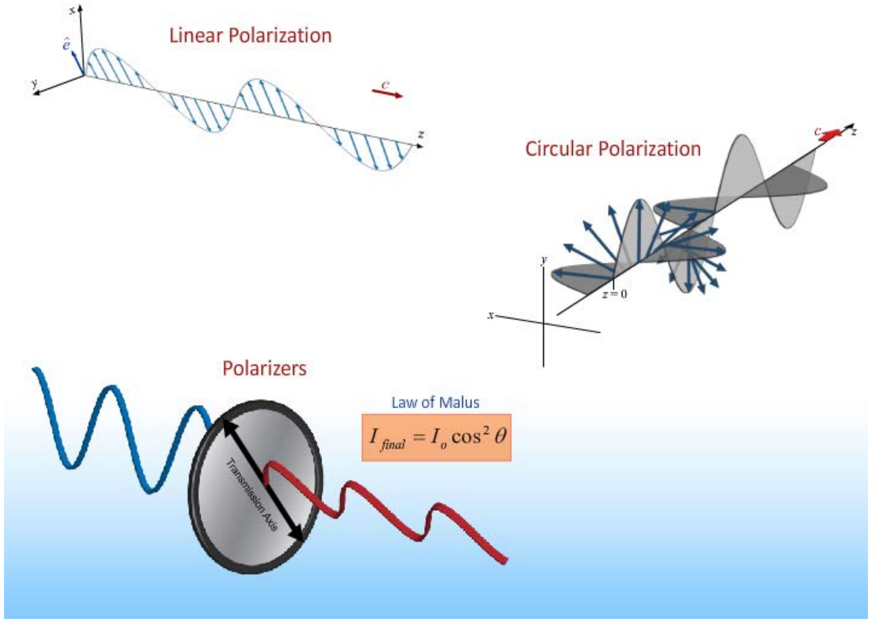
Physics 212
Lecture 24



Your Comments

what even is polarization?? like what does light look like after it is polarized vs before?

The circular polarized light part is kinda tricky, i can use more explanation of that.

Will the quarter-wave plate absorb any light? Or is it just slow down the light in one axis and speed up the light in another axis? Also, when the linear polarizer absorbs the light, will it create heat and thus change the property of the polarizer?

Wait i'm confused! How can an E-field exist in the x and y planes at the same time? I thought the E and B fields only existed in 1 plane at a time…

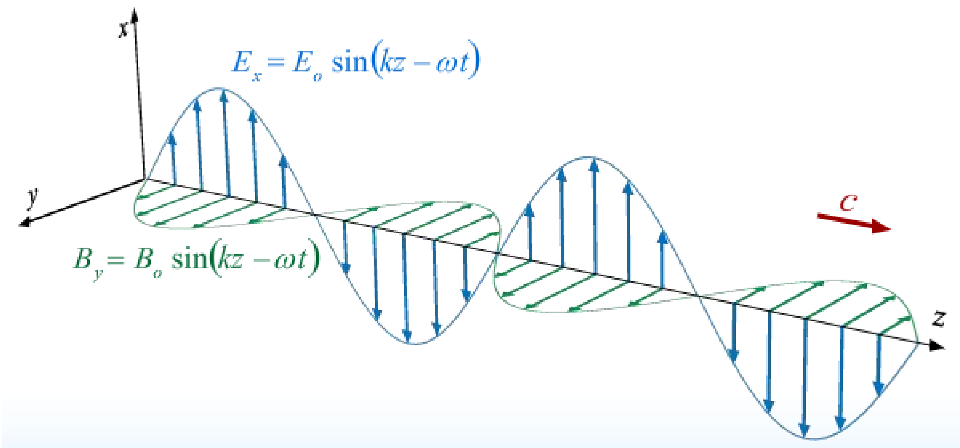
This stuff is pretty cool, BUT how do we use our right hand to cross from slow to fast to determine the handedness of a circularly polarized wave?

The question with removing the middle polarizer confuses me. How can adding something that works entirely by selectively absorbing certain types of light lead to an increased final intensity?

IMAX 3D using Linear Polarization

Linearly Polarized Light

So far we have considered plane waves that look like this:



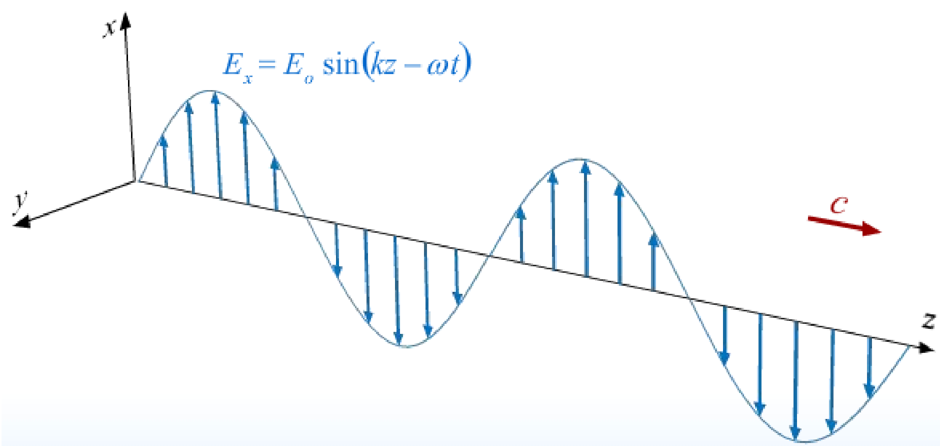
$$\omega = kc$$

$$E_o = cB_o$$

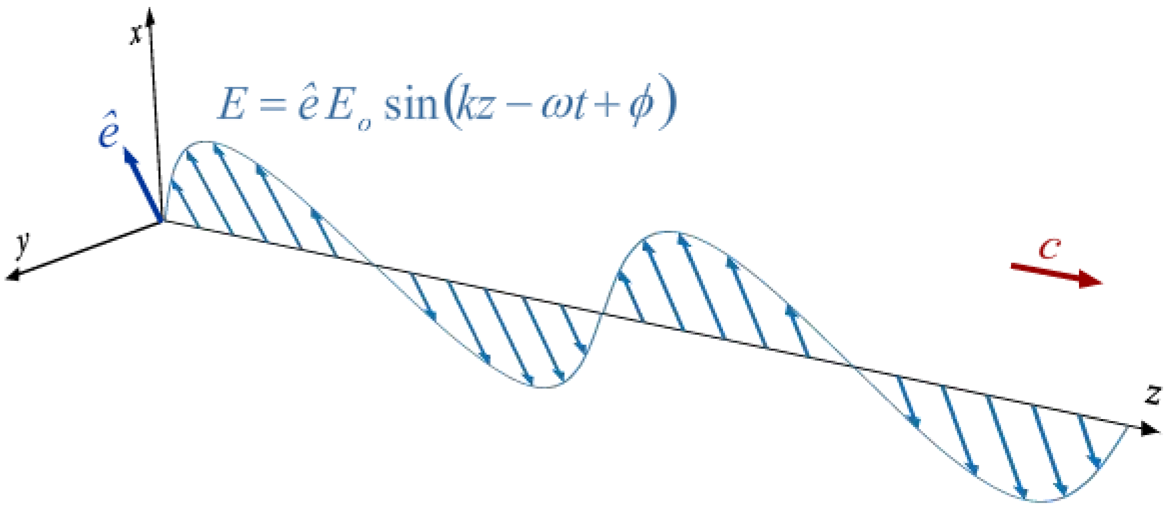
$$c = \frac{1}{\sqrt{\mu_o \varepsilon_o}}$$

From now on just draw E and remember that B is still there:

$\vec{E}$ Field determines Polarization



Linear Polarization

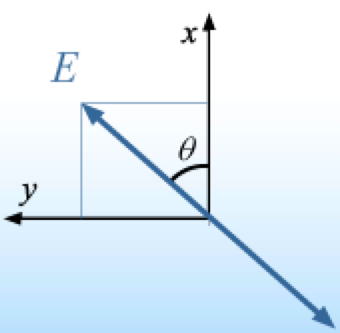


$$E = \hat{e} E_o \sin(kz - \omega t + \phi)$$

$$\omega = kc$$

$$E_o = cB_o$$

$$c = \frac{1}{\sqrt{\mu_o \varepsilon_o}}$$

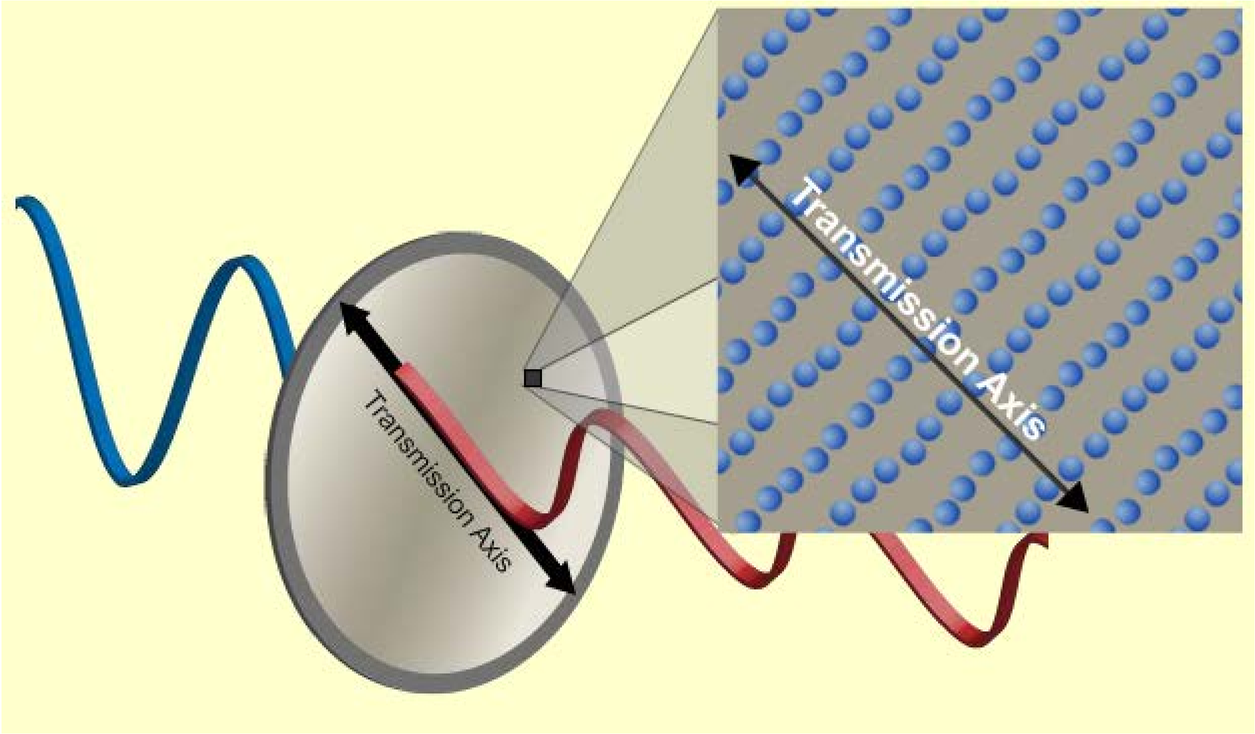


Wave Coming Out of the Screen

$$E_x = E_o \cos\theta \sin(kz - \omega t + \phi)$$

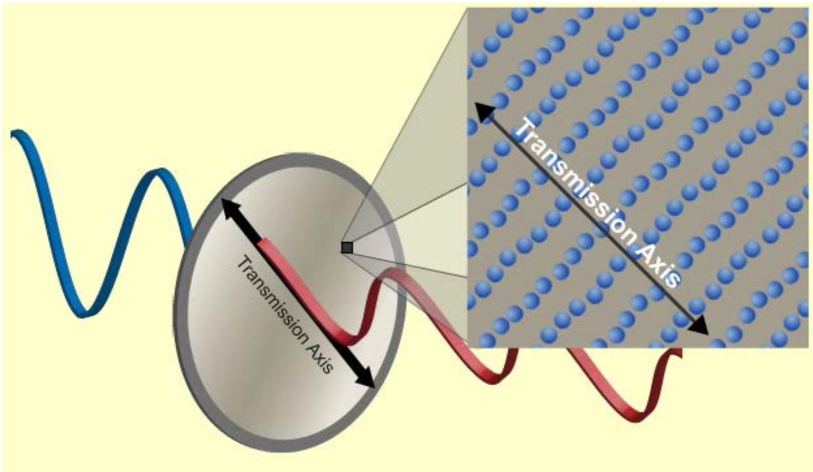
$$E_y = E_o \sin\theta \sin(kz - \omega t + \phi)$$

Polarizer

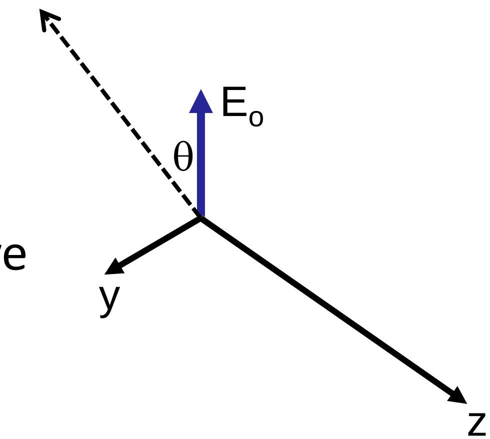


The molecular structure of a polarizer causes the component of the E field perpendicular to the Transmission Axis to be absorbed.

Clicker Question

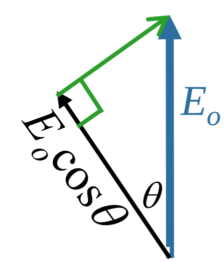


The molecular structure of a polarizer causes the component of the E field perpendicular to the Transmission Axis to be absorbed.



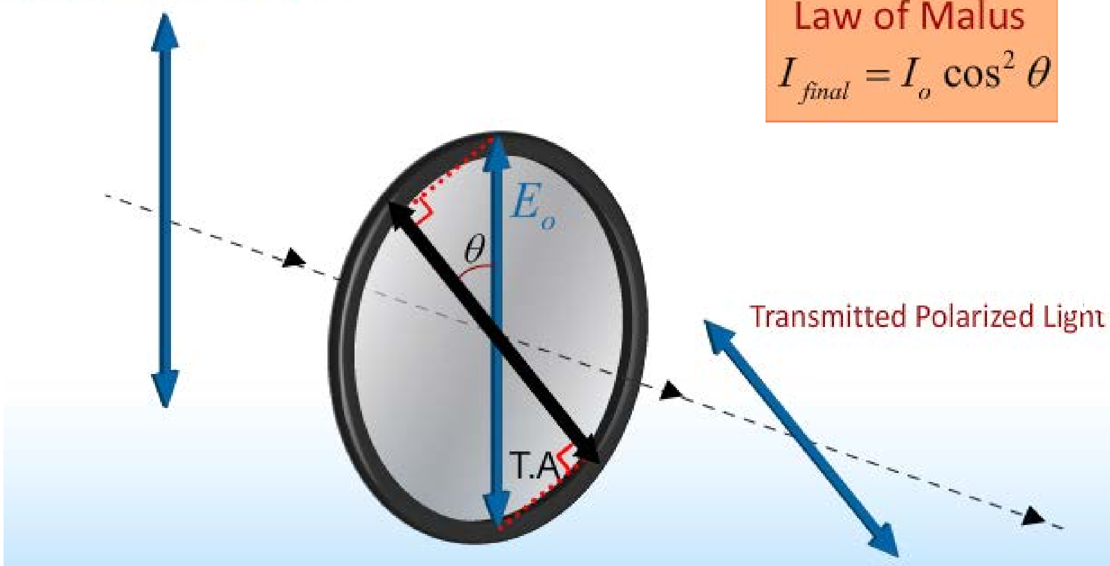
Suppose we have a beam traveling in the $+z-$ direction.
At $t = 0$ and $z = 0$, the electric field is aligned along the positive $x-$ axis and has a magnitude equal to E_o

What is the component of E_o along a direction in the $x - y$ plane that makes an angle of θ with respect to the $x-$ axis?



