Y. Strings and Percussion

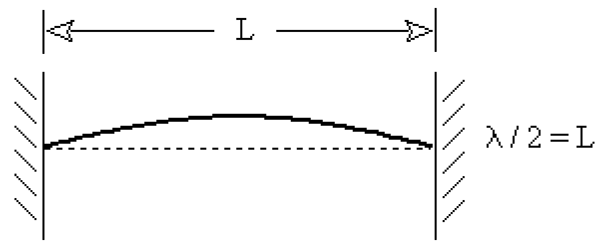
We now come to the application of strings in musical instruments. We begin with the violin family, the string section of the orchestra. Then we consider the guitar. The fundamental string physics we studied earlier applies to these. With the piano, strings get complicated. There is far more tension in the strings. The strings are stiffer, to some extent like a rod. Also, there are string wrappings about other strings for the lower tones. These features make the piano somewhat more complicated. Finally, we will briefly discuss drums and cymbals.

The Violin Family

The violin family brings us to the last major section of the orchestra. The first two, woodwinds and brass, deal with pipe physics. The violin and its cousins employ strings. In fact, the section of the orchestra with these instruments is called the string section or simply strings. Strings are employed the most by composers overall. The audience never seems to get tired of the nice blend of harmony strings offer. The woodwinds come second in use and the powerful brass last. The string family consists of the violin, viola, cello, and bass (also called the contrabass). Each member of the string family has 4 strings. We will consider the orchestral stringed instruments together.

1. Violin Family: The Physics. The vibrating string supplies the basic physics of the violin family. The fundamental has a wavelength equal to twice the length of the string. One half-wave fits between the fixed ends for the first mode of vibration (see Fig. Y-1). The string has the same overtone series as the open pipe.

Fig. Y-1. Vibrating String.

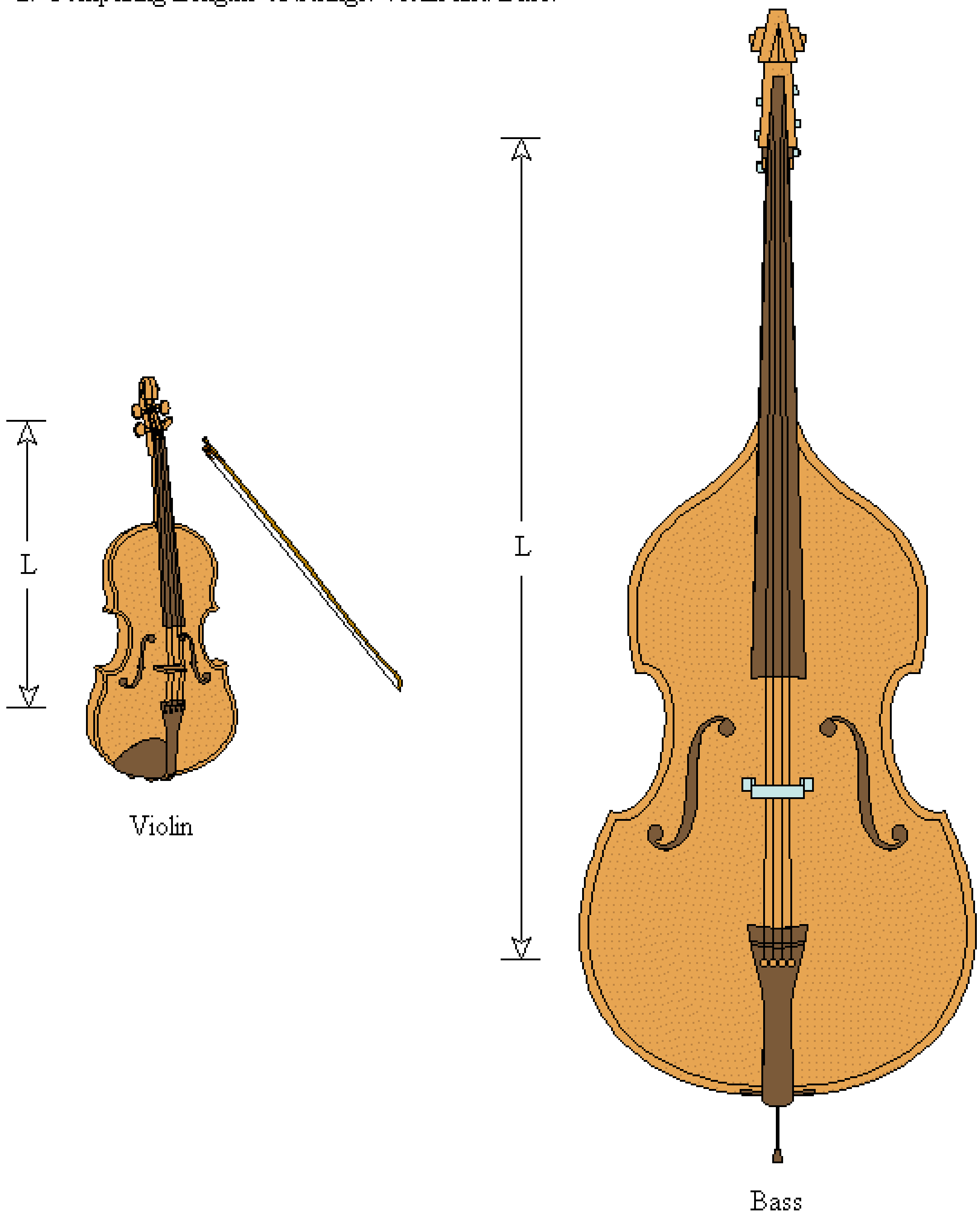


The violin is usually played by drawing a bow across the string. This supplies the energy for the string to resonate. The interaction between bow and string generates predominantly the fundamental. However, a rich amount of overtones is also produced. The violin cavity and wood enable us to hear the sound easily. They also enhance the overtones that fall into formant regions.

The overtones enrich the sound. Overtones are not used the way they are in woodwinds and brass instruments. There, one uses specific resonances of the higher harmonics. Playing the woodwinds at the fundamental mode is referred to as playing in the first register. Then, playing at the second harmonic by either cross fingering or using a register hole is called playing in the second register. You can carefully hold the center of a violin string gently and pluck it with your free hand. You will excite the second harmonic. But this is not done in practice. Instead, the violin has four separate strings to reach higher registers of pitch.

