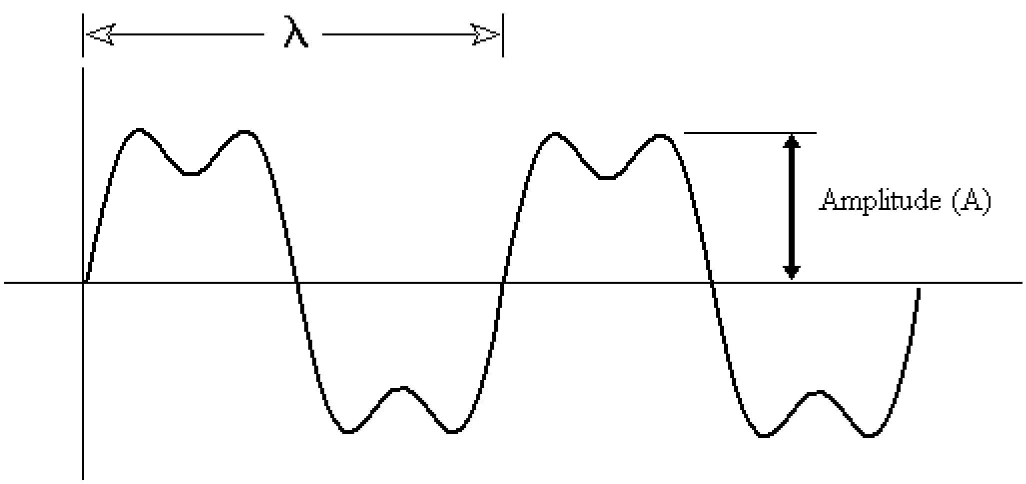
B. Vibrations

In this chapter we will learn about different kinds of periodic waves. We have already seen the sine wave, which results from simple harmonic motion. We will characterize periodic waves in general. The concepts of frequency and wavelength will still apply. We will then compare the physical characteristics of periodic waves with perceptual ones. How do different periodic waves sound? After this, we will see that no wave continues forever. Waves tend to die out; i.e., damp out. Energy must constantly be put into a system to maintain vibrations. We will see that driving a system at a special frequency gives the most efficient results. This is the subject of resonance. Resonance is very important in the design of musical instruments. It also has an analog in electrical circuits. It helps engineers design circuits that can respond to the least amount of energy.

Complex Periodic Waves

A periodic wave is any wave that repeats its pattern. Figs. A-11 and A-12 illustrate examples of periodic waves. There, you see sine waves, the simplest type of periodic wave. A complex periodic wave is any periodic wave that is not a sine wave. So that's everything else, as long as it repeats. An example of a complex periodic wave is given below in Fig. B-1. We include horizontal and vertical reference axes to help us describe the wave more clearly. Another example of a complex periodic wave is found on the cover of this text.

Fig. B-1. Example of a Complex Periodic Wave.



The *wavelength* λ is the distance from any point on the wave to the place where the pattern begins to repeat. It is easy for us to take the beginning point where the wave meets the horizontal axis and slopes upward in Fig. B-1. However, any starting point can be taken. The *frequency* is the number of patterns or cycles made per second.

Scientists like to use the second as the time interval. We will find this convenient since the sound we hear has frequencies easily expressed using this time unit. The *amplitude* is a measure from the horizontal reference (equilibrium) to the maximum point of the wave. The wavelength is measured in meters (m), centimeters (cm), or some other length unit of your choice. The metric system is simple since you only have to think in terms of 10, 100, etc. For example, the centimeter is 1/100 of a meter. This is better than having units like the yard, which breaks into 3rds to get feet, each of which then has 12 equal divisions (inches).

We will introduce metric units as we need them rather than hitting you with many at once. Often texts overwhelm the student with many metric units and then use less than half of them. You should not worry about learning all the metric units. The professional scientist doesn't know all of them either.

Let's consider frequency. Frequency tells us how many cycles or patterns occur per second. As an example, consider a source vibrating 50 times per second. We can write f = 50 "cycles" per second (50 cps), or f = 50 "cycles"/s. We can also write f = 50 "patterns"/s, 50 "vibrations"/s, 50 "oscillations"/s. How about f = 50 "wiggles"/s?

Since we can't get agreement on just what to call the repeating "things," we just write f = 50 1/s. We read this as 50 per second. Call them whatever you like. By convention, 1/s (per second, where cycles, patterns, or vibrations are understood) is named after the physicist that discovered radio waves, Hertz. So now we can write f = 50 hertz or f = 50 Hz for short. The lower case "h" is used when the word is written out as hertz and the upper case "H" is used when the unit hertz is abbreviated as Hz.

The hertz is a metric unit. The metric system consists of special units that scientists agree upon such as the meter, second, and hertz. The metric system also contains a series of prefixes which represents the numbers 10, 100, 1000, etc. and 1/10, 1/100, 1/1000, etc.

