Frequency and Music

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C O N N E X I O N S

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Chapter 1

Acoustics for Music Theory[1]

1.1 Music is Organized Sound Waves

Music is sound that's organized by people on purpose, to dance to, to tell a story, to make other people feel a certain way, or just to sound pretty or be entertaining. Music is organized on many different levels. Sounds can be arranged into melodies[2], harmonies[3], rhythms[4], textures[5] and phrases[6]. Beats[7], measures[8], cadences[9], and form[10] all help to keep the music organized and understandable. But the most basic way that music is organized is by arranging the actual sound waves themselves so that the sounds are interesting and pleasant and go well together.

A rhythmic, organized set of thuds and crashes is perfectly good music - think of your favorite drum solo - but many musical instruments are designed specifically to produce the regular, evenly spaced sound waves that we hear as particular pitches[11]. Crashes, thuds, and bangs are loud, short jumbles of lots of different wavelengths. These are the kinds of sound we often call "noise", when they're random and disorganized, but as soon as they are organized in time (rhythm[12]), they begin to sound like music. (When used as a scientific term, **noise** refers to **continuous** sounds that are random mixtures of different wavelengths, not shorter crashes and thuds.)

However, to get the melodic kind of sounds more often associated with music, the sound waves must themselves be organized and regular, not random mixtures. Most of the sounds we hear are brought to our ears through the air. A movement of an object causes a disturbance of the normal motion of the air molecules near the object. Those molecules in turn disturb other nearby molecules out of their normal patterns of random motion, so that the disturbance itself becomes a thing that moves through the air - a sound wave. If the movement of the object is a fast, regular vibration, then the sound waves are also very regular. We hear such regular sound waves as **tones**, sounds with a particular pitch[13]. It is this kind of sound that we most often associate with music, and that many musical instruments are designed to make.

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[1] This content is available online at <http://cnx.org/content/m13246/1.13/>.
[2] "Melody" <http://cnx.org/content/m11647/latest/>
[3] "Harmony" <http://cnx.org/content/m11654/latest/>
[4] "Rhythm" <http://cnx.org/content/m11646/latest/>
[5] "The Textures of Music" <http://cnx.org/content/m11645/latest/>
[6] "Melody": Section Melodic Phrases <http://cnx.org/content/m11647/latest/#s2>
[7] "Time Signature": Section Beats and Measures <http://cnx.org/content/m10956/latest/#s1>
[8] "The Staff": Section The Staff <http://cnx.org/content/m10880/latest/#s1>
[9] "Cadence in Music" <http://cnx.org/content/m12402/latest/>
[10] "Form in Music" <http://cnx.org/content/m10842/latest/>
[11] "Pitch: Sharp, Flat, and Natural Notes" <http://cnx.org/content/m10943/latest/>
[12] "Rhythm" <http://cnx.org/content/m11646/latest/>
[13] "Pitch: Sharp, Flat, and Natural Notes" <http://cnx.org/content/m10943/latest/>

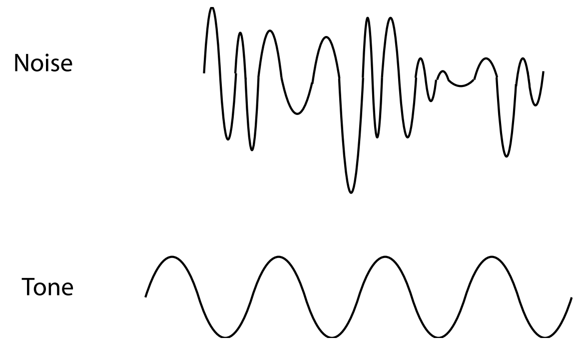

Figure 1.1: A random jumble of sound waves is heard as a noise. A regular, evenly-spaced sound wave is heard as a tone.

