Audio Machines

This module describes the parallel evolution of audio machines. Audio – in formats such as radio, streaming music, and podcasts delivered through Bluetooth speakers and wireless speakers - is ubiquitous in today's world. Before the electronic age, however, audio was primarily limited to live music performances and face-to-face conversations.

History of Electronic Audio Devices

The electronic age began with invention of the vacuum tube amplifier. Bell Telephone purchased the patent rights to the vacuum tube invented by Lee de Forrest, and used to it to create an amplifier that made coast-to-coast phone calls possible. In 1915 Alexander Graham Bell made the first transcontinental call. Bell was in New York and spoke with former assistant, Thomas Watson, in San Francisco.

Figure 1. Bell makes the first coast-to-coast telephone call.

Amplifiers then made commercial radio feasible. Station KDKA in Pittsburg made the first commercial radio broadcast in 1920. Next came the electrically amplified speake. In 1926 two engineers, Kellogg and Rice, invented the dynamic loudspeaker used in most speakers today.

Figure 2. Radiola vacuum tube amplifier and dynamic speaker (circa 1933).

The Radio Corporation of America (RCA) began selling Radiola radio receivers with electronically amplified loudspeakers in 1926. By the end of the decade, nearly half of all Americans owned radios.

The electrically amplified speaker allowed entire families to gather around the radio. Americans could experience national events like presidential addresses and baseball games together for the first time. Workers gathering around the office water cooler discussed the previous night's comedy show.

Figure 3. Radio was at the center of family entertainment.

Today in addition to loudspeakers, microphones, electric guitars, and other electronic musical instruments are all audio machines that make use of electromagnetism. A permanent magnet like a bar magnet always generates a magnetic field with positive and negative poles at each end of the magnet. An electromagnet can be created by sending an electrical current through a coil of wire. As long as an electrical current is flowing through the wire, the coil of wire also has a positive and negative magnetic pole at each end of the coil. Unlike a permanent magnet, the magnetic field is terminated when the electrical current is turned off. Electromagnets and permanent magnets make electrical motors and loudspeakers possible. Consequently, electromagnetism is an important pillar of today's civilization.

Acoustic Concepts and Music Synthesis

In the 1950s, vacuum tube amplifiers were replaced by transistors. The inventors shared the Nobel Prize in physics for this invention. Transistors made portable transistor radios possible. They made digital computers practical, culminating in the information age. Transistors also made the first commercial music synthesizer feasible. The Moog synthesizers used transistor circuits to create electronic music. Today the computers powered by integrated circuits containing the equivalent of millions of transistors can emulate the early hardware synthesizers of the 1960s at a fraction of the cost.

Chapter 5 will provide an introduction to electronic music. The first Moog synthesizers developed in the 1960s could cost $10,000 or more. Today software music synthesizers can be downloaded and installed for a fraction of the cost. The Caustic music synthesizer, for example, can be downloaded for installation on Windows and Macintosh computers at no charge. The cost for the Caustic app on Apple or Android tablets is ten dollars.

Consequently, anyone with an interest can create synthesized music … but use of a music synthesizer requires an understanding of basic acoustics concepts such as acoustic waveforms. The acoustic waveform below (Figure 4), is the graphical representation of the back-and-forth movement of a sound.

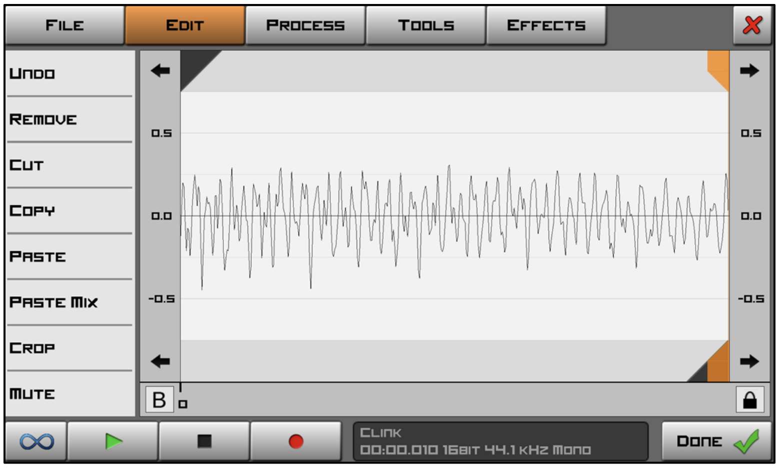

Figure 4. The Acoustic Music Synthesizer Waveform Editor.

All musical instruments with strings, such as guitar or a violin or a piano, produce sound through the back-and-forth movement of the vibration of the string. The movement of the string creates a back-and-forth motion in the air that can be translated into electrical energy by a recording device such as a microphone. Transmission and reproduction of sound at its most basic is the translation of a back-and-forth motion from acoustical to mechanical to electrical energy. The waveform displayed in the waveform editor in Figure 4 is the graphical representation of this back-and-forth movement.

Electrical and acoustic waveforms are invisible. Alexander Graham Bell, his father, and his grandfather – devoted their lives to the question of how to make sound visible. Bell's grandfather, wrote a book titled, *Visible Speech*, in an effort to address this problem. Ultimately, Bell's research led to invention of the telephone, the culmination of three generations of effort. Bell's understanding of acoustic waveforms led to this success, and indirectly made other inventions such as the electric guitar and the music synthesizer possible.

Fortunately, although electrical and acoustic waveforms are invisible, they share the characteristics and properties of mechanical waveforms. If we can understand the nature of mechanical waveforms, therefore by extension we will be able to understand their electrical and acoustic counterparts. A mechanical object such as a guitar string that moves back and forth at a fast enough rate creates an acoustic wave that is perceived as sound. A guitar string moves back-and-forth so fast that it is not possible to see the individual moves of the string.

