

Music is composed of sounds, so understanding the physics of sound helps us understand music from a scientific perspective. It is important to understand music because music is an essential part of most cultures around the world, including Canadian culture. Many components go into making music: singers, songwriters, song recorders, musicians, and of course musical instruments. In this section, you will learn how musical instruments produce music.

**music** sound that originates from a combination of musical notes that originate from a source that vibrates in a uniform manner with one or more constant frequencies

**noise** sound that originates from a source that vibrates in a random manner



(a) musical note



(b) noise

**Figure 1** Sound traces on an oscilloscope: (a) a musical note (b) noise

**pitch** the general perception of the highness or lowness of a sound; depends on the frequency, complexity, and loudness of the sound

**quality** the pleasantness of a sound; related to the waveform of the sound

## Music and Musical Sounds

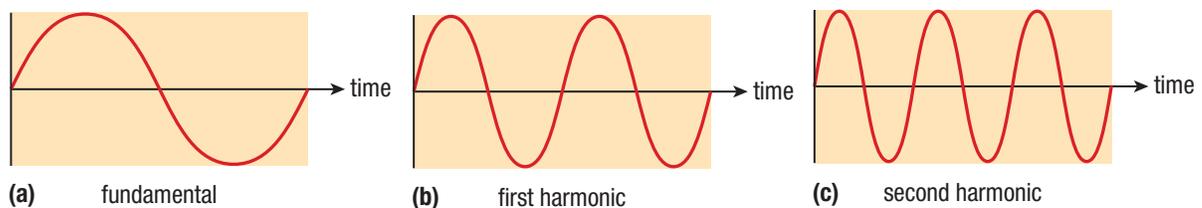
What some people call music others might call noise. To most people, noise is something that sounds unpleasant and annoying, while music is harmonious and pleasant. If we use these descriptions, we are forced to conclude that music and noise are a matter of opinion; that is, they are subjective. However, physicists need a more scientific definition for both music and noise.

A musical note originates from a source that vibrates in a uniform manner with one or more constant frequencies. **Music** is a combination of musical notes. A musical note looks like a constant waveform when displayed on an oscilloscope (**Figure 1(a)**). **Noise** originates from a source that vibrates in a non-uniform, random manner, and the waveform looks erratic in frequency and amplitude (**Figure 1(b)**).

## Characteristics of Musical Sounds

Musical sounds have three main characteristics: loudness, pitch, and quality. These characteristics are subjective because they depend not only on the source but on the perception of the listener. Recall from Section 8.5 that greater amplitudes of vibration of air molecules mean louder sounds. However, the loudness a person hears depends on both the ear hearing the sound and the source of the sound. For example, a person who cannot detect a particular frequency will report no loudness, while someone who can hear the frequency may claim that the sound is very loud.

The **pitch** of a sound is related to the frequency of the sound waves. Although there is an objective relationship between pitch and frequency, the pitch detected by a person depends on the observer, the complexity of the sound, and even the loudness. Generally speaking, a person will report a higher pitch when higher frequencies are produced by the source (**Figure 2**).



**Figure 2** Higher frequencies have shorter wavelengths and produce higher pitches.

A tuning fork makes a simple musical note consisting of one frequency, but most musical instruments produce music composed of a fundamental frequency ( $f_0$ ) as well as several harmonics ( $2f_0, 3f_0, 4f_0, \dots$ ). The **quality** of a musical sound is the pleasantness of the sound. Sound quality depends on the number of harmonics, besides the fundamental frequency, and the intensity of these harmonics.

## Musical Instruments

Musical instruments are grouped into three categories, depending on how they are used to produce vibrations (Figure 3).

- Stringed instruments: sound produced by plucking, striking, or bowing a string
- Wind instruments: sound produced via vibrating air molecules in columns
- Percussion instruments: sound produced by striking a surface

### Stringed Instruments

A string in a stringed instrument can be thought of as a tightly stretched spring fixed at both ends. Recall that strings can resonate with various frequencies, but the string must have a node at both ends. Increasing the tension in the string increases the fundamental frequency at which it will vibrate. Increasing the length, diameter, or tension of the string decreases the fundamental frequency. If the frequencies are high enough (20 Hz), the string can produce sounds audible to humans. This is how stringed instruments produce music.

