Music, Waves, Physics

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C O N N E X I O N S

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Chapter 1

Talking about Sound and Music[1]

Music is the art of sound, so let's start by talking about sound. Sound is invisible waves moving through the air around us. In the same way that ocean waves are made of ocean water, sound waves are made of the air (or water or whatever medium) they are moving through. When something vibrates, it disturbs the air molecules around it. The disturbance moves through the air in waves - each vibration making its own wave in the air - spreading out from the thing that made the sound, just as water waves spread out from a stone that's been dropped into a pond.

[1]This content is available online at <http://cnx.org/content/m13512/1.1/>.

Figure 1.1: A ripple in water causing waves to propagate from the point where presumably drops of water fell.

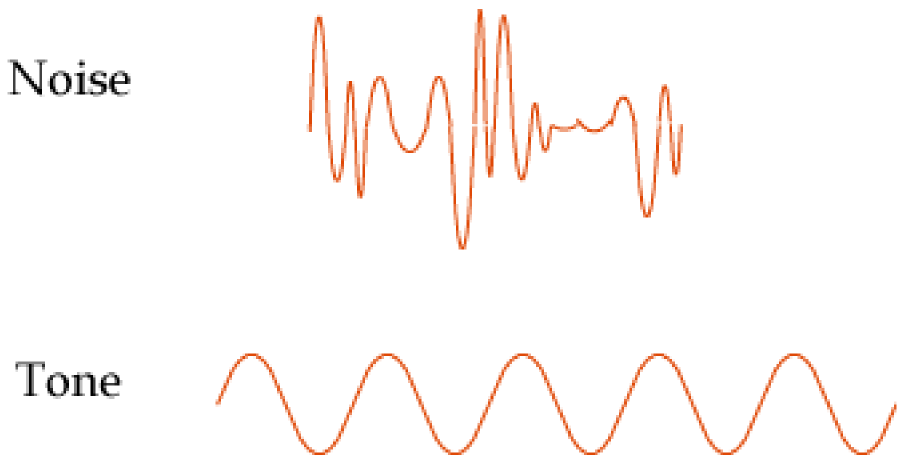

Figure 1.2

A tone (the kind of sound you might call a musical note) is a specific kind of sound. The vibrations that cause it are very regular - all the same size and same distance apart. Musicians have terms that they use to describe tones. But this kind of (very regular) wave is useful for things other than music, so scientists and engineers also have terms that describe tonal sound waves. It can be very useful to know both the scientific and the musical terms and how they are related to each other.

For example, the closer together the waves of a tonal sound are, the higher the note sounds.

Wave and Sound Interaction

The following link is to an animation that will help one build intuition between frequency (how close waves are to one another) and the tonal pitch one actually hears. Click here[2] .

- For starters, in the lower box on the right-hand side under "Audio Control", click on the box "Audio enabled".
- Within the "Audio Control" box, click on "Listener". This will allow you to hear the waves the person in the application is hearing.
- Adjust the "Amplitude" bar. How does the wave look differently? How does it affect the sound?
- Slide the "Frequency" bar. How does this affect how the waves appear as they travel to the listener. How does the pitch change to the listener?

Key Terms and Definitions of Them

Musicians talk about the pitch[3] of the sound, or name specific notes[4], or talk about tuning[5]. Scientists and engineers, on the other hand, talk about the frequency[6] and the wavelength[7] of the sound. They are all essentially talking about the same thing.

The Concepts and Where to Find Them

[2]http://cnx.org/content/m13512/latest/sound.jnlp
[3]"Pitch: Sharp, Flat, and Natural Notes" <http://cnx.org/content/m10943/latest/>
[4]"Duration: Note Lengths in Written Music" <http://cnx.org/content/m10945/latest/>
[5]"Tuning Systems" <http://cnx.org/content/m11639/latest/>
[6]"Frequency, Wavelength, and Pitch", Figure 1: Wavelength, Frequency, and Pitch <http://cnx.org/content/m11060/latest/#fig1b>
[7]"Frequency, Wavelength, and Pitch", Figure 1: Wavelength, Frequency, and Pitch <http://cnx.org/content/m11060/latest/#fig1b>

- **Wavelength** - An introduction to wavelength, frequency, and pitch is presented in Frequency, Wavelength, and Pitch[8]. You can find out more about the (Western) musical concept of pitch in Pitch: Sharp, Flat, and Natural Notes[9].
- **Wave Size** - The other measurement you can make of regular, tonal waves is the size of each individual wave - its "height" or "intensity" rather than its wavelength. In sound waves, this is a measurement of the loudness of the sound. Amplitude[10] is a short discussion of wave size. Musicians have many terms to discuss what they call Dynamics[11].
- **Types of Waves** - There are two basic types of waves. Most diagrams show **transverse** waves which "wave" up-and-down as they move left-and-right. These are easier to show in a diagram, and most of the familiar kinds of waves - light waves, radio waves, water waves - are transverse. But sound is made of **longitudinal** waves, which "wave" in the same direction that they move. These are harder to draw, and a little harder to imagine, than transverse waves, but you will find some helpful suggestions at Transverse and Longitudinal Waves[12].
- **Standing Waves** - Most natural sounds are not tones. In order to produce the extremely regular vibrations that make tonal sound waves, musical instruments, see Standing Waves and Musical Instruments[13] and Standing Waves and Wind Instruments[14]. To find out more about how the waves created in an instrument are related to each other musically, see Harmonic Series[15] and Tuning Systems[16].
- **Sound and Ears** - For a brief description of what happens when a sound reaches your ear, see Sound and Ears[17]
- **The Math** - Students struggling with the math needed for these ideas can look at Musical Intervals, Frequency and Ratio[18] and Powers, Roots, and Equal Temperament[19].

