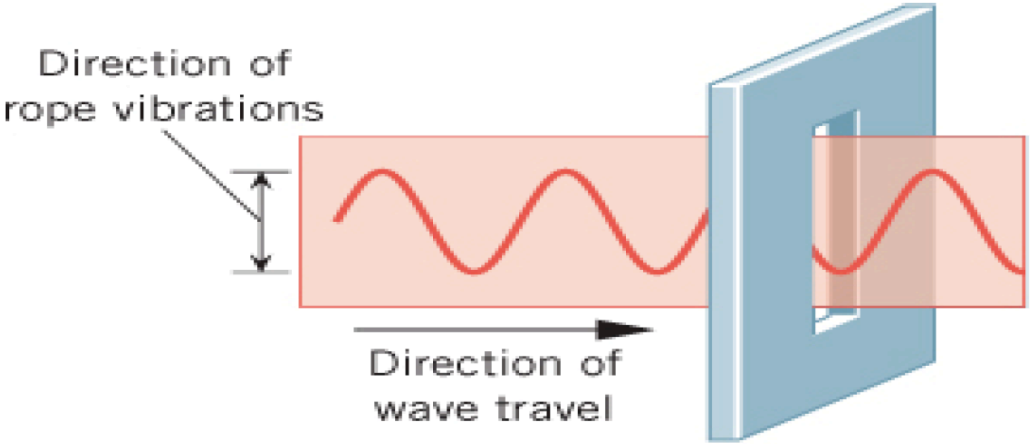
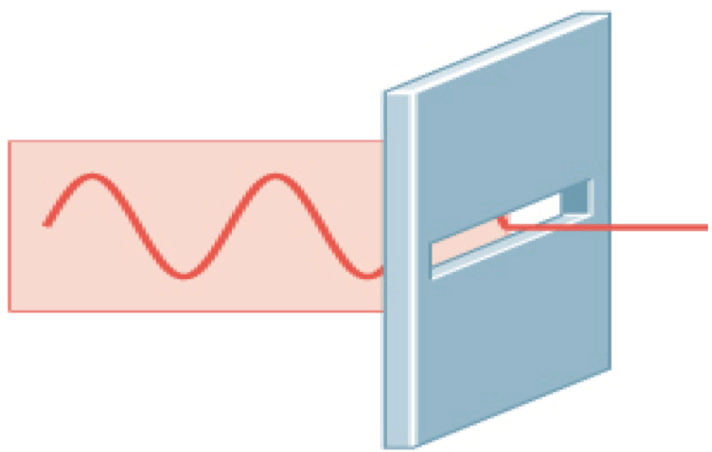
Polarization



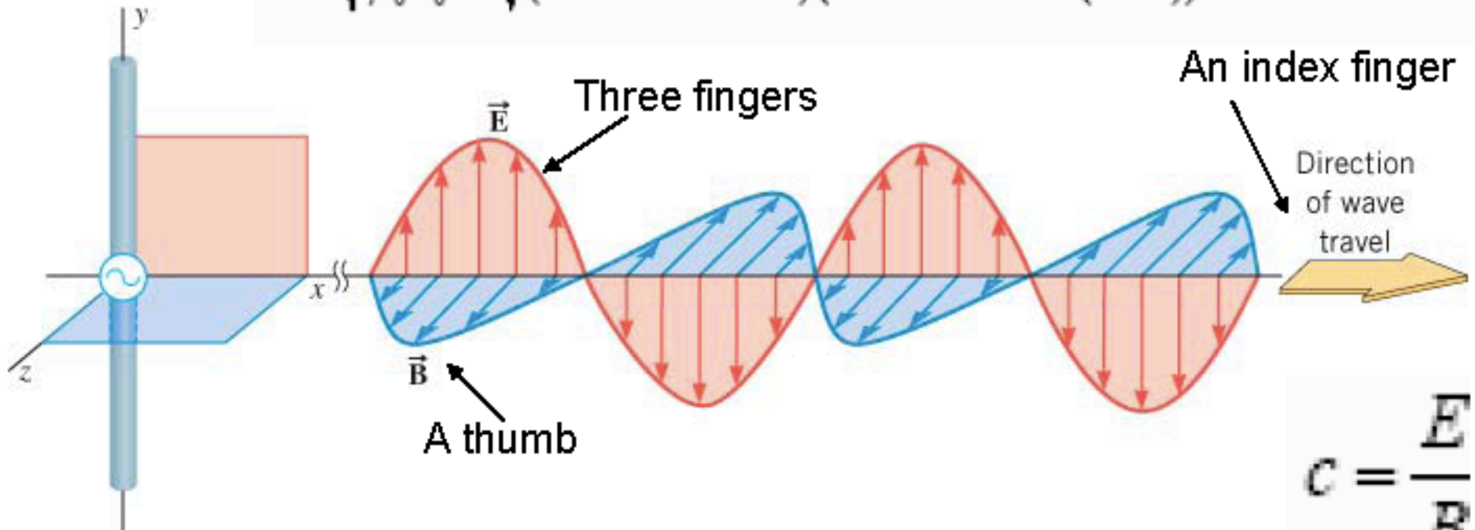
(a)


(b)

Linearly
polarized
wave
on a rope.

This picture shows the wave of the radiation field far from the antenna.

$$c = \sqrt{\frac{1}{\mu_0 \varepsilon_0}} = \sqrt{\frac{1}{(4\pi \times 10^{-7}\ \mathrm{Tm/A})(8.85 \times 10^{-12}\ \mathrm{C^2/(Nm^2)})}} = 3.00 \times 10^8\ \mathrm{m/s}\,.$$

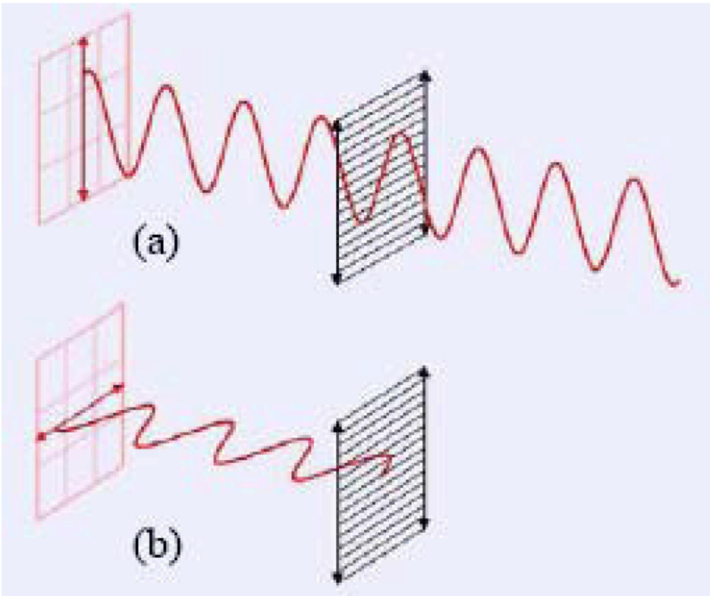


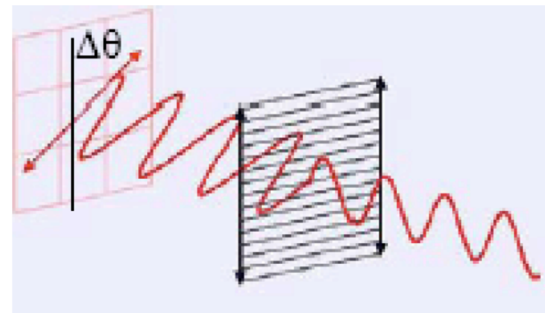
$$c = \frac{E}{B}$$

The speed of an electromagnetic wave in a vacuum is:

$$c = 3.00 \times 10^8\ \mathrm{m/s}$$

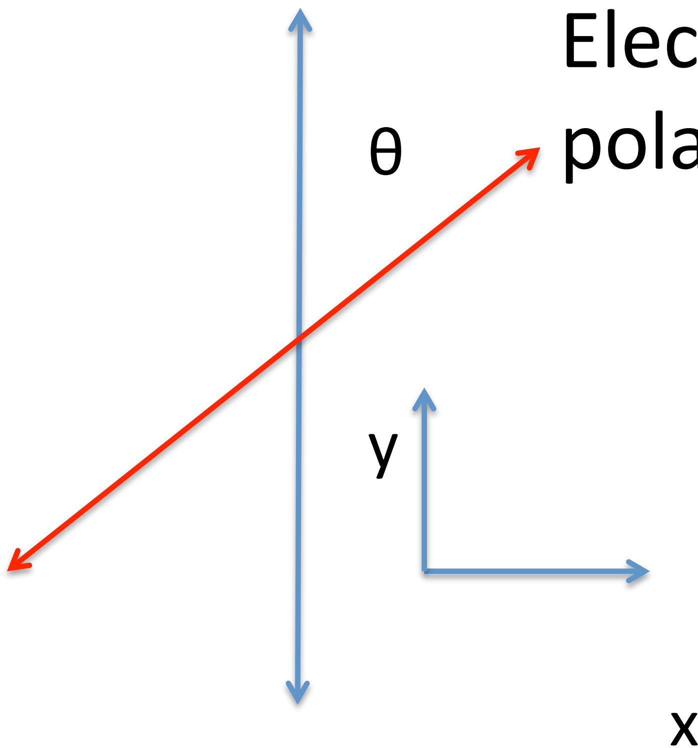
Linearly polarized EMW (only the *electric* filed is shown; **DEMO 1**).





The current induced in the rods by E- field creates an induced filed which interferes with the external one and cancel it out partially or completely.

Polarization axis = transmission axis
(long molecules are perpendicular to it!)

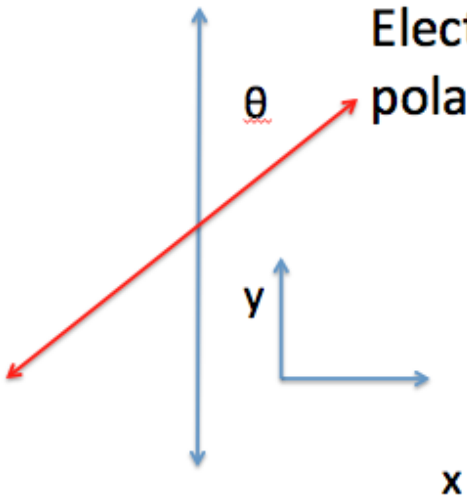


Electric field (E) of a linearly polarized light.

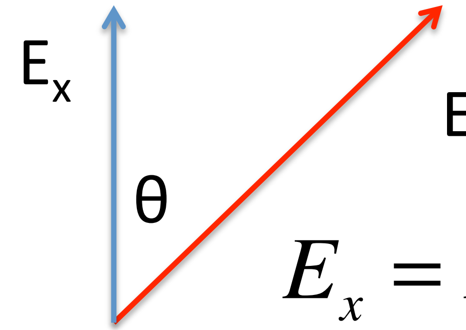
Which component of the electric field (E) does NOT get through the polarizer?

1. X 2. Y

Polarization axis
(long molecules)



Electric field (E) of a linearly polarized light.



$$E_x = E\cos\vartheta$$

Which component of the electric field (E) does NOT get through the polarizer?

