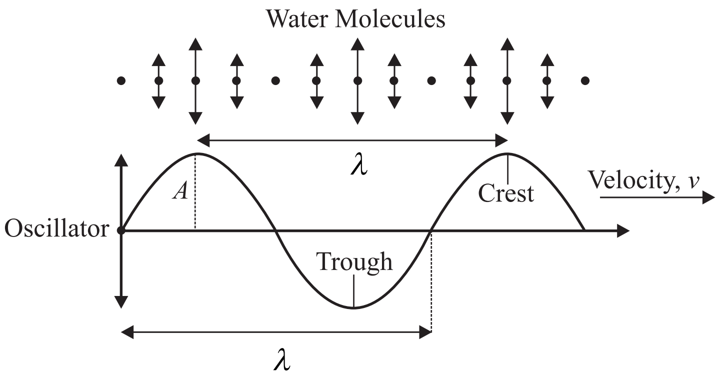
5 • Wave Nature of Sound

All sounds are waves produced by the vibrations of material objects.

Examples

- Pianos and violins produce sounds by vibrating strings.
- The human voice is produced by vibrating vocal cords.
- Wind instruments produce sounds by vibrating air columns.

The vibrating source sends a disturbance through the surrounding medium in the form of longitudinal waves. The frequency of the sound waves equals the frequency of the vibrating source. The human ear is sensitive to sounds which have frequencies between 20 Hz and 20 kHz.



It was explained earlier how a tuning fork produces a sound wave as a series of compressions and rarefactions. This wave is called a longitudinal wave as the molecules of air vibrate back and forth along the same direction as the wave progresses outwards.

Wave Nature of Sound

Sound is a wave motion. Waves have certain properties which include reflection, refraction, interference, diffraction etc... Sound has all of these properties.

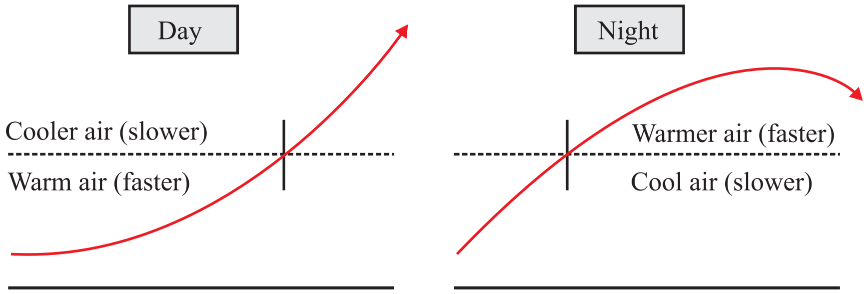
Reflection

Echoes provide practical evidence for the reflection of sound.

Demonstration of the reflection of sound
Sound from a loudspeaker travels down a tube and is reflected from a screen. The loudest sound is heard when a second tube is at the same angle to the normal as the first tube. Therefore like light waves the angle of incidence equals the angle of reflection.

Refraction

A practical example of this is the fact that sounds are more audible at night than during the day. This is because the speed of sound in warm air exceeds that in cold air. At night the air is usually colder near the ground than it is higher up and refraction towards the earth occurs. During the day the reverse is usually true.



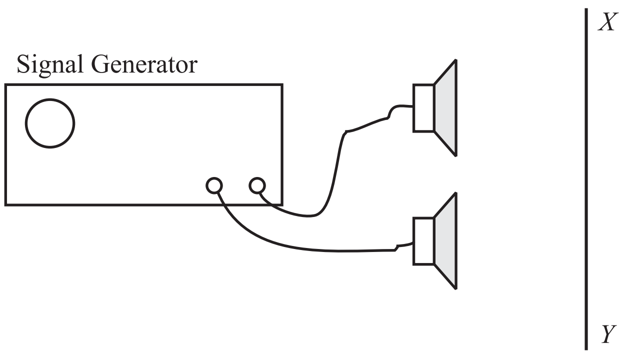
Diffraction

Sound can be heard around corners demonstrating its diffraction effects.

Interference

Demonstration of the interference of sound waves

Connect two identical loudspeakers to a signal generator. A person walking along the line *XY* will hear the loudness of the sound increasing and decreasing corresponding to an interference pattern. If one of the speakers is disconnected the effect disappears.



Another Demonstration

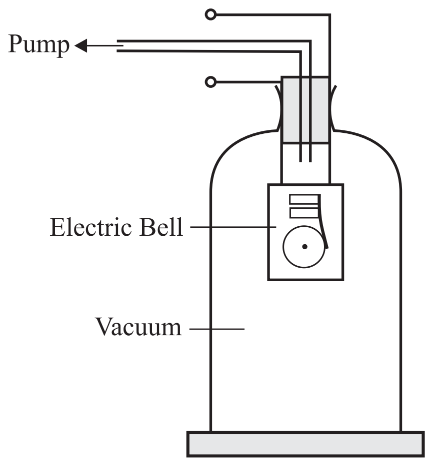
Strike a tuning fork and rotate it near your ear. The loudness increases and decreases in a regular way.

