DOPPLER EFFECT

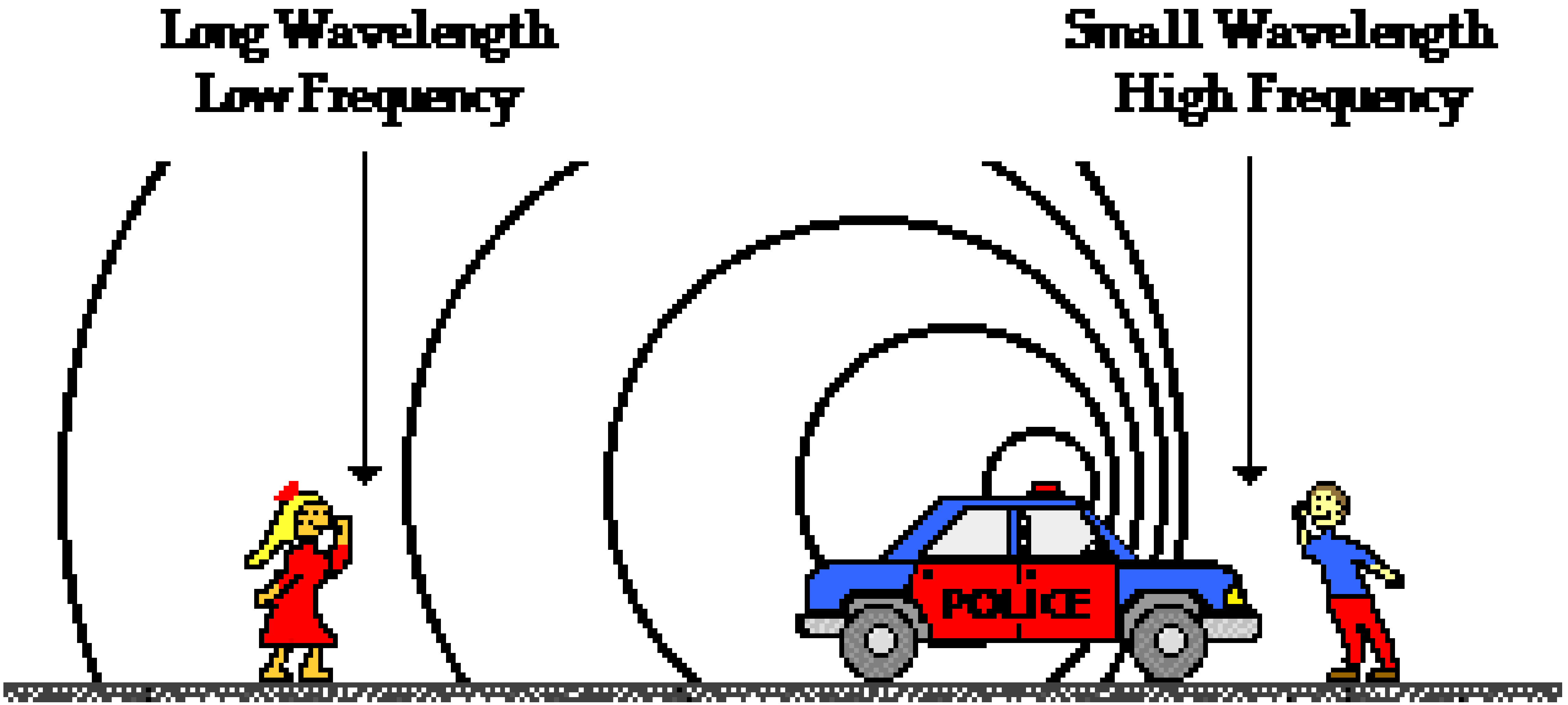
Doppler Effect

The apparent change in the frequency of sound due to relative motion between the observer and source of sound is called Doppler Effect.

- When an ambulance is racing toward you, the sound of its siren appears to be higher in pitch.

- When the ambulance is racing away from you, the sound of its siren appears to be lower in pitch.

The Doppler Effect for a Moving Sound Source



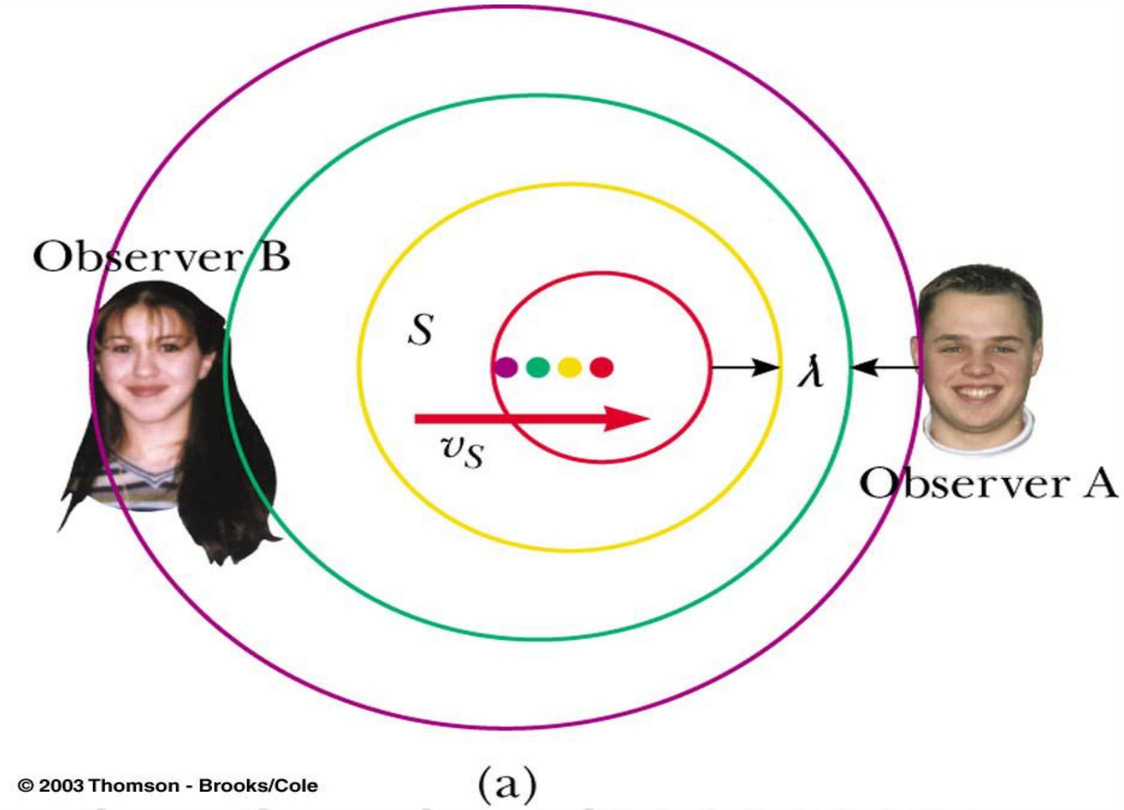
Doppler Effect

- A Doppler effect is experienced whenever there is relative motion between a source of waves and an observer.
- For instance, a fire engine or train passing you.
  - When the source and the observer are moving toward each other, the observer hears a higher frequency
  - When the source and the observer are moving away from each other, the observer hears a lower frequency
- Although the Doppler Effect is commonly experienced with sound waves, it is a phenomena common to all waves

Doppler Effect for a moving source

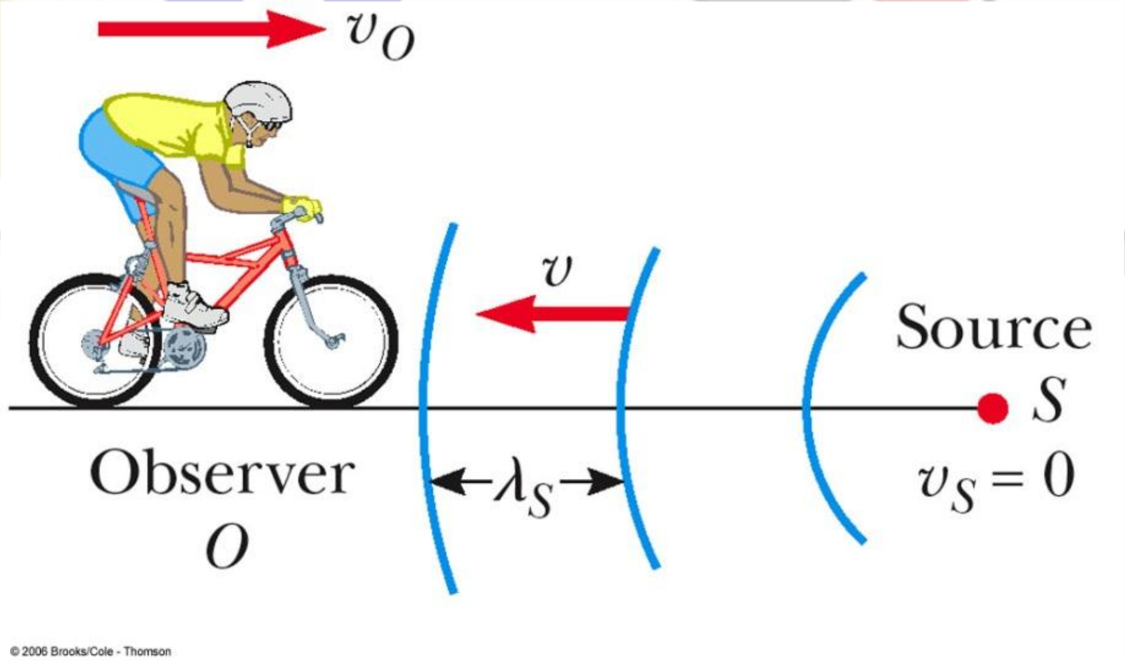
- As the source moves toward the observer (A), the wavelength appears shorter and the frequency increases

- As the source moves away from the observer (B), the wavelength appears longer and the frequency appears to be lower



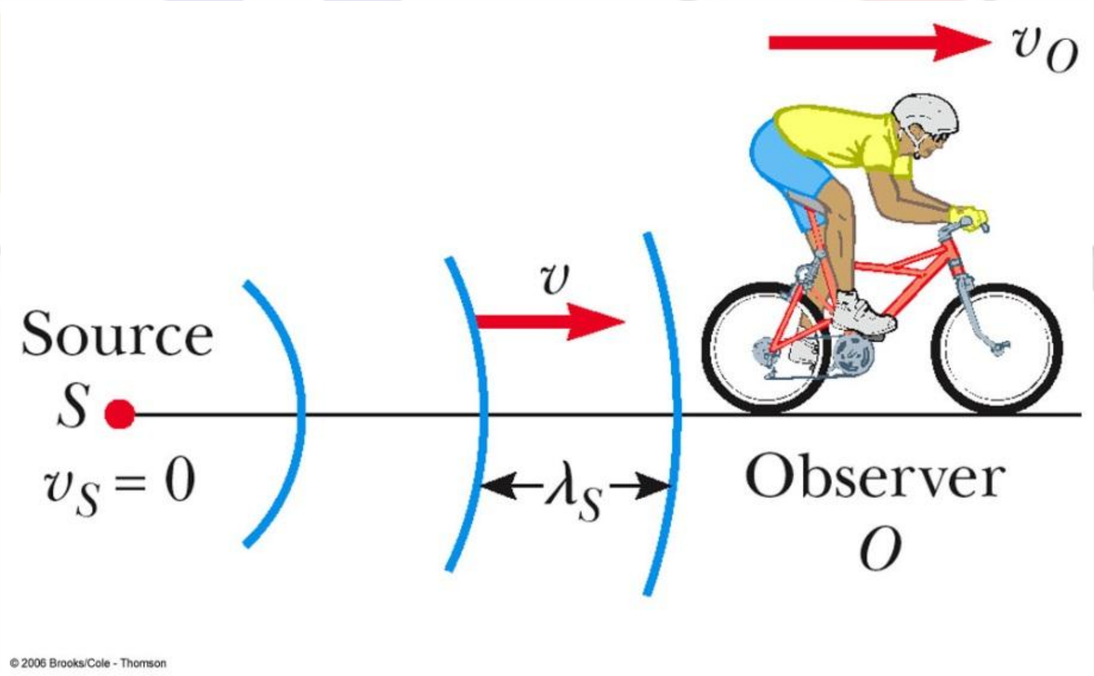
The Doppler Effect

- Due to this movement, the observer perceives a higher frequency.



The Doppler Effect

- The observer is moving away .
  - Due to this movement, the observer perceives a lower frequency.



