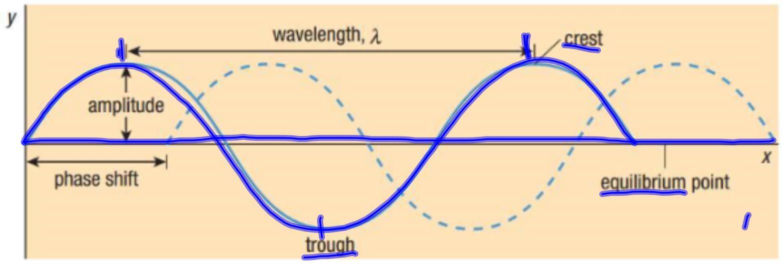
SPH4U 9.1 Properties of Waves and Light

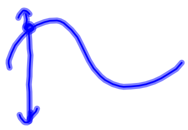
1. Geometric wave characteristics (freeze time)

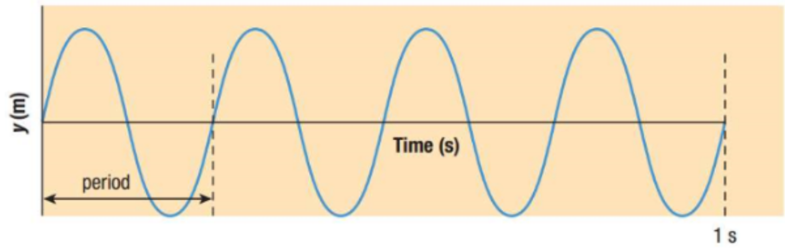
Periodic wave:	a wave with a repeated pattern.
Wave front:	the front of a wave as it travels in time.



Amplitude:	A: maximum displacement from equilibrium. $A = \frac{max - min}{2}$
Wavelength:	λ: distance (in m) between 2 similar points in 2 cycles.
Phase:	a shift in the x-axis relative to another value.

