Ch 30: Reflection & Refraction:

Geometrical Optics: propagation of light using light rays (ignoring wave properties such as interference, diffraction, polarization) → Physical Optics in later chapter

Law of reflection: \( \theta = \theta' \)

Incident angle \( \theta \): angle between incident ray & normal to mirror.
Reflected angle \( \theta' \): angle between reflected ray & normal.

Multiple reflections: using geometry, we can write \( \theta'' \) in terms of \( \theta \).
\[ 180^\circ = 90 - \theta_1' + 90 - \theta_2 + \alpha \implies \theta_2 = \alpha - \theta_1' \]
\[ \implies \theta_2' = \theta_2 = \alpha - \theta_1 \]

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**Refraction:** When light rays travel from one medium to another (light goes slower in a medium).

** Broken straw:**

\[ n = \text{index of refraction} = \frac{c}{v} > 1 \]

1. Incident ray
2. Reflected ray
3. Wave fronts are compressed as reflected ray bends toward the normal in agreement with lower speed in a medium.
Shell's law or law of refraction:

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]

**Consequences of Shell's Law**

**Critical Angle \( \theta_c \)**

1. Medium \( n_1 > 1 \)
2. Air \( n_2 = 1 \)

\( \theta_c \) is the angle of incidence at which the refracted ray goes parallel to the interface.

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

*Critical angle only when going from higher index to lower index.*

* \( n_1 \sin \theta_c = n_2 \sin 90^\circ \)

* \( \theta_c \): no refraction into medium \( n_2 = \) "Total internal reflection"
Critical angle: (higher index to lower index) happens when we all reflection, none refraction.

Any refraction where we have none reflection & all refraction.

YES! it happens at the polarizing angle or Brewster's angle

\[ \Theta_p = \Theta_B = \arctan\left( \frac{n_2}{n_1} \right) \]

\[ n_1 \]
\[ \mathbf{E} \]
\[ n_2 \]
\[ \Theta_B \]
\[ \Theta_p \]
\[ \mathbf{E} \]

When \( \Theta_1 = \Theta_p = \Theta_B \) & \( \mathbf{E} \) oscillates in the plane of the page → there none reflection & all refraction (all energy goes to medium #2)

\[ \Theta_2 \neq \Theta \]

→ Good when taking picture of something behind glass

Note: in general if \( \mathbf{E} \) is such that it has some component perpendicular to the page → you still have some reflection @ Brewster’s angle for this component of the electric field.

This is why the Brewster’s angle is called the polarizing angle; since if you observe any reflection @ \( \Theta_B \) incident angle → this reflection will be polarized (direction ± to page)
If I immerse prism in a liquid → $1 < n_2 < 1.52$ such that we no longer have total internal reflection?

Since $\theta_i = 45^\circ$ → if $n_2$ is such that $\theta_c = \sin^{-1}\left(\frac{n_2}{1.52}\right) = 45^\circ$

we may no longer have total internal reflection:

$$n_2 = 1.52 \sin 45^\circ$$

$$= 1.07$$

→ conclusion: if $n_2 \geq 1.07$ → $\theta_c \geq 45^\circ$ → our incident angle of $\theta_i = 45^\circ$ will be short for total internal reflection.
\( \theta_1 = 35^\circ \)

- Incident angle on boundary 1 is 35°.
- Reflected angle on boundary 1 is \( \theta_1 = \) incident angle on boundary 1.
- Refracted angle on boundary 1 is \( \theta_2 \).