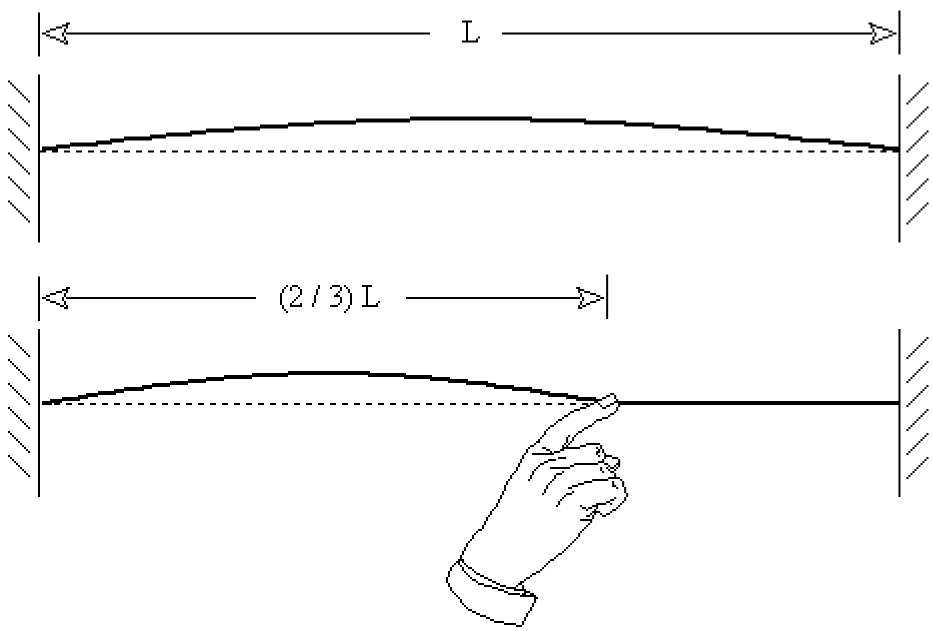
Fig. Y-2 illustrates the practical version of Fig. Y-1. The length of the string on the violin is compared to the length of a string on the bass (contrabass). The long string of the bass produces the low pitch we expect from a bass. This follows from Mersenne's First Law.

Fig. Y-2. Comparing Lengths of Strings: Violin and Bass.



2. The Violin Family: Producing the Tones in the Scale. Different pitches are obtained on a violin by placing a finger along the string. This shortens the section of the string undergoing the vibration. See Fig. Y-3 for an example where the string is shortened to two-thirds its original length. The new fundamental has a shorter wavelength. The wavelength is scaled down to two-thirds of the original value. The violinist can move up the string in this way to produce the half steps of the chromatic scale.

Fig. Y-3. Using a Finger to Obtain a "Shorter String Length."



The ratio of 2:3 for the wavelengths in Fig. Y-2 corresponds to the interval of a fifth. Recall that whenever you shorten the wavelength, the frequency increases. The frequency ratio is 3:2. The numbers are reversed for the frequency. Pythagoras measured such string-length ratios for the consonant intervals (see Table Y-1).

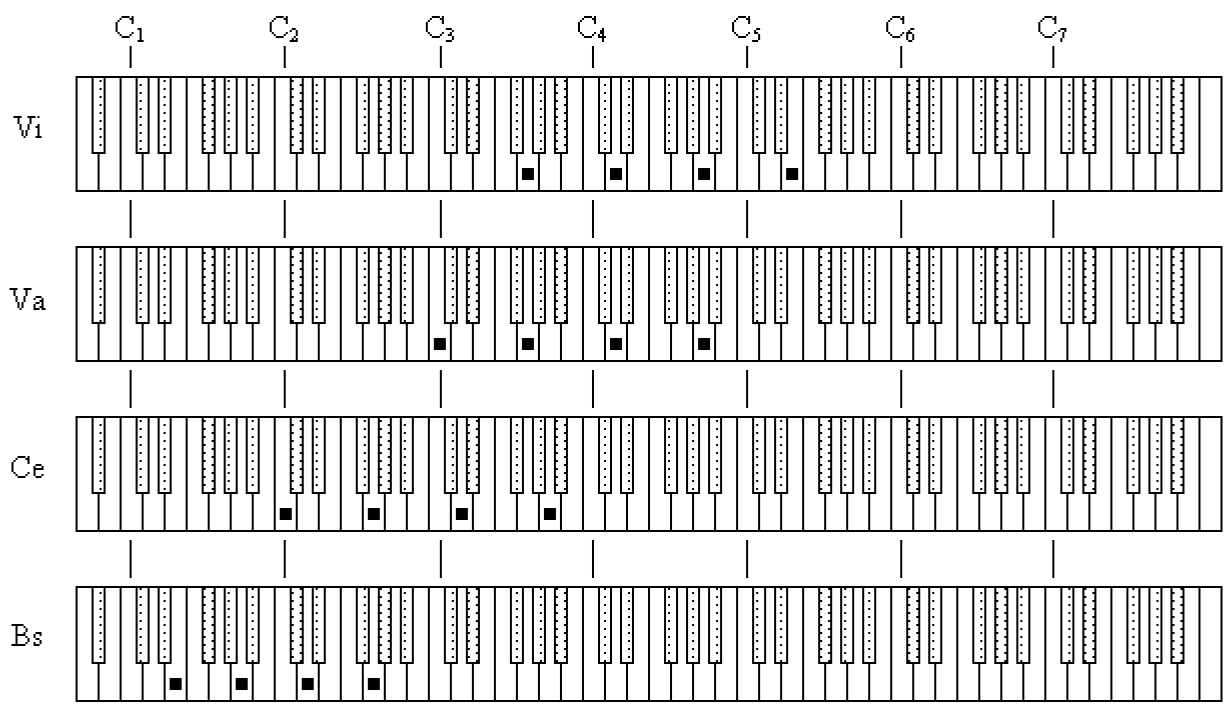
Table Y-1. Ratios of Frequencies, Wavelengths, and String Lengths for Common Intervals.

		Ratios		
Tones	Interval	Frequency	Wavelength	String Length
Do-Do	Unison	1:1	1:1	1:1
Do-Do'	Octave	2:1	1:2	1:2
Do-Sol	Fifth	3:2	2:3	2:3
Do-Fa	Fourth	4:3	3:4	3:4

3. The Violin Family: Extending Musical Range. Stringed instruments have more than one string to extend the range. See Fig. Y-4 for the four strings found on the violin (Vi), viola (Va), cello (Ce), and bass (Bs, or contrabass). The spacing interval is a fifth for the violin, viola, and cello. Three octaves are easily within reach this way.

The frequencies get lower overall as the instruments go from violin to bass. The cello and bass have longer strings to produce bass notes. The strings get so long for the bass, it's too much of a stretch (of the arm) to play many different notes on one string. The smaller spacing of a fourth cuts down on the number of notes each string must be responsible for.

Fig. Y-4. The Four Strings on the Violin, Viola, Cello, and Bass.



4. The Violin Family: Synthesis. To synthesize a very approximate violin-like sound, we observe that the string is pulled by the bow due to friction, then quickly slips back, is pulled again, and slips back, etc. like a ramp wave. A ramp wave is chosen for synthesizing bowing in Fig. Y-5. A gradual attack is employed for approximating a gentle approach of the bow. An abrupt release is used to reproduce a sudden release of the bow. Of course, the violin need not be played this way. We are only choosing one of the many characteristic ways to play the violin. One serious limitation of our synthesis is the lack of enhanced overtones that occur in the violin due to the formants.

