In terms of the amount of Doppler shift, is a moving observer equivalent to a moving source, that is, is it just the motion of the source and observer relative to each other that is important? Explain.

No, it is the motion of the source and/or observer relative to the medium through which the wave travels that determines the amount of the Doppler shift. A source moving relative to the air (the medium through which the sound wave is traveling) is not equivalent to an observer moving relative to the air since the velocity of each with respect to the medium is not the same in each case. Therefore, the amount of the Doppler shift will be different depending on whether it is the source of the sound or the observer of the sound that is in motion relative to the air.

Moving Source control variable: speed

Wave speed is the same relative to the observer but the wavelength actually increases or decreases so the frequency received by the observer increases or decreases.

Moving Observer control variable: wavelength

Wavelength remains the same relative to the medium but the wave speed increases or decreases relative to the observer so the frequency received by the observer increases or decreases.

Exception: However, light is unique in that there is no medium of propagation so it is the relative velocity of the source and detector that is relevant.

The Doppler Effect for Electromagnetic Waves

IB 12

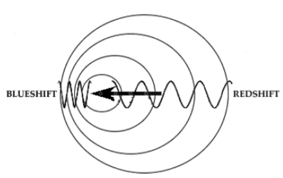
Sound – change in pitch

Light – change in frequency (color)

Blue shift:

source and observer moving towards each other

higher frequency, shorter wavelength



Red shift:

source and observer moving away from each other

lower frequency, longer wavelength

Doppler Formula (EM radiation)

$$\frac{\Delta f}{f} = \frac{\Delta \lambda}{\lambda} \approx \frac{v}{c}$$

Where:

$\Delta f =$ frequency shift = $|f - f'|$

$\Delta\lambda =$ wavelength shift = $|\lambda - \lambda'|$

$v =$ relative speed of source and observer

Note: This approximation is only valid when . . . relative speed is much less than the speed of light $v \ll c$

Note: Use this formula for . . . radio waves, light, etc.

1. A star is moving away from Earth at a speed of 3.000×10^5 m/s. One of the elements in the star emits light with a frequency of 6.000×10^{14} Hz.

   a) By how much is the frequency shifted when it is received by a telescope on Earth?

   $$\frac{\Delta f}{f} = .001$$

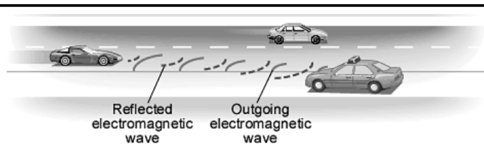
   6×10^{11} Hz

   b) What is the frequency received by the Earth-bound telescope?

   5.994×10^{14} Hz

   c) What frequency would be received on Earth if the star were moving toward the Earth at the same speed? 6.006×10^{14} Hz

Applications of the Doppler Effect



1. **Radar devices**

Police use radar to measure the speed of moving vehicles to see if they are breaking the speed limit. A pulse of radio waves of known frequency is emitted, reflected off the moving vehicle and reflected back to the source. The change between the frequency emitted and the frequency received is used to calculate the speed of the car.

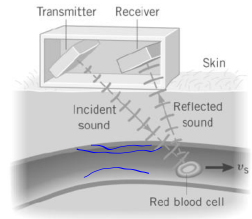
Example: A radar gun emitting a wave whose frequency is 8.0×10^9 Hz is aimed at an oncoming car whose speed is 39 meters per second. What is the difference between the frequencies of the outgoing and incoming radar waves?

Factor of 2 since car is both observer and source of radar wave

$$2\frac{V}{c} \qquad \frac{2 \times 39\,m/s}{3 \times 10^8} \times 8 \times 10^9 \approx 2100\ Hz$$

2. **Medical physics**

Doctors use a 'Doppler flow meter' to measure the speed of blood flow. Transmitting and receiving elements are placed directly on the skin and an ultrasound signal (sound whose frequency is around 5 MHz) is emitted, reflected off moving red blood cells and then received. The difference in transmitted and received frequencies is then used to calculate how fast blood is flowing which can help doctors identify constricted arteries.

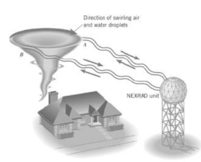


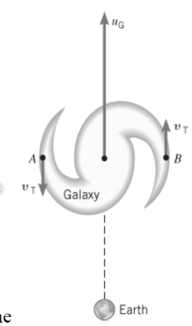
Doppler ultrasound is also used to detect fetal heartbeats.

3. **Weather forecasting and astrophysics**

Radar is used in weather forecasting by observing the motion of air masses.

Also, when an object such as a cyclone or a distant star rotates, one side is moving toward the observer and one side is moving away. For a cyclone, radio pulses known as radar are transmitted and reflected from each side of the rotating air mass and the difference in Doppler shift from each side can be used to calculate the rate at which it is rotating.



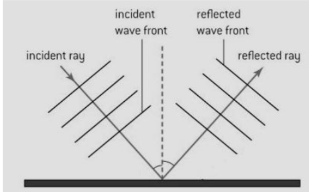


Similarly, the atomic absorption spectrum of the light from a star will be blue-shifted from one side and red-shifted from the other so this difference can be used to determine its rotational rate as well as how fast the galaxy is receding from Earth.