Sound is a longitudinal wave motion requiring a medium. Light is a transverse wave motion requiring no medium. Light, being a transverse wave, can be polarised; sound cannot.
Sound travels at different speeds through different media. It travels faster in denser materials.

	Speed of Sound
Air	340 m s^{-1}
Water	1500 m s^{-1}
Steel	5000 m s^{-1}

The speed of sound in air depends on the temperature of the air. Sound travels faster in a hot gas than in a cold gas, as was seen in the refraction of sound.

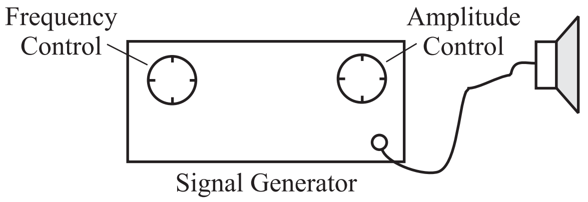
Demonstration showing sound requires a medium
An electric bell in a bell jar is ringing. As the air is gradually removed from the bell jar the sound fades.



Acoustics
The science of designing theatres and concert halls with the correct balance of reflection and absorption of sound is known as acoustics.
Noise Reduction by Destructive Interference
Large background noises can be reduced by destructive interference. Examples include the noise from exhaust systems in cars and air conditioning systems in buildings. A sample of this noise is taken electronically and inverted. It is fed into a microphone where the noise occurs where the two sounds destructively interfere.

Characteristics of Sound

Sound waves have certain characteristics. They can be examined by connecting a signal generator to a loudspeaker.



1. Loudness

When a loudspeaker cone vibrates, the amplitude of the oscillation is the maximum distance the loudspeaker cone moves backwards or forwards from its rest position. If its **amplitude** is increased, the amplitude of the sound waves is also increased and more sound energy travels out through the air every second passing into your ear. The loudness of the sound increases as the amplitude is increased.

The loudness of a sound wave depends on the amplitude of the sound wave.

2. Pitch

As the frequency of the generator is increased the notes emitted have a higher pitch. High pitched notes have a high frequency. The human ear can detect frequencies between about 20 Hz (20 waves every second) and 20 kHz.

The pitch of a sound wave depends on the frequency of the sound wave.

3. Quality

The quality or timbre of a note depends on the fundamental frequency of that note and the number of overtones present. The more overtones, the fuller and richer the note. The overtones to a basic note give the instrument its particular quality.

Dog Whistles: Dogs can hear frequencies higher than 20 kHz. A dog whistle produces sounds with a higher frequency than 20 kHz allowing dogs to hear it but leaving humans in peace.

Resonance

Consider a person going back and forth on a swing. The swing has a certain frequency, i.e. it completes a certain number of cycles every second. For example, a frequency of 2 Hz would mean it makes two complete cycles every second. If someone pushes the swing every time it makes it’s downward cycle then the amplitude of the swing becomes large.

This means that the amplitude of the swing will become large if the frequency of the pusher matches the natural frequency of the swing. If the frequencies do not match then the amplitude will not build up. If the swing was being pushed three times per second (the pusher has a frequency of 3 Hz) then there would be instants when the swing is pushed on the upward part of its cycle when it is moving towards the pusher. The effect of this is to kill off the amplitude. The term resonance is used to describe the build up of amplitude of a system when its natural frequency is matched by some external influence.

DEFINITION: **Resonance** occurs when a body is set vibrating at one of its natural frequencies by another body already vibrating at that frequency.

VOCAL CORDS: Sound produced by your vocal chords resonate in your larynx, throat, mouth and nose producing a louder sound.

EXAMPLES OF RESONANCE

1. **An army crossing a bridge**

An army is told to break step when crossing a bridge. A bridge has a certain natural frequency. If an army crossing the bridge happened to march with the same frequency as the natural frequency of the bridge then the amplitude could build up to such an extent that the bridge could crack and fall down.

2. **Sonometer**

The wire on a sonometer resonates when alternating current from a signal generator passes through it at one of the natural frequencies of the wire.

DEMONSTRATION OF RESONANCE USING TWO TUNING FORKS

Set a tuning fork vibrating. Put a non-vibrating tuning fork of the same frequency close by. Eventually the second fork starts vibrating due to resonance.