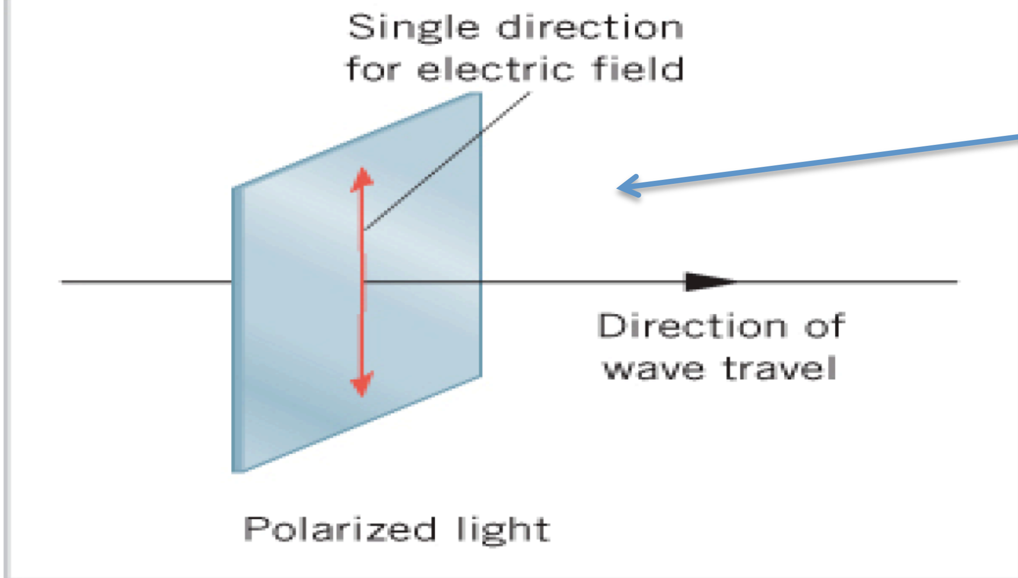
1. X

$$I_{transmitted} = (E_x)^2 = (E\cos\vartheta)^2 =$$
$$= E^2(\cos\theta)^2 = I_{initial}(\cos\theta)^2$$

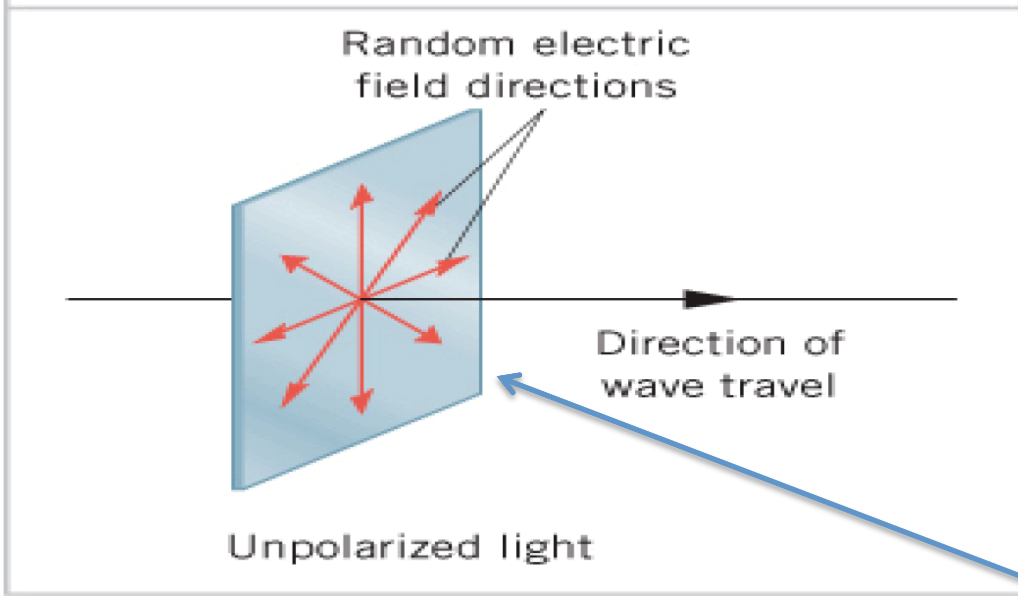
A polarizer:

(1) affects the intensity of light;

(2) Polarizes light along the polarization axis.

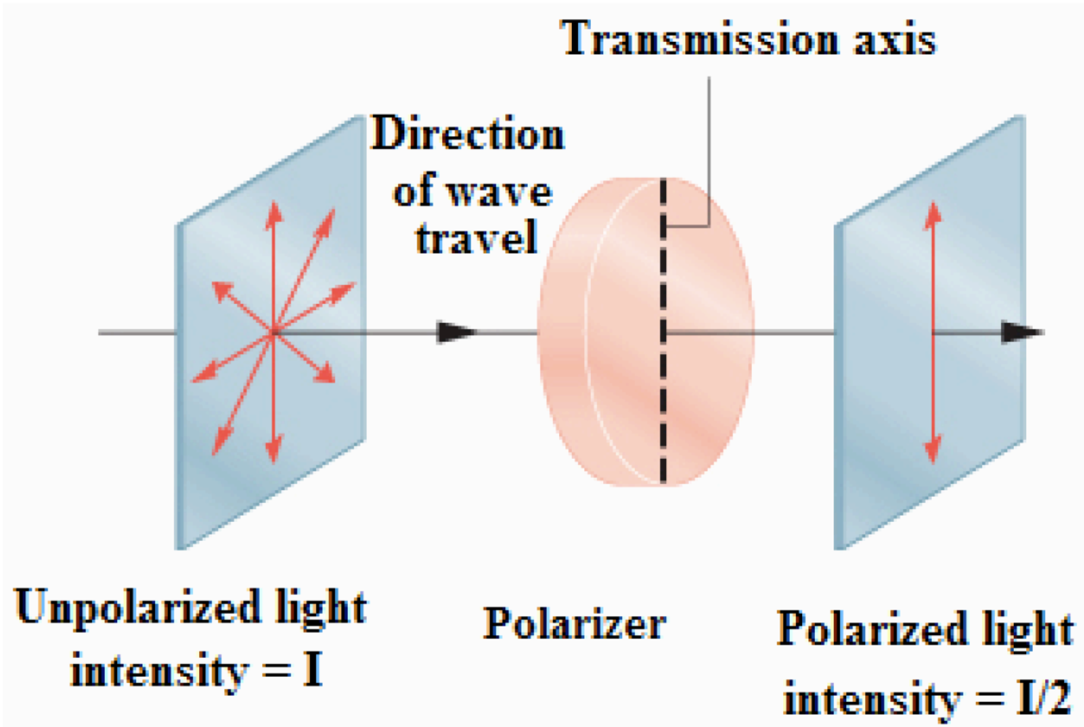


In polarized light, the ***electric*** field fluctuates along a single direction.



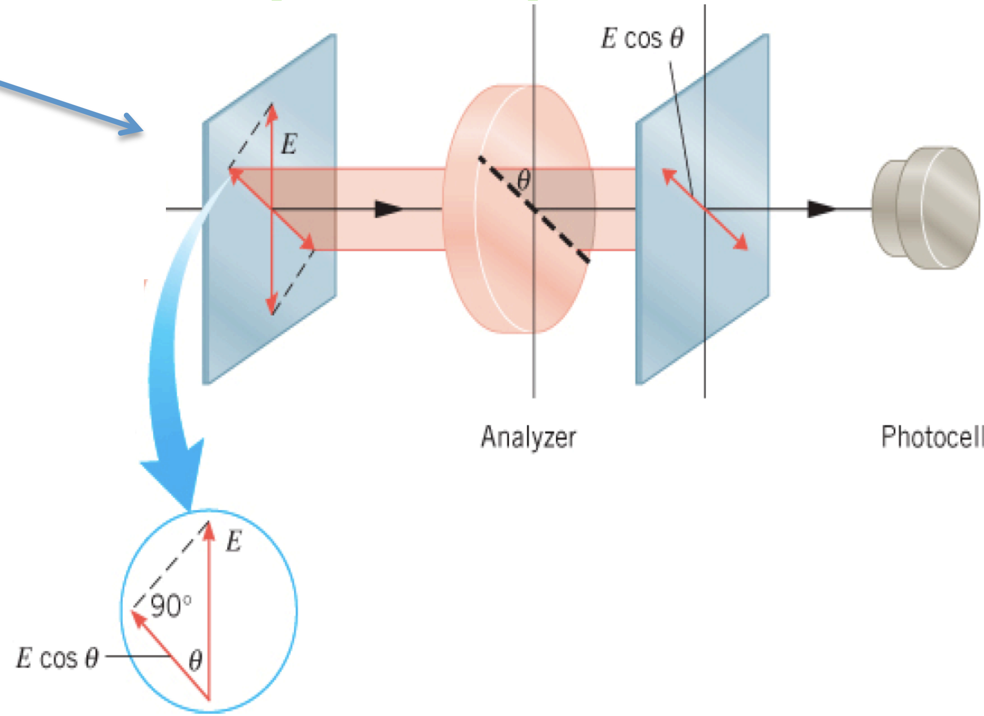
In unpolarized light the ***electric*** field fluctuates along ALL direction.

Unpolarized light passing through a polarizer



Polarized light may be produced from unpolarized light with the aid of polarizing material (a polarizer).