Refraction

IB 12

Law of Reflection: The angle of incidence is equal to the angle of reflection when both angles are measured with respect to the normal.



Wavefront and ray diagrams for reflection of waves

Refraction: the change in direction of a wave (due to a change in speed) when it crosses a boundary between two different media at an angle

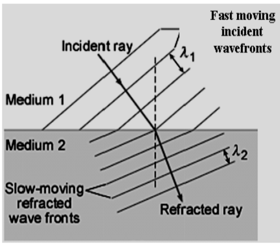
Control Variable: frequency

Rule: **FAST** into **F**ast bend **A**way – into **S**low bend **T**owards

Air to glass:

Fast to slow = bends toward the normal

n increases
v decreases
λ decreases



Formulas:

$$n = \frac{c}{v} \qquad n_1 \sin\theta_1 = n_2 \sin\theta_2 \qquad \frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1} = \frac{\lambda_2}{\lambda_1}$$

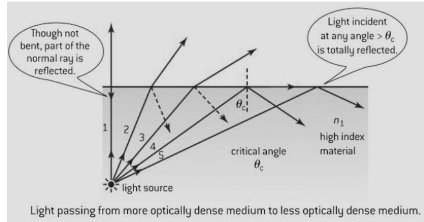
Critical Angle (θ_c): angle of incidence for which the angle of refraction is 90^0

Formula:

$n_1 \sin\theta_1 = n_2 \sin\theta_2$

$\theta_1 = \theta_c$, $\theta_2 = 90°$

$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$



Light passing from more optically dense medium to less optically dense medium.

Conditions for Total Internal Reflection:

a) ray of light must be traveling from the more optically dense to the less optically dense medium

b) ray must strike the boundary at an angle greater than the critical angle

Interference of Waves in Two Dimensions IB 12

Path Length (ℓ) – the distances a wave must travel from its source to a given point

Path Difference (Δℓ) – difference in the distances two waves must travel from their sources to a given point

Phase Difference – difference in the phases of the two waves when they overlap

1. The diagrams below represent the wavefronts produced by two point sources. The solid circles represent wave crests and the dashed circles represent wave troughs. In each case below, determine the path difference, phase difference, and type of interference.

   a) Path Difference:

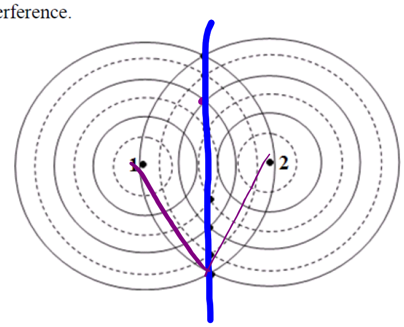
   $\Delta \ell = 0$

   Phase Difference:

   0

   Interference:

   constructive



b) Path Difference:

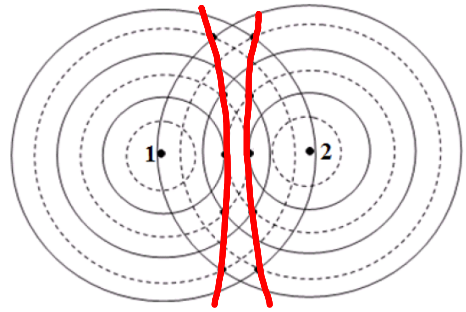
$\Delta \ell = \frac{1}{2}\lambda$

Phase Difference:

$180^\circ \quad \pi$

Interference:

destructive



c) Path Difference:

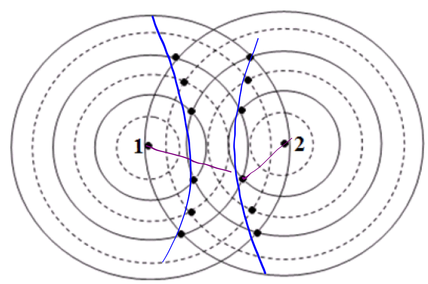
$\Delta \ell = 1\lambda$

Phase Difference:

0

Interference:

constructive



Conditions for Anti-nodal Line

Type of interference: constructive

Phase difference: 0

Path difference: $\Delta \ell = n\lambda$

Conditions for Nodal Line

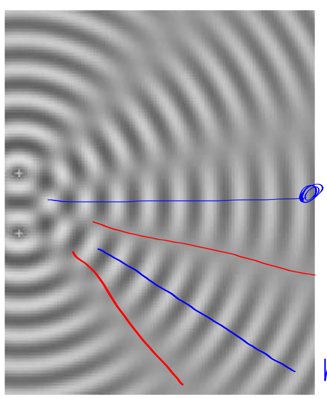
Type of interference: destructive

Phase difference: π

Path difference: $\Delta \ell = (n+\frac{1}{2})\lambda$

Resultant Interference Patterns

2. Determine the path difference for each of the nodal and anti-nodal lines indicated.



$n=0 \quad \Delta \ell = 0$

$n=0 \quad \Delta \ell = \frac{1}{2}\lambda$

$n=1 \quad \Delta \ell = 1\lambda$

$n=1 \quad \Delta \ell = 1\frac{1}{2}\lambda$