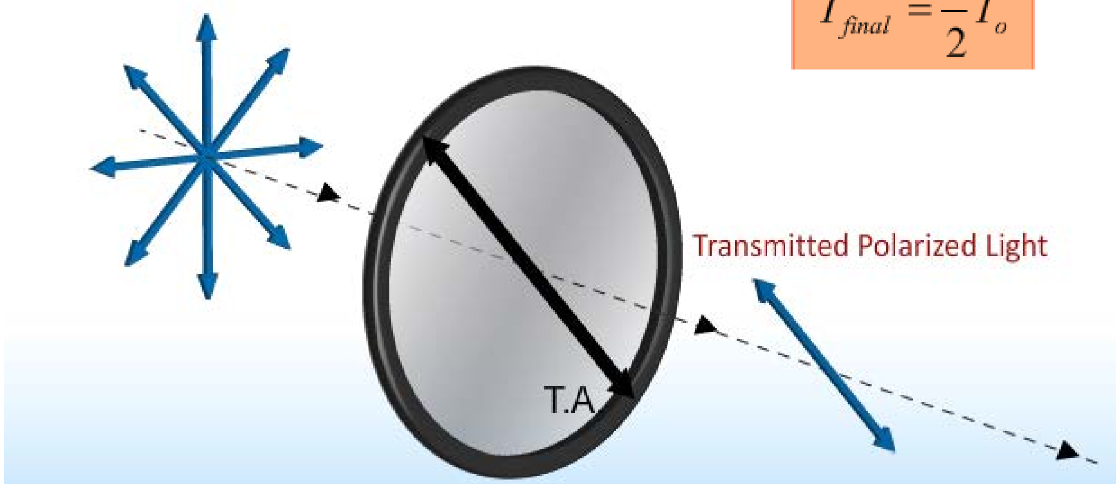
A) $E_o \sin\theta$ **B) $E_o \cos\theta$** C) 0 D) $E_o/\sin\theta$ E) $E_o/\cos\theta$

Linear Polarizers



Law of Malus

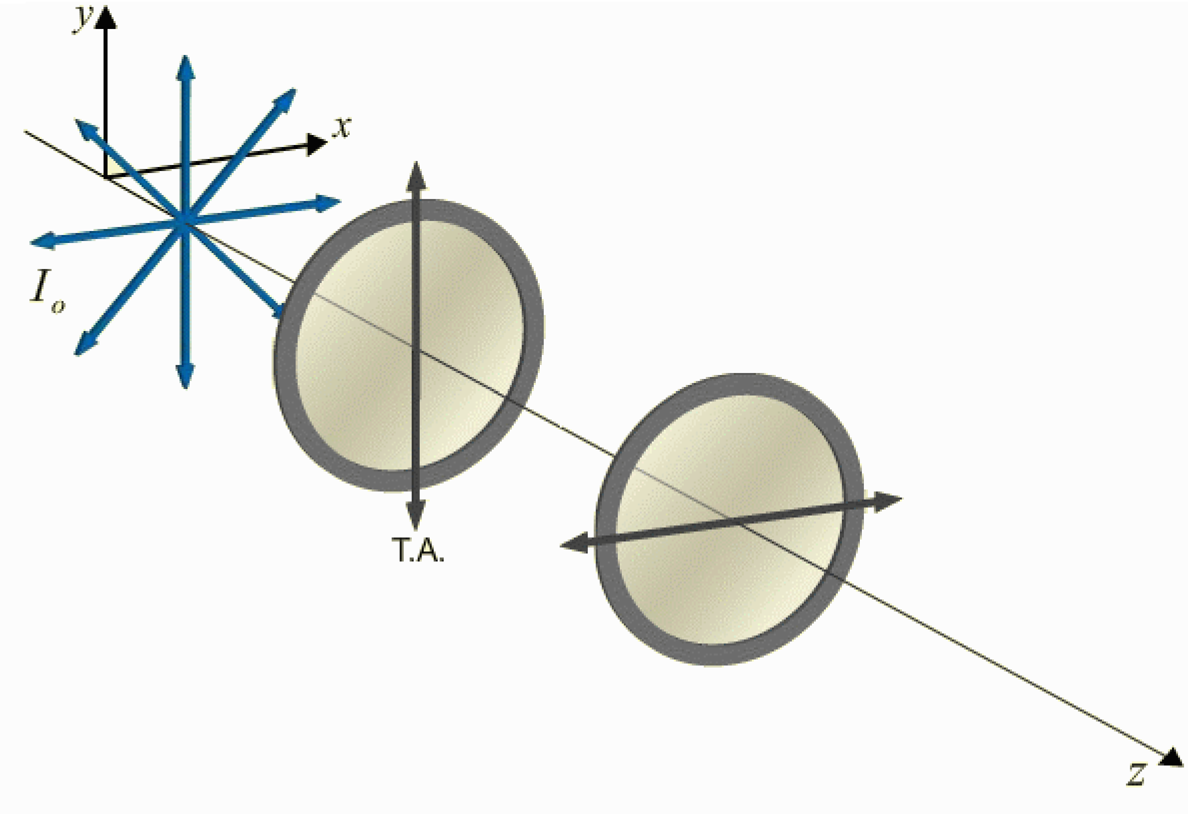
$$I_{final} = I_o \cos^2 \theta$$



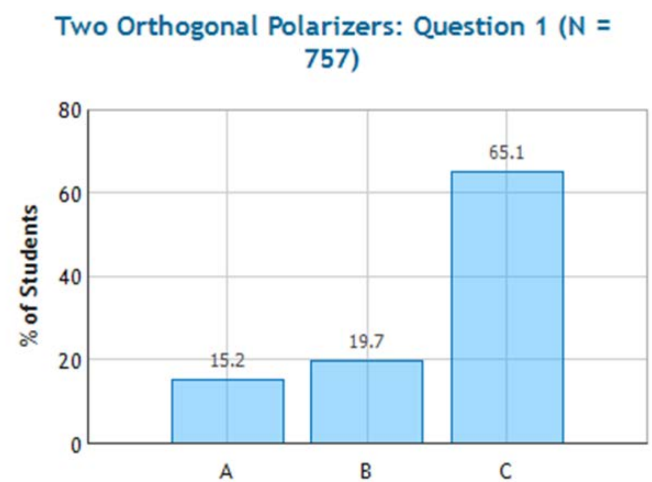
$$I_{final} = \frac{1}{2} I_o$$

CheckPoint 1a

An unpolarized EM wave is incident on two orthogonal polarizers.



Two Polarizers



What percentage of the intensity gets through both polarizers?