On the other hand, it is relatively easy to approximate the plucking sound of a bass (see Fig. Y-6). The plucking of the string produces a sound much closer to a sine wave than bowing. The formants aren't as important then, since the sine wave has no overtones.

Fig. Y-5. Synthesizing a Very Approximate Violin-Like Sound (Bowing).

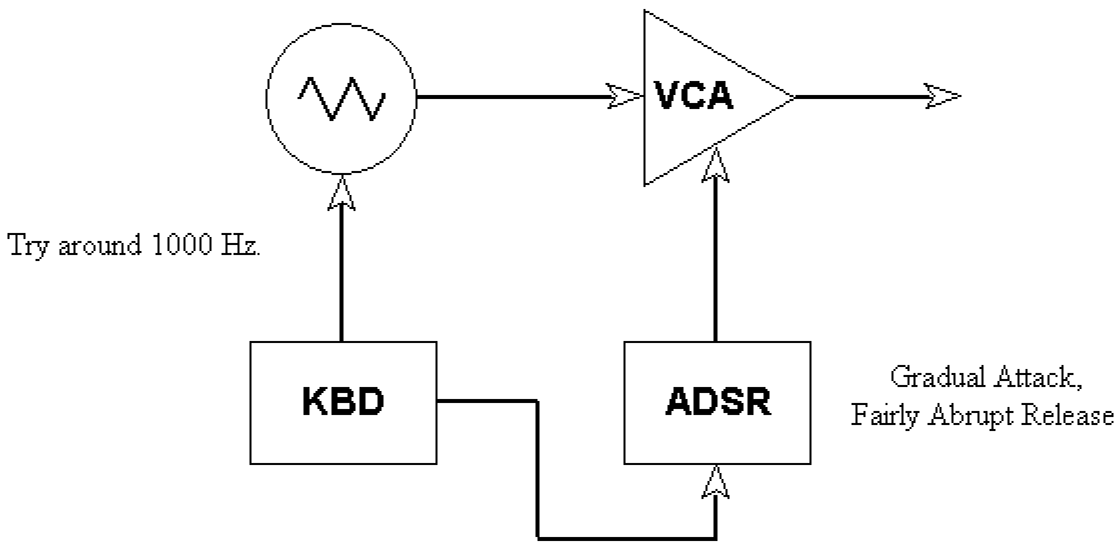
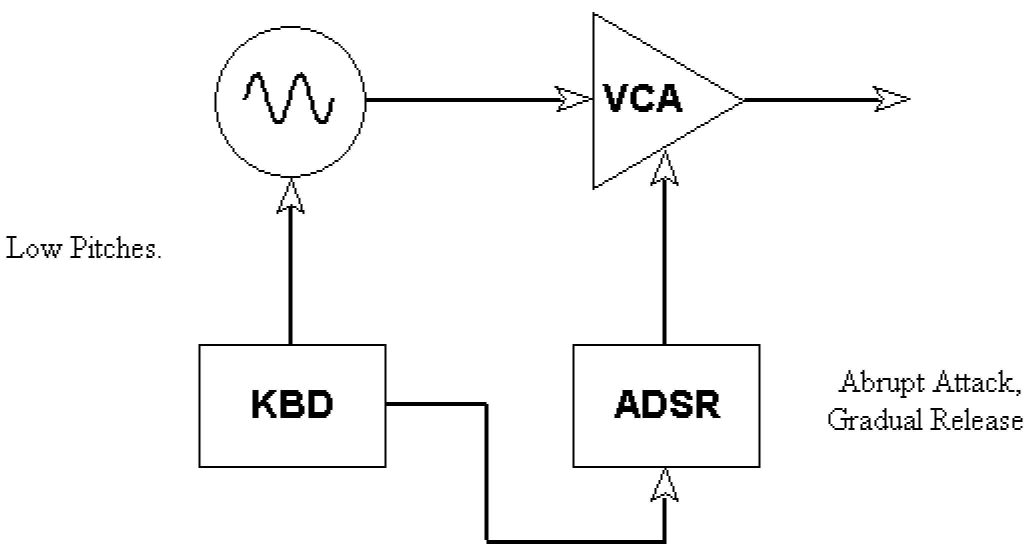


Fig. Y-6. Synthesizing a Plucking-Bass Sound.



An orchestra typically has 30 violins, divided into two sections, the first and second violins. There are approximately a dozen violas, a dozen cellos, and eight or ten cellos. The strings blend so well together due to their similar structure. They are used most of the time in musical compositions. The strings can be employed for long lengths of time because the performers do not get tired easily. Woodwind and brass players need to occasionally "catch a breath."

The String Choir

Fig. Y-7 illustrates the string choir of the orchestra. Think of this analogy with a choir of singers: violin (soprano), viola (alto), cello (tenor), and bass (bass).

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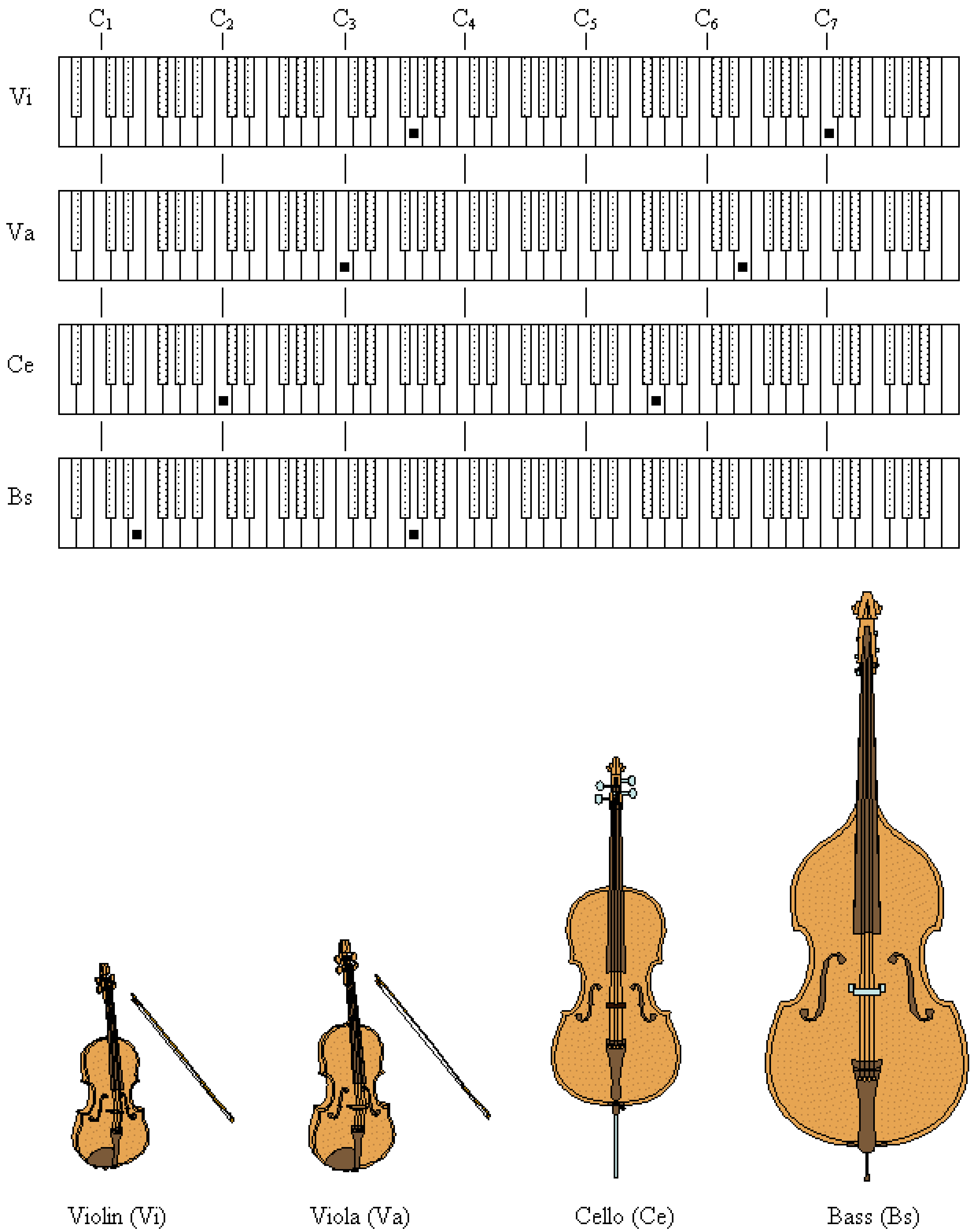
Fig. Y-7. String Ranges.