Suggestions for presenting these concepts to a class

- Decide which of the concepts you will be presenting to your class, and prepare your lectures/presentations accordingly. You will probably need about one class period for each related set of concepts. Sound and Ears[20] is particularly geared towards younger students. The concepts in Frequency, Wavelength, and Pitch[21], Transverse and Longitudinal Waves[22], and Amplitude[23] can be presented to just about any age. Standing Waves and Musical Instruments[24], Standing Waves and Wind Instruments[25], Harmonic Series[26] and Tuning Systems[27] are probably best presented to older students (middle school and up). Musical Intervals, Frequency and Ratio[28] and Powers, Roots, and Equal Temperament[29] can be used either to remind older students of the math that they have learned and its relevance to music, or as extra information for younger students working on these math concepts.

[8]"Frequency, Wavelength, and Pitch" <http://cnx.org/content/m11060/latest/>
[9]"Pitch: Sharp, Flat, and Natural Notes" <http://cnx.org/content/m10943/latest/>
[10]"Sound Amplitude and Musical Dynamics" <http://cnx.org/content/m12372/latest/>
[11]"Dynamics and Accents in Music" <http://cnx.org/content/m11649/latest/>
[12]"Transverse and Longitudinal Waves" <http://cnx.org/content/m12378/latest/>
[13]"Standing Waves and Musical Instruments" <http://cnx.org/content/m12413/latest/>
[14]"Standing Waves and Wind Instruments" <http://cnx.org/content/m12589/latest/>
[15]"Harmonic Series" <http://cnx.org/content/m11118/latest/>
[16]"Tuning Systems" <http://cnx.org/content/m11639/latest/>
[17]"Sound and Ears" <http://cnx.org/content/m12365/latest/>
[18]"Musical Intervals, Frequency, and Ratio" <http://cnx.org/content/m11808/latest/>
[19]"Powers, Roots, and Equal Temperament" <http://cnx.org/content/m11809/latest/>
[20]"Sound and Ears" <http://cnx.org/content/m12365/latest/>
[21]"Frequency, Wavelength, and Pitch" <http://cnx.org/content/m11060/latest/>
[22]"Transverse and Longitudinal Waves" <http://cnx.org/content/m12378/latest/>
[23]"Sound Amplitude and Musical Dynamics" <http://cnx.org/content/m12372/latest/>
[24]"Standing Waves and Musical Instruments" <http://cnx.org/content/m12413/latest/>
[25]"Standing Waves and Wind Instruments" <http://cnx.org/content/m12589/latest/>
[26]"Harmonic Series" <http://cnx.org/content/m11118/latest/>
[27]"Tuning Systems" <http://cnx.org/content/m11639/latest/>
[28]"Musical Intervals, Frequency, and Ratio" <http://cnx.org/content/m11808/latest/>
[29]"Powers, Roots, and Equal Temperament" <http://cnx.org/content/m11809/latest/>

- Include suggested activities, worksheets, and demonstrations whenever possible, particularly for younger students.
- Younger students will benefit from the activities and worksheets in Sound and Music[30].
- Worksheets that cover the basic concepts for older students are available here. Download and copy these PDF files as handouts for your class: Sound Waves handout[31] and Waves Worksheet[32] . There is also a Worksheet Answer Key[33] . In case you have any trouble with the PDF files, these handouts are also included as figures at the end of this module, but they will look better if you print out the PDF files.
- Use the exercises in the modules for class participation and discussion.

[30]"Sound and Music Activities" <http://cnx.org/content/m11063/latest/>
[31]http://cnx.org/content/m13512/latest/waves1.pdf
[32]http://cnx.org/content/m13512/latest/waves3.pdf
[33]http://cnx.org/content/m13512/latest/waves4.pdf