(i) When Source is Moving and Observer is at Rest When source is moving with 'velocity towards an observer at rest, then apparent frequency

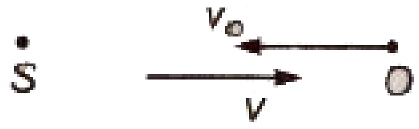
$$n' = n\left(\frac{v}{v - v_s}\right)$$

If source is moving away from observer, then

$$n' = n\left(\frac{v}{v + v_s}\right)$$

(ii) When Source is at Rest and Observer is Moving When observer is moving with velocity VO' towards a source at rest, then apparent frequency.

$$n' = n\left(\frac{v + v_o}{v}\right)$$

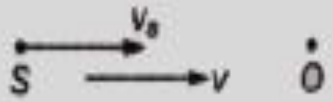


When observer is moving away from source, then

$$n' = n\left(\frac{v - v_o}{v}\right)$$

(i) When Source is Moving and Observer is at Rest When source is moving with 'velocity towards an observer at rest, then apparent frequency

$$n' = \left(\frac{v}{v - v_s}\right) n$$

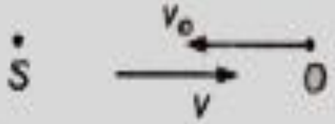


If source is moving away from observer, then

$$n' = \left(\frac{v}{v + v_s}\right) n$$

(ii) When Source is at Rest and Observer is Moving When observer is moving with velocity VO' towards a source at rest, then apparent frequency.

$$n' = \left(\frac{v + v_0}{v}\right) n$$



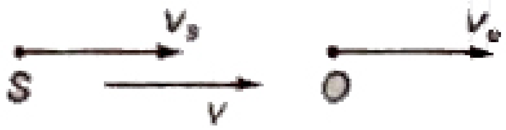
When observer is moving away from source, then

$$n' = \left(\frac{v - v_0}{v}\right) n$$

(iii) When Source and Observer both are Moving

(a) When both are moving in same direction along the direction of propagation of sound, then

$$n' = \left(\frac{V - V_0}{V - V_s}\right) n$$

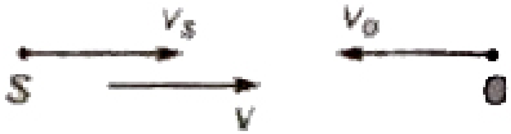


(b) When both are moving in same direction opposite to the direction of propagation of sound, then

$$n' = n\left(\frac{v + v_o}{v + v_s}\right)$$

(c) When both are moving towards each other, then

$$n' = n\left(\frac{v + v_o}{v - v_s}\right)$$



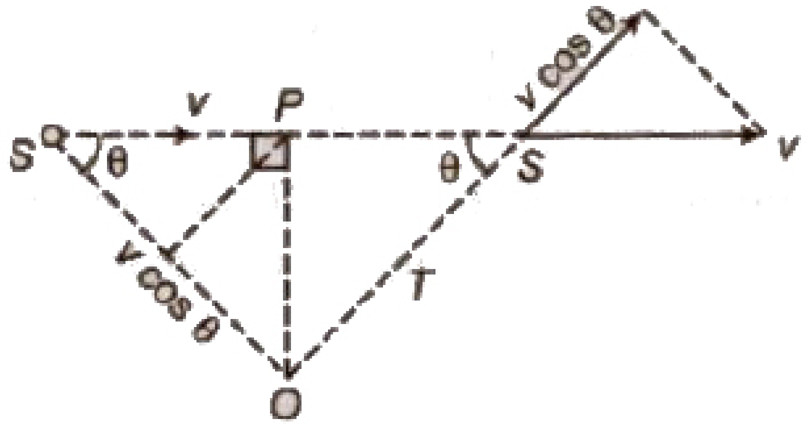
(d) When both are moving in opposite direction, away from each other, then

$$n' = n\left(\frac{v - v_o}{v + v_s}\right)$$

Transverse Doppler's Effect

(i) The Doppler's effect in sound does not take place in the transverse direction.

(ii) As shown in figure, the position of a source is S and of observer is O. The component of velocity of source towards the observer is V cos θ. For this situation, the approach frequency is



$$f' = \frac{v}{v - v_s \cos\theta} \times f$$

f ` which will now be a function of θ so, it will no more constant.

Similarly, if the source is moving away from the observer as shown above, with velocity component $V_s \cos\theta$ then,

$$f' = \frac{v}{v + v_s \cos\theta} \times f$$

(iii) If $\theta = 90°$, the $V_s \cos\theta = 0$ and there is no shift in the frequency.

Thus, at point P, Doppler's effect does not occur.

Effect of Wind

If wind is also blowing with a velocity w in the direction of sound, then its velocity is added to the velocity of sound. Hence, in this condition the apparent frequency is givenby

$$n' = n\left(\frac{v + w - v_o}{v + w - v_s}\right)$$

Applications of Doppler's Effect

The measurement of Doppler shift has been used

1. by police to check overspeeding of vehicles.
2. at airports to guide the aircraft.
3. to study heart beats and blood flow in different parts of the body.
4. by astrophysicist to measure the velocities of plants and stars.

If a car is moving while its horn is blowing, the frequency of the sound you hear is higher as the vehicle approaches you and lower as it moves away from you. This is one example of the Doppler effect. When the source and observer are moving toward each other, the observer hears a frequency higher than the frequency of the source in the absence of relative motion. When the source and observer are moving away from each other, the observer hears a frequency lower the source frequency. Doppler effect is a phenomenon common to all waves, not only to sound waves.

One finds the following general relationship for the observer frequency

$$f_o = f_s \left(\frac{v \pm v_o}{v \mp v_s} \right)$$

The upper signs ($+v_o$ and $-v_s$) refer to motion of one toward the other, and the lower signs ($-v_o$ and $+v_s$) refer to motion of one away the other.

- Q # 10. How should a sound source move with respect to an observer so that the frequency of its sound does not change?
- Ans. If the relative velocity between the source and the observer is zero, then there will be no change in frequency of the source and the apparent frequency will be zero.

Applications of Doppler effect.- **Radar System**

- In radar systems, the Doppler effect is used to determine the elevation and speed of aeroplane.
- Radar is a device, which transmits and receives the radio waves.
- If the aeroplane approaches towards the radar, then the wavelength of the wave reflected from the aeroplane would be shorter.
- If the aeroplane moves away from radar, then the wavelength of the wave reflected from the aeroplane would be larger.
- The speed of satellites moving around the earth can also be determined from the same principal.

SONARS In SONAR, the “Doppler detection” relies upon the relative speed of the target and the detector to provide and indication of the target speed. Its known military application include:

The detection and location of submarines

Control of anti-submarine weapons

Mine Hunting

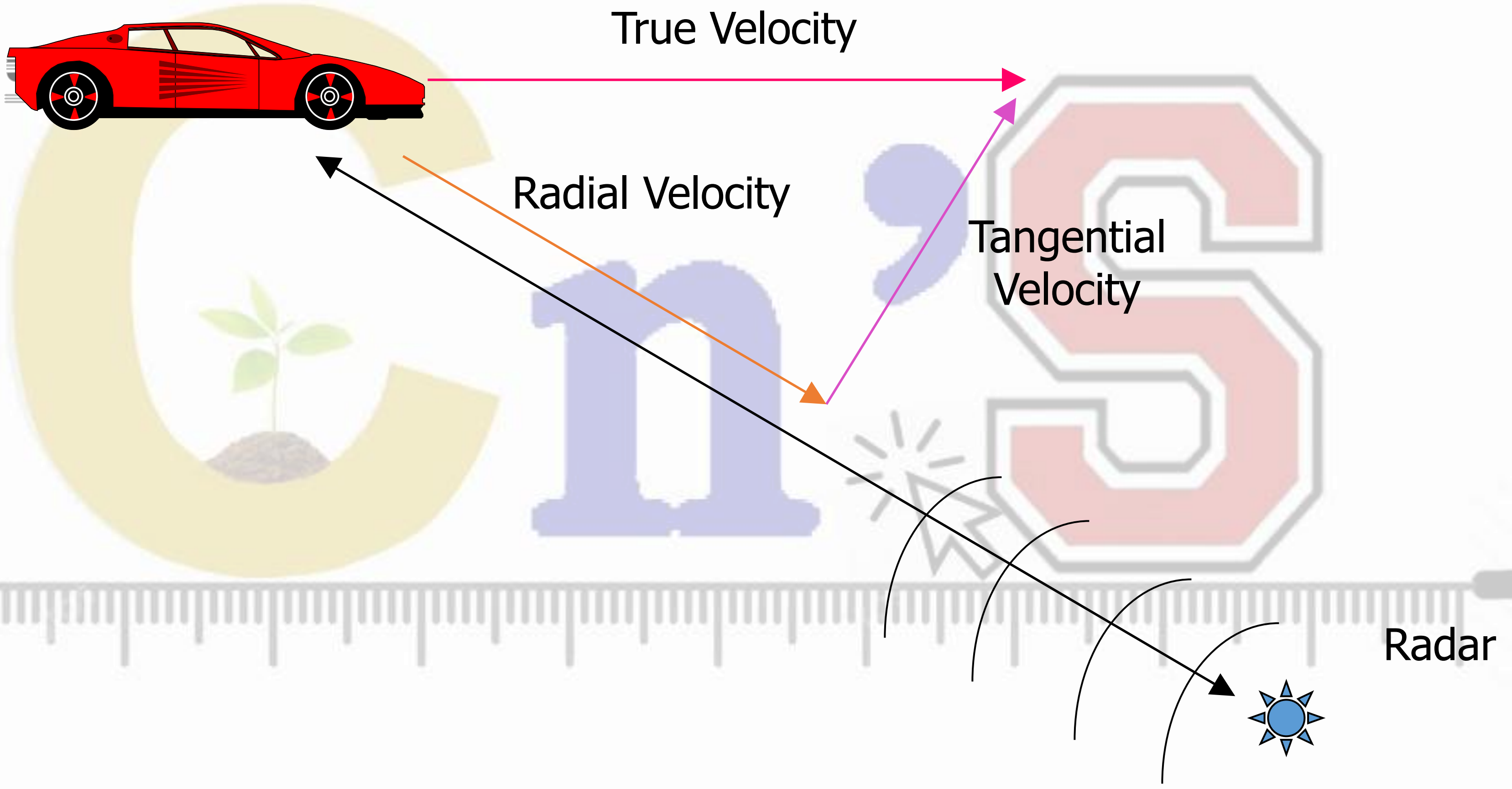
Depth measurement of sea

Applications in Astronomy

Astronomers use the Doppler Effect to calculate the speed of distant star and galaxies.

Star moving towards the Earth show a blue shift, while stars moving away from the Earth show a red shift. By comparing the line spectrum of light from the star with light from a laboratory source, the Doppler shift of the star’s light can be measured. Then the speed of star can be calculated. **Radar Speed Trap System** In radar speed tramp system, the microwaves are emitted from a transmitter in short bursts. Each burst is reflected off by any car in the path of microwaves. The transmitter is open to detect the reflected microwaves. If the election is caused by a moving obstacle, the reflected microwaves are Doppler shifted. By measuring the Doppler shift, the speed at which the car moves is calculated by the computer program

Police speed traps- Doppler shift gives radial velocity



- Applications

Doppler shift in Radar

Red & Blue Shifts – to study the motion of stars & galaxies.

- A train moving at a speed of 40 m/s sounds its whistle, which has a frequency of 500 Hz. Determine the frequency heard by a stationary observer as the train approaches the observer. (Take 340 m/s as the speed of sound in air.)

$$\begin{aligned} f_o &= f_s \frac{v}{v - v_s} \\ &= (500 \text{ Hz}) \frac{340 \text{ m/s}}{(340 \text{ m/s}) - (40 \text{ m/s})} = 567 \text{ Hz} \end{aligned}$$

Determine the frequency heard by the stationary observer as the train recedes from the observer.

$$\begin{aligned} f_o &= f_s \frac{v}{v + v_s} \\ &= (500 \text{ Hz}) \frac{340 \text{ m/s}}{(340 \text{ m/s}) + (40 \text{ m/s})} = 447 \text{ Hz} \end{aligned}$$

- An ambulance travels down a highway at a speed of 120 km/h, its siren emitting sound at a frequency of 400 Hz. What frequency is heard by a passenger in a car traveling at 90 km/h in the opposite direction as the car approaches?

$$
\begin{aligned}
v_s &= 120 \text{ km/h} = 33.3 \text{ m/s} \\
v_o &= 90 \text{ km/h} = 25.0 \text{ m/s} \\
f_o &= f_s \frac{v + v_o}{v - v_s} \\
&= (400 \text{ Hz}) \frac{340 \text{ m/s} + (25 \text{ m/s})}{(340 \text{ m/s}) - (33.3 \text{ m/s})} = 476 \text{ Hz}
\end{aligned}
$$

What frequency is heard as the car moves away from the ambulance?

$$
\begin{aligned}
f_o &= f_s \frac{v - v_o}{v + v_s} \\
&= (400 \text{ Hz}) \frac{340 \text{ m/s} - (25 \text{ m/s})}{(340 \text{ m/s}) + (33.3 \text{ m/s})} = 338 \text{ Hz}
\end{aligned}
$$

Qn

The siren of a police car emits a pure tone at a frequency of 1125 Hz. Find the frequency that you would perceive in your car.

