# Flute Physics from a Flutist's Perspective

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## Abstract

The basic physics of the flute is presented from the perspective of a professional flutist. The flutist can control loudness, pitch, and to some extent timbre. Oscilloscope images are provided to compare changes in these three fundamental sound characteristics. Readers can view a video (Ruiz M J 2017 *Video: The Flute* http://mjtruiz.com/ped/flute/) where coauthor flutist Erika Boysen demonstrates the topics covered in this paper.

## Background physics

There is a long history of scientific interest in the flute because of its relative simplicity [1]. Classic treatments on the mathematical physics of sound production with pipes include the texts of Rayleigh and Lamb from over a hundred years ago [2-3]. A recent excellent mathematical treatment of music and acoustics is the text by Guillaume [4]. The interdisciplinary discussion of the flute emphasizing concepts with little mathematics [1, 5-6] makes the subject accessible to introductory physics students. Furthermore, blending physics and music as an inquiry-based learning experience is a very effective way to illustrate the power of physics. [7]

As an example of an inquiry-based approach, ask students to give a rough estimate of the length of the orchestral flute from a photo such as figure 1. Students will probably hesitate, being afraid of saying something “wrong” and want to look the answer up. However, they can be prodded by suggesting that only a very rough estimate is desired, such as half meter, 1 meter, 2 meters. Quickly they will settle on 50 cm.

Figure 1. Coauthor Erika Boysen playing an orchestral flute.

This estimate can also be obtained from the perspective of physics using two formulas starting with a known frequency and the speed of sound. First find a wavelength corresponding to a typical flute pitch from the wave relation $v = \lambda f$ , where $v$ is the speed of sound, $\lambda$ is the wavelength, and $f$ is the frequency. Then find the length of an open pipe that produces this fundamental wavelength $\lambda$ from the formula $\lambda = 2L$ , where $L$ is the length of the pipe. The effective length of the flute in figure 1 is determined by the two open ends. One open end is determined by the number of keys that are pressed and the other open end is the embouchure hole over which the flutist blows without completely covering it.

Have students look at typical frequencies produced by a flute in figure 2, which gives the middle octave on a piano. The subscript 4 on the C indicates that this octave is the fourth full octave on the piano, ranging from the "Do" at $C_4$ to the "Do" at $C_5$. Ask your students which pitch is numerically close to the speed of sound. The note $E_4$ is a good choice since the speed of sound at freezing is $330 \text{ m} \cdot \text{s}^{-1}$. The corresponding wavelength is $\lambda = \frac{v}{f} = \frac{330 \text{ m} \cdot \text{s}^{-1}}{300 \cdot \text{s}^{-1}} = 100 \text{ m}$ and the associated pipe length is $L = \frac{\lambda}{2} = \frac{1 \text{ m}}{2} = 50 \text{ cm}$. Estimating with $F_4 = 349 \text{ Hz}$ and room-temperature sound speed gives essentially the same result: $\lambda = \frac{v}{f} = \frac{345 \text{ m} \cdot \text{s}^{-1}}{349 \cdot \text{s}^{-1}} = 100 \text{ m}$ and $L = \frac{\lambda}{2} = \frac{1 \text{ m}}{2} = 50 \text{ cm}$. The rough estimates from inspecting an actual flute and from a physics calculation agree, illustrating the beautiful connection between observation and theory.

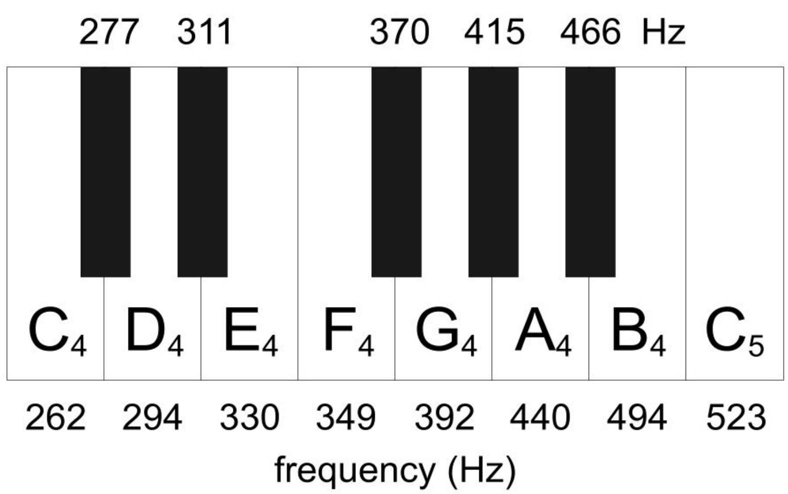


Figure 2. The middle octave on the piano, which falls within the range of the flute. Key names are given in letters as is the practice in music, along with their frequencies in hertz (Hz).