However, any mechanical system such as a pendulum that moves back and forth at regular (i.e., periodic) intervals shares the essential underlying characteristics of a vibrating guitar string. Therefore, if we can understand the periodic motion of a pendulum, by extension we will be able to understand the similar movement of a guitar string.

Periodic Motion

The pattern produced when the back-and-forth motion of an object is graphed can be more easily seen when the object is moving slowly. Figure 5 depicts a full paint bucket with a hole in the bottom attached to a rope that it becomes a pendulum. If you place a long strip of butcher paper under the can and pull the paper beneath the paint bucket at a slow, even rate, the paint dripping from the can records the path of the bucket as it swings back and forth.

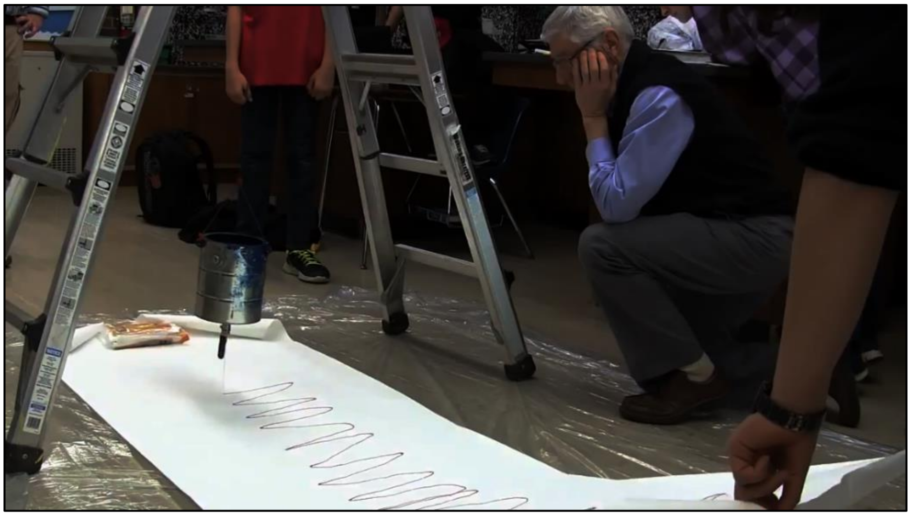

Figure 5. The back-and-forth movement of a paint bucket generates a sine wave.

As the paint bucket swings back and forth, the trail of paint creates a record of its movement. The distance that the bucket swings from the top of the paper to the bottom of the paper is known as its *peak-to-peak amplitude* – that is, the maximum swing from top to bottom. The strip of butcher paper is about three feet wide. The path left by the dripping paint covers about one-third of the paper. Therefore, the peak-to-peak amplitude is about one foot.

The rate at which an object moves is known as its *frequency*. Frequency refers to how frequently an event occurs. In this our demonstration depicted in Figure 5, the paint bucket pendulum was moving back and forth at a rate of about eight times per minute. That is, its frequency was eight cycles per minute.

The motion of a pendulum can be analyzed with greater accuracy by recording its movement with a video camera. When the video is played back, the position of the pendulum can be marked by placing a dot on transparent plastic overlay placed over the computer monitor for each frame of the video. Programs such as Video Physics (Figure 5) can automate this process. The distance that the pendulum travels from its midline to the top of the arc is known as its *peak amplitude*.

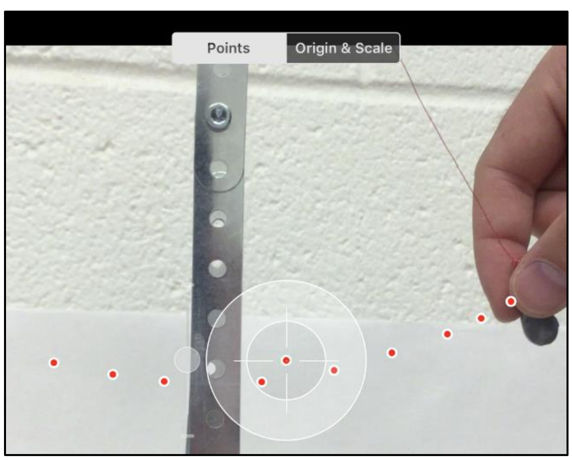

Figure 6. Graphing the movement of a pendulum with software.

The resulting table of distances can then plotted on a graph of distance over time. The resulting graph is a waveform that is similar to the one shown in Figure 7.

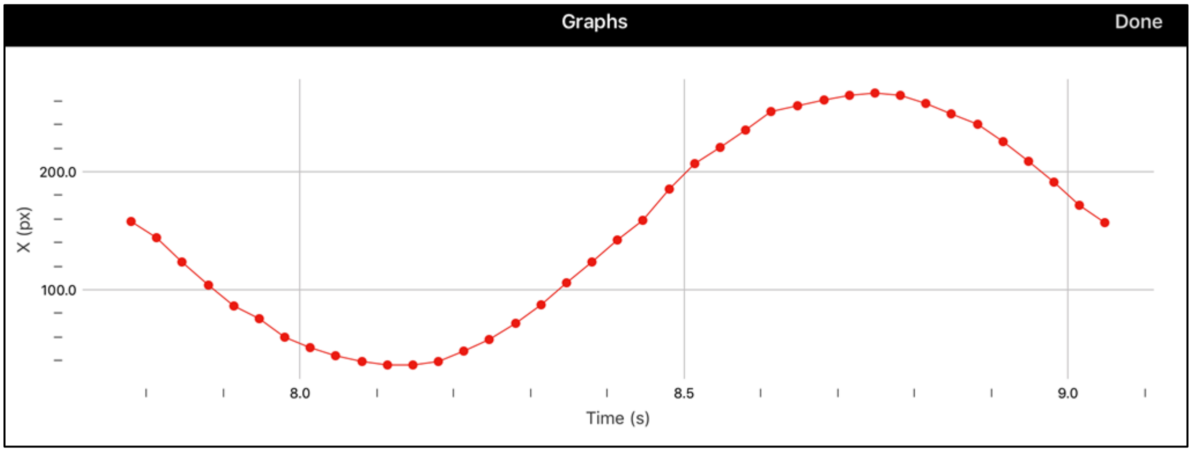

Figure 7. A graph of the motion of a pendulum.