A Review

What is the harmonic number n for the wave shown in the photo? __________

b. How many half-waves are there in the above photo? __________

c. How many half-waves are there in harmonic 2? __________

d. How many half-waves are there in harmonic 1? __________

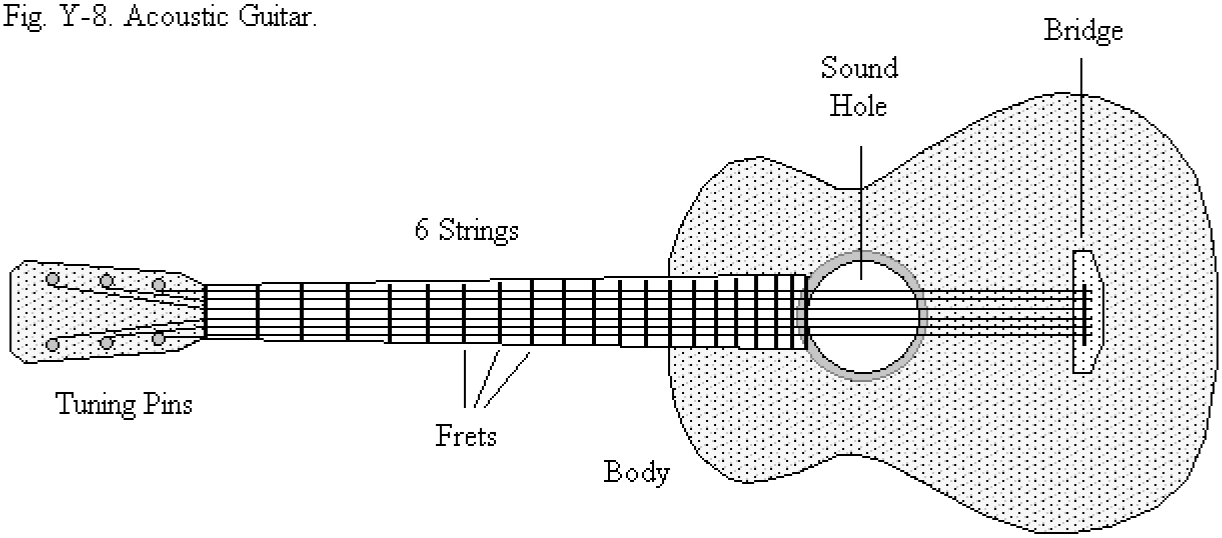
e. How many nodes are there in harmonic 8? __________

f. How many antinodes are there in harmonic 8? __________

Guitars

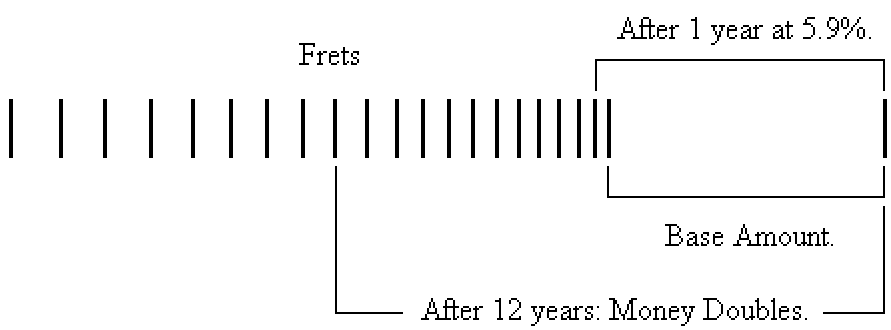
The guitar is one of the most popular instruments. It is light, portable, and offers excellent accompaniment to singers. It is used for classical, popular, folk, country, and rock music. Popularity soared in the 1950s with the fame of Elvis Presley and continued in the 1960s due to early rock groups such as the *Beatles*. The acoustic guitar is not electric. The sound is brought out by the body, cavity, and sound hole. See Fig. Y-8. The energy is supplied by plucking or strumming. The strings resonate. The vibrations are transmitted to the body by the bridge. The wood and cavity enable us to hear the sound. Their formant regions enhance some of the overtones. Tuning pins allow for control of tension. According to Mersenne's Second Law, greater tension produces higher pitch.

Fig. Y-8. Acoustic Guitar.



The guitar has frets (ridges) which enable the performer to easily find the correct positions to effectively shorten the strings for specific tones. Fig. Y-9 illustrates the spacings for the frets. Each step from fret to fret is a half step. We use our banking analogy with an investment interest of 5.9%. We start at the far right and move leftward. In this way, the far left-fret position gives the lowest frequency. This is an outcome of the inverse relation between frequency and wavelength we analyzed in the last section.

Fig. Y-9. Fret Positions and Banking Analogy.