The prefix for 1000 is kilo, which can be abbreviated simply as "k." Therefore, one thousand hertz is simply kHz (a kilohertz). The hearing range for humans (rounded off) is from 20 Hz to 20,000 Hz (or 20 kHz). Another example is one hundredth of a meter, 1 cm (one centimeter).

You see, the metric system is easy. Simply attach the appropriate prefix such as centi or kilo to the relevant unit such as meter or second. One thousand seconds is a kilosecond (ks). A hundredth of a second is a centisecond (cs). Some silly authors like to attach metric prefixes to anything they like, which technically is allowed. For example, one thousand lectures is a *kilolecture*. Two thousand mockingbirds is two kilomockingbird, i.e., *To Kill a Mockingbird*.

Another physical parameter is the *period*. The period, designated by T, is the time it takes to complete one pattern or cycle. This depends on the frequency. If the frequency is f = 10 Hz (i.e., 10 1/s), what is the period? In other words, if you do something 10 times per second, how long does it take to do it once? The answer is 1/10 second (0.1 s). If f = 5 Hz (i.e., 5 1/s), the period T = 1/5 s. Note that you simply flip the frequency to get the period. Flipping 10 gives 1/10 and flipping 5 gives 1/5. Also note that the units flip: 10 1/s becomes 1/10 s on the flip. Note that if you flip the period, you get the frequency back and vice versa. We summarize these relationships as follows: **T = 1/f** and **f = 1/T**. The mathematical name for this flip is reciprocal.

It's convenient to learn the metric prefix for a thousandth, which is milli. The period for a 1000-Hz sound wave is 1/1000 s = 0.001 s = 1 millisecond (or 1 ms). Let's do another example.

Consider a 100-Hz sound wave. The period T is 1/100 s by flipping the 100 1/s. Therefore, T = 1/100 s = 0.01 s, just like 1/100 of a dollar is $0.01. This answer is perfectly satisfactory. In order to convert to milliseconds, write the period as T = 0.010 s. This is still one hundredth of a second; however, it is expressed as 10 thousandths of a second. So our period is 10 ms (10 milliseconds). Another way to think of this is to move the decimal point three places to the right and you go from seconds to milliseconds in one sweeping step.

Continue the analogy with money. Consider $10 and proceed slowly. One tenth of a 10-dollar bill is one dollar. One hundredth of $10 is a dime. One thousandth of $10 is a penny, as you need

1000 pennies to make $10. Now, 10 pennies equals one dime; i.e., 10 thousandths of $10 equals one hundredth of $10. Are you confused? If so, this is normal. So what you do is read it over again slowly and perhaps write some things down to help you visualize it.

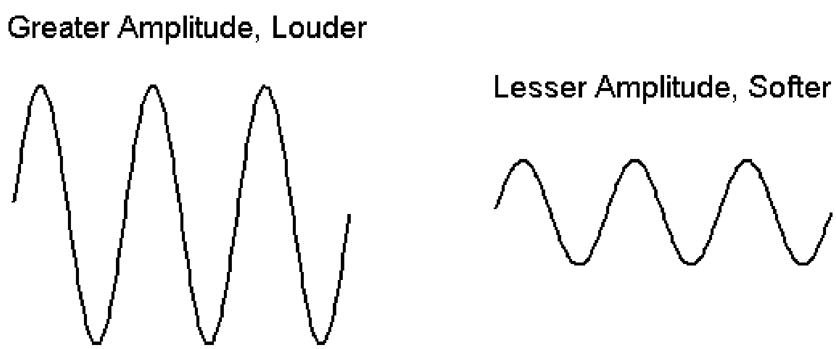
Perception of Periodic Waves

We would like to relate the physical descriptions of the previous section with perceptual characteristics. There are three basic perceptual features of periodic waves to consider.

1. Loudness. The easiest perceptual characteristic to investigate is loudness. The loudness of a wave is determined by the amplitude, as illustrated in Fig. B-2. However, the relationship is not simple. You can't say that if you double the amplitude, the sound is twice as loud. There is a good reason for this. If you want to be able to hear a whisper and a loud thunder crash, the ear has to be stubborn in perceiving loud sounds. It takes more than doubling the amplitude for the ear to be impressed. We will learn more about sound levels and loudness in a later chapter. The only thing we state here is qualitative: the greater the amplitude, the louder the sound. This also applies to non-periodic waves like explosions.

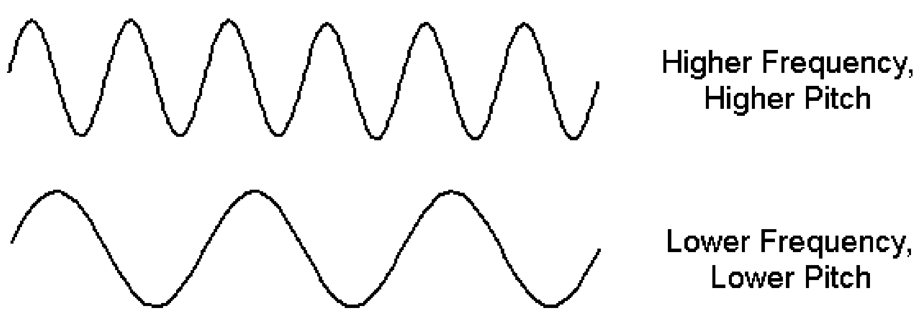
Periodic waves are heard as steady tones. Although amplitude mainly determines loudness, other factors affect how loud sounds appear. Our ears are not uniformly sensitive to all frequencies, so some sounds may sound louder simply due to our sensitivity, especially to high tones.