2. Time-based wave characteristics (one specific location).

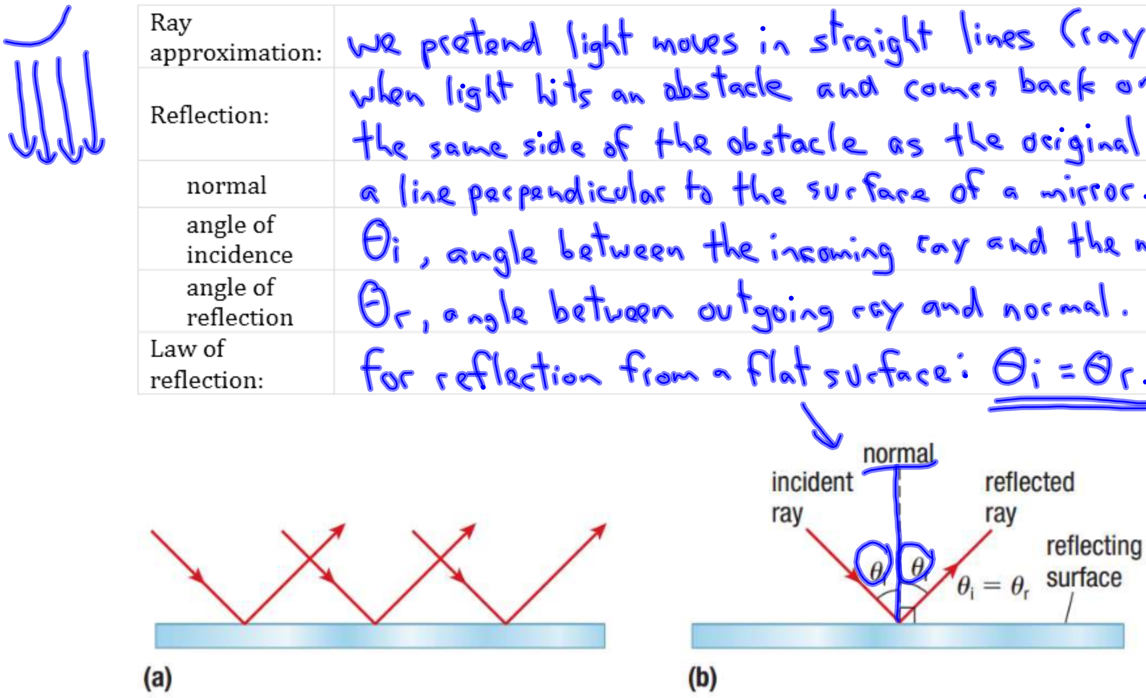




Period:	T: the time for a particle to complete 1 cycle. (s).	
Frequency:	f: the number of cycles per second. (Hz)	
equation	$f = \frac{1}{T}$	$T = \frac{1}{f}$.
Wave speed:	$v = f\lambda$ ↓	$v = \frac{\lambda}{T}$ ↓.
equation		

3. Reflection

Ray approximation:	we pretend light moves in straight lines (rays).
Reflection:	when light hits an obstacle and comes back on the same side of the obstacle as the original ray.
normal	a line perpendicular to the surface of a mirror.
angle of incidence	θ_i, angle between the incoming ray and the normal.
angle of reflection	θ_r, angle between outgoing ray and normal.
Law of reflection:	for reflection from a flat surface: $\theta_i = \theta_r$.



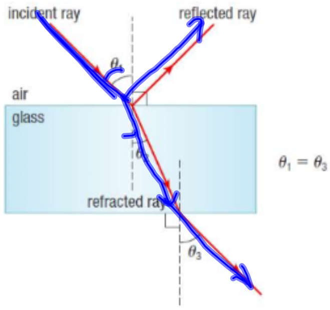
Homework: pg. 443 #6-10, 12, 14, 20

SPH4U 9.2 Refraction and Total Internal Reflection

1. Refraction

Refraction:	when light changes angles as it changes mediums.
Principle of reversibility:	light will follow exactly the same path if its direction of travel is reversed
Optical density:	a material's tendency to absorb light energy.
Index of refraction:	$n = \frac{c}{v}$, how much light is slowed down in a substance.
affected by	different substances and different wavelengths.

Medium	Index of refraction	Speed of light (m/s)	Medium	Index of refraction	Speed of light (m/s)
vacuum	1.00	2.9979×10^8	lens of human eye	1.41	2.1262×10^8
air	1.0003	2.9970×10^8	quartz crystal	1.46	2.0534×10^8
ice	1.30	2.3061×10^8	Pyrex glass	1.47	2.0394×10^8
liquid water	1.33	2.2541×10^8	Plexiglas (plastic)	1.51	1.9854×10^8
aqueous humour (liquid between the lens and cornea)	1.33	2.2541×10^8	benzene	1.50	1.9986×10^8
cornea of human eye	1.38	2.1724×10^8	zircon	1.92	1.5601×10^8
vitreous humour (liquid between the lens and retina)	1.38	2.1724×10^8	diamond	2.42	1.2388×10^8



Angle of refraction: θ_2	angle from the normal when light enters a different medium.
Snell's Law:	$n_1 \sin\theta_1 = n_2 \sin\theta_2$.
wavelengths	$\frac{n_2}{n_1} = \frac{\lambda_1}{\lambda_2}$.

Light moves from a vacuum into a plate of glass with index of refraction 1.47. The angle of incidence is 40.0°.

a. Calculate the angle of refraction.

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

$\sin\theta_2 = \frac{n_1 \sin\theta_1}{n_2}$

$\theta_2 = \sin^{-1}\left(\frac{n_1 \sin\theta_1}{n_2}\right)$

$= \sin^{-1}\left(\frac{1 \times \sin 40}{1.47}\right)$

$= 25.9°$.

b. The light continues through the glass and emerges back into a vacuum. Calculate the angle of refraction when the light exits the glass.

$n_2 \sin\theta_2 = n_3 \sin\theta_3$

$\theta_3 = \sin^{-1}\left(\frac{n_2 \sin\theta_2}{n_3}\right)$

$= \sin^{-1}\left(\frac{1.47 \sin 25.9}{1}\right) = 40°$.

c. Suppose the light exits into water instead of a vacuum. Calculate the angle of refraction for the light moving from glass into water (n_{water} = 1.33).

