Explorations in Physics

Sound, Vibrations and Musical Tones

"Music is a succession of tones and tone combinations so organized as to have an agreeable impression on the ear and it's impression on the intelligence is comprehensible…."

--Arnold Schoenberg

0. OBJECTIVES

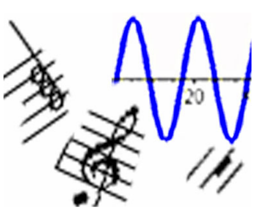
1. To identify and distinguish the characteristics of musical sound from other sounds.
2. To develop a model of sound generation, propagation and detection.
3. To define frequency and use the concept to describe and compare sounds.
4. To recognize the connection between frequency and musical pitch.
5. To learn to collect sound data with a computer based laboratory system and to learn to read and interpret time and frequency graphs of this data.
6. To recognize that consonant harmonic intervals occur when frequencies are related by ratios of small whole numbers.
7. To recognize that scales are sequences of notes with certain simple ratios of frequencies.
8. To develop the ability to analyze complex sounds in terms of their different frequency components.
9. To distinguish between different instruments and voices, which have unique patterns of frequency components.

OVERVIEW

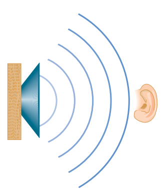
When we listen to music, an extraordinary process is occurring. Disturbances in air pressure are created by some device and then travel from the source through the air to our ears. There our ear/brain system analyzes an enormously complex pattern of pressure changes and interprets the information contained in that pattern. We hear an intelligible voice; we hear combinations of tones that we identify as consonant harmonies; we hear guitars, flutes, and other instruments; we hear a beautiful Beethoven symphony that produces a strong emotional response. The difference in the complex pattern produced by the Beethoven symphony may be different only in subtle ways from the pattern produced by a Beatles song. Yet very few people would have trouble identifying which is which!

How does this extraordinary process occur? What physical characteristics of sound can we identify and study? Clearly, sounds can be loud or soft. But what fundamental quantity describing sound is responsible for determining its loudness? Sounds also may be "high" or "low," and how do we relate that quality to a physical quantity we can investigate? How can we distinguish the sound of a flute from that of a violin playing the same note?

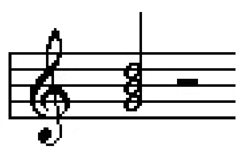
In Section 1 of this unit, we will begin by simply trying to determine what makes sounds alike or different. While most people can tell when two sounds are alike (or different), it is not a simple task to try and quantify just how similar two sounds are. In section 2, you will listen to sounds and identify the processes that produce them. You will also explore how sound is transmitted to your ear through air. You will learn several methods for detecting, measuring, and studying sounds. In particular, we will explore a characteristic of sound called *frequency*. In the Section 3, you will investigate how pitch and musical intervals are related to frequency and you will build the concepts of scales and harmony. Finally, in Section 4, you will learn to identify the characteristics of the sound that allows us to distinguish a flute from a violin. At this point, you will have the tools necessary to analyze a familiar piece of music from a more scientific perspective.



Section 1: What makes two sounds alike or different?



Section 2: Sounds, the building blocks of music.



Section 3: Frequency, harmony and musical scales.

Section 4: Complex tones and musical instruments.

Figure 1: In this unit, we will examine the basic properties of sound, explore frequency, define and construct harmonies and musical scales, analyze the differences between complex tones and see how these investigations can be used to better understand music.

1. *HYPOTHESIZING ABOUT SOUND*

You will begin this unit by listening to a variety of sounds and trying to determine which of those sounds are most alike and which are least alike.

You may need some of the following equipment for the activities in this section:

- Music Unit Sound Files (1.1)
- CD or Tape player (1.1)

1.1. WHAT MAKES A SOUND A SOUND?

We are continually bombarded with sound of all kinds, from the roar of a jet airplane taking off to the chirp of crickets on a warm summer night. Music is part of our everyday environment, whether we are at a football game, in a car, at a supermarket or in a concert hall. How do we know whether we are hearing composed music in a concert hall or "conversations" between geese in a flock flying south for the winter? What criteria do we employ to categorize some sounds as pleasing and others as unpleasant? How do we differentiate between musical and non-musical sounds?

Activity 1.1.1: Which Sounds are Similar?

a) Your instructor will have a series of different sounds for you to listen to. Working with your group, try to determine which two sounds from this collection sound most alike. Give a reason (as best you can) for your answer and be ready to discuss this with the class.

b) Again work with your group, but this time try to determine which two sounds are the "most different." Again, give a reason for you answer and be prepared to discuss this with the class.

If you found the above activity to be a little "weird," don't feel bad. Exactly what makes two sounds sound alike is a bit subjective and different people will have different responses regarding this question. In fact, trying to determine which sounds are least alike is even more difficult for most people. When two sounds are not at all similar, it is difficult to try and determine how "dissimilar" they are. If this all sounds very vague right now, that's all right. We will be investigating many of these topics again and again from a more scientific perspective throughout this unit.

Activity 1.1.2: Some Features of Sounds

a) Working alone, list a few (two or three) of the most important features of sound that you used to help you determine which sounds were most alike and which were least alike. Try to be as clear as possible about these features and if you use any terms that whose meaning is not completely obvious, make sure you explain what they mean.

b) Do you think that everyone will answer the above question in essentially the same way? After answering this questions, check with some of your classmates and comment on their responses below.

You may have noticed that there is not necessarily a lot of agreement on exactly what makes two sounds sound alike or different. In fact, there may not be complete agreement on which features of the sounds are the most important. On the other hand, you may also have noticed that when there is some agreement between you and your classmates, it is not easy to explain precisely what you are referring to when you are talking about a particular sound feature. This is a very common situation in science and in order to make progress, it is essential to come up with concrete definitions that everyone agrees with and understands. In addition, it is important to try and figure out the most essential aspects that are needed to explain the phenomenon under study. In our case, we need to try and determine which features of sound are the most important in trying to understand sound and then we will need to define precisely what we mean when we talk about these features. This is the topic of the next section.

2. *SOUNDS, THE BUILDING BLOCKS OF MUSIC*

As you probably noticed in the last section, trying to describe particular sounds is more difficult than you might think. One of the difficulties in describing sounds is the lack of a common language or terminology that we can all refer to. But even if we agree on the terms to use, it might not always be clear when two people are referring to the same property of the sound. For example, if two people refer to the volume or loudness of a sound, there is a good chance that both will have a pretty good idea of what that term means. However, if one person wants to discuss the "smoothness" of a sound or the "tone" of a sound, it is not entirely obvious what features they are referring to. Therefore, instead of immediately trying to agree on the terminology to describe sounds, it will be useful to first look at how sounds are created, how sounds reach our ears, and how we hear sounds.

You may need some of the following equipment for the activities in this section:

- Music Unit Sound Files (1.1)
- CD or Tape player (1.1)
- Implements for making sounds - tuning forks, rubber bands etc… (1.2)
- Signal generator (1.2 - 1.4)
- Loudspeaker (large woofer) (1.2 - 1.4)
- Stopwatch (1.2)
- Candle (1.3)
- A Slinky or Slinky Wave Simulator (1.3)
- QuickTime movie of a people wave (1.3)
- A micro-computer based laboratory system (1.4)
- An electronic sound sensor (1.4)

2.1. HOW IS SOUND PRODUCED?

We hear sounds from a variety of sources everyday from the roar of a jet airplane to the chirp of crickets on a warm summer night. Music and speech is also part of our everyday environment, whether we hear it at a sporting event, in a car, at the supermarket, or in a concert hall. A natural question to ask is whether or not these different sources have anything in common that allows them to actually produce these sounds?

Activity 2.1.1: Sound Generation

a) Imagine a guitar string that has been plucked. How you think the guitar string actually produces the sound you hear? (What is happening to the guitar string as it produces the sound?)

b) Your instructor will provide you with several sound producing items such as metal bars, tuning forks, rubber bands, etc. Figure out how to make a sound with each of these items. For example, stretch the rubber band and have someone pluck it. For each item, observe the object as it is making the sound and describe what is happening to each object when it is actually producing sound.

c) How is each object different when it is producing sound compared to when it is silent?

d) From these observations, try to draw a general conclusion about the production of sound. That is, can you make a statement that you think might be true for *all* sound producing objects?

Most students agree that there seems to be some kind of vibration involved in the production of sound. At this point, we can't be certain that *all* sounds are produced in this way, but it seems like a reasonable place to start our investigation. With that in mind, wouldn't it be nice if there was a simple way of controlling how much something vibrates so that we can study the effects of how vibrations might be related to sounds? Well, it turns out that there is.

Speakers and Signal Generators

Throughout this unit, you will use an electronic signal generator and a speaker to produce sounds. Quite simply, the signal generator produces a repeated electrical signal that causes the speaker cone to move back and forth. The following activity will help familiarize you with the signal generator.

Activity 2.1.2: Production of Sound by a Speaker

a) Before connecting the signal generator to the speaker, turn the *frequency* knob so that it reads 1 Hz and turn the *amplitude* knob all the way up. Check that the signal generator output is set to a "sine wave" (∿∿). (Don't worry if you don't understand any of this just yet.) Your instructor may have specific instructions on exactly how to accomplish this. When you have it set properly, connect your speaker to the frequency generator and describe the motion of the speaker. It may help to look at the cone from the side rather than head on. In addition to watching the speaker, gently touch the speaker cone.

b) Now slowly decrease and then increase the *amplitude* knob while watching (and gently touching) the speaker cone. Briefly explain what *amplitude* knob does.

c) Now try slowly increasing and decreasing the *frequency* knob while watching and gently touching the speaker cone. Briefly explain what the *frequency* knob does.

d) Next, with the amplitude turned all the way up, slowly increase the frequency knob up past 10 Hz, then past 20 Hz and continue increasing until you hear something. Gently touch the speaker. Is the speaker still moving? Explain how you think this sound is being produced by the speaker? Is this similar to how sounds were produced in Activity 2.1.1:? Explain briefly.

e) Continue slowly increasing (and decreasing) the frequency and describe how the sound changes? Also, try decreasing and increasing the amplitude and explain how this affects the sound.

Frequency of Vibration

It should be pretty obvious from the last activity that vibration appears to be an important characteristic of sound. Thus, it is important to make sure that we have a very solid understanding for precisely what we mean when we talk about a "vibration." We have already seen that amplitude and frequency are two important pieces of a "vibration," and in particular, frequency will be utmost importance throughout this unit.

Activity 2.1.3: Defining Frequency

a) Using the apparatus from Activity 2.1.2:, adjust the frequency of the signal generator to 1 Hz. Then, using a stopwatch, count how many times the speaker cone moves in and out in 10 seconds. Based on this measurement, determine how many times the speaker cone moves in and out in one second. Explain how you came to this conclusion.

b) Now adjust the frequency of the signal generator to 2 Hz and count the number of *oscillations* (going in and coming back out) the speaker undergoes in 10 seconds. Based on this measurement, determine how many times you think the speaker will oscillate in one second.

c) If you set the frequency of the signal generator to 5 Hz, how many oscillations will the speaker undergo in 1 second? What about for a frequency of 10 Hz or 100 Hz? Based on these answers, what would be an appropriate definition for the units Hz? Explain.

d) Explain once again how the sound you here is different for low frequencies versus higher frequencies. Then, or fun, use your speaker to try and determine the entire range of frequencies you can hear.

Checkpoint Discussion: Before proceeding, discuss your ideas with your instructor!

Scientific Definition of Frequency

As it is used in everyday language, the term frequency means how often something happens. This usage is very similar to the scientific definition for frequency. The formal definition for frequency can be stated as follows: The frequency associated with a motion that repeats on a regular basis is the number of repetitions that occur in particular time period. As you might have deduced in the previous activity, a good way to measure frequency is to count the number of vibrations or repetitions in some convenient period of time. By taking the ratio between the number of vibrations and the time period over which the vibrations were counted, we can write

$$f = \frac{\text{number of vibrations}}{\text{time period for counting}}$$

If we use seconds as the units for time, rather than minutes or hours, then the units for frequency will be Hertz or Hz for short.

$$1\ \text{Hz} = \frac{1\ \text{vibration (cycle)}}{1\ \text{second}}$$

2.2. TRANSMISSION OF SOUND

We have seen that many sounds, including musical sounds, involve vibrations. But, how does sound get from the vibrating source to our ears? Can we see or feel the oscillations that produce those disturbances that propagate through the air? When sound propagates from the vibrating source to your ear, does some of the air near the source actually travel to your ear? If so, how? If not, then how does the pattern of sound get from one place to another?

Activity 2.2.1: How are Sound Vibrations Transmitted?

3D picture of speaker and paper

a) In this activity you will hold a piece of paper vertically a few inches in front of a speaker that is producing sound by vibrating. Predict what will happen to the paper, if anything, when the speaker is turned on. Do you think the frequency of the sound will play a role? Explain briefly.

b) Now let's try the experiment. Suspend a sheet of paper about three inches in front you the speaker so that half the speaker is covered by the paper. Then, before turning on the speaker, set the frequency to about 4 Hz and turn on the speaker. Describe your observations below. (If you don't notice anything at all, try moving the paper slightly closer to the speaker.)

c) Now try slowly increasing and decreasing the frequency and explain what you see. In particular, try to look at the paper and the speaker simultaneously to see if there is anything similar about the vibrations in the speaker and those of the paper.

d) Now gently pinch the paper with your thumb and forefinger at a spot directly in front of the center of the speaker. Then slowly increase the frequency up to about 100 Hz. Describe what you feel. How does this change as the frequency increases?

e) Explain how you think the vibrations from the speaker are causing the paper to vibrate?

It appears that some of the speaker vibrations are somehow moving through the air and causing the paper to vibrate. We can set up a similar observation using the flame of a candle to help us observe the motion of the air caused by the passage of sound. Since a candle flame is made up of hot air and trace gases, it will move along with the air in its vicinity. By watching the flame of a candle placed in front of a vibrating speaker we can examine how the air changes in the presence of sound.

Activity 2.2.2: Observing Sound with a Candle

a) Your instructor will perform a demonstration in which a candle is placed in front of a speaker. Explain what you think will happen to the candle flame if the speaker is turned on and oscillates with a frequency of about 5 Hz. What if the frequency is about 10 Hz? Explain your reasoning.

Figure 2: A candle flame placed in front of an oscillating speaker. The vibration of the speaker is somehow transmitted to the candle flame.

b) When your instructor turned on the speaker, what happened to the candle flame? How did this correspond to your predictions in part a)? If what you observed was different than what you predicted, how was it different?

c) Compare the motion of the candle in this activity with the motion of the paper in the last activity? Describe how you think the vibrations are transferred from the speaker to the candle flame.

You may have noticed that the candle seemed to vibrate at the same frequency as the speaker. Is this true? The candle flame flickers back and forth too rapidly to measure its frequency with the naked eye. We have made a digital movie of the candle flame and the speaker so you can make quantitative measurements of the frequencies of both the speaker and the candle flame.