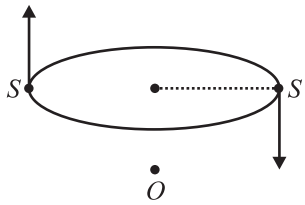
Doppler Effect

When an ambulance passes you the pitch of the siren changes. The pitch of the siren appears higher as it approaches you and then goes lower as it moves away (recedes) from you.

Definition: The **Doppler effect** is the apparent change in frequency due to the movement of the source emitting the waves or the observer or both.

Demo of the Doppler Effect

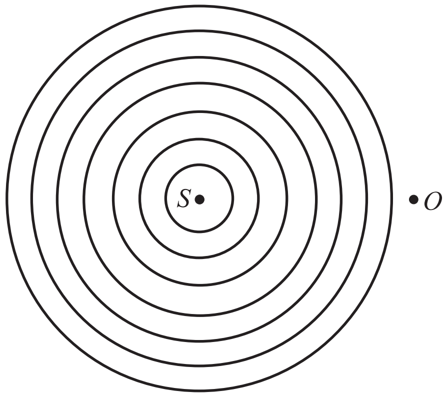
The Doppler effect can be demonstrated by swinging a whistle (the source *S*) above your head. An observer *O* will notice the pitch of the whistle changes. As the whistle approaches *O* the pitch appears higher and as it recedes from *O* it appears lower.



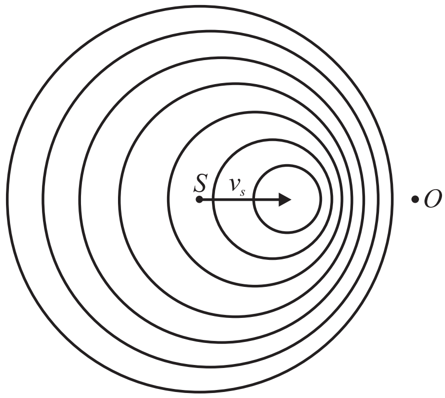
Explaining the Doppler Effect

Consider a source *S* emitting waves with a frequency *f* which travel with a velocity *v*. *O* is a stationary observer.

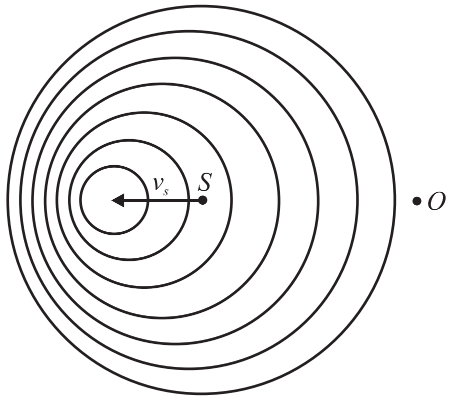
If both *S* and *O* are stationary, the number of waves emitted by *S* per second is the same as the number of waves received by *O* per second. The circles in the diagram represent the crests of the waves. The wavelength is the distance between the crests.



***S* approaches *O*:**
The wavelength decreases as the waves get "bunched up", i.e. the frequency increases as more waves pass *O* per second.



***S* recedes from *O*:** The wavelength increases as the waves get "spread out", i.e. the frequency decreases as fewer waves pass *O* per second.



DOPPLER PROBLEMS

$$f_1 = f\left(\frac{v}{v - v_s}\right)$$ **[APPROACHING]**

$$f_2 = f\left(\frac{v}{v + v_s}\right)$$ **[RECEDING]**

f: Actual frequency of the waves from the source (Hz)
v: Velocity of the waves (m s^{-1})
v_s: Velocity of the source (m s^{-1})
f_1: Apparent frequency as S approaches O (Hz)
f_2: Apparent frequency as S recedes from O (Hz)

NOTE: $f_1 > f > f_2$ always

Example: Bats use high frequency waves to detect obstacles. A bat emits a wave of frequency 68 kHz and wavelength 5·0 mm towards the wall of a cave. It detects the reflected wave 20 ms later. Calculate the speed of the wave and the distance of the bat from the wall. If the frequency of the relected wave is 70 kHz, what is the speed of the bat towards the wall?