$n_2 \sin\theta_2 = n_3 \sin\theta_3$

$\theta_3 = \sin^{-1}\left(\frac{n_2 \sin\theta_2}{n_3}\right)$

$= \sin^{-1}\left(\frac{1.47 \sin 25.9}{1.33}\right) = 29°$.

Light travels at 3.0 x 10^8 m/s. Laser light with a wavelength of 520 nm enters a sheet of plastic. The index of refraction for the plastic is 1.49.

a. Calculate the speed of the laser light in the plastic.

$n = \frac{c}{v}$

$v = \frac{c}{n} = \frac{3.0\times10^8}{1.49} = 2.01\times10^8$ m/s.

b. Calculate the wavelength of the laser light in the plastic.

$\frac{n_2}{n_1} = \frac{\lambda_1}{\lambda_2}$

$\lambda_2 = \frac{\lambda_1 n_1}{n_2} = \frac{(5.2\times10^{-7})(1)}{1.49} = 3.49\times10^{-7}$ m.

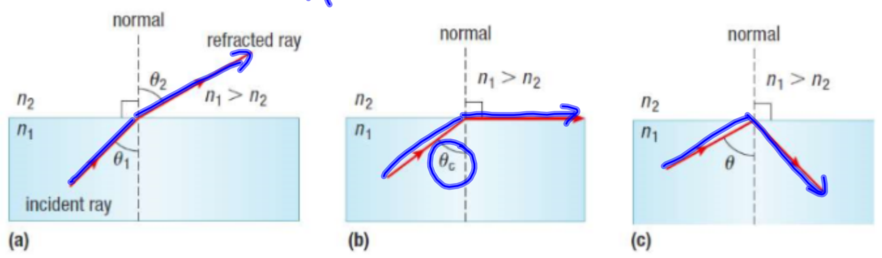
c. Calculate the frequency of the laser light in the plastic.

$v = f\lambda$

$f = \frac{v}{\lambda} = \frac{2.01\times10^8}{3.49\times10^{-7}} = 5.77\times10^{14}$ Hz.

2. Total internal reflection

Total internal reflection:	when light is totally reflected at a medium boundary. can only happen when n of the 1st medium is higher.
Critical angle:	the angle where light stops passing through from one medium to the next, and begins to reflect.
equation	$\sin\theta_c = \frac{n_2}{n_1}$.



Light passes through water (n = 1.33) into air (n = 1.0003).

a. Calculate the critical angle.

$\sin\theta_c = \frac{n_2}{n_1}$

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

$= \sin^{-1}\left(\frac{1.0003}{1.33}\right) = 48.8°$.

b. What does an underwater swimmer see if she looks toward the surface at angles 40°, θ_c, and 60° relative to the normal?

40°: she sees light from outside the water.

θ_c: she sees light along the surface of the water.

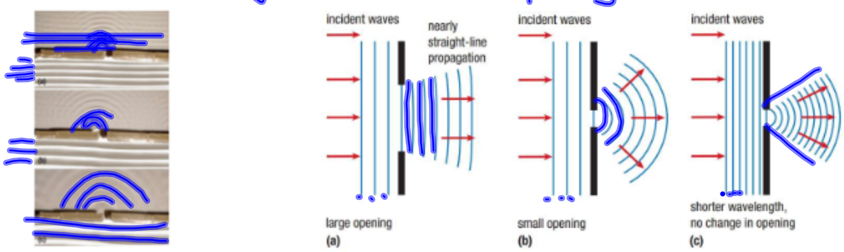
60°: she sees a reflection from underwater.

Homework: pg. 458 #3-5, 7-10

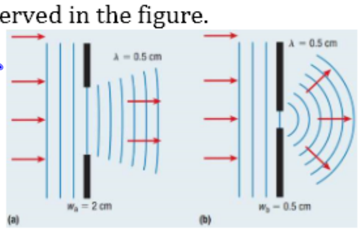
SPH4U 9.3 Diffraction and Interference of Water Waves

1. Diffraction

Diffraction:	when a wave bends and spreads after passing through an opening (acts like a new source)
depends on	wavelength and size of opening. $\frac{\lambda}{w} \geq 1$.