Fig. B-2. Amplitude and Loudness.



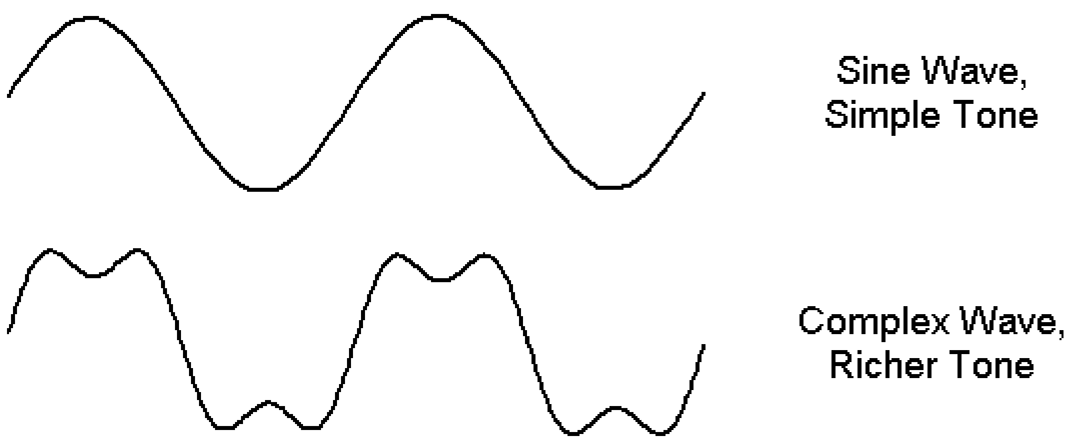
2. *Pitch*. Different frequencies of periodic waves are heard as different pitches or tones. The higher the frequency, the higher the pitch. Notice that our earlier discussion of frequency, wavelength, and period showed that all three of these are related. So we can alternately, say that wavelength and pitch are related, where short wavelengths mean high pitches (see Fig. B-3). Or we can alternately say period and pitch are related, where short periods indicate high pitches.

Fig. B-3. Frequency and Pitch.



3. *Timbre*. The timbre (TAM-ber) of a periodic tone is that quality which enables us to distinguish between the flute and the violin. These instruments may play the same pitch at the same loudness but we still hear a difference. The timbre (also spelled timber and also pronounced TIM-ber if you like) is determined by the shape of the waveform. In fig. B-4 below you find the waveform for a sine wave and one for the complex wave we encountered earlier. Note that the amplitudes and frequencies are essentially the same. The sine wave however will sound pure and innocent while the complex wave will sound richer and harsher.

Fig. B-4. Waveform and Timbre.



The correlation between physical properties and perceptual characteristics helps us understand the connection between physics (acoustics) and psychology (perception). Table B-1 summarizes these results.

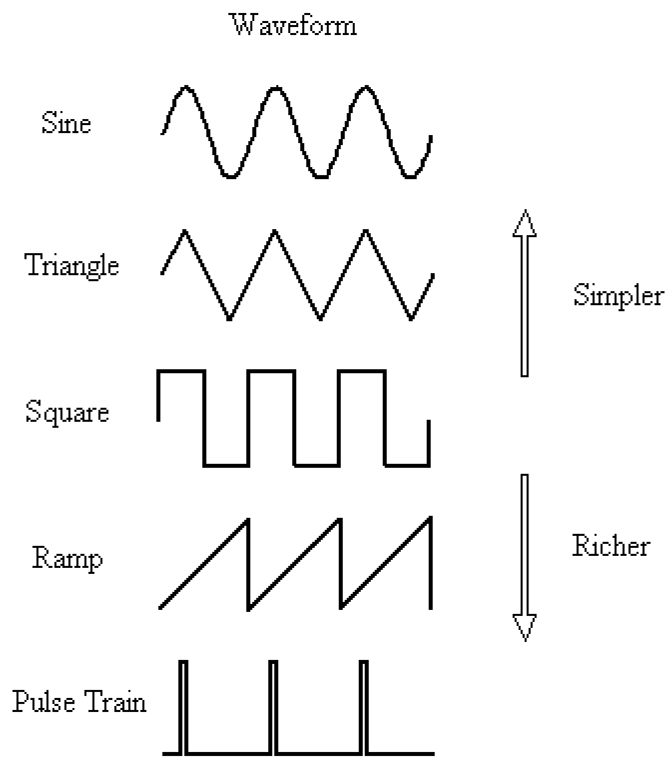
Table B-1. Basic Relationship Between the Physics and Psychology of Sound.