A weight attached to rope or string to create a pendulum moves back and forth at the same rate unless the length of the rope is altered. Any natural object that moves back and forth in this manner will move at a rate that is related to the length of the pendulum. The rate at which a freely moving object swings back and forth is known as its *resonant frequency*.

A guitar string also has a resonant frequency that causes it to move back and forth at a specific frequency as it vibrates. This is why each string of a guitar produces a specific note.

Analyzing Frequency

The number of back-and-forth movements of a guitar string in one second can be calculated by counting the number of peaks in the graph in that amount of time. For example, 40 peaks displayed in one second on the graph would indicate that the string moved back and forth 40 times in one second. This would be described as a frequency of 40 cycles per second, or 40 Hz. (The term *Hertz* or *Hz*, named in honor of the scientist Heinrich Hertz, can also be used in place of *cycles per second*.) This frequency approximates the guitar note that is perceived as E1.

The frequency can also be estimated by counting the number of peaks in one-tenth of a second and multiplying by ten. For example, if there are four peaks in one-tenth of a second, you could calculate there were 40 cycles in a full second. If there were three and one-half cycles in one-tenth of a second, this would indicate that there were approximately 35 cycles in a full second.

Frequency and Harmony

A monochord is a musical instrument with a single string. The monochord in Figure 7 has been constructed with a bass guitar string. The string in the monochord moves back and forth at a rate of 30 times per second when it is plucked.

Figure 8. A bass monochord.

Placing a finger in the middle of the monochord halves the segment of the string that is able to vibrate. If the vibrating length is half its previous length, the rate of vibration doubles. In the case of the monochord in Figure 7, a segment half the length of the entire string would vibrate at a rate of 60 times per second. Halving the portion of the string that can move has the same effect on the rate of back-and-forth movement as decreasing the length of a pendulum rope by half.

The relationship between the length of a vibrating string and the frequency of the sound produced was first discovered by Phythagoras. Pythagoras, who lived in the sixth century BC, found that combinations of frequencies that are the ratios of small whole numbers such as 1:2 or 2:3 create tones that sound appealing. If one vibrating string is half the length of a second string, the interval sounding by the combination of the two strings together forms an octave.

The height of the peaks (amplitude) is diminished when a segment that is half the length of the entire string vibrates because the shorter segment does not travel as far from the midline. Decreased amplitude affects the volume of the sound produced. It will not be as loud.

Overtones

A naturally vibrating guitar string not only vibrates as a whole, but also in halves, thirds, etc. This is the most difficult acoustical concept to understand, but understanding this concept is essential to understanding the nature of the sound.

By analogy we can used the example of the pendulum to understand what is occurring. Imagine that the paint bucket is wobbling as it swings back and forth. The wobble in the bucket will create a ripple in the larger waveform produced. The bucket is simultaneously moving in two ways at the same time. It is making the larger one-foot excursions as it swings back and forth, but it is also making smaller movements of an inch or two related to the wobble of the bucket.

The bucket in Figure 5 completed eight back-and-forth moments (cycles) in one minute. If the bucket wobbled ten times during one complete cycle, it would wobble at a rate of about 60 wobbles per minute. Consequently, the bucket would be simultaneously vibrating at two different frequencies at once. The lowest frequency (eight cycles per minute) is known as the *fundamental frequency*. The higher frequency is known as a musical *overtone*.

The natural rate at which a string vibrates as a whole is known as its fundamental frequency (F_0). The rate at which the two halves vibrate is known as the first overtone (F_1). Because a guitar string simultaneously vibrates in multiple ways, our ears perceive the sound as having a much richer quality. This quality of a perceived sound is known as its *timbre.*

A music synthesizer consists of a bank of oscillators that each generate a single frequency. A vibration consisting of only a single frequency with no overtones is known as a *pure tone*. A pure tone has a thin sound. The output of several oscillators can be combined to create a richer sound. By varying the frequency and intensity of the tones produced by several oscillators, virtually any musical sound can be synthesized.

The diagram shown in Figure 9 is a graph of the output of two oscillators. The output of Oscillator 1 is shown in blue. The output of Oscillator 2 is shown in red. The tone produced by Oscillator 2 is double the frequency of Oscillator 1 but lower in intensity.

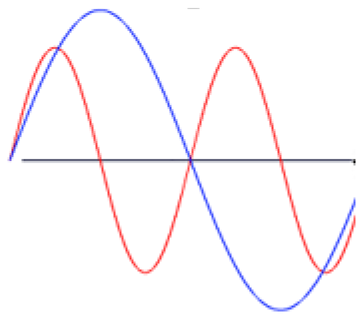

Figure 9. A graph of the tones produced by two oscillators.

When the tones produced by the two oscillators are mixed together, the graph of the combined tone looks like this.

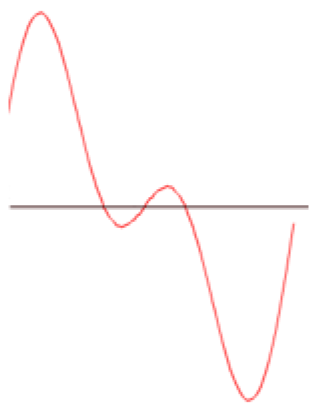

Figure 10 A graph of the combined tones.