**Snell's Law:**

1. \( \sin 35^\circ = 1.43 \sin \theta_1 \Rightarrow \theta_1 = \sin^{-1}\left(\frac{0.588}{1.43}\right) = 23.6^\circ \)

2. \( 1.43 \sin 23.6^\circ = n \sin \theta_2 \Rightarrow 2 \text{ unknowns} \ n \text{ & } \theta_2 \)

→ One more equation: from the geometry:

\[ \tan \theta_2 = \frac{y_2}{x_2} = \frac{\frac{L}{2} - y_1}{\frac{L}{2}} = \frac{\frac{L}{2}}{\frac{L}{2}} - \frac{y_1}{\frac{L}{2}} \]

→ \( \tan \theta_2 = 1 - \tan \theta_1 \Rightarrow \theta_2 = \tan^{-1}(1 - \tan 23.6^\circ) = 29.3^\circ \)
\[ n = \frac{1.43 \sin 22.6^\circ}{\sin 29.3^\circ} = 1.17 \]

Check: according to own figure: \( O_2 \rightarrow O_1 \rightarrow n_2 < n_1 = 1.43 \sqrt{\cdot} 

\[ V = \theta'' - \theta''' \quad \text{angular dispersion} \]

White light
\[ \downarrow \]
mix of all \( \lambda \)'s
\[ \text{Red} \rightarrow \text{Violet} \]
\[ \downarrow \]

Prism:
\[ n_{\text{Red}} = 1.582 \]
\[ n_{\text{Violet}} = 1.633 \]
\[ \text{Different wavelengths travel at different speeds inside prism. = "dispersion"} \]

\[ \Delta ABC = \theta'' + \theta''' + 120 = 180^\circ \quad \Rightarrow \theta''' = 60 - \theta'' \]
Shell's law at left boundary:

\[ l \sin 45^\circ = n_v \sin \theta_v \]

\[ \rightarrow \theta_v = \sin^{-1}\left(\frac{l \sin 45^\circ}{1.633}\right) = 25.5^\circ \]

\[ \theta_v = 60^\circ - 25.5^\circ = 34.5^\circ \]

Shell's law at right boundary:

\[ n_v \sin \theta_v = 1 \sin \theta_v'' \]

\[ \rightarrow \theta_v'' = \sin^{-1}\left(\frac{1.633 \sin 34.5^\circ}{1}\right) \]

\[ \theta_v'' = 67.7^\circ \]

For \( y \), we also need \( \theta_y'' \) by the same process except \( n_v \rightarrow n_2 = 1.582 \)

Shell's law at left boundary:

\[ l \sin 45^\circ = n_2 \sin \theta_2 \]

\[ \rightarrow \theta_2 = \sin^{-1}\left(\frac{l \sin 45^\circ}{1.582}\right) \]

\[ \theta_2 = 26.5^\circ \]

Equilateral prism:

\[ \theta_2' = 60^\circ - \theta_2 = 60^\circ - 26.5^\circ = 33.5^\circ \]

Shell's law at right boundary:

\[ n_2 \sin \theta_2' = 1 \sin \theta_2'' \]

\[ \rightarrow \theta_2'' = \sin^{-1}\left(\frac{1.582 \sin 33.5^\circ}{1}\right) \]

\[ \theta_2'' = 60.8^\circ \]

Angular dispersion:

\[ \Delta = \theta_v'' - \theta_2'' = 67.7^\circ - 60.8^\circ = 6.85^\circ \]
Ch 31  Images & Optical Instruments

How to form an image of an object through a mirror or a lens?

Image formation by a mirror:

1. How tall a mirror so we could see our whole body?
   a) as tall as the body,
   b) \( \frac{2}{3} \) height
   c) \( \frac{1}{2} \) height

Virtual image: formed by extension rays, not real rays.
No lights actually converging @ the virtual image.

Lights do not travel through the mirror (just our brain interpretation.)
Curved mirror:

- Focal point: 1) incident ray II axis, will reflect through F
  2) incident rays thru F, will reflect parallel to axis

Again: Image formed by extension rays \( \rightarrow \) virtual image

MIRROR EQUATION: \[
\frac{1}{l} + \frac{1}{l'} = \frac{1}{f}
\]

from geometrical optics

Magnification factor: \[
M = \frac{h'}{h} = -\frac{l'}{l}
\]

Sign conventions \( \rightarrow \) MIRRORS

\[
\begin{array}{c|c}
\text{Focal length} & f \\
\text{Image position} & l' \\
\text{Image located in} & \text{+ image located in the other side of the}\ (\text{real image}) \\
\text{same side as object} & \text{image located in the}\ (\text{virtual image}) \\
\end{array}
\]
Can we obtain a real image with a concave mirror?