Musicians have terms that they use to describe tones. (Musicians also have other meanings for the word "tone", but this course will stick to the "a sound with pitch" meaning.) This kind of (regular, evenly spaced) wave is useful for things other than music, however, so scientists and engineers also have terms that describe pitched sound waves. As we talk about where music theory comes from, it will 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 those evenly-spaced waves are, the higher the note sounds. Musicians talk about the pitch[14] of the sound, or name specific notes[15], or talk about tuning (Chapter 5). Scientists and engineers, on the other hand, talk about the frequency (p. 5) and the wavelength (p. 5) of the sound. They are all essentially talking about the same things, but talking about them in slightly different ways, and using the scientific ideas of wavelength and frequency can help clarify some of the main ideas underlying music theory.

1.2 Longitudinal and Transverse Waves

So what are we talking about when we speak of sound waves? Waves are disturbances; they are changes in something - the surface of the ocean, the air, electromagnetic fields. Normally, these changes are travelling (except for standing waves (Chapter 2)); the disturbance is moving away from whatever created it, in a kind of domino effect.

Most kinds of waves are **transverse** waves. In a transverse wave, as the wave is moving in one direction, it is creating a disturbance in a different direction. The most familiar example of this is waves on the surface of water. As the wave travels in one direction - say south - it is creating an up-and-down (not north-and-south) motion on the water's surface. This kind of wave is fairly easy to draw; a line going from left-to-right has up-and-down wiggles. (See Figure 1.2 (Transverse and Longitudinal Waves).)

[14]"Pitch: Sharp, Flat, and Natural Notes" <http://cnx.org/content/m10943/latest/>
[15]"Clef" <http://cnx.org/content/m10941/latest/>

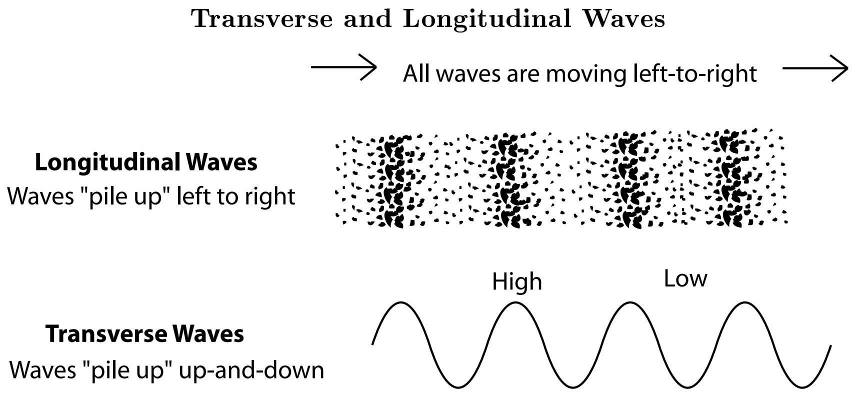

Figure 1.2: In water waves and other **transverse waves**, the ups and downs are in a different direction from the forward movement of the wave. The "highs and lows" of sound waves and other **longitudinal waves** are arranged in the "forward" direction.

But sound waves are not transverse. Sound waves are **longitudinal waves**. If sound waves are moving south, the disturbance that they are creating is giving the air molecules extra north-and-south (not east-and-west, or up-and-down) motion. If the disturbance is from a regular vibration, the result is that the molecules end up squeezed together into evenly-spaced waves. This is very difficult to show clearly in a diagram, so **most diagrams, even diagrams of sound waves, show transverse waves**.

Longitudinal waves may also be a little difficult to imagine, because there aren't any examples that we can see in everyday life (unless you like to play with toy slinkies). A mathematical description might be that in longitudinal waves, the waves (the disturbances) are along the same axis as the direction of motion of the wave; transverse waves are at right angles to the direction of motion of the wave. If this doesn't help, try imagining yourself as one of the particles that the wave is disturbing (a water drop on the surface of the ocean, or an air molecule). As it comes from behind you, a transverse waves lifts you up and then drops down; a longitudinal wave coming from behind pushes you forward and pulls you back. You can view here animations of longitudinal and transverse waves[16], single particles being disturbed by a transverse wave or by a longitudinal wave[17], and particles being disturbed by transverse and longitudinal waves[18].