The harmonic frequencies represented by the overtones in combination with the fundamental frequency give a tone its characteristic sound, allowing us to distinguish the sound of a guitar from the sound of a trumpet.

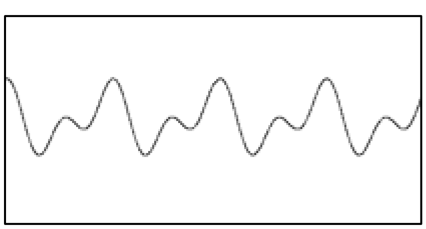

Figure 11. A graph of a tone played on a guitar.

Tones can be constructed electronically by combining the outputs of a series of oscillators to form a complex wave form. A music synthesizer combines tones in this way, by adjusting the amplitude and frequency of each tone to create the desired output. The first music synthesizers consisted of hardware with knobs and dials to adjust the frequencies. The output of oscillators was combined using a series of patch cords.

Figure 12. A hardware music synthesizer generates tones electronically.

Today synthesized tones are often created in software, offering the benefit of more control at a lower cost.

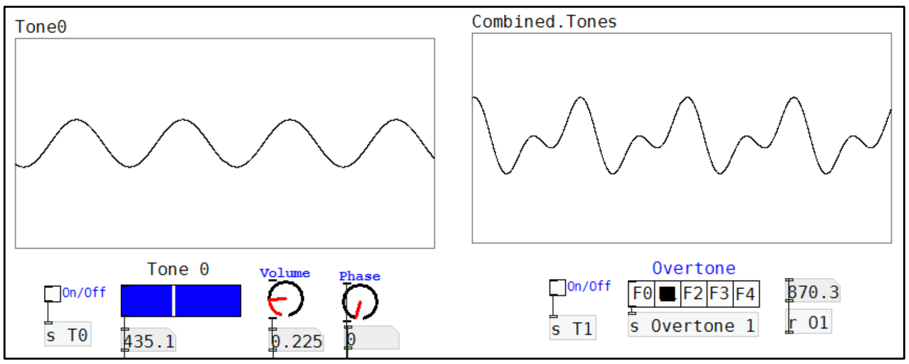

Figure 13. Electronic tones can also be generated with computer software.

Open source programs such as Caustic and Pure Data make it possible for anyone with the interest to experiment with synthesized tones.

Designing a Dynamic Speaker

Sound is generated by a back-and-forth movement such as the vibration of a violin string. The cone of a dynamic speaker can be moved back and forth in a similar fashion through use of electromagnetism. Electromagnetism is also the force used to move electric motors back and forth.

The CAD files and assembly instructions for construction of a dynamic speaker are available on the *Make to Learn* web site. The theory underlying a speaker is provided in the section that follows.

Electric Motor

A speaker is essentially a special version of a linear motor. A linear motor consists of a coil of wire with a permanent magnet inside the coil.

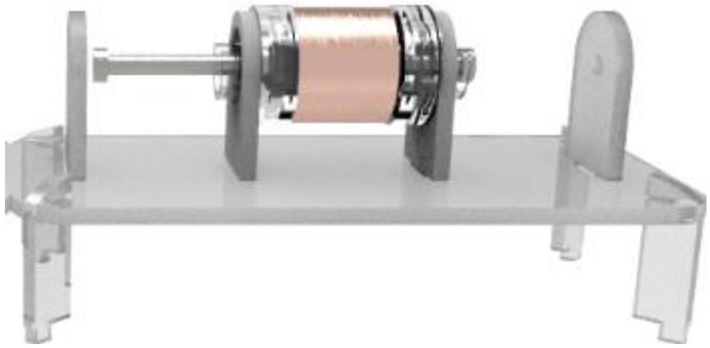

Figure 14. A linear motor consists of an electromagnet with a permanent magnet inside the coil.

If a battery is attached to the coil of wire, the electrical current traveling through the coil generates a magnetic field. In other words, the coil of wire is an *electromagnet*. If the terminals of the battery attached to the coil are reversed, the electrical current flows in the opposite direction, which in turn reverses the north and south poles of the magnetic field. (The direction in which the north and south poles of the magnet face is known as the *polarity* of the magnet.) The reversal of the magnetic field causes the permanent magnet to move in the opposite direction. A more detailed discussion of motors is available in Chapter 6, *Animatronic Figures.*

When the negative and positive terminals of the battery are repeatedly reversed – for example, by turning the handle of a crank attached to the case of the battery – the permanent magnet moves back and forth at the same rate.

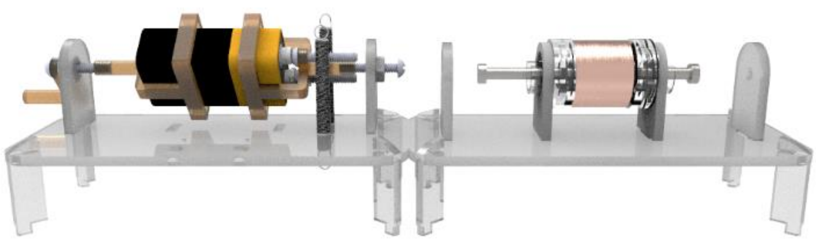

Figure 15. Each half-turn of the battery reverses the polarity of the electromagnet.

The battery alternates the direction that the current flows each time the battery completes a half turn.

Electronic Tone Generator

An electronic tone generator serves a similar function as a rotating battery. It reverses the direction of the current at the specified rate. An electronic tone generator (i.e., an electronic oscillator) is one of the tools available on the *Make to Learn* web site:

https://maketolearn.org/tools/soundscope/

In the screen shot below, the *Make to Learn* tone generator has been set to a rate of 6 back-and-forth movements per second.