Determine and explain the difference between the diffractions observed in the figure.

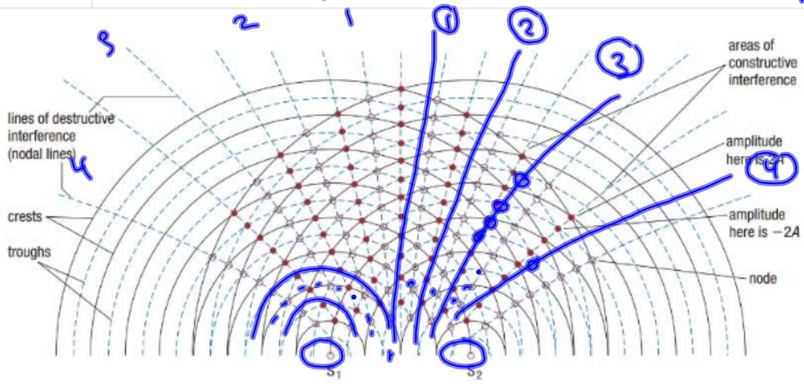


(a) $\frac{\lambda}{w} = \frac{0.5}{2} = \frac{1}{4} < 1$. ∴ no diffraction occurs.

(b) $\frac{\lambda}{w} = \frac{0.5}{0.5} = 1$. ∴ diffraction occurs.

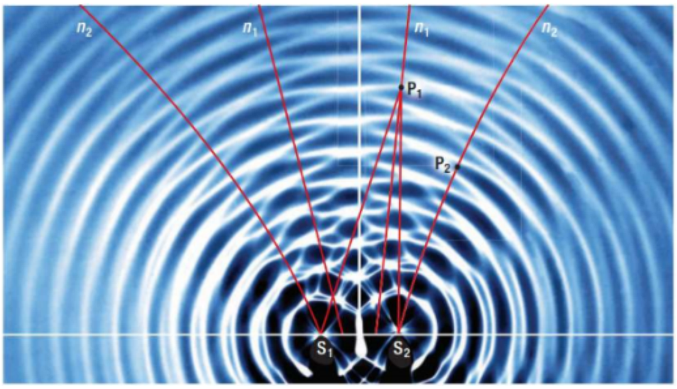
2. Interference

Interference:	two waves interacting.
constructive interference	waves add together to become a larger wave
destructive interference	waves cancel out, leaving a smaller wave
Node:	a point where the wave has 0 displacement.
nodal line	a line of destructive interference (0 displacement).



3. Interference in two dimensions

nth nodal line:	the nodal lines can be numbered: count outward in one direction, starting with #1 closest to the middle.
Finding λ:	nodal lines can be used to find λ, by picking a point P_n on the nth nodal line, and using the distance to it from each source (P_nS_1, P_nS_2):
equation	$\lvert P_nS_1 - P_nS_2 \rvert = (n - \frac{1}{2})\lambda$ (n is nodal line #).



Two identical point sources are 5.0 cm apart, in phase, and vibrating at a frequency of 12 Hz. They produce an interference pattern. A point on the first nodal line is 5 cm from one source and 5.5 cm from the other.

a. Determine the wavelength.

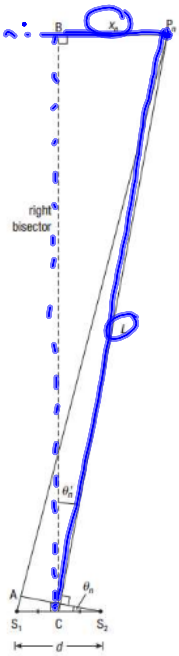
$$\lvert P_nS_1 - P_nS_2 \rvert = (n - \tfrac{1}{2})\lambda$$

$$\lambda = \frac{\lvert P_nS_1 - P_nS_2 \rvert}{n - \frac{1}{2}} = \frac{\lvert 5.5 - 5 \rvert}{1 - \frac{1}{2}} = \frac{0.5}{0.5} = \underline{1.0\text{ cm}}$$

b. Determine the speed of the waves.

