Part 2

Wave Properties

1. Reflection

2. Refraction

3. Inverse Square Law for Sound Intensity

4. Huygens’s Principle

5. Interference and Superposition of Waves

6. Diffraction and Superposition of Waves

7. Beats

8. Polarization

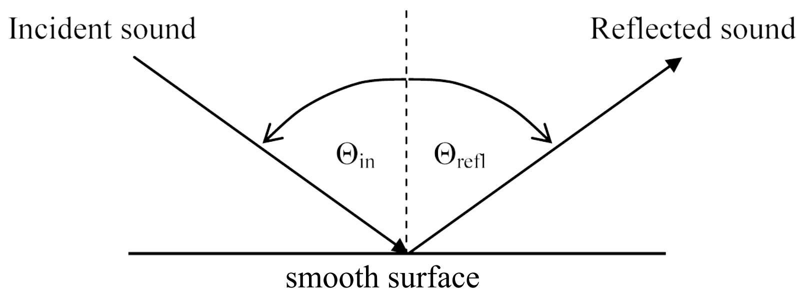
9. Transverse Waves

10. Longitudinal Waves

11. Doppler Effect

Law of Reflection
When a wave strikes a surface, the angle of incidence is equal to the angle of reflection with both angles counted from a line perpendicular to the surface.

$$\theta_{in} = \theta_{reflected}$$



Condition for reflection: The surface must be smooth compared to the wavelength.

Question: Where does reflection of sound occur?
Answer: On exterior walls (echo), interior walls of buildings, room walls, lecture halls, concert halls, theaters, churches.

Question: Where is reflection important?
Answer: It may improve the acoustic quality of a room or make it worse.

Reflection of sound is desirable when trying to keep the sound intensity in a room high and evenly distributed. Multiple reflections from surfaces cause longer reverberation times that may be favorable for the reproduction of some types of music.

Reflection of sound may be undesirable when concentrated on “hot spots” in a room. Multiple reflections from hard surfaces in large rooms give rise to too long reverberation times that make the sound linger. Speech in large churches constructed of stone may become unintelligible. But organ music does sound good!

Additional Examples for Reflection
1. Amphitheaters.
2. Parabolic reflector microphone for recording distant sounds, e.g. from birds.
3. “Whisper chamber” with ellipsoidal reflectors: You stand at one focus of the ellipsoid, your friend hears you clearly at the other focus, even when you are speaking softly. (The Science Spectrum in Lubbock has such a setup.)
4. Parabolic mirrors in terrestrial and astronomical telescopes for concentration of light.

Demonstrations
Show a parabolic “mirror” microphone.
Show an optical parabolic mirror inside a flashlight or camping lantern.

Refraction of Waves

Refraction occurs when a wave that travels in a medium enters another medium. The direction of propagation changes at the interface between the two media. This effect is called *refraction*. It happens for instance when a light wave enters glass. Eyeglasses and lenses work on the principle of refraction. The amount of bending of the wave at the interface between the two media is described by Snell's law (mathematical form not needed here). The wave bends towards the surface normal when it enters a medium where the wave velocity is lower than in the medium from what it came.

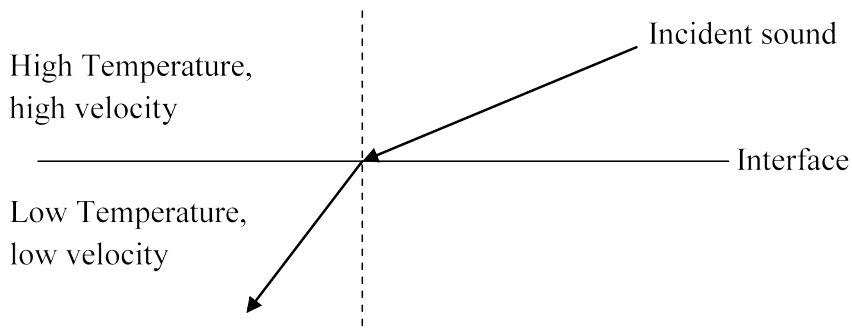


Figure. Refraction of a sound wave traveling from high to low temperature regions through a boundary layer (interface).

Refraction of sound waves occurs mostly outdoors. It is not very important for room acoustics. The following interesting natural phenomena are based on refraction.

1. **Temperature Inversion in the Atmosphere**
A temperature inversion may exist above a placid lake at night when the air is cooler near the water and warmer higher above. Sound waves are bent down as they travel from the source to the listener. This increases the sound intensity heard by the observer. This way you may hear campers from the far side of a lake at night. You may not hear them during the day when there is no temperature inversion and the air is warmer near the water and cooler higher up.