The result of these "forward and backward" waves is that the "high point" of a sound wave is where the air molecules are bunched together, and the "low point" is where there are fewer air molecules. In a pitched sound, these areas of bunched molecules are very evenly spaced. In fact, they are so even, that there are some very useful things we can measure and say about them. **In order to clearly show you what they are, most of the diagrams in this course will show sound waves as if they are transverse waves**.

1.3 Wave Amplitude and Loudness

Both transverse and longitudinal waves cause a **displacement** of something: air molecules, for example, or the surface of the ocean. The amount of displacement at any particular spot changes as the wave passes. If there is no wave, or if the spot is in the same state it would be in if there was no wave, there is no displacement. Displacement is biggest (furthest from "normal") at the highest and lowest points of the

[16]See the file at <http://cnx.org/content/m13246/latest/Waves.swf>
[17]See the file at <http://cnx.org/content/m13246/latest/Pulses.swf>
[18]See the file at <http://cnx.org/content/m13246/latest/Translong.swf>

wave. In a sound wave, then, there is no displacement wherever the air molecules are at a normal density. The most displacement occurs wherever the molecules are the most crowded or least crowded.

Displacement

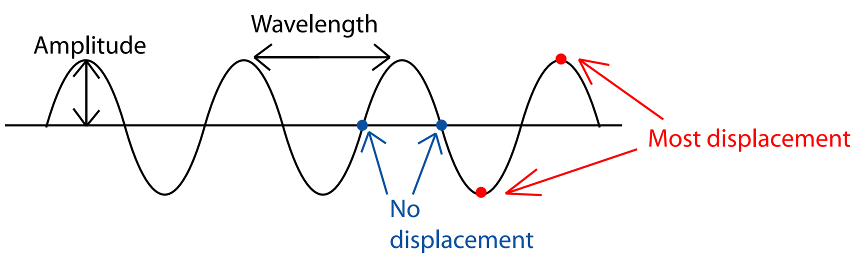

Figure 1.3

The **amplitude** of the wave is a measure of the displacement: how big is the change from no displacement to the peak of a wave? Are the waves on the lake two inches high or two feet? Are the air molecules bunched very tightly together, with very empty spaces between the waves, or are they barely more organized than they would be in their normal course of bouncing off of each other? Scientists measure the amplitude of sound waves in **decibels**. Leaves rustling in the wind are about 10 decibels; a jet engine is about 120 decibels.

Musicians call the loudness of a note its **dynamic level**. **Forte** (pronounced "FOR-tay") is a loud dynamic level; **piano** is soft. Dynamic levels don't correspond to a measured decibel level. An orchestra playing "fortissimo" (which basically means "even louder than forte") is going to be quite a bit louder than a string quartet playing "fortissimo". (See Dynamics[19] for more of the terms that musicians use to talk about loudness.) Dynamics are more of a performance issue than a music theory issue, so amplitude doesn't need much discussion here.

Amplitude is Loudness

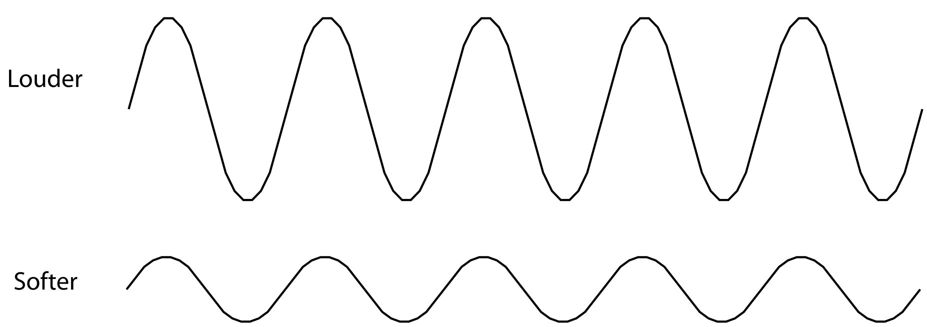

Figure 1.4: The size of a wave (how much it is "piled up" at the high points) is its **amplitude**. For sound waves, the bigger the amplitude, the louder the sound.