$$v = f\lambda$$
$$= (12)(1.0)$$
$$= 12\text{ cm/s}$$
$$= \underline{0.12\text{ m/s}}.$$

When P is far away:	We use different measures for more precision: x_n: perpendicular distance from the right bisector L: distance from midpoint to P_n.
θ_n	angle of the nth nodal line. $\sin\theta_n = \frac{x_n}{L}$.
λ	$\sin\theta_n = \frac{x_n}{L} = (n-\frac{1}{2})(\frac{\lambda}{d})$. d: distance between sources.



The distance from the right bisector to a point P on the second nodal line in a two-point interference pattern is 4.0 cm. The distance from the midpoint between the two sources, which are 0.5 cm apart, to point P is 14 cm.

a. Calculate the angle θ_2 for the second nodal line.

$x_n = 4.0\text{cm}, L = 14\text{cm}, d = 0.5\text{cm}$

$$\sin\theta_2 = \frac{x_n}{L} = \frac{4}{14}$$

$$\theta_2 = \sin^{-1}\left(\frac{4}{14}\right) = 17^\circ.$$

b. Calculate the wavelength.

$$\frac{x_n}{L} = \left(n-\frac{1}{2}\right)\left(\frac{\lambda}{d}\right)$$

$$\lambda = \frac{x_n d}{L(n-\frac{1}{2})}$$

$$= \frac{(4)(0.5)}{14(2-\frac{1}{2})}$$

$$= 0.095\text{cm}.$$

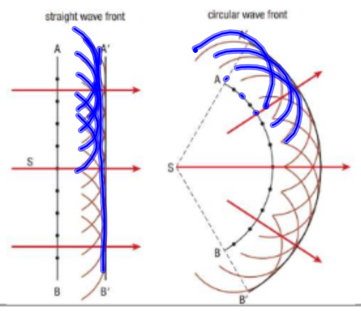
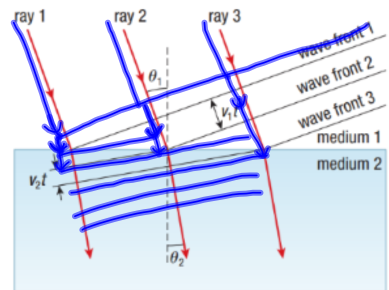
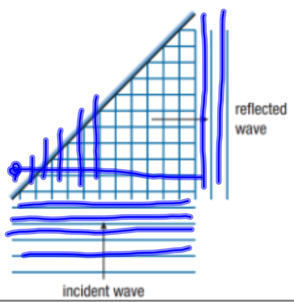
Homework: pg. 469 #1, 3-4, 6

SPH4U 9.4 Light: Wave or Particle?

1. Theories of light

Early theories of light:	1650-1710, debate over light as a particle vs wave.
Wave theory of light:	1665, Francesco Grimaldi claimed that light diffracted when it went through a narrow slit (light = wave!)
Huygens' principle	all points on a wave front can be thought of as new sources of spherical waves.
drawbacks	requires invisible 'ether' to travel through. waves spread out, while light moves in straight lines.
Particle theory of light:	more popular, led by Isaac Newton. easier to understand, didn't require 'ether'
rectilinear propagation	light travels in straight lines, not spreading out.