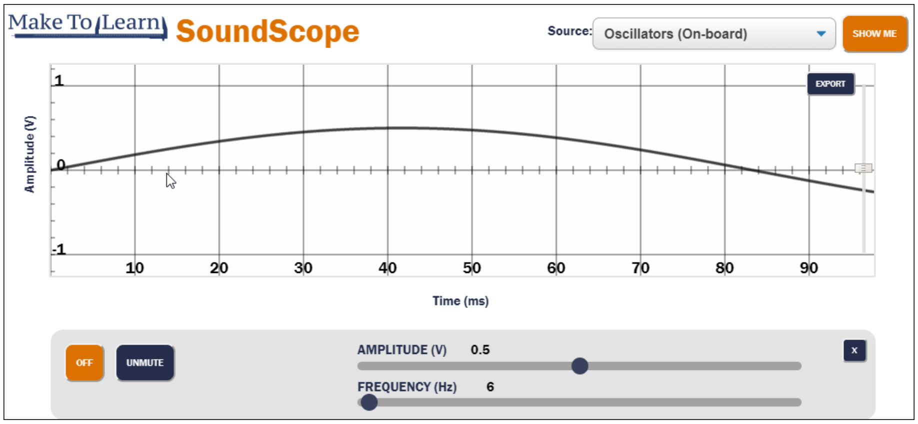

Figure 16. An electronic tone generator can also be used to reverse the polarity of an electrical current.

When the output of the tone generator is attached to a linear motor, the permanent magnet will move back and forth at the same rate.

When the rate of movement is increased to 20 or 30 times per second, the movement becomes a blur. Eventually it is not possible to see the movement at all … but the vibration can still be felt by placing a finger on the linear motor.

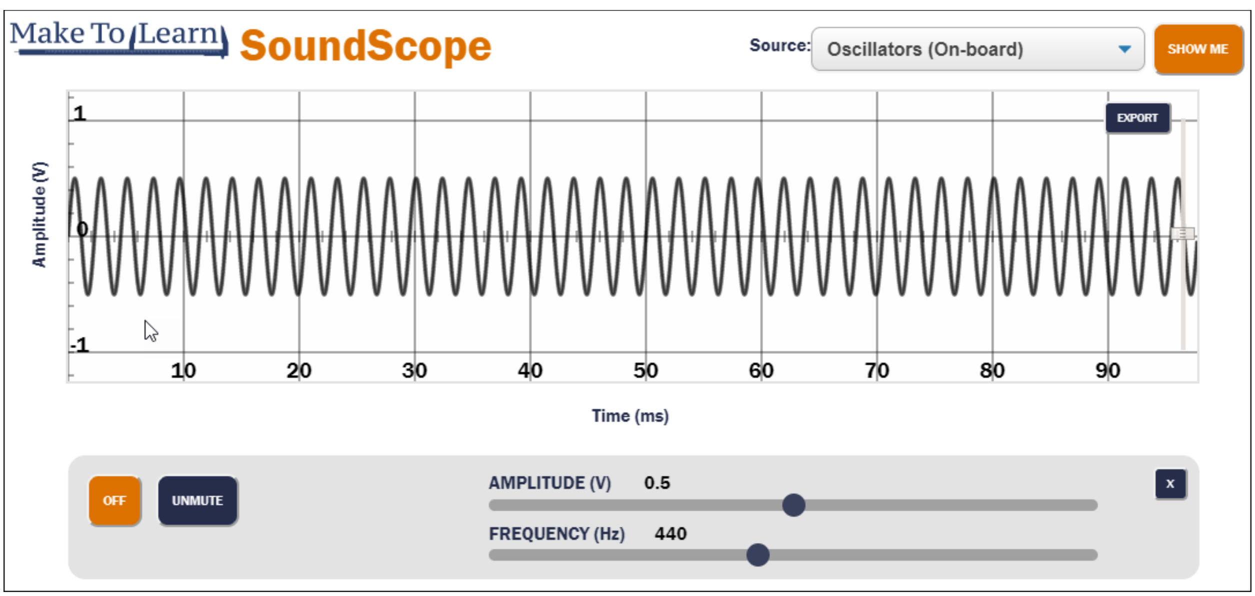

Figure 17. A rapid back-and-forth movement is perceived as sound.

As the rate of movement is increased to more than 60 times per second, an audible tone produced by the movement of the linear motor can be heard. The term *frequency* refers to how frequently an event occurs. In this instance, the magnet is moving back and forth at a rate of 440 times per second. This movement is perceived auditorily as the musical note of A above middle C (the modern standard note used as a reference for tuning instruments).

The same phenomenon of back-and-forth movement can be seen visually at lower rates, felt kinesthetically through touch at higher rates, and heard as a sound at still higher rates. The same phenomena of back-and-forth movement is occurring in all three cases, but it is perceived by our senses in different ways depending upon the rate of movement.

If a song is played in place of a tone, the music can be heard faintly. In other words, a linear motor is a speaker … if a weak one. We can increase the loudness of the speaker by adding a speaker cone. The speaker cone moves a greater mass of air, producing a louder sound.

Elements of a Dynamic Speaker

An improved speaker with a cone can be constructed by first placing the magnet into a base. This allows a coil of wire to be placed over the magnet.

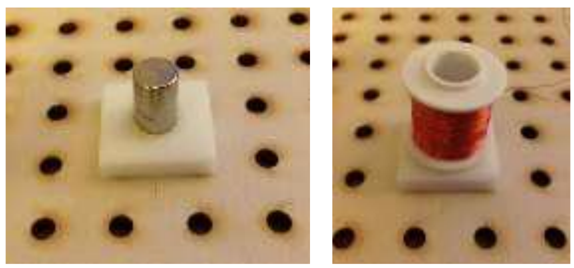

Figure 18. A coil of wire is place over a permanent magnet.

A paper cone can then be attached to the top of the coil of wire. The ends of the coil of wire can be attached to a music player.