Concave mirror

Real image!

Lens:

Converging lens or convex lens

Diverging lens or concave lens

Image formation in lenses:

Need 2 rays:
1) Parallel to axis incident ray emerges through F in the other side of the lens.
2) Incident ray thru F emerges ll axis the other side of lens.
3) Incident ray thru C keep its direction.
lens equation: \[ \frac{1}{l} + \frac{1}{l'} = \frac{1}{f} \]

- concave lenses (diverging)
- convex lenses (converging)
- image located in the other side of the lens
- image located same side as object.

Other types of lenses:

1) Curved lens equation:

\[ \frac{n_2}{\ell} + \frac{n_2}{\ell'} = \frac{n_2 - n_1}{R} \]

2) With different radii of curvature on the left and right side:

Lens maker's equation:

\[ \frac{1}{f} = (n-1) \left( \frac{1}{R_1} - \frac{1}{R_2} \right) \]

Note:

\[ \left( \frac{1}{R_1} - \frac{1}{R_2} \right) = \frac{2}{R} \]
Eyes:

- Lens muscles to control the focal length for built-in lens
- Retina
- Brain
- Good eye: sharp image

Near sighted (myopic):
- Blurred image

Far sighted (hyperopic):
- Clear or sharp image

Corrective lenses:

\[
L = \frac{1}{f} \quad (\text{in meters})
\]

\[
L = \frac{1}{f} \quad \text{(in m)}
\]
Near-sighted

can see closer objects clear

Far-sighted

Air → Water → Image bubble smaller than actual

Actual diameter of air bubble (spherical) if it appears to be 1.5 cm along your line of sight : image of the far side A, which is the object appears is 1.5 cm behind point B:

1) is image of 0 or 0, then the concave lens DBE.

→ Actual diameter = location of object 0 or A with this lens.

\[ \frac{n_1}{l} + \frac{n_2}{l'} = n_2 - n_1 \]

\[ l = \frac{1}{2R} + \frac{1.333}{-1.5cm} = \frac{0.333}{-1.5cm} \]

\[ l' = \frac{1 + 0.666}{2R} = \frac{1.333}{1.5} \]

\[ 2R = 1.87 \text{ cm} \]
Location of an object to get an upright image \( M = 1.8 \)

\[
M = \frac{h'}{h} = 1.8
\]

\[
\frac{1}{l} + \frac{1}{l'} = \frac{1}{f}
\]

\[
\frac{1}{l'} = \frac{1.8}{25cm}
\]

\[
\frac{1}{l} = \frac{1}{1.8} - \frac{1}{25cm}
\]

\[
l = 25cm \left(1 - \frac{1}{1.8}\right) = 11.1cm
\]
Ch 32  Interference & Diffraction

Physical optics: using wave properties of light in addition to geometry of the problem.

Superposition of waves, \( \text{constructive (in phase)} \), \( \text{destructive (out of phase \( \pi \) or \( 180^\circ \))} \)

Double-slit interference.

One source \( \rightarrow \) two identical light waves after double slit

Waves 1 & 2 will arrive at B with different phase b/c of the different paths they followed. These phase difference come from Dpath (assume \( L >> d \)) waves travel along parallel paths.

\[
\{ \begin{align*}
\text{Dpath} &= m \lambda \\
& \quad (m = 0, 1, 2, 3, ...) \\
& \quad \text{in phase or constructive interference} \\
& \quad \rightarrow \text{bright spot at B} \\
\text{Dpath} &= (2m + 1) \frac{\lambda}{2} \\
& \quad (m = 0, 1, 2, 3, ...) \\
& \quad \text{out of phase or destructive interference} \\
\end{align*} \]

Screen along Y axis
a) Tank is empty: air → air: no refraction.

