TYPES OF WAVES

• Consider a set of playground swings attached by a rope from seat to seat
• If you sit in the first swing and begin oscillating, this disturbs the equilibrium
• The connecting ropes cause the other swings along the line to oscillate as well
• Thus a travelling disturbance is created
• A disturbance that propagates from one place to another is referred to as a wave
• Waves propagate with well defined speeds determined by the properties of the material through which they travel
• Waves also carry energy (e.g. sound waves)
• It is important to distinguish between the motion of the wave itself and the motion of the individual particles that make up the wave
• For example a Mexican wave at a football match: the wave propagates around the stadium quicker than a person can, yet the individual people making up the wave stay in one place
TRANSVERSE WAVES (1)

- Consider a string, where one end is fixed to a wall
- The free end is pulled, thus producing a tension in the string
- As you move your hand up and down, a wave will travel along the string toward the wall
- If your hand moves up and down with simple harmonic motion, the wave on the string will be sinusoidal, and such a wave is called a **harmonic wave**
- The wave travels in the horizontal direction, even though the hand oscillates vertically in one spot
- Any point on the string moves vertically up and down
- The displacement of particles in a string is at right angles to the direction of propagation of the wave
- In a **transverse wave**, the displacement of individual particles is at **right angles** to the direction of propagation of the wave
As a wave on string moves horizontally, all points on the string vibrate in the vertical direction, as indicated by the blue arrow.
LONGITUDINAL WAVES

- In a **longitudinal wave**, the displacement of individual particles is **parallel** to the direction of propagation of the wave (e.g. sound waves)
- A speaker diaphragm vibrates horizontally with simple harmonic motion
- As it moves to the right, it compresses the air momentarily; as it moves to the left it rarefies the air
- A series or compressions and rarefactions then travel horizontally away from the loudspeaker with the speed of sound
WATER WAVES

- If a pebble is dropped into a pool of water, a series of concentric waves move away from the drop point.
- To visualise the movement of water as a wave travels by, the motion of a small piece of cork can be used to trace out the motion of the water itself.
- The cork moves roughly in a circular path, returning to approximately its starting point.
- Each element of water moves vertically and horizontally as the wave propagates in the horizontal direction (i.e. water wave is both transverse and longitudinal).
WAVELENGTH, FREQUENCY AND SPEED

- A wave is a regular, rhythmic disturbance that propagates from one point to another, repeating itself in both space and time.
- Points on the wave corresponding to maximum upward displacement are **crests**.
- Points of maximum downward displacement are **troughs**.
- Distance from one crest to the next (or between troughs) is the **wavelength**, \( \lambda \) (metres).
- **Period**, \( T \), is the time required for one wavelength to pass a given point.
- **Frequency**, \( f = 1/T \).
- Speed \( v = \lambda/T = \lambda f \) m/s.

\( t = 0 \)
\( t = T/4 \)  
\( t = T/2 \)  
\( t = 3T/4 \)  
\( t = T \)
THE SPEED OF A WAVE ON A STRING

- Speed of a wave is dependent by the properties of the medium through which it propagates.
- For a string, the speed of a wave depends on the tension and mass of the string.
- There has to be tension in a string in order for it to propagate a wave.
- The greater the tension (i.e. the less slack), the faster waves will travel through the string.
- A heavy string responds slowly to a given disturbance because of its inertia.
- The heavier a rope or string, the slower the speed of waves in it.
- Need to define the mass per unit length, \( \mu \), which is given simply by string mass/string length \( (\mu = m/L) \).
- Units of this quantity are kg/m.
- The speed \( v \) increases with tension, \( F \), and decreases with \( \mu \).
- Thus \( v = \sqrt{(F/\mu)} \).
- Units proven by \( \sqrt[(kg \ m/s^2)]/(kg/m)] \).
A wave on a rope: Example