Physical	**Perceptual**
Amplitude	Loudness
Frequency	Pitch
Waveform	Timbre

Later we will learn about the decibel (dB) scale which ranges from 0 dB (a pin drops) to 140 dB (near a jet, which damages your ears). Actually, damage can occur in a machine shop with 90 dB. The range of frequencies we hear is from 20 Hz to 20,000 Hz, as noted earlier. Later we will also analyze complex periodic tones and learn more about timbre.

However, for now, let's look at some different waveforms. We will simply note their pictures. Five waveforms can be found in Fig. B-5 below. These have nice shapes and are easy to synthesize with electronics. The sine wave is the simplest waveform. It sounds the purest in tone. The others are arranged depending on how different they appear compared to the sine wave. Later we will learn precise justification for this order. The pulse train sounds the harshest. Try moving your hand in step with each of these and imagine your eardrum vibrating likewise in step.

Fig. B-5. Five Different Waveforms.

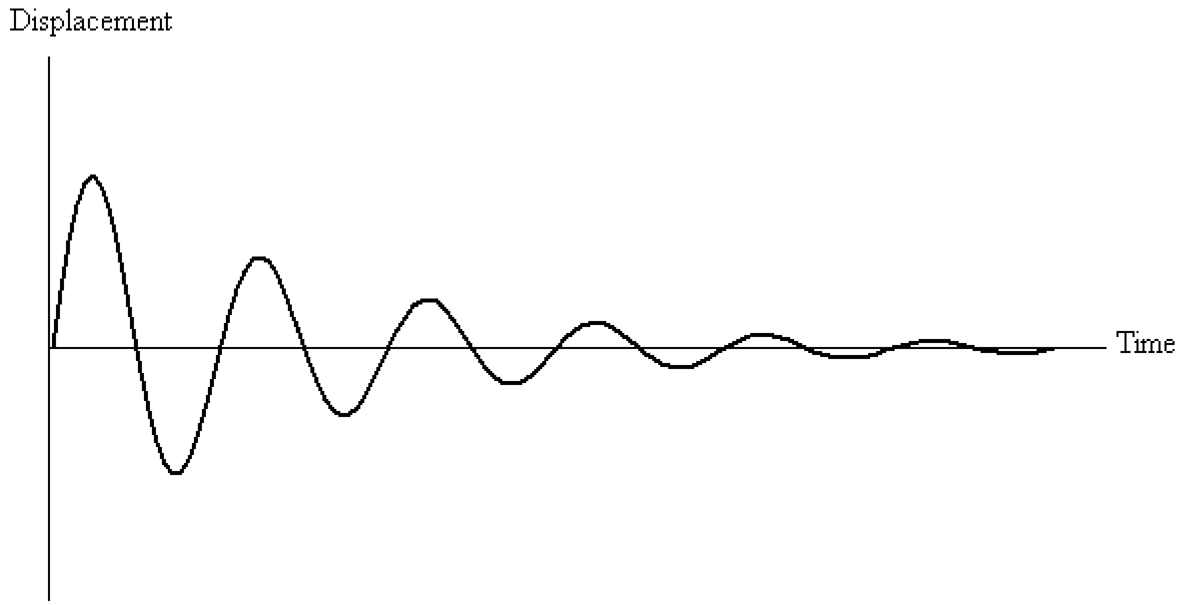


Damped Periodic Waves

Unfortunately, oscillations die down unless there is new input of energy. If you start a pendulum swinging, its amplitude decreases as it swings until it eventually stops. The oscillations are said to be damped. Fig. B-6 below illustrates such motion. It is a plot of displacement (position away from the equilibrium position) versus time. Scientists like to say it's a plot of displacement as a function of time. This may represent a pendulum. You kick it when the clock is set to zero (see beginning of the graph). The pendulum ball or bob starts to swing away from equilibrium (say to the right). It reaches some maximum displacement to the right, then starts to come back. It overshoots the center and proceeds to the left. This is represented in the graph as the curve dips below the horizontal axis. The bob swings back and forth but doesn't reach the larger distances from the center that it originally did. So the graph below indicates a gradually decreasing amplitude. Note that the motion is damped simple harmonic motion since it is represented by a sine wave decreasing in amplitude.

The graph in Fig. B-6 can also represent the vibration of a mass attached to a spring. However, the mass is not pulled back in this case but hit with an object. For a mass pulled back and let go, the graph starts somewhere away from the equilibrium line. The graph can also represent a dying sound wave. There is a law of nature that says there is no such thing as perpetual motion. It is the *second law of thermodynamics*. You may have heard about entropy (disorder) and the law that everything tends toward disorder. This is the same law. The *first law of thermodynamics* states that you can't get anything for nothing (conservation of energy); the second law states that you can't break even. Some energy is lost to friction. The pendulum stops swinging, the mass attached to a spring stops oscillating, the sound we hear dies down.