[19]"Dynamics and Accents in Music" <http://cnx.org/content/m11649/latest/>

1.4 Wavelength, Frequency, and Pitch

The aspect of evenly-spaced sound waves that really affects music theory is the spacing between the waves, the distance between, for example, one high point and the next high point. This is the **wavelength**, and it affects the pitch[20] of the sound; the closer together the waves are, the higher the tone sounds.

All sound waves are travelling at about the same speed - the speed of sound. So waves with a shorter wavelength arrive (at your ear, for example) more often (frequently) than longer waves. This aspect of a sound - how often a peak of a wave goes by, is called **frequency** by scientists and engineers. They measure it in **hertz**, which is how many peaks go by per second. People can hear sounds that range from about 20 to about 17,000 hertz.

Wavelength, Frequency, and Pitch

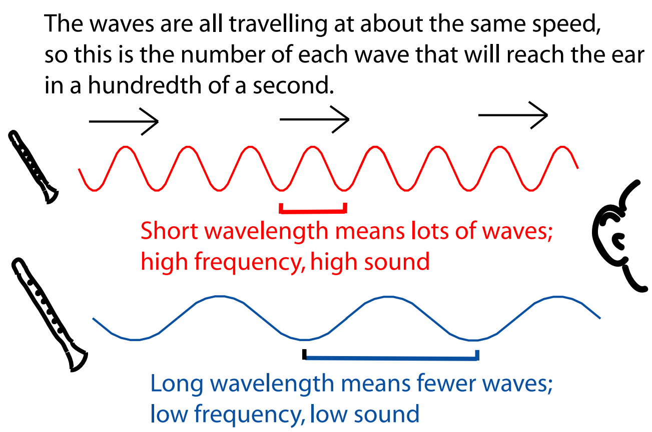

Figure 1.5: Since the sounds are travelling at about the same speed, the one with the shorter wavelength "waves" more frequently; it has a higher frequency, or pitch. In other words, it sounds higher.

The word that musicians use for frequency is **pitch**. The shorter the wavelength, the higher the frequency, and the higher the pitch, of the sound. In other words, short waves sound high; long waves sound low. Instead of measuring frequencies, musicians name the pitches[21] that they use most often. They might call a note "middle C" or "second line G" or "the F sharp in the bass clef". (See Octaves and Diatonic Music (Chapter 4) and Tuning Systems (Chapter 5) for more on naming specific frequencies.) These notes have frequencies (Have you heard of the "A 440" that is used as a tuning note?), but the actual frequency of a middle C can vary a little from one orchestra, piano, or performance, to another, so musicians usually find it more useful to talk about note names.

Most musicians cannot name the frequencies of any notes other than the tuning A (440 hertz). The human ear can easily distinguish two pitches that are only one hertz apart when it hears them both, but it is the very rare musician who can hear specifically that a note is 442 hertz rather than 440. So why should we bother talking about frequency, when musicians usually don't? As we will see, the physics of sound waves - and especially frequency - affects the most basic aspects of music, including pitch[22], tuning (Chapter 5),

[20] "Pitch: Sharp, Flat, and Natural Notes" <http://cnx.org/content/m10943/latest/>
[21] "Clef" <http://cnx.org/content/m10941/latest/>
[22] "Pitch: Sharp, Flat, and Natural Notes" <http://cnx.org/content/m10943/latest/>

consonance and dissonance[23], harmony[24], and timbre[25].

[23]"Consonance and Dissonance" <http://cnx.org/content/m11953/latest/>
[24]"Harmony" <http://cnx.org/content/m11654/latest/>
[25]"Timbre: The Color of Music" <http://cnx.org/content/m11059/latest/>

Chapter 2

Standing Waves and Musical Instruments[1]

2.1 What is a Standing Wave?

Musical tones (p. 7) are produced by musical instruments, or by the voice, which, from a physics perspective, is a very complex wind[2] instrument. So the physics of music is the physics of the kinds of sounds these instruments can make. What kinds of sounds are these? They are tones caused by standing waves produced in or on the instrument. So the properties of these standing waves, which are always produced in very specific groups, or series, have far-reaching effects on music theory.