Polarized light passing through a polarizer



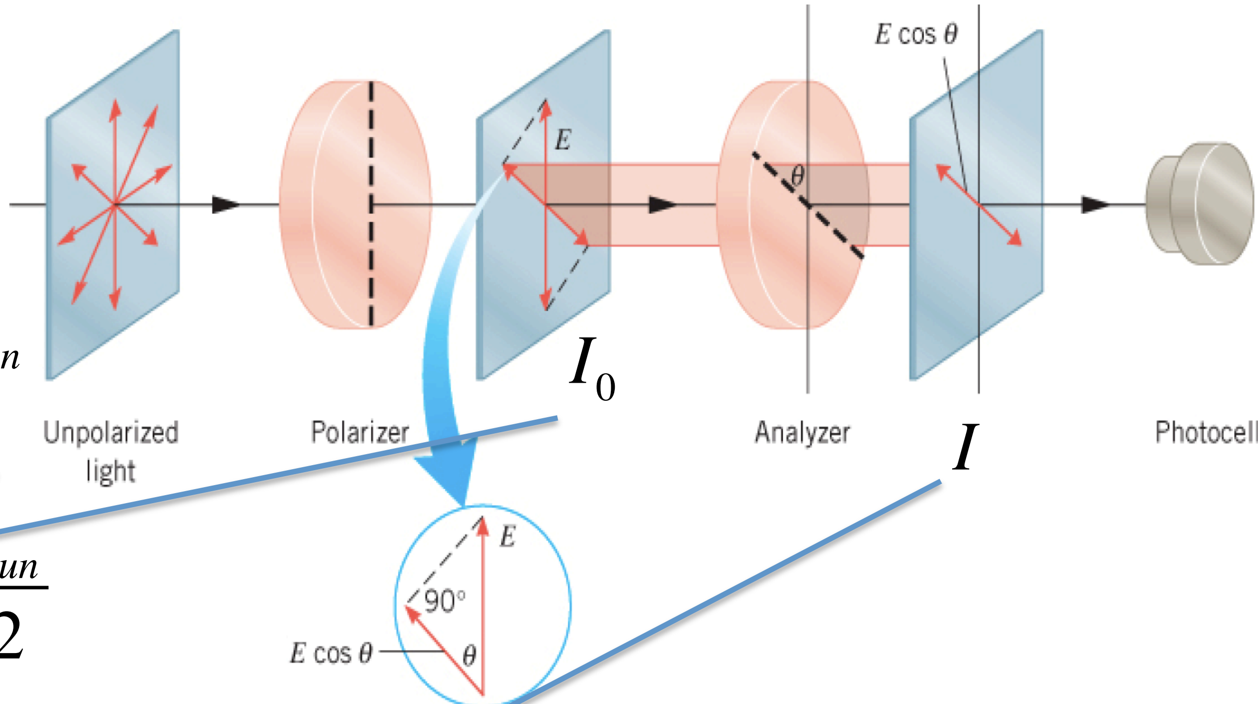
MALUS' LAW

$$I = I_o \cos^2 \theta$$

intensity after analyzer

intensity before analyzer

A combination of polarizers



$$I_0 = \frac{I_{un}}{2}$$

MALUS' LAW

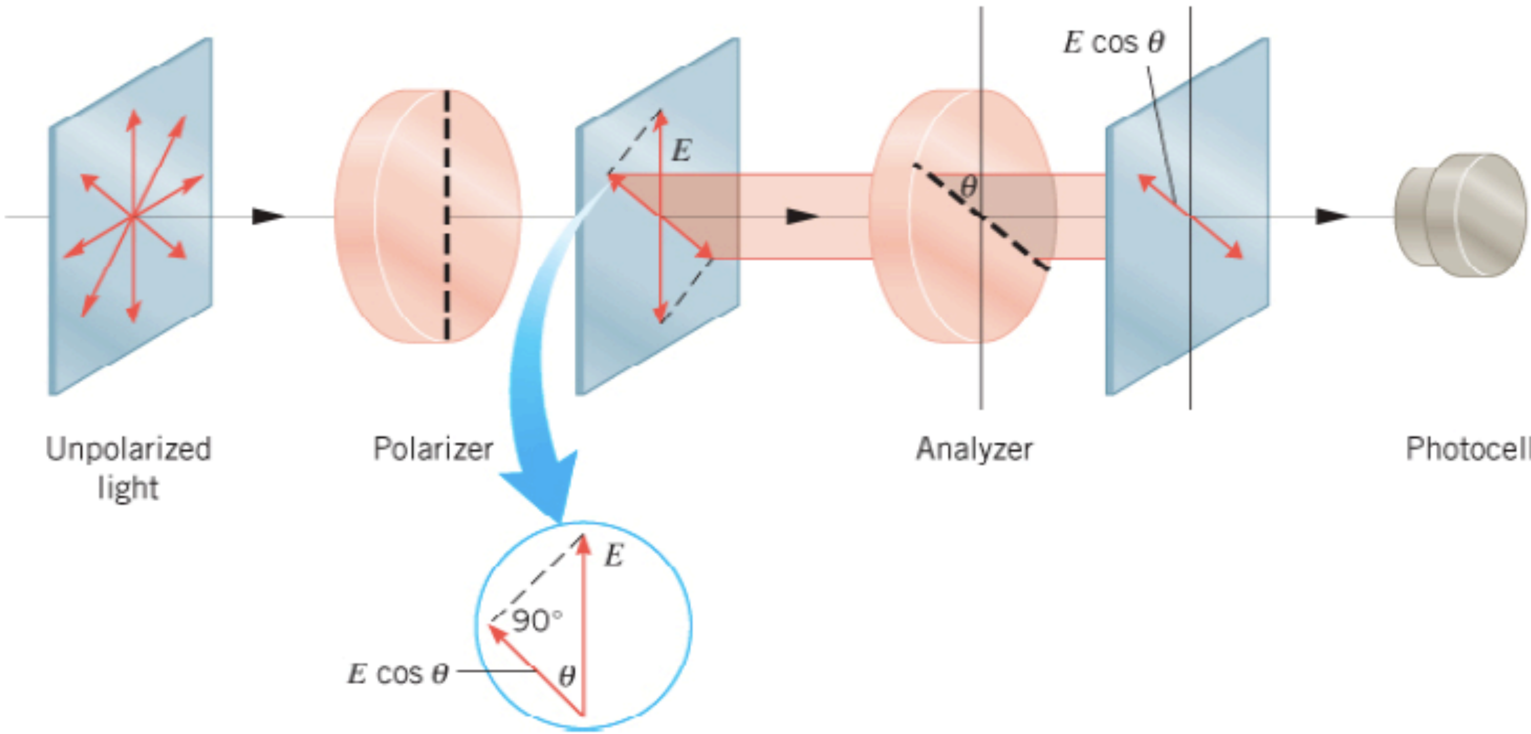
$$I = I_o \cos^2 \theta$$

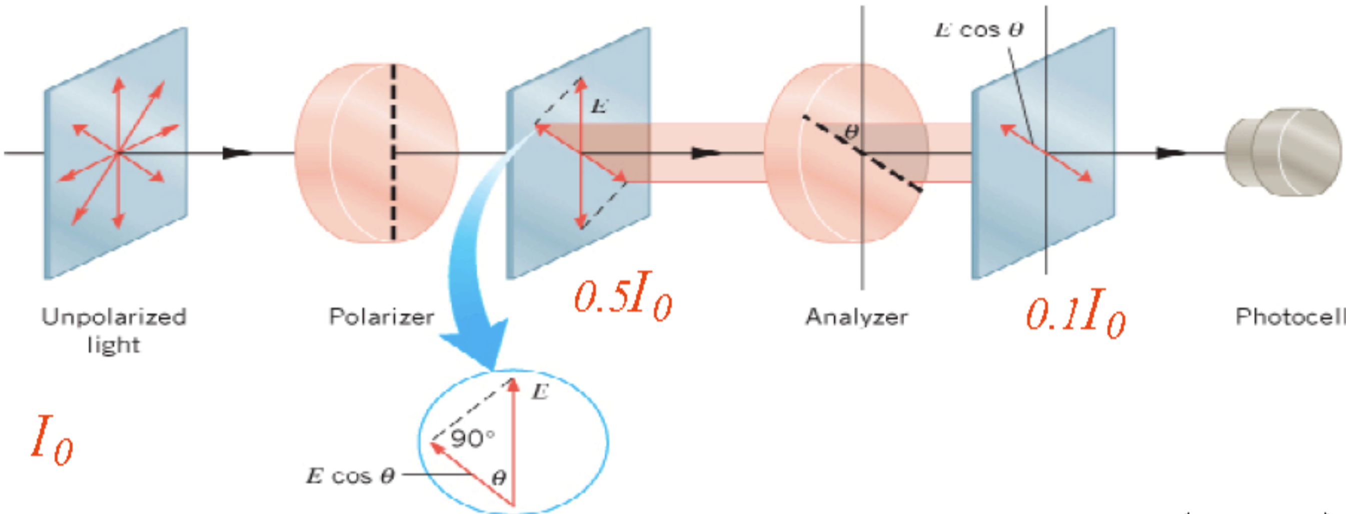
intensity after analyzer

intensity before analyzer

Example Using Polarizers and Analyzers

What value of θ should be used so the average intensity of the polarized light reaching the photocell is one-tenth the average intensity of the unpolarized light?





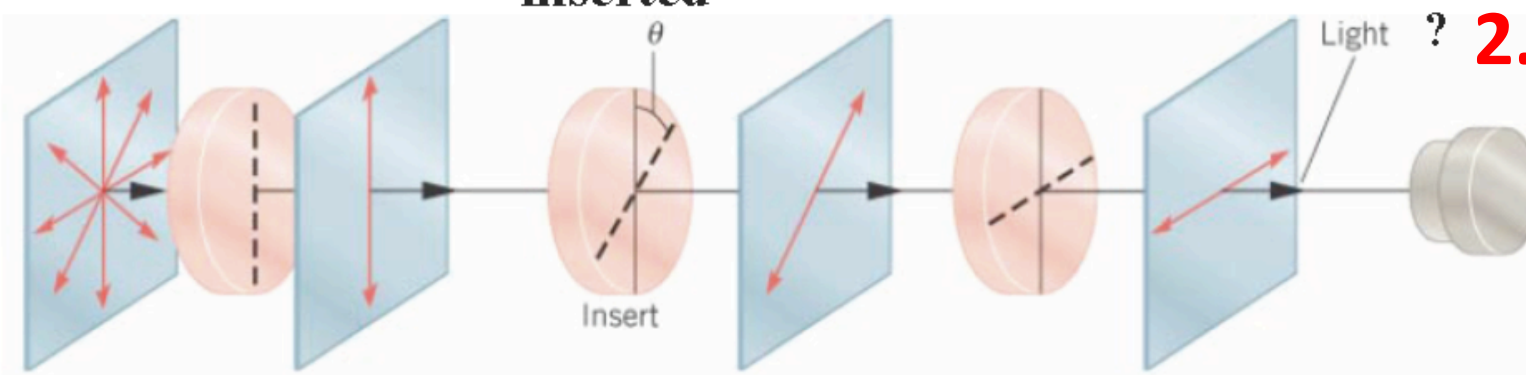
$$\frac{1}{10} I_o = \left(\frac{1}{2} I_o\right)\cos^2\theta$$

$$\frac{1}{5} = \cos^2\theta$$

$$\cos\theta = \sqrt{\frac{1}{5}}$$

$$\theta = 63.4^\circ$$

the third polarizer inserted

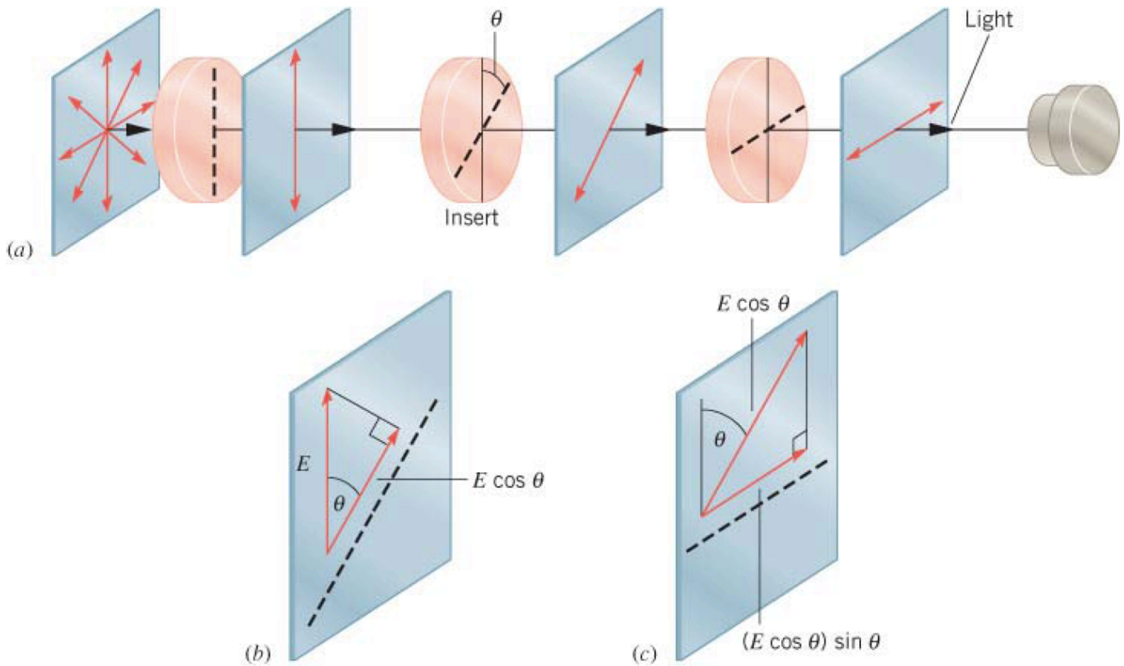


?

1. Yes
2. No

Can a Crossed Polarizer and Analyzer Transmit Light ?

Suppose that a third piece of polarizing material is inserted between the polarizer and analyzer which transmission axes are perpendicular to each other.
Does light now reach the photocell? **(A) Yes** (B) No

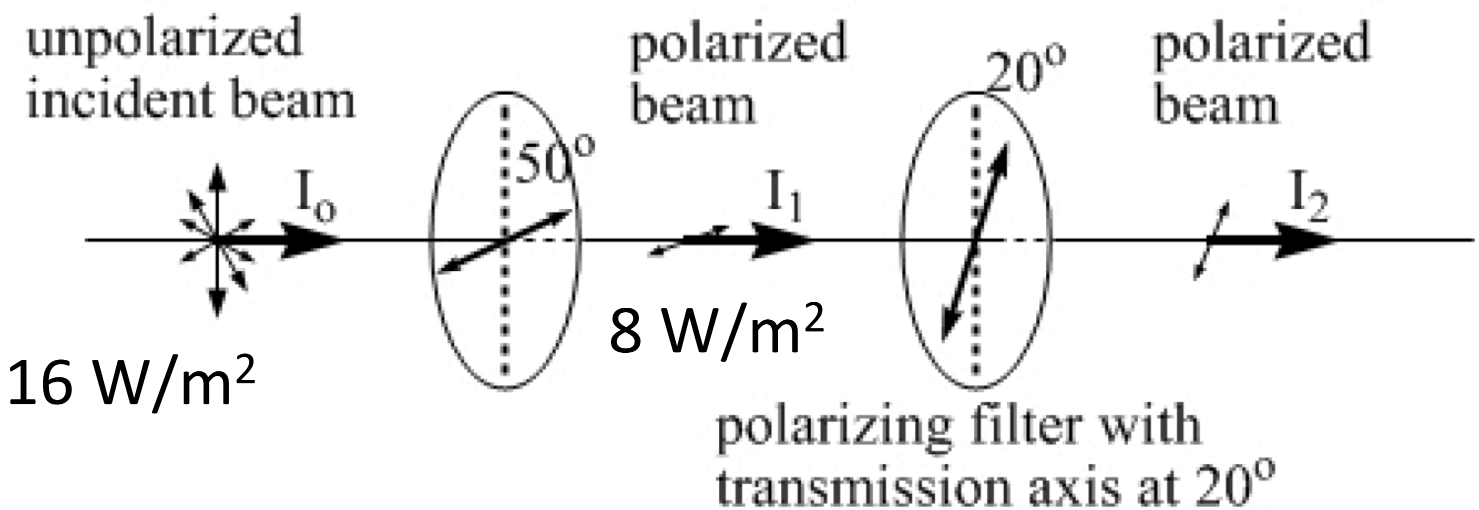


Polarizer example

Unpolarized light with an intensity of I_0 = 16 W/m^2 is incident on a pair of polarizers. The first polarizer has its transmission axis aligned at 50° from the vertical. The second polarizer has its transmission axis aligned at 20° from the vertical.

$$I_1 = \frac{1}{2} I_0 = \frac{1}{2}\left(16\ \mathrm{W/m^2}\right) = 8\ \mathrm{W/m^2}$$