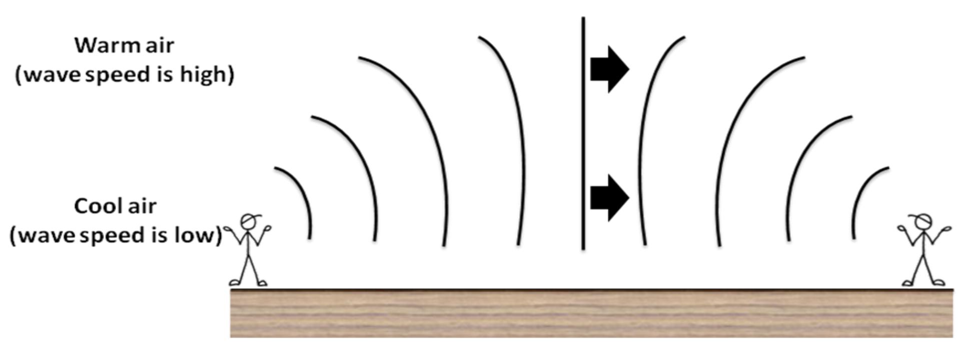


Figure. A temperature inversion occurring above a placid lake at night. Sound waves originally traveling upward are refracted back down and reach the observer.

2. **Maximum Distance for Hearing Thunder**

A normal temperature gradient without inversion usually exists at the beginning of a thunderstorm. The air is warmer near the surface and the speed of sound is higher there. Sound waves will then bend upward. When thunderheads typically are at an elevation of about 4 km, the maximum range for hearing thunder is about 22 km. Beyond that the sound is refracted back up and cannot be heard at larger distances.

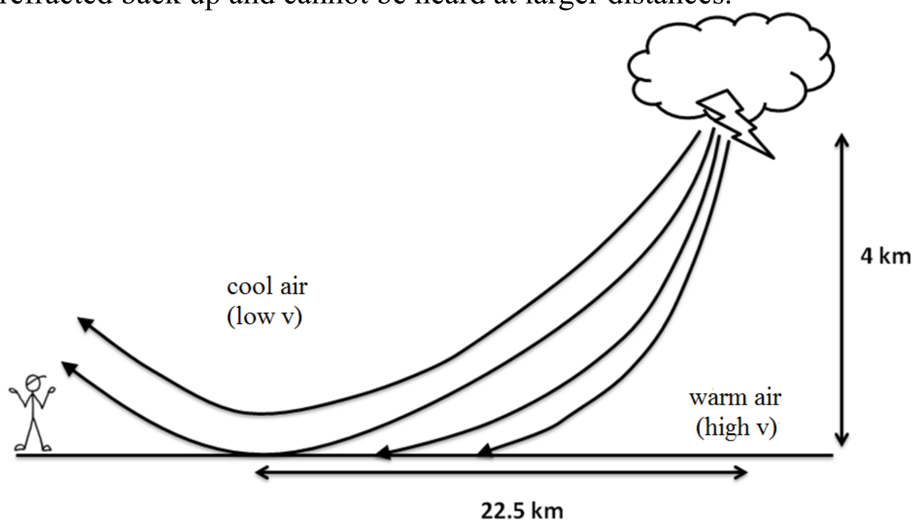


Figure. Upward bending of sound waves from a thunderhead in the normal atmosphere. The air near the ground is warmer and the wave speed larger than farther above.

3. **Ocean Waves Near a Beach**

Waves approaching a beach under an angle to the shore generally become more parallel to the shore. The reason is that the waves closer to the shore slow down due to the shallower water. The faster waves in the deeper water catch up and align their wave fronts parallel to the shore. The bending is gradual if the water depth decreases gradually.

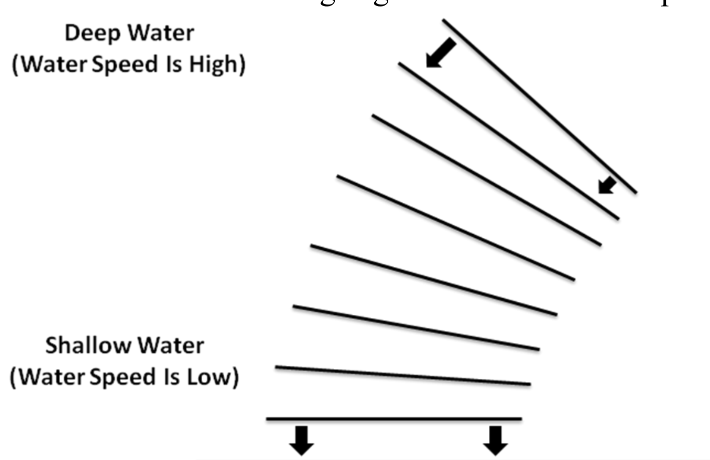


Figure. Water waves approaching a beach line up parallel to the shore. The wave in the shallower water is slower than in the deeper water farther. Refraction bends the wave.

4. A **Mirage** shows the “blue sky” on the “watery” surface of a dry highway.

Doppler Effect

The so-called Doppler effect occurs when the sound source or observer are moving with respect to each other. The frequency (pitch) of the sound changes.

Case 1
The source is moving towards the observer or the observer moving towards the source.
The wave fronts crowd together and the wavelength decreases.
The pitch of the sound increases.
Example
A police car is approaching. The siren sound has a higher pitch than at rest.

Case 2
The source or the observer are moving away from each other.
The wave fronts are farther apart and the wavelength increases.
The pitch decreases.
Example
A police car speeds away. The siren sounds at a lower pitch than when approaching.