Fig. B-6. Damped Harmonic Motion



Driven Oscillations

Due to the laws of thermodynamics, we want to be careful when we pump energy into a system. We want to maximize our efforts. Suppose we want to push a child on a swing. We would of course push the youngster at the frequency that the swing wants to go at. This is common sense. In this way, our energy use is maximized. When we stop pushing the child, of course the swing will eventually stop.

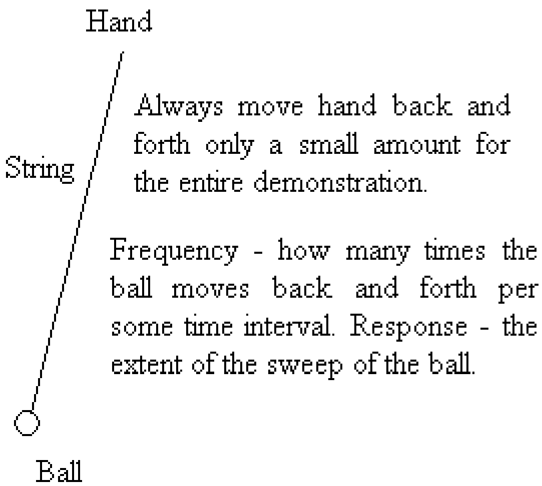
But if we were to push the swing at some crazy frequency, we would be wasting our efforts. This wasted effort could be demonstrated by moving a hand back and forth at some different frequency than the swing. Perhaps, one time when the kid arrives at the hand, the push helps. But most times the push will not be with the swing. Occasionally, we will actually be trying to stop the kid when our hand pushes too soon and collides with the child's back. The second law of thermodynamics is bad enough for us to throw our efforts away. Let's find out when the driven system responds the best to our efforts. This brings us to an analysis of driven oscillations.

Fig. B-7 describes an experimental arrangement to study driven oscillations. Tape a small ball to the end of a string. Grab the end of the string opposite the ball. Shake your hand back and forth, keeping your sweep within a short space (1 or 2 cm). You may have a friend bracket this space with a thumb and forefinger for you.

Can you find the frequency that makes the ball respond most dramatically? Your driving frequency is then called the *resonance frequency*. You are driving the pendulum at the frequency it likes to swing.

Stop, pull back the ball, and let it go so that it swings on its own. Isn't this the same frequency you used earlier? It will be unless you do the experiment in a thick medium like "oil."

Fig. B-7. Hand Driving a Pendulum.

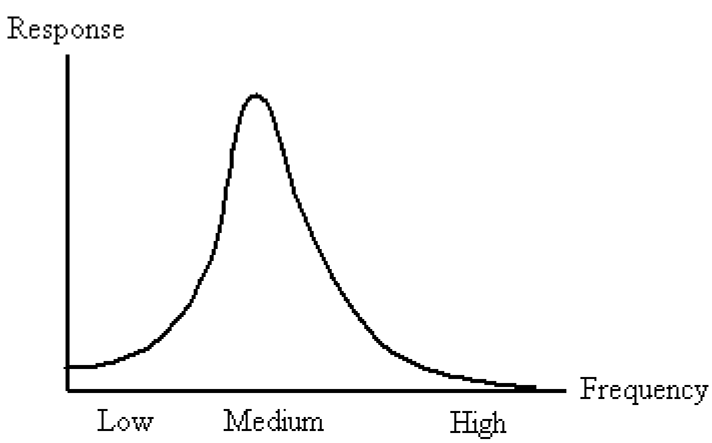


Get a feel for the ball swinging on its own by counting or having someone clap each swing. Now stop the ball and start driving it from rest at this frequency. The ball will gradually increase its swing until it reaches a maximum as you continue to drive the pendulum at the resonance frequency. Resonance occurs when the ball responds with maximum swing. Resonant vibrations are also called *sympathetic vibrations* (the system "is in sympathy" with your vibrations). Compare the responses of the ball (total extent of swing) for different driving frequencies (low, high, medium). Note that the ball moves a little with a low-frequency driving force, and hardly moves at all when driven at high frequency. Somewhere at a medium frequency, the response is greatest (resonance).

Now we are going to make a graphical sketch of our results. In Fig. B-8 below we view a graph of response (vertical axis) versus frequency (horizontal axis). A low response is found at low frequencies. When you shake the pendulum slowly, the ball moves very little. When you shake the string rapidly, the response is even less. You change directions so rapidly that the ball cannot respond quickly enough. So it just sits there. However, at a medium or intermediate frequency, the ball responds the greatest.

Take your pencil and place it at the peak of the graph in Fig. B-8. Now place a ruler vertically and draw a dotted vertical line downward until you hit the horizontal axis. Your dotted line should be parallel to the vertical axis at the left in Fig. B-8. Now make a dark dot where your vertical line touches the horizontal line. This marks the spot for the value of the resonance frequency. If our graph had numbers on the frequency axis instead of the words low, medium, and high, you could read off the value of the resonance frequency.

Fig. B-8. Plot of Response versus Frequency: The Resonance Curve.



Resonance is important in musical instruments. When a violin is played, the energy action of the bow drives the string into resonance. Certain frequencies are further enhanced as the wood and cavity support additional resonances. This gives a richer quality to the tone.