(a) your car at rest, police car moving toward you at 29 m/s;

(b) police car at rest your moving toward it at 29 m/s

(c) you and police car moving toward one another at 14.5 m/s

(d) you moving at 9 m/s, police car chasing behind you at 38 m/s

Solution:

(a) Here $v_0 = 0 \quad v_s = 29 m/s$

$$f' = \frac{v}{v - v_s} f = \left(\frac{343}{343 - 29}\right) f = 1229 Hz$$

(b) $v_s = 0 \qquad v_0 = 29 m/s$

$$f' = \frac{v + v_0}{v} f = \frac{343 + 29}{343} (1125 Hz) = 1220 Hz$$

(c) $v_s = v_0 = 14.5 m/s$

$$f' = \frac{v + v_0}{v - v_s} f = \frac{343 + 14.5}{343 - 14.5} \times 1125 = 1224 Hz$$

(d) $v_0 = -9 m/s \qquad v_s = +38 m/s$

$$f' = \frac{343 - 9}{343 - 38} f = 1232 Hz$$

Q # 8. Two cars P and Q are travelling along a motorway in the same direction. The leading car P travels at a steady speed of 12 ms^{-1}; the other car Q, travelling at a steady speed of 20 ms^{-1}, sound its horn to emit a steady note which P's driver estimates, has a frequency of 830 Hz. What frequency does Q's own driver hear?

(Speed of sound = 340 ms^{-1})

Given Data: Speed of Car P: $v_P = 12\ ms^{-1}$, Speed of Car Q: $v_Q = 20\ ms^{-1}$, Apparent Frequency: $f' = 830\ Hz$, Speed of Sound $v = 340\frac{m}{s}$
To Determine: Frequency emitted by Q: $f_Q = ?$
Calculations: Relative Velocity $v_S = v_Q - v_P = 20 - 12 = 8\ ms^{-1}$ As source is approaching observer, therefore $f' = \left(\frac{v}{v-v_S}\right) f_Q \Rightarrow f_Q = \left(\frac{v-v_S}{v}\right) f'$ $\Rightarrow f_Q = \left(\frac{340-8}{340}\right) \times 830 = 810\ Hz$

Q # 9. A train sounds its horn before it sets off from the station and an observer waiting on the platform estimates its frequency at 1200 Hz. The train then moves off and accelerates steadily. Fifty seconds after departure, the driver sounds the horn again and the platform observer estimates the frequency at 1140 Hz. Calculate the train speed 50 s after departure. How far from the station is the train after 50 s? (Speed of sound = 340 ms^{-1})

Given Data: Speed of Sound $v = 340\frac{m}{s}$, Time $t = 50\,s$, Initial Velocity $v_i = 0\,ms^{-1}$ Frequency when Source is at rest $f = 1200\,Hz$, Apparent Frequency $f' = 1140\,Hz$
To Determine: (a) Speed of Source after 50 s: $v_S = ?$, **(b)** Distance Covered $d = ?$
Calculations: (a) As source is moving away from observer, therefore: $f' = \left(\frac{v}{v+v_S}\right)f$ $\Rightarrow v + v_S = \left(\frac{v}{f'}\right)f \Rightarrow v_S = \left(\frac{v}{f'}\right)f - v = \left(\frac{340}{1140}\right) \times 1200 - 340 = 17.9\,ms^{-1}$ **(b)** Average Velocity $v_{av} = \frac{v_i+v_S}{2} = \frac{0+17.9}{2} = 8.95\,ms^{-1}$ Distance Covered $d = v_{av} \times t = 8.95 \times 50 = 447.5\,m \approx 448\,m$

Q # 10. The absorption spectrum of faint galaxy is measured and the wavelength of one of the lines identified as the Calcium α-line is found to be 478 nm. The same line has a wavelength of 397 nm when measured in a laboratory. (a) Is the galaxy moving towards or away from the Earth? (b) Calculate the speed of the galaxy relative to Earth. (Speed of light = 3.0 x10^8 ms^{-1})

Given Data: Apparent Wavelength $\lambda' = 478\ nm = 478 \times 10^{-9} m$,

Actual Wavelength $\lambda = 397\ nm = 397 \times 10^{-9} m$, Speed of light $v = c = 3 \times 10^8 ms^{-1}$

To Determine: (a) Is the galaxy moving towards or away from the Earth?

(b) Speed of the galaxy relative to Earth v_S =?

Calculations: (a) Actual Frequency $f = \frac{v}{\lambda} = \frac{3\times10^8}{397\times10^{-9}} = 7.56 \times 10^{14}\ Hz$

Apparent Frequency $f' = \frac{v}{\lambda'} = \frac{3\times10^8}{478\times10^{-9}} = 6.28 \times 10^{14}\ Hz$

As $f' < f$, so galaxy is moving away from earth

(b) As source (galaxy) is moving away from earth, therefore: $f' = \left(\frac{v}{v+v_S}\right) f$

$\Rightarrow v + v_S = \left(\frac{v}{f'}\right) f \Rightarrow v_S = \left(\frac{3\times10^8}{6.28\times10^{14}}\right) \times 7.56 \times 10^{14} - 3 \times 10^8$

$\Rightarrow v_S = 3.611 \times 10^8 - 3 \times 10^8 = 0.611 \times 10^8 ms^{-1} = 6.11 \times 10^7 ms^{-1}$

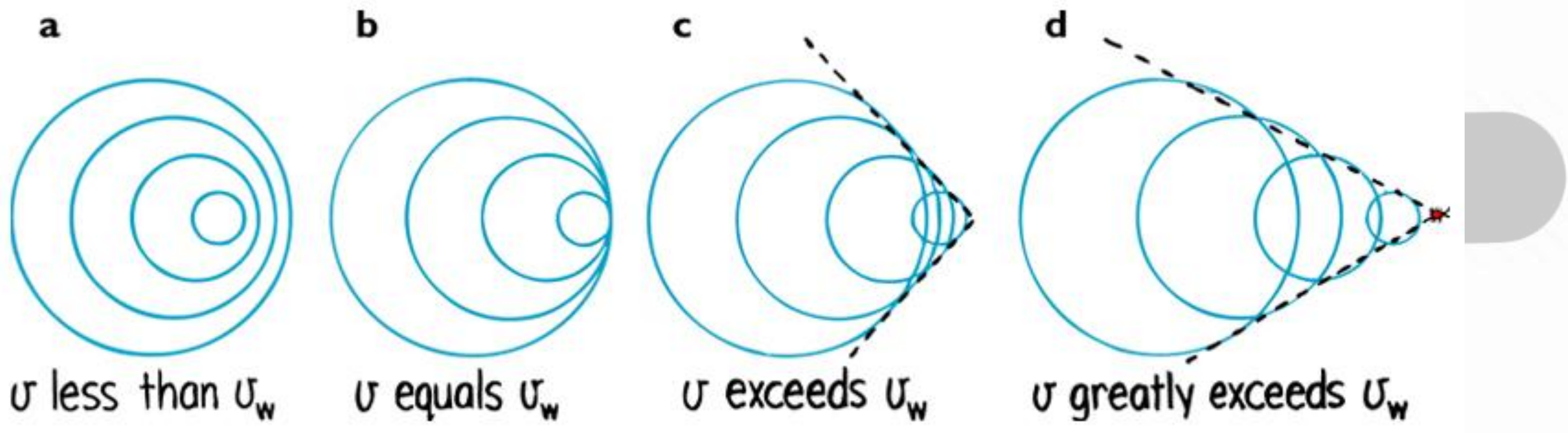
Bow Wakes

- **Bow Wake** – is created when a wave source move faster than the propagation speed of the wave.

  - Bow wakes are V-Shaped wakes seen in the wake of passing boats.

Bow Waves

- Wave shape produced when an object moves faster than the speed of the wave surrounding it
  - Two-dimensional



Boat Wake

Breaking the 'sound' barrier in a canoe!

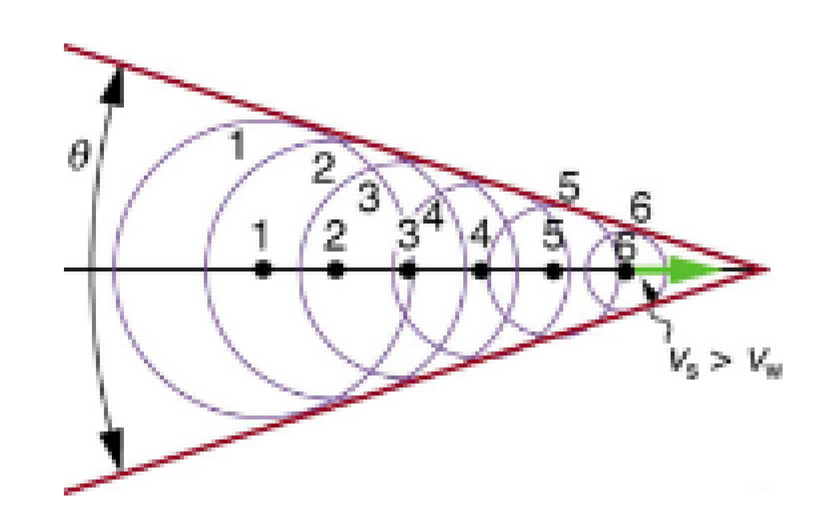
If the canoe moves faster than the water wave velocity, shock wave also builds up where all the crests line up.

For water wave velocity ~1 m/s, so Mach 2 is 2 m/s
= 4.5 mph !!

Bow Wakes

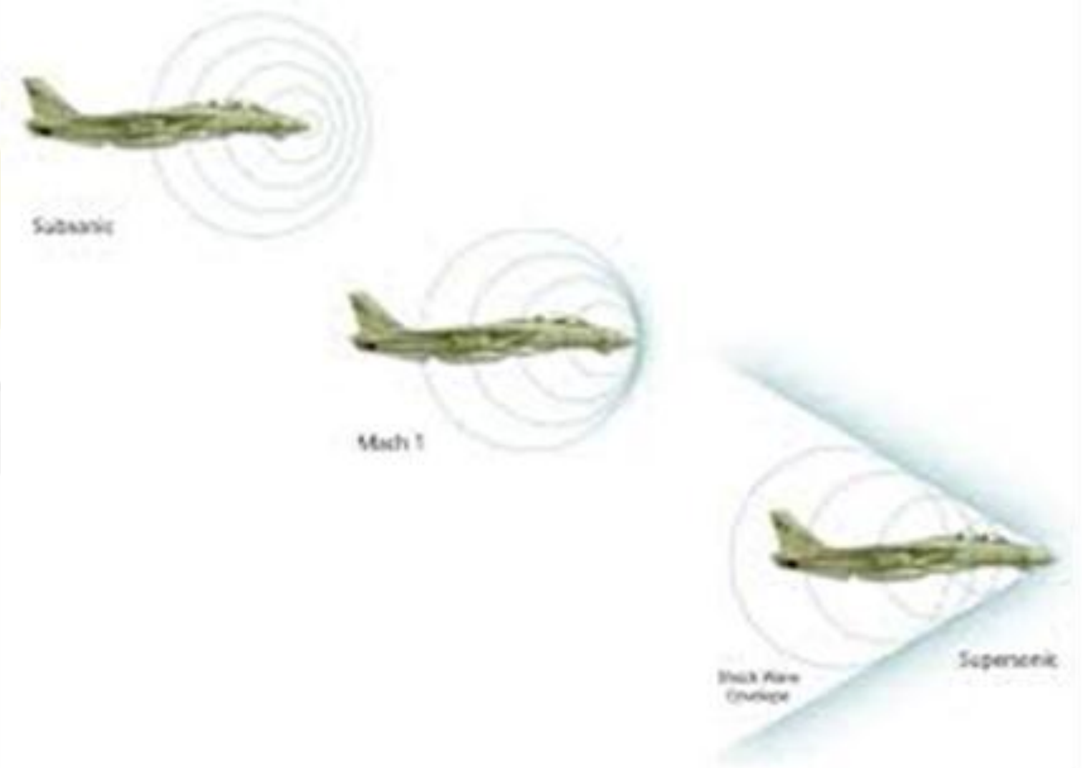
- The waves made by the object constructively interfere with each other making a high amplitude wake.

