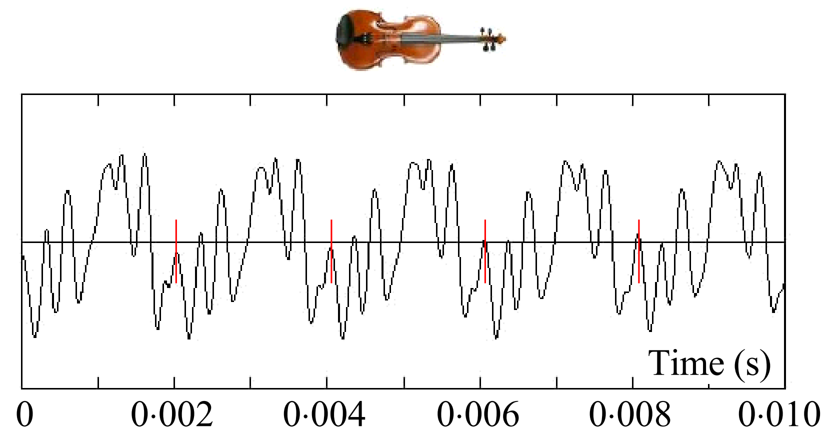
The mode patterns of the top plate (soundboard) of a classical guitar at higher frequencies. The motion is very complex.



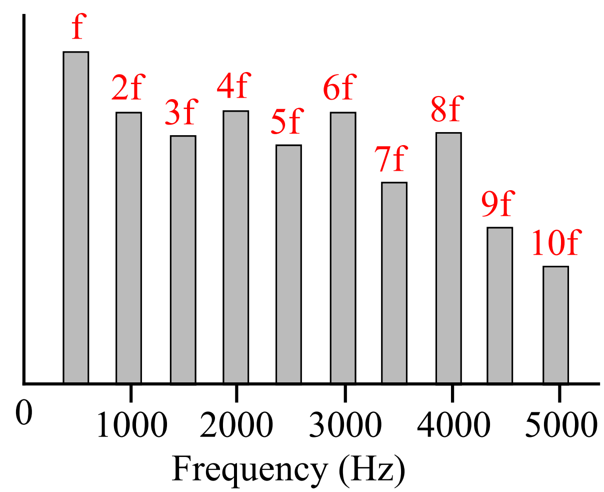
An exploded view of a violin. A violin has 4 strings tuned to G_3 (196 Hz), D_4 (294 Hz), A_4 (440 Hz) and E_5 (660 Hz).



Vibrational modes of a violin bridge.

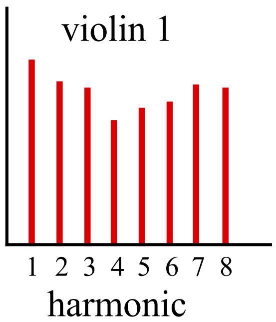


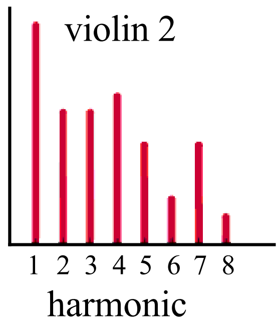
Waveform of a violin playing B_4 (494 Hz).



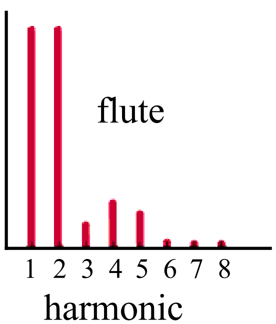
The corresponding frequency spectrum.

Here are two different violins playing the same note D_4 (294 Hz).



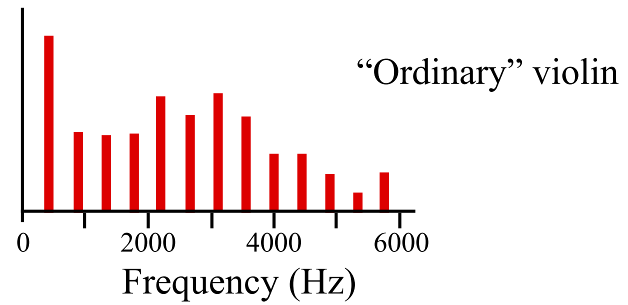


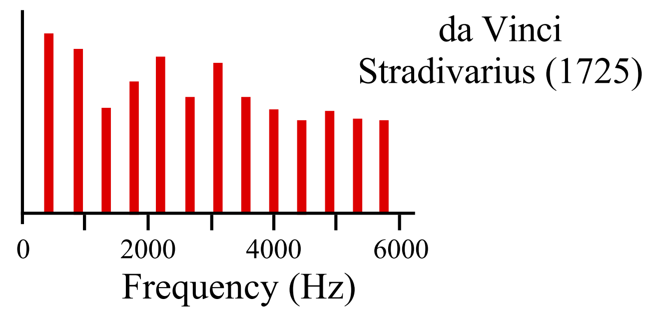
Even though the violins are playing the same note , the frequency spectra are different and so they will sound slightly different.



For comparison, here is the frequency spectrum for a flute playing the same note D_4 (294 Hz).

It is these small differences in frequency spectra that differentiate an “ordinary” instrument from a “quality” instrument.