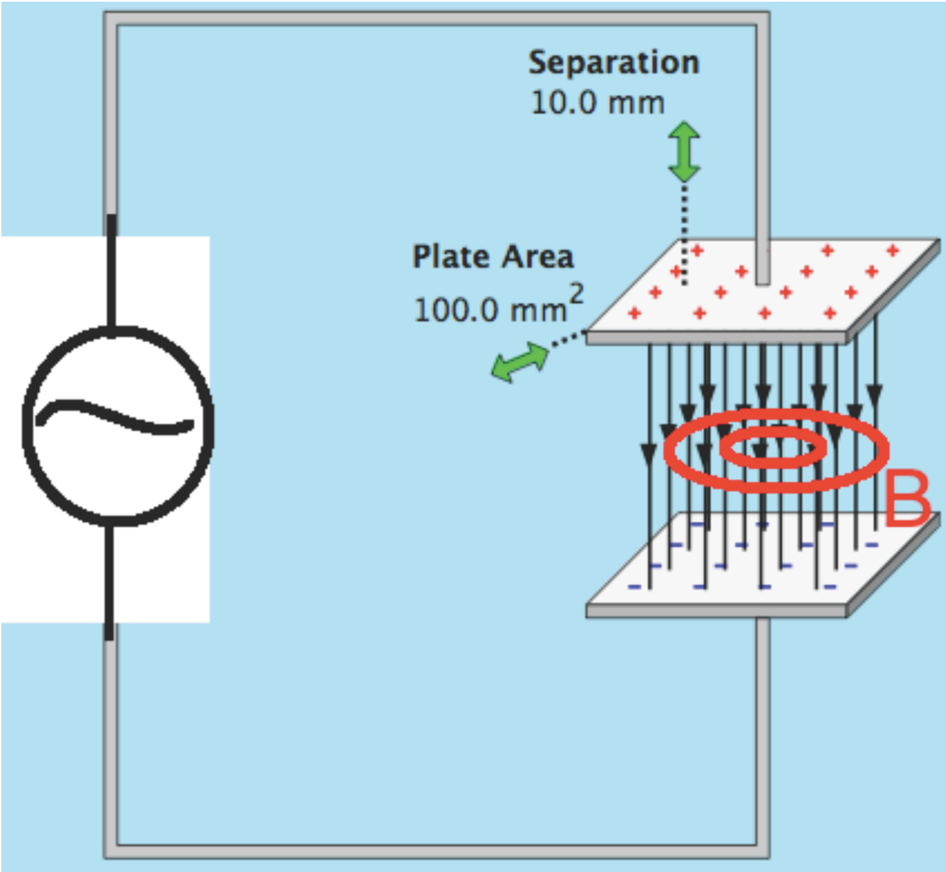
Through the second polarizer



$$I_2 = I_1 \cos^2(50° - 20°)$$

$$= 8 \text{ W/m}^2 \times \cos^2(30°)$$

$$= 8 \text{ W/m}^2 \times \left(\frac{\sqrt{3}}{2}\right)^2 = 6 \text{ W/m}^2$$



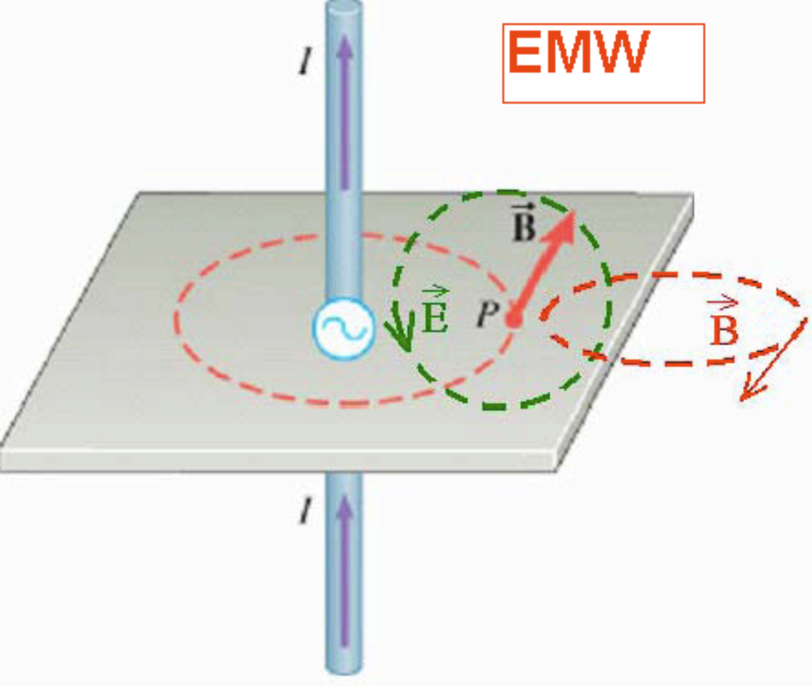
Changing E generates B!

But changing B generates E!

Etc.

If we *open* the capacitor we create EMW!

EMW



The changing current used to generate the electric wave creates a magnetic field.

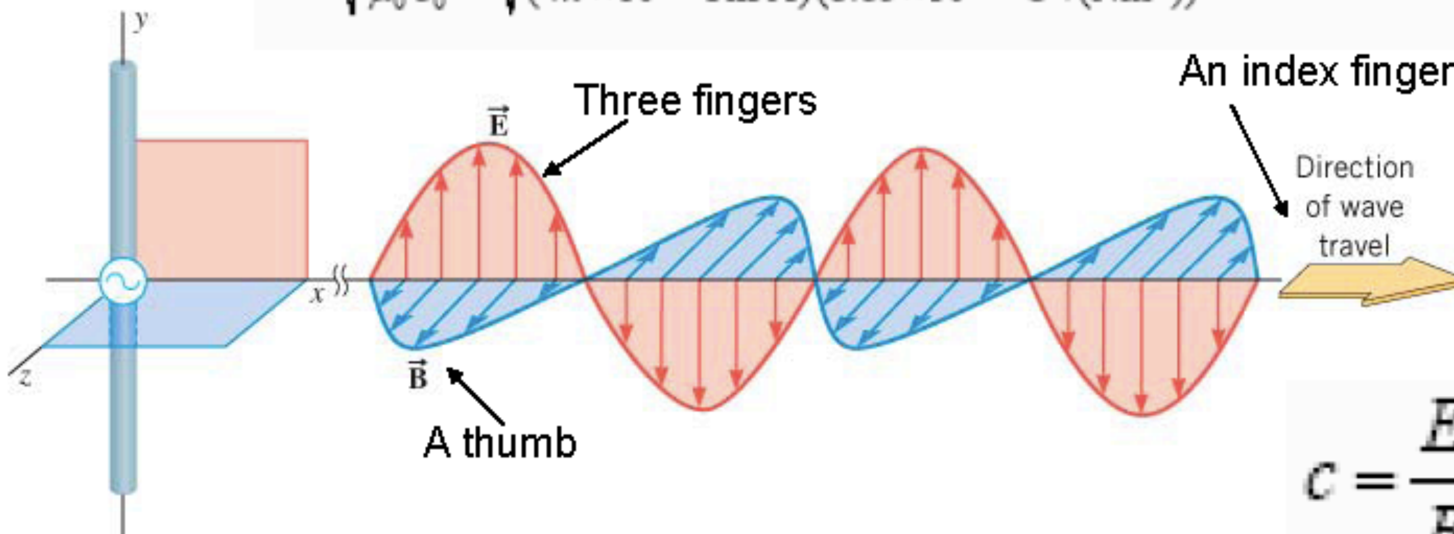
Changing magnetic field creates changing electric field.

Changing electric field creates changing magnetic field.

The EMW is created and traveling away form the wire.

This picture shows the wave of the radiation field far from the antenna.

$$c = \sqrt{\frac{1}{\mu_0 \varepsilon_0}} = \sqrt{\frac{1}{(4\pi \times 10^{-7}\ \text{Tm/A})(8.85 \times 10^{-12}\ \text{C}^2/(\text{Nm}^2))}} = 3.00 \times 10^{8}\ \text{m/s}\,.$$

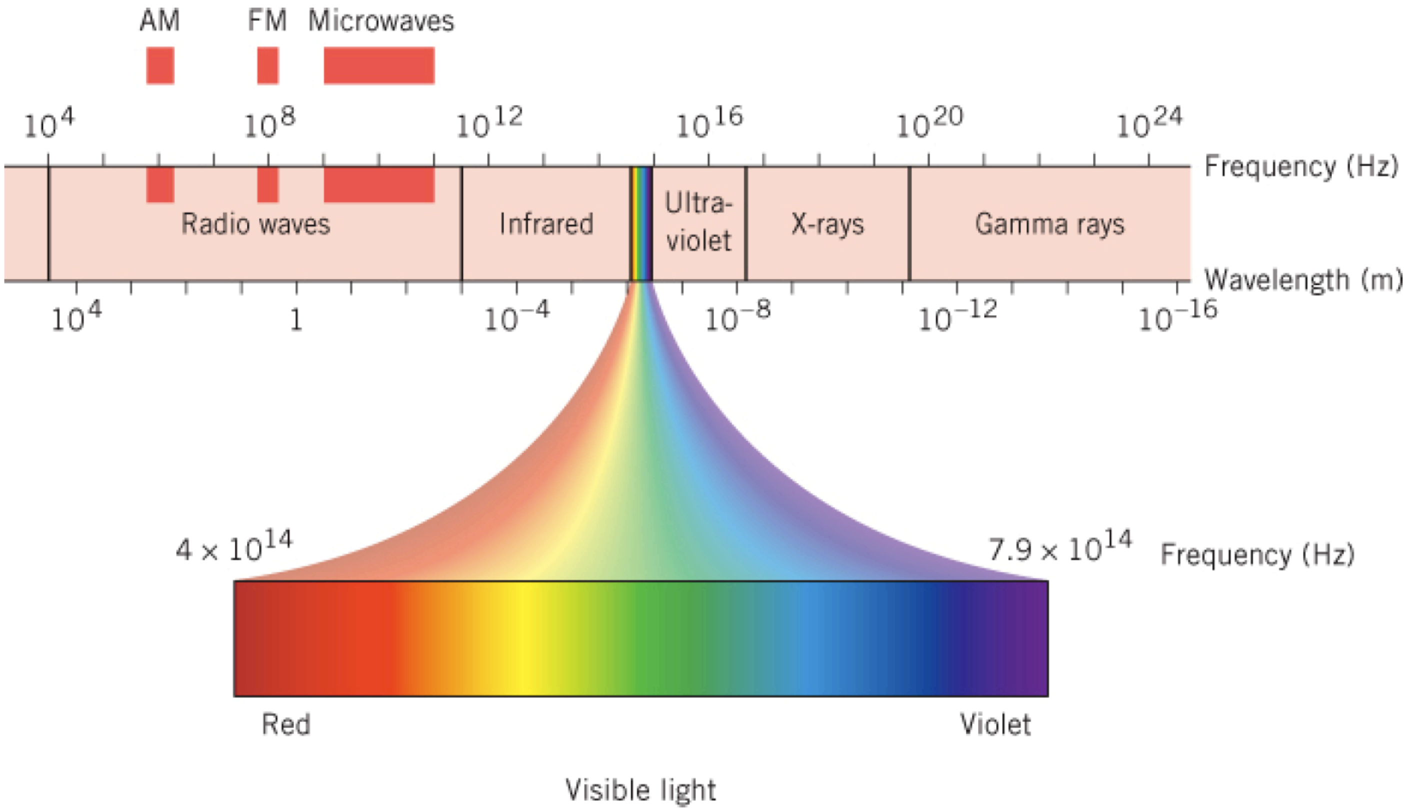


$$c = \frac{E}{B}$$

The speed of an electromagnetic wave in a vacuum is:

$$c = 3.00 \times 10^{8}\ \text{m/s}$$

The Electromagnetic Spectrum



Like all waves, electromagnetic waves have a wavelength and frequency, related by:

$$c = f\lambda$$

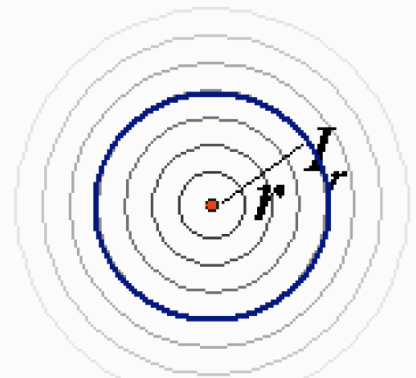
The Wavelength of Visible Light

Find the range in wavelengths for visible light in the frequency range between $4.0\text{x}10^{14}$ Hz and $7.9\text{x}10^{14}$ Hz.

$$\lambda_{red} = \frac{c}{f} = \frac{3.00\times10^{8}\ \text{m/s}}{4.0\times10^{14}\ \text{Hz}} = 7.5\times10^{-7}\ \text{m} = 750\ \text{nm}$$

$$\lambda_{violet} = \frac{c}{f} = \frac{3.00\times10^{8}\ \text{m/s}}{7.9\times10^{14}\ \text{Hz}} = 3.8\times10^{-7}\ \text{m} = 380\ \text{nm}$$

A point source



(As long as we use a *point* source the nature of a wave does NOT matter!)