2. Huygens' principle

Wave fronts:	Refraction:
	
Reflection:	**Diffraction:**
	

3. **Comparing theories**

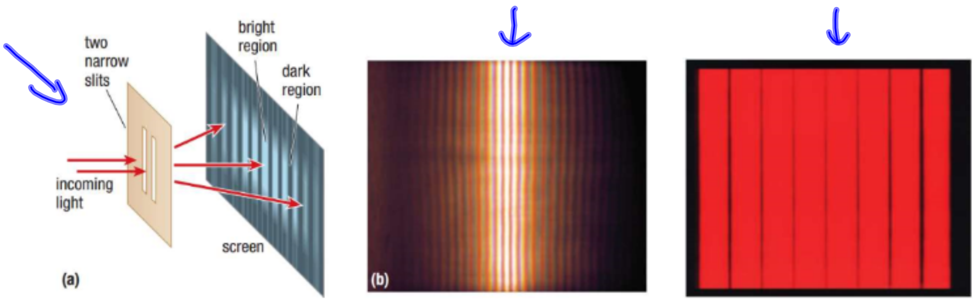
Property	Newton (Particle)	Huygens (Wave).
rectilinear propagation	strong: particles at extremely high speeds move in straight lines.	Huygens' principle - the wave front propagates forward.
diffraction	weak. light 'diffraction' is actually just collisions between light particles.	strong: each point acts as a point source for new spherical wavelets.
reflection	strong. reflection ⇒ perfectly elastic collision.	strong. points on reflecting surface act as new point sources.
refraction	weak: accelerate and bend toward the normal when their speed increases (completely false!)	strong. wave front moves at different speeds, bending toward normal in slower media.

Homework: pg. 476 #1-3, 5, 9

SPH4U 9.5 Interference of Light Waves

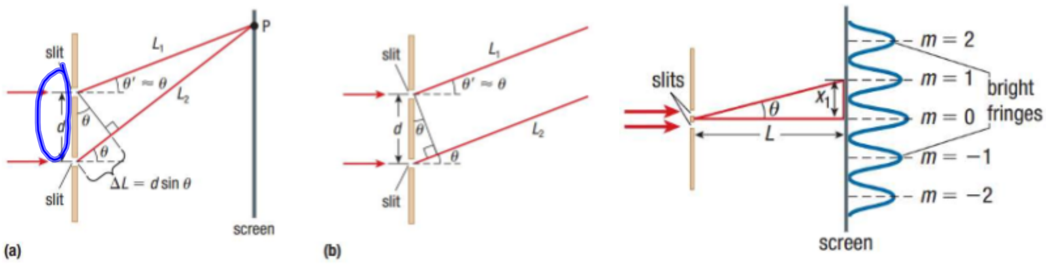
1. Young's double-slit experiment

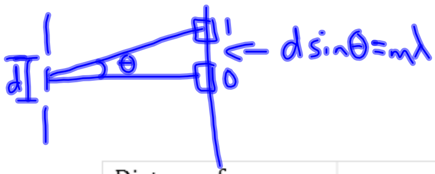
Continued debate:	1600s-1700s, people didn't buy the wave theory because no interference was detected.
problems	λ of light is very small (need small slits and large distances), and lights were out of phase.
Young's experiment:	late 1700s, single light source, two narrow slits.

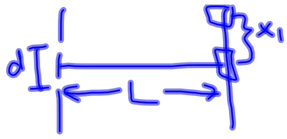


Maxima:	light fringes (constructive interference), called zero-order maximum (centre), first-order, 2nd, ...
equation	$d\sin\theta = m\lambda$, $m = 0, 1, 2, 3, \ldots$
Minima:	dark lines (destructive interference).
equation	$d\sin\theta = (n - \frac{1}{2})\lambda$, $n = 1, 2, 3, \ldots$

d: distance between slits.

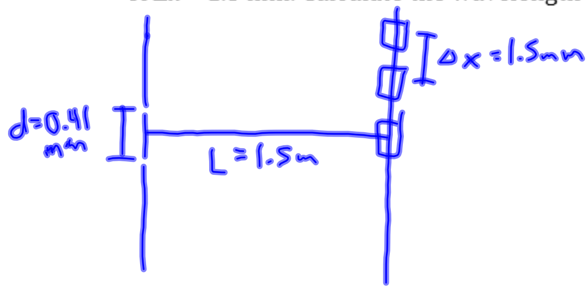






Distance from centre to a max:	$x_m = m\frac{L\lambda}{d}$. $\Delta x = \frac{L\lambda}{d}$.
Distance from centre to a min:	$x_n = (n-\frac{1}{2})\frac{L\lambda}{d}$ $\Delta x = \frac{L\lambda}{d}$.