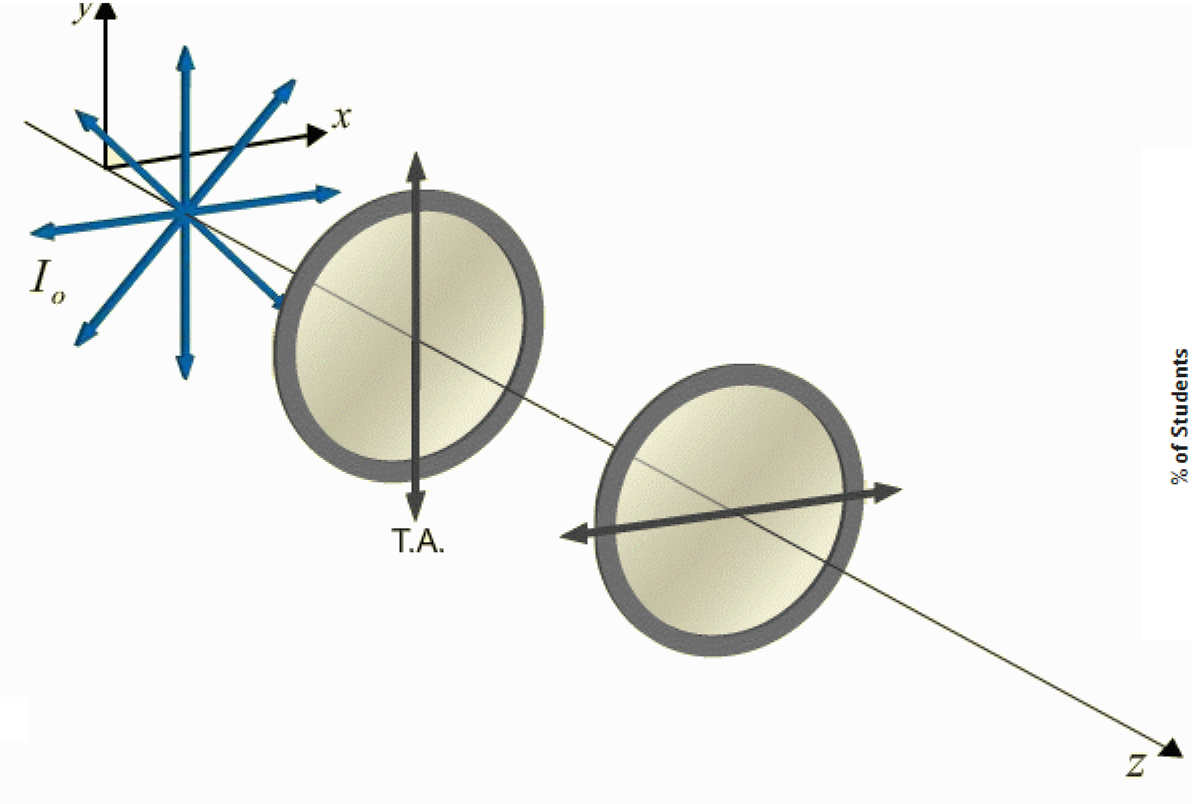
A. 50% ***B.*** 25% ***C.*** 0%

No light will come through. $\cos(90^o) = 0$

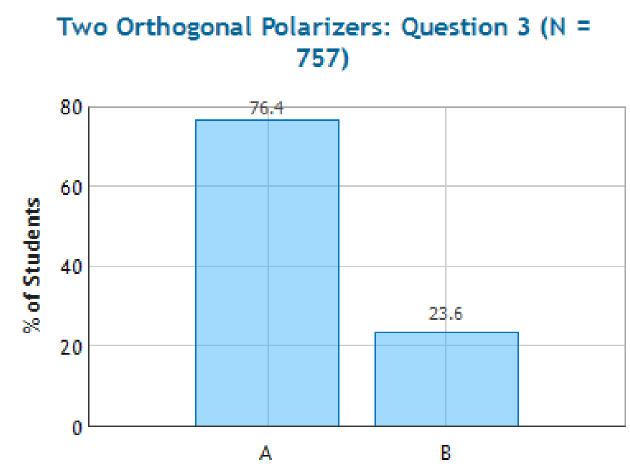
DEMO

CheckPoint 1b

An unpolarized EM wave is incident on two orthogonal polarizers.



Two Polarizers



Is it possible to increase this percentage by inserting another Polarizer between the original two?

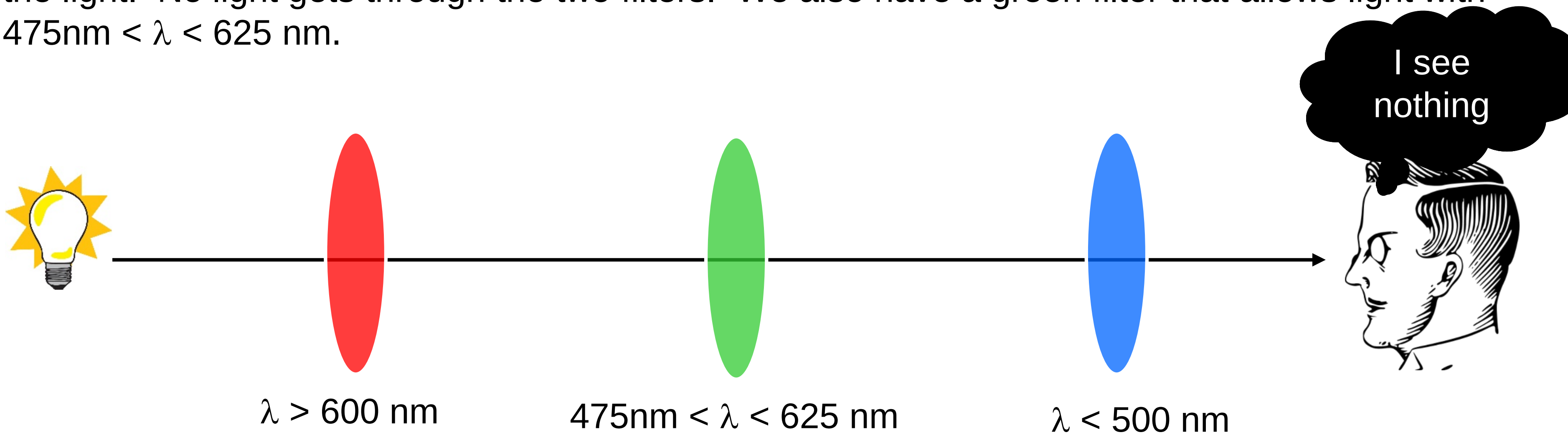
A. Yes **B.** No

DEMO

Adding a polarizer that is neither vertical nor horizontal will polarize light at an angle, and the waves passing through will have a horizontal component. Thus, some intensity will be able to travel past the last polarizer.

Color Filters

White light consists of many wavelengths (350 nm – 750 nm). A red filter that only allows light with $\lambda > 600$ nm and a blue filter that only allows light with $\lambda < 500$ nm are placed in the path of the light. No light gets through the two filters. We also have a green filter that allows light with 475nm $< \lambda <$ 625 nm.



If we place the green filter between the red and blue one, will any light get through the three filters?

A. Yes

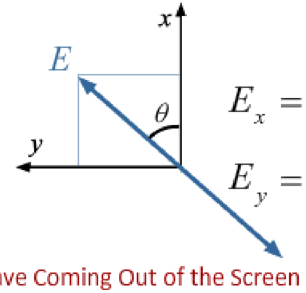
B. No

Light that passes through both red and green filter will have wavelength 600nm $< \lambda <$ 625 nm.