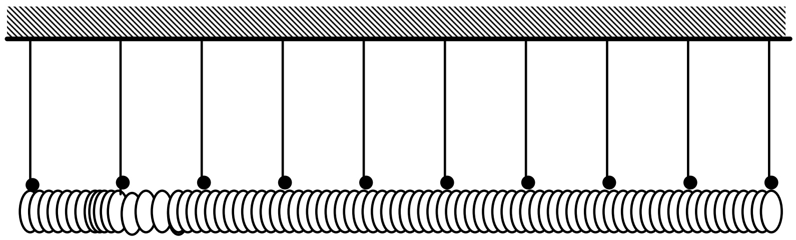
How do Disturbances Travel Through Matter

The fact that the candle flame moves back and forth is our first real piece of evidence that sound travels through *air*. Clearly, the candle flame is affected by the vibrating speaker and it is plausible that all of the air in the room is somehow affected by the vibrations in the speaker. Does that mean the air molecules actually travel from the speaker to our ears?

In the previous activities, you saw that the candle flame moved back and forth over a small distance. Since the candle flame is made up of mostly hot air it will likely move along with the air in its local environment. Thus, it is reasonable to conclude that the air in the vicinity of the candle flame moves back and forth over a small distance just like the candle flame you observed. Still, we know that sound can travel large distances (for example from an airplane flying far overhead). How can sound travel over large distances while the air only moves a small distance?

There is no easy way to observe the air as sound travels through it from the speaker to your ear. However, in order to gain a better understanding of how air might transmit sound, let's look at some other situations in which a disturbance travels in a medium we can see. In the activities that follow, we will examine the way that a disturbance propagates through a slinky and through a crowd of people. These examples will help us draw some conclusions about how sound travels.

Activity 2.2.3: Pushes on a Slinky



a) Describe what happens when someone creates a disturbance by giving a single quick push on the end of a slinky? What happens when someone gives a series of pushes on the slinky by causing her hand to vibrate back and forth?

b) Do the individual coils actually travel along the slinky? If not, how do the individual coils actually move? What exactly *is* traveling along the slinky?

c) Is there any similarity between what happened to the slinky coils in this activity and what happens to a candle flame placed in front of a vibrating speaker? Explain briefly.

What is a Wave?

You should have noticed in the last activity that while the waves traveled the length of the slinky, individual coils moved back and forth only a small distance. Just like the candle flame, the *medium* is only slightly perturbed but the disturbance travels over a long distance. How does this happen? What do the individual coils in the slinky do to make the disturbance propagate? That is, how does the disturbance move from one coil to the next? In scientific terminology, a wave is a disturbance that travels through a *medium* (some material like air or water) without the constituents of the medium moving very far. According to this definition the disturbance we saw in the slinky is a wave. In the next activity, we will look at how a wave travels through a crowd of people.

Activity 2.2.4: People Waves

a) Your instructor will show you a video clip of a disturbance moving through a crowd. Describe the motion of the people in the crowd.

b) What are the individual people in the crowd doing to make the disturbance propagate forward? Explain how the motion of the people in this video clip can be related to the motion of air in the speaker/candle flame system described in Activity 2.2.2:.

Both of the last two activities demonstrated situations in which waves propagated over large distances while the medium (spring coils and people) moved back and forth by only a small amount. In the case of the slinky, the wave is propagated, when each coil pushes on its neighboring coils. Thus, the push is transmitted from one coil to the other while the coil itself moves only a small distance. The wave in the crowd propagates similarly. When one person is pushed her natural reaction is to move away from the push. The result is that she pushes on someone else. As this process repeats, the wave propagates, but the individuals only move a short distance.

How are these situations related to the motion of air in a sound wave? In order to make this connection it is easiest to think of the air as made up of many tiny molecules. The molecules are so small that we cannot see them, but there are so many of them that we can feel their effects. Individual molecules can move freely until they collide with another molecule.

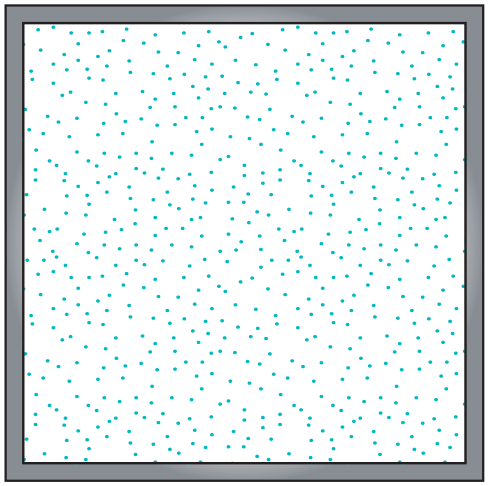


Figure 3: We can think of air as made up of many tiny molecules. While these molecules are too small to be seen, it is convenient to represent them as tiny dots. What happens to the air molecules as a sound wave passes?

Activity 2.2.5: Picturing Sound Propagation

a) Describe in words what you think is happening to the air molecules when a sound wave passes by.

b) As best you can, draw a rough sketch of the air molecules in the midst of a sound wave.

Sound Waves

The observations you have made provide the basis for constructing a simple model for how sound is generated and propagates in air. As you saw in Section 1.2, most sources of sound vibrate. In section 1.3, you found that these vibrations are somehow transmitted to the air. You also saw that while the vibrations travel over large distances, the individual air molecules move back and forth over relatively small distances. Based on these observations, it is reasonable to conclude that as a sound source vibrates it pushes against the air. In pushing against the air, the vibrating source creates a disturbance that propagates through the air just as the waves moved through the crowd and slinky. This propagating disturbance is called a *sound wave*.

But, what happens when the sound reaches our ear? In the next section, we will explore how the vibrations we call sound are detected in our ears.

Checkpoint Discussion: Before proceeding, discuss your ideas with your instructor!

2.3. DETECTING SOUND WAVES

We have explored how sound waves are generated and how they move through the air, but have not addressed the question of how we hear sound. By exploring methods for detecting sound, we can gain insight into some of the basic principles of the human ear. Based on what we know so far about sound, how might we go about building a simple sound detector?

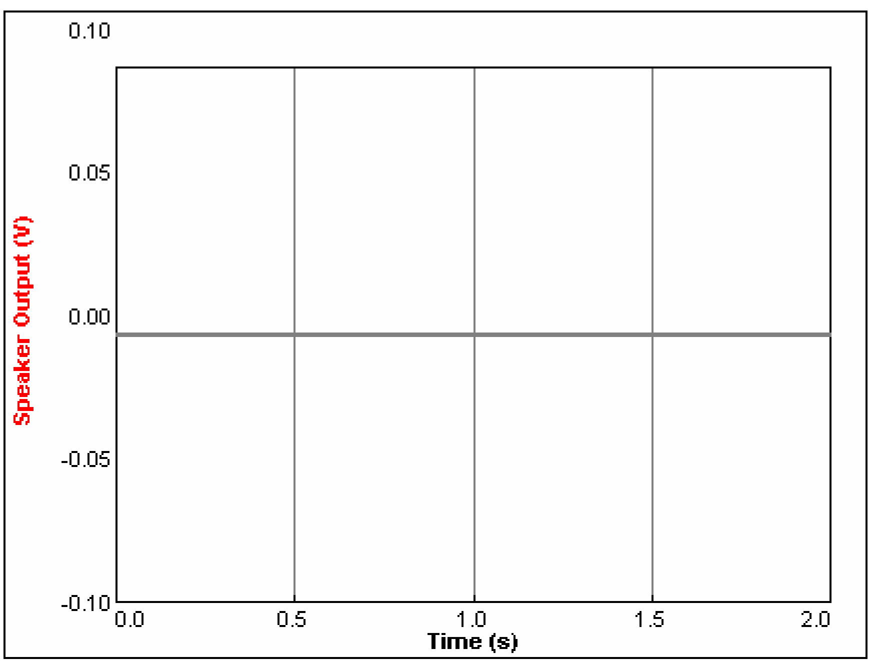
We know that a sound source, such as a speaker, vibrates. These vibrations push on the air and create waves in the air that we call sound. Thus, detecting sound is as simple as detecting these sound waves. Throughout this subsection, we will develop a means for detecting sound waves and learn a little about how the ear works.

Note: In many of the activities that follow, you will be using a computer based laboratory system with a sensor to record sounds electronically. The system consists of an interface, sensors and software that turn a computer into a powerful measuring device for the laboratory. This system can detect signals from sensors, record these signals and display them graphically. This type of system is sometimes called a Microcomputer Based Laboratory system (MBL)

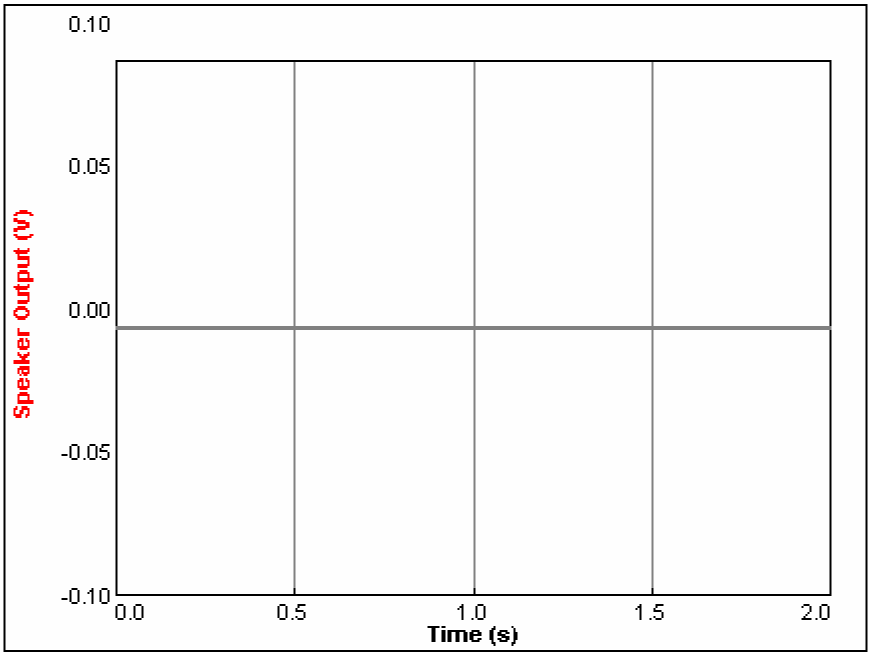
Activity 2.3.1: Measuring the Motion of a Speaker

a) Connect the voltage probe leads from your MBL system to the two terminals on the back of the speaker. Open the file A020301.mbl and begin collecting data. Experiment by pressing gently on the speaker and releasing it a few times. Describe what you notice on the computer screen.

b) Now give a quick but gentle push on the speaker and hold it for a brief moment and then quickly release it. Repeat this process at a frequency of about 1 Hz. In the diagram below, make a rough sketch of what you see on the computer screen. Make on the graph where you pushed and where you released.



c) Now press gently in and out on the speaker cone and try to make the graph on the screen a smooth oscillating curve (∿∿). Press in and out quickly (and smoothly) at a frequency of about 5 Hz. In the diagram below, make a rough sketch of what you see on the computer screen.



d) Do you think that you could use this setup to measure sound? Explain how this might be possible. **Hint:** Recall what happened when a piece of paper was held in front of a speaker producing a sound.

Although we won't go into the details of how a speaker works (although that would make a great project), we have seen that it can turn an electrical signal into motion that can result in sound, depending on the frequency and amplitude. Interestingly, this last activity demonstrated that this process also seems to work in reverse. That is, if you force the speaker to move, an electrical signal can be generated. While this graph does not give the position of the speaker, it is clearly related to the motion of the speaker in a systematic way (a detailed analysis of this relationship would make a great project). For our purposes right now, this interesting behavior can be used to turn the speaker into a simple sound detector.

Detecting Sound with a Speaker

Think about Activity 2.2.1: in which you held a piece of paper in front of the speaker. In that activity, the vibrations generated in the speaker traveled through the air as disturbances to make the paper vibrate. If these vibrations in the paper could be measured in some way, presumably we could learn something about the air disturbances that caused the vibrations in the first place. Thus, observing the oscillations in the paper should lead us to knowledge about the disturbances in the air.

The speaker cone used in the last activity acts very much like the piece of paper. As we saw in the last activity the speaker coil and MBL system allow us to measure the movement of the speaker cone very precisely. Putting these together, it should be possible to measure the disturbances in air we have been calling sound. In the next activity you will see if it is possible to use the speaker/MBL system to detect sound.

Activity 2.3.2: Can a Speaker be a Microphone?

a) Open the file A020302.mbl. Begin collecting data and make a continuous but loud sound with your voice into the speaker. What do you observe on the screen? What conclusion can you thus draw regarding the speaker cone?

b) If we assume that only air is in contact with the speaker cone, it seems reasonable to assert that the air is somehow causing the speaker cone to move. Explain how the sound waves (air disturbances) might cause the speaker cone to move?

Checkpoint Discussion: Before proceeding, discuss your ideas with your instructor!

In the last activity you used a speaker to detect sound. As sound waves hit the speaker, it responded by vibrating. These vibrations were translated into electrical signals that were picked up by the MBL system and displayed on your screen. As a result, the graph on the computer screen gives a representation of the air disturbances that cause the speaker cone to move. This means a speaker can function as a basic sound detector. Unfortunately, since the speaker was designed to produce sounds, its use as a sound detector is fairly limited. Because it is relatively difficult to move the large speaker cone, the speaker can only detect relatively loud sounds. Also, the it is not entirely clear how the output signal from the speaker is related to the disturbances of air that produced the signal.

Microphones

A microphone works in a manner very similar to the speaker. Sound waves vibrate a small diaphragm (similar to the large one in the speaker cone), which in turn is translated into an electrical signal. Since a microphone is designed with a small diaphragm, it will be much more sensitive than a speaker at detecting sounds. In addition, the output signal from a microphone is much more easily related to sound waves than is the output signal from a speaker. This is illustrated below.

Time Graphs of Sound

As previously mentioned, when a wave travels through a medium (such as sound traveling through air), the individual "particles" of the medium (the air molecules) only move a small amount even though the wave itself can travel a large distance. Recall the dancing candle flame from Activity 2.2.2:. The candle flame is made mostly of air and thus represents the motion of the air in its vicinity. Since the air particles in the vicinity of the sound wave move forward and backward, they cause the candle flame to move forward and backward. Likewise, if the air was in contact with the diaphragm from a microphone, the diaphragm would also move back and forth. When the diaphragm in the microphone moves forward, this results in a high point on our graph. As the diaphragm moves in the opposite direction, we get a low point in our graph. This is depicted graphically in the figure below. These "time graphs" are a common way to examine the characteristics of a sound.