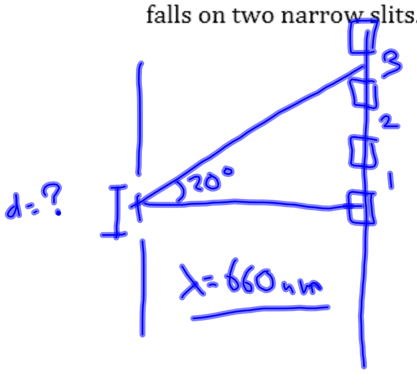
A double-slit experiment is carried out with slit spacing d = 0.41 mm. The screen is at a distance of 1.5 m. The bright fringes at the centre of the screen are separated by a distance of Δx = 1.5 mm. Calculate the wavelength of the light.



$$\Delta x = \frac{L\lambda}{d}.$$

$$\lambda = \frac{\Delta x\, d}{L} = \frac{(0.0015)(0.00041)}{1.5} = 4.1\times10^{-7}\text{ m}.$$

The ~~third-order~~ dark fringe of 660 nm light is observed at an angle of 20.0° when the light falls on two narrow slits. Determine the slit distance.



$$d\sin\theta = (n-\tfrac{1}{2})\lambda \quad \text{(Dark lines).}$$

$$d = \frac{(n-\frac{1}{2})\lambda}{\sin\theta} = \frac{(3-\frac{1}{2})(660\times10^{-9})}{\sin 20^\circ} = 4.8\times10^{-6}\text{ m} = 4.8\ \mu\text{m}$$

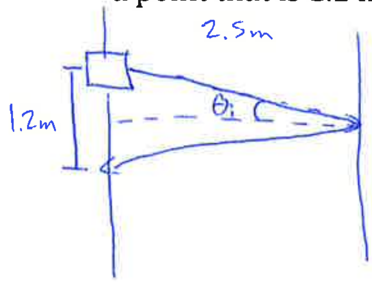
Homework: pg. 484 #2, 4-6, 8

Name: SOLUTIONS

SPH4U: Chapter 9 Quiz – Waves and Light

Marks: **NOT FOR GRADES**

1. ***(Properties)*** A light ray from a source on one wall strikes a flat mirror on the opposite wall. The distance between the walls is 2.5 m. The reflected ray hits the original wall at a point that is 1.2 m below the light source. Determine the angle of incidence, θ_i.



$\tan\theta_i = \frac{0.6}{2.5}$

$\theta_i = \tan^{-1}\left(\frac{0.6}{2.5}\right)$

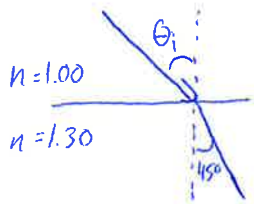
$= 13.496°$

$= 13°$

∴ θ_i is 13°.

2. ***(Refraction and total internal reflection)*** Light travels from air into a transparent material that has an index of refraction of 1.30. The angle of refraction is 45°.

   a. Calculate the angle of incidence.



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

$\theta_1 = \sin^{-1}\left(\frac{n_2 \sin\theta_2}{n_1}\right)$

$= \sin^{-1}\left(\frac{1.30 \sin 45°}{1.00}\right)$

$= 66.82° = 67°$

∴ θ_i is 67°.

   b. Determine the critical angle for total internal reflection to occur in the material.

$\sin\theta_c = \frac{n_2}{n_1}$

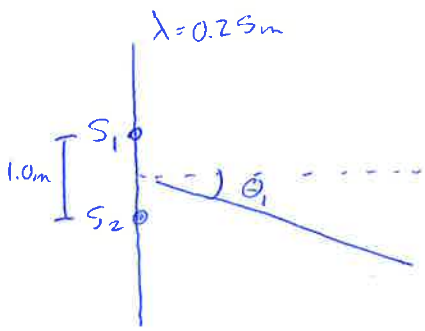
$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$

$= \sin^{-1}\left(\frac{1.00}{1.30}\right)$

$= 50.28° = 50°$

∴ θ_c is 50°.