Most stringed instruments, such as the guitar and piano, consist of a **resonator** (usually a case box or sounding board) and several strings (vibrator) fixed at each end under tension. A string alone produces very little sound, and the sound is often unpleasant. The resonator helps improve loudness and quality. The vibrations of the string are forced into the resonator, causing resonance. Even a tuning fork produces a louder and higher-quality sound when attached to a case box.

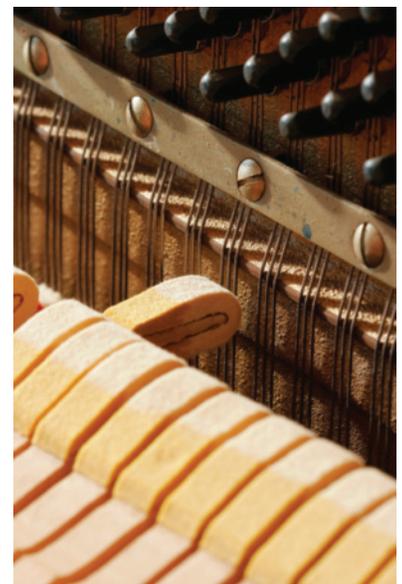
Stringed instruments that are usually played by plucking include the guitar, banjo, mandolin, ukulele, harpsichord, and some types of violin. If the string is plucked gently in the middle, a strong first harmonic is produced (Figure 4(a)). If the string is plucked one-quarter of its length from one fixed end, then other harmonics are produced and the quality of the sound changes (Figure 4(b)). In this case, the string vibrates with two simultaneous frequencies superimposed on each other. If the position where the string is plucked is even closer to the fixed end, the harmonics produced change again, resulting in a different quality of sound (Figure 4(c)).

Another common stringed instrument is the piano. The keys of a piano are connected to a series of levers. The levers cause a small hammer to strike a string (or strings) to make the string vibrate, thereby producing a musical note (Figure 5). The strings vary in length, thickness, and tension to enable them to produce different notes. The shorter, thinner, and higher-tension strings produce higher notes (up to 4186 Hz), and the longer, thicker, and lower-tension strings produce lower notes (as low as 27.5 Hz). The sounds from the strings are enhanced in loudness and quality by the wooden sounding board (resonator) of the piano.

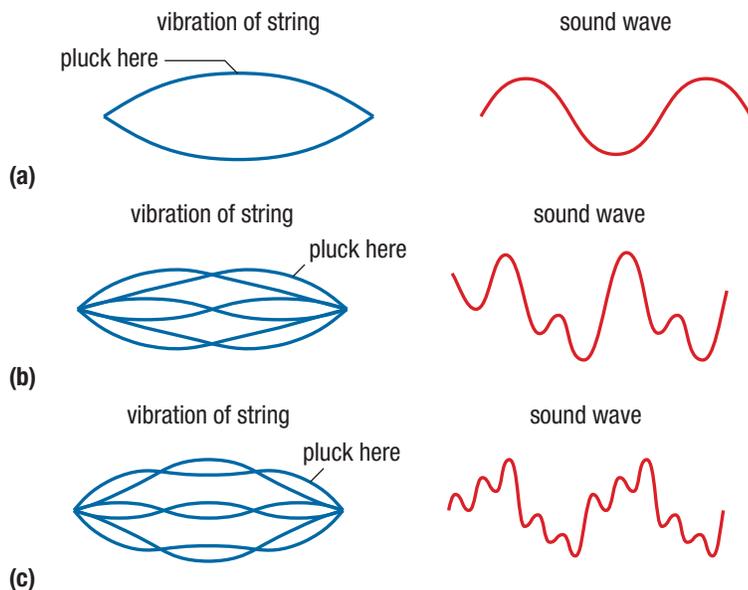


**Figure 3** There is a large variety of musical instruments. They are grouped by how they produce sound.

**resonator** an object, usually a hollow chamber called a case box or a sounding board, that vibrates in resonance with the source of sound



**Figure 5** When struck by the hammer, the piano string vibrates. The wooden sounding board increases the loudness and the sound quality.



**Figure 4** Changing the quality of sound produced by a vibrating string (a) First harmonic (b) Superposition of first and second harmonics (c) Superposition of first and third harmonics

Stringed instruments that are played using a bow usually belong to the violin family, which includes the viola, cello, violin, and string bass. The bow has long fibres on one side that are rubbed with rosin (a substance produced from tree resin) to increase the coefficient of friction. When stroked across a string, the bow causes the strings to vibrate. Each of the above instruments has four strings and two wooden sounding boards at the front and back of the case.