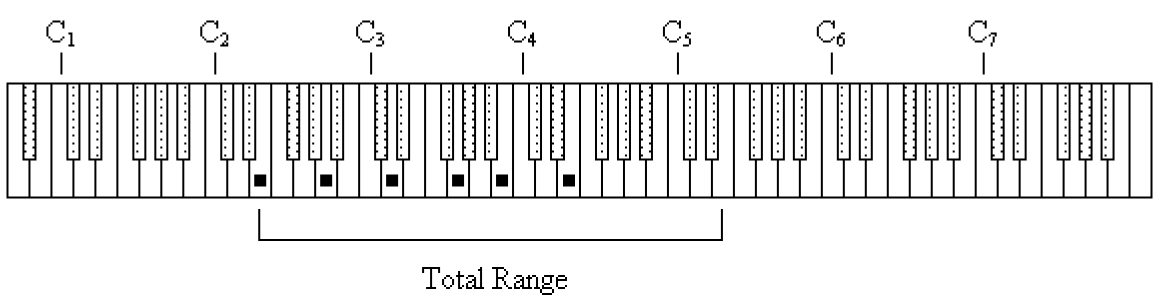
Artisans crafting stringed instruments with frets over the centuries discovered a simple guideline in spacing. They started construction at the end near the tuning pins and placed each fret at 1/18 the distance of the remaining section of string. After you construct a fret, you forget about the string to the left (using the orientation in Fig. Y-8). You measure from the last fret you finished to the bridge. Then proceed to the right 1/18 of this new distance and install the next fret. Since the remaining string distance keeps shrinking, the distances between the frets get smaller and smaller.

We can arrive at this rule from theory. Pick any fret in Fig. Y-8. The distance from the fret to the bridge represents our savings according to Fig. Y-9. By moving to the right from any fret, we reduce the length of the string, or go back in time for our investment analogy. This means we lose some interest. How do we take interest away? First, let's find out what the applied interest is as a fraction. The value 5.9% is about 1/15 or 1/16 as we approximated it earlier from the just diatonic scale. But we must be more precise now. We are no longer working with the just diatonic scale but the equal-tempered scale.

The decimal corresponding to 5.9% is 0.059, just like 50% corresponds to 0.50. The fraction 1/16 = 0.0625 is too large. The better fraction is actually 1/17 since 1/17 = 0.0588 (very close). When we proceed into the future (moving from the bridge to the tuning pins) we increase our length by 1/17 year by year. Fix your attention on any fret. The next fret to the left increases the effective string length by 1/17. The new longer string length is now 18/17 (the original 17/17 plus the extra 1/17). Now to go backwards, we need to make a cut from 18/17 to 17/17. If we start with 18/17, in order to get 17/17, we need to cut off 1/18 of the 18/17-length. We amazingly arrive at the 1/18-rule. This is a subtle use of arithmetic to arrive at a "golden rule" of guitar design.

The guitar extends its range with the help of additional strings. The 6 strings, along with the total range for the guitar, are illustrated in Fig. Y-10. There is also a 12-string guitar. Other plucked instruments include the dulcimer (American folk version has 3 or 4 strings), banjo (4 or 5 strings), lute (4 or more strings), sitar (7 or more strings), zither (30 to 40 strings), and harp (almost 50 strings). All except the harp have frets. The harp is also unique in that it is considered a standard instrument in the symphony orchestra even though it is not used in many works.

Fig. Y-10. Guitar Strings and Total Range.



We saw earlier that a sine wave can be used to synthesize the plucking of a bass. A square wave provides for a richer sound, more comparable to what we hear on a guitar or banjo. Fig. Y-11 illustrates a modular diagram to synthesize such a sound. The resulting sound is more like that of a banjo. The best results use a waveform between a square wave and a pulse train. Square waves have crests that are 50% of the total waveform. The best results are found with crests between 10% and 25%. Increasing the pulse in the range between 25% and 33% produces a harpsichord sound.

Fig. Y-11. Synthesizing the Plucking Sound of a Banjo.

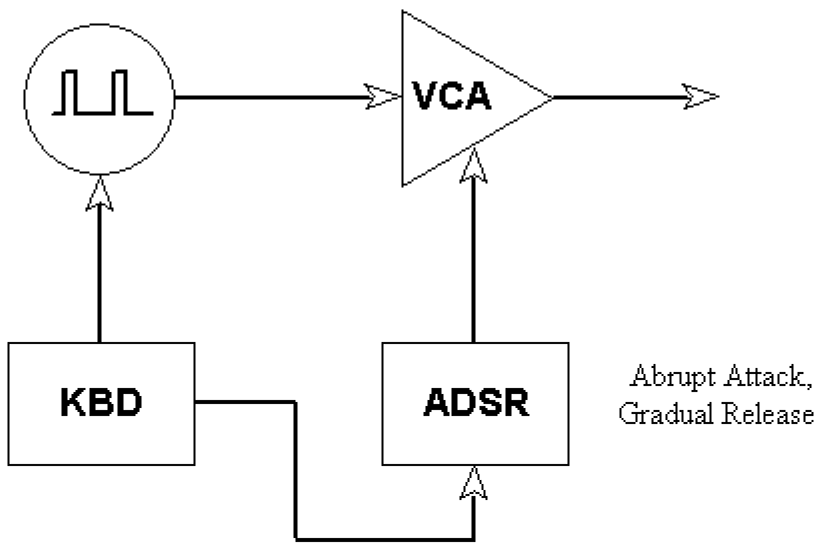
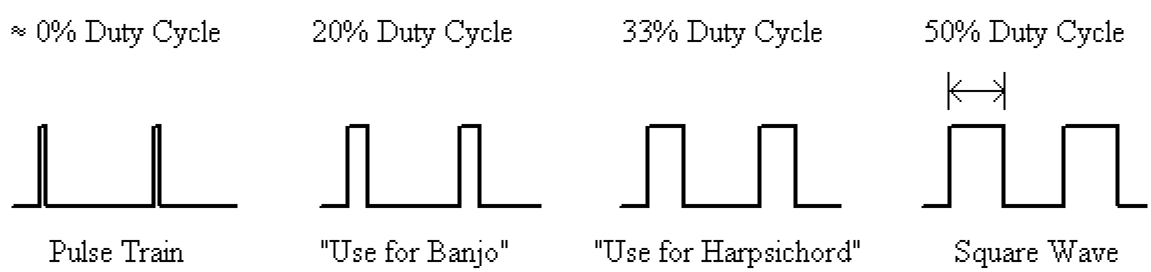


Fig. Y-12 shows some waveforms with different pulse widths. The pulse width compared to the wavelength is called the duty cycle. A square wave has a duty cycle of 50%. The pulse train has a theoretical duty cycle of 0%. The Fourier spectra for the 20% and 33% cases below are more complicated than those for the pulse train and square wave, which we have encountered earlier.