SOLUTION

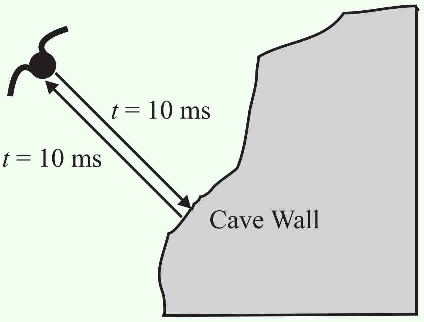
$f = 68 \text{ kHz} = 68 \times 10^3 \text{ Hz}$

$\lambda = 5 \text{ mm} = 5 \times 10^{-3} \text{ m}$

$t = 10 \text{ ms} = 10 \times 10^{-3} \text{ s} = 10^{-2} \text{ s}$

$v = f\lambda = 68 \times 10^3 \times 5 \times 10^{-3} = 340 \text{ m s}^{-1}$

$v = \dfrac{\text{Distance}(s)}{\text{Time }(t)} \Rightarrow s = vt = 340 \times 10^{-2} = 3 \cdot 4 \text{ m}$



Actual frequency, $f = 68 \text{ kHz}$

Apparent frequency, $f_1 = 70 \text{ kHz}$

Velocity of wave, $v = 340 \text{ m s}^{-1}$

Velocity of bat, $v_s = ?$

$$f_1 = \left(\frac{v}{v - v_s}\right) f \Rightarrow 70000 = \left(\frac{340}{340 - v_s}\right) 68000$$

$$\Rightarrow (340 - v_s) = 340\left(\frac{68}{70}\right) \Rightarrow (340 - v_s) = 330 \cdot 3$$

$$\therefore v_s = 9 \cdot 7 \text{ m s}^{-1}$$

· **Red Shift of Stars**
When a light source approaches, there is an increase in its measured frequency, and when it recedes there is a decrease in its frequency. An increase in light frequency is called a blue shift as the increase is towards the high frequency or blue end of the spectrum of colours. A decrease in frequency is called a red shift, referring to the lower frequency or red end of the spectrum.
A rapidly spinning star shows a red shift on the side turning away from us and a relative blue shift on the side turning towards us, which enables a calculation of the star's spin rate.
Stars in general show a red shift indicating that the universe is expanding.

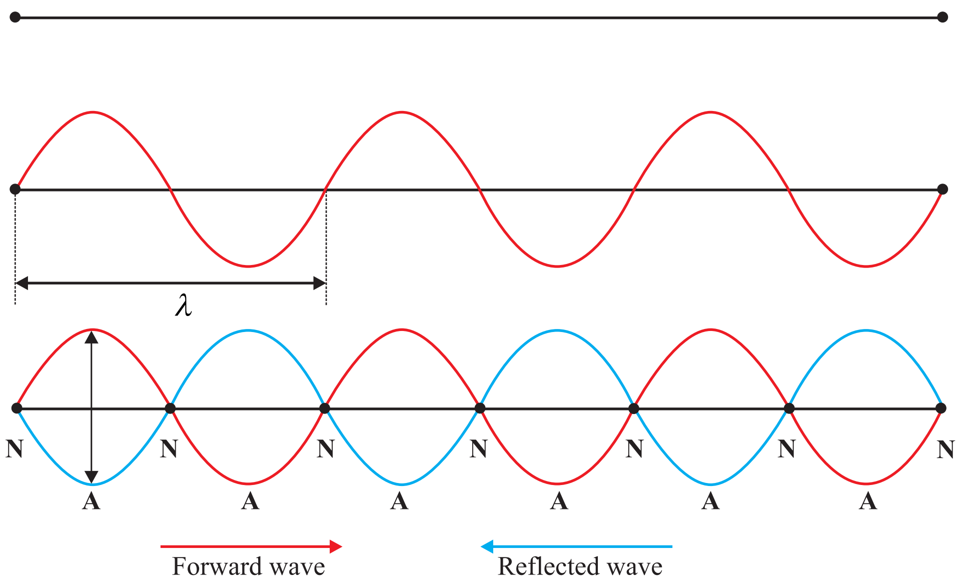
• **Speed Traps**
Microwaves encountering a moving object are reflected from it, and the frequency of the reflected signal is changed (Doppler shifted) relative to the emitted signal as there is relative motion between the source (reflecting object) and the observer (i.e. the receiver). This is the principle used in speed traps.

Standing Waves
Standing waves are created when two waves of equal frequency and amplitude travelling in opposite directions combine with one another when they are exactly out of phase (step).

This can occur when a wave is reflected. Send a wave along a string fixed at both ends. On reaching the end the wave is reflected back along the string, having suffered a phase change of $\frac{1}{2}\lambda$. There are now two waves of equal amplitude and frequency travelling in opposite directions.

As a result of interference a pattern of stationary or standing waves is set up. Certain points in the string are at rest and do not vibrate at all. These are called **nodes** (N). Other points vibrate with maximum amplitude. These are called **antinodes** (A).

Definition: When two periodic travelling waves of the same frequency and amplitude moving in opposite directions meet, they interfere with each other producing places of maximum amplitude (antinodes) and places of zero amplitude (nodes). The resulting wave formed is called a **stationary wave** or a **standing wave**.