Some stringed instruments, such as the guitar, have frets that mark where the fingers of the non-strumming hand can be placed. When you press your finger against a string and then down onto a fret, you are effectively changing the length of the string by turning that point into a fixed end (node). This change in length changes the frequency at which the string will resonate, which changes the pitch. The members of the violin family do not have frets. This allows the frequency to be changed gradually rather than in steps.

### FREQUENCY AND LENGTH OF THE STRING

Assume that a string fixed at both ends is plucked in the middle, producing an antinode at the fundamental frequency, similar to the example in Figure 4(a) on page 455. In this case, the length of the string represents half the wavelength and we can write  $L = \lambda/2$ , where  $L$  is the length of the string. Rearranging, we have  $\lambda = 2L$ . Now substitute this expression into the universal wave equation:

$$\begin{aligned}v &= f\lambda \\v &= f(2L) \\ \frac{v}{2} &= fL\end{aligned}$$

If the tension is constant, then the speed of the wave is also constant, which implies that the quantity  $fL$  is also constant. We can write this new relationship as

$$f_1L_1 = f_2L_2$$

This equation implies that if you decrease the length of the string by pressing down on a fret, then the frequency of vibration must increase to keep the product of the frequency and length constant. You will see this equation applied in Tutorial 1.

## Tutorial 1 Waves in Strings

The following Sample Problem will clarify the concepts of waves in strings when the length of the string is changed.

### Sample Problem 1: A Wave in a Guitar String

A 0.650 m guitar string vibrates with a fundamental frequency of 120.2 Hz. The guitar player pushes the string down on the fret and changes the length of the string to 0.570 m.

- What is the new fundamental frequency of the string?
- Show that the speed of the wave in the string remained the same when the length was changed.

### Solution

(a) **Given:**  $L_1 = 0.650$  m;  $f_1 = 120.2$  Hz;  $L_2 = 0.570$  m

**Required:**  $f_2$

**Analysis:** Use the relationship  $f_1L_1 = f_2L_2$  to determine the new fundamental frequency.

**Solution:**  $f_1L_1 = f_2L_2$

$$\begin{aligned}f_2 &= \frac{f_1L_1}{L_2} \\ &= \frac{(120.2 \text{ Hz})(0.650 \text{ m})}{0.570 \text{ m}} \\ f_2 &= 137 \text{ Hz}\end{aligned}$$

**Statement:** The new fundamental frequency is 137 Hz.

(b) Calculate the wavelengths in the string before and after the player pressed on the string, as well as the speed of the waves in each string. Then compare answers.

**String before Pressing**

**Given:**  $L_1 = 0.650$  m;  $f_1 = 120.2$  Hz

**Required:**  $v_1$

**Analysis:**  $\lambda = 2L$  and  $v = f\lambda$

**Solution:**  $\lambda_1 = 2L_1$

$$\lambda_1 = 2 \times 0.650 \text{ m}$$

$$\lambda_1 = 1.3 \text{ m}$$

$$\begin{aligned} v_1 &= f_1 \lambda_1 \\ &= (120.2 \text{ Hz})(1.3 \text{ m}) \\ &= 156.3 \text{ m/s} \end{aligned}$$

$$v_1 = 156 \text{ m/s}$$

**String after Pressing**

**Given:**  $L_2 = 0.570$  m;  $f_2 = 137.1$  Hz

**Required:**  $v_2$

**Analysis:**  $\lambda = 2L$  and  $v = f\lambda$

**Solution:**  $\lambda_2 = 2L_2$

$$\lambda_2 = 2 \times 0.570 \text{ m}$$

$$\lambda_2 = 1.14 \text{ m}$$

$$\begin{aligned} v_2 &= f_2 \lambda_2 \\ &= (137.1 \text{ Hz})(1.14 \text{ m}) \\ &= 156.3 \text{ m/s} \end{aligned}$$

$$v_2 = 156 \text{ m/s}$$

The speed of the waves in the longer string is 156 m/s. The speed of the waves in the shorter string is 156 m/s.