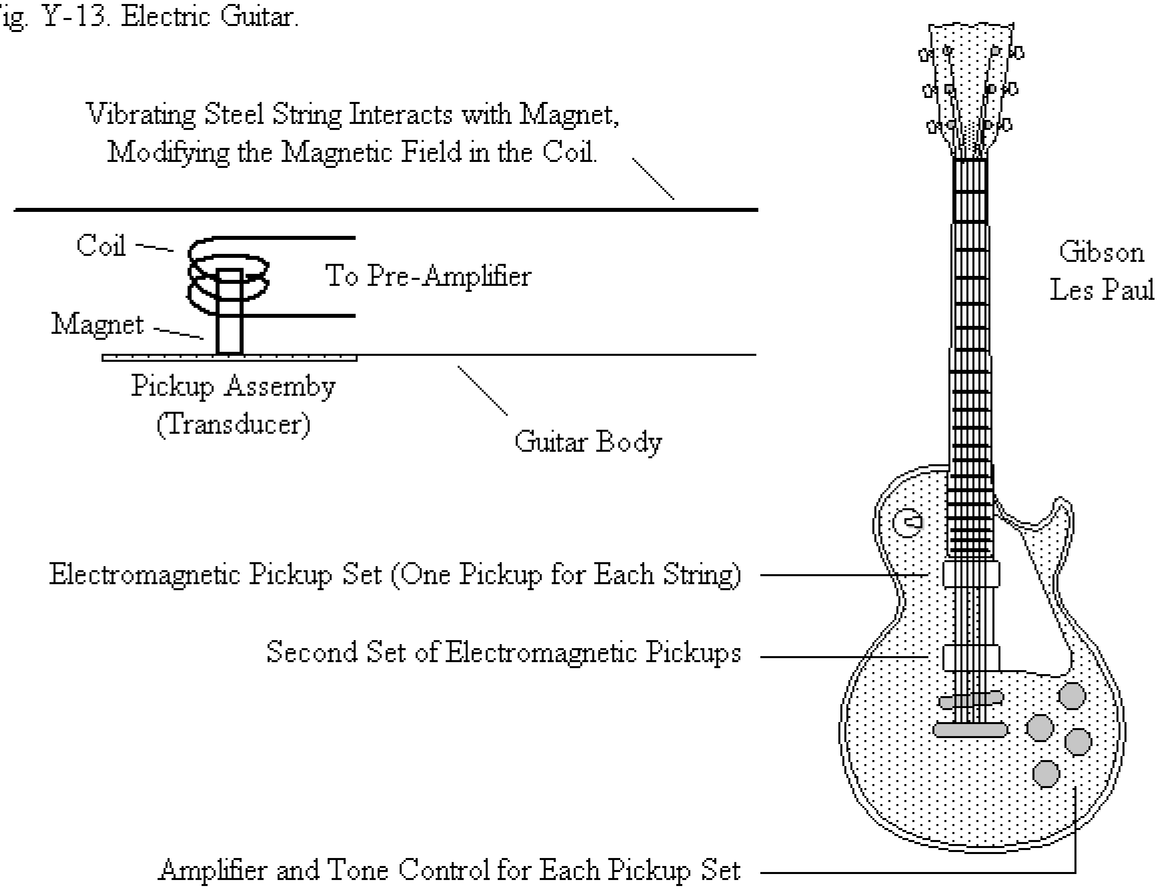
Fig. Y-12. Pulses and Duty Cycle.



The electric guitar amplifies sound by electromagnetic pickups. Fig. Y-13 illustrates the procedure. The metallic strings vibrate near coil-magnet assemblies. The string is not attached to the coil. However, the metal string influences the magnetic field inside the coil as it gets near it, due to the presence of the pickup's permanent magnet. The fluctuating magnetic fields are in step with the vibration of the string. These generate electrical currents in the coil. The electrical signal is sent to an amplifier inside the guitar. The internal amplifier is a *preamplifier*, whose output goes to the regular amplifier for driving the speakers.

There are usually two sets of pickups. Each set contains 6 pickups, one for each string (electric bass guitars have 4 strings). The upper set picks up mostly the fundamental while the lower set registers overtones better. The combination of the two signals gives the resulting sound. The acoustic body is not needed. This method is superior to attaching a coil gently to the wood surface to pick up vibrations. Such pickups are called *pressure transducers*. Pressure variations are converted into electrical signals. The wood plays the role that the diaphragm does in a microphone in such an arrangement. The electric guitar does not use such body vibrations. Therefore its outside design has evolved into something quite different from the acoustic guitar. The development of the modern electric guitar goes back to the work of musician-inventor Les Paul in the 1940s. The manufacturer *Gibson* worked with Les Paul in the 1950s to produce top-quality electric guitars.

Fig. Y-13. Electric Guitar.



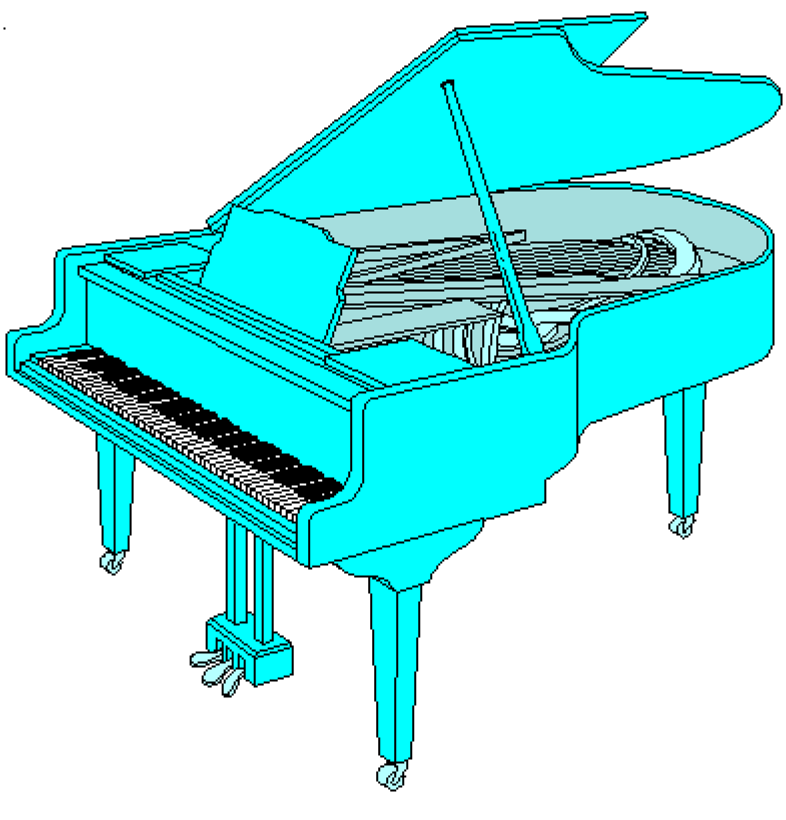
The Piano

Hammers strike the strings in a piano. The piano (see Fig. Y-14) is considered a percussion instrument. The strings are under great tension. A tuning instrument is needed to change the string tension. A lower string consists of a metal string wound on another metal piece. The lower notes have one string, middle tones have two, and the highest strings have three. The strings get shorter (Mersenne's First Law) and thinner (Mersenne's Third Law) toward the top.