It is remarkable that the physics calculation for the length leads to an instrument size that allows the flute to be carried. Pondering this fact can lead to a further inquiry-based discussion. The wavelengths of tones corresponding to musical notes are on the order of human size and the formulas $L = \frac{\lambda}{2}$ for an open pipe (flute) and $L = \frac{\lambda}{4}$ for a closed pipe (clarinet) reduce the sizes needed for constructing pipes to produce these wavelengths.

## The Big Three: Loudness, Pitch, and Timbre

The three fundamental characteristics of musical tones are loudness, pitch, and timbre. Each is considered below from the point of view of the flutist controlling each parameter. Oscilloscope images are provided to relate the characteristics to physics wave properties.

### Dynamics

Varying the volume of air when producing a sound on the flute achieves louder and softer dynamics (sound levels). More air, both in volume and speed, will produce a louder sounding tone. Conversely, less air with its slower speed and decreased volume produces a softer sounding tone.

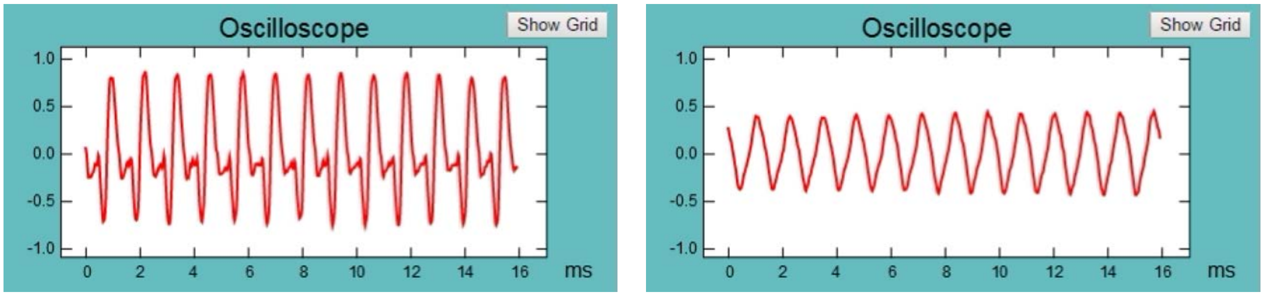

Figure 3. Oscilloscope display for a louder sound (left) and softer sound (right). The amplitude (vertical measure of the wave) is greater for the louder sound.

The oscilloscope gives a plot of wave amplitude against time. The amplitude of a wave is usually taken in physics to be the vertical measure of the wave from its center equilibrium level ("sea level") as mathematical equations appear elegant this way. On the other hand, engineers often measure from the very bottom of the wave to the very top since such a measure is easy to make on an oscilloscope. The latter measure is often referred to as the peak-to-peak amplitude. The energy and intensity of a wave are proportional to the square of the amplitude. The perceived sound level by a human in terms of decibels is proportional to the logarithm of the energy. The sound level in decibels is given by

$$\beta(\text{in dB}) = 10\log\frac{I}{I_0} = 10\log\frac{P^2}{P_0^2} = 20\log\frac{P}{P_0},$$

where $P$ is the pressure amplitude, $I$ is intensity (energy per unit area per time), the subscripts zero refer to values at the human threshold of hearing, and the logarithm is base 10. Note that the intensity is proportional to the square of the pressure amplitude.

## Pitch

Another inquiry-based discussion begins with asking the students to use physics in order to estimate the minimum number of keys needed on the flute to produce the pitches of one octave by changing the effective length of the open pipe. When an open pipe is driven to sound its second harmonic, the pitch is an octave higher. Referring to figure 2, one can count the notes in the octave from $C_4$ to $C_5$. There are 13 pitches, requiring a dozen keys since $C_4$ and $C_5$ can use the same length for the first and second harmonics. This analysis indicates that the minimum number of keys is one dozen tone holes. Orchestral flutes typically have a few additional keys to assist with trills (rapid alternation between two pitches) and intonation (obtaining a more accurate frequency in pitch).

The production of lower and higher pitches is achieved through the manipulation of the resonating tube's length. By depressing the keys, in order of their placement in relation to the first tone hole closest to where the lips are applied, the length of the resonating tube is made longer or shorter. A longer tube produces longer wavelengths and a shorter tube produces shorter wavelengths. When this method is used in conjunction with overtones[1] the flute produces over three octaves of pitches.