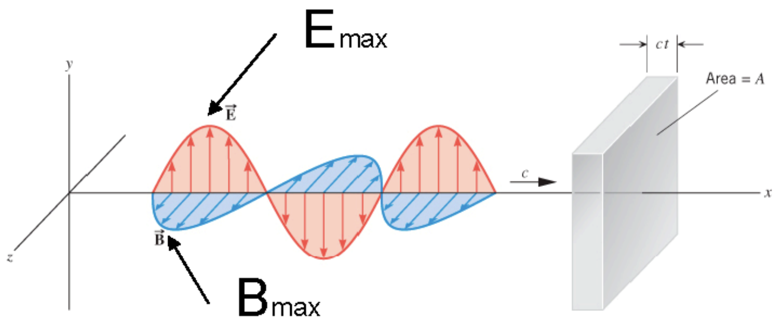
A point source of the power **P** uniformly emits an EMW in all directions.

The average energy of the EMW passing through *the sphere of radius* ***r*** per a second is

$$\frac{\text{Energy}}{\text{time}} = \text{P}$$

The intensity (average) of the WME at the distance ***r*** from the source is

$$I_{r\,ave} = \frac{P_{ave}}{A} = \frac{P}{A} = \frac{P}{4\pi r^2}$$



Instantaneous intensity

$$I = cu$$

Instantaneous energy density

$$u = \frac{EB}{\mu_o c}$$

Instantaneous intensity $I = \frac{EB}{\mu_0}$

$I_{min} = 0$ $\quad I_{max} = \frac{E_{max} B_{max}}{\mu_0}$ → $I_{ave} = \frac{P_{ave}}{A}$ is somewhere in between

Irradiance =
Average intensity

$$I_{ave} = \frac{1}{2} \cdot \frac{E_{max} B_{max}}{\mu_0} = \frac{E_{max} B_{max}}{2\mu_0}$$

Example Problem

How close do you have to be to a 100 W light bulb with the efficiency of 5 % to observe light of the same intensity as that from a 5 mW laser with a 3 mm diameter spot size?

For the laser beam the intensity is:

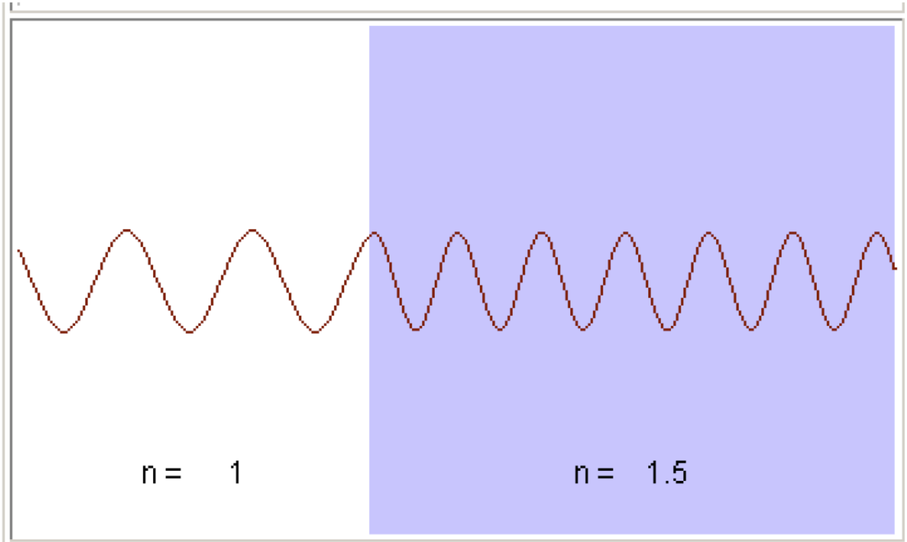
$$I = \frac{\text{Power}}{\text{Area}} = \frac{0.005\ \text{W}}{\pi r^2} = \frac{0.005\ \text{W}}{\pi\,(0.0015)^2} \approx 700\ \text{W/m}^2$$

100 W *spherical* bulb emits only 5 % via light => P = 5 W

$$700\frac{W}{m^2} = \frac{5W}{4\pi r^2}$$

This gives r = 2.4 cm

Light in a medium



f does NOT change!

λ changes!

v changes!

In vacuum	In medium
c – speed of light λ – wavelength f – frequency $c = \lambda f$	v – speed of light; $v < c$ λ_n – wavelength; $\lambda_n < \lambda$ f – frequency (<u>the same</u>!) $v = \lambda_n f$ n – index of refraction $n = c/v$ $\lambda_n = \lambda/n$

The reflection of light

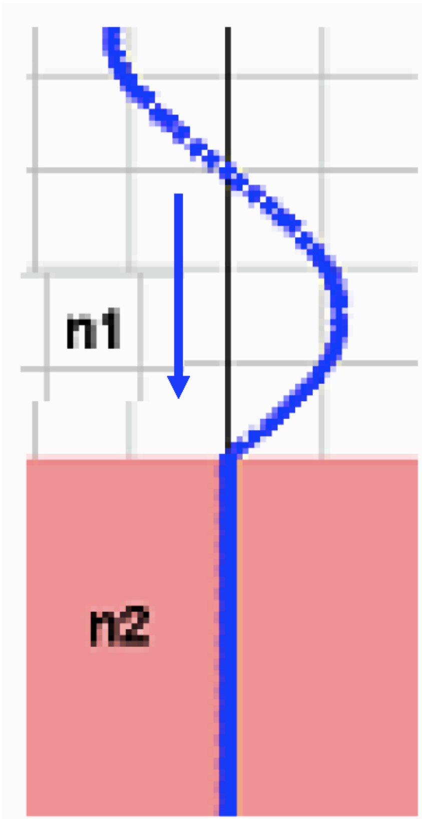
(one more new fact about light!)

Light waves, experience a 180° phase shift when reflecting from a higher-*n* medium ($n_2 > n_1$). This is equivalent to a shift of half a wavelength.

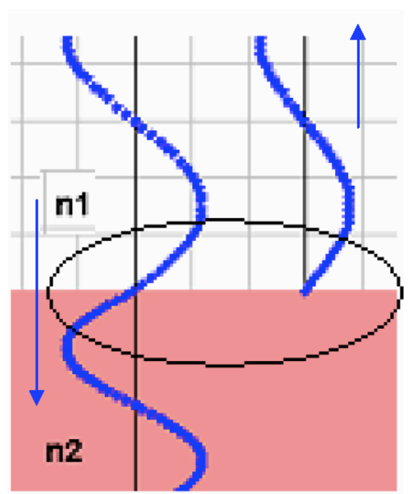
Waves reflecting from a medium of lower index of refraction experience no phase shift ($n_2 < n_1$).

A wave is incident on a surface of a medium

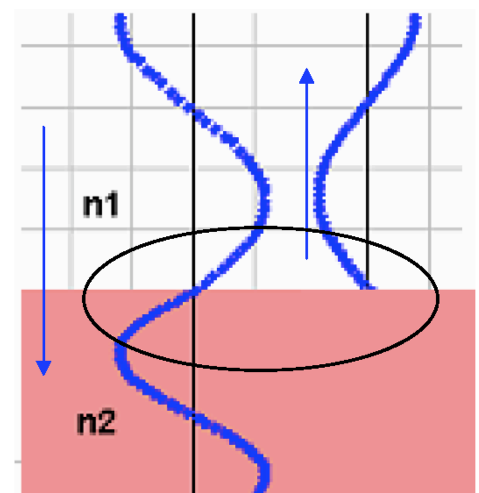
When it reflects from the interface between the media, two options are possible.



n2 < n1
no phase shift



n2 > n1
180^0 phase shift

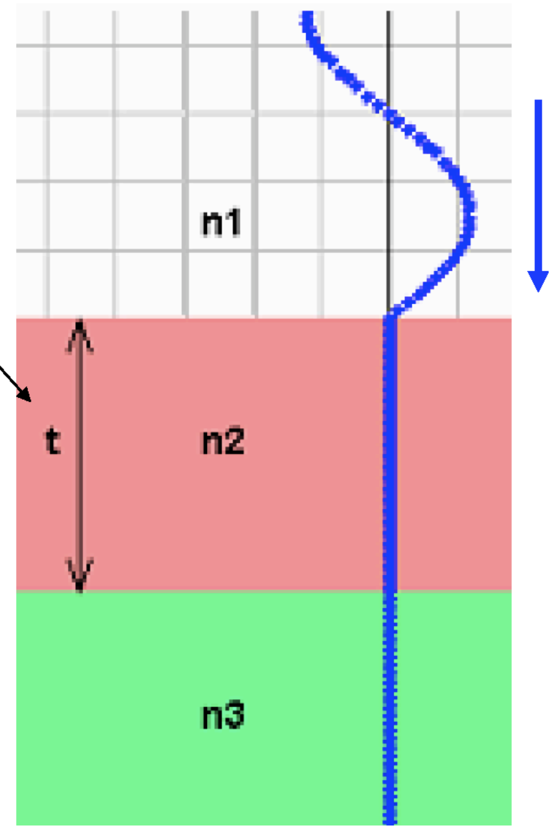


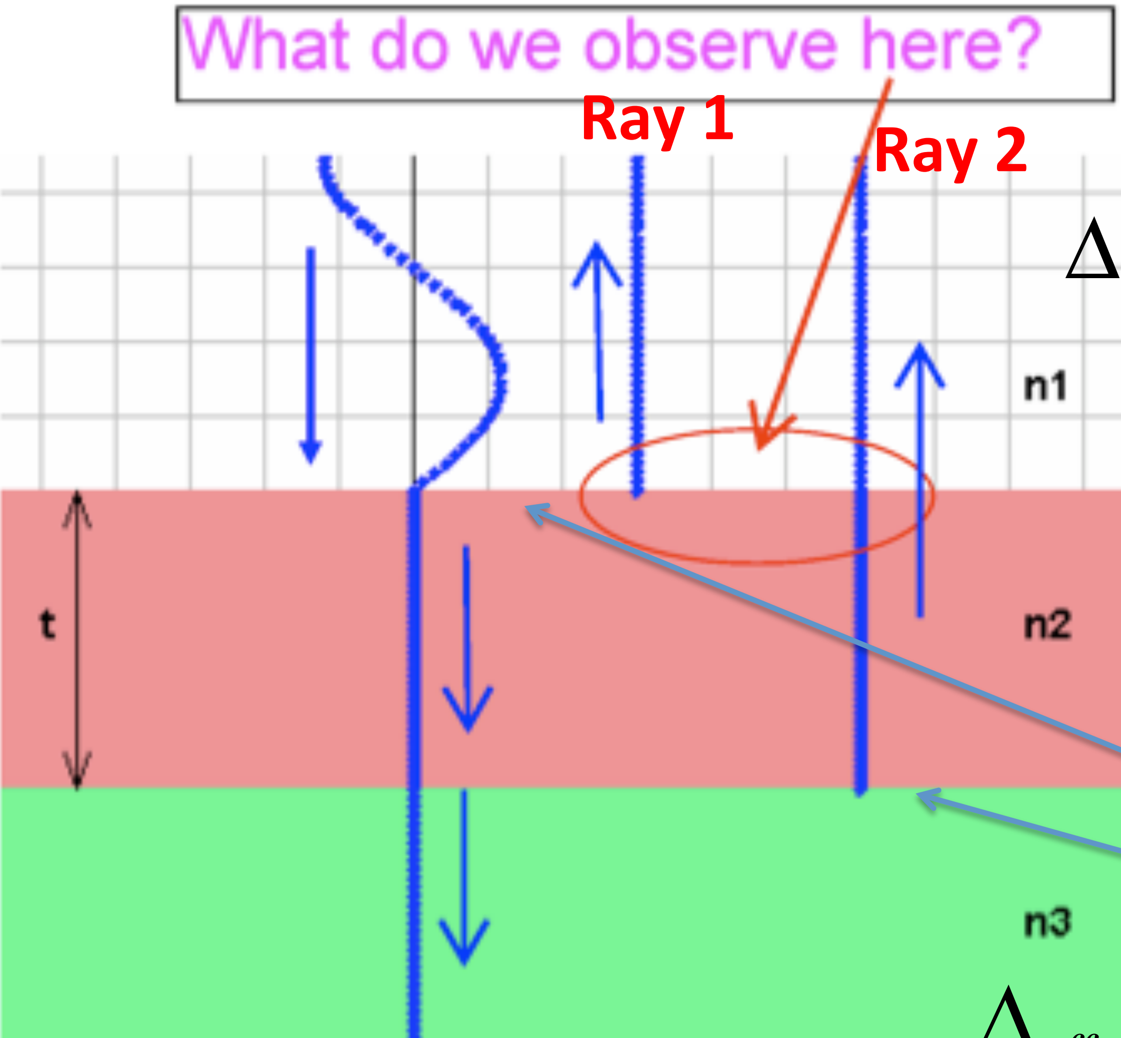
Thin films – sequence of events

A film is a very thin layer of some medium.