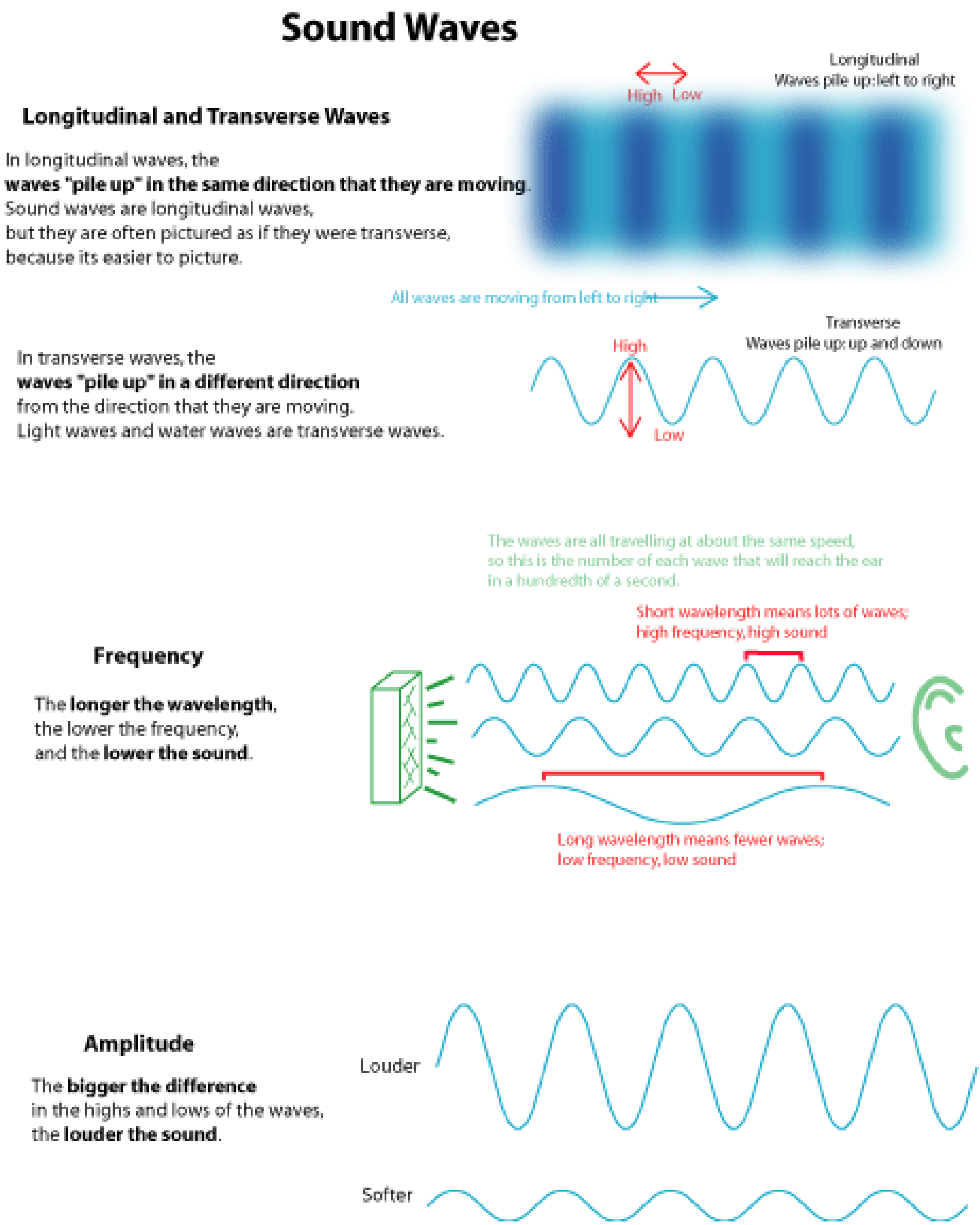
Sound Waves
Longitudinal and Transverse Waves
In longitudinal waves, the
waves "pile up" in the same direction that they are moving.
Sound waves are longitudinal waves,
but they are often pictured as if they were transverse,
because its easier to picture.
High Low
Longitudinal
Waves pile up:left to right
All waves are moving from left to right
In transverse waves, the
waves "pile up" in a different direction
from the direction that they are moving.
Light waves and water waves are transverse waves.
High
Low
Transverse
Waves pile up: up and down
Frequency
The **longer the wavelength**,
the lower the frequency,
and the **lower the sound**.
The waves are all travelling at about the same speed,
so this is the number of each wave that will reach the ear
in a hundredth of a second.
Short wavelength means lots of waves;
high frequency, high sound
Long wavelength means fewer waves;
low frequency, low sound
Amplitude
The **bigger the difference**
in the highs and lows of the waves,
the **louder the sound**.
Louder
Softer

Figure 1.3

Sound and Music Worksheet

Match both the science/engineering terms on the left and the music terms on the right with the definitions in the middle. You will use some of the definiitons twice.

____ Low Frequency

____ Longitudinal Waves

____ Frequency

____ High Amplitude

____ White Noise

____ Amplitude

____ Sound Waves

____ Standing Waves

____ Transverse Waves

____ Wavelength

____ High Frequency

____ Low Amplitude

A. Waves in the air caused by vibrations

B. Waves that move in one direction, but "wave" in another direction

C. Waves that move and "wave" in the same direction

D. The distance between one wave and the next wave

E. How often a single wave goes by

F. How big the difference is between the high points and the low points of the waves

G. Big difference between highs and lows

H. Small difference between highs and lows

I. Lots of short waves

J. Very few long waves

K. Waves that can keep vibrating in or on something for a long time. because they "fit"

L. A sound that is a mixture of all wavelengths

M. Sounds that are organized by people

____ Low note

____ Pitch

____ Dynamic level

____ Soft note

____ Music

____ High note

____ Sounds

____ Loud note

Give short answers:

1. Can sound travel through empty space? Why or why not?

2. How are sound waves like water waves? How are they not like water waves?

3. Name 2 ways a player of a musical instrument can change the sound of the instrument.

4. How can an instrument with only 4 strings get more than 4 different pitches?

5. When a trumpet player pushes down a valve, she opens an extra loop of tubing. What does this do to the trumpet? To the sound?

Figure 1.4

Sound and Music Worksheet

Match both the science/engineering terms on the left and the music terms on the right with the definitions in the middle. You will use some of the definiitons twice.