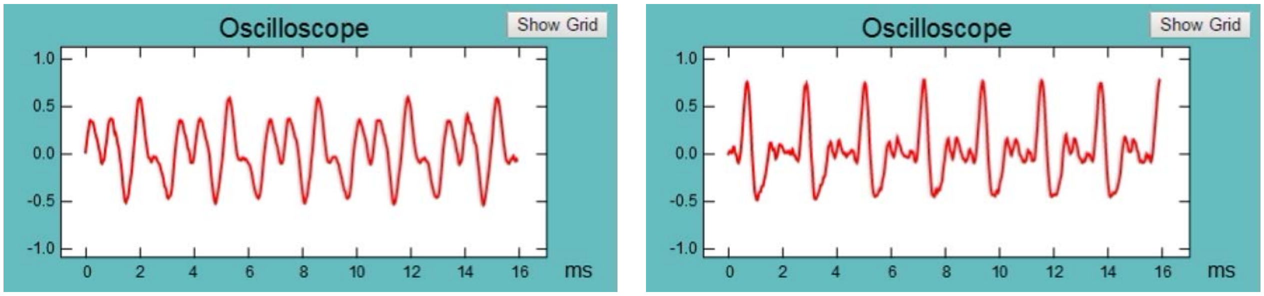


Figure 4. Oscilloscope display for a lower pitch (left) and higher pitch (right). The period of the wave is the horizontal time interval for one "picture pattern" of the wave.

[1] The first overtone is the second harmonic, the second overtone is the third harmonic, and so on. The frequency of the nth harmonic is n times the frequency of the first harmonic (the fundamental).

Another question that can be posed to students is to ascertain the notes played for the two tones illustrated in the oscilloscope images of figure 4. Consider the left image fist. There are 5 repeating “picture patterns” for the left wave, spanning a time frame of 16 ms. Therefore, the period is $T = \frac{16 \text{ ms}}{5} = 3.20 \text{ ms}$. The frequency is given by

$$f = \frac{1}{T} = \frac{1000}{T \text{ (in ms)}}, \tag{1}$$

where the later form is very convenient since our period is in milliseconds. The frequency for the lower pitch is then

$$f_{lower} = \frac{1000}{T \text{ (in ms)}} = \frac{1000}{3.20} = 310 \text{ Hz}, \tag{2}$$

to two significant figures since the number of periods during the 16-ms interval was estimated. Referring to figure 2, this frequency best matches the 311-Hz black key between $D_4$ and $E_4$, namely $D_4^{\#}$ or $E_4^{b}$. The sharp symbol $\#$ indicates the adjacent key to the right and the flat symbol $b$ means the adjacent key to the left.

For the higher pitch in figure 4 (the right wave) there are about 7 periods in 16 ms, giving $T = \frac{16 \text{ ms}}{7} = 2.29 \text{ ms}$ and

$$f_{higher} = \frac{1000}{T \text{ (in ms)}} = \frac{1000}{2.29} = 440 \text{ Hz}, \tag{3}$$

to two significant figures since we again estimated the count for the number of periods in 16 ms. From figure 2, the higher pitch is $A_4$ (440 Hz).

## Timbre

Timbre is the characteristic or quality of a tone. In physics terms, different timbres are represented by different waveform shapes. Timbre can be influenced by a variety of factors. Note the slight variations in timbre found in figures 3 and 4. Though the timbres are not identical, they are close enough for the hearer to perceive that the instrument is a flute.

The primary means through which a flutist changes the timbre or “color” of a sound is through the shape of the performer’s oral cavity. The oral chamber through which air flows before escaping the lips and traveling across the flute’s embouchure hole dictates the brightness or dullness of the tones produced. Space in the oral cavity is created by utilizing movement in the soft palate and tongue. A brighter and sharper sounding tone is achieved by moving the tongue forward and higher, producing an “EE” vowel, thereby minimizing the space in the oral cavity. Conversely, by lowering the tongue in addition to raising the soft palate, maximizing the space in the oral cavity, a flutist will produce an “AH” vowel, creating a darker, flatter quality of sound. See figure 5 for two timbres.

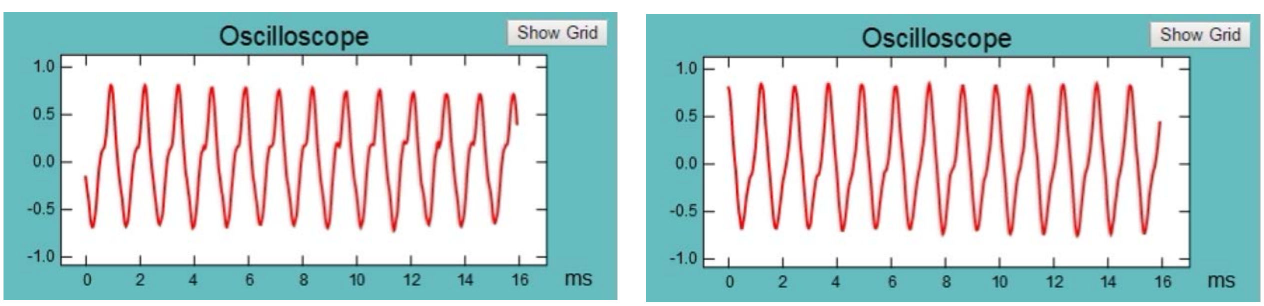


Figure 5. Oscilloscope display for a brighter timbre (left) and darker timbre (right). Note that the loudness and pitch are approximately the same in each case.