The middle octave is tempered equally. Then other strings are tuned by octaves. Piano strings present some tuning challenges. Piano strings are thicker in order to withstand the greater tension. Such strings lose some flexibility and begin to behave to some extent like metal rods. The higher modes of excitation for a metal rod do not correspond to the overtone series of strings and open pipes. Therefore, the second harmonic of the piano string falls a little beyond twice the frequency of the fundamental. To avoid having the note an octave higher beat with the slightly-raised second harmonic of the lower octave, the piano tuner stretches the tuning of the higher octave. The higher octaves on the piano get tuned slightly sharper and sharper, the lower octaves flatter and flatter.

It is apparent that a tuning expect is needed. Pianists do not tune their own pianos unless they happen to be piano tuners also. The piano was invented (early 1700s) since its precursor, the harpsichord, played over a very limited range of loudness (*dynamics*). The new instrument was called the *pianoforte* (soft-loud). The research and development by *Steinway* in the 1800s contributed significantly to the modern piano of today.

Fig. Y-14. Piano.



Drums and Cymbals

Drums are vibrating membranes. The two-dimensional surface of a membrane is much more complicated than the narrow string or pipe, both of which can be considered as one dimensional. The kettledrum is illustrated in Fig. Y-15. A set of 2, 3 or 4 usually make up the timpani in an orchestra. Each is tuned to a pitch. The membrane produces the pitch. The cavity below enhances the sound. The inside is not slender like a pipe, but wide. Therefore, thin-pipe physics does not apply. In thin pipes, standing waves are set up; in wide containers, the mass of air swishes around. The result is a characteristic low-emphasis of frequencies (see Fig. Y-16). This jar-type of resonator is called a *Helmholtz resonator*, which we encountered earlier in discussing speaker design.

Fig. Y-15. Kettledrum.

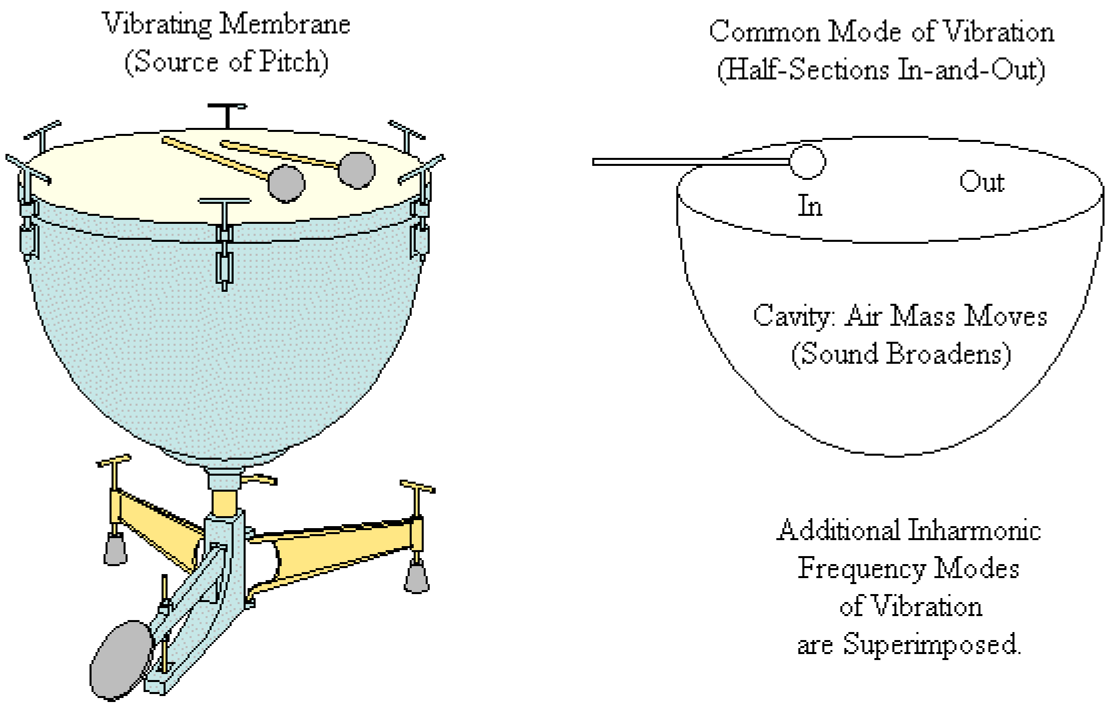
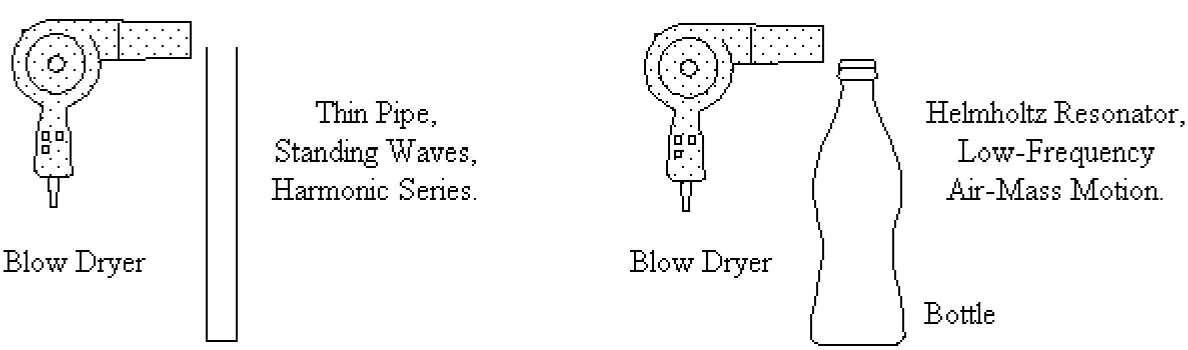


Fig. Y-16. Thin-Pipe Resonator Compared with Helmholtz Resonator.



Other drums do not produce a pitch. See Fig. Y-17 for examples of such drums. These drums produce broadband noise. The cymbals produce a concentration of high-frequency noise.

Fig. Y-17. Band Drum Set.