A wave is incident on the top surface of the film.

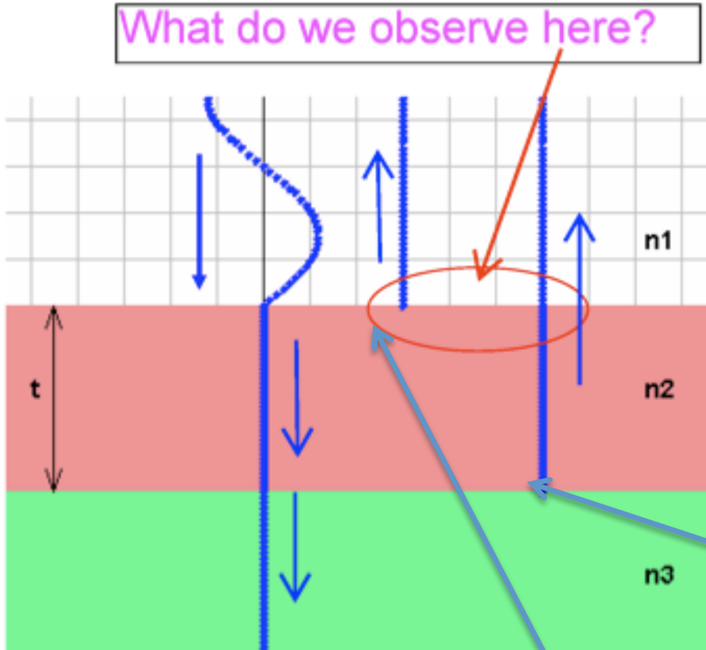
What we see when looking at a film depends on a color(s) of light, the thickness of the film, relative values of indices of refraction.





$$\Delta_{geometrical} = t + t = 2t$$

$$\Delta_{effective} = 2t + phase\,shift$$



$$\Delta r_{ef} = 2t + \left| \Delta_t - \Delta_b \right|$$

	Δ_t
$n_1 > n_2$	0
$n_1 < n_2$	$\lambda/2$

	Δ_b
$n_2 > n_3$	0
$n_2 < n_3$	$\lambda/2$

What kind of interference? PRS

Let be the film thickness t is exactly one wavelength (in the film), so, so t = λ_f. In this case the wave that reflects off the bottom surface of the film travels a down-and-back extra distance of $2\lambda_f$ compared to the wave reflecting off the top surface.

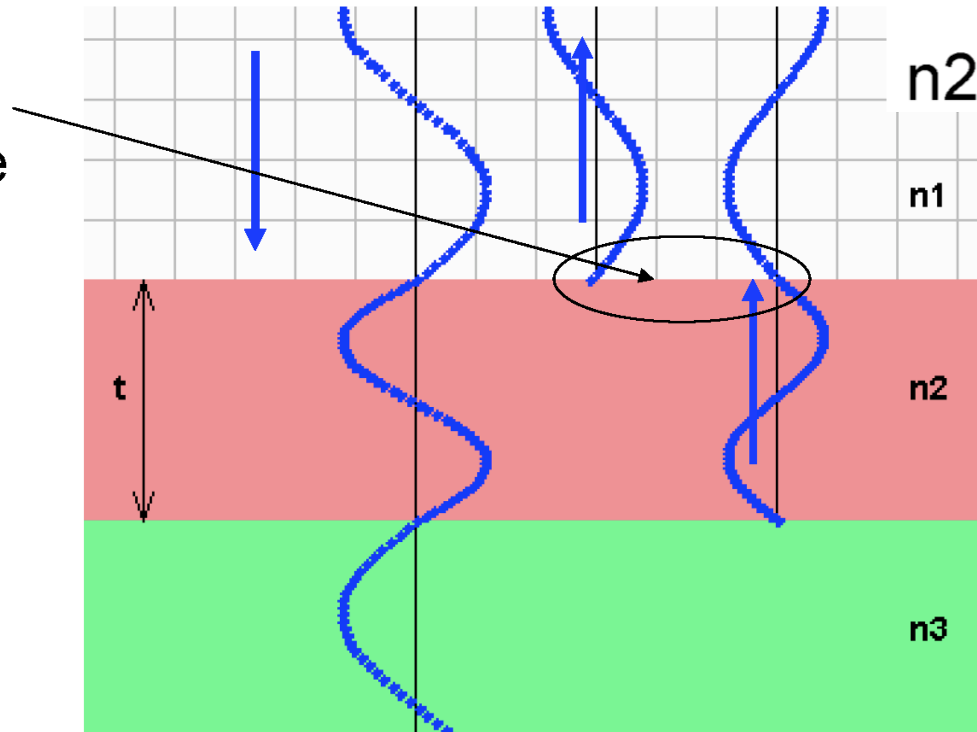
Let's set:

n1 > n2

n2 < n3

What kind of interference do we get between the two reflected waves?

1. Constructive
2. Destructive



What kind of interference? PRS

$t = \lambda_f$. The path length difference is $\Delta r = 2\lambda_f$

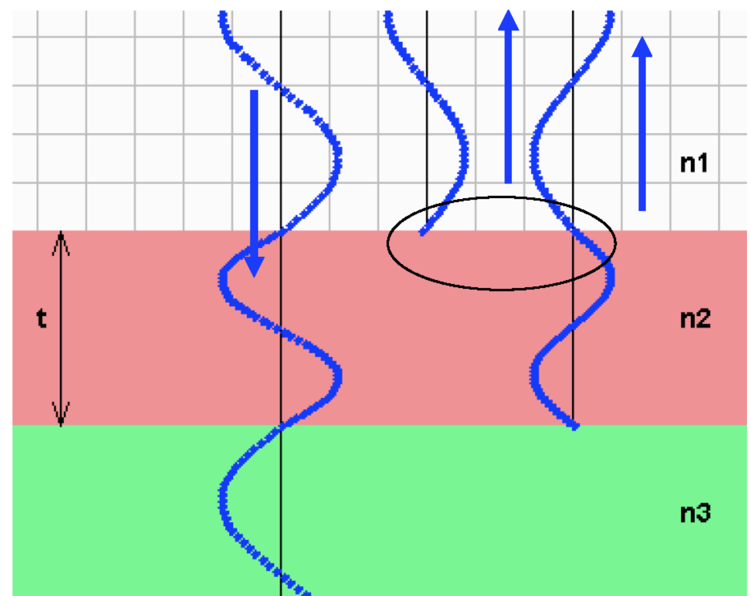
But, *in addition to that*, there is also $\frac{1}{2}\lambda_f$ difference because the first reflected wave is not inverted, but the second reflected wave is inverted!

So, the total *effective* path length difference is

$$\Delta r_{ef} = 2\lambda_f + \frac{1}{2}\lambda_f = (5/2)\lambda_f$$

This is a condition for a minimum!

2. Destructive



Thin films – a systematic approach

Every inversion a wave makes when it reflects is equivalent to a half-wavelength shift.

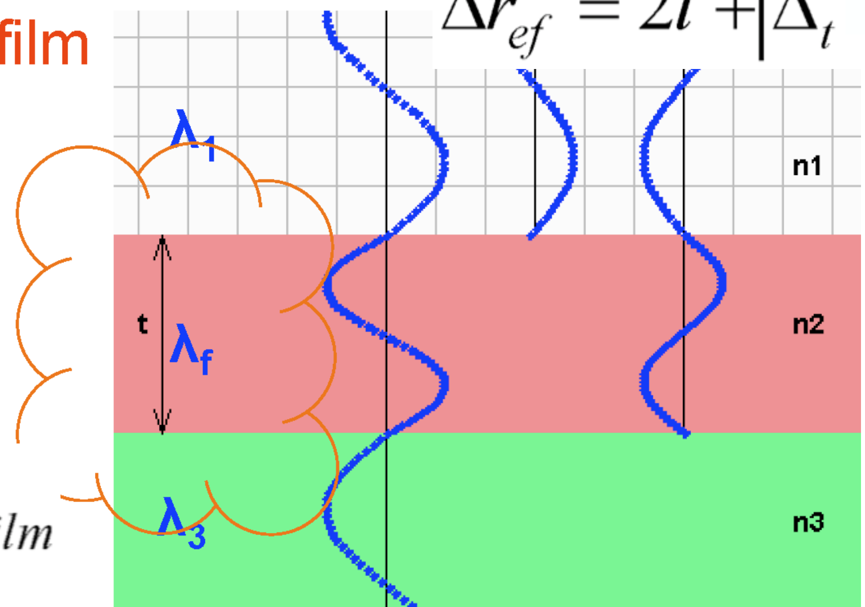
$$\lambda_{film} = \frac{\lambda_{vacuum}}{n_{film}}$$

However, we have three media, and thus three different wavelengths!

Because we're matching the wave that goes into the film with the wave bouncing off the top,

it is the wavelength in the film λ_{film} that appears in the equations.

$$\Delta r_{ef} = 2t + \left|\Delta_t - \Delta_b\right|$$



$$\Delta r_{ef-\max} = m\lambda_{film}$$

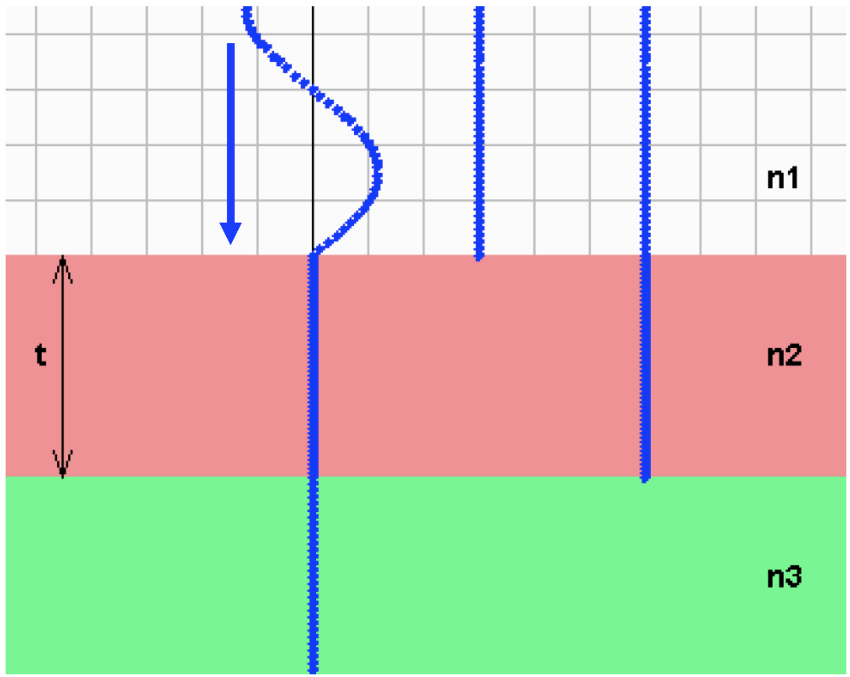
$$\Delta r_{ef-\min} = (m - 1/2)\lambda_{film}$$

Thin films – the five-step method

Step 1 – Determine Δ_t , the shift for the wave reflecting from the top surface of the film.

If $n_2 > n_1$, $\Delta_t = \dfrac{\lambda_{film}}{2}$

If $n_2 < n_1$, $\Delta_t = 0$

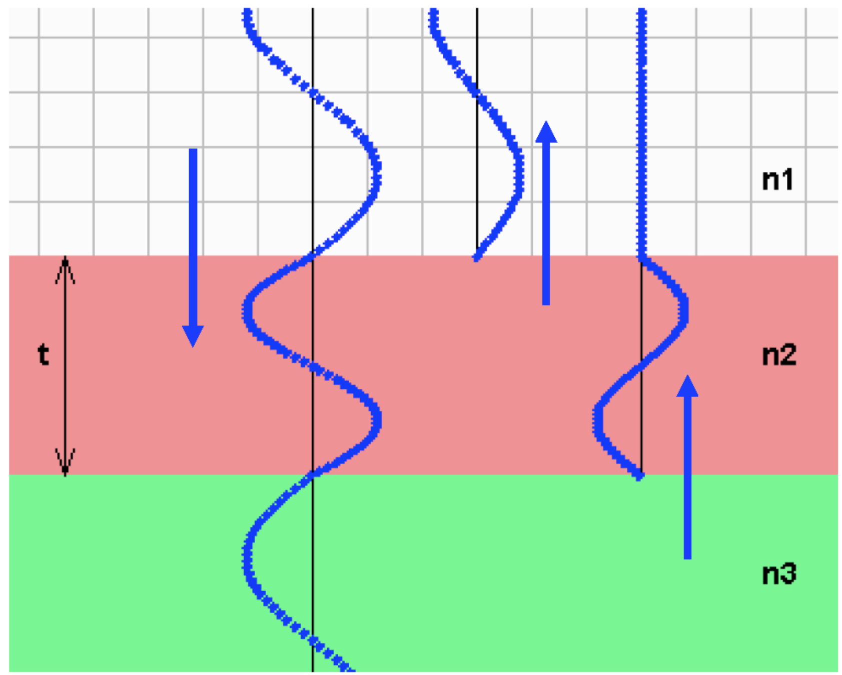


Thin films – the five-step method

Step 2 – Determine Δ_b, the shift for the wave reflecting from the bottom surface of the film.