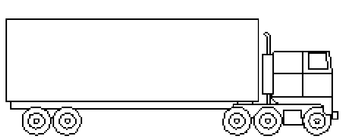
When one softly blows across the opening in a flute, the energy supplied drives the pipe into a resonance, depending on the effective length of the flute (controlled by pressing key pads). Playing a recorder or toy flute, one covers holes. Depending on which hole is uncovered, the pipe acquires a different resonance frequency. Rather than trying to guess this frequency and whistle into the pipe, you gently blow, creating a turbulence of many frequencies.

The amplification due to resonance is so impressive that you will readily generate a tone. The multi-frequency breath sound at the mouthpiece is called noise. But only that frequency component that corresponds to the resonance frequency of the pipe is picked out and amplified as the pipe resonates at that frequency.

Examples of Resonance

Your author has searched extensively for 10 examples of resonance to help you master this important concept. Examples were found in such diverse places as the author's home, *Star Trek*, and the *Bible*. All of these involve vibrations of some kind or another. You should try to identify the source of energy in each case, the system being driven or excited, and the actual resonance effect itself.

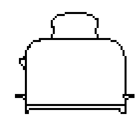
R1. A Passing Truck Shakes Things in a House. Large trucks generate low frequencies.

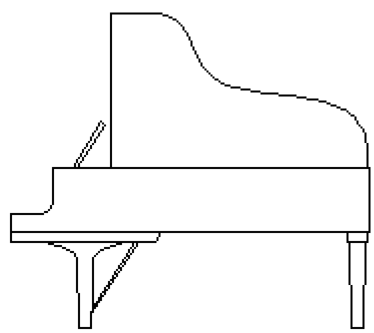


Such low frequencies can cause items in one's home to vibrate. The author was often scared in Philadelphia (at his in-laws' former home) when he felt the entire house shaking from the third-floor bedroom as large city buses passed outside.

R2. Piano Note Rattles Toaster. In the author's former apartment at the *University of Maryland*, hitting a key near the middle of the piano caused a toaster element across the room to rattle. Only one key near the center of the piano did the trick. The notes produced by keys to the left were too low in frequency, while those produced by keys to the right were too high.

It is good to remember that the lowest note on the piano is about 30 Hz and the highest note is about 4000 Hz (or 4 kHz). The key causing the resonance was about 300 Hz. An important middle key on the piano is called middle C and has a frequency of near 260 Hz.

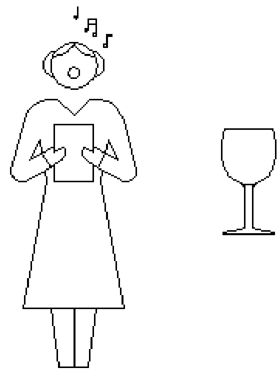




R3. Singer Breaks Wineglass. This is the classic case of a singer who sings a particular note that shatters a glass. In the 1980s, a *Memorex Commercial* on TV featured Ella Fitzgerald singing into a microphone and breaking a glass. They taped her. Then they played the tape and yes, the recording broke the glass also.

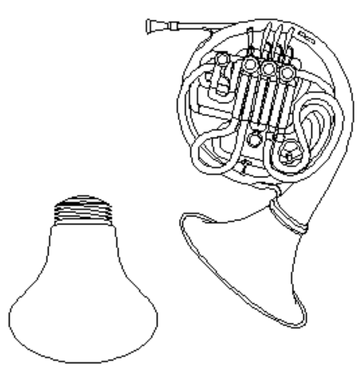
Resonance is used dramatically in the movie *The 4th Tenor* (2002) as our star (Rodney Dangerfield) "shatters" more than a wine glass with his new operatic voice.

The author once found broken pieces of glass from a lamp on the floor in *Lipinsky Hall*. He inquired as to what was going on the night before, suspecting resonance. He discovered that the *UNCA Choir* had been practicing.



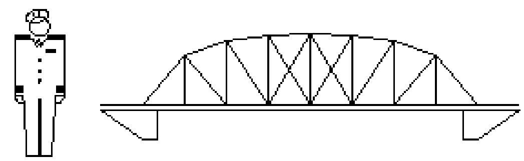
Interestingly, breaking a glass without a microphone was not documented until 2005, when Jamie Vendera did it for *MythBusters*. He hit 105 decibels at 556 Hz and had to try 12 delicate wine glasses before finding one with a proper structural defect.

R4. An Orchestra and Floodlights. The author was at a concert at the *University of Maryland* in the early 1970s. The university orchestra was playing the Brahms *4th Symphony*. The 3rd movement opened with the usual French horns playing the E (330 Hz) above middle C. As the horns held this note, the same tone could be heard coming from a source somewhere to the left. It was an eerie sound.