J Low Frequency

C Longitudinal Waves

E Frequency

G High Amplitude

L White Noise

F Amplitude

A Sound Waves

K Standing Waves

B Transverse Waves

D Wavelength

I High Frequency

H Low Amplitude

A. Waves in the air caused by vibrations

B. Waves that move in one direction,
but "wave" in another direction

C. Waves that move and "wave" in the same direction

D. The distance between one wave and the next wave

E. How often a single wave goes by

F. How big the difference is between the high points
and the low points of the waves

G. Big difference between highs and lows

H. Small difference between highs and lows

I. Lots of short waves

J. Very few long waves

K. Waves that can keep vibrating in or on something
for a long time, because they "fit"

L. A sound that is a mixture of all wavelengths

M. Sounds that are organized by people

J Low note

E Pitch

F Dynamic level

H Soft note

M Music

I High note

A Sounds

G Loud note

Give short answers:

1. Can sound travel through empty space? Why or why not?
   No; there can be no sound vibrations where there is no air.

2. How are sound waves like water waves? How are they not like water waves?
   Both can have frequency and amplitude, but water waves are transverse and sound waves are longitudinal.

3. Name 2 ways a player of a musical instrument can change the sound of the instrument.
   They can make the pitch higher or lower or make the sound louder or softer.

4. How can an instrument with only 4 strings get more than 4 different pitches?
   You can make the vibrating part of the string shorter, and the pitch higher, by holding the string down with one finger.

5. When a trumpet player pushes down a valve, she opens an extra loop of tubing. What does this do to the trumpet? To the sound?
   This in effect makes the trumpet longer, so the sound is lower.

Figure 1.5

Chapter 2

Understanding Wave Jargon; Building Waves on Strings Intuition[1]

If you are unfamiliar with the terms **frequency**, **wavelength** and **amplitude** and how they relate to pitch, we recommend you read and follow the exercises at Talking about Sound and Music (Chapter 1) and Frequency, Wavelength, and Pitch[2].

Click on the word: Animation[3] to visit a great animation created by the PhET Project at the University of Colorado

There are many interesting concepts and exercises to be done with the above animation. We will leave most of it to the user to explore the various concepts of waves on a string, but we will provide a few suggestions and observations to make.

1. Wiggle the free end. See how the beads move together like a string or piece of rope. Now decrease the tension. What happens to the as you wiggle it?
2. Put the tension back to high. Now increase the damping to the 1. What do you observe happening now? In real life, what often causes damping?
3. Bring the tension down to 0. What do you observe now? Since most theory deals with ideal and lossless strings, leave the damping at 0.
4. Now create a pulse by quickly wiggling the free end of the string up and then down. What happens now? When the pulse/wave hits the fixed end, what happens to the pulse? We typically call the pulse that returns the reflected wave. Does the reflected wave stay upright or flip?
5. Now increase the damping back to 0.5. Click on the "Loose End" option. The clamp should now be replaced by a ring and rod. Perform the same exercises as the previous points. How does having a loose end affect the reflected wave.
6. Now click on the "No End" option. Notice how the rod is replaced by a window. At this point, the string is considered infinite, meaning the string continues forever out the window. What is a consequence of having such a string? What does the reflected pulse look like? Is there a reflected pulse?
7. Play around with the other features of this animation. For example, click on the "Oscillate" button. What happens now? What can you do with the free end oscilating that you could not previously do?

[1] This content is available online at <http://cnx.org/content/m13513/1.2/>.
[2] "Frequency, Wavelength, and Pitch" <http://cnx.org/content/m11060/latest/>
[3] http://phet.colorado.edu/simulations/stringwave/stringWave.swf

Chapter 3

Another way of viewing the world[1]

Up to this point, we have mainly focussed on waves as a function of time. Now what do we mean by a function of time? Well, in Understanding Wave Jargon; Building Waves on Strings Intuition (Chapter 2), wiggling the end of the string affected how the rest of the string responded in time. In other words, we are used to seeing everything as causal because our actions have consequences that we observe. If I eat too much, I get a stomache ache an hour later. If my ears are ringing, it wouldn't be surprising if I had just come out of a rock conert.

Well, another way of seeing events is in the frequency domain. Now what does this mean? As described in Talking about Sound and Music (Chapter 1) and Frequency, Wavelength, and Pitch[2], frequency is the number of times a wave occurs per second. However, the concept of frequency does not have to apply to just waves. It can apply to any event, observation, or even concept that occurs multiple times. For example, one can say that the sun rises at a frequency of once per day. One can also say that in each year, a season changes once every three months.

Now why should you care? What possible relevance does this have to your daily life? Well, as discussed in Talking about Sound and Music (Chapter 1), pitches that our ear hears correspond to waves; and since waves have a regularity of repeating itself, all pitches that we hear have frequencies associated with them. Note that the pitches we hear do not necessarily correspond to one frequency. For example, when you strike a string on a guitar, you hear not waves of a single frequency, but the sum of many waves with differing frequencies. However, when striking the strings of an instrument or blowing into a wind instrument, the frequencies that the resulting sound/wave has, is not accidental or random. There is a theory/pattern behind it, but we will not delve into that at this point.