- A 12m rope is pulled tight with a tension of 92N. When one end of the rope is shaken, it takes 0.45s for the disturbance to propagate to the other end. What is the mass of the rope?
• What happens when the wave reaches the end of the string?
• Suppose one end is firmly anchored to the wall
• When the pulse reaches the end, it exerts an upward force on the wall, trying to pull it into the pulse
• Since the end is tied down, the wall exerts an equal and opposite downward force to keep the end at rest
• As a result, the pulse is pushed back along the string, but is inverted
• If the far end is free by tying the string to a ring that is free to slide without friction up and down a vertical pole, then a pulse reaching that end lifts the ring upward, then lowers it again
• The pulse flicks the far end of the string in the same way that the other end was flicked to generate the pulse
• Therefore what is reflected is an identical pulse
SOUND WAVES (1)

• Sound is a wave propagating through the air at a speed of about 770mph (1240kph) (343m/s)
• A slinky is a useful mechanical model of a sound wave
• Oscillating a slinky at one end sends out a longitudinal wave that travels in the horizontal direction
• Wave consists of compressions and widely spaced regions
• A speaker produces sound waves by oscillating a diaphragm back and forth horizontally, and the corresponding wave travels away from the source horizontally
SOUND WAVES (2)

- The rarefactions and compressions of a typical sound wave are shown below.
- Also shown are the fluctuations in the density of the air and of the pressure versus $x$.
- The density and pressure oscillate in wave like fashion.
- Where the density is high, so is the pressure.
- The speed of sound is determined by the properties of the medium through which it propagates.

<table>
<thead>
<tr>
<th>Material</th>
<th>Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>6420</td>
</tr>
<tr>
<td>Granite</td>
<td>6000</td>
</tr>
<tr>
<td>Steel</td>
<td>5960</td>
</tr>
<tr>
<td>Pyrex glass</td>
<td>5640</td>
</tr>
<tr>
<td>Copper</td>
<td>5010</td>
</tr>
<tr>
<td>Plastic</td>
<td>2680</td>
</tr>
<tr>
<td>Fresh water (20 °C)</td>
<td>1482</td>
</tr>
<tr>
<td>Fresh water (0 °C)</td>
<td>1402</td>
</tr>
<tr>
<td>Hydrogen (0 °C)</td>
<td>1284</td>
</tr>
<tr>
<td>Helium (0 °C)</td>
<td>965</td>
</tr>
<tr>
<td>Air (20 °C)</td>
<td>343</td>
</tr>
<tr>
<td>Air (0 °C)</td>
<td>331</td>
</tr>
</tbody>
</table>
You drop a stone from rest into a well that is 7.35 m deep. How long does it take before you hear the splash? Hint: You might find it useful to use the following formula: \( x = x_0 + v_0 t + \frac{1}{2} at^2 \)
THE FREQUENCY OF A SOUND WAVE

- The frequency of a sound wave determines the **pitch** of a sound
- Piano keys produce sound with frequencies ranging from 55Hz to 4187Hz
- Humans can hear sounds between 20Hz and 20kHz
- Above this range, sounds are referred to as **ultrasonic**
- Sounds are classified **infrasonic** below 20Hz
- Bats and dolphins produce ultrasonic sounds, and use **echolocation** to navigate
- Ultrasound is commonly used in medicine, particularly to image a foetus in the womb
- This is achieved by sending bursts of ultrasound into the body and measuring the time delay of the resulting echoes, and it is thus possible to map out the location of structures hidden under the skin
- Ultrasound can also produce changes in the body that would otherwise require surgery
- A technique called **shockwave lithotripsy** involves sending an intense beam of ultrasound concentrated onto a kidney stone. After being hit by 1000-3000 pulses (23 joules per pulse), the stone is fractured into small pieces that the body can then eliminate
SOUND INTENSITY

- Loudness of sound determined by its **intensity** \((I)\)
- It is determined by the amount of energy \((E)\) that passes through a given area \((A)\) in a given time \((t)\)
- \(I = \frac{E}{At} \) units: W/m\(^2\) \((P = \frac{E}{t})\) so \(I = \frac{P}{t}\)
- Intensity applies to all types of wave, i.e. light intensity
- The loudness of a sound decreases as we move away from the source, thus the intensity also decreases
- This reduction in intensity is due to the fact that the energy emitted per time by the source spreads out over a larger area
- Consider the sound source (bat) and two observers (moths) at distances \(r_1\) and \(r_2\)
- Waves from bat propagate outwards spherically, forming concentric spheres
- Intensity detected by first moth is \(I_1 = \frac{P}{4\pi r_1^2}\)
- Area of sphere is \(4\pi r^2\)
- For 2\(^{nd}\) moth: \(I_2 = \frac{P}{4\pi r_2^2}\)
- \(P\) is same in each case
- Thus \(I_2 = \left(\frac{r_1}{r_2}\right)^2 I_1\)
- The intensity falls off with the square of the distance
SOUND INTENSITY: EXAMPLE