RealD 3D using Circular Polarization

Circularly Polarized Light

There is no reason that ϕ has to be the same for E_x and E_y:



$$E_x = E_o \cos\theta \sin(kz - \omega t + \phi_x)$$
$$E_y = E_o \sin\theta \sin(kz - \omega t + \phi_y)$$

Satisfies Wave Equation

$$\frac{\partial^2 E_x}{\partial z^2} = \mu_o \varepsilon_o \frac{\partial^2 E_x}{\partial t^2}$$
$$\frac{\partial^2 E_y}{\partial z^2} = \mu_o \varepsilon_o \frac{\partial^2 E_y}{\partial t^2}$$

Making ϕ_x different from ϕ_y causes circular or elliptical polarization:

Example:

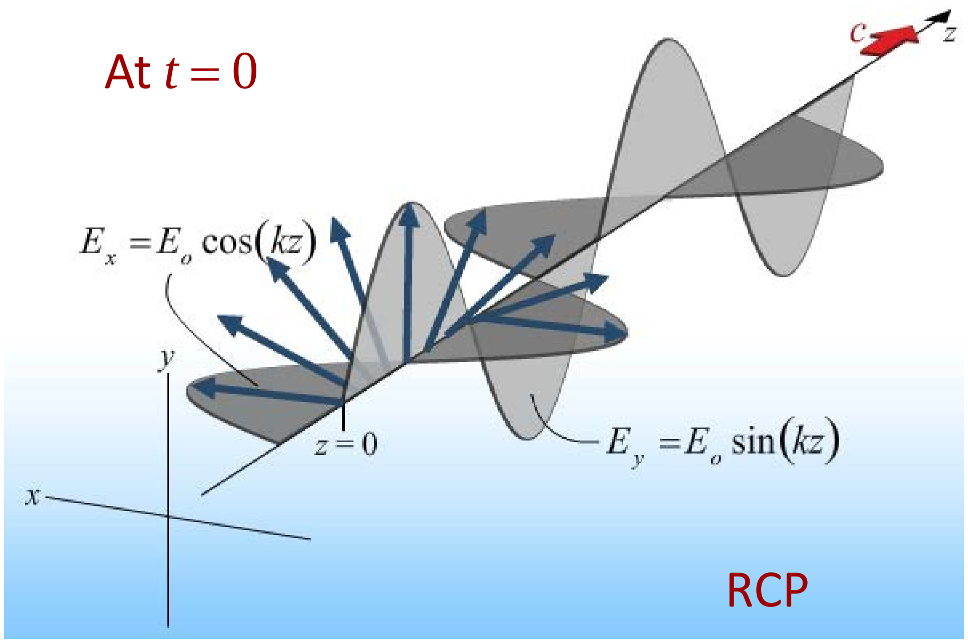
$$\phi_x - \phi_y = 90^\circ = \frac{\pi}{2}$$

$$\theta = 45^\circ = \pi / 4$$

$$E_x = \frac{E_0}{\sqrt{2}} \cos(kz - \omega t)$$

$$E_y = \frac{E_0}{\sqrt{2}} \sin(kz - \omega t)$$

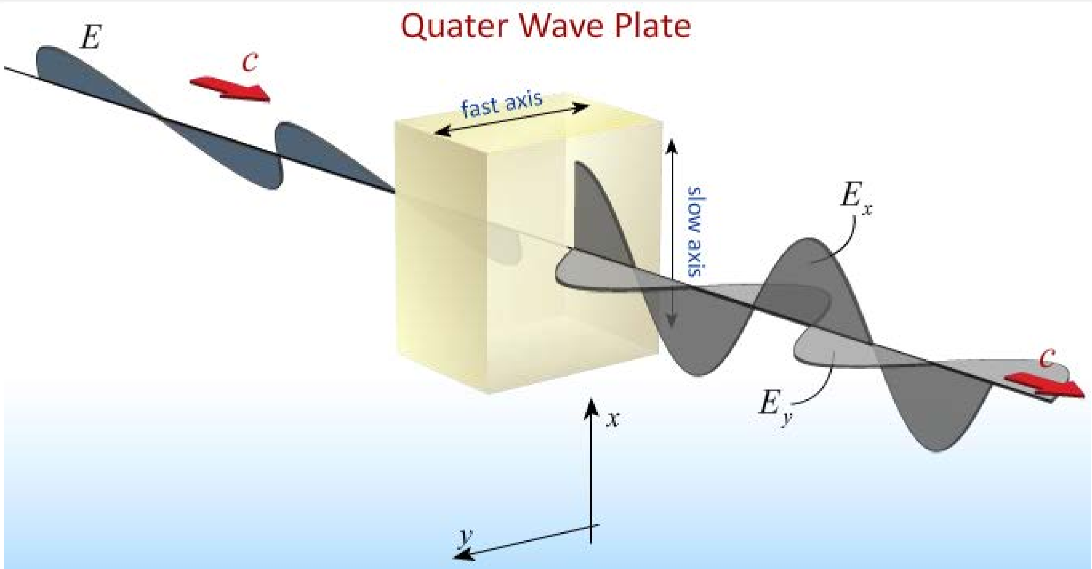
At $t = 0$

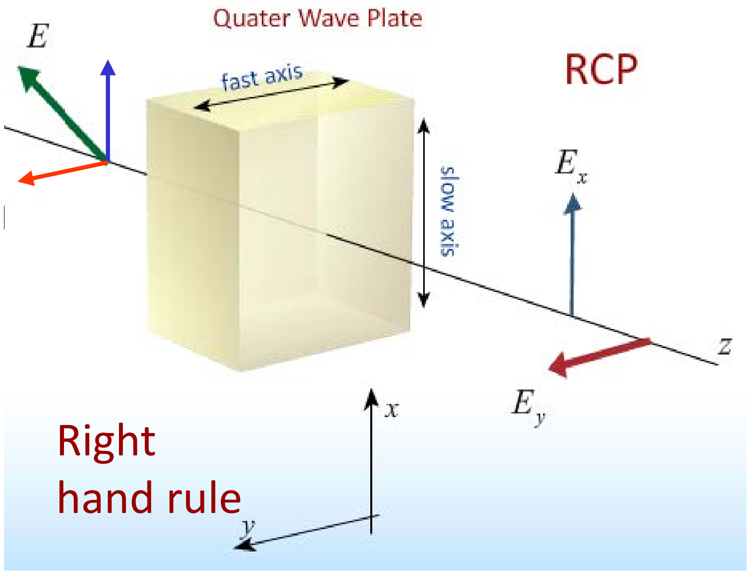


Quarter Waveplates

Q: How do we change the relative phase between E_x and E_y?

A: Birefringence





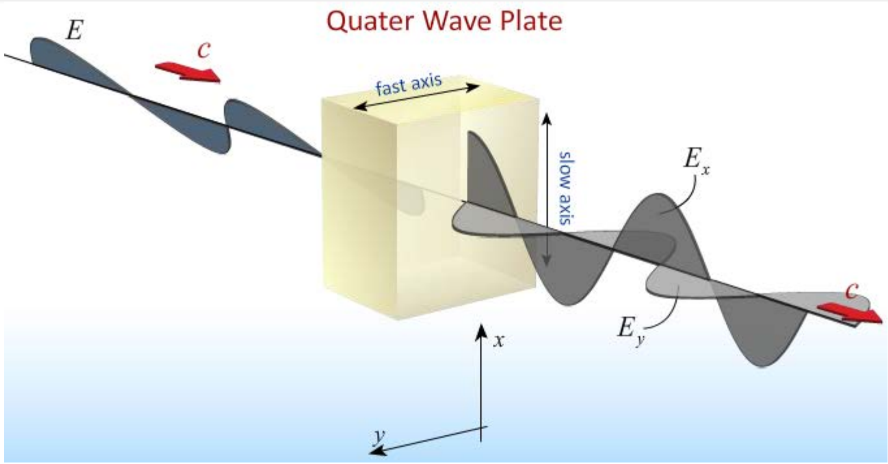
By picking the right thickness we can change the relative phase by exactly 90^o.