- Bow wakes are also known as shock waves.



Sonic Boom

- **Sonic Boom** – is the sound associated with the bow wake of an object traveling through air at a speed greater than the speed of sound.



Sonic BOOM

- An aircraft traveling through the atmosphere continuously produces air-pressure waves similar to the water waves caused by a ship's bow.

- When the aircraft exceeds the speed of sound, these pressure waves combine and form visible shock waves →

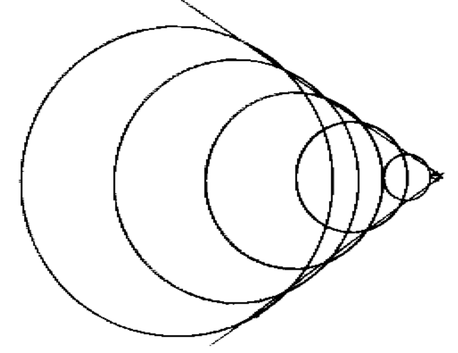
Sub & Super Sonic

Subsonic - slower than the speed of sound

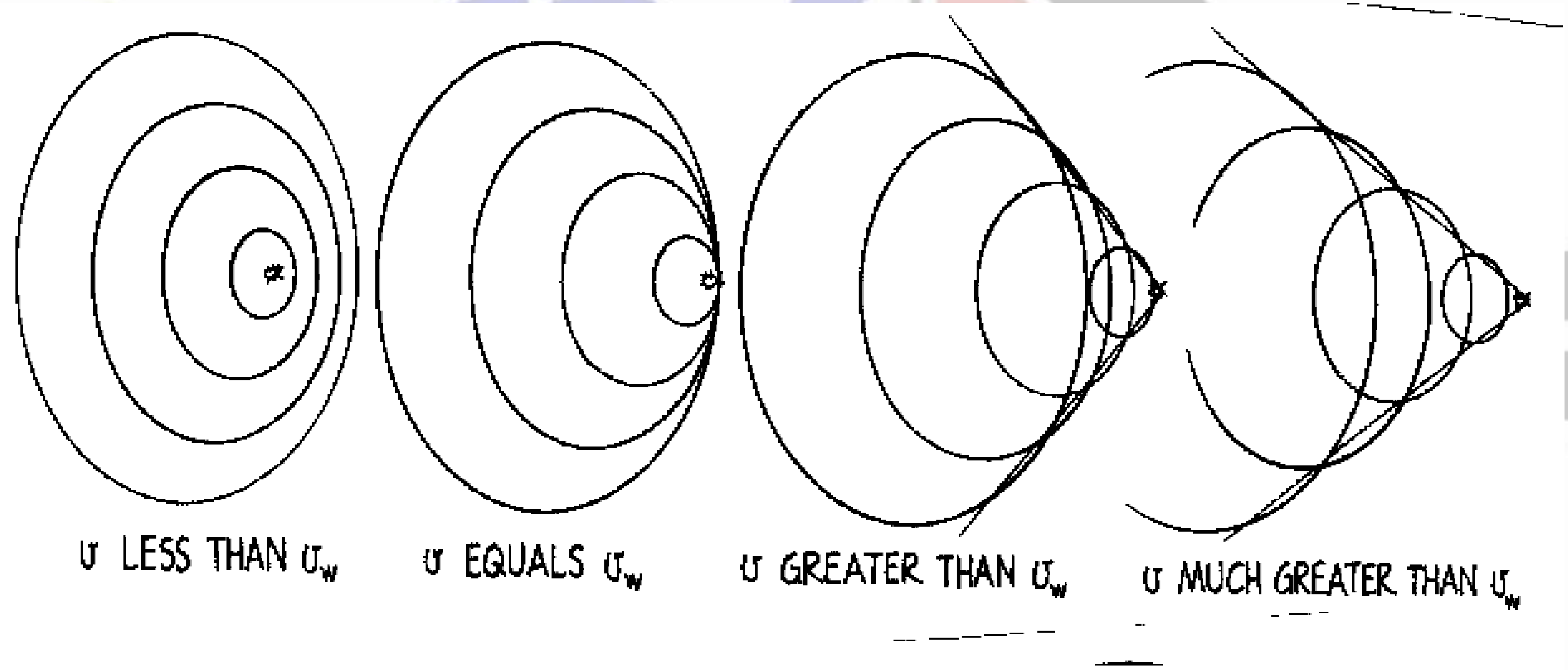
Supersonic - Faster than the speed of sound

- Mach Number $= \dfrac{\text{speed of object}}{\text{speed of sound}}$

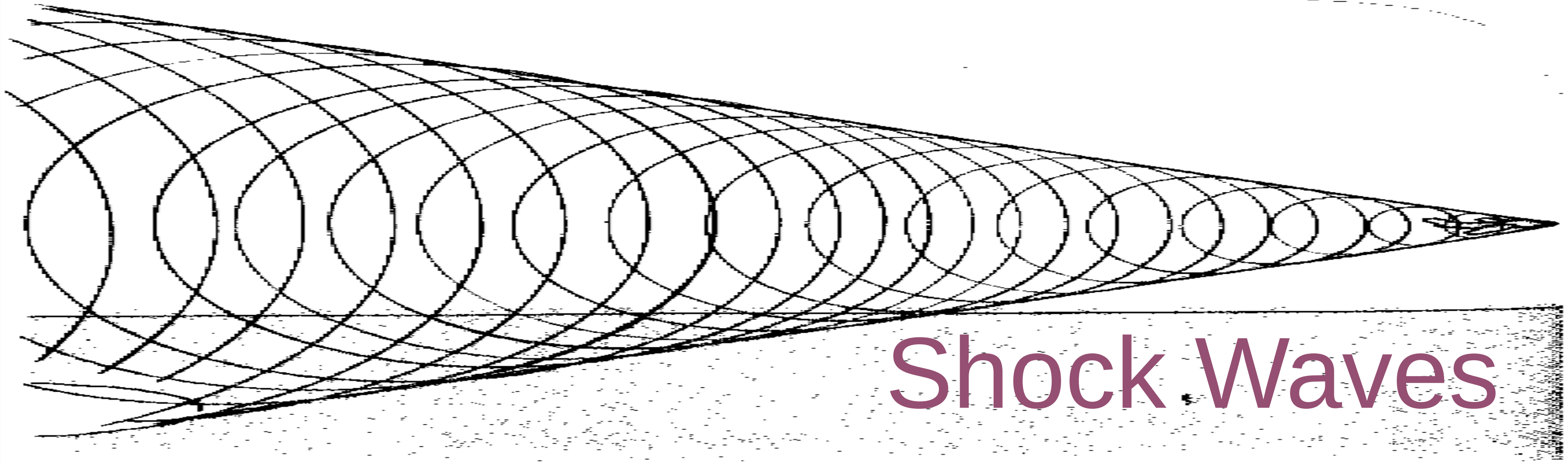
Bow waves



V-shaped pattern made by overlapping crest

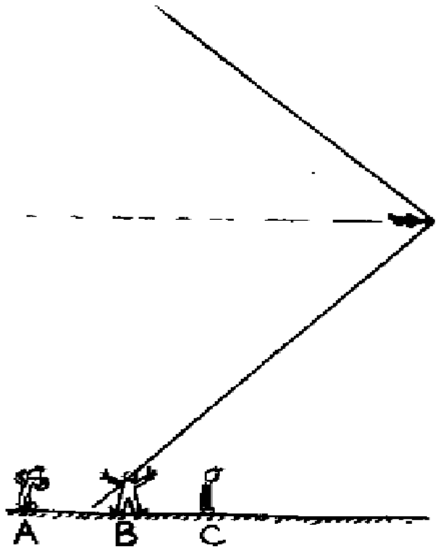


Shock Waves



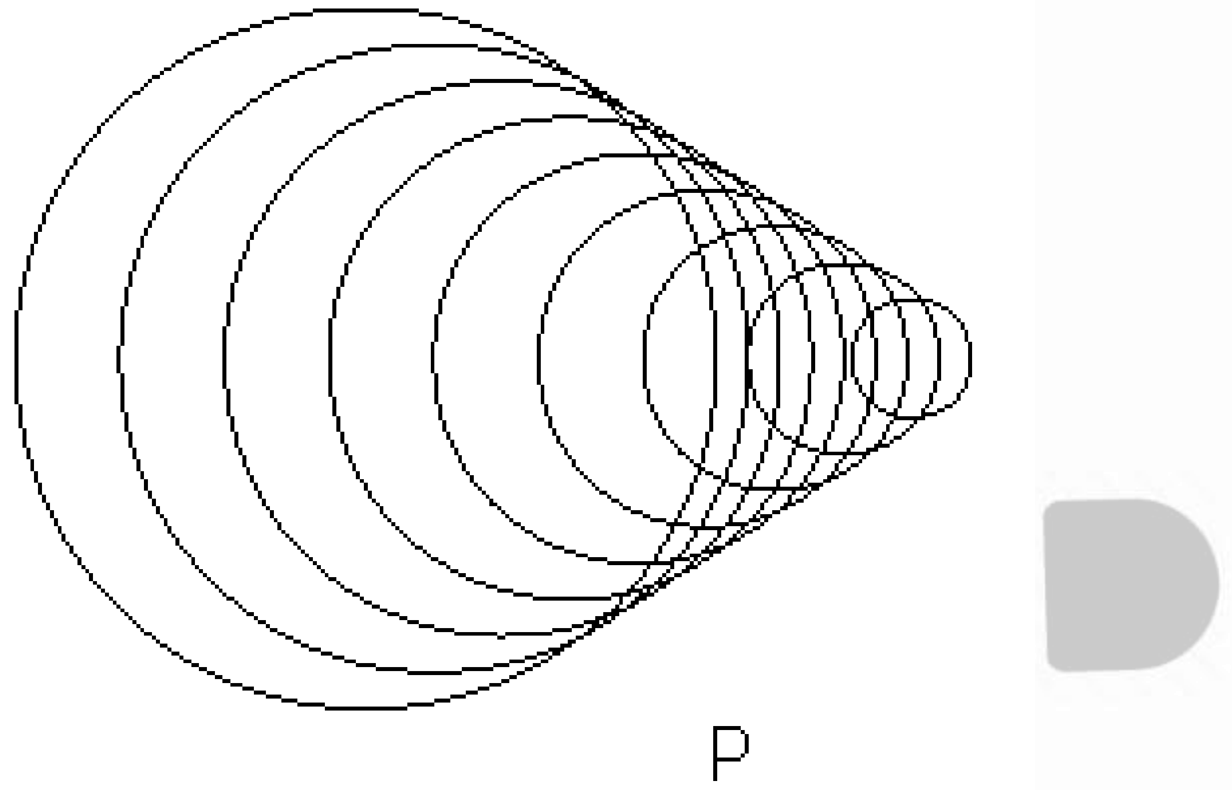
- Produced by supersonic aircraft, three-dimensional cone shaped

- Sonic boom – sharp crack heard when conical shell of compressed air that sweeps behind a supersonic aircraft reaches listeners on the ground below.