Where does the Doppler effect play a role?
1. One can determine the speed of underwater objects (submarine, whales, etc.) with *sonar*. A sound wave is emitted in the direction of the object under study. The wave is reflected from the object and shows a shift in frequency. The formula for the frequency shift includes the speed of the object, and thus the speed can be calculated.
2. Bats navigate in dark caves and at night by emitting ultrasound (1 kHz – 150 kHz) and processing the reflected sound. They emit short pulses of ultrasound and detect the frequency shift and the time it takes for the sound to return. In this way, they find out how far an object is and how fast it is moving, even in which direction. Their auditory system is so sensitive that they can catch flying insects, their favorite meal. “Bats can see with their ears.”

Demonstrations
1. Launch a foam ball containing a high-pitched mine-speaker. Note the change in pitch due to the Doppler effect.
2. Use a tuning fork and move it toward or away from an observer. Can you hear the change in pitch?
3. Use three tuning forks sounding the major triad C4, E4, and G4. Have three students move the forks back and forth to produce small frequency changes. Listen to the rather pleasant vibrato in the major triad.

Inverse Square Law for Sound Intensity

When you move away from a sound source in an open space, the sound intensity decreases because the total power emitted by the source is spread over a larger surface.

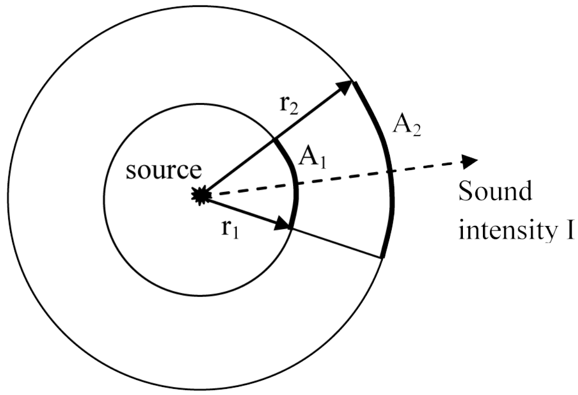


Figure. A sound wave from an unobstructed point source moves spherically outward.

Definition of Sound Intensity

Intensity = Power/Area $\quad I = P/A$

Area of a sphere $\quad A = 4\pi r^2$

Hence $\quad I = P/4\pi r^2 \propto 1/r^2$ or $\mathbf{I \propto 1/r^2}$

The total emitted power P is the same through any sphere at a distance *r* from the source. But the intensity decreases proportional to $1/r^2$. This is the *inverse square law.*

Example

You double the distance from a sound source from 10 m to 20 m. The sound intensity decreases 4-fold (not 2-fold!).

Question: Increase the distance 4-fold. By what factor does the sound intensity decrease?
Answer: It decreases _________fold.

In open-air theaters or concert stages, the sound decreases rapidly with distance from the stage if no remedies are used. The problem can be addressed with sound reflectors near the stage and seating on sloping surfaces such as in amphitheaters.

The ground and uneven terrain are obstacles that can alter the sound intensity and cause substantial deviations from the inverse square law. The law is of little practical importance for sound propagation and reproduction in *enclosed* spaces.
Challenge question. Do reflections from the ground at an open-air concert increase or decrease the sound intensity from what can be expected from the inverse square law?
Answer: Decrease _________ Increase _________ (Give your reasons.)

Wavelength λ, Frequency f, Period T, Amplitude A, Wave Speed $v = \lambda f$

Displacement of the Medium in a Traveling Wave versus Time and Distance - A Thought Experiment

Imagine water waves traveling in the ocean.
1. Observe the displacement of the water in its up-and-down motion in the y-direction as a function of time ("movie") at a fixed position x.
2. Take a snapshot of the wave in which you see the displacement y of the water waves as a function of x in the direction of propagation, but with the time t now fixed ("snapshot"). Note the period T, the wavelength λ, and the speed v of the wave. Make two drawings.