**Producing Harmonics**

Many of the flute's sixteen or seventeen keys (this number can vary) correlate to different pitches as the tone holes determine the effective length of the pipe. But further combinations of keys and quality of air allow the flutist to produce over three octaves of pitches.

For the discussion of air, an analogy of a water hose is helpful when explaining the flutist's manipulation of air volume, speed and direction. In the case of the water hose, imagine you are watering a flower bed that is at the far edge of your backyard. Unfortunately, your water hose is not long enough to reach your farthest flower bed. What options do you have with a stream of water that doesn't reach the parched flowers? First, you can turn up the amount of water so the faster stream might effectively propel itself to the flowers. Second, you can change the angle of the water hose from the horizontal so that the stream goes farther in distance. Third, if the aforementioned solutions fail, you can place your thumb over the opening of the water hose, decreasing the area through which the water flows out of the hose, thereby increasing the speed of the water.

These three "options" mirror the flutist's manipulation of air when achieving higher harmonics. First, in the series of harmonics, higher pitches require an increased air speed. Second, a longer reed of air is produced by raising the direction of the air, which is found to produce a higher pitch. The reed of air concept is discussed in more detail in the next section. Third, narrowing the aperture size increases the air speed, which helps to produce a higher harmonic.

Starting in the fundamental register, the flutist's volume of air is less, the aperture is larger to facilitate a slower speed of air, and the air direction is down into the flute. As the flutist progressively ascends to higher harmonics, the volume of air increases, the aperture size diminishes so the speed of air increases, and the flute slightly pivots out, elevating the direction of airflow.

**Pitch bending**

A more minute manipulation of frequency variation on a single pitch requires an understanding of a flutist's air column. The flute is the only instrument in the woodwind family that doesn't use a reed made of cane. Instead, the flutist's reed consists of air. The length of this reed is measured from the point at which the air leaves the musician's mouth and ends where the column of air splits on the back wall of the embouchure hole. This distance is controlled in three different ways: 1) the angle at which the flute is rolled in toward or away from the head, 2) the degree to which the lower lip covers the embouchure hole, 3) the angle at which the air is blown across the lip plate thereby affecting the speed of air at the embouchure hole.

Pivoting the angle of the flute towards the head of the flutist will shorten the reed of air, thereby making the pitch lower in frequency and vice versa. The second way of manipulating the air reed's length is by moving the lip plate up and down on the flute player's lower lip. By moving the lip plate down on the lower lip, the flutist's air is more direct and the reed is shortened making a lower pitch. Conversely, by moving the flute up, the air has a longer distance to travel and the pitch is higher. Finally, the third way of changing the reed's length is changing the angle at which the air is blown across the embouchure hole. By moving the lower lip back, the upper lip is able to more directly angle the airstream towards the back wall of the embouchure hole. Therefore, a shorter reed is produced, lowering the pitch. By moving the lower lip forward, the airstream is higher and therefore longer, raising the pitch.

## Conclusion

The basic physics of the flute has been presented with emphasis on the perspective of the flutist. Through guided questions the student can realize the connections between physics and music regarding the flute. A surprise is how the flutist can transcend the basic physics that predicts a constant pitch based on the length of the pipe. The flutist in our video [8] demonstrates three waves to bend the pitch using flute techniques.

In summary, the flute is an excellent application of the basic physics topics such as amplitude (loudness), frequency (pitch), and waveform (timbre) as well as harmonics. The oscilloscope display provides for a nice visualization of amplitude, frequency, and waveform. Quantitative concepts are also included using the open-pipe formula $\lambda = 2L$, wave relation $v = \lambda f$, frequency-period formula $f = \frac{1}{T}$, and period measurements with the oscilloscope. Finally, the inquiry-based approach encourages student thought and participation. Students acquire a deeper appreciation of the power of physics as they apply science principles to the flute.

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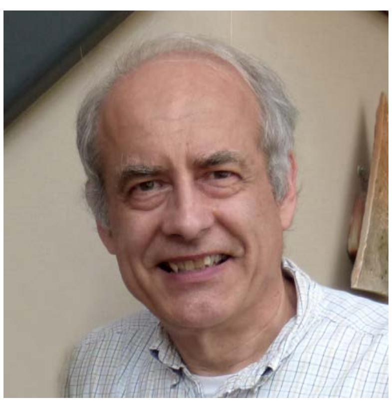

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