If $n_3 > n_2$, $$\Delta_b = \frac{\lambda_{film}}{2}$$

If $n_3 < n_2$, $$\Delta_b = 0$$



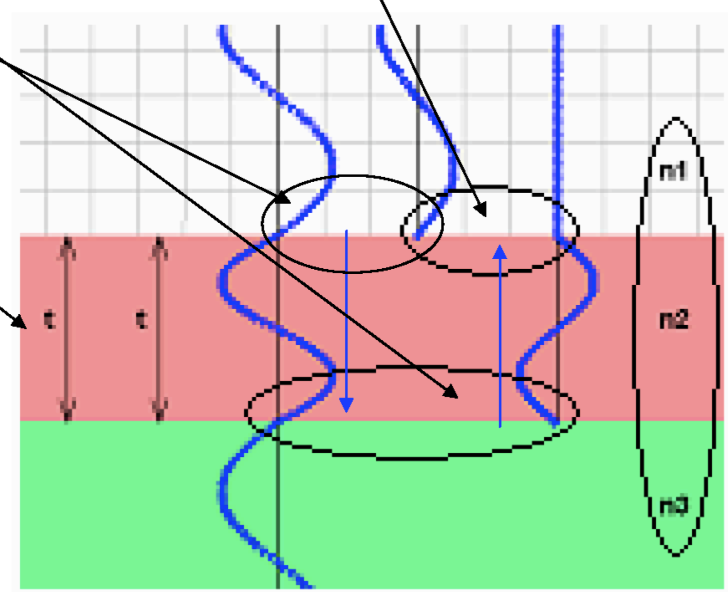
Thin films – the five-step method

Step 3 – Find the effective path-length difference, Δr_{ef}.

$$\Delta r_{ef} = 2t + \left|\Delta_t - \Delta_b\right|$$

Here interference is happening

2*t* is the extra distance the second wave traveled.



Thin films – the five-step method

Step 4 – Bring in the appropriate interference condition, depending on the situation.

For *constructive* interference, $\Delta r_{ef} = m\lambda_{film}$ $m = 0, 1, 2$

For *destructive* interference, $\Delta r_{ef} = (m - 1/2)\lambda_{film}$

$m = 1, 2, 3$

Remember: $\lambda_{film} = \dfrac{\lambda_{vacuum}}{n_{film}}$

Thin films – the five-step method

Step 5 – Solve the resulting equations.

The equation generally connects the thickness of the film to the wavelength of the light in the film.

$$\Delta r_{ef} = 2t + \left|\Delta_t - \Delta_b\right| \qquad \lambda_{film} = \frac{\lambda_{vacuum}}{n_{film}}$$

$$\Delta r_{ef-\max} = m\lambda_{film} \quad \text{or} \quad \Delta r_{ef-\min} = (m - 1/2)\lambda_{film}$$

An example using the five-step method

White light in air shines on an oil film of thickness *t* that floats on water. The oil has an index of refraction of 1.50, while the refractive index of water is 1.33.

When looking straight down at the film, the reflected light looks orange, because the film thickness is just right to produce *completely constructive interference* for a wavelength, in air, of 600 nm.

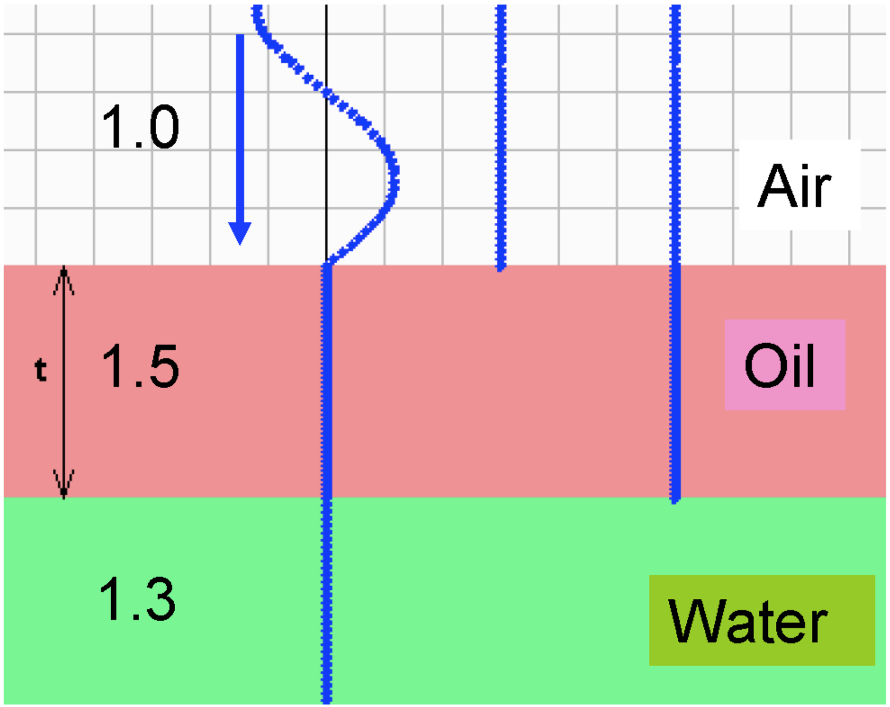
What is the minimum possible thickness of the film?

Step 1 PRS

Step 1 – Determine Δ_t , the shift for the wave reflecting from the top surface of the film.

1. $\Delta_t = \dfrac{\lambda_{film}}{2}$

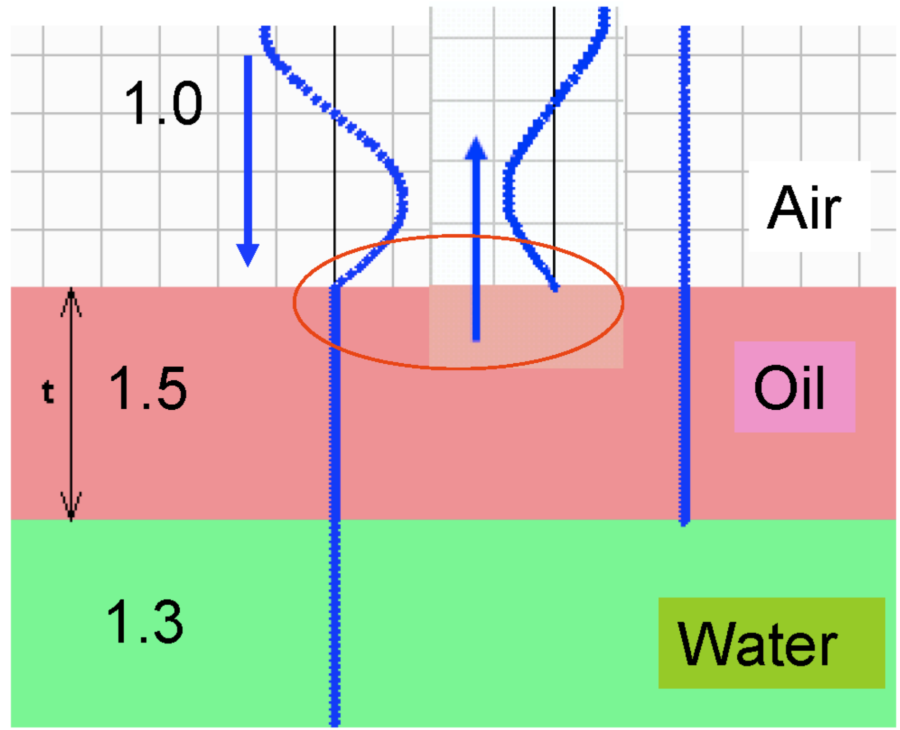
2. $\Delta_t = 0$



Step 1

Step 1 – Determine Δ_t , the shift for the wave reflecting from the top surface of the film.

1. $\Delta_t = \frac{\lambda_{film}}{2}$

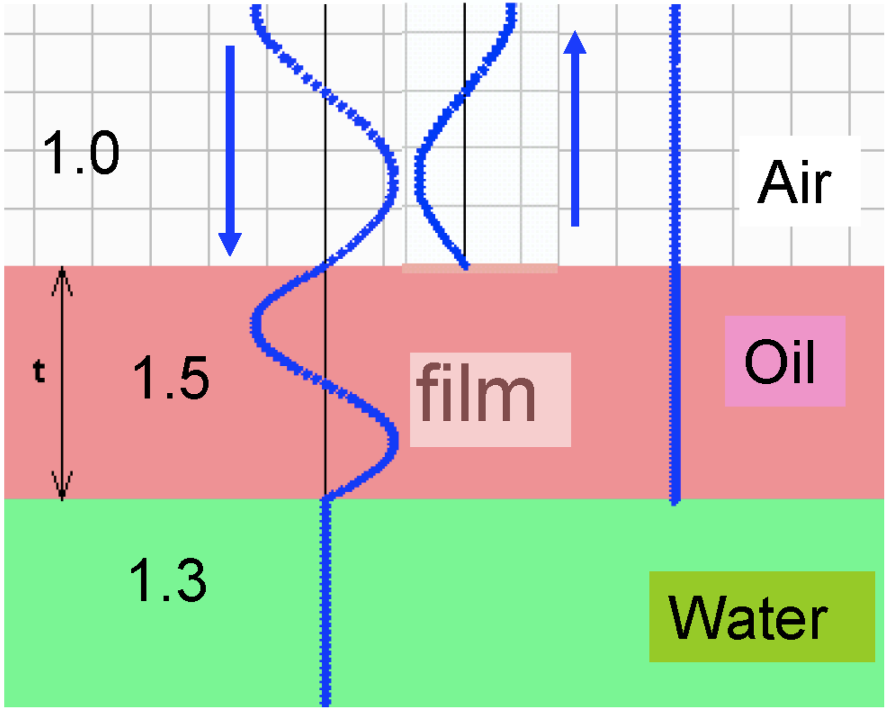


Step 2 PRS

Step 2 – Determine Δ_b , the shift for the wave reflecting from the bottom surface of the film.

1. $$\Delta_b = \frac{\lambda_{film}}{2}$$

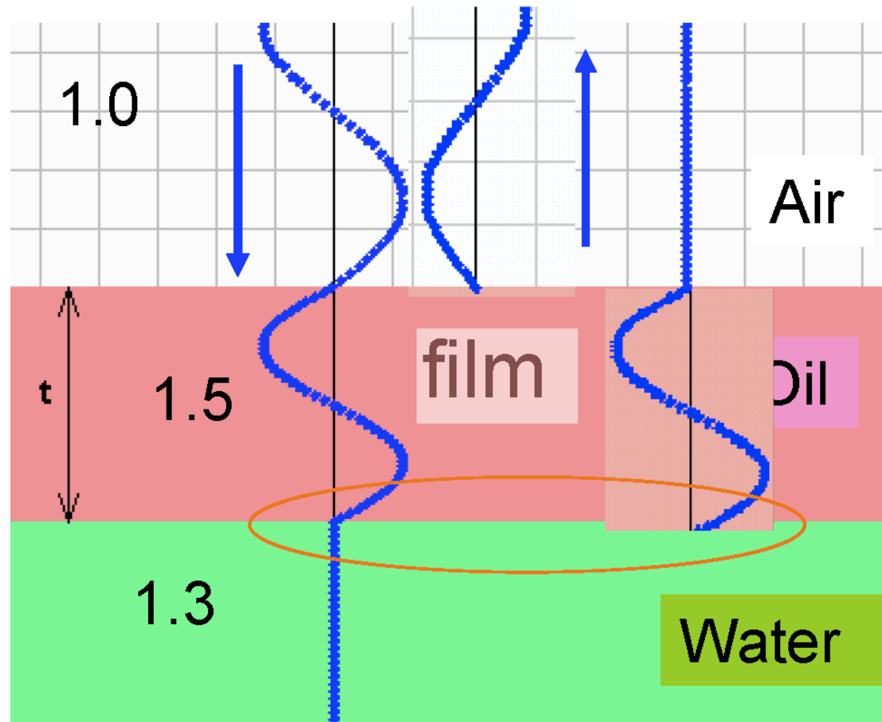
2. $$\Delta_b = 0$$



Step 2 PRS

Step 2 – Determine Δ_b, the shift for the wave reflecting from the bottom surface of the film.