**Statement:** The speeds are equal. Therefore, changing the length of the string did not change the speed of the waves.

**Practice**

1. A guitar string is 63 cm long and has a fundamental frequency of 110 Hz. How long should the string be to produce a fundamental frequency of 150 Hz? T/A [ans: 46 cm]
2. A violin string is 22 cm long with a wave speed of 140 m/s. T/A
  - (a) Calculate the fundamental frequency of the string. [ans: 320 Hz]
  - (b) Calculate the fundamental frequency of the string if the length is decreased by 15 % by pressing the string on a fret. [ans: 370 Hz]

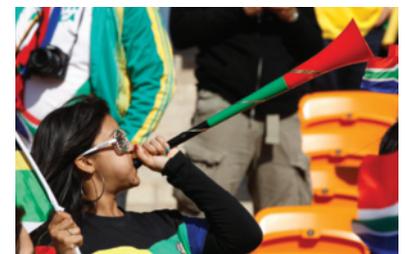
**Wind Instruments**

Wind instruments contain at least one resonant air column, and most are open air columns. The frequency with which the column resonates depends on the length of the air column and whether the ends are open or closed. Longer air columns produce lower-frequency sounds, and shorter air columns produce higher-frequency sounds. The long air column in a vuvuzela (vu-vu-SAY-la), popular with soccer fans (**Figure 6**), produces a loud, low-frequency sound.

The source of the sound in a wind instrument may come from air vibrating over an opening (flute), vibrating lips on a brass instrument (trumpet, trombone), or a vibrating reed—a thin strip of material (oboe, clarinet). In some wind instruments, such as the trombone, the length of the air column can be changed, which in turn changes the frequency of the sound produced (**Figure 7**). In other wind instruments, such as the pipe organ, the length of the air column is fixed. In a pipe organ, different air columns are used to produce different frequencies. In other cases, the length of the air column is fixed but the resonant frequency can be altered by opening or closing holes in the column (clarinet, recorder, and trumpet).



**Figure 7** Changing the length of the air column changes the frequencies that resonate inside the column. The bends in the air column have no effect on resonance. They simply help make the instrument more compact.



**Figure 6** The vuvuzela is popular with soccer fans.

## CAREER LINK

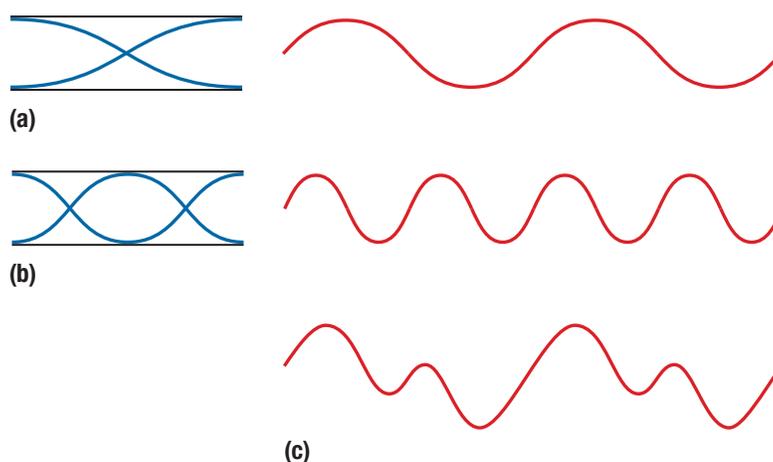
There are many job opportunities for audio engineers; for example, recording musical artists, post-production for movies and television, and producing sound components for video games. To learn more about becoming an audio engineer,



GO TO NELSON SCIENCE

The quality of sound produced by a wind instrument depends on the skill of the musician, the quality of the instrument, and the resonant frequencies in the air column. Recall that a standing wave pattern is set up in an air column when resonance occurs. In wind instruments, not only is the fundamental frequency (first harmonic) present, but higher harmonics are also present simultaneously. Generally, the loudest frequency detected is due to the fundamental frequency, which is used to determine the note you hear. However, the combination of harmonics produces a more complex wave pattern, which increases the quality of the sound. 🌐

Consider an instrument that uses an open air column resonating with antinodes at both ends and one node in the middle (**Figure 8(a)**). In this case, the first harmonic ( $f_0$ ) is produced and the wavelength is twice the length of the air column. The corresponding waveform as seen on an oscilloscope, for example, is shown beside the air column in **Figure 8(a)**. Assume that the length of the air column is constant when a second standing wave is produced in the air column. To produce another standing wave, a higher frequency is required, which can be achieved by various means, such as blowing harder. For example, we can double the frequency ( $2f_0$ ) and produce a wavelength half as long (**Figure 8(b)**). If the waveform for the first harmonic is combined with the waveform for the second harmonic, a higher-quality sound is produced (**Figure 8(c)**). If other harmonics are present in this open air column ( $3f_0, 4f_0, \dots$ ), they will further enhance the quality.