- Assuming no sound is reflected, that no sound is absorbed and that the sound propagates outward spherically, the intensity with distance from a point source is given by:

\[ I = \frac{P}{4\pi r^2} \quad \text{units: W/m}^2 \]

- Two people relaxing on a balcony listen to a songbird song. One person, only 1.0m from the bird, hears the sound with an intensity of \[2.8 \times 10^{-6}\] W/m\(^2\). What intensity is heard by the second person who is 4.25m away from the bird? Assume that no sound is reflected by either person. What is the power output of the bird’s song?
HUMAN PERCEPTION OF SOUND

• Human hearing is very sensitive
• Sounds can be detected that are about a million times fainter than a typical conversation to those that are a million times louder before experiencing pain
• We are able to hear sounds over a wide range of frequencies, from 20Hz to 20,000Hz (20KHz)
• A faint sound with an intensity of $10^{-11}$ W/m$^2$ causes a displacement of molecules in the air of about $10^{-10}$ m – roughly the diameter of an atom
• The way we perceive the loudness of a sound is also interesting
• Suppose you hear a sound of intensity $I_1$
• Next you hear a sound of intensity $I_2$, which seems “twice as loud”
• But when measured, $I_2$ turns out to be 10 times the intensity of $I_1$
• Similarly a third sound with intensity $I_3$ is twice as loud as $I_2$, but has 10 times the intensity
• Thus $I_2 = 10I_1$, $I_3 = 10I_2 = 100I_1$
• So our perception of sound is such that uniform increases in loudness correspond to intensities that increase by multiplicative factors
INTENSITY LEVEL AND DECIBELS

- Loudness is measured by the **intensity level** of a wave, and is given the symbol $\beta$
- Where $\beta = (10\text{dB})\log(I/I_0)$ units: decibel (dB)
- Log represents the logarithm to base 10, and $I_0$ is the intensity of the faintest sounds that can be heard, and experiments have shown that $I_0 = 10^{-12}$ W/m$^2$
- For the faintest of sounds, if this sound has intensity $I = I_0$, the corresponding intensity level is
  - $\beta = (10\text{dB})\log(I_0/I_0) = 10\log(1) = 0$
- Increasing the intensity by a factor of 10 makes the sound twice as loud
  - $\beta = (10\text{dB})\log(10I_0/I_0) = 10\log(10) = 10\text{dB}$
- Increasing the intensity by another factor of 10
  - $\beta = (10\text{dB})\log(100I_0/I_0) = 10\log(100) = 20\text{dB}$
- The loudness of a sound doubles with each increase in intensity level of 10dB
- The human ear detects increases of 1dB
- **Example:** A child crying emits sound with an intensity of $8.0\times10^{-6}$ W/m$^2$. Find the intensity level in dB for the child’s sounds. Find the intensity level for this child and its twin, both crying with identical intensities
  - A change of 3dB means that the intensity has increased twofold
THE DOPPLER EFFECT