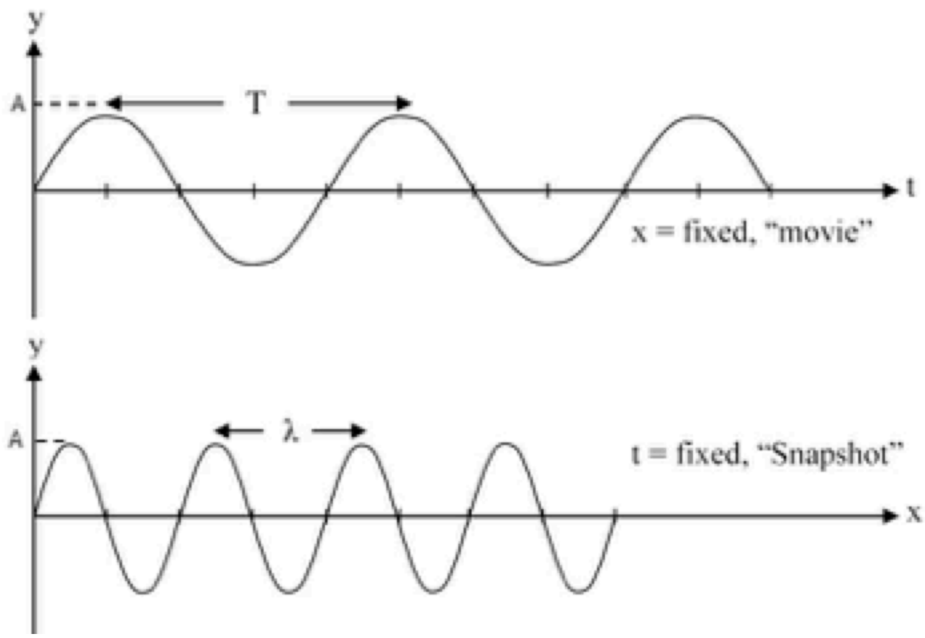


Figure. Upper graph: "Movie" of a water wave or sine wave as a function of time, at a fixed position x, with period T. Lower graph: "Snapshot" of a water wave as a function of location x, at a fixed time t, with wavelength λ. The amplitude A is shown in both cases.

Note that both graphs are sine curves, but the labels on the horizontal axes are different. It is the time *t* in the first drawing and the position *x* in the second drawing. The reason for the similarity is that the displacement *y* of the traveling transverse wave has a sinusoidal dependence on both variables (x,t). The displacement y(x,t) of the simplest traveling wave is a sine wave. Assuming that the wave has zero displacement at x = 0 and t = 0, i.e. no phase shift, it is given by (for the mathematically interested)

$$\mathbf{y(x,t) = A \cdot \sin[2\pi(x/\lambda - t/T)]}, \text{ where } A = \text{amplitude}, \lambda = \text{wavelength}, T = \text{period}.$$

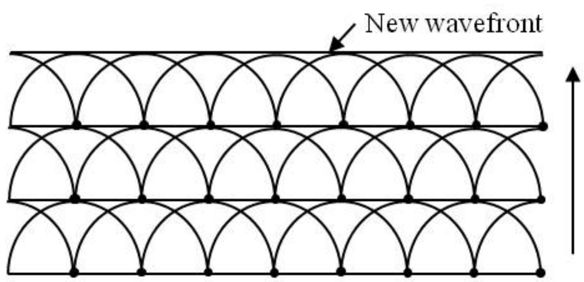
Question

You bob up and down with an ocean wave by hanging onto a buoy. Then you surf the wave. Describe how the wave looks to you in either case. When do you see it move?

Huygens's Principle

Christians Huygens's (1629-1695) principle explains the wave phenomena of interference, diffraction, reflection, and refraction, more specifically the creation of new waves from existing waves. The principle can be stated as follows:
"All points on a wave act as sources of small circular (2-D) or small spherical (3-D) wavelets. The wave pattern at a later time is the superposition or sum of these wavelets. The leading edge of the individual wavelets forms the next wave front."

Plane wave fronts



Circular wave fronts

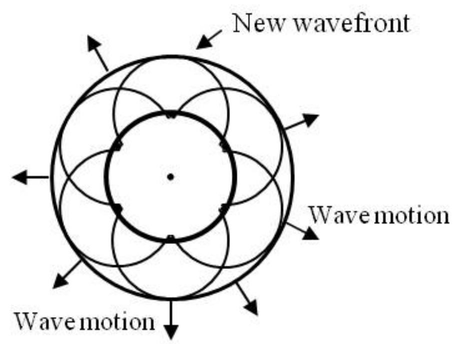


Figure. Huygens's principle applied to plane waves and circular (spherical) waves. Note that the direction of propagation of the wave is always perpendicular to the wave fronts.

Examples
1. Drop a stone into a pond. The expanding wave fronts are circles around the impact.
2. The sound of a firecracker high up in the air expands in spherical wave fronts.
3. Dip a long board periodically into water and observe the emitted plane waves. .

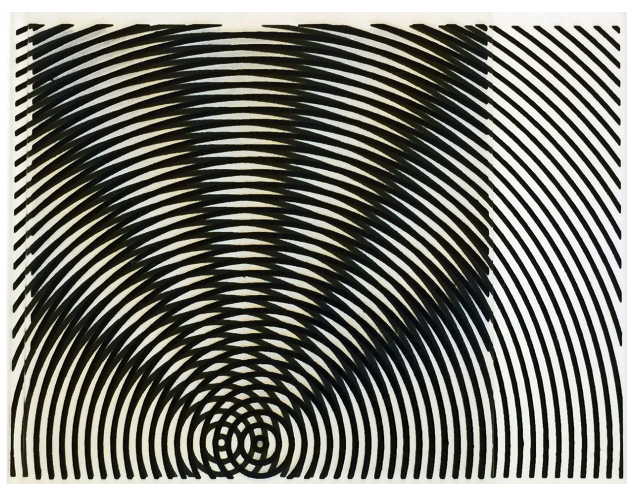


Figure. Simulated interference of waves from two point sources (located at the bottom of the picture, for instance two dippers periodically touching a water surface). The bright and dark regions show constructive and destructive interference, respectively. Two transparent plates were overlaid, each having black concentric circles for the "waves".