**Figure 8** The quality of sound in a wind instrument depends in part on the harmonics present. (a) First harmonic (b) Second harmonic (c) Resulting waveform due to first and second harmonics

Recall from Chapter 9 that the higher harmonics for an open air column are always whole-number multiples of the fundamental frequency. Most wind instruments are open air columns. An air column that is closed at one end has higher harmonics that are odd-number multiples of the fundamental frequency ( $f_0, 3f_0, 5f_0, \dots$ ). This will change the quality of sound produced because the resulting waveform will be caused by different frequencies. The clarinet is an example of a wind instrument that acts like a closed air column.

The resonant lengths of air columns are directly related to the wavelength of the sound inside the column. However, if the temperature changes, then the speed of sound changes, which in turn changes the wavelength of sound. Since the length of the air column determines the resonant frequencies, wind instruments should be tuned by adjusting the length of the air column to account for these changes in wavelength.



**Figure 9** Several examples of percussion instruments

## Percussion Instruments

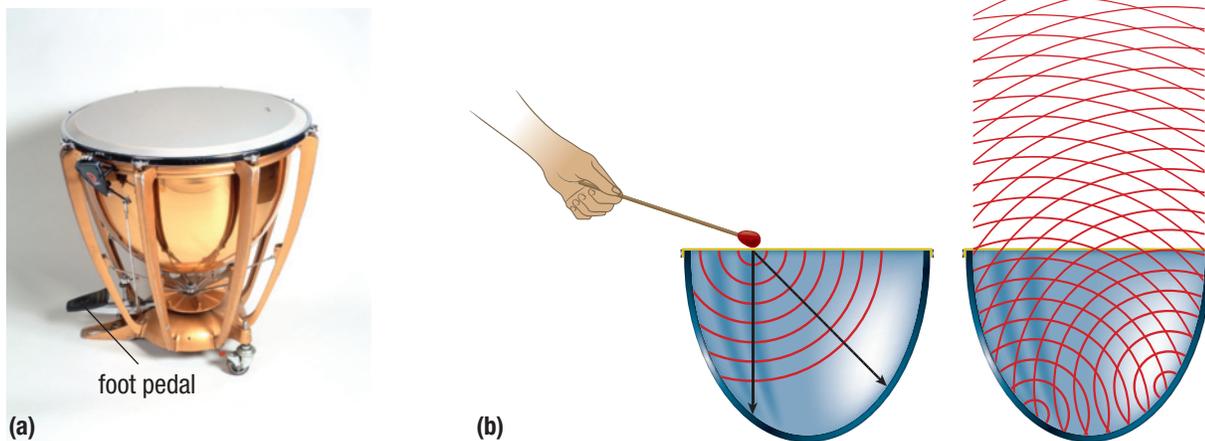
To produce a sound with a percussion instrument, you strike one object against another. The instrument is usually struck by a firm object, such as a stick, a hammer, or a bar. Some examples of percussion instruments are shown in **Figure 9**. There are three categories of percussion instruments: single indefinite pitch, multiple definite pitch, and variable pitch.

**Investigation 10.2.1****Waveforms of Instruments (p. 476)**

In this investigation, you will use what you have learned about instruments to compare their waveforms and try to identify the different harmonics.

Single indefinite pitch instruments produce more than one frequency at a time, and no one pitch can be heard above the others. Examples are the triangle, the bass drum, and castanets. Single indefinite pitch instruments are often used to keep the beat of the music. Multiple definite pitch instruments produce different resonant frequencies. They include tuning forks, orchestra bells, the marimba, the xylophone, the carillon, and bars or bells of different sizes. Variable-pitch instruments can rapidly change the pitch to a limited set of frequencies. An example is the kettledrum (or timpani), which has a foot pedal that can be used to change the pitch.