\[ L = 0.4 \text{m} \]

\[ 1 \text{m} \]

\[ 0.4 \text{m}. \]

b) Tank is half full: refraction: water → air: higher to lower index → ray goes further from the normal ↓ Vertical in this case.

\[ \theta_1 < \theta_2 \]

We will see mark set by \( x_1 + x_2 \):

\[ x_1 = 0.2 \text{m} \]

\[ x_2 \rightarrow \frac{x_2}{0.2} = \tan \theta_1 \]

\[ 1.333 \sin \theta_1 = 1 \sin \theta_2 \]

\[ \theta_2 = 45^\circ \rightarrow \theta_1 = \sin ^{-1} \left( \frac{\sin 45}{1.333} \right) \]

\[ x_2 = 0.2 \tan \left( \sin ^{-1} \left( \frac{\sin 45}{1.333} \right) \right) = 12.5 \text{ cm, } = 0.125 \text{ m} \]

\[ x_1 + x_2 = 0.325 \text{ m} \]
c) Tank is full of water

\[
\sin \theta_i = 1 \sin 45^\circ \Rightarrow \theta_i = \sin^{-1}\left(\frac{\sin 45^\circ}{1.333}\right)
\]

\[
\Rightarrow x = 0.4 \tan \theta_i = 25 \text{cm} \Rightarrow 0.25 \text{m}
\]

\[\text{30.37}\]

\[
\frac{0.5}{x_1} = \tan 50^\circ \Rightarrow x_1 = 0.5 \text{m} = 0.42 \text{m} \; ; \; \frac{x_2}{1.6} = \tan \theta_i \Rightarrow x_2 = 1.6 \tan \theta_i
\]

Snell's Law:

\[
1.333 \sin \theta_i = 1 \sin 60^\circ \Rightarrow \theta_i = \sin^{-1}\left(\frac{\sin 60^\circ}{1.333}\right) = 28.8^\circ
\]

\[
x_2 = 1.6 \tan 28.8^\circ \Rightarrow x_1 + x_2 = 0.42 \text{m} + 1.6 \tan 28.8^\circ = 1.3 \text{m}\]
Double-slit experiment: (cont.)

on screen:

bright spot: constructive interference of two waves 1 & 2 from the two slits.

\[ \text{Path} = m \lambda \quad (m = 0, 1, 2, 3, \text{etc}) \]

\[ d \sin \theta_m = m \lambda \rightarrow \gamma_m = L \tan \theta_m \]

\[ \theta_m = \sin^{-1} \left( \frac{m \lambda}{d} \right) \rightarrow \gamma_m = L \tan \left( \sin^{-1} \left( \frac{m \lambda}{d} \right) \right) \]

Location 1st bright spot: \( m = 1 \)

\[ \gamma_1 = L \tan \left( \sin^{-1} \left( \frac{\lambda}{d} \right) \right) \]

2nd bright spot: \( \gamma_2 = L \tan \left( \sin^{-1} \left( \frac{2 \lambda}{d} \right) \right) \]

dark spot: destructive interference of waves 1 & 2

out of phase \( \text{Path} = (2m+1) \frac{\lambda}{2} \quad (m = 0, 1, 2, \text{etc}) \)

\[ d \sin \phi_m \]

loc. of dark spots: \[ \gamma_m = L \tan \left[ \sin^{-1} \left( \frac{(2m+1) \lambda}{2d} \right) \right] \]

\[ \gamma_0 = L \tan \left[ \sin^{-1} \left( \frac{\lambda}{2d} \right) \right] \]

\[ \gamma_1 = L \tan \left[ \sin^{-1} \left( \frac{2 \lambda}{2d} \right) \right] \]
Thin film interference:

\[
\text{Interference between 1 and 2 \ waves: going in parallel \& in the double slit experiment. Hence they are not identical:}
\]

\[\begin{align*}
\text{a) 1 is a reflection from lower to higher index \rightarrow get inverted} & \text{ includes an extra phase of } 2\pi \text{ or } \text{path } = \frac{\lambda}{2} \\
\text{b) 2} & \text{ causes a path of } 2d\text{ (approx of vertical paths in whole film)}
\end{align*}\]

\[
\begin{align*}
\text{Constructive in in phase:} \\
2d = n\lambda + \frac{\lambda}{2} = (2n+1)\frac{\lambda}{n} \quad (n = 0, 1, 2, 3, \ldots) \\