- The **Doppler effect** is the change in pitch (frequency) of a sound due to the relative motion of the source of sound and the receiver.
- For example, as a car moves past as its horn is being pressed.
- The pitch of a sound increases as the source and receiver move closer together, and decreases as they move further apart.
- The Doppler effect is applicable to all types of wave phenomena, e.g. light waves.
- For light, this change in frequency means a change in colour.
- Distant galaxies are observed to be red shifted in the colour of their light which means they are moving away from the Earth.
- Objects in space moving towards Earth show a blue shift.
- The Doppler effect is different depending on whether the observer or the source is moving, and when both are moving – these will all be considered in the next slides.
• Consider a stationary source of sound in still air
• Sound is radiated from source with speed \( v \)
• Distance between compressions (circular pattern) is the wavelength \( \lambda \), and sound frequency \( f \), where \( v = \lambda f \)
• As observer moves closer to source, the sound appears to have a higher speed \((v + u)\), although the speed of sound relative to air is always the same
• Thus more compressions move past the observer than if he had been at rest
• Thus to the observer the sound has a frequency \( f' \)
• Where \( f' = \frac{\nu'}{\lambda} = \frac{(v + u)}{\lambda} \)
• Recall that \( \lambda = \frac{v}{f} \) and so \( f' = \frac{(v + u)}{(\nu / f)} = [\frac{(v + u)}{v}]f \)
• Finally \( f' = (1 + \frac{u}{v})f \), where \( f' > f \) (The Doppler effect)
• For an observer moving away: \( f' = (1 - \frac{u}{v})f \)
• General case: \( f' = (1 \pm \frac{u}{v})f \) with units s\(^{-1}\)
A street musician plays the A string of his violin, producing a tone of 440 Hz. What frequency does the cyclist hear as he (a) approaches and (b) recedes from the musician with a speed of 11.0 m/s?
For a moving source and stationary observer, the speed of a sound wave depends on the properties of the medium through which it propagates.

Once a source emits a sound wave, it travels through the medium with speed $v$ regardless of what the source is doing.

Sound waves from a moving source are bunched up in the direction of travel, thus causing a shorter wavelength and a higher frequency.

If the frequency of the source is $f$, it emits one compression every $T$ seconds ($1/f$).

During one cycle of the wave a compression travels a distance $vT$, and the source moves $uT$.

Thus the next compression is emitted behind the previous compression by a distance of $vT - uT$.

Wavelength in forward direction is thus

$$\lambda' = vT - uT = (v - u)T$$
• The speed of the wave is still $v$, so $v = \lambda f'$

• Where $f' = v/\lambda' = v/\left[(v - u)T\right]$ 

• Since $T = 1/f$, $f' = [1/1-(u/v)]f$

• Note that $f'$ is greater than $f$

• In the reverse direction $\lambda' = vT + uT = (v + u)T$

• Hence $f' = [1/1+(u/v)]f$

• General case: $f' = [1/1\pm(u/v)]f$

• The minus sign is used when the source moves towards the observer

• The plus sign is used when the source moves away from the observer
A train sounds its whistle as it approaches a tunnel in a cliff. The whistle produces a tone of 650.0Hz, and the train travels with a speed of 21.2m/s. Find the frequency heard by an observer standing near the tunnel entrance. The sound from the whistle reflects from the cliff back to the driver. What frequency does the driver hear?
DOPPLER-SHIFTED FREQUENCY ANALYSIS

- Graph above shows the Doppler-shifted frequency versus speed for a 400Hz sound source
- Upper curve corresponds to a moving source, lower curve to a moving observer
- Both cases have similar results for low speeds
- For a moving source the Doppler frequency grows without limits for speeds near the speed of sound
- If a source moves faster than the speed of sound, the sound it produces is perceived not as a pure tone, but as a shockwave – the **sonic boom**
- For a moving source, the wave crests become bunched up in the forward direction
- As the source approaches the speed of sound, the separation between crests approaches zero
DOPPLER EFFECT: GENERAL CASE

\[ f' = \left( \frac{1 \pm u_o/v}{1 \mp u_s/v} \right) f \]

- Above is the general case of the Doppler effect for situations in which both observer and source move.
- Let \( u_s \) be the speed of the source, \( u_o \) the speed of the observer, units are s\(^{-1}\).
- The Doppler effect is used in many technological applications.
- A radar gun measures the Doppler shifted frequency of radio waves reflected from an object to determine speed.
- The Doppler shift is used to measure the speed of blood flow in an artery or the heart itself, where a beam of ultrasound is directed towards to area.
- Some of this sound is reflected back by red blood cells moving through artery.
- The reflected sound is detected and its frequency used to determine the speed of blood flow.
- The Doppler effect is also used to measure speeds of galaxies using light waves.
- Light emitted from galaxies moving away from us have a lower frequency (red light) than those moving towards us.