Most sound waves, including the musical sounds that actually reach our ears, are not standing waves. Normally, when something makes a wave, the wave travels outward, gradually spreading out and losing strength, like the waves moving away from a pebble dropped into a pond.

But when the wave encounters something, it can bounce (reflection) or be bent (refraction). In fact, you can "trap" waves by making them bounce back and forth between two or more surfaces. Musical instruments take advantage of this; they produce pitches[3] by trapping sound waves.

Why are trapped waves useful for music? Any bunch of sound waves will produce some sort of noise. But to be a **tone** - a sound with a particular pitch[4] - a group of sound waves has to be very regular, all exactly the same distance apart. That's why we can talk about the frequency (p. 5) and wavelength (p. 5) of tones.

[1]This content is available online at <http://cnx.org/content/m12413/1.15/>.
[2]"Wind Instruments: Some Basics" <http://cnx.org/content/m12364/latest/>
[3]"Pitch: Sharp, Flat, and Natural Notes" <http://cnx.org/content/m10943/latest/>
[4]"Pitch: Sharp, Flat, and Natural Notes" <http://cnx.org/content/m10943/latest/>

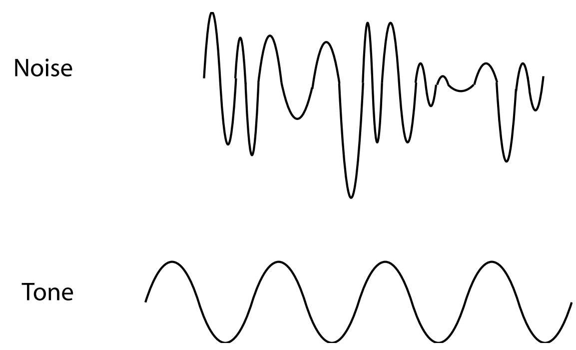

Figure 2.1: A noise is a jumble of sound waves. A tone is a very regular set of waves, all the same size and same distance apart.

So how can you produce a tone? Let's say you have a sound wave trap (for now, don't worry about what it looks like), and you keep sending more sound waves into it. Picture a lot of pebbles being dropped into a very small pool. As the waves start reflecting off the edges of the pond, they interfere with the new waves, making a jumble of waves that partly cancel each other out and mostly just roils the pond - noise.

But what if you could arrange the waves so that reflecting waves, instead of cancelling out the new waves, would reinforce them? The high parts of the reflected waves would meet the high parts of the oncoming waves and make them even higher. The low parts of the reflected waves would meet the low parts of the oncoming waves and make them even lower. Instead of a roiled mess of waves cancelling each other out, you would have a pond of perfectly ordered waves, with high points and low points appearing regularly at the same spots again and again. To help you imagine this, here are animations of a single wave reflecting back and forth[5] and standing waves[6].

This sort of orderliness is actually hard to get from water waves, but relatively easy to get in sound waves, so that several completely different types of sound wave "containers" have been developed into musical instruments. The two most common - strings and hollow tubes - will be discussed below, but first let's finish discussing what makes a good standing wave container, and how this affects music theory.

In order to get the necessary constant reinforcement, the container has to be the perfect size (length) for a certain wavelength, so that waves bouncing back or being produced at each end reinforce each other, instead of interfering with each other and cancelling each other out. And it really helps to keep the container very narrow, so that you don't have to worry about waves bouncing off the sides and complicating things. So you have a bunch of regularly-spaced waves that are trapped, bouncing back and forth in a container that fits their wavelength perfectly. If you could watch these waves, it would not even look as if they are traveling back and forth. Instead, waves would seem to be appearing and disappearing regularly at exactly the same spots, so these trapped waves are called **standing waves**.