Comparison of the harmonics of an “ordinary” violin with the da Vinci Stradivarius (1725) both playing A_4 (440 Hz).

Synthesizers

Music synthesizers produce "notes" by mimicking the frequency spectra of instruments. There are several methods of producing synthetic frequency spectra. Two of the more traditional are:

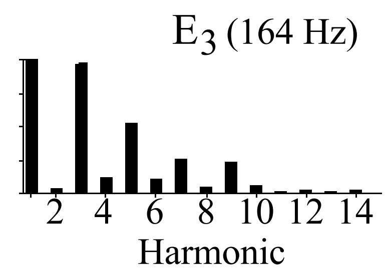
- *Additive synthesis.*
- *Subtractive synthesis.*

Additive synthesis is a technique that creates notes by adding sine waves together. With subtractive synthesis one starts with a waveform comprising all harmonics and the unwanted components are filtered out or attenuated.

Additive synthesis

Clarinet playing E_3:

Corresponding frequency spectrum:



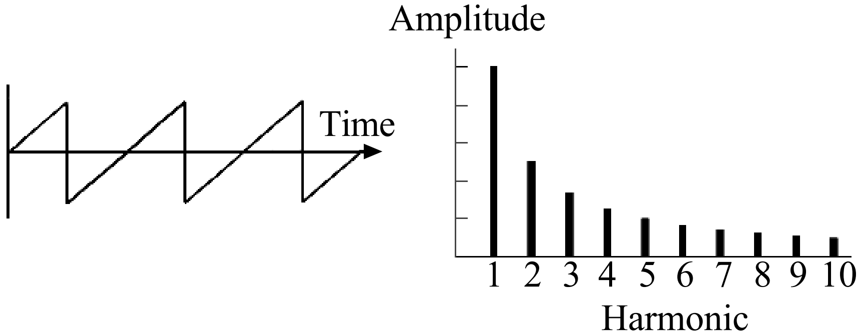
Synthesized sound created by adding together sine-waves with harmonic frequencies and the intensities in the frequency spectrum

An organ with a great many pipes. Together they function exactly like an additive synthesis

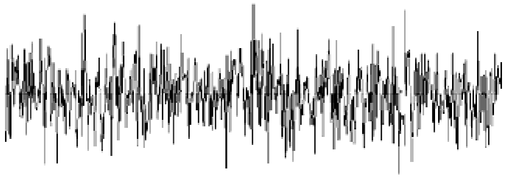
machine. Each pipe produces an approximate sine-wave and by selecting different combinations of harmonically related pipes, different sounds (stops), such as trumpet, clarinet, flute. Organists are experts on additive synthesis (though they may not know it!).

Subtractive synthesis

Starting with a waveform rich in harmonics, like a sawtooth wave:

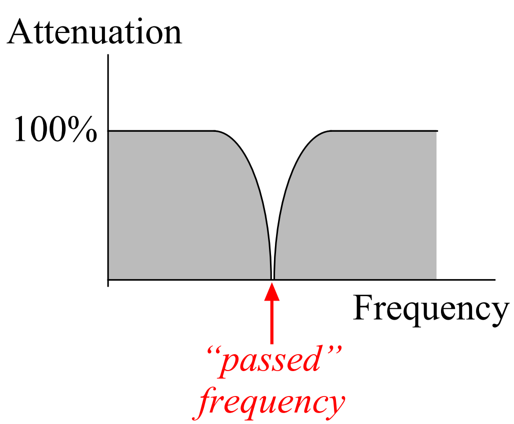


or "*white noise*",



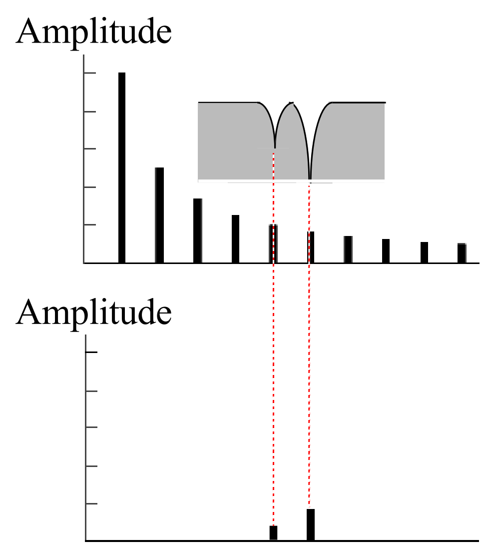
which contains many frequencies over the audible range (20 - 20,000 Hz) rather like "white light" does over the visible range.

The unwanted frequencies are filtered out by a series of filters:



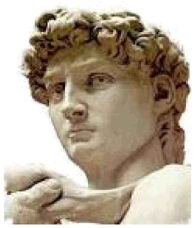
Characteristics of a typical single-pass filter

In this simple example, only the 5th (5f) and 6th harmonics (6f) are passed. The other harmonics are severely attenuated.



Additional amplifiers produce the required amplitude of the passed frequencies. All analog and virtual analog synthesizers use subtractive synthesis to generate sound.

Subtractive synthesis



A great definition of subtractive synthesis was given by Michelangelo. According to legend, when he was asked how he managed to carve David out of a block of stone, he replied,

"*I just cut away everything that doesn't look like David.*"