Interference of Waves and Superposition Principle

When two waves meet, they interfere with each other in the region of overlap. The resulting wave is the sum of the two superimposed waves (Superposition Principle).

Constructive and Destructive Interference

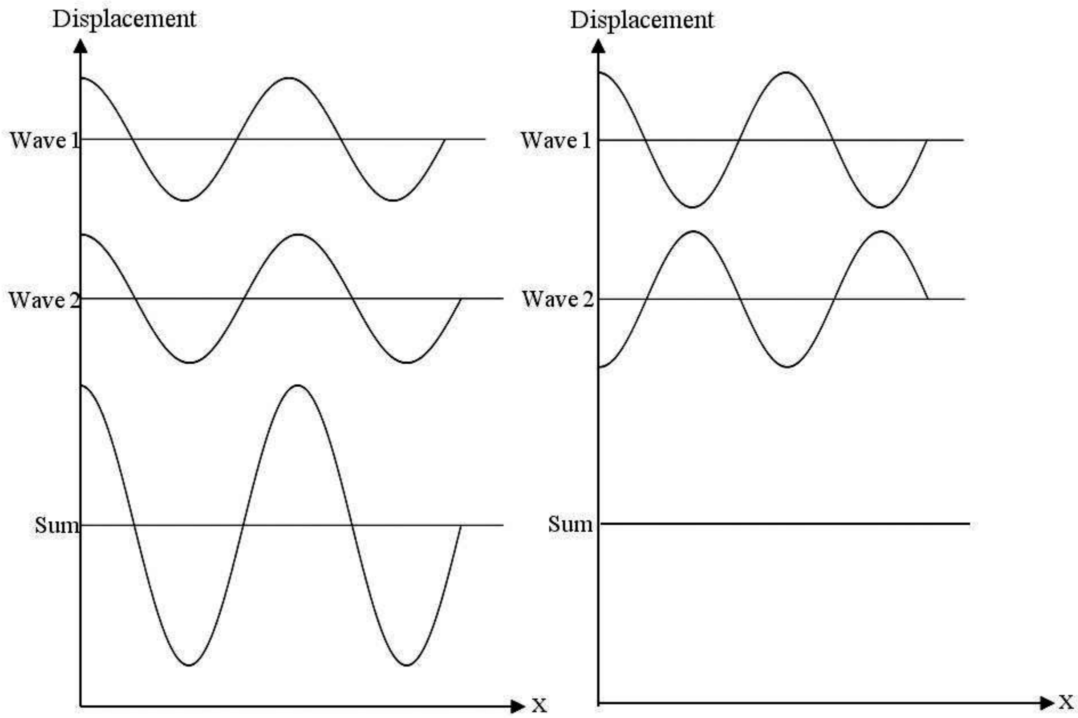


Figure. Left: Constructive interference of two waves of equal amplitude that are in phase. The amplitude of the resulting wave is twice as large. Right: Destructive interference of two waves of equal amplitude 180^0 out of phase. The resulting wave has zero amplitude.

Demonstrations

1. Play a sine function of 700 Hz from a single frequency generator into two loudspeakers. Pass in front of the speakers. Hear the interference maxima and minima.
2. Show two overlapping interference plates on the overhead projector. Observe the maxima and minima. The interference effect becomes pronounced as the separation *d* between the two sources becomes comparable to the wavelength λ, i.e. $\mathbf{d \approx \lambda}$.
3. Show the TTU mechanical wave maker on the overhead projector.
4. Throw two pebbles into a lake and observe the expanding circular wave fronts and how they merge. Note the interference maxima and minima.

Interference of sound and room acoustics

Interference of sound waves should be avoided in rooms where an even distribution of sound intensity is desired without "hotspots". The problem can be corrected with multiple reflections from walls and ceilings and the strategic placement of sound absorbers.

Diffraction and Superposition of Waves

Diffraction occurs around the edges of obstacles and narrow openings. Waves travel into "shadow regions" behind obstacles and sound can be heard "around corners".

Example

You are hiding from your mother behind a tree or below a window, but you hear her well because of the diffraction of the sound around the edges of the tree or window.

Demonstrations

1. Stand in the hallway to the side of the open classroom door. Say something. Students in the lecture room may hear you although they cannot see you.
2. Look at a CD or DVD and note the color spectrum from diffraction of the white light on the grooves of the disc.
3. Interference and diffraction of water waves are demonstrated effectively in our laboratory with a "ripple tank". What you see there is similar to what you hear in the case of sound waves.