This changes linear (if @45°) to circular polarization and is called a *quarter wave plate*

Intensity does not change!

"talk something about intensity"

NOTE: No Intensity is lost passing through the QWP !



BEFORE QWP:

$$E = E_o \sin(kz - \omega t)\left[\frac{\hat{i}+\hat{j}}{\sqrt{2}}\right] \rightarrow I = c\varepsilon_o\langle E^2\rangle = c\varepsilon_o\langle E_x^2 + E_y^2\rangle$$

$$= c\varepsilon_o\left(\frac{E_o^2}{2}+\frac{E_o^2}{2}\right)\langle\sin^2(kz-\omega t)\rangle = c\varepsilon_o E_o^2\frac{1}{2}$$

AFTER QWP:

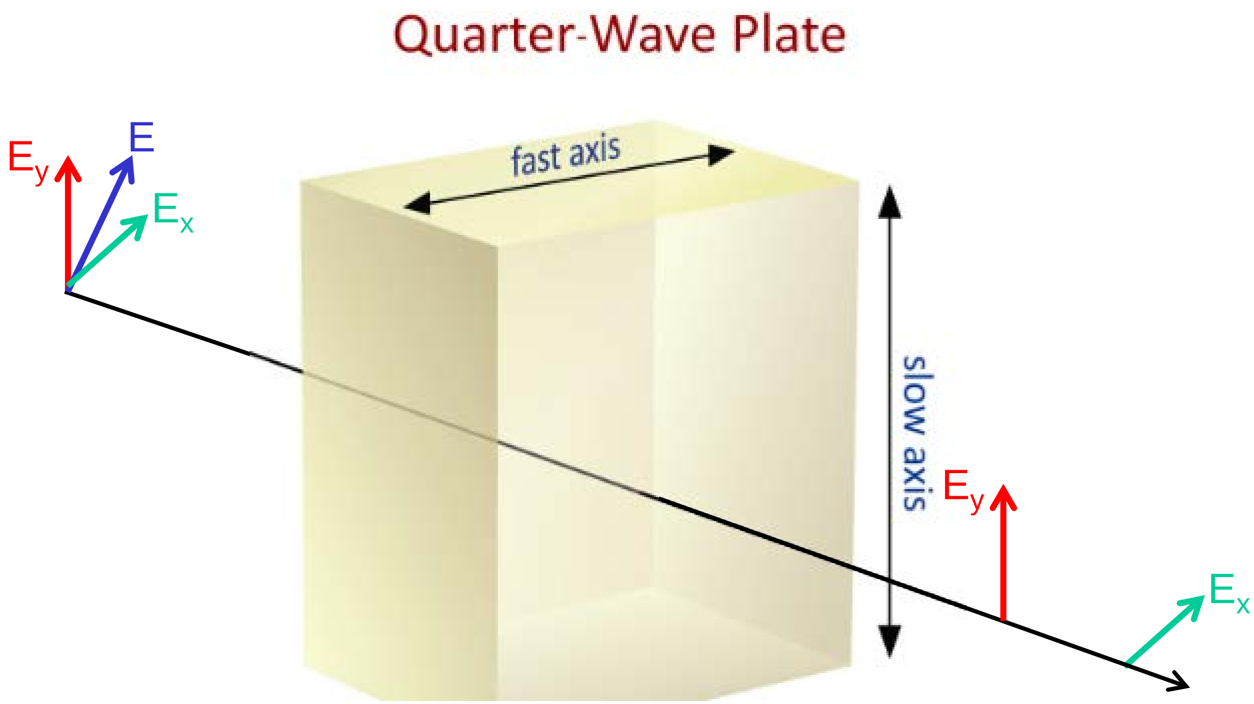
$$E = \frac{E_o}{\sqrt{2}}\left[\hat{i}\cos(kz-\omega t) + \hat{j}\sin(kz-\omega t)\right] \rightarrow I = c\varepsilon_o\langle E^2\rangle = c\varepsilon_o\langle E_x^2 + E_y^2\rangle$$

$$= c\varepsilon_o\frac{E_o^2}{2}\langle\cos^2(kz-\omega t)+\sin^2(kz-\omega t)\rangle$$

$$= c\varepsilon_o\frac{E_o^2}{2}\langle 1\rangle = c\varepsilon_o\frac{E_o^2}{2}$$

THE SAME!

Right or Left Circularly Polarized



A linearly polarized EM wave is incident on a quarter-wave plate as shown above. The resulting wave is

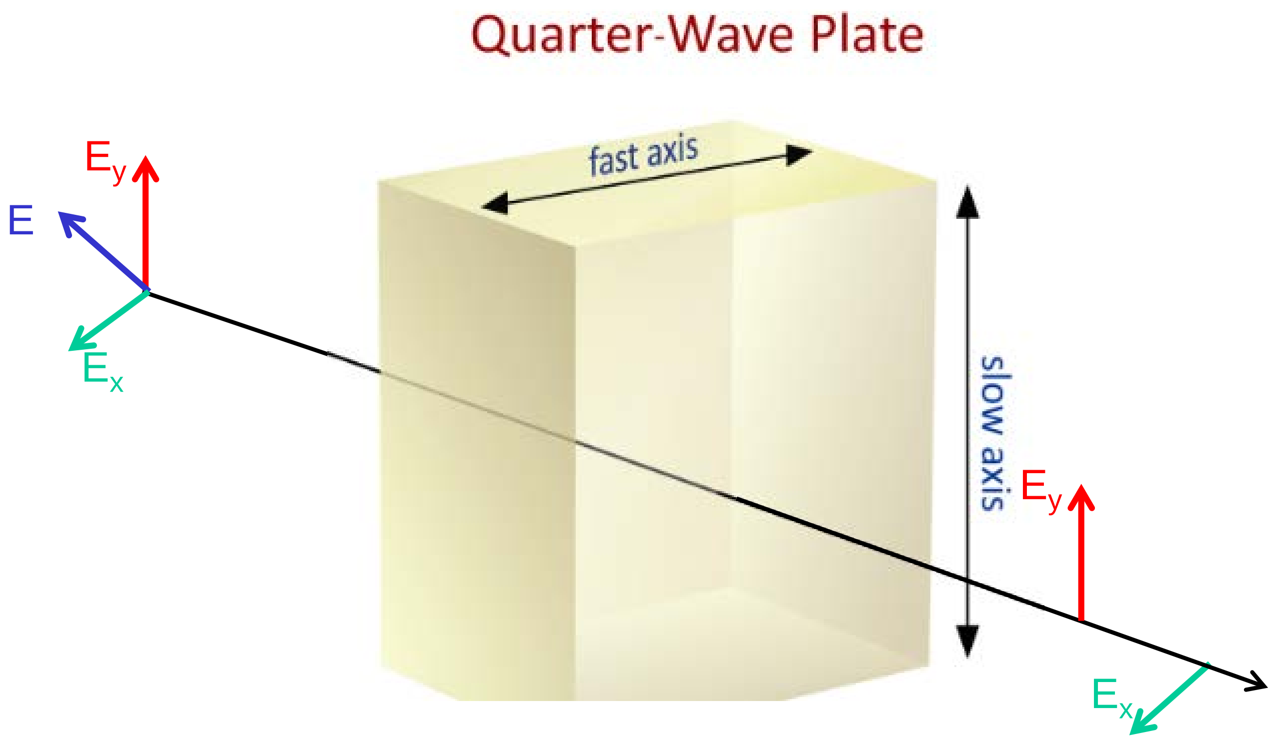
A) Right Circularly Polarized

B) Left Circularly Polarized

C) Linearly Polarized

Curve fingers from slow to fast, thumb must be direction of propagation.