3. ***(Diffraction and interference)*** Two speakers are 1.0 m apart and vibrate in phase to produce waves of wavelength 0.25 m. Determine the angle of the first node.



$\sin\theta_n = \left(n - \frac{1}{2}\right)\frac{\lambda}{d}$

$\theta_1 = \sin^{-1}\left[\left(1 - \frac{1}{2}\right)\frac{0.25}{1}\right]$

$= \sin^{-1}(0.125)$

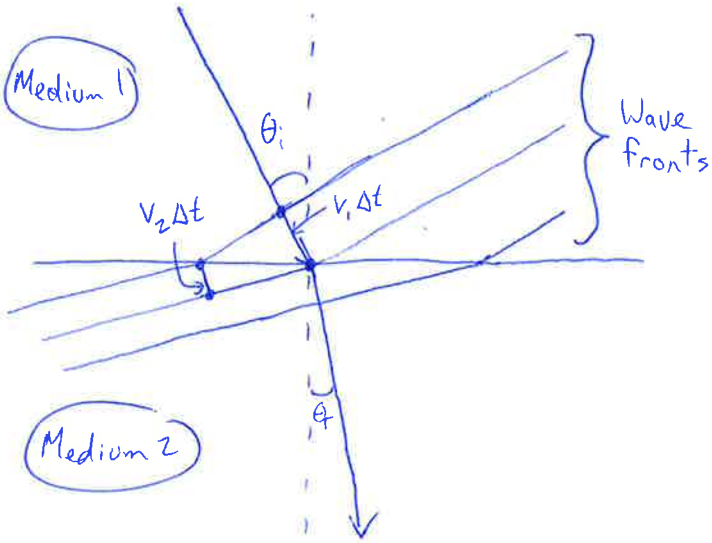
$= 7.181°$

$= 7.2°$

∴ the first nodal line is at 7.2°.

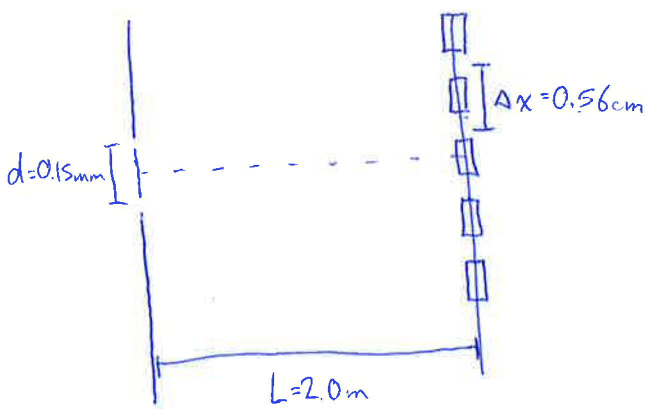
Name: ______________________________

4. ***(Light: Wave or particle?)*** Draw a diagram to show how light behaves like a wave during refraction.



5. ***(Light interference)*** In a double-slit experiment, the distance to the screen is 2.0 m, the slits are 0.15 mm apart, and the dark fringes are 0.56 cm apart.

   a. Determine the wavelength of the source.



$$\Delta x = \frac{L\lambda}{d}$$

$$\lambda = \frac{d\,\Delta x}{L}$$

$$= \frac{(0.15\times10^{-3})(0.56\times10^{-2})}{2.0}$$

$$= 4.2\times10^{-7}\ \text{m}$$

$$= 420\ \text{nm}$$

∴ the wavelength is 4.2×10^{-7} m (420 nm).

   b. Determine the spacing of the dark fringes with a source of wavelength 600 nm.

$$\Delta x = \frac{L\lambda}{d}$$

$$= \frac{(2.0)(600\times10^{-9})}{0.15\times10^{-3}}$$

$$= 8.0\times10^{-3}\ \text{m}$$

$$= 0.80\ \text{cm}$$

∴ the spacing of the dark fringes would be 8.0×10^{-3} m (0.80 cm).