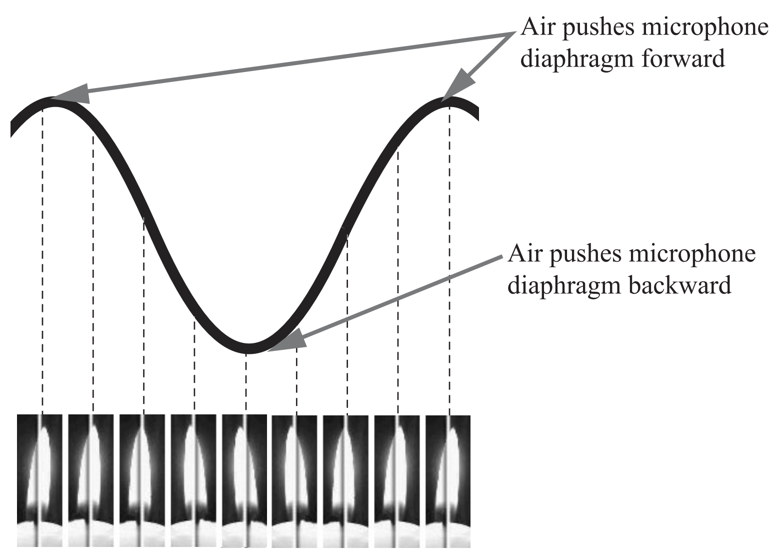


Figure 4: The curve depicted in a speaker output vs. time graph represents the motion of the air as a sound wave passes. As a sound wave passes, the diaphragm of the microphone moves forward and backward resulting in an oscillatory electrical signal. The corresponding motion of the candle flame reveals that the motion of the air in a sound wave is oscillatory.

Activity 2.3.3: Microphones and Time Graphs

a) Plug the microphone into your MBL station and open the program A020303.mbl. When you are ready, try making a long steady sound with your voice, similar to when you were using the speaker as a microphone. Does the time graph look like it repeats? When you have a nice “clean” run, print out a copy for your Activity Guide.

b) Now connect the signal generator to the speaker and set the frequency to 200 Hz. Use the microphone to collect sound data for this 200 Hz signal and print out a copy for your Activity Guide. Explain whether this sound graph looks simpler or more complicated than the one for your voice. Does this mean that the signal generator is producing a “simpler” sound? Explain briefly.

c) Next, let’s pretend that you *didn’t* know the frequency setting on the signal generator was 200 Hz. Explain how you could deduce the frequency of the sound just by viewing the time graph.

d) Now carry out the procedure you just described to determine the frequency of the sound from the time graph alone. Write down your result in the following table. Then carry out this procedure two more times **using frequency settings that you do not know** (use frequencies that are quite different from each other). This can be accomplished by having one person in the group set up the signal generator and everyone else deduce the frequency from the time graph. Then, switch choose a new person to set up the signal generator.

Setting on Signal Generator (Hz)	Measured Frequency (Hz)
200	

e) Compare the signal generator settings to your frequency measurements. Were your measurements different from the signal generator settings? If so, by how much? Describe what you think might be the source of this inconsistency. **Note:** A blanket statement such as "human error" is not an acceptable answer. If you think human error is the problem, explain exactly how.

f) Do you think you can do the same kind of frequency analysis for the time graph of your voice? What kind of difficulties might you run into? Try it and see what you get.

Checkpoint Discussion: Before proceeding, discuss your ideas with your instructor!

Human Hearing

In many ways, the functionality of the human ear is very similar to the microphone we have been using. Sound travels to the ear and causes a diaphragm, the ear drum, to vibrate. These vibrations are transferred to the cochlea by the bones of the middle ear (ossicles). In the cochlea, the vibrations are translated into electrical signals that are sent to the brain by the auditory nerve. The brain interprets these electrical signals as sound. One of the most amazing features of the human ear is its ability to sense a very wide range of volume levels, from extremely soft to very loud. Not quite so impressive is the range of frequencies that the human ear is sensitive to. Recall that in Activity 2.1.3: you determined the range of frequencies that you could hear. Typically, humans can hear frequencies in the range from 20 Hz to 20,000 Hz although most people have difficulties hearing at either the low end or the high end of this spectrum.

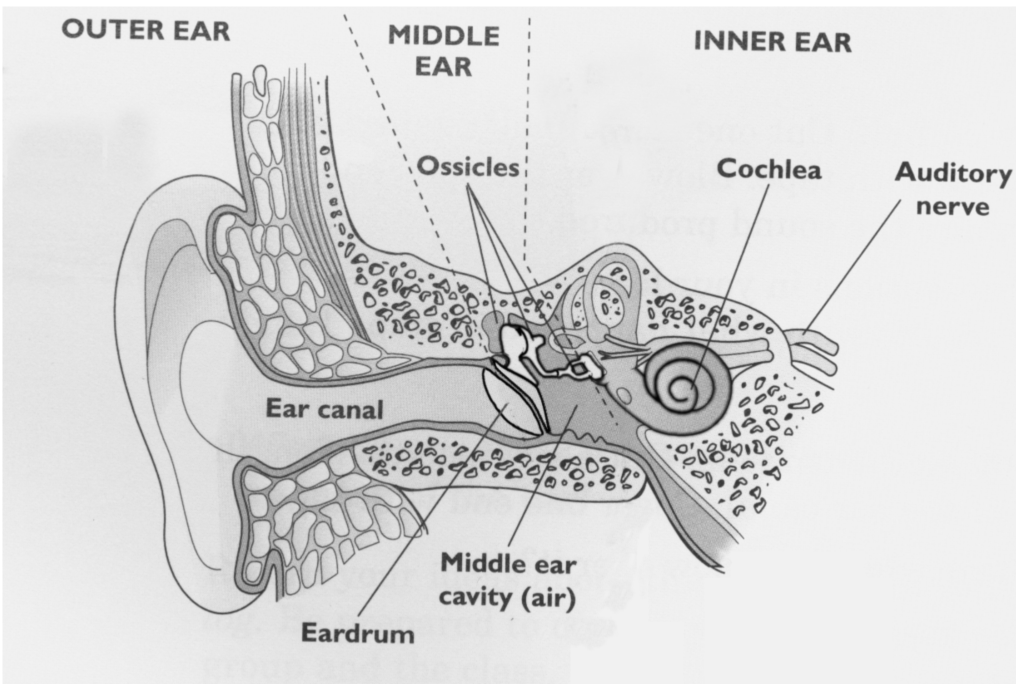


Figure 5: A diagram of the human ear. The ear functions in a manner very similar to a microphone. Vibrations in the air (sound waves) cause the ear drum to vibrate. These vibrations are transferred to the inner ear where they are converted into electrical impulses that the brain interprets as sound.

2.4. CHARACTERIZING SOUNDS USING TIME GRAPHS

In the last several activities, you used time graphs of sounds to measure some of their characteristics. Examining time graphs makes it possible to observe certain aspects of sound that are difficult to characterize just by listening. For example, you have been able to measure the frequencies of several sounds very accurately by analyzing the time graph of the sound. Is it possible to observe other characteristics of sounds with time graphs? That is the topic of the next activity.

The next activity will require some setup. You will need two computers to make time graphs of your sounds. Carry out the following instructions to set up the activity.

1. On one computer, open the MBL file A020401.mbl.
2. On another computer, open up the sound file that you want to make a time graph of.
3. Connect your microphone to the MBL system and set it up a few inches from the speaker on the computer you will use to play the sounds.

In order to generate time graphs of the sounds, press the collect button on the MBL system and begin playing the sound. After the time graph appears on the screen, press the stop button on the MBL system.

Activity 2.4.1: Time Graphs of Steady Sounds

a) Begin by collecting a time graph of a "steady" sound, but not one of the two sounds you thought sounded "most alike" back in Activity 1.1.1:. (A *steady* sound is one that remains the same for a few seconds.) Make sure you look at the time graph on a number of different time scales (0.1 sec, 0.05 sec, 0.02 sec) and when you find one looks "understandable," print out a copy for your activity guide. Describe the sound you hear using words and describe any obvious features of the time graph.

b) Now choose another sound that is reasonably different from the sound you just analyzed (but still steady). Perform the same kind of analysis of this sound and its time graph. Don't forget to look at the sound on different time scales until you find one that looks "understandable." Describe any features of the sound and the time graph that are different from the previous case.

c) Now analyze the two sounds you thought sounded most alike back in Activity 1.1.1: and describe how their time graphs are similar and/or different. Again, be sure to check different time scales and print out copies for your Activity Guide.

d) Of all the time graphs you've seen so far (including any from previous activities), which do you think is the "simplest" and which is the most "complex?" When you listen to the sounds, do you agree with this categorization? Explain briefly.

Checkpoint Discussion: Before proceeding, discuss your ideas with your instructor!

Summary

In this unit, we have begun to develop quantitative methods for analyzing and describing sounds. We have defined frequency and devised methods for measuring the frequency of sounds. We have learned how to generate and interpret time graphs of sounds. In addition, you have explored how sound is generated, travels and how it is detected.

In the next section, we will begin to look more closely at musical sounds and the role that frequency plays in music. Among other things, this will lead us to investigate scales and explore the nature of harmony.

3. *FREQUENCY, HARMONY AND MUSICAL SCALES*

In the last section, we focused our attention on the generation, transmission, and detection of sound. This led us to a scientific definition for frequency and gave us some direct experience with time graphs of sound. In this section, we will take a closer look at how frequency is related to what we actually hear and then explore how frequencies might help us to understand (or define) harmony and musical scales.

You may need some of the following equipment for the activities in this section:

- Music Unit Sound Files (2.1)
- Signal generator (2.2)
- Loudspeaker (2.2)
- An MBL system (2.1 - 2.3)
- A microphone with sound software (2.1 - 2.3)
- Keyboard synthesizer software (QTKeys for Macintosh works well)

3.1. A CLOSER LOOK AT FREQUENCY

Before you begin the next activity, open the keyboard synthesizer software package and familiarize yourself with the controls. Set the volume to a medium value and choose an instrument that will give you a pure tone. (**Note:** For the next few activities, you will need an instrument that can generate a pure tone like that generated by a signal generator. The important thing is that the instrument can be set up to play only one frequency. Ocarina and flute are often good choices for generating a pure tone.)

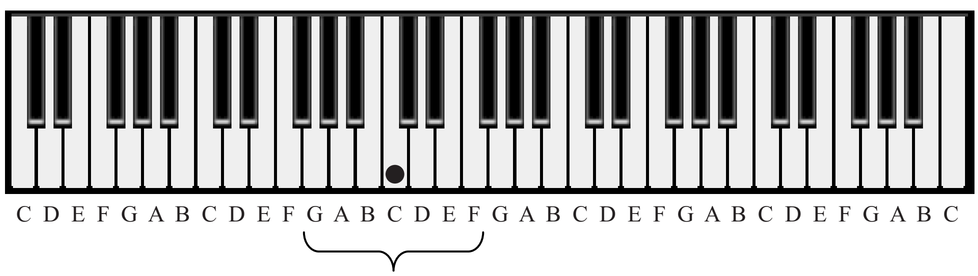
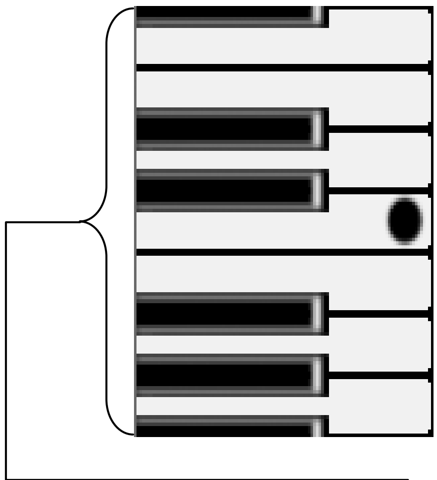


Figure 6: You will use a keyboard for several of the activities in this unit. The white keys (notes) on a keyboard are labeled A through G represent one *octave*. Several octaves are shown here.

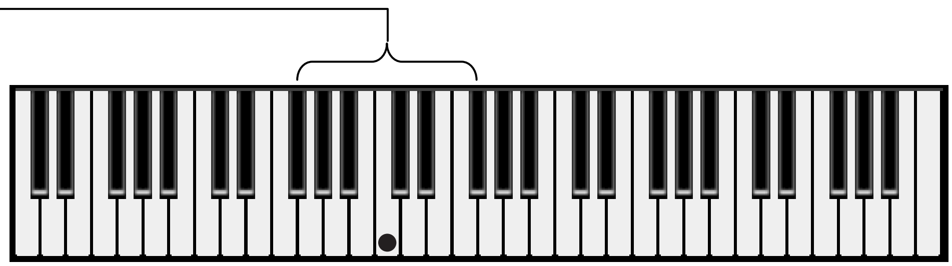
Activity 3.1.1: Frequency and Pitch

a) Play the white keys (G, A, B, C, D, E, F) indicated in the figure above. How does the *sound* of the notes change as you play the keys from G to F. **Note:** The sensations that your ear/brain system experiences when moving from note to note is called *pitch*.

b) Now use a microphone to produce time graphs and determine the frequency for each of the these notes. Tabulate your results below.



Note	Frequency (Hz)
F	
E	
D	
C	
B	
A	
G	



c) How does the frequency of the notes change as you go from G to F in part b)? Compare this observation to the changes in pitch that you observed. What conclusion can you draw about the relationship between frequency and pitch?

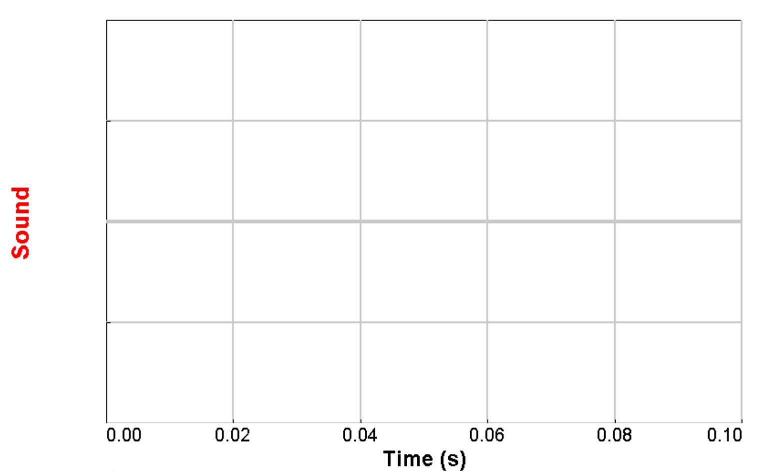
Multiple Tones in Music

It is common for musical sounds to consist of two or more tones played simultaneously. For example, one might play a chord or a band might play several instruments together. The resulting sound is undoubtedly more complicated than a single pure tone. In the next activity we will begin to look at how we might analyze sounds containing multiple tones.

Activity 3.1.2: The "Frequency" of Multiple Tones

a) Play middle C and another note simultaneously (a pair of pure tones) and capture a time graph of the sound created. Describe what you hear, then sketch the time graph below and try to determine the frequency of the sound.