\text{Destructive in out of phase:} \\
2d = (2n+1)\frac{\lambda}{2} + \frac{\lambda}{2} = (n+1)\lambda \quad (n = 0, 1, 2, 3, \ldots)
\end{align*}
\]

\[\Rightarrow \text{Diffraction} \quad \Rightarrow \text{Interference in 3 slits.} \quad \Rightarrow \text{tomorrow.}\]
Three-slit interference:

One source → 3 identical waves

Young's
multiple

Note: A path

Approximation: (good)

$L >> d$ → paths are parallel (we assume)

A) If A path = multiple of the wavelength → constructive interference

@ B:

\[
\begin{align*}
1 & \times 2 \rightarrow \sin \theta_m = m \lambda \\
2 & \times 2 \rightarrow \sin \theta_m = m \lambda \\
1 & \times 3 \rightarrow 2 \sin \theta_m = 2m \lambda
\end{align*}
\]

\[\sin \theta_m = m \lambda\]

B) If A path is such that \(b/w 2 \text{ waves out of phase by } \frac{\lambda}{2} \text{ or an odd multiple of } \frac{\pi}{4} \text{ or } 180^\circ\)

\(l = 0\)

\[\rightarrow \]Destructive interference

Location of dark spots:

\[
\sin \theta_n = (n + \frac{1}{3}) \lambda \quad (3 \text{ slits})
\]

\[
\sin \theta_n = \frac{n \lambda}{2} \rightarrow (N \text{ slits})
\]
Diffraction: superposition of waves coming from one slit.

Thuyghens principle:
Each point on the wave front will become a new source of waves → each point within one slit will be a source of wave

→ Destructive interference:
\[ \text{Path}_2 = \frac{a \sin \Theta}{2} = \frac{(2n+1)\lambda}{2} \]
\[ (n = 0, 1, 2, \text{etc.}) \]

Location of dark spots for diffraction:
\[ a \sin \Theta_n = (2n+1)\lambda \]
\[ (n = 0, 1, 2, \text{etc.}) \]

Diffraction limit:
\[ \theta_{\text{min}} = \frac{1.22\lambda}{D} \]
\[ D \text{ diameter of slit.} \]
Visible light \( \lambda = 400 \text{nm} \) (higher \( f \) → higher energy)

\( \lambda = 700 \text{nm} \) (lower \( f \) → lower energy)

red to violet

\( \rightarrow \) lowest pair of consecutive orders for some overlap b/w visible spectra as dispersed by a grating?

slit

\[ L \gg a \]

Dark spot on screen: \( \sin \theta_n = n \lambda \)

\( \theta_n \rightarrow \) location of spot of order \( n \) (\( y_n = L \tan \theta_n \)) on screen.

\[
L \rightarrow \begin{cases} 
\theta_n^{\text{red}} = \sin^{-1} \left( \frac{n \lambda_{\text{red}}}{a} \right) \\
\theta_n^{\text{violet}} = \sin^{-1} \left( \frac{n \lambda_{\text{violet}}}{a} \right)
\end{cases}
\]

For a same order \( n \), dark spot for red is further up from the middle (or x axis) than that for violet.