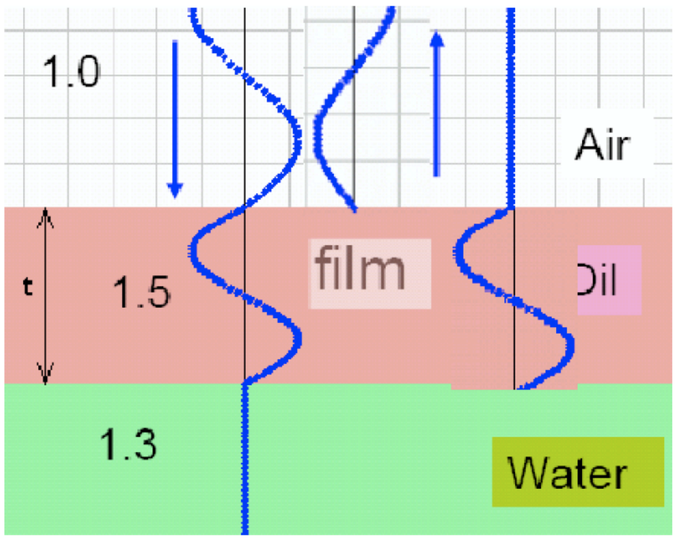
2. $\Delta_b = 0$



Step 3

Step 3 – Determine Δr_{ef}, the effective path-length difference for the two reflected waves.

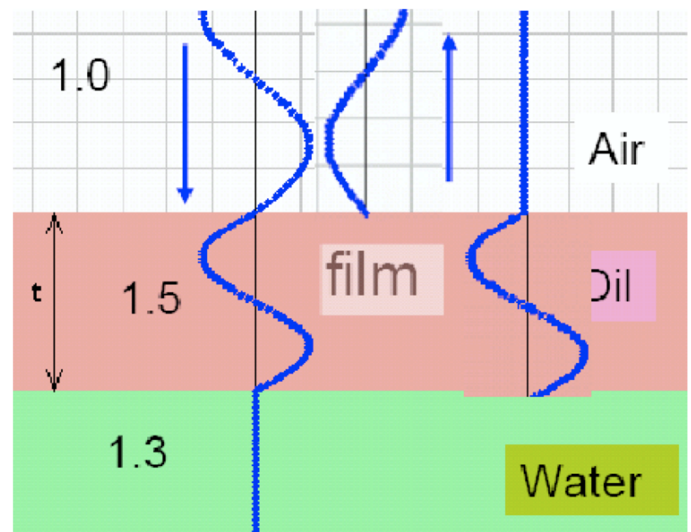
$$\Delta_{ef} = 2t + \frac{\lambda_{film}}{2}$$



Step 4

Step 4 – Bring in the appropriate interference condition. For *constructive interference*

$$2t+\frac{\lambda_{film}}{2}=m\lambda_{film}=0,\lambda_{film},2\lambda_{film},3\lambda_{film},\ldots$$



Step 4 (cont)

$$2t + \frac{\lambda_{film}}{2} = m\lambda_{film} = 0, \lambda_{film}, 2\lambda_{film}, 3\lambda_{film}, \ldots$$

If we rearrange it (and keep only positive values, because a thickness is positive), we have

$$2t = \frac{1}{2}\lambda_{film}, \frac{3}{2}\lambda_{film}, \frac{5}{2}\lambda_{film}, \ldots$$

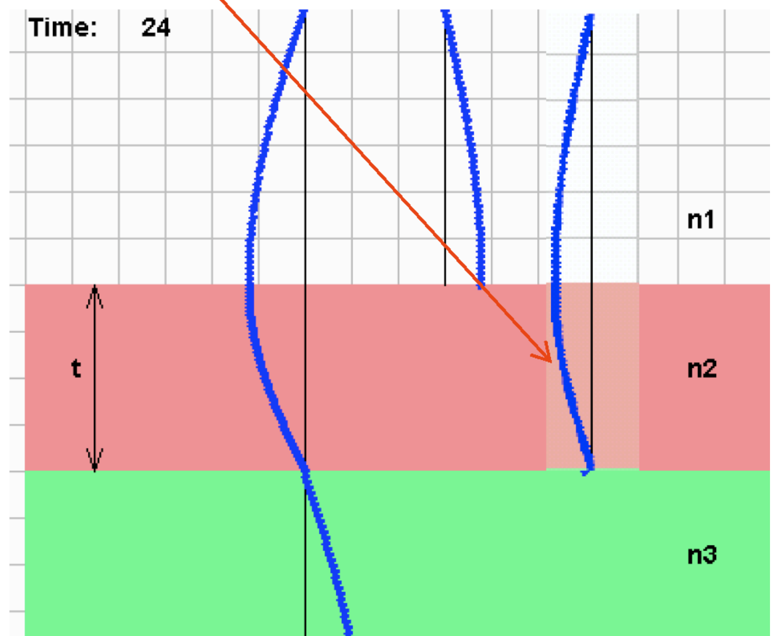
It looks like a condition for destructive interference, but it is NOT!

Step 5

Step 5 – Solve for the minimum film thickness.

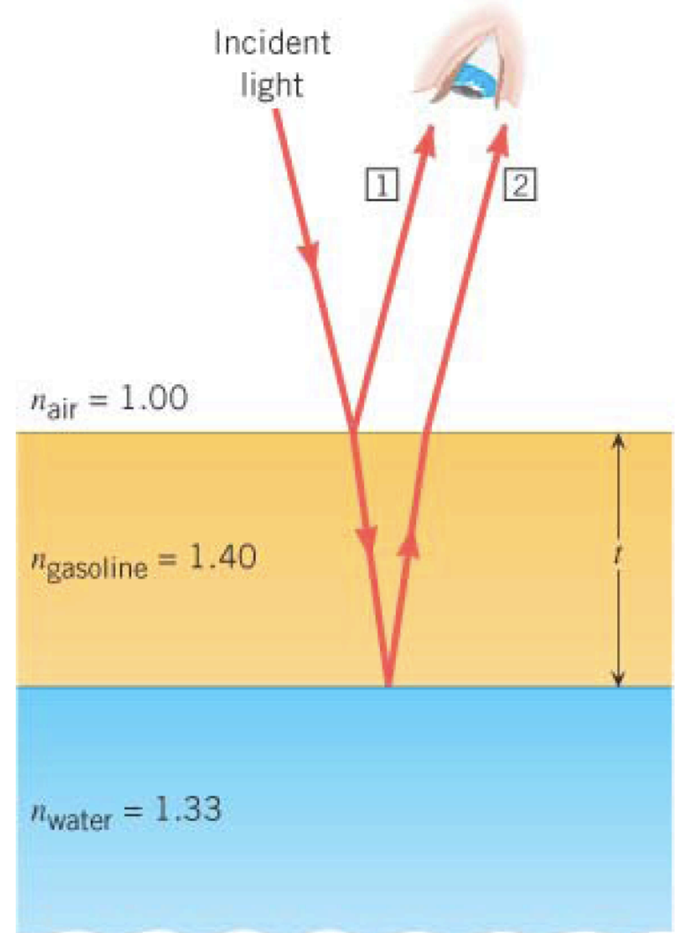
$$2t_{\min} = \frac{1}{2}\lambda_{film} \quad \Rightarrow \quad t_{\min} = \frac{1}{4}\lambda_{film} = \frac{1}{4}\frac{\lambda}{\text{n}} = \frac{\lambda}{4\text{n}}$$

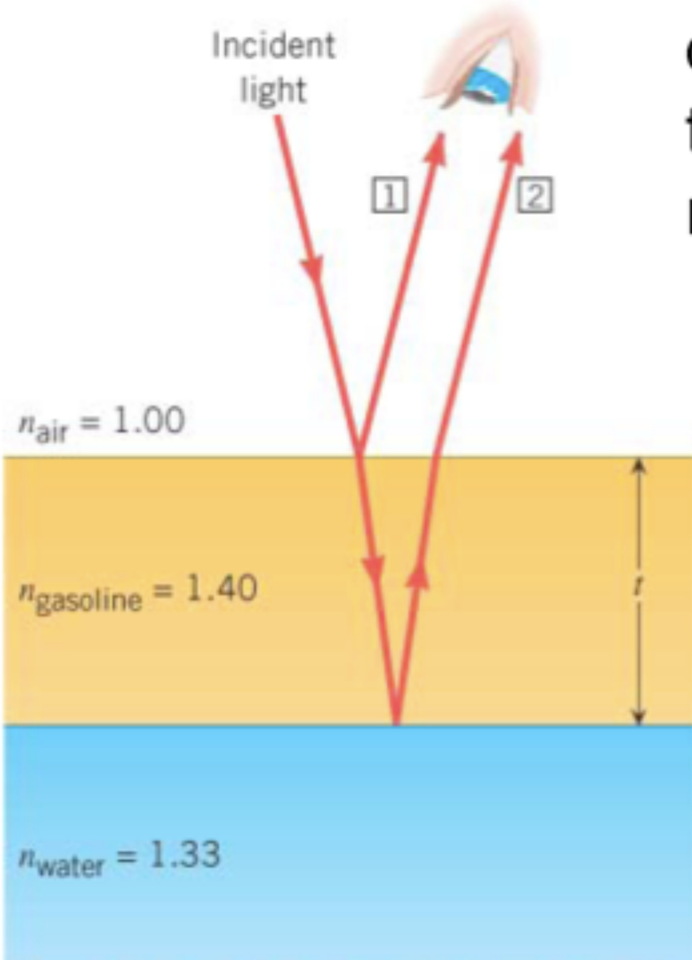
$$t_{\min} = \frac{600\ \text{nm}}{4 \cdot 1.5} = 100\ \text{nm}$$



Example A Colored Thin Film of Gasoline

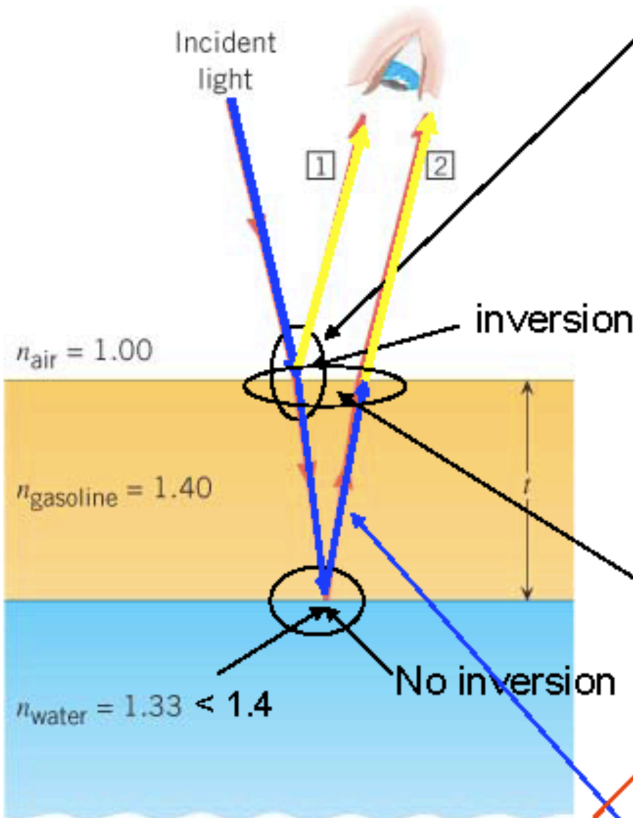
A thin film of gasoline floats on a puddle of water. Sunlight falls perpendicularly on the film and reflects into your eyes. The film has a yellow hue because destructive interference eliminates the color of blue (469 nm) from the reflected light. The refractive indices of the blue light in gasoline and water are 1.40 and 1.33. Determine the minimum non-zero thickness of the film.





destructive interference eliminates the color of blue (469 nm) from the reflected light. The refractive

$$2t + \frac{1}{2}\lambda_{\text{film}} = \frac{1}{2}\lambda_{\text{film}}, \frac{3}{2}\lambda_{\text{film}}, \frac{5}{2}\lambda_{\text{film}}$$



Clearly, the smallest none zero value of *t* we obtain from the equation

$$2t + \frac{1}{2}\lambda_{\text{film}} = \frac{3}{2}\lambda_{\text{film}}$$

The **blue** light disappears because of destructive interference

$$t = \frac{\lambda_{\text{film}}}{2} = \frac{(469\ \text{nm}/1.40)}{2} = 168\ \text{nm}$$