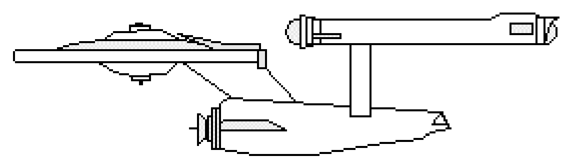
Then there was a pop and a floodlight exploded. In the movie *The Mask* (1994), Jim Carrey uses a surrealistic toy sound maker and blows out the windshield of a car.

R5. Soldiers Marching Across a Bridge. Soldiers do not march across bridges because the uniform steps could induce resonant vibrations in the bridge. They break step to prevent any possible driven oscillations.



R6. The Avalanche. An avalanche can be started by vibrations. You do not want to shout in an environment where an avalanche can occur. This might involve an unstable arrangement of snow or rocks. Vibrations at the proper frequency can shake the snow or rock formation causing an avalanche.

In a very early *Star Trek* episode, *Friday's Child* (December 12, 1967), Captain Kirk and Science Officer Spock are running from bad guys on a planet. The medical Doctor McCoy is in the mountains assisting a lady about to give birth. Kirk and Spock come up to a mountain. They are trapped.



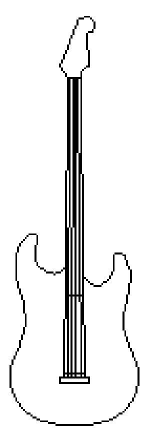
Spock suggests that they try to induce sympathetic vibrations in the mountains, dislodging the rocks. Spock knows his science - that's resonance. Kirk asks for the probability of success, which Spock points out is not real good.

They of course try it anyway. Unfortunately, they turn on their communicators to do it. The communicator sends out radio waves, not sound waves. Well, let's imagine they have a setting for high-frequency acoustic waves we can't hear. They need a high frequency since the stones they wish to excite are very small. At this point, we are trying to save the story from incorrect physics. The rocks do come down and the bad guys get wasted. But there is 25 minutes remaining in the story, so Kirk and Spock get caught by a new wave of bad guys. Kirk uses psychology to get out of the mess at the end of the episode.

An avalanche scene also appears in the Disney movie *Herbie Goes to Monte Carlo* (1977). Here they get the physics right. Don Knots (in the car "Herbie" with his friend driving) yodels in the mountains, impressed with the echoes. They are actually lost and he is calling for help. A small avalanche starts, then stops.

Bad guys show up, as the good guys were tricked into making a wrong turn during a race. But Herbie has the idea by now and begins to yodel (the car's horn). A larger avalanche occurs, where rocks land on the bad guys' car.

R7. Rock Concert. There was a rock concert at Princeton during the 1970s where everyone starting stomping to the music. The gym started shaking. Remember, soldiers know to break step when walking across bridges. However, rock lovers don't know that they shouldn't stomp in unison inside a large auditorium. Police ran in to get the audience to stop. Can you imagine the confusion?

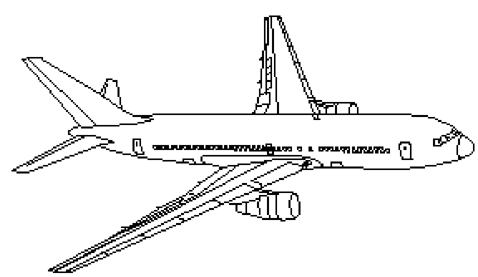


Hippies entranced with the music probably didn't notice the police at first. With all the noise and distraction, some thought the police might be after them. Some probably shouted "Fuzz, Fuzz" to their friends, worrying about the "joint" they were passing around. The police had more urgent concerns - the gym itself. Well, the gym did not collapse.

However, skywalks in a Midwest hotel did collapse in the early 1980s. People were dancing, so resonance was a possibility. But the investigation showed that the floor wasn't bolted correctly. The collapse was due to weight, not oscillations.

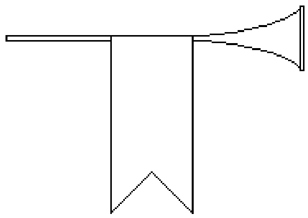
R8. Jet and Construction. A jet (DC 10) on its way to landing at Chicago's *O'Hare Airport* flew over a stadium undergoing construction in 1979. Things shook, some of the structure collapsed, and tragically, five people were killed. The *Asheville-Citizen* (August 14, 1979) reported that a worker described the event by saying "Suddenly, everything began to vibrate. You could hear the roof cracking and then it started falling in."

The paper quoted a spokesman for the *Federal Aviation Administration* (*FAA*) stating that planes were flying "just a couple hundred feet" over the site. These are the clues for resonance - low-flying jets, sympathetic vibrations picked up in the unstable roof. However, the *FAA* spokesmen went on to say that he never heard of airplane turbulence causing any destruction on the ground. He obviously did not know his physics. It's not the air turbulence that caused the destruction, it



was sound resonance!

R9. The Walls of Jericho. Suppose a scientist who was not familiar with the Bible began studying the Bible with the Jericho story. What would our scientist learn about the characters and the events that transpire in the story?



Our scientist would first learn that Joshua is in some sort of trouble. Joshua is leading a group wandering in the desert. Joshua's people need to get into a city, but walls prevent them. So Joshua goes off to a desolate place to get help from God. Joshua hears a voice that responds to his requests and proceeds to tell him what to do.