\( \rightarrow \) We may have an overlap: a dark spot for red of order \( n \) coincides with a dark spot for violet of order \( n+1 \)

\( \sin \theta_n^{\text{red}} = \sin \theta_n^{\text{violet}} \)

\[
\frac{n \lambda_{\text{red}}}{a} = \frac{(n+1) \lambda_{\text{violet}}}{a}
\]
\[ n(\lambda_{\text{red}} - \lambda_{\text{violet}}) = \lambda_{\text{violet}} \rightarrow n = \frac{\lambda_{\text{violet}}}{\lambda_{\text{red}} - \lambda_{\text{violet}}} \]

\[ n = \frac{400\text{nm}}{700\text{nm} - 400\text{nm}} = \frac{4}{7 - 4} = \frac{4}{3} = 1.33 \]

\[ n \text{ can only be integer} \rightarrow n = 2 \quad (\text{red}) \]

\[ n + 1 = 3 \quad (\text{violet}) \]

103.9 MHz FM radio station

- \(\Delta \text{path} = d \tan \Theta\)
- \(L = 6.5\text{km}\)
- \(y_{n+1} = L \tan \Theta_{n+1}\)
- \(y_n = L \tan \Theta_n\)
- Dark spots:
  - \(d \sin \Theta_{n+1} = \frac{(2n+1)A}{2d}\)
  - \(d \sin \Theta_{n+1} = \frac{(2n+2+1)A}{2d}\)

How often do you hear the radio signal fade? Radio wave as an EM wave \(\rightarrow\) behaves as a light wave \(\rightarrow\) interference \(\rightarrow\) like the double-slit interference.

If we know, \(\Delta y\) = separation b/w consecutive dark spots: \(\rightarrow\) how often: \(\frac{\Delta y}{v} = \text{time b/w fadeups}\).

\[ \Delta y = y_{n+1} - y_n = L \left[ \tan \Theta_{n+1} - \tan \Theta_n \right] = L \left[ \tan (\sin^{-1} \left( \frac{(2n+1)A}{2d} \right)) - \tan (\sin^{-1} \left( \frac{(2n+3)A}{2d} \right)) \right] \]
We don't have $n \rightarrow $ small angle approximation

\[ \theta_n, \theta_{n+1} \rightarrow \text{small} \quad (L \gg d) \]

\[ \sin \theta_n \approx \theta_n \rightarrow \tan \theta_n \approx \theta_n \]

\[ \sin \theta_{n+1} \approx \theta_{n+1} \rightarrow \tan \theta_{n+1} \approx \theta_{n+1} \]

\[ \Delta y = y_{n+1} - y_n = L(\theta_{n+1} - \theta_n) \]

\[ \text{Dark spot:} \quad d \sin \theta_n = \frac{(2n+1)\Lambda}{2} \rightarrow \begin{cases} 
\theta_n = \frac{(2n+1)\Lambda}{2d} \\
\theta_{n+1} = \frac{(2n+3)\Lambda}{2d}
\end{cases} \]

\[ \Delta y = L \frac{(2n+3)\Lambda - (2n+1)\Lambda}{2d} = \frac{L2\Lambda}{2d} = \frac{L\Lambda}{d} \]

\[ \text{Time by wedges} = \frac{\Delta y}{v} = \frac{L\Lambda}{v2d} = \frac{6500 \times \frac{3 \times 10^8}{103.9 \times 10^6}}{400 \times \frac{60}{3.6}} \]

\[ = 2.82 \text{ s}. \]

\[ \frac{\Lambda}{T} = c = \lambda f \rightarrow \lambda = \frac{c}{f} \]

\[ v = 60 \text{ km/h} = 60 \text{ m/s} \times \frac{5}{s} \]
laser $\lambda = 633\text{nm}$

$\lambda = 633\text{nm}$

$L = 1.7\text{m} \gg d$

$\text{good parallel path assumption}$

$\text{bright fringe}$: const. interfer. $\text{Path} = n\lambda$

$\frac{\text{Path}}{d \tan \theta} = n\lambda$

$1\text{st bright}$: $\theta_1 = \sin^{-1} \frac{\lambda}{d}$

$2\text{nd bright}$: $\theta_2 = \sin^{-2}\frac{2d}{\lambda}$

\[ y_2 - y_1 = L \tan \theta_2 - L \tan \theta_1 \]

\[ y_2 - y_3 = L \left( \tan \theta_2 - \tan \theta_3 \right) \]

\[ a) \quad y_2 - y_1 = L \left[ \tan \left( \frac{\sin^{-1} \frac{2d}{\lambda}}{d} \right) - \tan \left( \frac{\sin^{-1} \frac{\lambda}{d}}{d} \right) \right] \]