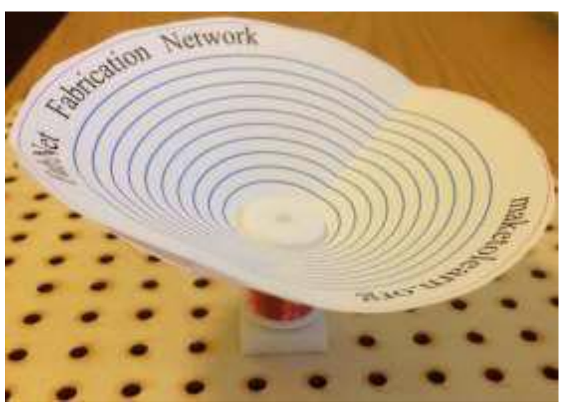

Figure 19. A paper cone is attached to the coil of wire.

The sound produced by a coil attached to a cone will be louder than the coil alone. This improved audio machine combines a linear motor with a speaker cone. However, the quality of the sound could best be described as low fidelity. Higher fidelity speakers suspend the coil in mid-air with springs.

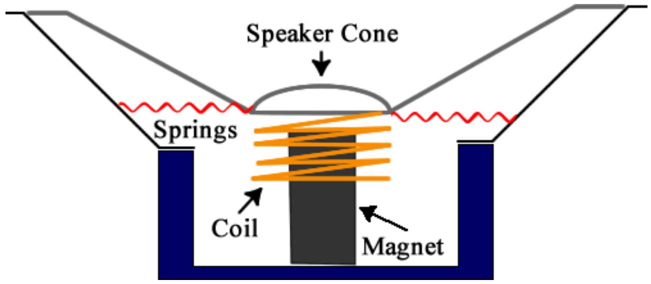

Figure 20. Springs in a high fidelity speaker suspend the coil of wire in mid-air.

The springs allow the coil to move back and forth more freely, creating a higher fidelity sound.

Figure 21. The springs suspending the coil of wire are visible in the side view of this speaker.

Speaker Fidelity

A speaker, like all natural vibrating objects, has a resonant frequency. The resonant frequency of a speaker can be analyzed by playing a series a tones through the speaker (such as 125, 250, 500, 1000, 2000, 4000 Hz, etc.) and recording the intensity of the output with a sound level meter.

Figure 22. Measuring the intensity of a tone with a sound level meter.

The standard unit for measuring the intensity of a sound is the Bell, named after Alexander Graham Bell. These measurements are typically recorded in tenth of a Bell, or decibels (dB). The graph in Figure 23 records the sound level readings for two speakers. The blue line displays the frequency response for a woofer (which is more responsive to lower frequencies), while the red line displays the frequency response for a tweeter (which is more response to higher frequencies).

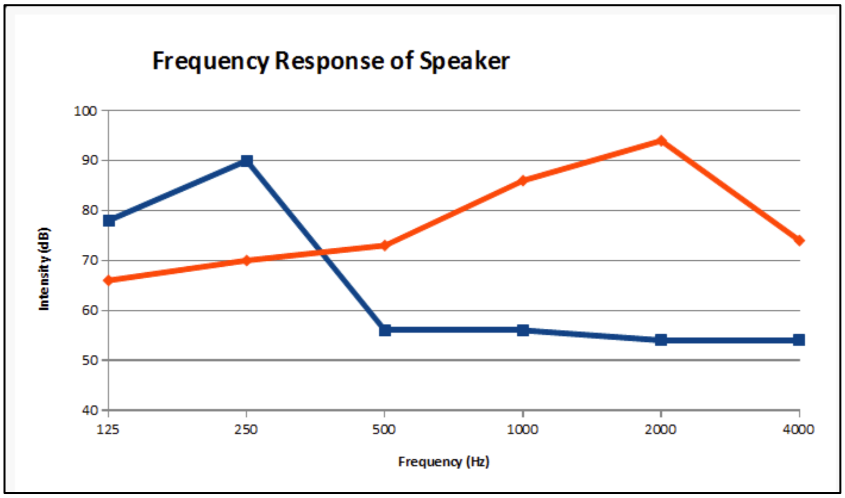

Figure 23. Graphing the frequency response of a small speaker (red line) and a larger speaker (blue line).

Most high fidelity stereo speakers combine two or more speakers. Larger speakers with a greater mass are more responsive to lower frequencies, while smaller speakers with a lower mass are more responsive to higher frequencies. By combining speakers of different sizes that are more responsive to different segments of the overall frequency range, a higher fidelity system is attained that reproduces sound more accurately.

Designing an Electric Guitar

The elements of an electric guitar are the inverse of a speaker. Electromagnetism converts the electrical waveform into a magnetic waveform. This moves the speaker cone back and forth, converting mechanical energy into acoustic energy. In the case of the electric guitar, the process is reversed. The movement of the guitar wire through a magnetic field generates an electrical current that converts mechanical energy into electrical energy. Because this device picks up the sound and coverts it to electrical energy, it is known as a guitar pickup.

A simulation on the *Make to Learn* website demonstrates generation of an electrical current by a magnet traveling through a coil of wire. Click the link below to access the simulation.

Linear Generator Simulation

Once you are at simulation website, use the mouse to slide the cursor across the screen to move the generator back and forth. Observe what happens to the linear motor as the linear generator moves back and forth.

If the permanent magnet in the center of the coil of wire on the left in Figure 24 is moved back and forth, it will generate an electrical current that travels across the wires to the second coil of wire on the right. The electrical current traveling through the second coil of wire on the right will then generate a magnetic field. This electromagnetic force will cause the magnet on the right to move back and forth in unison with the magnet on the right.