Right or Left Circularly Polarized



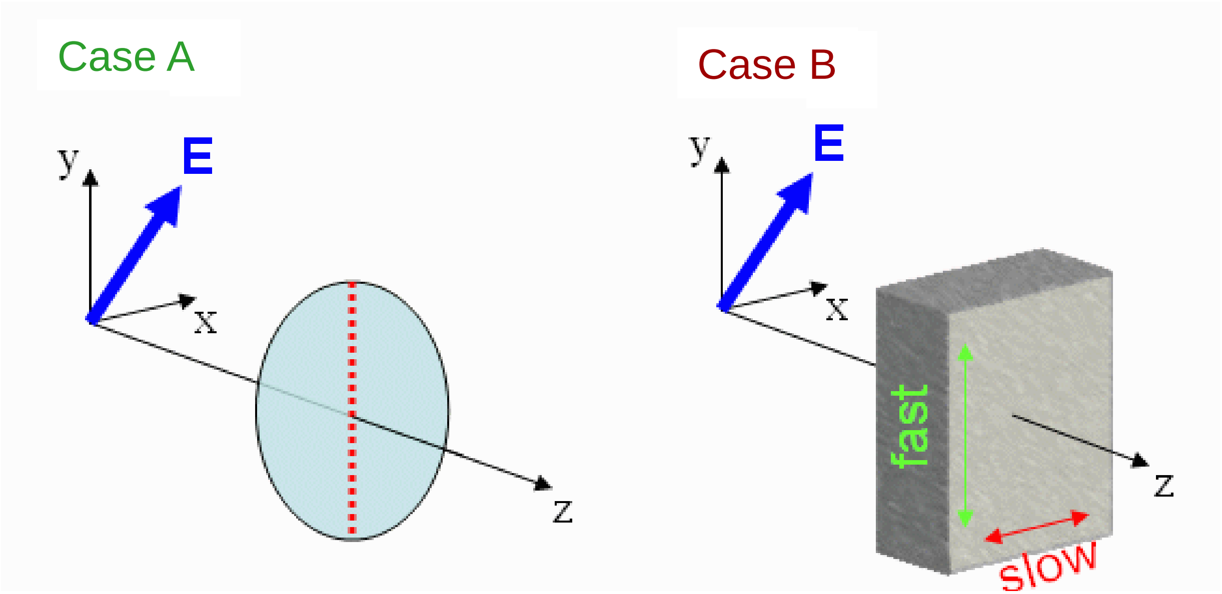
A linearly polarized EM wave is incident on a quarter-wave plate as shown above. The resulting wave is

A) Right Circularly Polarized
B) Left Circularly Polarized
C) Linearly Polarized

Curve fingers from slow to fast, thumb must be direction of propagation.

Identical linearly polarized light at 45º from the y-axis and propagating along the z axis is incident on two different objects. In Case A the light intercepts a linear polarizer with polarization along the y-axis In Case B, the light intercepts a quarter wave plate with vast axis along the y-axis.

the light intercepts a quarter wave plate with fast axis along the y-axis



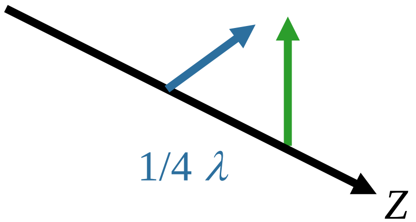
What is the polarization of the light wave in Case B after it passes through the quarter wave plate?.

A. linearly polarized

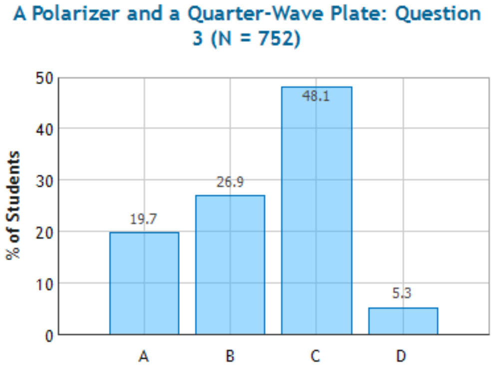
B. left circularly polarized

C. right circularly polarized

D. undefined



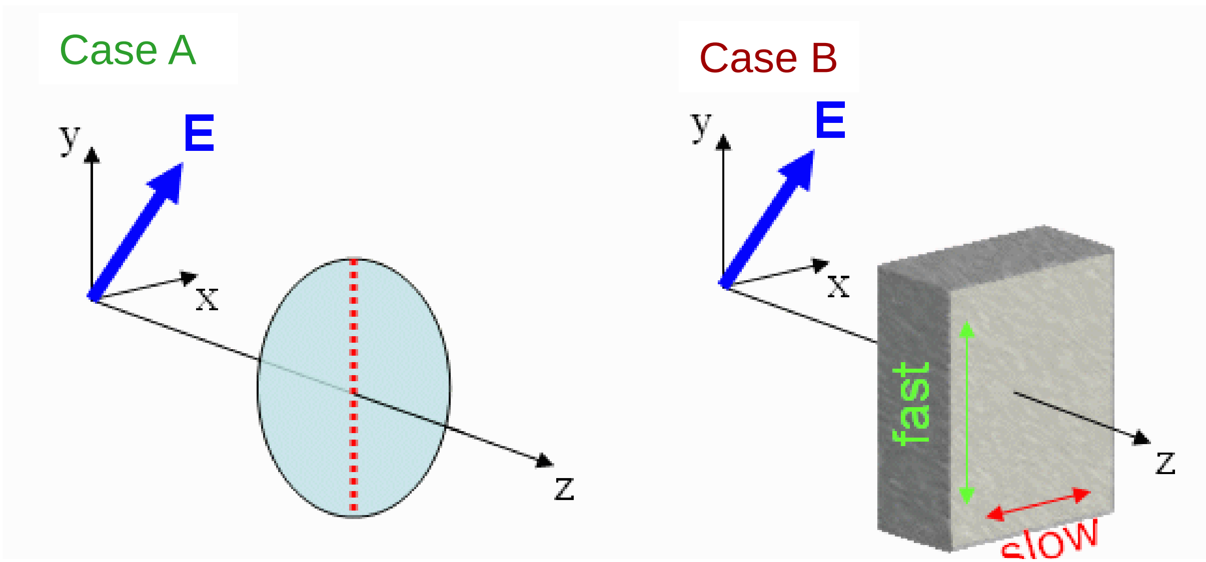
RCP



Curl fingers from slow to fast, thumb should point in direction of propagation

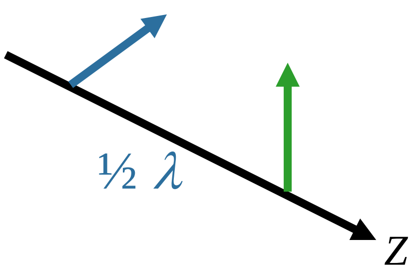
CheckPoint 2c

Identical linearly polarized light at 45º from the y-axis and propagating along the z axis is incident on two different objects. In Case A the light intercepts a linear polarizer with polarization along the y-axis In Case B, the light intercepts a quarter wave plate with vast axis along the y-axis.