\[ = 1.7 \left[ \tan \left( \frac{\sin^{-1} \frac{2 \times 633 \times 10^{-9}}{6.5 \times 10^{-6}}}{6.5 \times 10^{-6}} \right) - \tan \left( \frac{\sin^{-1} \frac{633 \times 10^{-9}}{6.5 \times 10^{-6}}}{6.5 \times 10^{-6}} \right) \right] \]

\[ = 17.17\text{cm} \]

\[ b) \quad y_2 - y_3 = L \left( \tan \theta_2 - \tan \theta_3 \right) \]

\[ a_0 \text{ in } m = 20\text{cm} \]

\[ \text{by } 32.38, \text{ there is more separation than } y_1 \text{ or } 2 \]
Thin soap film: \((n = 1.333)\) for \(\lambda_0 = 550\text{nm}\) light to undergo constructive interference:

Thin film:

\[
2d = \frac{(2m+1) \lambda}{2} 
\]

\begin{align*}
\text{air } n &= 1 & \lambda_0 \\
\text{film, } n &> 1 & \lambda \\
\text{air } n &= 1 & \lambda
\end{align*}

\[
v = \frac{c}{n} = \frac{\lambda f}{c} = \frac{\lambda_0 f}{\lambda f} = \frac{\lambda_0}{n} \rightarrow \lambda = \frac{\lambda_0}{n} 
\]

Order of interference:

\[
2d = \frac{(2m+1) \lambda_0}{2n} \quad \rightarrow \text{thicknen: } \frac{\lambda}{\lambda_0} = \frac{(2m+1) \lambda_0}{2n} 
\]

Minimum thickness:

\[
d_{\text{min}} = \frac{\lambda_0}{4n} = \frac{550\text{nm}}{4 \times 1.333} = 103\text{nm}.
\]

Index of refraction for film.
Physics: Law of reflection on O₁ and O₂

Geometry:

\[ y = 37.5° + \alpha + 2\theta_2 \]

\[ \beta = 90 - \theta_1 \]

\[ \alpha = 90 - \theta_2 \]

\[ \angle ABC = \alpha + \beta + 75° = 180° \]

\[ \theta_1 = 90 - 37.5° = 52.5° \rightarrow \beta = 90 - 52.5° = 37.5° \]

\[ \alpha = 180 - 75 - 37.5° = 67.5° \]

\[ \theta_2 = 90 - 67.5° = 22.5° \]

\[ y = 37.5° + 67.5° + 2 \times 22.5° = 150° \]

Outgoing ray @ 150° CCW from incident ray.

in 210° CW.
a) **Near-sighted**

\[
\text{Corrective lens: } \frac{1}{f(m)} = \text{50 diopters}
\]

\[
\begin{align*}
\text{Power - diopters} &= \frac{1}{f(m)} \\
\text{Use corrective lens.}
\end{align*}
\]

\[
\text{Power} = 4.5 \text{ diopters}
\]

\[
\frac{1}{e} + \frac{1}{e'} = \frac{1}{f}
\]

\[
\begin{align*}
h &= 5.7 \text{ cm} \\
h' &= 9.5 \text{ cm} \\
l &= 22 \text{ cm}
\end{align*}
\]

\[
 M = \frac{h'}{h} = -\frac{e'}{e} \Rightarrow \frac{9.5}{5.7} l = -e'
\]

\[
\begin{align*}
\frac{1}{e} + \frac{1}{e'} &= \frac{1}{f} \\
\Rightarrow \frac{1}{e} + \frac{9.5}{5.7} &= \frac{1}{f} \\
\Rightarrow \frac{1}{e} (1 - \frac{5.7}{9.5}) &= \frac{1}{f}
\end{align*}
\]

\[
f = \frac{22 \text{ cm}}{1 - \frac{5.7}{9.5}} = 55 \text{ cm}
\]

\[
\rightarrow R = 2f = 110 \text{ cm}
\]