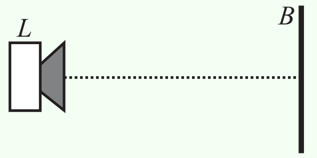
The distance between successive nodes is half a wavelength ($\frac{1}{2}\lambda$).

The distance between a node and antinode is a quarter of a wavelength ($\frac{1}{4}\lambda$).

Note: They are called standing waves because they don't go anywhere outside a certain region. The energy is trapped between the ends of the string where they bounce back and forth interfering with one another and producing a series of nodes and antinodes.

Example: A loudspeaker *L* emits sound waves of frequency 2 kHz. They are reflected off the board *B* setting up standing waves. If the average nodal distance is 8·5 cm, find the speed of sound in air.

Solution



$f = 2\times10^3$ Hz

Internodal distance $= 8\cdot5\times10^{-2}$ m $= \frac{\lambda}{2}$

$\therefore \lambda = 17\times10^{-2}$ m

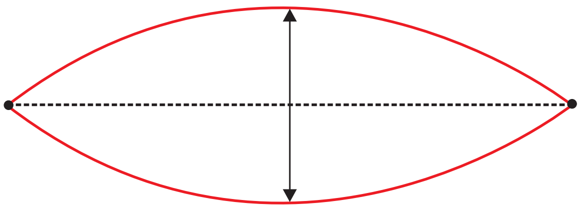
$v = f\lambda = 2\times10^3\times17\times10^{-2} = 340$ m s^{-1}

Vibrations in Strings and Pipes

Consider a stretched elastic string fixed at both ends. When a guitar string is plucked, transverse waves are sent along the string in both directions. The waves are reflected at the fixed ends and as they pass each other they combine to produce a standing wave. The standing waves have exactly the same frequency and wavelength as the progressive waves which produced them.

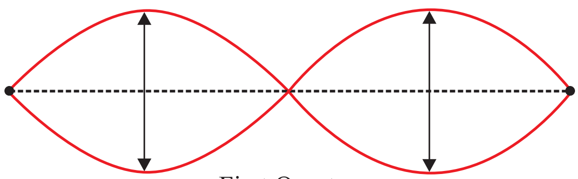
ALL THE HARMONICS

The simplest standing wave is one which has a node at either end and an antinode in the middle. It is vibrating in its **fundamental mode**. This mode of vibration is called the **first harmonic**.



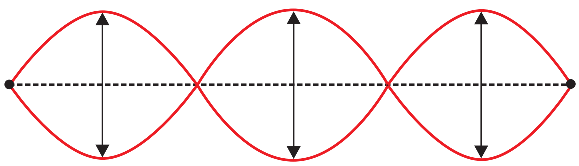
Fundamental Frequency

By plucking the string in a different way other possible modes of vibration occur at 2, 3 and 4 times the fundamental frequency. The second mode of vibration is called the second harmonic or **first overtone**.



First Overtone

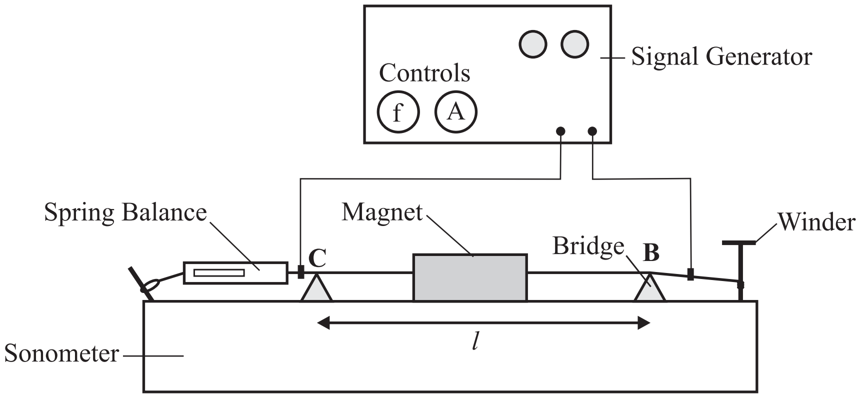
A string can vibrate with any of these frequencies or with a number of them at the same time. It is the combination of the fundamental note and overtones which gives the sound from a guitar string its particular quality.



Second Overtone

String section and woodwind section in orchestras: An orchestra produces a variety of standing waves from both their string instruments and wind instruments.

A **sonometer** is used to investigate what factors the frequency of a stretched string depends.
A signal generator and a magnet can be used to find the natural frequency of the string. If the string is plucked at its centre it vibrates at its natural frequency. A signal generator connected to the string sends alternating current (A.C.) down the wire string at any desired frequency. When the frequency of the generator matches the natural frequency of the wire it vibrates with a large amplitude, i.e. it resonates. This allows us to measure the natural frequency of the wire.