Pair of Pure Tones Sound vs. Time

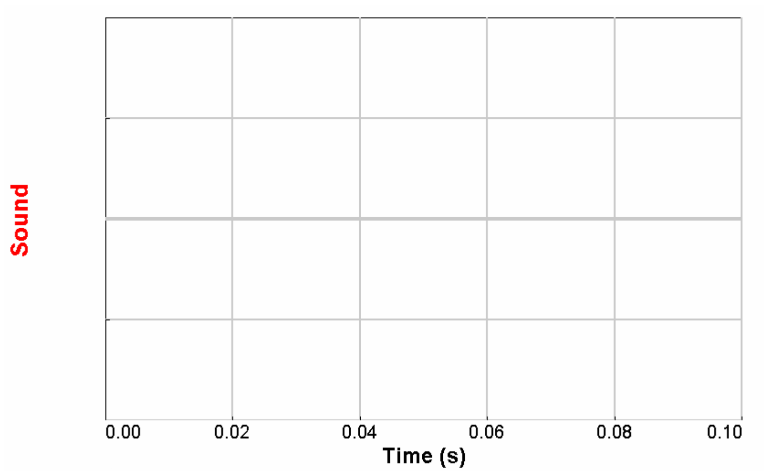


Frequency = _______

b) Explain how you measured the frequency in part a). Describe any difficulties you encountered. Why do you think it was more difficulty to measure the frequency of this sound? Explain briefly.

c) Now play three notes together and capture a time graph of the sound. Describe what you hear and sketch the time graph of the sound below.

Three Pure Tones Sound vs. Time



d) Do you think it is possible to measure the frequency of the sound in part c)? Why do you think it would be more difficult (or impossible) to measure the frequency of this sound compared to a pure tone? Explain.

Checkpoint Discussion: Before proceeding, discuss your ideas with your instructor!

Limitations of the Oscillation Counting Method for Measuring Frequency

The method for determining frequency that we have been using is called the *oscillation counting* method (count the number of oscillations and divide by the time). You probably found it more difficult to measure the "frequency" of a sound that had more than one not being played simultaneously. This is in stark contrast to how easy it is to determine the frequency of a single pure tone. Why is that? Well, when playing two pure tones together, the sound contains more than a single frequency (it contains *two* frequencies). Similarly, when three pure tones the sound contains three frequencies. The resulting time graphs of 2 or 3 tones typically look much more complex than a time graph of a single pure tone. For this reason, the oscillation counting method is only capable of discerning a single frequency and is therefore incapable of characterizing multiple tones or sounds other than a pure tone. Since music is filled with harmonies and rich tones, we need to find another method for determining the frequencies in a sound when several frequencies are present. In the next subsection, we will examine a very sophisticated (yet simple to use) tool that will allow us to measure many frequencies present in a single sound.

3.2. FREQUENCY GRAPHS: WHAT FREQUENCY IS THAT SOUND?

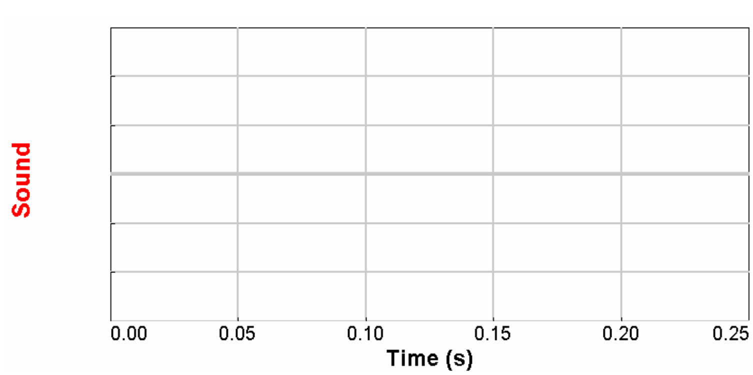
So far you have learned a lot about the nature of sound by investigating single pure tones. However, most music has much more character than pure tones. Music often involves several tones played together. For example, an orchestra or a choir often play multiple tones simultaneously. While analyzing time graphs is an excellent tool for investigating sounds, we found that time graphs of multiple tones are often difficult to interpret. In the next few activities you will explore frequency graphs, another method for displaying information about a sound.

Note: Frequency graphs are produced through a mathematical process known as a *Fourier Transform*. On computers, there is a beautiful algorithm that allows Fourier Transforms to be performed very quickly. This is called a *Fast Fourier Transform*, or *FFT*. Thus, although it is not necessary for you to understand the details of a Fourier Transform, it is important to know that frequency graphs are also called FFT graphs.

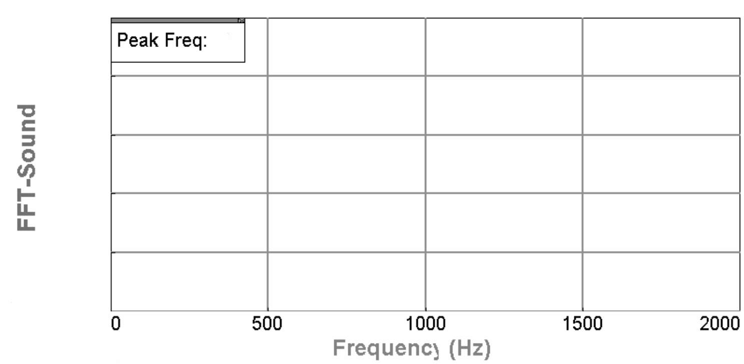
Activity 3.2.1: Frequency Graphs of Pure Tones

a) Using a signal generator and speaker, play a pure tone with a frequency of about 200 Hz. Then, using a microphone and MBL system, open the file A030201 and record this sound. Sketch the curves shown in the time and frequency graphs below.

Sound vs. Time



Sound vs. Frequency



b) Describe the contents of the frequency graph. For what value of the frequency do you find a large peak? How do you think this is related to the frequency of the curve in the time graph?

c) Predict what will happen to the frequency graph when the frequency of the sound is increased to 400 Hz.

d) Before changing the frequency on the signal generator, start collecting data again. Now watch the computer screen and then increase the frequency by a small amount and wait for graph to settle down. Increase the frequency again and wait for the graph to settle. Repeat this process several times. Describe what happens to the large peak on the frequency graph as you increase the frequency of the sound.

e) Now predict what will happen to the peak in the frequency graph if you increase the *volume* of the sound.

f) Begin collecting data and watch the computer screen. Increase the volume of the sound by turning up the amplitude knob on the signal generator (if it is already at the maximum setting, decrease it and take note of what happens). Describe what happens to the large peak in the frequency graph as you increase the loudness of the sound.

g) Explain how you think the characteristics of the peak in the frequency graph correspond to the properties of the sound. What does the horizontal position of the peak correspond to? What does the height of the peak correspond to?

Frequency Graphs and Fourier Transforms

In the last activity you looked at the frequency graph of a pure tone. You should have noticed that the frequency graph accurately depicts the frequency of the pure tone that is being played. The position of the peak along the frequency axis indicates the frequency of the pure tone. Thus, peaks that appear farther to the right correspond to higher frequency pure tones, while peaks appearing toward the left correspond to lower frequency pure tones. The height of the peak gives some indication of the volume of the tone. Louder tones are indicated by taller peaks and softer tones are indicated by shorter peaks.

Note: You may have noticed several other small peaks in the frequency graph. In the case of a pure tone, these peaks are caused by noise and imperfections in the sound generation and detection systems. For the purposes of these activities, you may ignore these small peaks. It is also worth mentioning that as you work through these activities, you must remember to auto-scale your graphs so that all of the data is displayed on the screen. If you do not auto-scale, smaller peaks may appear larger than they actually are.

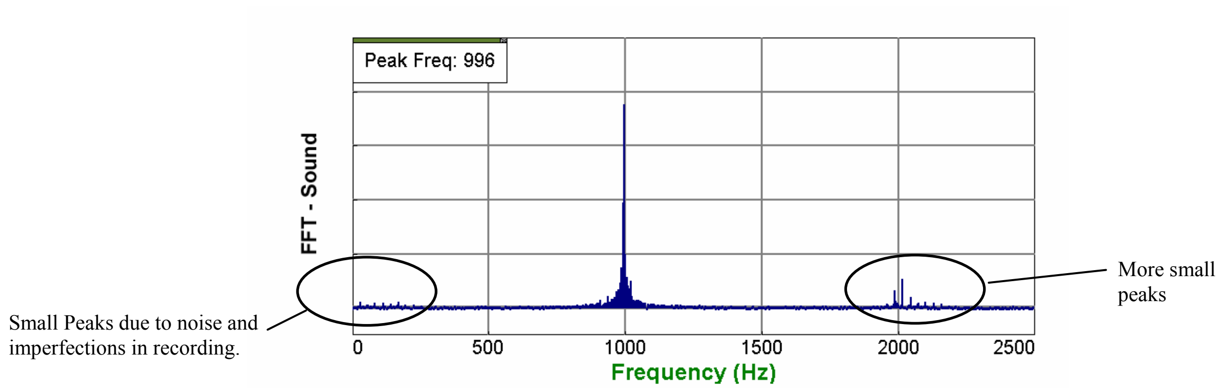


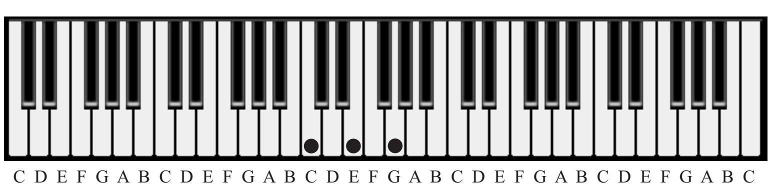
Figure 7: In some instances, small peaks may appear in a frequency graph due to noise and imperfections in the recording systems. For the purposes of these activities you may ignore these small peaks.

The Fast Fourier Transform algorithm is pretty remarkable. You put in a pure tone and the FFT tells you the frequency and relative amplitude of the tone. A natural question to ask is whether or not a frequency graph works with more than one pure tone? Recall that when working with time graphs, it was not possible to determine more than one frequency in a sound. Perhaps frequency graphs don't suffer from this weakness? This will be explored in the following activity. **Note:** As previously mentioned, you do not need to understand the details of the FFT process, however, it is essential that you know how to interpret frequency graphs. Make sure you are comfortable with this before moving on.

On many of the activities that follow, you will need to use one computer to play to keyboard simulation software and a second computer to record the sound with an MBL system and microphone.

Activity 3.2.2: Frequency Graphs of Multiple Tones

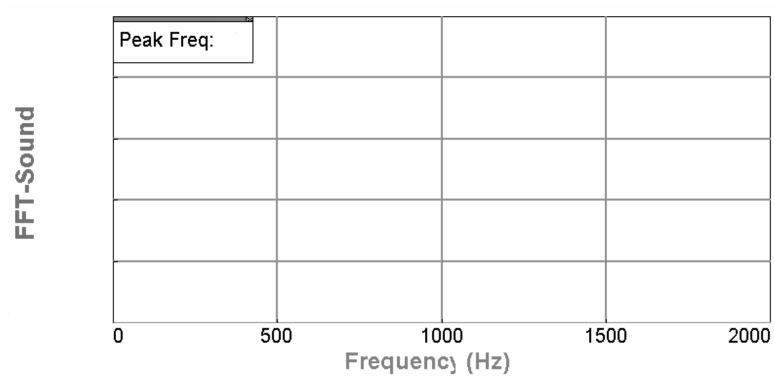
a) Open file A 030202.mbl and using a pure-tone setting on the keyboard (Ocarina, for example), play the C indicated below on the keyboard and record its frequency. Then do the same for the E and G above middle C.



Frequency of Middle C: ________
Frequency of E: ________
Frequency of G: ________

b) Now play Middle C and the G above it at the same time. Collect data for this sound. Sketch the frequency graph for this sound on the axes below and describe the most important features of the frequency graph.

Middle-C and G - Sound vs. Frequency

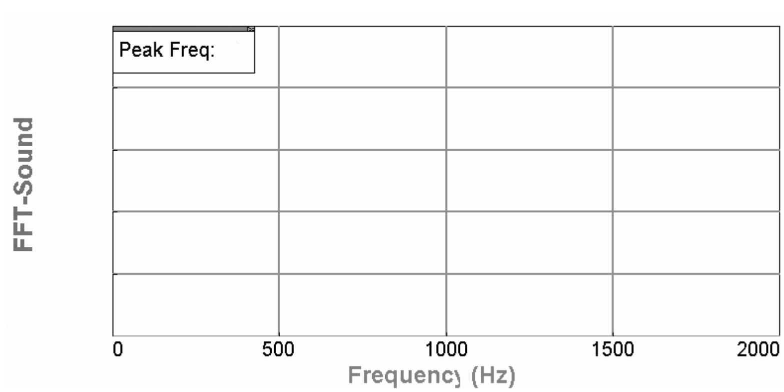


Important Features:

c) How many large peaks are present in this frequency graph? What are the frequencies of each peak? What do you think each peak corresponds to?

d) Now play a chord with Middle-C, E and G. Collect data for this sound and sketch the frequency graph on the axes below.

Middle-C, E and G - Sound vs. Frequency



e) How many large peaks are present in this frequency graph and what is the frequency of each peak? What do you think each of the peaks in the frequency graph corresponds to?

f) In Activity 3.1.2: you used time graphs to examine the sound made by several notes played together. Compare those time graphs to the frequency graphs you generated in this activity. Describe carefully what information is displayed in each type of graph?

Checkpoint Discussion: Before proceeding, discuss your ideas with your instructor!

In the last few activities, you used a frequency graph to examine the different frequencies present in a sound. This type of graph provides a quick and convenient way of measuring the frequency of a pure tone. In fact, as we just observed, frequency graphs are very useful when there is more than one frequency being played at the same time. This will be useful not only when dealing with multiple pure tones, but also when dealing more complex sounds that are not pure tones. The graph of frequencies present in a particular sound is often called the *frequency spectrum* of that sound.

3.3. NOTES, OCTAVES AND SCALES

Earlier in this unit, you found that you could make pure tone sounds of essentially any frequency with a signal generator. However, in Activity 3.1.1: we found that the keys on a piano keyboard only produce sounds with certain frequencies. In fact, most instruments cannot play all the frequencies we can produce with the signal generator. Nearly all music is played with only a few selected frequencies. These frequencies are called *notes* and in western culture these notes correspond to the keys on a piano. Why do musicians restrict themselves to only these notes?

Activity 3.3.1: Why do we use Notes?

a) Answer this question individually. Why do you think musicians tend to use only a few selected frequencies (notes) rather than all of the frequencies as we did with the signal generator?

b) Discuss the question from part a) with your group and try to come to a consensus about why your group thinks musicians use only a selected few frequencies to make music. Write your explanation below.