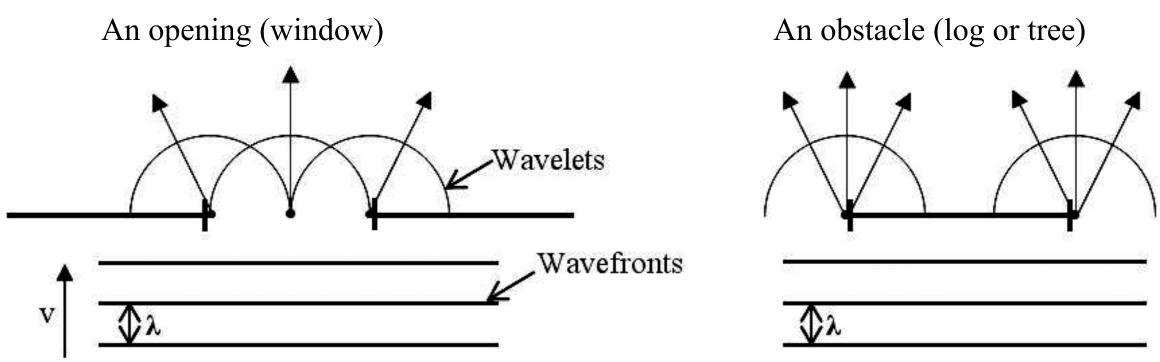


Figure. Application of Huygens's principle showing diffraction of sound waves into the "shadow region" behind an obstacle.

Condition for Diffraction

The size *s* of the obstacle (e.g. tree diameter, window opening) must be comparable to or not much larger than the wavelength λ of the wave, i.e. $\boldsymbol{\lambda \approx s}$. Otherwise the waves travel in straight paths without showing much diffraction into the "shadow regions".

Difference between Interference and Diffraction

Interference of waves occurs in free space without obstacles and around obstacles, while diffraction occurs only around obstacles.

Common Features of Interference and Diffraction

Waves resulting from interference and diffraction are explained by the Principle of Superposition of waves (Huygens's principle).

Diffraction and Interference in Room Acoustics

Diffraction of sound occurs around obstacles and openings in rooms, concert halls, auditoriums, and outdoors. Diffraction screens and reflectors at odd angles can be used to minimize diffraction and optimize the uniformity of sound. Interference of sound waves may occur without obstacles and produce areas of low and high intensities.

Beats

When two sine waves of similar frequencies and amplitudes interfere, so-called *beats* occur. You hear a swelling and decrease in sound intensity at the *beat frequency*, which is much lower than the frequency of either wave.
The amplitude of the beating wave varies between zero and the sum of the amplitudes of the component waves (assuming that the two waves have equal amplitude).

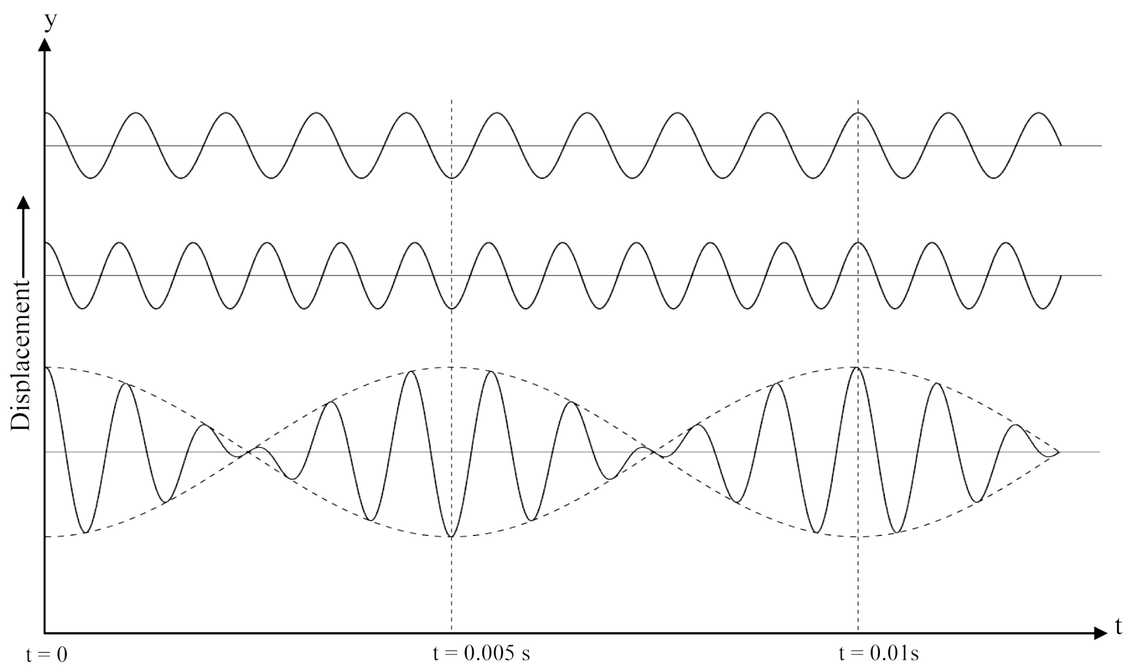


Figure. Beats calculated from the superposition of two sine waves having the same amplitude and frequencies of 900 Hz and 1100 Hz. The dashed line shows the "beating" of the resulting wave. The large frequency difference of 200 Hz was chosen for a better display and would not be realistic for actually hearing beats. (The two frequencies would be heard separately.)