Since the pitches we hear in music typically have flavor to them, in musical terms, differing timbre, (ie. the different sound we hear when playing the same pitch on a guitar and clarinet), most of this phenomenon corresponds to differing spectrograms (graphs of the frequency domain). To solidify this concept, we will provide a few sound examples and their corresponding spectrograms. Don't worry, there'll be plenty of explanation.

Below, I have provided two recordings. One is a recording of me striking the 'A' string of my guitar. The other is a recording of striking the high 'E' string of my guitar.

[1]This content is available online at <http://cnx.org/content/m13514/1.6/>.
[2]"Frequency, Wavelength, and Pitch" <http://cnx.org/content/m11060/latest/>

3.1 Plucking the 'A' String of a Guitar

This is an unsupported media type. To view, please see
http://cnx.org/content/m13514/latest/note_a_animation.swf

Figure 3.1: Flash animation of the following figures

Plot of the sound signal versus time

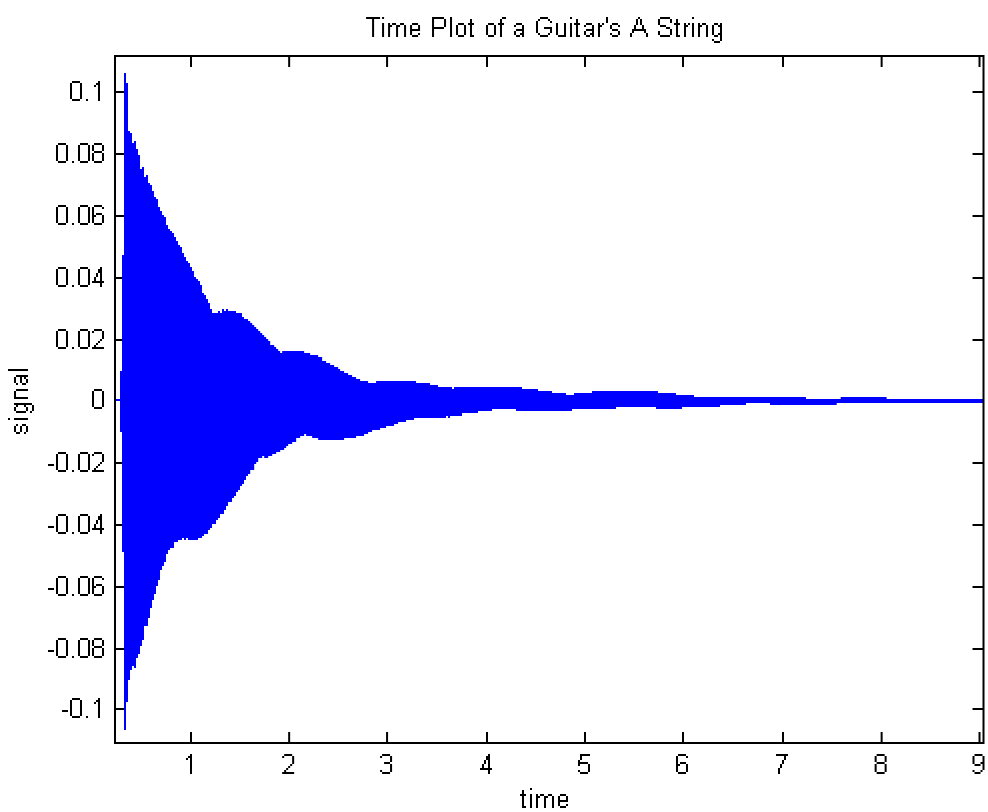

Figure 3.2: The plot of the guitar plucked at the 'A' string over time.