> NOTE: Although standing waves are harder to get in water, the phenomenon does apparently happen very rarely in lakes, resulting in freak disasters. You can sometimes get the same effect by pushing a tub of water back and forth, but this is a messy experiment; you'll know you are getting a standing wave when the water suddenly starts sloshing much higher - right out of the tub!

For any narrow "container" of a particular length, there are plenty of possible standing waves that don't fit. But there are also many standing waves that do fit. The longest wave that fits it is called the **fundamental**. It is also called the **first harmonic**. The next longest wave that fits is the **second**

[5]See the file at <http://cnx.org/content/m12413/latest/ReflectingWave.swf>
[6]See the file at <http://cnx.org/content/m12413/latest/WaterWaves.swf>

harmonic, or the **first overtone**. The next longest wave is the **third harmonic**, or **second overtone**, and so on.

Standing Wave Harmonics

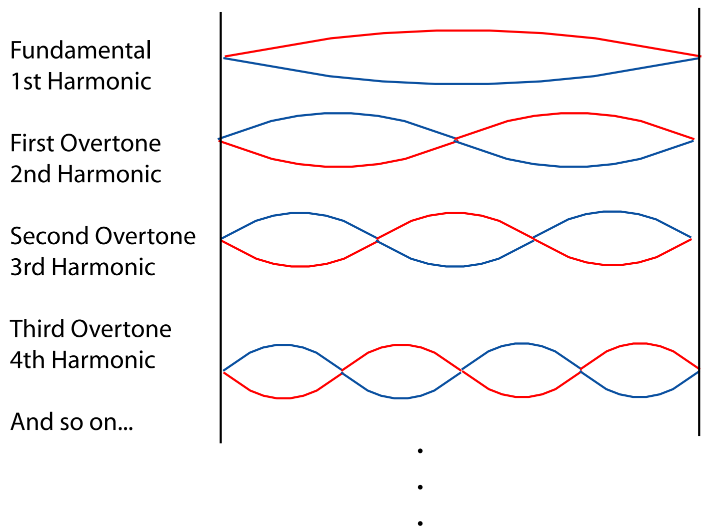

Figure 2.2: There is a whole set of standing waves, called **harmonics**, that will fit into any "container" of a specific length. This set of waves is called a **harmonic series**.

Notice that it doesn't matter what the length of the fundamental is; the waves in the second harmonic must be half the length of the first harmonic; that's the only way they'll both "fit". The waves of the third harmonic must be a third the length of the first harmonic, and so on. This has a direct effect on the frequency and pitch of harmonics, and so it affects the basics of music tremendously. To find out more about these subjects, please see Frequency, Wavelength, and Pitch[7], Harmonic Series (Chapter 3), or Musical Intervals, Frequency, and Ratio[8].

2.2 Standing Waves on Strings

You may have noticed an interesting thing in the animation (p. 8) of standing waves: there are spots where the "water" goes up and down a great deal, and other spots where the "water level" doesn't seem to move at all. All standing waves have places, called **nodes**, where there is no wave motion, and **antinodes**, where the wave is largest. It is the placement of the nodes that determines which wavelengths "fit" into a musical instrument "container".

[7]"Frequency, Wavelength, and Pitch" <http://cnx.org/content/m11060/latest/>
[8]"Musical Intervals, Frequency, and Ratio" <http://cnx.org/content/m11808/latest/>

Nodes and Antinodes

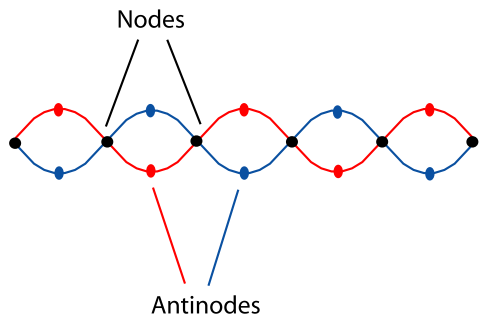

Figure 2.3: As a standing wave waves back and forth (from the red to the blue position), there are some spots called **nodes** that do not move at all; basically there is no change, no waving up-and-down (or back-and-forth), at these spots. The spots at the biggest part of the wave - where there is the most change during each wave - are called **antinodes**.