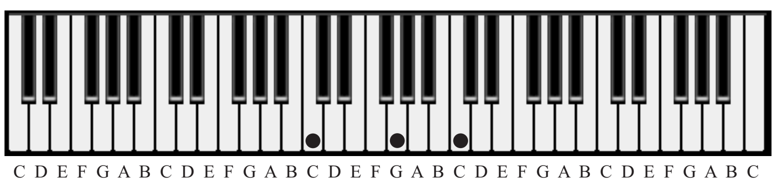
c) Your instructor will lead a class discussion about the topics described in parts a) and b). Write any additional information you learn from this discussion below.

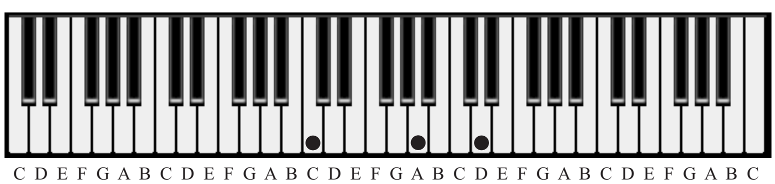
It may not be entirely obvious why only specific frequencies are chosen for the notes on a piano. In fact, different cultures don't necessarily choose the same frequencies so that the notes in one culture might not be the same as the notes in another culture. To understand how this might come about, we will begin investigating how particular notes sound when played together. This may shed some light on how notes are chosen.

In the next few activities you will investigate several fundamental musical elements including *notes*, *octaves* and *scales*. In the next activity we will listen to several notes played together. To prepare for this activity, open the keyboard simulation software and set the instrument to ocarina (or flute). Adjust the volume to an audible but pleasant level.

Activity 3.3.2: Multiple Frequency Sounds

a) Set up the keyboard program so the sound is a pure tone (Ocarina or flute) and set the volume to an audible level. Play the first set of notes indicated below at the same time and then play the second set of notes below at the same time. Compare these two sounds using whatever terms you think are appropriate to distinguish one sound from the other. Then, your instructor may lead a class discussion so that you can see what terms other students used to describe the difference between these sounds.





In the last activity, you played two combinations of notes and tried to describe the difference between them. There are a lot of different words that are typically used to distinguish between these kinds of sounds, most of which are somewhat subjective. For example, many people think the first sound above is more "pleasing" than the second, or that the first sound is "cleaner" in some way. We will use the terms *consonant* and *dissonant* to describe these sounds relative to one another. That is, we say the first sound is more consonant (or less dissonant) than the second sound. Unfortunately, these terms are still a bit vague and it is difficult to give a precise meaning to the terms consonant and dissonant. Later on in this unit, we will be able to make these terms a little bit more meaningful from a scientific perspective.

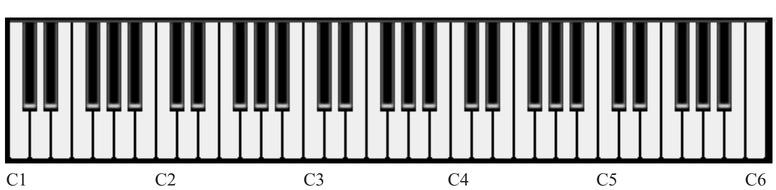
Since music is intended to be pleasing to the ear, it is reasonable to assert that perhaps the notes on a piano keyboard where chosen from the infinite possible frequencies available because many of the notes sound consonant when played together. This would lead to many "pleasing" sounds, which seems like a logical goal for music. While this is certainly a logical assertion, it is still not clear exactly which notes should be chosen and what constitutes a consonant sound versus a dissonant sound. Before giving you a chance to choose your own notes from the infinite frequencies available, we first need to learn about *octaves*.

You may have noticed in Figure 6 that the letter designations of the white keys on a keyboard repeat in a cyclic pattern (ABCDEFGABCDEFGA…). The set of eight notes between any two (white) keys labeled with the same letter is called an *octave*. Indeed the Latin root for the word octave is octo which means eight. But, why does the octave contain eight notes? What do the notes with the same letter designation have in common with each other (if anything)? Is there a physical basis that underlies this cyclic structure of the octave? These questions will be answered in the following activity.

Activity 3.3.3: What makes a C a C?

a) Play the lowest C on the keyboard and record its frequency using the computer frequency graph. We will call this note C1 and label each higher C note as C2, C3, C4, etc. Now, play each of the other C notes record their frequencies in the table below. Do you notice any similarities in the way these notes sound?

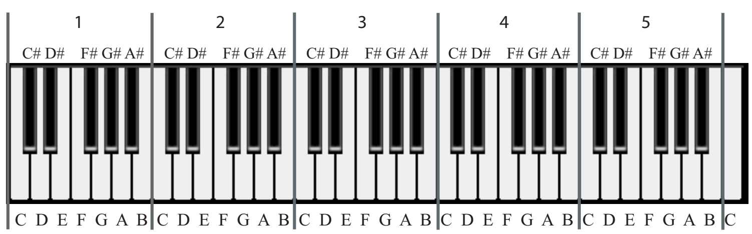
Note	Frequency (Hz)
C1	
C2	
C3	
C4	
C5	



b) Do you notice any pattern in these frequencies? How is the frequency of C2 related to C1? How is the frequency of C3 related to C2? How is the frequency of C4 related to C3?

c) Now repeat the measurements you made above using another note of your choice (instead of C). That is, record the frequencies of each occurrence of that note from the lowest to the highest on the keyboard. Circle the letters associated with the notes you chose on the keyboard provided.

Note	Frequency (Hz)
__1	
__2	
__3	
__4	
__5	



d) Do you notice any pattern in these frequencies? How is this pattern related to the pattern you found in part c)? Do you notice any similarities in the way these notes sound?

e) Based on the patterns you saw in parts c) and d), make a hypothesis about the relationship between the frequencies of two notes separated by one octave anywhere on the keyboard? Write this hypothesis below. How would the frequencies be related for two notes that are separated by two or three octaves?

f) Test this hypothesis using a note other than C or the note you chose in part c). Write down the frequencies you find for notes separated by one, two and three octaves.

Checkpoint Discussion: Before proceeding, discuss your ideas with your instructor!

It should be pretty clear from the previous activity that all of the "C" notes are simply related to each other. In fact, this is true for any other note as well. It is interesting that all of the "C" notes sound somewhat similar as do all of the "E" notes (or any other set of notes for that matter). Clearly, some "C" notes have a higher pitch than others, but there is definitely a strong "resemblance" between them. Since there is such a simple relationship between the frequencies, this may not be entirely surprising. However, the precise way that the brain interprets sound waves that enter the ear is a topic that will not be discussed in this class.

Musical Scales

When musicians play together, they agree to use a common set of notes called a *scale*. As already mentioned, since musicians often play several notes at the same time, it seems reasonable to choose particular notes (frequencies) that sound consonant together. So how, exactly does one go about choosing such a set of notes? Well, we discussed earlier that there is really no right or wrong way to do this. Different cultures have developed different musical scales over the years. In general, a scale can be thought of as any set of distinct notes we define for use in playing music. Thus, *any* set of frequencies can define a scale. However, some sets of notes might be preferable to others. In the next few activities, we will explore what criteria one might use to define a scale.

Activity 3.3.4: Defining a Musical Scale

a) Your task in this activity is to develop your very own musical scale using nothing more than a function generator and a recording device. Your instructor will show you how to record sounds on your computer. This scale will consist of 4 notes (frequencies) between C3 (262 Hz) and C4 (524 Hz). Describe how your group came up with your scale and tabulate the frequencies for your scale in the table below.

Name	C3					C4
Frequency (Hz)	262					524

b) After you have determined which notes you want in your scale, decide how you would extend your scale to another octave. Explain your procedure below and tabulate the frequencies for you notes between C4 and C5.

Name	C4					C5
Frequency (Hz)	524					1048

c) Now try to record your scale one note at a time from lowest to highest so you can play the scale to the rest of the class. Be prepared to explain the method you used to choose the notes in your scale.

d) Now try playing a little song that consists of the lowest three notes of your scale. If we label these three notes as 1, 2 and 3, the song goes, 1-2-3-2-1. Try playing this song starting on C3 and then try playing this song starting on C4. Apart from being a higher pitch, does it sound the same? Does this make sense? Explain briefly.

e) Now try playing this song starting on note 2. That is, play the song 2-3-4-3-2. Does this song sound the same or different (apart from pitch) from when you began on note 1? Explain why this may or may not be a desirable feature of your scale.

Checkpoint Discussion: Before proceeding, discuss your ideas with your instructor!

In the last activity you took a stab at defining your own scale. What were your goals as you developed this scale? Did you choose notes that were pleasing to the ear? Did you want to distribute the notes evenly over the frequency range between low and middle C? Whatever your goals, the scale you produced is as valid as any other. In fact, the frequency structure of a scale is essentially arbitrary, although some scales have more useful features than other.

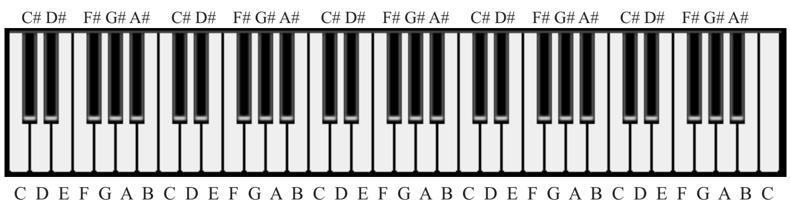
3.4. STANDARD SCALES

Musicians often choose to use a *standard scale*. A standard scale is essentially a set of notes (frequencies) that have a name (*pentatonic* scale, *just* scale, *minor* scale, *major* scale, etc…). Musicians use standard scales because they make it easier for several musicians to play together. Imagine what it would sound like if all of the groups in your class decided to play a tune together, but each group used its own scale. The resulting "music" might sound quite chaotic. By choosing a common scale, several musicians can play together and be assured that the notes (frequencies) they play will sound reasonably well together. Over the course of history, musicians of different cultures has settled on several standard scales. In the next activity, you will explore some properties between the frequencies that characterize the notes in a standard western scale called the *chromatic* scale.

Before you begin the next activity, open up the keyboard simulation software and set the instrument to Ocarina (or flute). Then adjust the volume to a pleasant level.

Activity 3.4.1: Exploring a Standard Scale

a) Using frequency graphs, measure the frequency of each note from a C to higher C, making sure to include the black keys as well as the white keys. Write your frequency values in the table below and also enter them in the Excel spreadsheet A030401.xls.



Name	C	C#	D	D#	E	F	F#	G	G#	A	A#	B	C
Frequency (Hz)													

b) Determine which notes in this scale sound most consonant with the low C. To do this, play combinations of the low C and each of the other notes in the scale (i.e. C and C#, C and D, etc.) Listen to each pair of notes and decide whether the sound is more consonant or more dissonant. **Note:** This is clearly a bit subjective. Some combinations will be very consonant and some will be very dissonant. It is the ones that are in between that are difficult to categorize. Just do your best. Tabulate these results below and in the spreadsheet A030401.xls. Print out a copy of this spreadsheet.

<u>Consonant Combinations</u> **<u>Dissonant Combinations</u>**

Fraction	Decimal Equivalent
$\frac{1}{4}$	0.25
$\frac{1}{3}$	0.33
$\frac{1}{2}$	0.50
$\frac{2}{3}$	0.67
$\frac{3}{4}$	0.75
$\frac{5}{4}$	1.25
$\frac{4}{3}$	1.33
$\frac{3}{2}$	1.50
$\frac{5}{3}$	1.67
$\frac{7}{4}$	1.75

Figure 8: The decimal equivalents of some common whole number fractions.

c) In the Excel spreadsheet provided, the 3rd column shows the ratio of the frequency in that row to the frequency of the low C. Using the table of fractions provided, identify which of the notes you examined in part a) have frequencies that are approximately equal to a simple fraction multiplied by the frequency of middle C. **Note:** For the purposes of this activity, any number that is within ± 0.02 of a whole number fraction should be considered approximately equivalent.

d) There should be a pattern between the note combinations you found consonant and the note combinations that corresponded to frequencies which were a whole number fraction multiplied by middle C? describe this pattern in your own words.

You may have noticed that the note combinations that sounded consonant had frequencies that were simple whole number ratios. In fact, one can even define the term consonant precisely in terms of this frequency ratio. The structure of many of the scales in common use today have been strongly influenced by this correspondence. While this correspondence may seem like a coincidence, there is something quite profound about it. The fact that our ears can detect a difference between consonant and dissonant sounds suggests that there is something fundamentally different between these two types of sounds. The following activity explores this question.

Activity 3.4.2: Consonance Versus Dissonance

a) Which of the following do you think is more consonant sounding, the C-G combination or the C-F# combination. To answer this question, you can either play these combinations on the keyboard or go back and look at your notes from Activity 3.4.1:

b) Most students find the C-G combination to be more consonant than the C-F# combination. Let's try to determine why. Begin by setting the keyboard to a pure-tone sound such as Ocarina. Then, open file A030402.mbl and record a C for 0.1 seconds and save this data. Then, record a G so that the graph lies right on top of the graph for the C. Again, save this data. Do these two sound-time graphs exhibit any kind of pattern with each other? Explain.

c) Now record the C-G combination sound using your microphone. Your instructor will show you how to view this graph below the separate C and G graphs you just made. Does this graph repeat at all? If so, how does this repetition compare to the pattern exhibited between the separate C and G graphs above? Explain briefly.

d) Now repeat the above process with the C-F# combination. That is, first record a C by itself and save it and then record an F# by itself and save it. Look very closely at these two graphs when they are on top of each other and describe whether there is any pattern between the two graphs.

e) Lastly, record a C-F# combination and view this on the graph below the separate C and F# graphs. Does this graph repeat at all? If so, how does this repetition compare to the pattern exhibited between the separate C and F# graphs above? Explain briefly.

f) Describe the difference between the C-G combination compared to the C-F# combination. Explain how you think this difference relates to what your ears hear as consonant versus dissonant sounds.

You should have noticed in the last activity that in both situations, the sound-time graph would repeat itself. However, in one case, the repetition was very easy to notice because it took less time to repeat than in the other case. This is because the pattern of the sound-time graphs "fit together" more easily in one case than in the other. Not surprisingly, this same language is often used by people when they describe notes as sounding consonant. They say the notes sound like the "fit" or "blend" together nicely. Hopefully, you now have an appreciation for what this means on a more physical basis.

Activity 3.4.3: The Chromatic Scale (a Tempered Scale)

a) In the last activity, you measured the frequency of each of the notes in an octave starting with a C. Using this data, calculate the frequency difference and the frequency ratio between the C# and the lowest C. Then do the same for the D and C#.