Zoomed in graph of the signal versus time

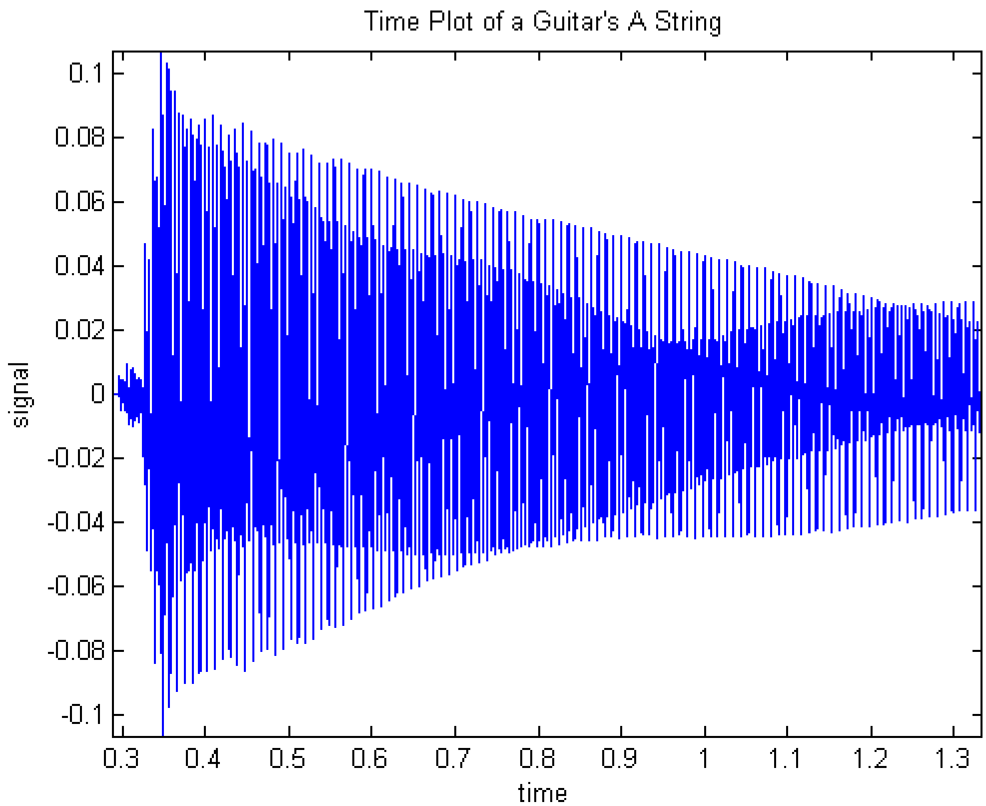

Figure 3.3: The zoomed-in plot of the guitar plucked at the 'A' string over time.

There are a few things to note. In Figure 2, we notice that the sound peaks as it is struck and decays to zero close to 8 seconds. This should resonate well with your intuition from hearing the sound file. Now in Figure 3, you'll notice that there are patterns to the signal heard. Furthermore, you'll also notice that there is not just one wave of a single frequency, but that you can eyeball several waves. For example, there is the large wave that has higher signal than other parts of the wave, as there also appears to be a cross of two waves with higher frequencies in the signal.

From this type of observation, a whole slew of theory and algorithms have been developed to characterize such behavior. By taking the **Fourier Transform** of our sound file, we can see what frequencies make up the signal. Another way of thinking about it, the sound file can be decomposed as the sum of waves of differing frequencies, and the **Fourier Transform** provides a way of seeing the sound file in the time domain, as in Figures 2 and 3, to the frequency domain shown below in Figure 4.

Spectrogram of Figure 1's sound file

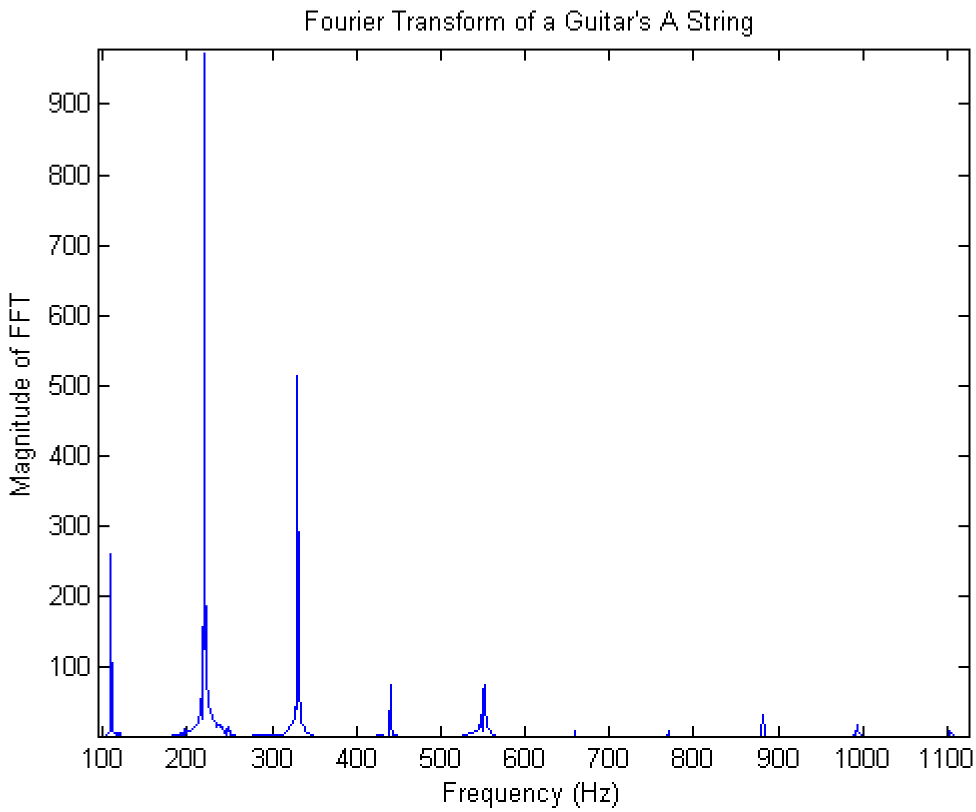

Figure 3.4: Spectrogram (Frequency Domain) plot of the sound file corresponding to plucking of the guitar A string.

The spectrogram shows us how the signal can be broken down into an infinite sum of waves with different frequencies. As Figure 4 shows, the most dominant frequency occurs at about 220Hz. This corresponds to the second harmonic of the signal. The fundamental frequency being 110Hz, which is correct, since the 'A' string of the guitar should be tuned to 110Hz. Apparently the guitar was in tune when the recording was made. Furthermore, you will also notice other dominant waves with frequencies of about 330Hz and 440Hz. Of the musicians out there reading this, this makes sense since 330Hz corresponds to an 'E' which would be the fifth of the 'A' and the third harmonic to the 'A' at 110Hz. But the take away message from these figures is that there are two ways of seeing the same phenomenon of the recorded sound file. One is to simply plot the resulting signal versus time. Another is to view the same signal and its spectrogram, or rather, what frequency components make up the sound file.