It is found by experiment that the frequency of the wire depends on the following factors:

1. Frequency is inversely proportional to the length: $f \propto \frac{1}{l}$

2. Frequency is proportional to the square root of the tension: $f \propto \sqrt{T}$

3. Frequency is inversely proportional to the mass per unit length, μ: $f \propto \frac{1}{\sqrt{\mu}}$

Putting everything together, the fundamental frequency, *f*, of a stretched string is given by:

$$f = \frac{1}{2l}\sqrt{\frac{T}{\mu}}$$

f: Fundamental frequency (Hz)
l: Length of the wire (m)
T: Tension in the wire (N)
μ: Mass per unit length (kg m^{-1})

Example: A wire of length 0·8 m and mass 0·05 kg is stretched between two points, so that the tension in the wire is 100 N. Find its mass per unit length and its fundamental frequency of vibration.

SOLUTION

$l = 0{\cdot}8$ m, $m = 0{\cdot}05$ kg, $T = 100$ N, $\mu = ?$, $f = ?$

$$\mu = \frac{\text{Mass}}{\text{Length}} = \frac{0\cdot 05 \text{ kg}}{0\cdot 8 \text{ m}} = 0\cdot 0625 \text{ kg m}^{-1}$$

$$f = \frac{1}{2l}\sqrt{\frac{T}{\mu}} = \frac{1}{2(0\cdot 8)}\sqrt{\frac{100}{0\cdot 0625}} = 25 \text{ Hz}$$

RESONANCE OF AIR COLUMNS

If a tuning fork is held over an air column, the sound of the tuning fork can be greatly amplified at a certain length, l. This is the position at which the air in the tube resonates. In fact there are several lengths at which the air resonates.

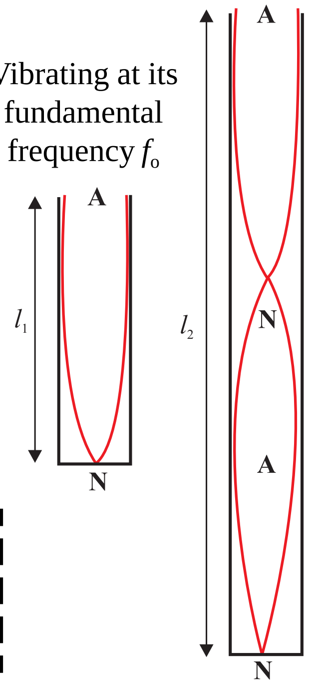
The prong of the tuning fork sends a longitudinal wave down the tube. The water reflects it and it moves back up where it is reflected once again by the vibrating source. If the tube is the proper length, the reflected wave will be reinforced by the vibrating source as it travels down the tube a second time. This situation is the same as the amplitude of the swing building up when the frequency of the pusher matches it.

Standing waves have been set up in the tube. The reflected longitudinal wave interferes with the oncoming wave to produce a standing wave pattern. A **node** (no displacement of the molecules) must occur at the closed end as the water at this end will not allow the air molecules to move downward. At the open end, the molecules can move easily into the open space. At this end there will be a maximum motion, i.e. an **antinode**. Therefore, there is an antinode at the open end of the tube where the air vibration is a maximum, and a node at the closed end where the air is unable to vibrate. The air column is now vibrating at its fundamental frequency, f_o.

Like the string other modes of vibration occur at higher frequencies than the fundamental frequency. In each case there must be a node at the closed end and an antinode at the open end. The first overtone occurs at a frequency that is **three** times (odd number) the fundamental frequency.

Vibrating at its fundamental frequency f_o

Vibrating at its first overtone $3f_o$



> **In a pipe closed at one end resonance occurs at the fundamental frequency and odd number multiples of this frequency.** (Only odd-numbered harmonics are present).

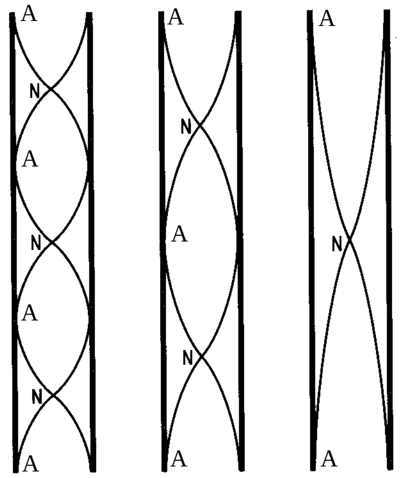
> The **flute**, **tin whistle** and the **recorder** are all examples of musical instruments in which a column of air resonates in a pipe open at both ends.