Question
What is the maximum and minimum amplitude of the beating wave in the above figure, given equal amplitudes of the two original waves?
Answer: Maximum = ________ Minimum = _________

The beat frequency is the absolute value of the frequency difference

$$\mathbf{\Delta f_{beat} = | f_2 - f_1 |}$$

It does not matter which of the two waves has the higher frequency.

Exercise
Calculate the beat frequency of 200 Hz from the above formula and also read it off directly from the graph.

The frequency of the resultant wave is the average of the two frequencies:

$$\mathbf{f_{resultant} = (f_2 + f_1)/2.}$$

Exercise

Calculate the frequency of the resultant wave from the two frequencies in the preceding graph and also read it off directly from the graph.

Condition for Beats

The frequencies of the two sine waves that give rise to beats should be within about 5% of each other. For larger differences you start hearing the two frequencies separately and a low frequency roughness, which is called a "difference tone" instead of beats.

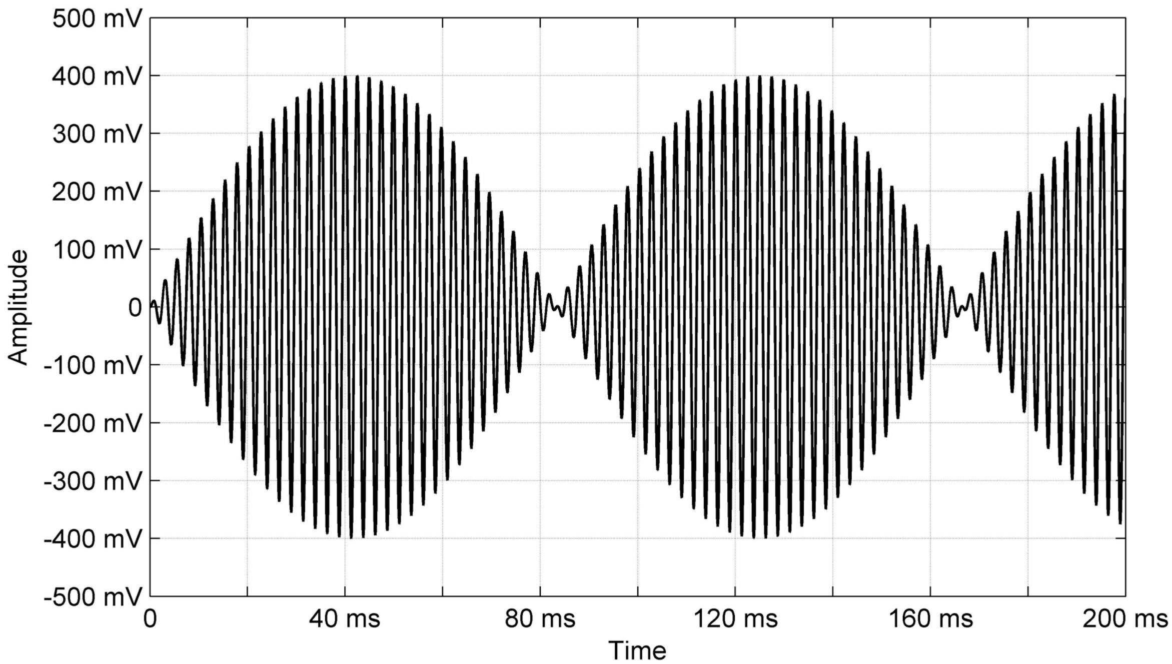


Figure. Beats recorded from the superposition of two sine waves with amplitudes of 200 mV and frequencies 400 Hz and 412 Hz, respectively. The beat frequency is 12 Hz and could be heard clearly. The frequency of the resultant sum wave as shown is 406 Hz.)The two individual sine waves are not shown.)

Demonstration

Use two frequency generators and set them to f_1 = 400 Hz and f_2 = 412 Hz, respectively. Listen to the beat frequency of 12 Hz.

Demonstrations of Beats

1.Use two speakers, each driven with a sine-wave generator. Start with the same frequency. Then slowly change one frequency and hear the beats. Start for instance with $f_1 = f_2 = 500$ Hz. Then go to $f_2 = 510$ Hz. You should hear a beat frequency of $\Delta f_{beat} = 10$ Hz and a frequency of $f_{tone} = 505$ Hz of the resultant wave.

2. Increase f_2 further. The beats will disappear at a frequency difference of about 5 – 10% and you will start hearing the two individual frequencies together with a rough deep tone.

3. Use a keyboard and play two adjacent semitones together. These are separated by about 6% in frequency. Listen to the fast beats. This interval sounds dissonant to most people. Now play larger musical intervals 2, 3, or 4 semitones apart. The beats disappear at two semitones, but the interval still sounds rough. Increase the interval further and hear the two separate frequencies. Once you reach the intervals of a minor third (3 semitones), major third (4 semitones), fourth (5 semitones), and fifth (7 semitones), a pleasing sound can be heard. This is especially true for musical fifths.

Example

Where do beats play a role?

You can tune string instruments by beats. Any musical fifths between neighboring open strings on a violin, viola, or cello that are out of tune will produce beats, because certain overtones from the two strings will beat with each other. Adjust the string tension to make these beats go away and you have tuned the instrument to perfect fifths as desired.