From what Joshua is told to do, our scientist concludes that God has a very insightful understanding of the laws of physics. Below we give the instructions Joshua receives and alongside include a scientific commentary of these instructions.

Our guide here for the interpretation is what we know about resonance and physics.

Bible	Scientific Commentary
"... On the seventh day march around the city seven times, and have the priests blow the horns. When they give a long blast on the ram's horn and you hear that signal, all the people shall shout aloud. The wall of the city will collapse, and they will be able to make a frontal attack." *Joshua 6:4-5*	1. *March Around* - to spread out. 2. *Blow the Horns* - start the resonance. 3. *Ram's Horn* - resonance frequency. 4. *Long Blast* - so response builds up. 5. *Shout* - noise for reinforcement. 6. *Collapse* - due to resonance.

Everyone needs to *march around* so that the sound can better reach the wall. The driven oscillations begin when *the priests blow the horns*. The *ram's horn* is important as its frequency is near the resonance frequency of the wall. It's necessary to a make a *long blast* so that the wall oscillations can build up. Having the people *shout aloud* adds to the ram's horn. Present in the overwhelming noise is the resonance frequency that reinforces the ram's horn. The *collapse* occurs when the stress limit is reached in the wall due to the resonance vibrations.

Our scientist may wonder why God doesn't explain the physics to Joshua more fully. Probably, Joshua wouldn't understand it. Rather than confuse Joshua, it is more efficient to just tell him what to do. Note that Joshua is told the outcome. In this sense, a scientific principle <u>is</u> explained - s*ound can make a structure collapse* (like our previous roof collapse caused by the low-flying jet).

Our scientist may also wonder why God doesn't just knock out the wall for Joshua. Our scientist surmises that perhaps God interacts only through voice. But wait, God could then perform the "sound" resonance for Joshua. So our scientist concludes that God is willing to assist Joshua, who asks for help, but that Joshua has to do some of the work himself. How does our scientist's interpretation of the Joshua story compare to yours?

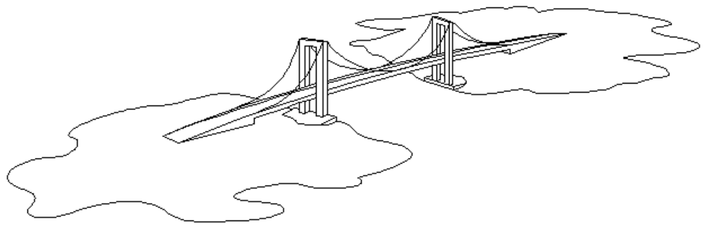
R10. The *Tacoma Narrows Bridge*. Physics teachers have discussed the *Tacoma Narrows Bridge* as the "granddaddy" of resonance for several decades. The bridge was completed around 1940. Winds were able to get the bridge oscillating dramatically. The wind in the ravine supplied the energy for the oscillations. If you are somewhat confused as to how the wind caused the oscillations, don't worry, so are many physics teachers.

Today we believe the oscillations were not caused by resonance, but rather by some more complicated interactions.

For an obvious scenario of bridge resonance, consider a monster like *King Kong* giving gentle pushes on an appropriate place of the bridge at the right frequency. In a short time, the oscillations of the bridge build up impressively. This would be resonance.

However, we include the *Tacoma Narrows Bridge* here for its historical association with resonance and its spectacular display of catastrophic behavior.

The bridge's road surface oscillated in a twisting fashion. Such waves are called *torsional waves*. The *Tacoma Narrows Bridge* collapsed one morning after about 40 minutes of twisting. A film of the incredible oscillatory bridge motion is observational proof of the elasticity of solid structures. The bridge vibrated like a large string. There was plenty of time for all the cars except one to vacate the bridge. One car got stuck on the bridge. The driver of this car crawled toward one of the bridge's towers. He heard concrete crackling. He made it off the bridge. However, his main concern afterwards was how to explain to his daughter that he couldn't save her dog, who was riding with him in the car.



In 1995, a commercial advertising a Pioneer Sound System used footage from the *Tacoma Narrows Bridge Collapse*. They sped up the movie. The commercial won 1995 *Grand Clio Award*, the top award for cleverness and creativity in advertising.

Chladni Plates

The German physicist Ernst Chladni (KLAD-knee), regarded by some as the father of acoustics, discovered an ingenious way to visualize resonance vibrations of a plate. You sprinkle some sand or white powder on the plate and then use an oscillator to produce frequencies. When you hit a resonance frequency of the plate, the plate goes wild. Regions where the plate vibrates become free of the powder as it gets shaken off. However, some paths along the membrane do not move and the white powder stays there. One finds beautiful patterns for the various modes of vibrations. Plates are two dimensional and very complicated compared to the thin strings and pipes will be discussing later. Strings and pipes are more like one-dimensional structures as the long length predominates over the small cross-sectional area.

Fig. B-9. Chladni Pattern

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