3.2 Plucking the 'E' String of a Guitar

This is an unsupported media type. To view, please see http://cnx.org/content/m13514/latest/note_e_animation.swf

Figure 3.5: Flash animation of the following figures

Similar to plucking the guitar's 'A' string, here we provide the same graphs but for the sound file in Figure 5.

Plot of the sound signal versus time

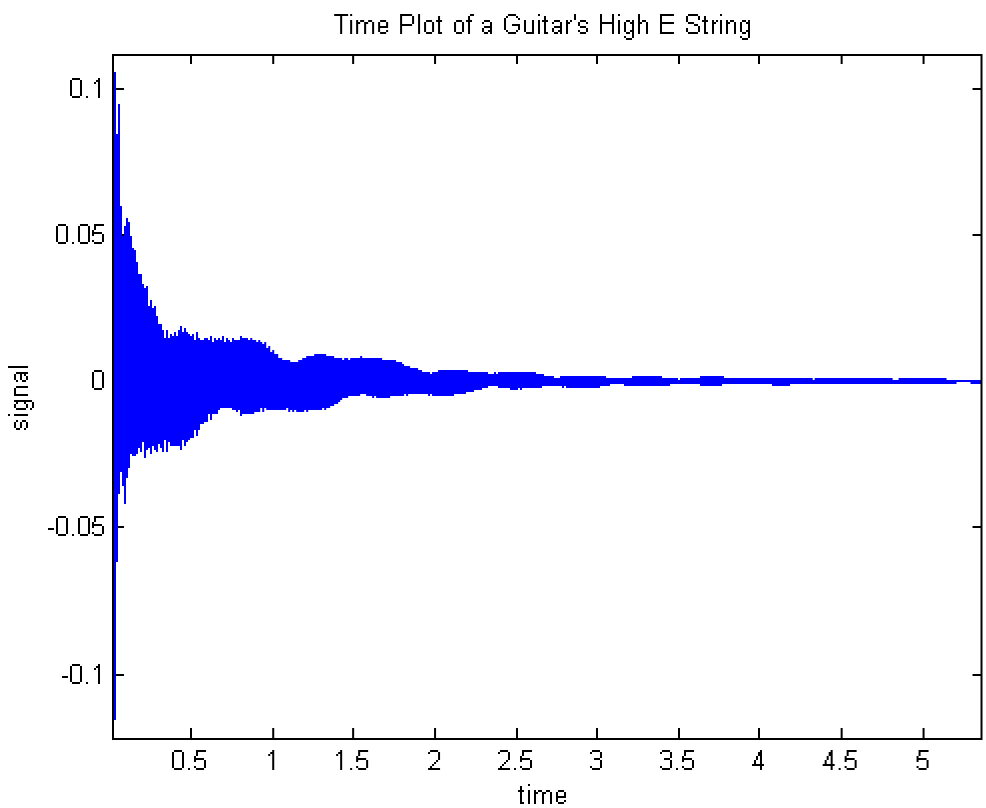

Figure 3.6: The plot of the guitar plucked at the 'E' string over time.

Zoomed in graph of the signal versus time

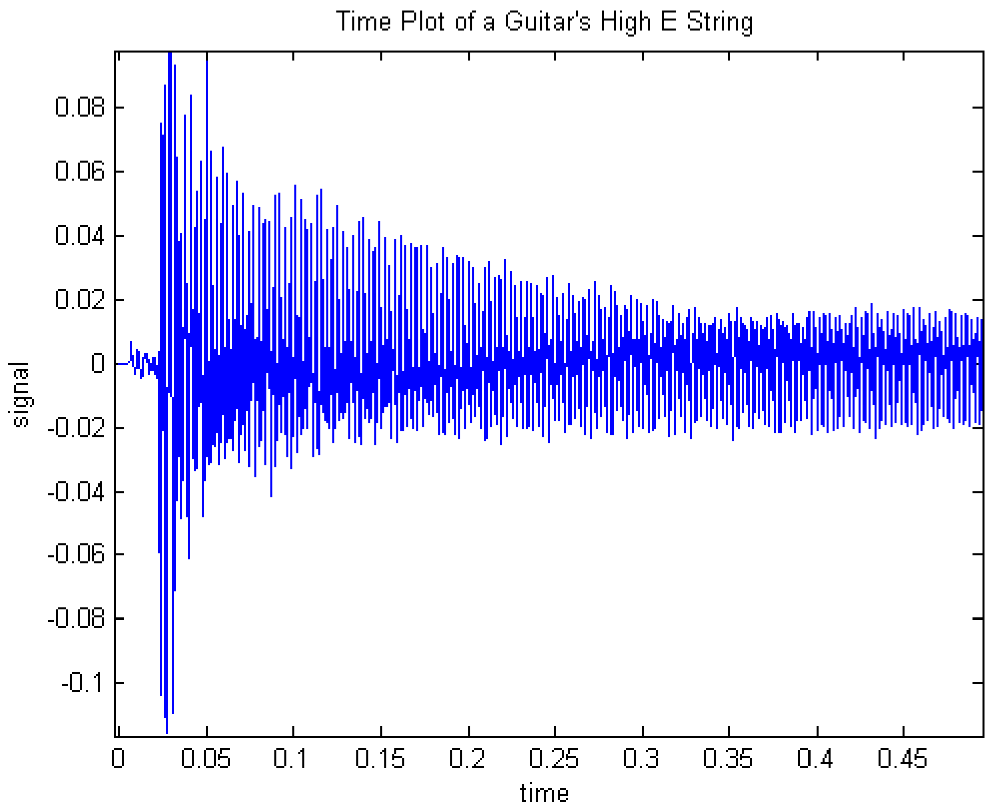

Figure 3.7: The zoomed-in plot of the guitar plucked at the 'E' string over time.