One "container" that works very well to produce standing waves is a thin, very taut string that is held tightly in place at both ends. Since the string is taut, it vibrates quickly, producing sound waves, if you pluck it, or rub it with a bow. Since it is held tightly at both ends, that means there has to be a node (p. 9) at each end of the string. Instruments that produce sound using strings are called chordophones[9], or simply strings[10].

[9]"Classifying Musical Instruments": Section Chordophones <http://cnx.org/content/m11896/latest/#s21>
[10]"Orchestral Instruments": Section Strings <http://cnx.org/content/m11897/latest/#s11>

Standing Waves on a String

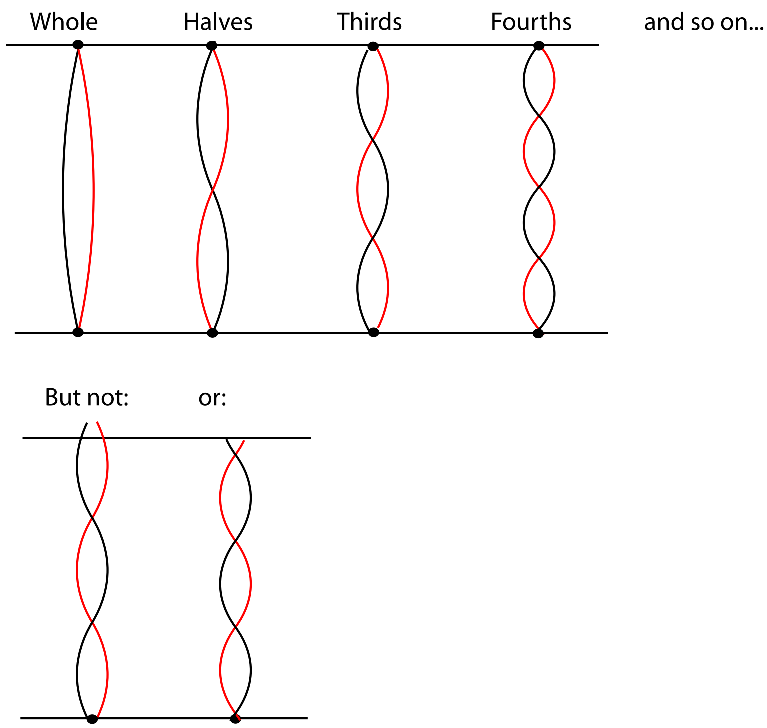

Figure 2.4: A string that's held very tightly at both ends can only vibrate at very particular wavelengths. The whole string can vibrate back and forth. It can vibrate in halves, with a node at the middle of the string as well as each end, or in thirds, fourths, and so on. But any wavelength that doesn't have a node at each end of the string, can't make a standing wave on the string. To get any of those other wavelengths, you need to change the length of the vibrating string. That is what happens when the player holds the string down with a finger, changing the vibrating length of the string and changing where the nodes are.

The fundamental (p. 8) wave is the one that gives a string its pitch[11]. But the string is making all those other possible vibrations, too, all at the same time, so that the actual vibration of the string is pretty complex. The other vibrations (the ones that basically divide the string into halves, thirds and so on) produce a whole series of **harmonics**. We don't hear the harmonics as separate notes, but we do hear them. They are what gives the string its rich, musical, string-like sound - its timbre[12]. (The sound of a single frequency alone is a much more mechanical, uninteresting, and unmusical sound.) To find out more about harmonics and how they affect a musical sound, see Harmonic Series (Chapter 3).

Exercise 2.1 ***(Solution on p. 16.)***

When the string player puts a finger down tightly on the string,

1. How has the part of the string that vibrates changed?
2. How does this change the sound waves that the string makes?

[11]"Pitch: Sharp, Flat, and Natural Notes" <http://cnx.org/content/m10943/latest/>
[12]"Timbre: The Color of Music" <http://cnx.org/content/m11059/latest/>