Pipe Open at Both Ends

Stationary waves can also be set up in an open pipe (open at both ends). In an open pipe there must be an antinode at each end. The diagram below shows the 3 simplest stationary waves that can occur.

The wavelength in the middle pipe is one-half of the wavelength in the first pipe. The wavelength in the third pipe is one-third of the wavelength in the first pipe. Therefore, the frequencies are f_o, $2f_o$, $3f_o$, ...

In an open pipe all harmonics may be present.



Sound Intensity Level

The intensity of a wave is a measure of how much energy it is carrying. The intensity is defined as follows: Set up a unit area perpendicular to the direction in which the wave is moving and measure the amount of energy passing through it every second. The more sound energy passing through it per second the greater the intensity.

Definition: The **sound intensity** at a point is the rate at which energy is crossing a unit area perpendicular to the direction in which the sound is travelling.

The units of sound intensity are Watts per metres squared (W m^{-2}).
Some approximate sound intensities:

Type of Sound	Intensity (Wm^{-2})
Barely audible sound	10^{-12}
Whisper	10^{-10}
Ordinary conversation	10^{-6}
Busy street traffic	10^{-5}
Pain producing	1

The loudness of a sound is a physiological response to the sound energy travelling into our ears. The sound intensity is an objective scientific measurement of the sound energy in a wave. The loudness of a sound does not seem to correspond directly to its intensity. For example, although the sound of ordinary conversation is certainly louder than the sound of a whisper, it is certainly not 10,000 times louder even though the intensities differ by this factor. What is needed is a new scale which corresponds more closely with the way the ear judges the loudness of a sound. An intensity level scale called the **decibel** scale was devised.

Sound intensity is measured in Watts per metre squared (W m^{-2}). **Sound intensity level** is measured in decibels (dB).

When the sound intensity in Watts per metre squared doubles, the sound intensity level increases by 3 dB.

Sound Level Meters and Ear Protection

Humans can hear sounds between 20 – 20 kHz of frequency. Frequencies greater than 20 kHz are known as ultrasonic sound. Dogs and bats are capable of hearing frequencies up to 35 kHz. Dog whistles transmit frequencies which humans cannot hear but dogs can hear.

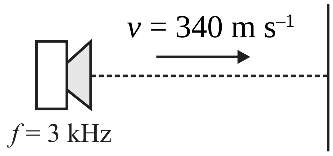
Even though the ear can hear quite a large range of frequencies, it is most sensitive to frequencies between 2 kHz and 4 kHz. Loud sounds outside these frequencies are not as damaging to the ear.

A sound level meter measures intensity level in decibels (dB). It has a frequency weighted scale where it suppresses those frequencies to which the ear is not sensitive. It is said to have a decibel adapted (dBA) scale. Long term exposure to excessive noise levels will be damaging to the ear. Ear protection is worn in the workplace where such noise levels exist.

Numerical Problems

Standing Waves

1. Find the average nodal distance of the standing waves set up.



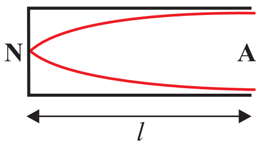
2. Standing waves of frequency 5 Hz are produced on water. If the speed of the waves is 60 cm s^{-1}, what is the distance between adjacent nodes?

3. A wave of frequency 550 Hz is reflected back along its own path, so that a standing wave is set up. If the distance between consecutive nodes on the standing wave is 31 cm, what is the speed of the wave?

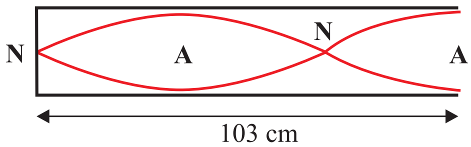
4. A stationary sound wave is set up between a loud-speaker and a wall. The distance between the 6th. and 16th. nodes is 3 m and the speed of sound in air is 340 m s^{-1}. Find the frequency of the sound wave.

5. A standing wave is set up between a loudspeaker, which is emitting a note of 1850 Hz, and a wall. If the distance between the first and ninth nodes is 73.5 cm calculate the velocity of the sound.

6. Stationary sound waves are set up in a tube closed at one end using a tuning fork of frequency 550 Hz. Find the minimum length, l, of tube required to get a standing wave (a node at the closed end and an antinode at the open end).
Constant: Velocity of sound in air = 340 m s^{-1}



7. Stationary sound waves are set up in a tube closed at one end using a tuning fork of frequency 250 Hz as shown.



Calculate the speed of sound in air.

Doppler Effect

8. A train is travelling at a speed of 45 m s^{-1} when its whistle emits a note of frequency 480 Hz. If the speed of sound in air is 340 m s^{-1}, what is the frequency of the note heard by a person standing near the track when the train is: (a) approaching; (b) receding?