Let's point out some differences between Figures 2 and 6. Notice that in Figure 2, the signal decays to 0 a couple of seconds after the signal in Figure 6. Also notice that in Figure 7, the spacing between the oscillations of the signal is smaller than those in Figure 3.

Also, again notice that in Figure 7, the zoomed-in graph of the signal versus time, there are recurring patterns in the signal. See if you can convince yourself that the signal can be described as the sum of waves with differing frequencies.

Spectrogram of Figure 5's sound file

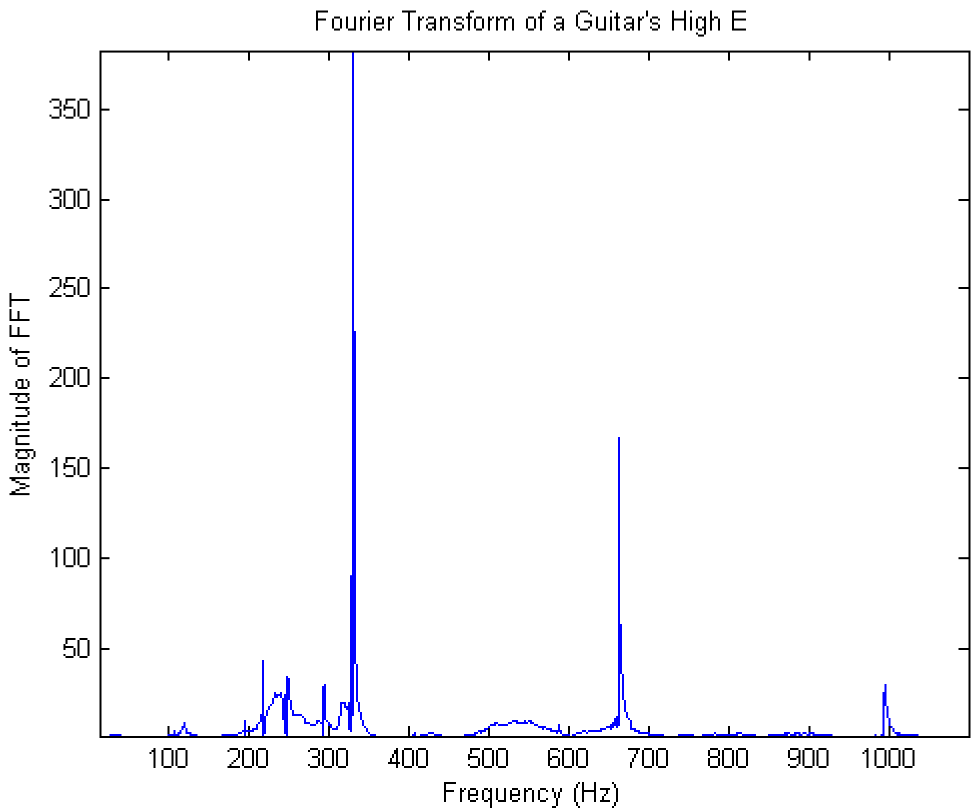

Figure 3.8: Spectrogram (Frequency Domain) plot of the sound file corresponding to plucking of the guitar's high E string.

Figure 8 shows the spectrogram of the sound file in Figure 5. The dominant peak occurs at 330Hz, which from our previous discussion is not surprising. The high 'E' string of a guitar should be tuned to 330Hz.

However, there are some differences to note between Figures 4 and 8. The spectrogram in Figure 8 has less prominent peaks. Between 200 and 300Hz, there seems to be a lump of frequencies that our sound wave has. One of the reasons the spectrum is not as "clean" as the one in Figure 4, is because the high E string causes the lower strings on the guitar to vibrate. Thus one sees lumps in the spectrogram below the fundamental frequency of 330Hz as well as the harmonics of the frequencies of the lower strings.

3.3 Extra Readings

For more information on the algorithm/procedure that takes you to/from the frequency domain, Derivation of the Fourier Transform [3] and The Fast Fourier Transform (FFT) [4] are good mathematical sources.

[3]"Derivation of the Fourier Transform" <http://cnx.org/content/m0046/latest/>
[4]"The Fast Fourier Transform (FFT)" <http://cnx.org/content/m10783/latest/>

Index of Keywords and Terms

Keywords are listed by the section with that keyword (page numbers are in parentheses). Keywords do not necessarily appear in the text of the page. They are merely associated with that section. *Ex.* apples, § 1.1 (1) **Terms** are referenced by the page they appear on. *Ex.* apples, 1

Attributions

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Music, Waves, Physics
This course teaches students in high school in advanced physics courses the concept of waves as seen in sound. A solid understanding of calculus is a prerequisite.