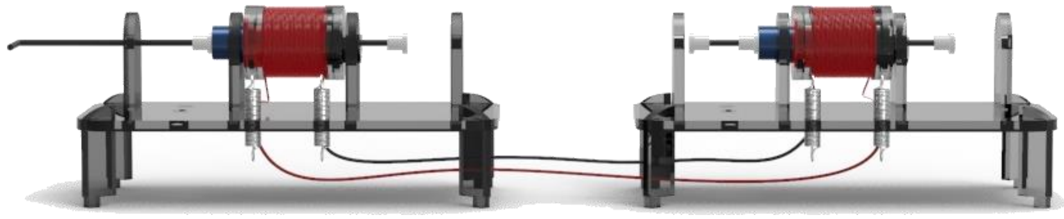

Figure 24. Movement of the magnet in the coil of wire on the left generates an electrical current.

The same phenomenon occurs on a larger scale in the power grid. An electrical generator in a power plant transmits electricity across the electrical network. This electrical current, in turn, can cause a motor in a home to move.

Elements of an Electric Guitar

Electric guitars and other electrical musical instruments also make use of this electromagnetic force. A guitar pickup consists of a coil of wire wrapped around a permanent magnet. When the steel string of the guitar moves back and forth across the magnetic field of the permanent magnet, an electrical current flows through the wire coil wrapped around the magnet.

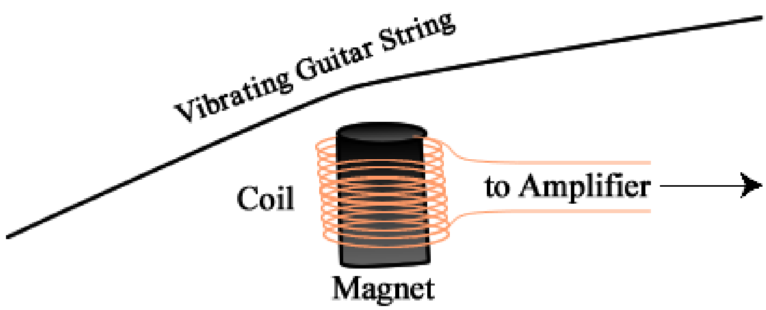

Figure 25. A guitar pickup converts movement of a steel string into an electrical current.

The electrical current generated by the guitar pickup is then transmitted to a wire coil in a speaker. The electrical current traveling through the wire coil in the speaker generates an electromagnetic field. This electromagnetic force, in turn, moves a permanent magnet inside the speaker. The movement of the wire coil and permanent magnet inside the speaker causes the speaker cone to move, producing sound.

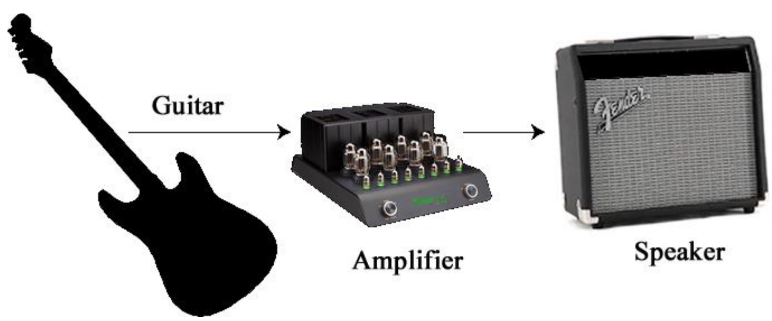

Figure 26. An amplifier increases the strength of an electrical signal.

The electrical current generated by the guitar pickup is not very strong. Therefore an amplifier is required to make the electrical current generated by the pickup strong enough to move the speaker.

The frequency of the sound produced by a guitar string is affected by its length, thickness, and tension. A longer string produces a lower frequency. That is why a cello produces lower notes than a violin.

Figure 27. The longer strings of a cello produce lower tones.

A monochord is a one-string instrument used for centuries to explore the relationship between the characteristics of a stringed musical instrument and the notes produced.

Figure 28. A monochord constructed with a guitar string.

A monochord can be constructed with a bass guitar string been paired with a subwoofer designed to produce low frequency sounds. If the monochord is connected to the subwoofer with an amplifier, the speaker cone will move back and forth when the string is plucked.

If it were physically possible to attach a pencil to the string of a monochord and pull chart paper beneath the pencil as the string moves back and forth, a graph similar to the graph produced by the movement of the paint buck pendulum (Figure 4) would result.

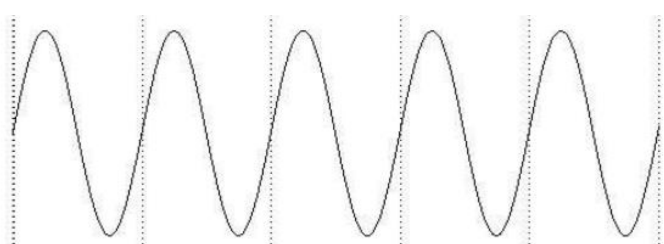

Figure 29. A graph of the movement of the guitar string is similar to the graph of the paint bucket in Figure 4 (above).

If the monochord string and the speaker cone are recorded in the same frame, it is apparent that the back-and-forth movement of the string and the back-and-forth movement of the speaker cone follow one another. As the string of the monochord moves forward, the speaker cone also moves forward. As the string of the monochord moves backward, the cone of the speaker also moves backward. In other words, the movement of the speaker cone faithfully reproduces the movement of the monochord string. Recall that the movement of the steel wire of the guitar string generates an electrical current as it passes through the magnetic field of a magnet in the guitar pickup. The monochord pickup is a specialized instance of an electrical generator, while a loudspeaker is a specialized instance of an electrical motor. Just as the linear motor in the earlier example faithfully followed the movement of the linear generator, the speaker exactly reproduces the movement of the monochord string.

The bass monochord in this example vibrates at a rate of about 30 back-and-forth movements per second. A slow motion video recording can slow down this movement so that that is visible. The video can be used to analyze and graph the motion of the string in the same manner as the pendulum.