$f_2 - f_1 = f_{C\#} - f_C = \_\_\_\_\_\_$ $\quad$ $f_3 - f_2 = f_D - f_{C\#} = \_\_\_\_\_\_$

$$\frac{f_2}{f_1} = \frac{f_{C\#}}{f_C} = \_\_\_\_\_\_ \qquad \frac{f_3}{f_2} = \frac{f_D}{f_{C\#}} = \_\_\_\_\_\_$$

b) Now continue calculating these frequency differences and ratios of adjacent notees and complete the table below.

n	Note	Frequency (Hz)	$f_n - f_{n-1}$	$\frac{f_n}{f_{n-1}}$
1	C		NA	NA
2	C#			
3	D			
4	D#			
5	E			
6	F			
7	F#			
8	G			
9	G#			
10	A			
11	A#			
12	B			
13	C			

c) What pattern do you see in the table above? What does this tell you about how any two notes in the chromatic scale are related?

d) Based on this pattern, predict the frequency of the C# above the high C in the table above. Then check your prediction by measuring this frequency. Was your prediction correct?

e) Using your own words, describe the frequency structure of the chromatic scale.

Checkpoint Discussion: Before proceeding, discuss your ideas with your instructor!

The Chromatic Scale: An Evenly Tempered Scale

Musical language is filled with terminology that is often difficult to digest. Even so, learning a bit about this language will aid in our discussion of the science of music. To this end, we will introduce several simple definitions. Much of the language of musical scales can be explained using the piano keyboard as an example. It should be noted, however, that the ideas discussed here can be applied to other musical instruments as well.

Modern music in the west is based on the chromatic scale. In the chromatic scale, the octave is divided into twelve notes. These notes correspond to any twelve adjacent (white and black) keys on a piano. You should have noticed in the last activity that there are a reasonably large number of consonant combinations in the chromatic scale. This is one of many reasons why this scale is in common use. Any two adjacent notes are separated by a *half step*. Note that the frequency difference between notes separated by a half step is not the same everywhere on the keyboard. This frequency difference changes depending on where you are on the scale. However, in the last activity, you measured that the frequency *ratio* associated with a half step is the same no matter where you are on the scale. This ratio is about 1.06. That is, any note in the chromatic scale has a frequency of about 1.06 times the frequency of the note one half step below it. In fact, the frequency ratio between two notes one half step apart is exactly the twelfth root of two, denoted as $\sqrt[12]{2}$. The decimal equivalent of this number is 1.059463094…

Not surprisingly, a *full step* is equivalent to two half steps. Thus, since D and C are separated by one full step, the frequency of D above middle C would be

$$\sqrt[12]{2} \times \sqrt[12]{2} \times f_C \cong 1.06 \times 1.06 \times 262\,Hz = 294\,Hz\,.$$

The chromatic scale is known as an *evenly tempered* scale, because the frequency ratios are all equivalent ($\frac{f_n}{f_{n-1}} = \sqrt[12]{2} = 1.059\ldots$). This means that a song will sound the same (apart from pitch) no matter which note is chosen as the starting note. This is another very desirable feature of the chromatic scale that was probably not present in the scale you devised earlier. You may have noticed, however, that although the frequency ratios in the chromatic scale are very close to ratios of small whole numbers, they are not exact. If these ratios were *exact*, so that the frequency ratio of a G to a C was precisely 1.5 instead of 1.4983071…, then the C-G combination would sound even more consonant. The problem is, if this ratio is made to be exactly 1.5, then the frequency ratios between neighboring notes will not be constant.

So far, we have been exploring the basics of sound and musical scales by using pure tones. Pure tones are very simple to understand and provided a nice way to begin our investigation into sound. However, most of the instruments that musicians use generate rich tones that are very different from the pure tones we have explored thus far. The richness of these sounds makes it easy to tell the difference between a violin and a trumpet, even if they are playing the exact same note. But how? Each instrument has it's own "sound," but what exactly makes up that sound? In the next section, we will explore the properties of these *complex tones*.

4. COMPLEX TONES AND MUSICAL INSTRUMENTS

Every musical instrument has a different sound. Most people can easily tell the difference between a flute, a violin and a piano, even if they are playing the same note. For example, if Jimmy Hendrix played a 440 A on his electric guitar and Gheorghe Zamfir played the same note on his pan flute, you would have no difficulty being able to tell which was which. How are the sounds from these instruments different and how can we tell the difference between them scientifically? In this section we will apply what we have learned about sound and frequencies to answer these questions.

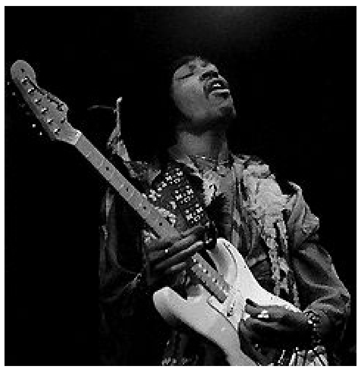


Figure 9: How can we tell the difference between a 440 A played by Jimmy Hendrix on the electric guitar and a 440 A played by Zamfir on the pan flute.

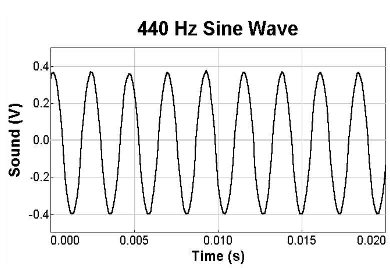
You may need some of the following equipment for the activities in this section:

- Music Unit Sound Files
- A computer based laboratory system
- An electronic sound sensor
- Keyboard synthesizer software (QTKeys for Macintosh works well)
- A long spring (unstretched length ~2 m)- (3.2.2)

4.1. WHAT INFLUENCES THE SOUND OF MUSICAL INSTRUMENTS?

Pure and Complex Tones

In the last two sections, we have learned about the nature of sound and the basis for musical notes and scales. While exploring these ideas, you have worked almost exclusively with pure tones. Pure tones are the simplest possible tone because they involve only a single frequency. Their time graph is a simple, smooth, repeating curve called a sine wave. The frequency graph of a pure tone consists of a single spike at the frequency associated with the tone.



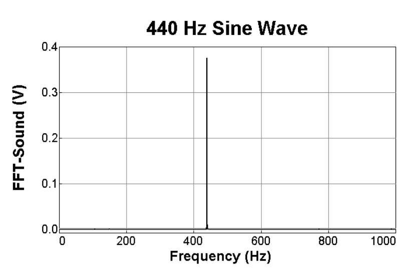


Figure 10: A pure tone of 440 Hz. The time representation of a pure tone is a sine wave. Since a pure tone contains only one frequency, its frequency representation is a single spike at that frequency.

So far, we have worked primarily with the pure tones, but most instruments have a richer more complex sound. The simplicity of pure tones enabled us to look at the fundamental aspects of sound and music without the difficulties of dealing with more complex sounds. But now we are in a position to look closely at these complex tones and try to discover how they differ from the simple pure tones we have been dealing with.

Activity 4.1.1: Spectra of Musical Sounds—Part I

a) Open up the MBL file A040101 on a computer and open the keyboard synthesizer software on another. Play a 440 A on the ocarina instrument and capture the sound with your MBL system. Print your time and frequency graphs and save this data. Give a brief description of this sound based on the time and frequency graphs. **Note:** Your instructor will show you how to save your data to a file.

b) Now choose one instrument from each of the lists shown in the adjacent table. Indicate which instruments you choose and then generate time and frequency graphs of a 440 A for each instrument. Print the time and frequency graphs and save these files as before. Compare these three instruments and rank these sounds from simplest to most complex. How are they similar? How are they different?

<u>List 1:</u>
French Horn
Piano
Clarinet
Oboe
Bassoon

<u>List 2:</u>
Violin
Flute
Trumpet
Piccolo
Guitar

c) What is the lowest frequency in the FFT graph for each instrument? Do you think this is related to the note that you played for each? Explain briefly.

d) How many different frequencies are present in each of these sounds? Do you think this has anything to do with the “richness” or “character” of the sounds? Explain briefly.

e) Many people would claim that the ocarina sound is not as rich as the other sounds. Based on the frequency spectra of the sounds, explain why the ocarina might sounds simple and sterile to some.

What Makes a Sound Sound Musical?

All of the sounds you listened to in the last activity can arguably be called musical. But that is not true of all sounds. Most people would not consider the sound of fingernails on a blackboard musical. Nor would they judge as musical the sound of a car crash. What makes some sounds musical and others not? In the next activity you will listen to some sounds that are clearly non-musical. How are these sounds different from the musical sounds in the last activity?

Activity 4.1.2: Spectra of Non-Musical Sounds

a) Play the sound A040102a.wav and capture the sound with your MBL system. Print out the time and frequency graphs for this sound. What do you hear? Describe this sound based on your time and frequency graphs as well as your own hearing.

b) Play the sound A040102b.wav and capture the sound with your MBL system. Print out the time and frequency graphs for this sound. What do you hear? Describe this sound based on your time and frequency graphs as well as your own hearing.

c) Compare these sounds to the musical sounds from the last activity. How are the musical sounds different from the non-musical sounds?

d) Your instructor will lead you in a class discussion about the difference between musical and non-musical sounds. Be prepared to discuss the time and frequency graphs of the sounds you heard in the last two activities. Describe below any new insights you gain from this discussion.

Checkpoint Discussion: Before proceeding, discuss your ideas with your instructor!

Characteristics of Musical Sounds

You may have noticed in the last two activities that the musical sounds often consist of only a few *discrete frequencies* that seem to have a simple pattern whereas non-musical sounds contain many frequencies that do not appear to have any pattern to them. This is demonstrated in the following figure.

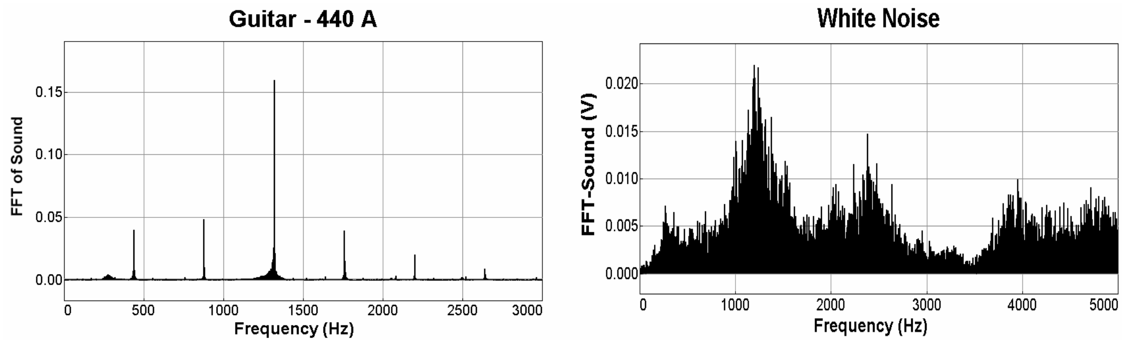


Figure 11: Frequency graphs of a 440A sound from a steel stringed guitar and white noise. Notice that the steel stringed guitar contains only a few discrete frequencies while the white noise contains a continuum of frequencies.

We call the frequency spectrum of the guitar sound *discrete*, because only a few separate frequencies are present. That is, there are many frequency values that are not present in this sound and only a few well defined frequencies that make up the sound. The frequency spectrum of the white noise is called *continuous* because a large number of "connected" frequencies are present.

You may have noticed something peculiar about the frequency spectra of the musical instruments. In the next activity we will explore the mathematical relationship between the discrete frequencies in some musical sounds.

Activity 4.1.3: Spectra of Musical Sounds—Part II

a) Open up the data files you saved for the two instruments of your choice in Activity 4.1.1. For each of these sounds, measure the frequency value of the first seven frequencies present and tabulate them in the table below.

Frequency # (n)	Instrument 1 ________ Frequencies (Hz)	Instrument 2 ________ Frequencies (Hz)
1		
2		
3		
4		
5		
6		
7		

b) You should notice a clear pattern in the frequencies above. Explain the pattern you observe.

c) Using the frequency table you made in part a), take the ratio of each frequency with the lowest frequency. That is, divide each frequency by the lowest frequency for that instrument. Tabulate these values in the table below.

Frequency # (n)	**Instrument 1** ____________ $\frac{f_n}{f_1}$	**Instrument 2** ____________ $\frac{f_n}{f_1}$
1		
2		
3		
4		
5		
6		
7		

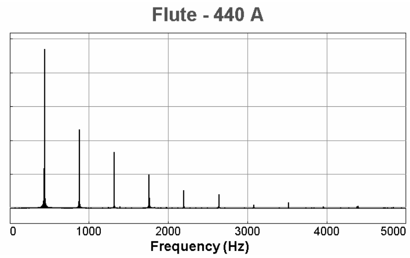
d) Do you notice any pattern in the ratios you calculated in part c)? Explain.

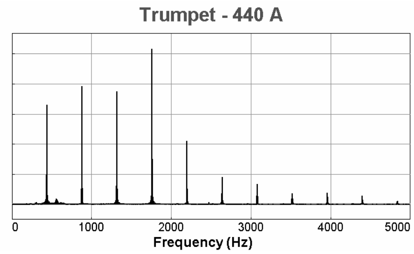
e) Based on the patterns you saw in part c), draw a general conclusion about the frequencies that are present in sounds from musical instruments when a single note is being played. Explain this conclusion below.

f) Taking into account your conclusion from part e), what do you think makes different instruments sound different? Your instructor may lead a class discussion around this topic.

In the last activity, you likely saw that the frequency spectra for both of your instruments contained the same set of frequencies! Still, these instruments sound quite different.

How is this possible? If the frequencies present in a 440 A from a trumpet are the same as those in a 440 A from a flute, what makes them sound different?





A quick comparison of these spectra illustrates that while the frequencies present in the spectra are the same, the relative *amplitudes* of each frequency are very different. The tone from a flute sounds more pure than the tone from a trumpet. This is reflected in the frequency spectra. The largest amplitude peak in the flute spectrum corresponds to the lowest frequency and only a few of the other peaks have a large amplitude. In the trumpet spectrum however, the four lowest harmonics are of comparable amplitude. The resulting trumpet tone sounds "richer" and "huskier" than the flute sound. Close examination of frequency spectra from a variety of musical instruments leads to the conclusion that the amplitudes of the individual frequency components of a tone determine the characteristic sound of an instrument.

4.2. HARMONICS AND OVERTONES

You should have noticed that the frequencies present in the sounds from your musical instruments were all integer multiples of the lowest frequency. That is, the frequency spectrum is given by *f, 2f, 3f, 4f, 5f…* This pattern is called a *harmonic series* and each frequency in the series is called a *harmonic* (the lowest frequency is called the first harmonic, the next lowest is called the second harmonic, etc.). To make matters a bit confusing, this spectrum of frequencies is also called the *fundamental* and its *overtones*. The lowest frequency is called the *fundamental* and the other frequencies are called *overtones*. Thus, the first harmonic is the fundamental while the second harmonic is the first overtone and the third harmonic is the second overtone.