9. An ambulance travelling at 28 m s^{-1} emits a sound from its siren at 400 Hz. What is the change in frequency heard by an observer standing on the side of the road as it passes?
Constant: Speed of sound in air = 340 m s^{-1}

10. A car, travelling at a constant speed of 25 m s^{-1}, passes a person standing at the side of the road. As the car passes, the frequency of the note from its horn, as heard by the pedestrian, falls from 388 Hz to 335 Hz. Calculate the actual frequency of the note and the speed of sound in air.

11. Standing on the side of the road you hear a frequency of 478 Hz from the siren of a police car as it approaches and 410 Hz as it recedes. Find the speed of the police car.
Constant: Speed of sound in air = 340 m s^{-1}

12. A bat at rest emits a signal of 35 kHz and receives back a signal of 35·3 kHz from a moving insect. What is the speed of the moving insect?
Constant: Speed of sound in air = 340 m s^{-1}

13. A train is moving at a speed of *u*. It emits a whistle of frequency, *f*. Show that the change in frequency heard by a man standing on a station is given by $\dfrac{2fu}{v - \frac{u^2}{v}}$, where *v* is the velocity of sound in air.

14. A moving sub emits a sonar at 600 kHz. It is observed by another stationary sub which picks up a frequency of 630 kHz. What is the speed of the moving sub.
Constant: Speed of sound in water = 1300 m s^{-1}

15. A whistle which is emitting a note of 1 kHz is whirled in a horizontal circle on the end of a string 1.2 m long at a constant angular speed of 50 rad s^{-1}. What are the highest and lowest frequencies heard by a person standing some distance away?
Constant: Velocity of sound in air = 340 m s^{-1}

Standing Waves in Strings

16. A wire of length 2.5 m and mass 0.85 kg is stretched between two points so that the tension in the wire is 180 N. Calculate its fundamental frequency of vibration.

17. A string of mass per unit length 0.06 kg m^{-1} and length 0·75 m is placed under a tension of 150 N. Calculate its fundamental frequency of vibration.

18. A string on a guitar is vibrating at its fundamental frequency of 350 Hz. Its length is 0·7 m and its mass per unit length is 0.04 kg m^{-1}. Calculate the tension in the string.

19. A wire of length 0·8 m and mass 0·05 kg is stretched between two points, so that the tension in the wire is 150 N. Find its mass per unit length and its fundamental frequency of vibration.

20. A wire of length 5 m and mass 0.05 kg is stretched between two points so that the tension in the wire is 350 N. Calculate its fundamental frequency of vibration.

21. When the tension in a stretched string is 50 N, its fundamental frequency is 280 Hz. Find its fundamental frequency if its tension is increased to: (i) 200 N, (ii) 250 N.

22. When the length of a stretched string is 80 cm its fundamental frequency is 360 Hz. Find its fundamental frequency if its length is increased to (i) 160 cm, (ii) 200 cm.

Sound Intensity

23. A hi-fi set consumes power at a rate of 10 W. It has a loudspeaker with an area of 65 cm^2 from which the sound comes. If 0·025 W of sound power comes from the speaker, what is the sound intensity at the speaker? With what efficiency does the set convert electrical energy to sound energy?

24. A certain loudspeaker has a circular opening with a diameter of 12 cm. Assume that the sound it emits is uniform and outward through the entire opening. If the sound intensity at the opening is 2.5×10^{-4} W m^{-2}, how much power is being radiated by sound by the loudspeaker?

25. A tube of length 16 cm, closed at one end, vibrates at its fundamental frequency. What is the frequency of the note emitted? What is the frequency of the first overtone from such a pipe?
Constant: Velocity of sound in air = 340 m s^{-1}

Answers

Standing Waves

1. 5·7 cm

2. 6 cm

3. 341 m s^{-1}

4. 566·7 Hz

5. 340 m s^{-1}

6. 15·4 cm

7. 343·3 m s^{-1}

Doppler Effect

8. (a) 553·2 Hz (b) 423·9 Hz

9. 66·3 Hz

10. 360 Hz; 341 m s^{-1}

11. 26 m s^{-1}

12. 1·45 m s^{-1}

14. 31·7 m s^{-1}

15. 1.214 kHz, 850 Hz.

Standing Waves in Strings

16. 5·27 Hz

17. 44·2 Hz

18. 7200 N

19. 0·08 kg m^{-1}, 38·7 Hz

20. 25 Hz

21. (i) 520 Hz, (ii) 581 Hz

22. 230 Hz, 184 Hz

Sound Intensity

23. 3·8 W m^{-2}; 0·25%

24. 2.8×10^{-6} W

25. 531·25 Hz, 1593·75 Hz