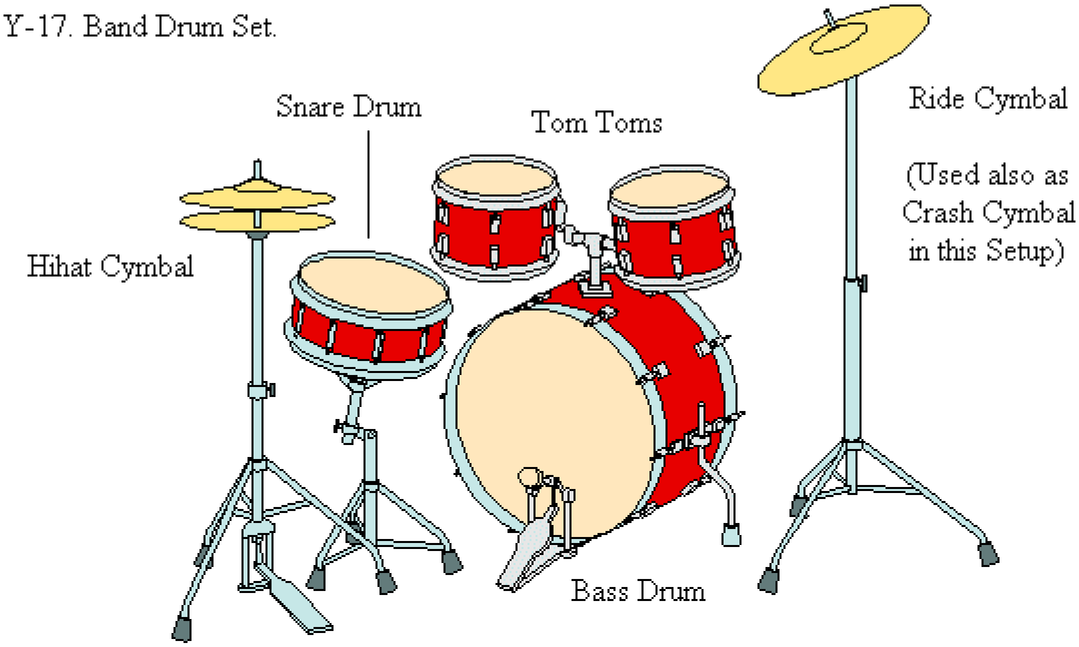
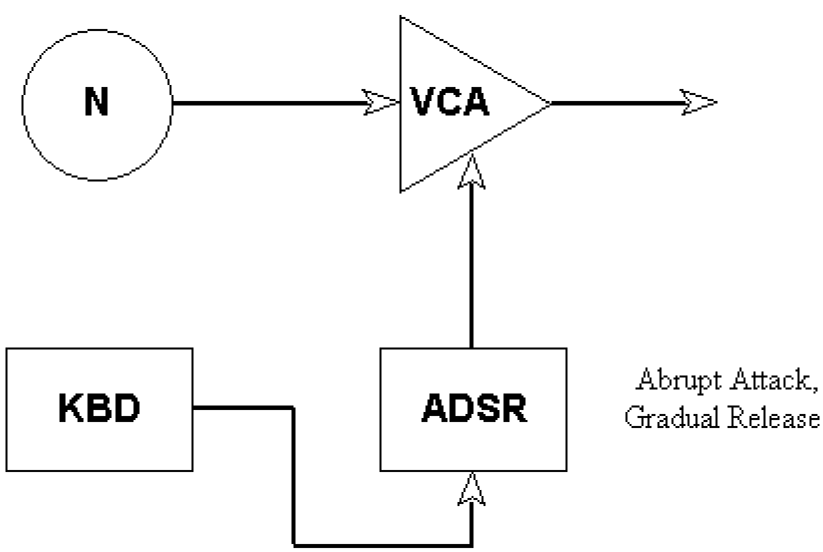


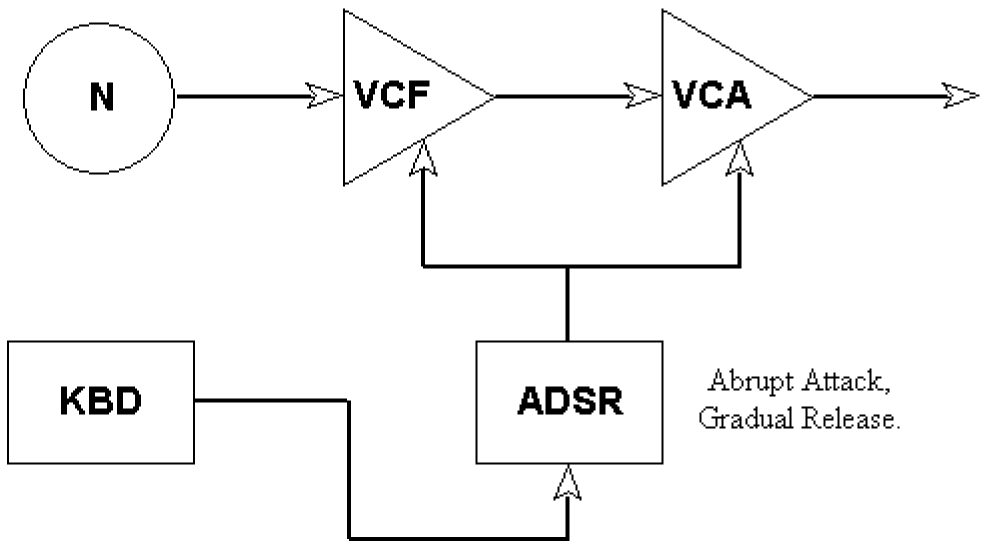
Fig. Y-18 illustrates a modular-synthesizer arrangement to produce band drums. A low-pass or high-pass filter can be used to highlight the lower or higher frequencies accompanying large or small drums. No filter-tracking should be employed since the keyboard is only used as a trigger for the ADSR.

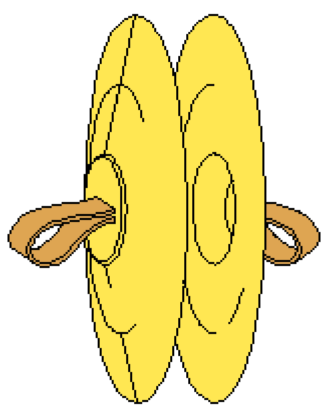
Fig. Y-18. Synthesizing Band Drums.



The cymbal produces a crash. The sound changes rapidly. A sweeping filter produces changes in the spectrum of a sound. Fig. Y-19 employs a sweeping filter to simulate a fleeting change in the broadband spectral characteristics of the noise. Better control can be achieved with two ADSR units, where one sweeps the filter while the other shapes the amplitude. However, the spirit of our modular diagrams is to assume we have one of each unit to work with.

Fig. Y-19. Approximating a Cymbal Sound.





Some Exercises

Statement	T	F
Drums typically have abrupt attacks.	○	○
Cymbals produce sounds with many combined frequencies.	○	○
Drums and cymbals have long sustain phases (ADSR).	○	○
Air mass moves in kettledrums.	○	○
The kettledrum resonates like a closed pipe.	○	○
The kettledrum is a Helmholtz resonator.	○	○

Answer below either true or false for synthesizing a cymbal sound.

Statement	T	F
Choose the noise generator for the source.	○	○
Choose a ramp wave for the source.	○	○
Do not use a VCA.	○	○
Use the LFO to control the VCA.	○	○
Use the VCF if "colored noise" is desired.	○	○
Use a gradual release on the ADSR.	○	○

--- End of Chapter Y ---