The sounds from most musical instruments are made up of frequencies related by a harmonic series. Thus, the only frequencies present in sounds from these instruments are multiples of the fundamental frequency. Recall that in a previous activity, we noticed that frequencies that are related by simply related to each other (e.g. their ratios correspond to simple whole number ratios) sound consonant when played together. The frequencies seem to "blend together" very well. Amazingly, the frequencies in a harmonic series are precisely those frequencies that sound consonant together. The harmonic series is therefore a very special set of frequencies. This suggests that these frequencies can be combined in such a way as to "blend together" so well that perhaps it is difficult to tell that there is more than one frequency present. This is the topic of the next few activities.

Activity 4.2.1: Building a Complex Musical Tone

a) Let us begin by determining the frequencies that are present in one particular harmonic series. Use 440 Hz (A above middle C) as the fundamental and calculate the first 10 frequencies present in the harmonic series. Tabulate these values in the table below. **Note: Each person in the group should make these calculations independently and then you should compare them.**

	Note	f (Hz)
1	C	32.70
1	C#	34.65
1	D	36.71
1	D#	38.89
1	E	41.20
1	F	43.65
1	F#	46.25
1	G	49.00
1	G#	51.91
1	A	55.00
1	A#	58.27
1	B	61.74
2	C	65.41
2	C#	69.30
2	D	73.42
2	D#	77.78
2	E	82.41
2	F	87.31
2	F#	92.50
2	G	98.00
2	G#	103.8
2	A	110.0
2	A#	116.5
2	B	123.5
3	C	130.8
3	C#	138.6
3	D	146.8
3	D#	155.6
3	E	164.8
3	F	174.6
3	F#	185.0
3	G	196.0
3	G#	207.7
3	A	220.0
3	A#	233.1
3	B	246.9
4	Middle C	261.6
4	C#	277.2
4	D	293.7
4	D#	311.1
4	E	329.6
4	F	349.2
4	F#	370.0
4	G	392.0
4	G#	415.3
4	A	440.0
4	A#	466.2
4	B	493.9

Figure 12: Frequencies associated with notes on the chromatic scale. (continued on next page.)

Harmonic #	Frequency (Hz)
1 (Fundamental)	440
2	
3	
4	
5	
6	
7	
8	
9	
10	

b) Next use the tables in Figures 12 and 13 to determine which notes are closest to these frequencies and tabulate those notes below. **Note: Once again, each person in the group should do this work independently and then your results can be compared.** Are there any notes that have frequencies different by more than a few Hertz from those calculated above? Do you think this is a problem with the chromatic scale? Explain briefly.

Harmonic #	Note
1 (Fundamental)	4 A
2	
3	
4	
5	
6	
7	
8	
9	
10	

c) Now open up the keyboard simulation software (with the Ocarina setting) and play all of these notes simultaneously. When you are done, turn down the volume completely and wait for a few seconds and then turn up the volume again. Does it sound like a single note is being played? **Note:** Adjust the volume to a level that is just audible with only a single note played. If you have difficulties here, try playing only the lowest 6 notes. Compare this sound to a single 440-A played using an oboe or a bassoon sound. Do they sound similar? Describe your observations below.

d) Considering that most musical sounds consist of frequencies in a harmonic series, explain why different instruments do not sound the same. What is different about the frequency spectra of different instruments?

	Note	f (Hz)
5	C	523.3
5	C#	554.4
5	D	587.3
5	D#	622.3
5	E	659.3
5	F	698.5
5	F#	740.0
5	G	784.0
5	G#	830.6
5	A	880.0
5	A#	932.3
5	B	987.8
6	C	1047
6	C#	1109
6	D	1175
6	D#	1245
6	E	1319
6	F	1397
6	F#	1480
6	G	1568
6	G#	1661
6	A	1760
6	A#	1865
6	B	1976
7	C	2093
7	C#	2217
7	D	2349
7	D#	2489
7	E	2637
7	F	2794
7	F#	2960
7	G	3136
7	G#	3322
7	A	3520
7	A#	3729
7	B	3951
8	C	4186
8	C#	4435
8	D	4699
8	D#	4978
8	E	5274
8	F	5588
8	F#	5920
8	G	6272
8	G#	6645
8	A	7040
8	A#	7459
8	B	7902

Figure 13: Frequencies associated with notes on the chromatic scale. (continued on next page)

The last activity demonstrated that multiple notes played simultaneously can sound like a single note. This is particularly true if the notes are all sounded simultaneously instead of being played one note at a time. Although this is true to some degree for any set of frequencies, it is particularly true for the frequencies that make up a harmonic series. These consonant sounds "blend together" so very well that it is not easy to distinguish between the different frequencies. The following activity, which may be done as a class activity, takes this concept one step further.

Activity 4.2.2: What Sound is That?

a) Begin by making a frequency graph of an instrument (such as a violin) playing either a 440-A or a 220-A. Your instructor may tell you a different instrument and a different note. Print out a copy of this frequency graph for your Activity Guide. Which of the frequencies to you think are the most important in this sound? Explain briefly.

b) Next, using a set of frequency generators and a microphone/MBL system, set the frequency and amplitude of each generator so that you are producing a sound that gives the same frequency graph as the sound from part a). Print out a copy of the frequency graph for your Activity Guide. How closely does it match the sound from part a)?

c) Now record the two sounds and play them back through the computer. If you are not told which one is which, can you tell them apart? Describe your observations below.

Checkpoint Discussion: Before proceeding, discuss your ideas with your instructor!

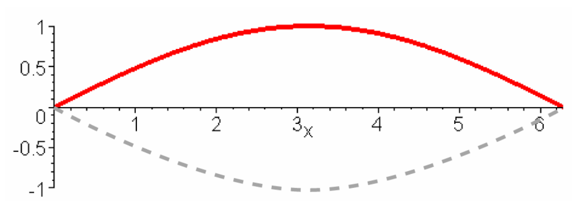
Why do Instruments Vibrate Harmonically?

In the last few activities, you found that the frequency spectra of different musical instruments playing the same note contain a set of frequencies instead of just a single frequency. In fact, different instruments contain the same set of frequencies. As we have seen, the frequencies present in a single tone is called a harmonic series and the fundamental corresponds to the frequency of the note that is actually played. A natural question to ask is where this harmonic series comes from? That is, why does the same set of frequencies show up in the spectrum of different musical instrument?

In the next activity, you will explore the natural vibration frequencies of a long spring. The vibrations of this spring are very similar to the vibrations of a guitar string or piano wire. The advantage of using a spring is that the vibrations are more visible since the amplitude of oscillation is larger and the frequency of oscillation is much lower.

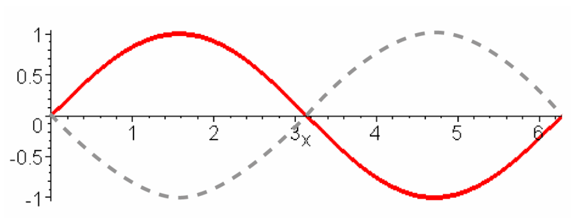
Activity 4.2.3: The Origins of Harmonics

a) Stretch a long spring between two fixed points (clamp the ends to ring stands) to a length of about 6.5 m. Near one end, wiggle the spring side to side so that the spring vibrates with the shape shown in the following diagram. Using a stopwatch, measure how long it takes for the spring to undergo 40 complete oscillations (back and forth). Using this time measurement, determine the frequency of this oscillation. Show your calculations

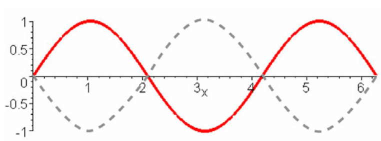


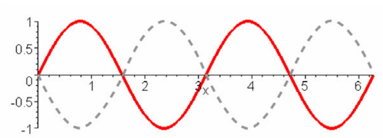
b) Now, try to wiggle the spring back and forth so that it oscillates at a lower frequency and describe what you observe. Then try wiggling the spring at a **slightly** higher frequency and describe what you observe. **Note:** Each member of the group should take a turn wiggling the spring.

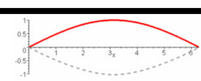
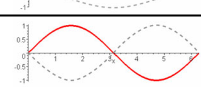
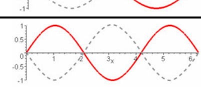
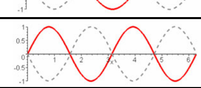
c) Next try to wiggle the spring so that it vibrates with the shape shown in the following diagram. Measure the time it takes for the spring to undergo 40 complete oscillations and calculate the frequency of this oscillation. **Note:** You may have tow wiggle a bit faster than you did in part a).



d) Each of the stable patterns you have seen is called a *mode of vibration*. Repeat the steps in part c) for the following two modes. Record the results for all four patterns in the table below. Show your calculations.





Mode #	Pattern	Oscillations	Time (s)	Frequency (Hz)
1		40		
2		40		
3		40		
4		40		

e) What relationship do you see between the frequencies of these different modes?

f) In a few sentences, relate your observations of the spring oscillations in this activity to the frequency spectra of musical instruments. How are the allowed frequencies similar?

Natural Frequencies and Resonance

In the last activity you should have observed that it is easier to make the spring oscillate at certain frequencies. These frequencies are called *natural frequencies* or *resonant frequencies* and they correspond to the simple *modes of vibration* that the spring can undergo. You may have noticed that at these frequencies, you could get a large oscillation even though you were only moving the spring very lightly.

This scenario is similar to the behavior of a playground swing. If you push a swing once and let it go, it will oscillate at its natural (or resonant) frequency (unlike the spring, the swing has only a single resonant frequency). If you lightly push the swing in time with this frequency, the height of the swing will increase greatly after a few cycles even though you are only applying a small push each time. If you push the swing out of time with its natural frequency, the height of the swing will not increase very much. Thus, *driving* (pushing) the swing at its resonant frequency results in a large amplitude oscillation and driving it at another frequency results in a small amplitude oscillation.

Similarly, if you drive (wiggle) the stretched spring at one of its resonant frequencies, the result will be a large-amplitude oscillation and if you drive it at a frequency other than one of the natural frequencies, the amplitude will be smaller.

In this activity, you saw how individual modes of oscillation behaved. Stimulating individual modes made it possible for you to examine the details of the oscillation. However, there is no rule that says we can't stimulate several modes simultaneously. This is precisely what is happening in a musical instrument. For example, when a guitar string is plucked, a large number of resonant frequencies are stimulated simultaneously. Luckily, these modes oscillate independently of each other, so we can treat this more complex situation by simply adding up the effects of the simple cases. An example of two modes being stimulated simultaneously is shown in Figure 14. In this case, the first and twelfth modes have been stimulated with the amplitude of the first mode being larger than the amplitude of the 12^{th} mode.

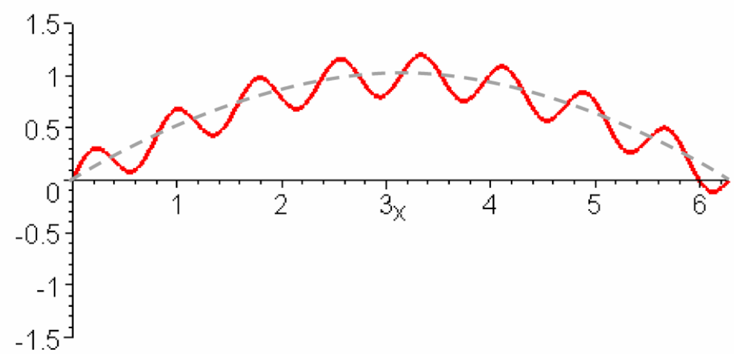


Figure 14: The shape of a guitar string with the first and twelfth harmonic modes stimulated

Instruments as Resonators

Many objects in the world have natural oscillation frequencies. In fact, the sounds you produced at the beginning of this unit using rubber bands, beakers, and tuning forks, were all produced by objects that were oscillating at their resonant frequencies. Objects that have natural frequencies of oscillation are called *resonators*. In particular, most musical instruments have natural frequencies. Compare the string of a guitar to the stretched spring you observed in the last activity. The natural frequencies of both the stretched spring and the guitar string correspond to the harmonic series (*f, 2f, 3f, 4f…*). In fact, the natural frequencies of most resonators correspond to this harmonic series[1]. Your instructor may demonstrate these resonant frequencies using sound in a tube.

In Activity 3.1.3, you found that the frequency spectra of two instrument playing the same note contained exactly the same frequencies. Yet these spectra looked different because the amplitudes of the individual frequencies varied from instrument to instrument. You likely concluded that characteristic sounds of different instruments was related to the particular pattern of amplitudes present in the frequency spectrum of that instrument. It is reasonable to conclude that this pattern is a result of the particular way that the instrument resonates. This resonance behavior is directly related to the size and shape of an instrument as well as the materials the instrument is made from. Of course,

[1] There are a few resonators that contain only the odd harmonics. That is, their harmonic series is given by *f, 3f, 5f, 7f…* The most notable of these resonators is the organ pipe.

the size and shape of an instrument is also an important factor for increasing the amplitude of these frequencies as well.

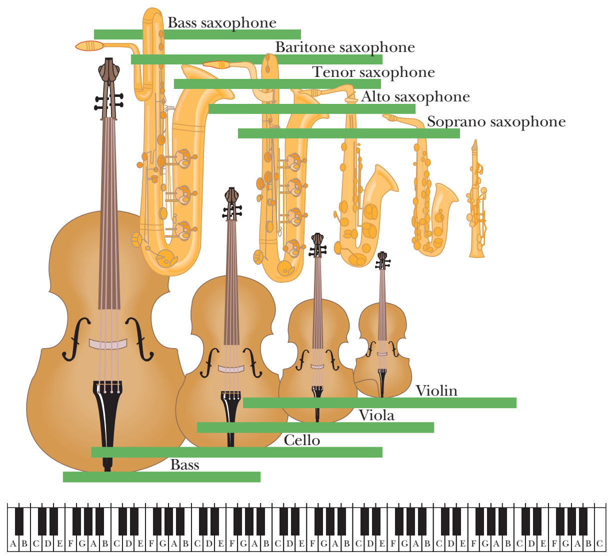


Figure 15: The shape and construction of musical instruments determines how they will resonate. As a result, different instruments sound different and have a different range over which they can play. The bar next to each instrument indicates the rage of frequencies over which it can be played.

4.3. MIXTURES OF TONES

Up to this point, we have examined single tones almost exclusively. While we can learn a lot about music by looking at single tones, music often contains combinations of tones played simultaneously. Understanding the details of a complex piece of music is beyond the scope of this course. Instead, we will examine the explore the characteristics of simple note combinations or *chords*. Back in Activity 3.2.2:, we examined multiple pure tones played simultaneously using a frequency graph. We are now in a position to analyze the frequency graphs of multiple complex tones. This is the topic of the next few activities.

Activity 4.3.1: Multiple Complex Tones

a) Open up the keyboard synthesizer software. Set the instrument to output a pure tone and play the following notes simultaneously (middle C, E, G). Capture this sound with the MBL system on another computer. What frequencies are present in the frequency graph of the sound? Which note does each frequency correspond to?