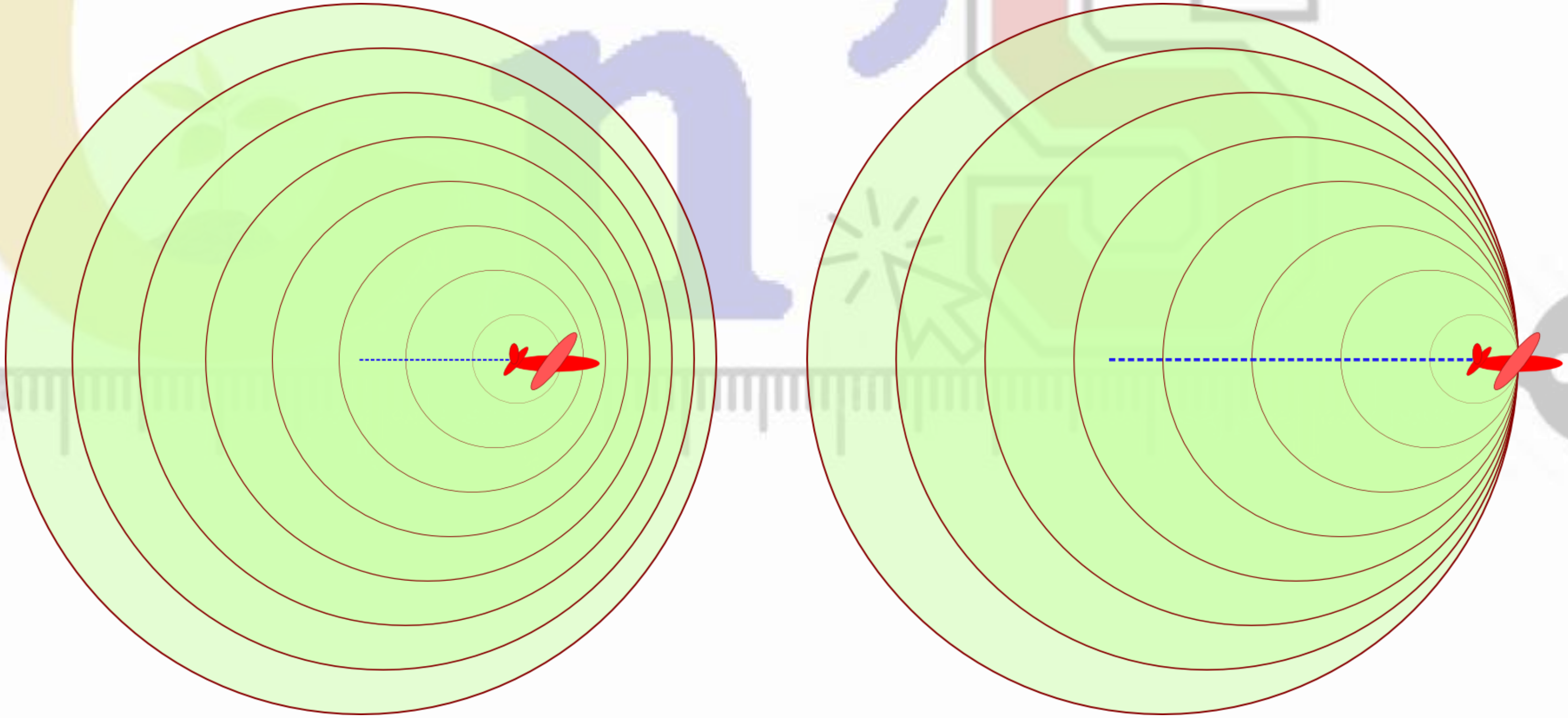


Shock Waves and Sonic Booms

- A shock wave results when the source velocity exceeds the speed of the wave itself
- The circles represent the wave fronts emitted by the source

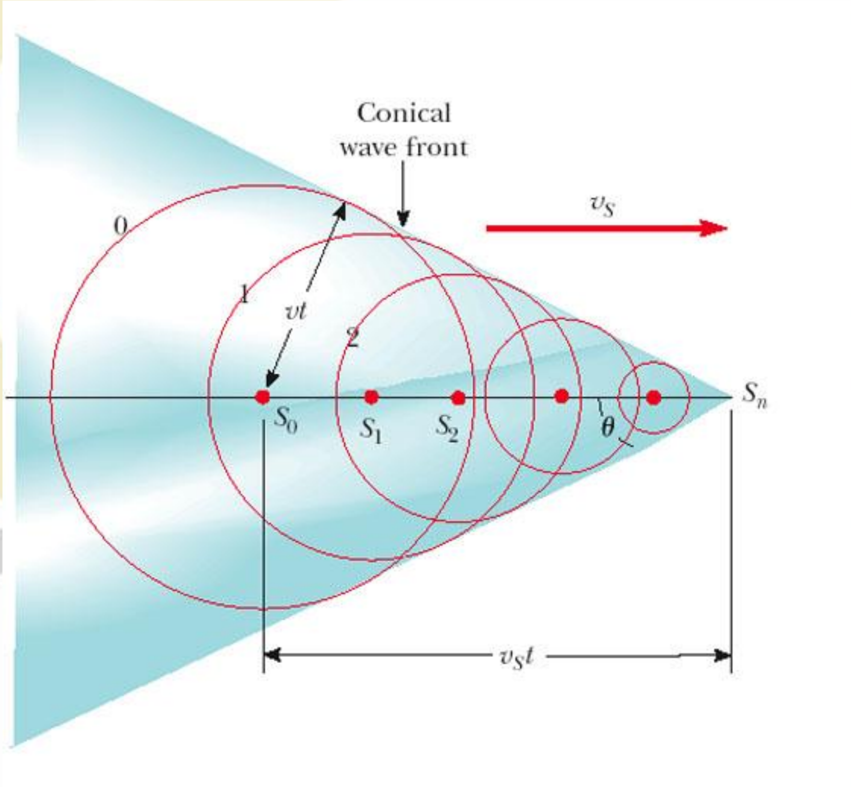


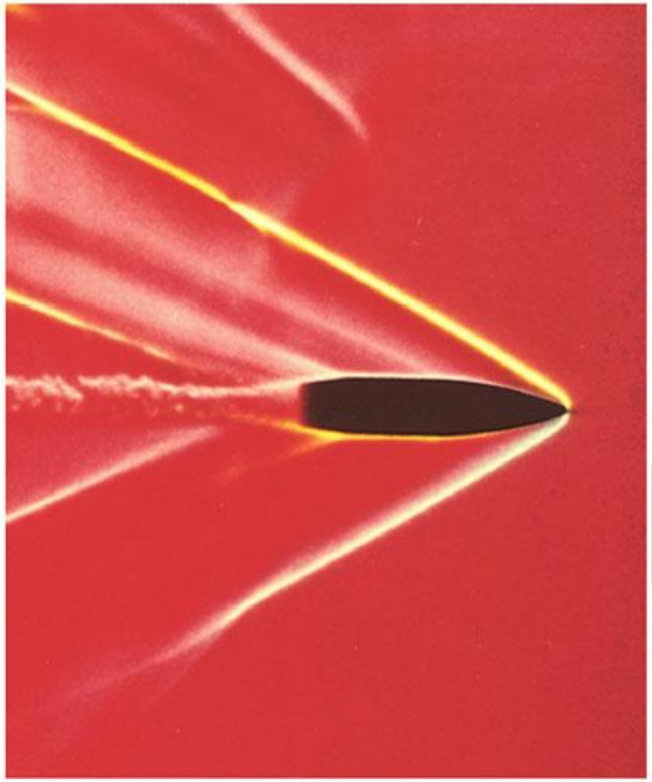
Breaking the Sound Barrier



Sonic Boom

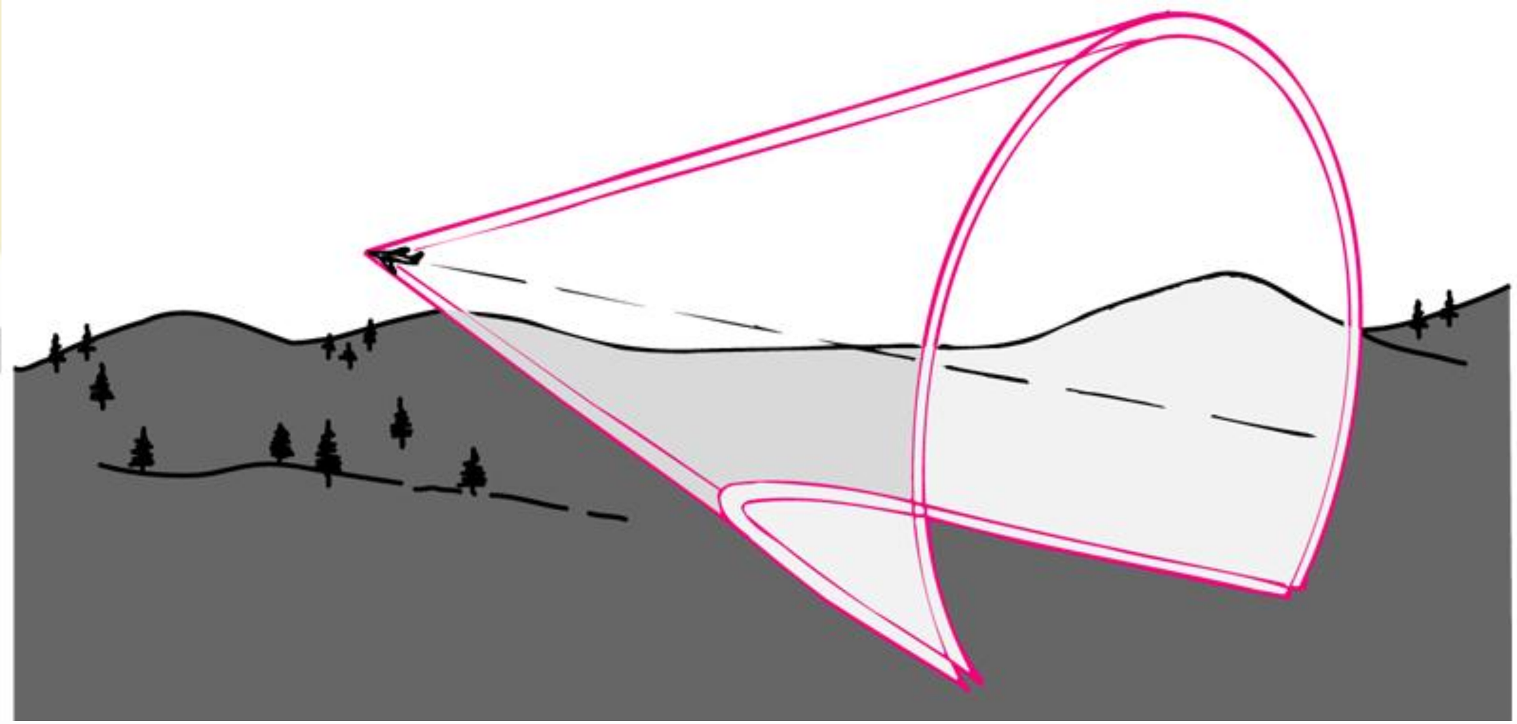
- Source of sound approaching the listener is equal to or faster than the speed of sound
  - Each successive wave is superimposed on the previous one
  - Shock wave results as air compression in crest gets very large





Shock Waves

- Similar to a bow wave, except three-dimensional
  - Cone shaped

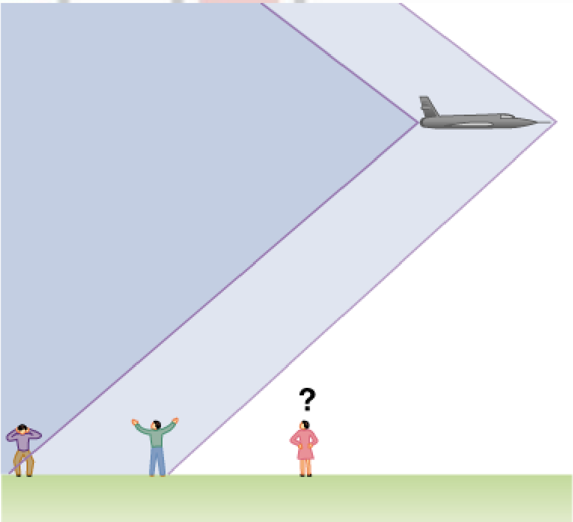


Shock Waves

- An object exceeding the speed of sound will produce a shock wave
- When the compressed air at the edges of the shock wave reach the ground, a sonic boom is heard
  - The object does *not* have to initially make any sound in order to produce a sonic boom
  - i.e.) The cracking of a whip is actually a mini sonic boom!

Breaking the sound barrier

- No sound received till after the source passes the listener - then a sonic boom - followed by normal sound from the source
- Conical bow wake from condensed water vapor at high pressure shock wave front.



Seismic Waves & Tsunami

- What is seismology?
- Seismology is the study of earthquakes and seismic waves that move through and around the earth.
- What are seismic waves?
- Seismic waves are the waves of energy caused by the sudden breaking of rock within the earth or an explosion. They are the energy that travels through the earth and is recorded on seismographs.
- Types of Seismic Waves
- There are several different kinds of seismic waves, and they all move in different ways. The two main types of waves are body waves and surface waves. Body waves can travel through the earth's inner layers, but surface waves can only move on surface of the earth.

Seismic Waves

Seismic waves use Earth itself as their medium. The seismic waves are produced during earthquakes. Primary (P) waves - the first to arrive - longitudinal waves Secondary (S) waves - second to arrive - transverse waves Surface waves - last to arrive - these do the most damage P and S type waves are called body waves, since they are not confined to the surface. Rayleigh waves do most of the shaking during a quake.