Demonstration

Tune a violin. The open strings of the violin are G3, D4, A4, and E5. The intervals between them are musical fifths. Tune the A-string to "Concert A4 = 440 Hz" by comparing with the key A4 on the piano. Then tune the D4 and E5 strings to perfect fifths by listening to any beats. Eliminate these beats by adjusting the tension of the strings. Finally tune the lowest string G3 on the violin by eliminating beats. Most people have a natural tendency to discern perfect fifths very acutely.

More Details on the Tuning by Beats

The vibrating strings of string instruments produce overtones. Certain overtones from different strings have the same frequency and they beat with each other when out of tune. By eliminating these beats you are tuning overtones to the same frequencies. The overtones include the especially important musical fifths. Tuning these is accomplished by adjusting the string tension. For more, see the harmonic series later.

Example

Start with A4 = 440 Hz on the A-string. The overtones of A4 are **A5** - E6 - A6 - etc. The overtones on the D4 string are D5 - **A5** - D6 - etc. Hence the A5 overtone from the D4 string beats with the A5 overtone from the A4 string. Eliminate these beats and you have tuned the D4 string! Similarly, the E6 overtone from the D4 string beats with the E6 overtone from the A4 string.

Polarization

A phenomenon called polarization occurs with transverse (but not with longitudinal) waves. In a polarized wave, the oscillating medium such as a steel string vibrates in one direction, e.g. up and down, while the wave propagates in the horizontal direction.

Example

1. Ocean waves are polarized largely in the vertical direction.
2. The blue sky consists of partially polarized light and becomes a deeper blue when you wear polarizing sunglasses.
3. The reflected light from glass and water surfaces is partially polarized, and sunglasses can reduce the glare. This allows you to see better through store windows or into the water when fishing. Light is a transverse electromagnetic wave with electric and magnetic fields oscillating perpendicular to the direction of propagation. The wave is *linearly polarized* if the electric field oscillates only in one direction.

Challenge Question

Why can sound waves not be polarized?

Answer: ____

Demonstration

A slinky is stretched in the horizontal direction. Shake an end in the vertical direction and a wave propagates parallel to the ground. The wave is “vertically polarized.”
Similarly, if you shake the wave horizontally (on a table) it is “horizontally polarized”.
In both cases the direction of polarization is perpendicular to the direction of propagation.

More Examples

1. The waves on vibrating strings and the solid material of timpani, cymbals etc. may be polarized. But note that the sound waves radiated from them are not polarized. Why?
2. Earthquake waves in Earth’s crust consist of longitudinal and transverse waves. The direction of polarization of the transverse waves can give information about the direction of movement of the underlying rock in the fault region.

Demonstrations with Polarized Light

Light is a transverse electromagnetic wave. Polarized light can be demonstrated with polarizers and polarizing sunglasses on an overhead projector.

a) Demonstrate how light can be extinguished with “crossed polarizers.”

b) Show how glare can be reduced with polarizing sunglasses.

Transverse and Longitudinal Waves
For transverse waves, the medium vibrates perpendicular to the direction of wave propagation. The medium consists of an elastic, solid material such as steel, aluminum, etc. Transverse waves do not occur in liquids or gases.

Demonstrations – Transverse Waves
1. Send transverse waves down a rope or slinky.
2. Demonstrate waves on the string of a monochord (sonometer) or violin.
3. Show transverse vibrations on a string. One end of the string is fastened to a vibrator on the table. The other end runs over a pulley at the edge of the table with a weight attached. The vibrator excites transverse standing waves on the string. The frequency can be adjusted to see various vibrational modes (harmonics).
4.Show transverse and longitudinal waves with a hand-cranked mechanical wave machine.

Longitudinal Waves
The medium oscillates back and forth along the propagation direction.
Such longitudinal or pressure waves occur in gases, liquids, and solids.

Examples
Sound waves in air are longitudinal waves.
Sound waves emitted by whales or submarines in the ocean are longitudinal waves.
Earthquake waves produce both longitudinal and transverse waves.

Demonstrations - Longitudinal Waves
1. Strike the coils of a slinky in the direction of propagation. This sends compressions and rarefactions down the spring and creates longitudinal waves.
2. Suspend a spring from a stand. Attach a vibrator to the bottom end of the spring. Vary the frequency of the vibrator. At certain discrete frequencies, standing longitudinal waves can be seen from the expansion and compression of the coils of the spring.
3. Rotate an upright vibrating tuning fork about its axis. When the tines vibrate toward and away from a listener, the sound is much louder than when they vibrate transversally with respect to the listener.

What Travels in a Wave?
A wave is a displacement of the vibrating medium from an equilibrium position. This displacement - not the medium - travels with the wave. The medium itself only oscillates back and forth about the equilibrium position.
The displacement of the medium in a wave contains *energy* that travels with the wave. This energy can do useful work.

Examples
1. A sound wave does work by moving your eardrum or the diaphragm of a microphone.
2. Ocean waves can move a buoy up and down and do work. A generator connected to such a "wave motor" can produce electricity.