$f_{middleC} =$

$f_E =$

$f_G =$

b) Predict what frequencies you think will be present in the frequency spectrum of a violin playing the same chord (that is, the same three notes). List these frequencies below and explain the reasoning for your choices.

c) Change the instrument on the keyboard simulator to violin and play the chord from part a) (middle C, G, E). Determine what frequencies are present in this spectrum? Tabulate these frequencies below and specify which note you think is responsible for producing each of these frequencies. Also, specify which harmonic each frequency corresponds to.

Frequency (Hz)	Note	Harmonic

As you may have noticed, the frequency spectrum of a mixture of non-pure tones is quite complicated. However, since you now know a lot about the frequency characteristics of individual complex tones, it should not be too difficult to analyze the frequency spectrum when multiple notes are played together. In the following activity, you will determine the notes that are present in a chord by looking only at the frequency graph.

Activity 4.3.2: Decomposing a Chord

a) The file A040302 contains data corresponding to the sound produced when a chord was played. Your task in this activity is to identify which notes were played in the chord. Tabulate the frequencies in the FFT graph and make sure you show all of your work and explain clearly how you determined which notes were played in the chord.

b) If time permits, have your partner play an unknown chord using an unknown instrument and then try to determine the notes in this chord from the frequency graph alone. Were you able to do it?

Checkpoint Discussion: Before proceeding, discuss your ideas with your instructor!

You should take a moment to reflect back on this last activity and be impressed. Both the time graph and frequency graph for a chord of complex tones are very intricate and complicated. Nevertheless, you now have enough understanding to analyze such a complicated frequency graph to determine exactly which notes are being played, regardless of what instrument is playing the chord. This is quite an accomplishment!

There is one final topic of importance that we have been overlooking throughout this entire unit. So far, we have only dealt with "steady" sounds—sounds that do not change with time. We concentrated on these steady sounds so that the time graphs and frequency graphs would not change with time. However, our ability to distinguish different instruments from each other is due to more than just the frequency spectra of the different instruments. The sound of each instrument must be "turned on" and "turned off." This is what's referred to as *attack* and *decay*.

4.4. ATTACK AND DECAY—SOUND ENVELOPES

Over the course of this unit, you have learned several other methods for exploring the characteristics of sounds. In particular, you have learned to collect and examine time and frequency graphs of sounds. As we have seen, time graphs can be simple, but typically, there are very complicated and it is difficult to obtain useful information from them. In contrast, frequency graphs tend to be much more useful in analyzing the sound. Here, we take another look at time graphs, but instead of looking closely at the detailed features of the graph (using a small time scale), we will instead focus our attention on the large-scale features of the graph (by using a much larger time scale). This will allow us to look at the *sound envelope*, a feature that can be as useful as the frequency spectrum for analyzing sounds.

Sound Envelope

The sound envelope characterizes how the amplitude of a sound changes with time. The sound envelope is most easily seen on a time graph and can be visualized by drawing a line connecting the peaks of the oscillations in the graph. As an example, the envelope of a single short tone from a trumpet is shown in Figure 16.

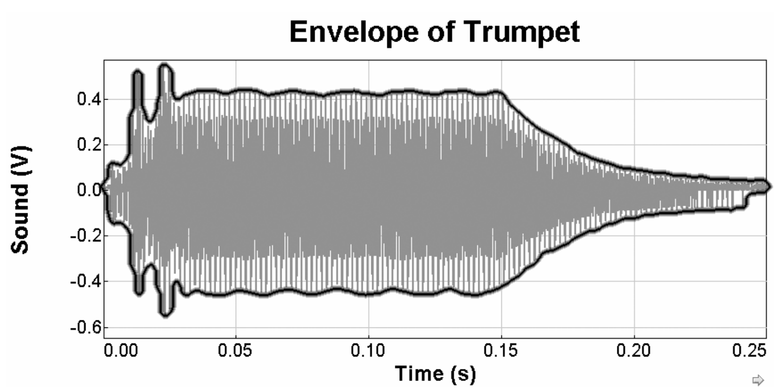


Figure 16: The sound shown here is from a trumpet playing a 440 A. The envelope is indicated by the dark line connecting the peaks of the time graph.

Many of the features of a sound's envelope can be heard as well as seen on the time graph. If the envelope of a sound changes slowly enough, it is possible to actually hear the changes in volume. It is often the case, however, that the amplitude has very sudden changes, particularly at the beginning of the sound and at the end of the sound. These changes are referred to as *attack* (the beginning of the sound) and *decay* (at the end of the sound). It is possible to determine sound simply by looking at the attack, decay, and sound envelope of the sound. When coupled with the frequency spectrum of the sound, a reasonably complete understanding of the sound can be obtained.

Activity 4.4.1: A First Look at Sound Envelopes

a) Begin by opening file A040401.mbl and setting up the computer keyboard on a separate computer with the sound set to the ocarina. Begin recording before playing anything, and then play a single note for a short time, making sure to stop playing before the computer stops recording. Make a rough sketch of the sound envelope for this sound below and comment on how it is related to what you actually hear. **Note:** It is OK to auto-scale your graphs, but do not re-scale the time axis on your time graphs.

b) Now predict what the sound envelope will look like if you play the same note three or four times in a row with a small amount of silence in between each note. Explain how you think the sound envelope would change if you were to play different notes instead of the same note over and over.

c) Now try the experiment and explain how the sound envelope corresponds to what you are actually hearing. Does the envelope change if you use different notes? Explain briefly.

d) Now predict what the sound envelope would look like if you played and single note and held it down but adjusted the volume so that it would go up and down a few times. Make a rough sketch of your prediction and then try the experiment and comment on what you observe.

e) Now predict what the sound envelope would look like if you simply clapped your hands a few times. Make a rough sketch of your prediction and then try the experiment and comment on what you observe.

This last activity demonstrates that there is more to sounds than just the frequency spectrum. Notes can be played for a long time or a short time and the time graphs, when viewed on a large time scale, correspond very simply to what is being heard. These envelope graphs can be very useful in helping distinguish different instruments from one another. Some instruments, like a piano, have a very *sharp attack*, meaning that the sound from the instrument comes in very suddenly. Others instruments, such as a violin, have a much *softer attack*. Of course, musicians have some control over the attack and decay of the sounds they play, but they are somewhat limited by the instrument they are playing.

In addition to being useful tool for helping us analyze sounds, sound envelopes have another interesting connection to music. It should be clear that a note that is played for a longer time will have an envelope that is quite different than the same note when played for a very short time. Thus, the same note can have dramatically different sound envelopes, depending on the length of time the note is held. In music, notes are often played for different lengths of time to help create melodies. Thus, notes of varying length must be readily recognized by the musician. One option would be to use sound envelopes to display this information, but that would be somewhat tedious. Musicians have a notation whereby they know how long to hold a note for. We won't go into the details of this musical notation, but the difference between whole notes, half notes, quarter notes and eighth notes is all due to the length of time they are played.

Now that we've seen how the sound envelope can change when a note is played for a longer or shorter time, a natural question to ask is whether or not the frequency graph will change? That is the subject of the following activity.

Activity 4.4.2: Sound Envelopes and Frequency Graphs

a) Open file A040402.mbl and again set your computer keyboard to ocarina. Play a single note and record the sound for the entire 2 seconds. **Note:** It's OK to auto-scale your frequency graph, but you should set the frequency scale from 0 to 1000. Try the same experiment, but this time record the same note for about a half a second (even though the experiment runs for two seconds). Then try recording the same note for a very short time. Make a rough sketch of the frequency graphs below and comment on the main differences.

b) Based on the data you just collected, predict what the graph would look like if you were to play a three note sequence, say, A-B-C, one note at a time. Do you think this graph would change depending on the order in which you play the notes? Explain briefly.

c) Now try the experiment by recording a three note sequence. Was your prediction correct? Does anything change if you play the notes in a different order? Describe your observations.

d) To illustrate the behavior of frequency graphs even more, try plying the sounds 440A1.wav, 440A2.wav, 440A3.wav, and 440A4.wav and making a frequency graph of each one. Each of these sounds is a 440 Hz pure tone that has been recorder for a smaller and smaller time interval. Describe the frequency graph for each of these sounds and explain whether you hear a “note” or not.

e) Finally, make a prediction of what the frequency graph might look like if you simply clap your hands. Make a rough sketch of your prediction and then try the experiment. Sketch the actual frequency graph and comment on the result. Explain how this result is related to the frequency graphs in part d).

This last activity demonstrates that frequency graphs are also affected by how long a sound is played for. In fact, you should have noticed that if a sound is played for a short enough period of time, it ceases to sound like a note. This should make sense based on your knowledge of frequency. Our definition of frequency was based on a repeating pattern. If the pattern doesn't have time to repeat, the concept of frequency begins to lose its meaning. The frequency graphs in the last activity demonstrate that this is indeed the case. In fact, it turns out that shorter sounds are actually much more complicated in the sense of what frequencies are present. Thus, these very short sounds begin to lose their "musical" quality, at least in the sense of being able to carry a melody. Of course, that does not mean that these sounds are not useful in keeping a rhythm of some sort. Many percussion instruments fall into this category.

Checkpoint Discussion: Before proceeding, discuss your ideas with your instructor!

The last activity in this unit is a culminating summary of everything you have learned so far. We will use both time and frequency graphs to help describe a series of sounds, some of which may be familiar and some of which may not. It is important to avoid using vague terms as much as possible. Much of what we learned throughout this unit resulted in terms that can be accurately used to describe sounds. Such terms as frequency spectrum, harmonic series, pure tones, complex tones, attack, decay, and sound envelope, have a lot of meaning and should be used whenever appropriate.

Activity 4.4.3: Describing Sounds More Accurately

a) Play the sound file A040403a.wav and make both a time and frequency graph of the sound. Talk with your group and discuss how you can describe this sound fairly precisely using the terms we have learned in this unit. Then write this description below.

b) Do the same for sound A040403b.wav.

c) Do the same for sound A040403c.wav.

d) Do the same for sound A040403d.wav.

e) Do the same for sound A040403e.wav.

f) Do the same for sound A040403f.wav.

Hopefully, this last activity demonstrated that you are now able to analyze and describe sounds using a much more systematic procedure than when you first began this unit. Hopefully, this will give you more appreciation for sounds, both musical and non-musical, when you hear them in the future.

5. *PROJECT IDEAS*

It is now time for you to play the role of scientific investigator. Discuss with your group things that you found interesting about this unit and choose a project that focuses on these interests. Please do not feel limited by these suggestions. You may modify any of these or come up with a completely new one on your own.

As before, you will need to write a brief proposal that outlines your mission and how you plan to accomplish it. Refer to the proposal guidelines for more information on what to include in your proposal. Also keep in mind that you will be presenting your project to your classmates, so be prepared to discuss your results, how you measured them, and what conclusions you can draw from them.

Good luck, and have fun!!

5.1. SINGING IN THE SHOWER

Have you ever noticed how different people's voices sound while singing in the shower? Why is this so? What makes singing in the shower any different from singing anywhere else? Explore the acoustics of small spaces by looking at the frequency spectra of sounds in and out of the shower. Some questions that may be interesting include:

1. For the same note, how does the frequency spectrum of a voice change in and out of the shower? How does the frequency spectrum of a pure tone change in and out of the shower?
2. As you change the note sung, how does the frequency spectrum of a voice change in and out of shower? Does the affect of the shower depend on the frequency of the sound? How?
3. How do the size and shape of the shower affect the frequency spectrum of the sound?

5.2. VOICES IN THE CHOIR

The human voice is a complex instrument capable of the intricate intonations required for speech and song. How does the human voice work? What is the mechanism behind the human voice? How do we make different sounds with our voice and why do different people sound different when they sing?

1. How are the frequency spectra of male and female singers similar? How are they different?
2. What is the difference between a bass, a tenor, and a soprano? What is falsetto? How are these tied to the physiology of the human voice?

5.3. HELIUM AND THE HUMAN VOICE

We've all heard people speak after they have breathed in helium (and if you haven't you should). They sound "funny." But why? How does helium affect the human voice? What is happening that makes the voice sound so weird?

1. How is the frequency spectrum of the voice different when a person is exhaling helium?
2. Research the physiology of the human voice and the dependence of sound on the medium in which it is produced. Based on this research, explain the mechanism behind the change in the frequency spectrum of a person's voice when they are exhaling helium.
3. Read about the factors that affect the speed of sound in different gases and the affects of the speed of sound on frequency. Use what you learn to predict what would happen to the frequency spectrum of someone's voice if a they were to exhale while breathing a 50% / 50% combination of helium and air. Measure this frequency spectrum and compare it to your predictions.

5.4. GUITAR EFFECTS

Investigate the background of amplifiers, effects, distortion, tube vs. transistor, pickups, guitars. What sort of distortion is produced by different techniques? Project: Enter sine wave into effects generator, look at frequency spectra and wave shapes of outputs. Present sounds from sine wave and from guitar strings, discuss use of distortion for musical purposes

5.5. THE SPEED OF SOUND

We hear about supersonic jets and breaking the sound barrier, but how fast does sound travel? Figure out a way to measure the speed of sound.

5.6. VOICES ON THE PHONE

People sound different over the telephone. Why is this?

1. How does the frequency spectrum of a voice change when heard through a telephone?
2. Using a pure tone, determine how the telephone transmits different frequencies? Are there any frequencies that are not transmitted?

5.7. SPEECH RECOGNITION

Modern telephone systems can respond to the human voice. For example, some phone systems can respond when you say numbers or letters. How do these systems know what you are saying?

1. What do the time and frequency graphs for the numbers one through nine look like?
2. Compare these graphs for several people. How are they similar? How are they different?
3. Propose a method by which a computer could determine what numbers a person was saying based on time and frequency graphs?

5.8. COMPARING REAL AND SYNTHESIZED INSTRUMENTS

Compare the sound of a real instrument with the sound of the synthesized instrument. How are they similar? How are they different? Compare to the QTKeys synthesizer as well as some other small electronic keyboards. What are the properties that make one synthesizer sound better than another?

5.9. DOES TIMBRE CHANGE WITH FREQUENCY?

The frequency spectrum of an instrument reveals a lot of information about the Timbre (characteristic sound) of an instrument. Measure the frequency spectrum of an instrument for several notes and compare these to see how the spectrum changes as the frequency is changed.

5.10. ALTERNATIVE TEMPERED SCALES

Why is the 12 note chromatic scale so popular in Western music? We could just as easily have chosen an 11 note or a 13 note tempered scale, but we have settled on the 12 note scale. What makes this scale so special? Develop several tempered scales with varying numbers of notes. Determine the frequencies of these notes and record the scales. How do each of these scales sound compared to the standard chromatic scale? Compare the frequencies of these notes to whole number ratios. How well do the notes in each scale match up to these ratios?