Name	Type	Info
P Wave	Longitudinal	Also known as primary, compressional, or acoustic waves; fastest seismic wave
S wave	Transverse	Also known as secondary, or shear waves; do not travel through fluids;
Rayleigh Wave	Surface	Rolls along surface like a water wave; large amplitude
Love Wave	Surface	Ground moves side to side as wave moves forward

Body waves

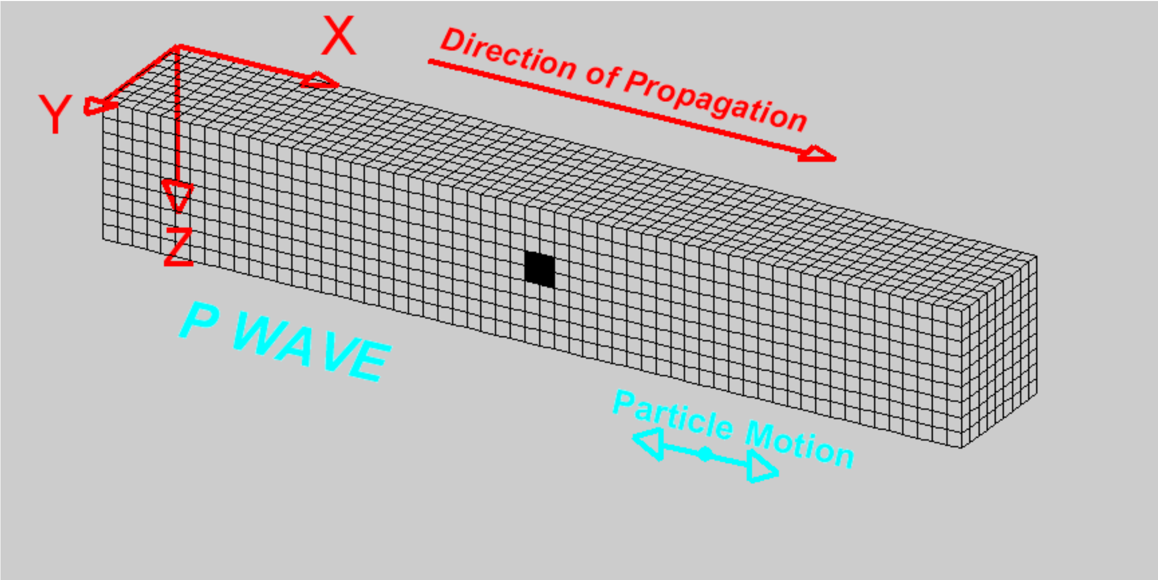
Travelling through the interior of the earth, body waves arrive before the surface waves emitted by an earthquake. These waves are of a higher frequency than surface waves.

P waves

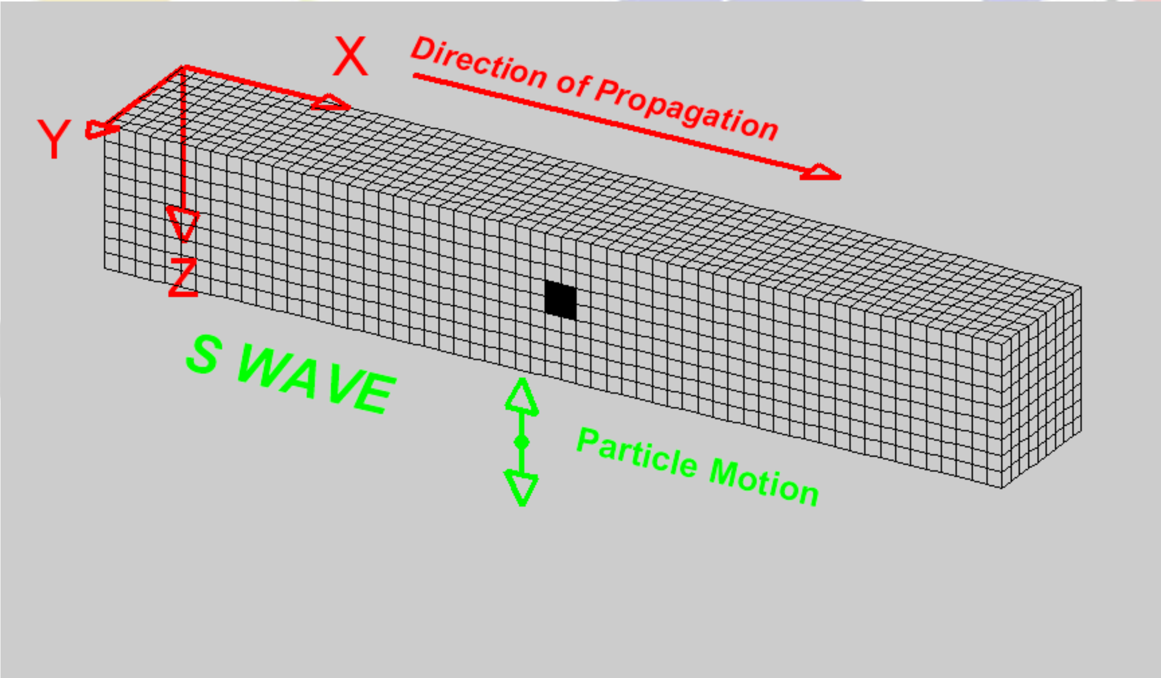
- The first kind of body wave is the P wave or primary wave. This is the fastest kind of seismic wave, and, consequently, the first to 'arrive' at a seismic station. The P wave can move through solid rock and fluids, like water or the liquid layers of the earth. It pushes and pulls the rock it moves through just like sound waves push and pull the air. Have you ever heard a big clap of thunder and heard the windows rattle at the same time? The windows rattle because the sound waves were pushing and pulling on the window glass much like P waves push and pull on rock. Sometimes animals can hear the P waves of an earthquake. Dogs, for instance, commonly begin barking hysterically just before an earthquake 'hits' (or more specifically, before the surface waves arrive). Usually people can only feel the bump and rattle of these waves.

Seismic waves

Waves in the earth generated by earthquake



P (primary) wave:
compressional
$v_P \sim 6$ km/s



S (secondary) waves:
transverse
$v_S \sim 3.5$ km/s

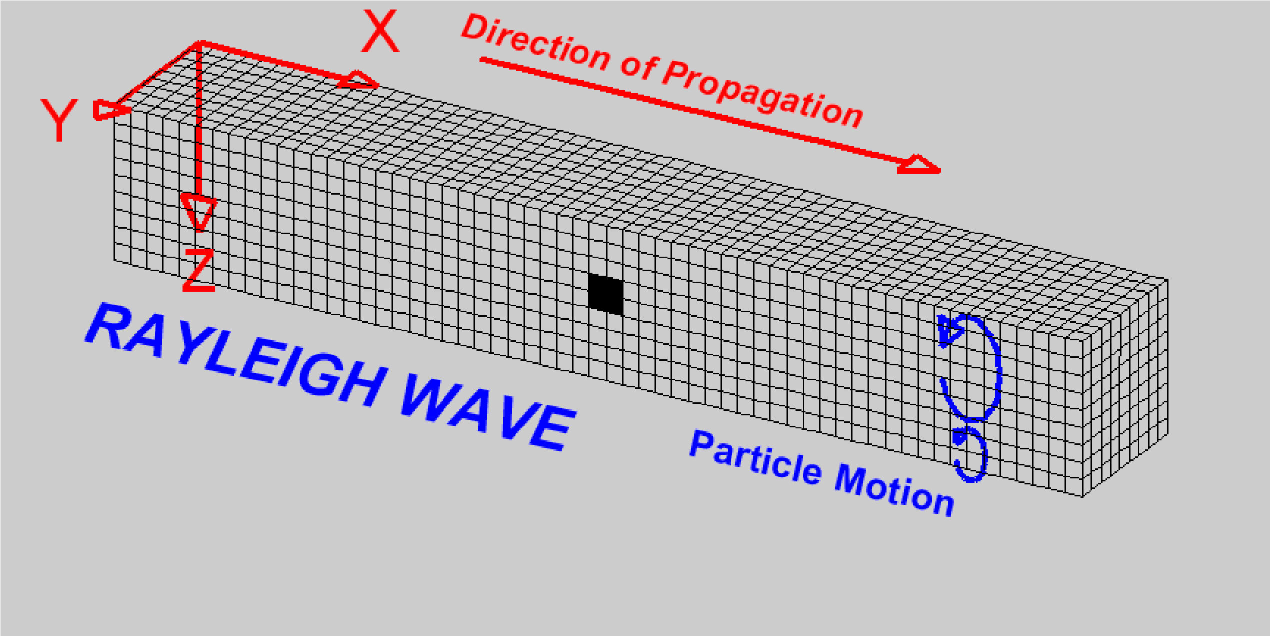
- P waves are also known as compressional waves, because of the pushing and pulling they do. Subjected to a P wave, particles move in the same direction that the wave is moving in, which is the direction that the energy is travelling in, and is sometimes called the 'direction of wave propagation'. P waves are longitudinal waves.

S waves

- The second type of body wave is the S wave or secondary wave, which is the second wave you feel in an earthquake. An S wave is slower than a P wave and can only move through solid rock, not through any liquid medium. It is this property of S waves that led seismologists to conclude that the Earth's outer core is a liquid. S waves move rock particles up and down, or side-to-side perpendicular to the direction that the wave is travelling in (the direction of wave propagation). S waves are transverse waves.

- Surface waves
- Travelling only through the crust, surface waves are of a lower frequency than body waves, and are easily distinguished on a seismogram as a result. Though they arrive after body waves, it is surface waves that are almost entirely responsible for the damage and destruction associated with earthquakes. This damage and the strength of the surface waves are reduced in deeper earthquakes.
- Richter scale
- The Richter scale is the best known scale for measuring the magnitude of earthquakes. The magnitude value is proportional to the logarithm of the amplitude of the strongest wave during an earthquake. A recording of 7, for example, indicates a disturbance with ground motion 10 times as large as a recording of 6. The energy released by an earthquake increases by a factor of 30 for every unit increase in the Richter scale

Seismic Rayleigh wave (R-wave)



•Rayleigh wave: another wave from earthquakes

— Particle motion roughly circular.

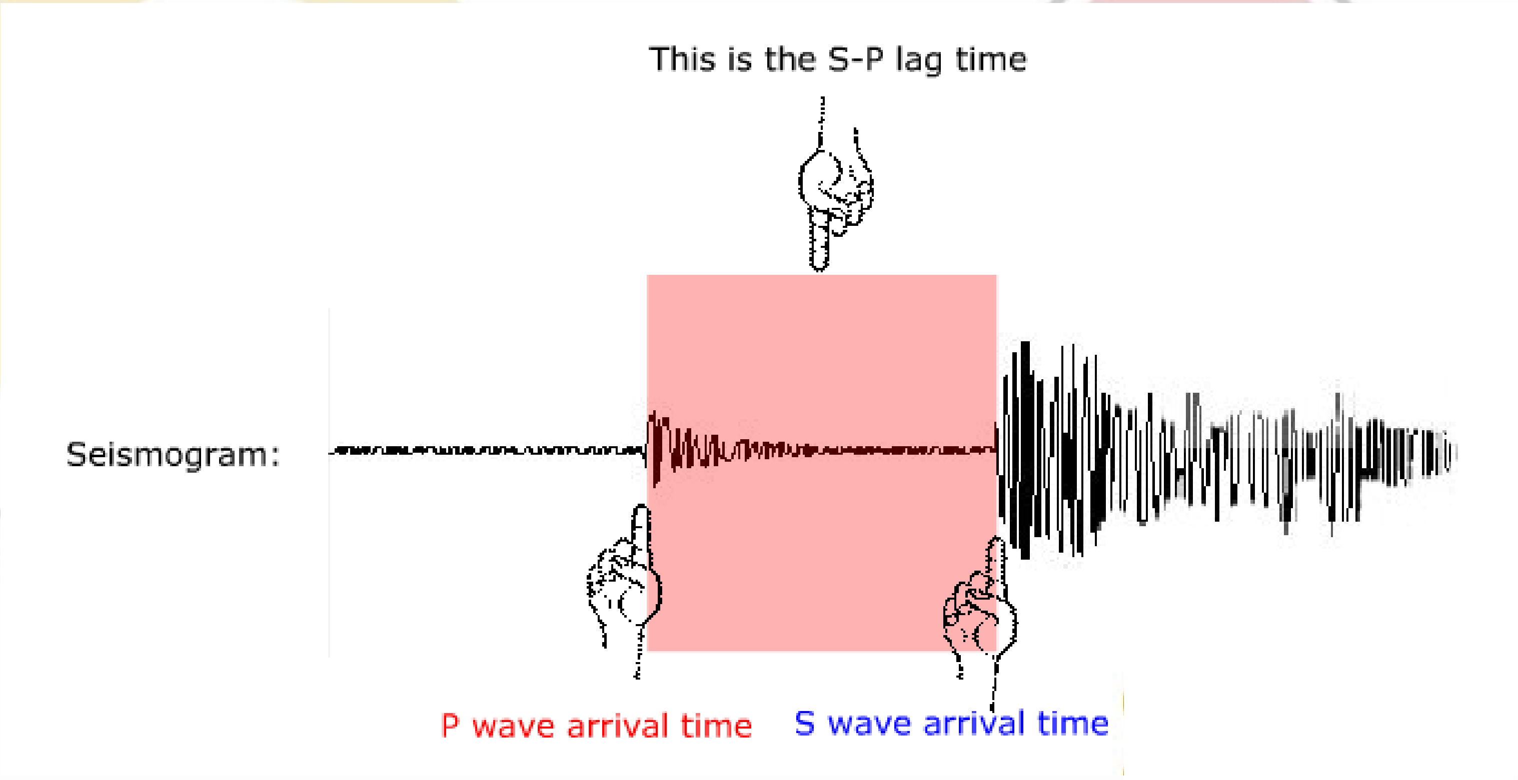
— Amplitude decreases with depth.