The head of the kettledrum is fabric stretched over a large copper (or fibreglass) bowl (**Figure 10(a)**). You cannot tune most drums; that is, you cannot adjust the frequency produced by most drums. Kettledrums, however, are always tuned to a specific pitch. To tune a kettledrum, you press on the foot pedal. When the pedal is pressed, it changes the tension in the head, which then changes the resonant frequencies of the head. When the head of the kettledrum is struck, the head vibrates up and down. The vibrations move into the large bowl and reflect off the inner surface. The reflected waves then pass out through the top of the drum and interfere with each other, giving the drum a rich, booming sound (**Figure 10(b)**).



**Figure 10** (a) A typical kettledrum, or timpani (b) Sound waves from the head of a kettledrum reflect off the inner surface of the bowl and interfere as they pass out through the top of the bowl. This diagram shows the reflection of the waves from only two points. The actual interference pattern is much more complicated.

## 10.2 Summary

- Music is a combination of musical notes (standing waves) produced from a source or sources with constant frequencies. Noise is sound produced from a source with constantly changing frequency and amplitude.
- Pitch, loudness, and quality are three subjective characteristics of sound because they depend on the perception of the listener. Pitch increases when frequency increases. Loudness increases when the amplitude of the sound wave increases.
- Musical quality depends on the number of harmonics.
- Musical instruments produce sound with a vibrating source. Most instruments are structured to enhance the sound using resonance.
- Stringed instruments consist of vibrating strings and a resonator, which resonates with the string. The resonator improves the loudness and quality of the sound produced.
- Wind instruments are composed of open or closed air columns. Vibrations are produced by vibrating lips or vibrating air over the opening or reeds.
- Percussion instruments produce sound by striking one object against another.

## UNIT TASK BOOKMARK

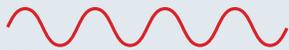
As you carry out the Unit Task on page 486, apply what you have learned, about how each type of musical instrument produces sound, to your research or design project.

## 10.2 Questions

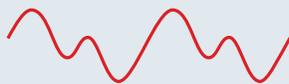
1. Each waveform in **Figure 11** represents a musical sound. Which one represents the highest (a) pitch? (b) loudness? (c) quality? **K/U**



(i)



(ii)



(iii)

**Figure 11**

2. You place a string, fixed at both ends, under tension. When the string vibrates, it produces a sound that has no musical quality. Explain why. **K/U**
3. A sonometer (**Figure 12**) is a sounding board with at least one string whose length and tension can be varied. Why does a sonometer produce sound with higher quality than the string in Question 2? **K/U**



**Figure 12**

4. A guitar string with a length of 0.66 m vibrates with a fundamental frequency of 140 Hz. The player presses down on the string on top of a fret, decreasing the length by 11 cm. Calculate the new fundamental frequency. **K/U**
5. A 0.60 m string is stretched between two fixed points and vibrates with only one crest at a frequency of 120 Hz. **K/U T/I**
- What is the wavelength in the string?
  - What are two other resonant frequencies for this string that could improve the quality of the sound?
  - What is another way to improve the quality of the sound?

6. If you twirl a long, flexible, corrugated plastic tube around your head in a circle, a musical note is produced. **T/I**
- Why is a musical note produced?
  - What happens to the pitch of the musical note if the frequency of rotation is increased?
7. Use diagrams and the universal wave equation to show that an air column of fixed length will resonate with only
- whole-number multiples of the fundamental frequency if the column is open at both ends
  - odd-number multiples of the fundamental frequency if the column is open at one end and closed at the other **K/U T/I C**
8. You tune a wind instrument inside when the temperature is 22.0 °C. You then bring the instrument outside where the temperature is 11.0 °C. Assume that the instrument acts like an open air column of length 0.800 m. **K/U T/I**
- Predict how the fundamental frequency (first harmonic) will change when you go from inside to outside. Explain your answer.
  - Calculate the fundamental frequency for the instrument when it is
    - inside
    - outside
9. You are constructing a wooden case box for a 420 Hz tuning fork to improve the loudness and quality of the sound. What is the minimum length of the box if the temperature is 24 °C and the box is
- open at both ends?
  - open at one end and closed at the other? **T/I**
10. Organ pipes, which are open at one end, of lengths 23.0 cm, 30.0 cm, and 38.0 cm, resonate best at their fundamental frequency. If the speed of sound in air is 342 m/s, calculate
- the wavelength of the sound produced by each pipe
  - the fundamental frequency produced by each pipe **T/I**