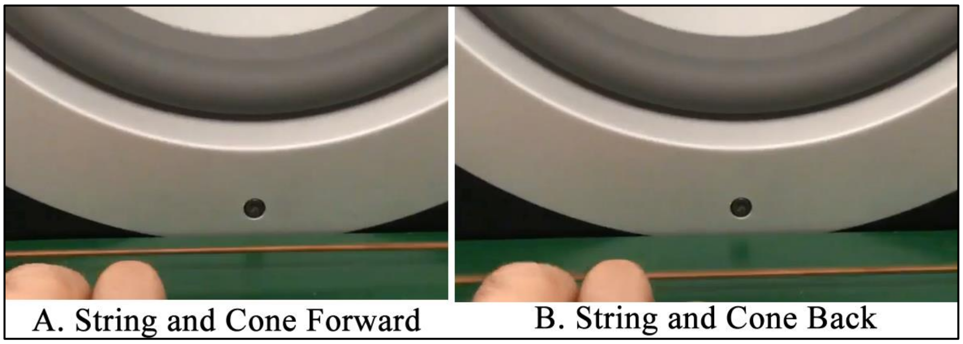

Figure 30. Screen shots from two frames of a video of the guitar string and speaker cone.

The slow motion video of the simultaneous movement of the guitar string and speaker cone reveals that the string and cone move together. As the string moves forward the cone also moves in the same direction (Figure 30.A). When the string moves back, the cone also follows this motion (Figure 30.B).

Another method to graph the motion of the vibrating string that is even more convenient involves recording the intensity of the electrical signal generated by the guitar's pickup coil. The level of the electrical voltage of the signal at each moment in time is converted to a number and stored inside the computer. This process is known as *digitization*. The digitized signal can then be displayed on the computer screen.

The digitized signal generated by the movement of the monochord string resembles the pattern produced by the paint bucket pendulum at the beginning of this chapter (Figure 5). As the movement of the string reaches its outermost point, it gradually slows down. At its furthest outward movement, the string stops and begins moving back toward the midline. The string is moving fastest as it moves through the midline, just as the swing is moving fastest at the lowest point on its downward arc.

Consequently, the graph of the digitized signal displayed on the computer screen is a record of the movement of the string. The height of the graph (also known as its amplitude) corresponds to the distance of the movement of the string from its midline.

The Make to Learn Electric Guitar

The CAD model for the *Make to Learn* electric guitar are depicted in Figure 30. As the preceding section suggests, the most crucial elements of an electric guitar are a steel guitar string and the electrical pickup. As the vibration of the steel string moves it back and forth through the magnetic field of the permanent magnet in the pickup, an electrical current is generated that travels through the coil of wire in the pickup to the amplifier.

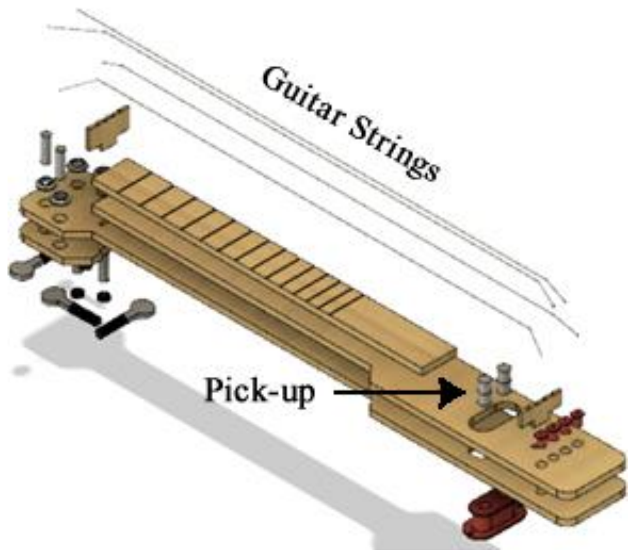

Figure 31. The Make to Learn CAD Model

There are a number of mechanical factors to consider in design of the guitar. The steel strings must be attached to the body of the guitar in some manner. A bridge is needed to hold the strings above the body. Each string is attached to a screw known as a *tuning machine* that is used to adjust the tension on the string to tune it.

One of the most crucial aspects of design of a guitar involves calculation of the spacing between the frets. Pressing down on the guitar string to divide into two segments on either side of the finger changes the rate at which the string vibrates, which in turn affected the note produced. The frets must be spaced correctly in order for the notes to match those of the predominant Western musical scale.

Summary

The pick-up of an electric guitar and the coil of a dynamic speaker are the inverse of one another. The steel string of the guitar generates an electrical current as it passes through a magnetic field. The electrical current is transmitted to an amplifier which increases the intensity of the signal. The output of amplifier, in turn, is transmitted to a coil of wire attached to the speaker cone. The magnetic field generated by the electrical current traveling through the speaker coil causes the cone of the speaker to move back and forth.

In this manner mechanical energy represented by the movement of the guitar string is transmitted into an electromagnetic signal that is converted back into mechanical energy as the speaker cone moves back and forth. Thomas Jefferson used a copying machine known as a pantograph (Figure 31). As he moved one pen, a mechanical linkage attached to a second pen caused it to make an exact copy.

Figure 32. Pantograph in the Collections of the Smithsonian Institution

An electric guitar and a speaker work in a similar manner except that an electrical linkage rather than a mechanical linkage connects the two devices. In a high fidelity system, the movement of the speaker cone should faithfully follow the exact movement of the guitar string as it moves back and forth. In reality factors such as mechanical inertia and distortion in the electrical signal result in slight differences in the movement of the guitar string and the movement of the speaker cone. However, advances in technology have resulted in reproductions of sound that, while not perfect, are close to the original.