— A 'surface wave'.

This is same as a water wave!
But counterclockwise

Detecting with seismometer

- *P* (transverse) wave travels faster than *S* (compressional) wave, so it registers first on seismometer.



Locating an earthquake

Time difference between *P* arrival time and *S* arrival time due to difference in velocities.

P travel time = distance / *P*-velocity

S travel time = distance / *S*-velocity

$$\text{Arrival time difference} = (\text{P travel time}) - (\text{S travel time}) = \frac{\text{distance}}{\text{P velocity}} - \frac{\text{distance}}{\text{S velocity}}$$

$$\Delta t = \frac{d}{v_S} - \frac{d}{v_P} = d\left(\frac{1}{v_S} - \frac{1}{v_P}\right) = d(0.119 \ \ s/km)$$

$$d = (8.4 \ \ km/s)\Delta t$$

What is a tsunami?

A tsunami is a series of ocean waves with very long wavelengths caused by large-scale disturbances of the ocean, such as:

- an underwater earthquake,
- Landslide
- sub-marine rockslide,
- volcanic eruptions
- explosions
- an asteroid or meteoroid crashing into in the water from space.

- Most tsunamis are caused by underwater earthquakes. An earthquake has to be over about magnitude 6.75 on the Richter scale for it to cause a tsunami. About 90 percent of all tsunamis occur in the Pacific Ocean.

- The word tsunami comes from the Japanese word meaning "harbor wave." Tsunamis are sometimes incorrectly called "tidal waves" . Tsunamis are not caused by the tides (tides are caused by the gravitational force of the moon on the sea). Regular waves are caused by the wind.

- These disturbances can either be from below

(e.g. underwater earthquakes with large vertical displacements, submarine landslides)

or from above (e.g. meteorite impacts).

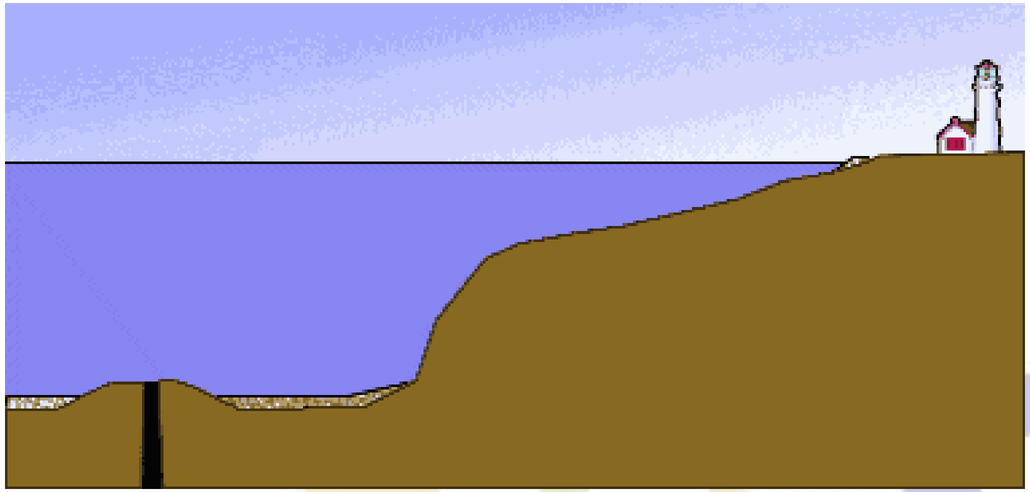
- "Seismic" implies an earthquake-related generation mechanism, but a tsunami can also be caused by a non-seismic event, such as a landslide or meteorite impact.

- The Size of a Tsunami: • In the deep ocean, a tsunami has a small amplitude/ height (about 1 metre) but have an extremely long wavelength (10 up to 100 km long) • The period is also very long (about an hour in deep water)
- Tsunamis are often barely visible when they are in the deep sea. This makes tsunami detection in the deep sea very difficult.
- The Speed of a Tsunami: • In the deep ocean, the typical water depth is around 4000 m, so a tsunami will therefore travel at around 200 m/s, or more than 700 km/h.(as fast as a jet flies) • takes a few hours to travel across an entire ocean. A regular wave (generated by the wind) travels at up to about 90 km/ h.
- Height of the tsunami: • A tsunami may rise vertically up to 30 m. • Most tsunamis cause the sea to rise 3 m. • The last tsunami caused waves as high as 9 m in some places.

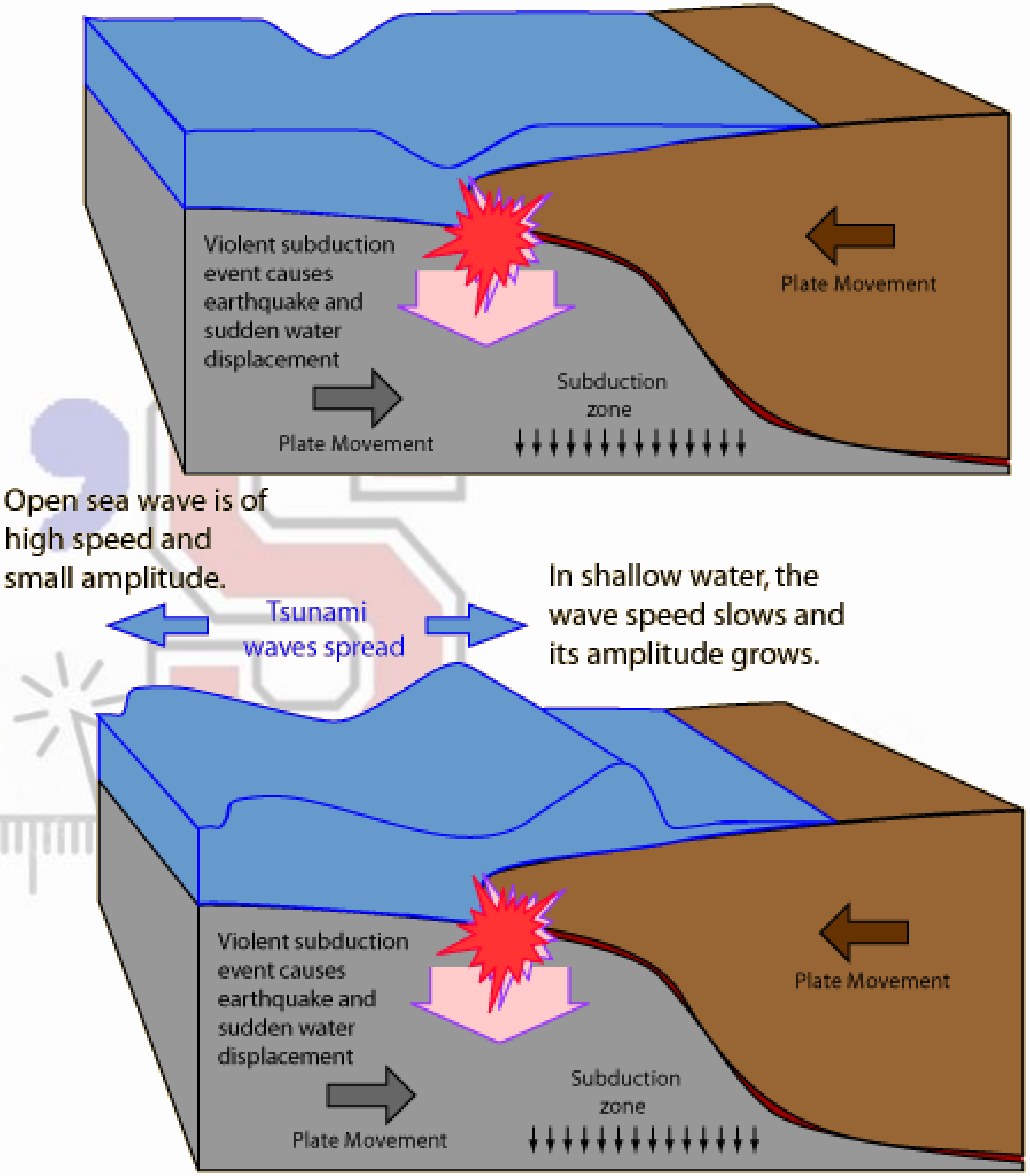
- December 26, 2004 tsunami was generated from the 9.0 “megathrust”- Richter scale- Sumatra earthquake
- Like all waves, tsunami transported energy but not mass.
  - The water that impacted the beaches in Sri Lanka, for example, did not "come from" Sumatra;
  - Just the energy "came from" Sumatra.
- Wavelength, period, and velocity:

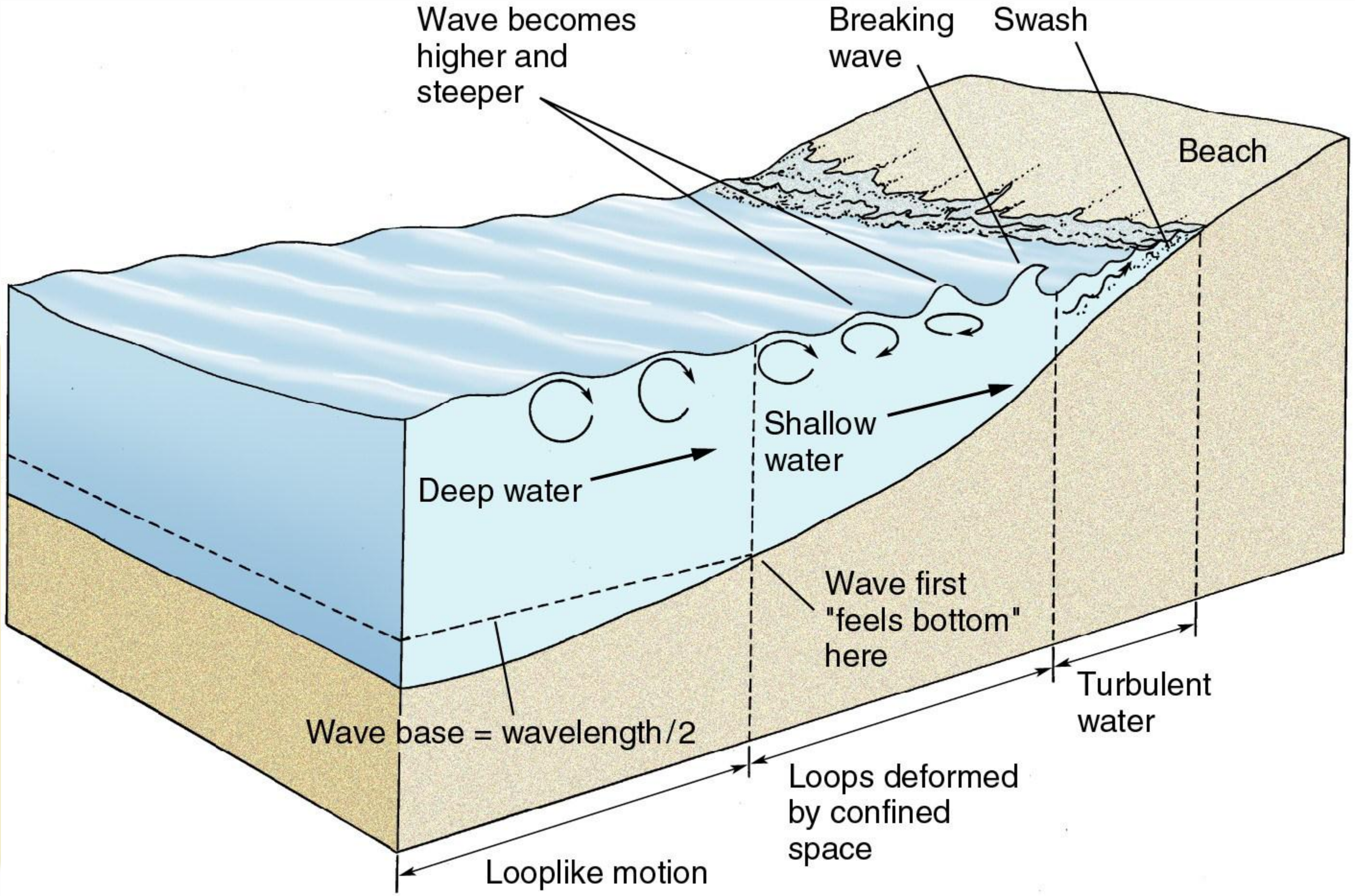
  velocity = wavelength × frequency
- Frequency = 1 / period:
  - period of 40 minutes gives frequency of about 0.0004Hz (cycles per second).
  - The wavelength of this tsunami in deep water is about 500km
  - From this we can compute the tsunami velocity to be about 200m/s or 450 miles an hour - about as fast as a jet airplane!

Tsunamis



- Generate by some disturbance
  - Landslide
  - Undersea earthquake
- Generates long-wavelength propagating water wave





As the wave approaches shallower water, the surface component becomes higher and steeper.

“Mini Seismic” Waves

Though we might not refer to them as seismic, anything moving on the ground can transmit waves through the ground. If you stand near a moving locomotive or a heard of charging elephants, you would feel these vibrations. Even something as small as a beetle generates pulses when it moves. These pulses can be detected by a nocturnal sand scorpion. Sensors on its eight legs can detect both longitudinal and surface waves. The scorpion can determine the direction of the waves based on which legs feel the waves first. It can determine the distance of the prey based on the time delay between the fast moving longitudinal waves and the slower moving surface waves. The greater the time delay, the farther away the beetle. This is the same way seismologists determine the distance of a quake’s epicenter. Sand is not the best conductor of waves, so the scorpion will only be able to detect beetles within about a half meter.

Lasers

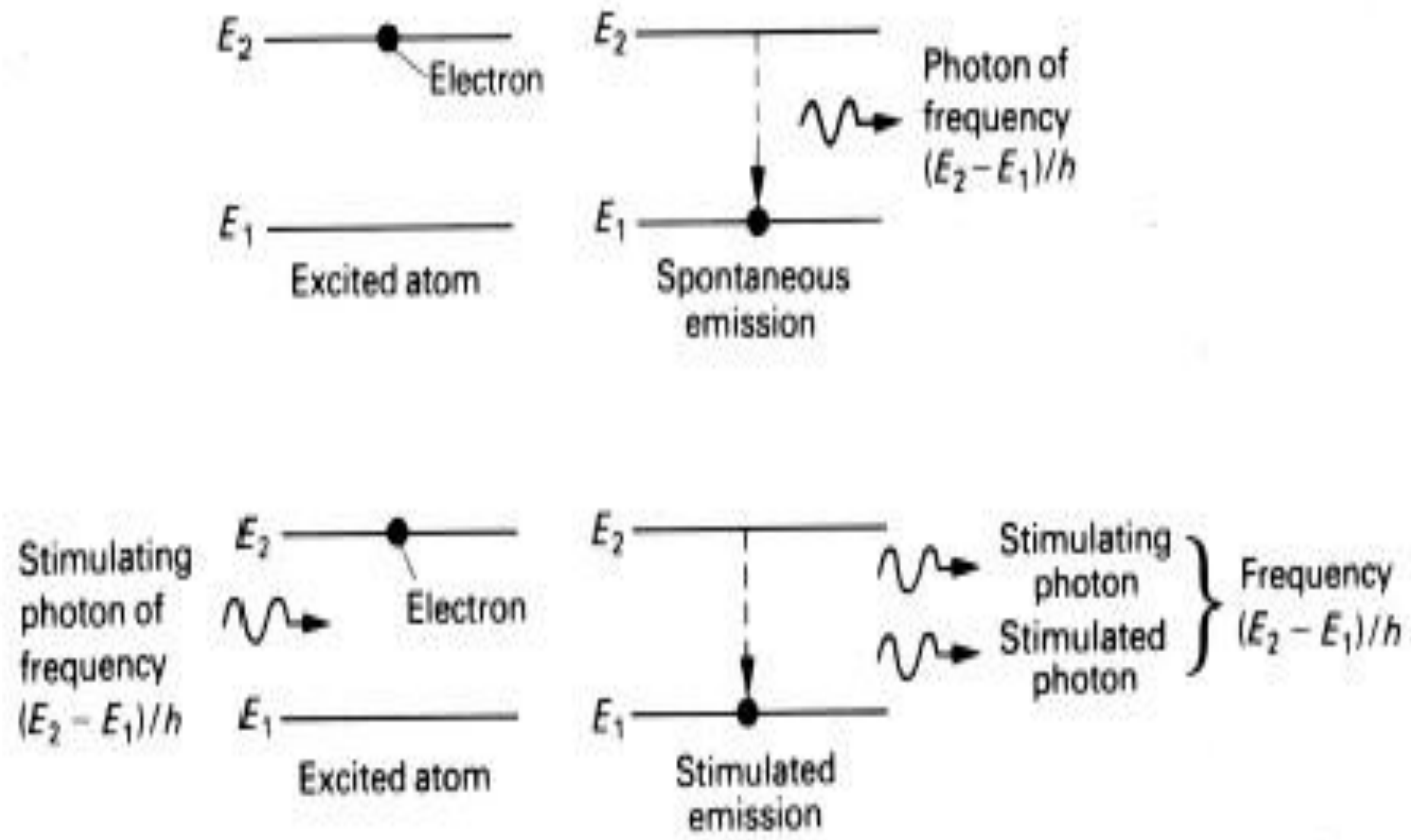
- The term LASER is an acronym for Light Amplification by Stimulated Emission of Radiation. The first laser was constructed in 1960.

(a) Action.

(b) The action of a laser can be explained in terms of energy levels.

  - A material whose atoms are excited emits radiation when electrons in higher energy levels return to lower levels. Normally this occurs randomly, i.e. spontaneous emission occurs, Figure 3.6 ., and the radiation is emitted in all directions and is incoherent.

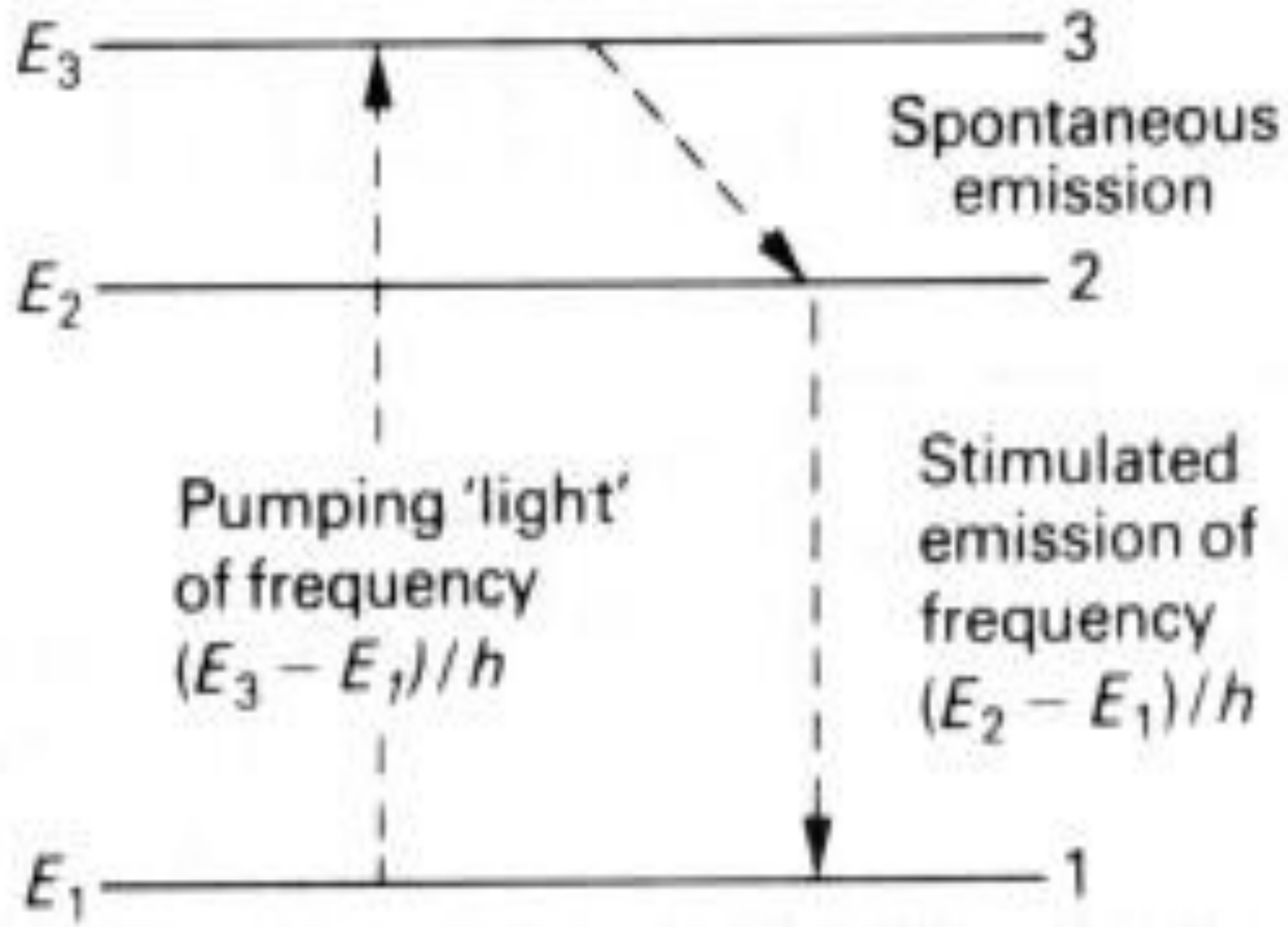
- The emission of light from ordinary sources is due to this process. However, if a photon of exactly the correct energy approaches an excited atom, an electron in a higher energy level may be induced to fall to a lower level and emit another photon. The remarkable fact is that this photon has the same phase. frequency and direction of travel as the stimulating photon which is itself unaffected. This phenomenon was predicted by Einstein and is called stimulated emission; it is illustrated in Figure 3.7.,


E_2
Electron
E_1
Excited atom
E_2
Photon of
frequency
$(E_2 - E_1)/h$
E_1
Spontaneous
emission
Stimulating
photon of
frequency
$(E_2 - E_1)/h$
E_2
Electron
E_1
Excited atom
E_2
E_1
Stimulated
emission
Stimulating
photon
Stimulated
photon
Frequency
$(E_2 - E_1)/h$

- In a laser it is arranged that light emission by stimulated emission exceeds that by spontaneous emission. To achieve this it is necessary to have more electrons in an upper than a lower level. Such a condition, called an inverted population" is the reverse of the normal state to affairs but it is essential for light amplification, i.e for a beam of light to increase in intensity as it passes through a material rather than to decrease as is usually the case.

- One method of creating an inverted population is known as ' optical pumping" and consists of illumination the laser material with light. Consider two levels of energies E_1 and E_2 where $E_2 > E_1$. If the pumping radiation contains photons of frequency $(E_2-E_1)/h$, electrons will be raised from level 1 to level 2 by photon absorption. Unfortunately, however. as soon as the electron population in level 2 stats to increase, the pumping radiation induces stimulated emission from level 2 to level 1, since it is of the correct frequency and no build up occurs.

- In a three level system. Figure 3.8., the pumping radiation of frequency $(E_3-E_1)/h$, raises electrons from level 1 to level 3, from which they fall by spontaneous emission to level 2. An inverted population can arise between level 2 and 1 if electrons remain long enough in level 2. The spontaneous emission of a photon due to an electronic fall from level 2 to level 1 may subsequently cause the stimulated emission of a photon which in turn releases more photons from other atoms. The laser action thus occurs between level 2 and 1 and the pumping radiation has different frequency from that of the stimulated radiation.



E_3
3
Spontaneous emission
E_2
2
Pumping 'light' of frequency $(E_3 - E_1)/h$
Stimulated emission of frequency $(E_2 - E_1)/h$
E_1
1