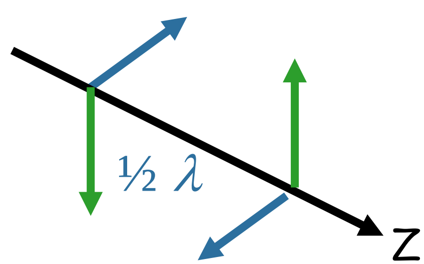


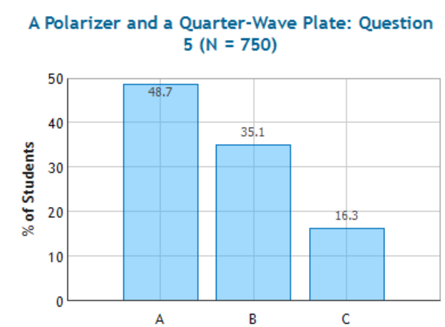
If the thickness of the quarter-wave plate in Case B is doubled, what is the polarization of the wave after passing through the wave plate?

A. linearly polarized ***B.*** circularly polarized ***C.*** undefined



But there is more!





Circular Light on Linear Polarizer

Q: What happens when circularly polarized light is put through a polarizer along the y (or x) axis ?

A) $I = 0$

B) $I = \frac{1}{2} I_0$

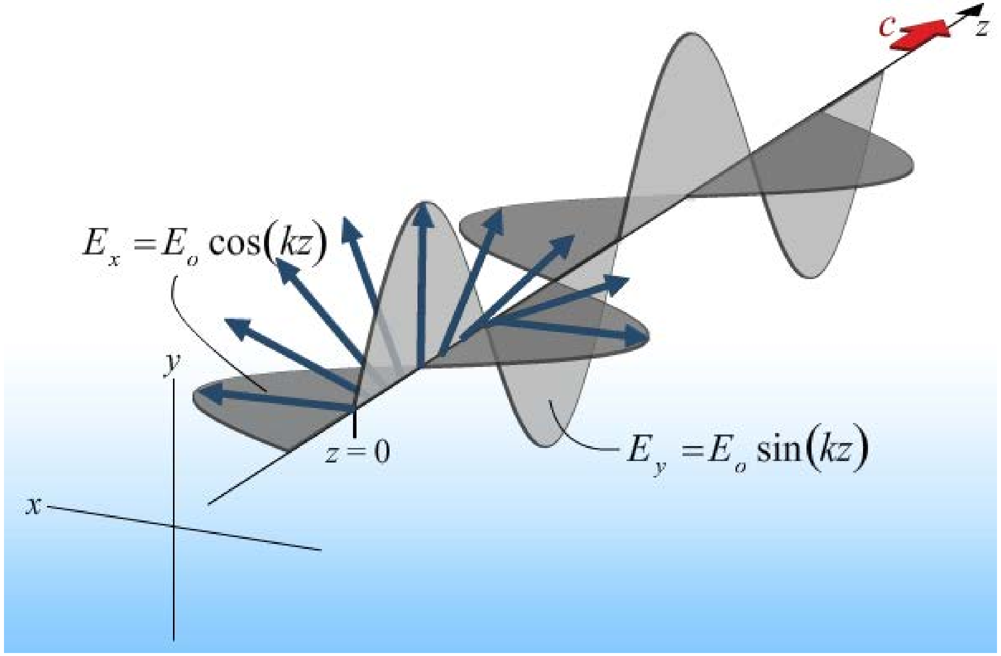
C) $I = I_0$

$$I = \varepsilon_0 c \left\langle E^2 \right\rangle$$

$$= \varepsilon_0 c \left\langle E_x^2 + E_y^2 \right\rangle$$

(the E_y^2 term is crossed out with a red X)

$$= \varepsilon_0 c \frac{E_0^2}{2} \underbrace{\left\langle \cos^2(kz - \omega t) \right\rangle}_{1/2}$$

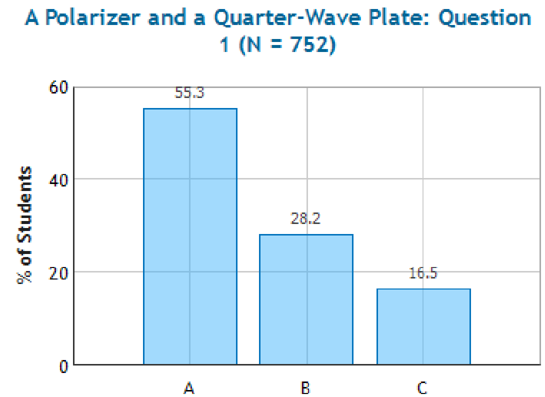


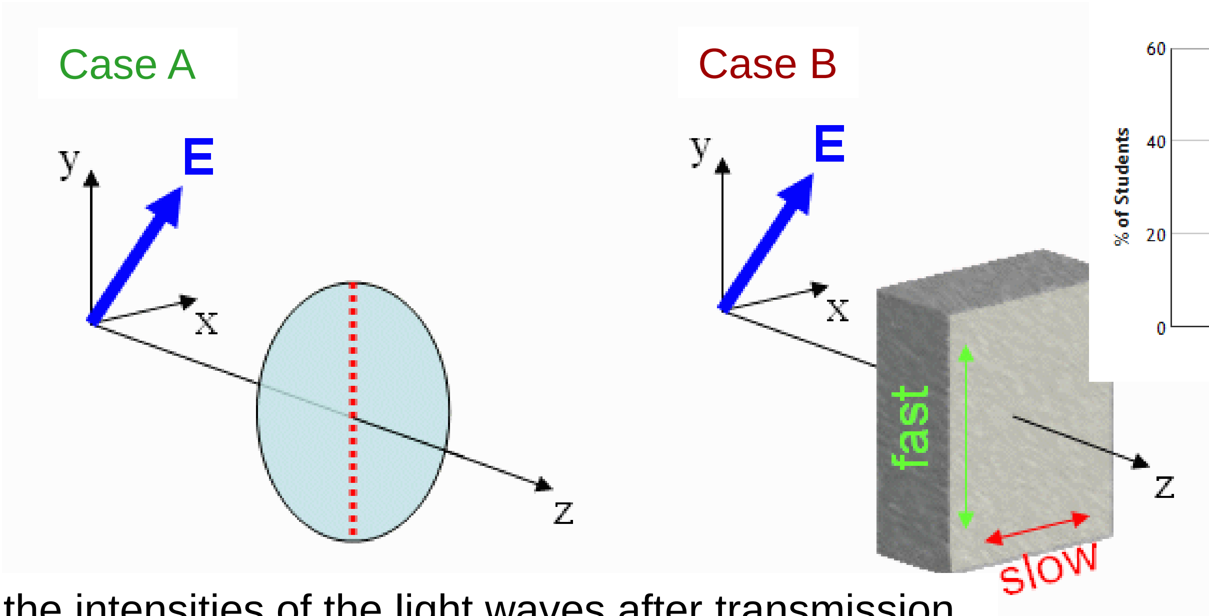
$$= \frac{1}{2} \cdot \frac{1}{2} \varepsilon_0 c E_0^2$$

Half of before

CheckPoint 2a

Identical linearly polarized light at 45º from the y-axis and propagating along the z axis is incident on two different objects. In Case A the light intercepts a linear polarizer with polarization along the y-axis In Case B, the light intercepts a quarter wave plate with fast axis along the y-axis.





Compare the intensities of the light waves after transmission.

A. $I_A < I_B$ **B.** $I_A = I_B$ **C.** $I_A > I_B$

Case A:

E_x is absorbed

$$I_A = I_0 \cos^2(45^o)$$

$$I_A = \tfrac{1}{2} I_0$$

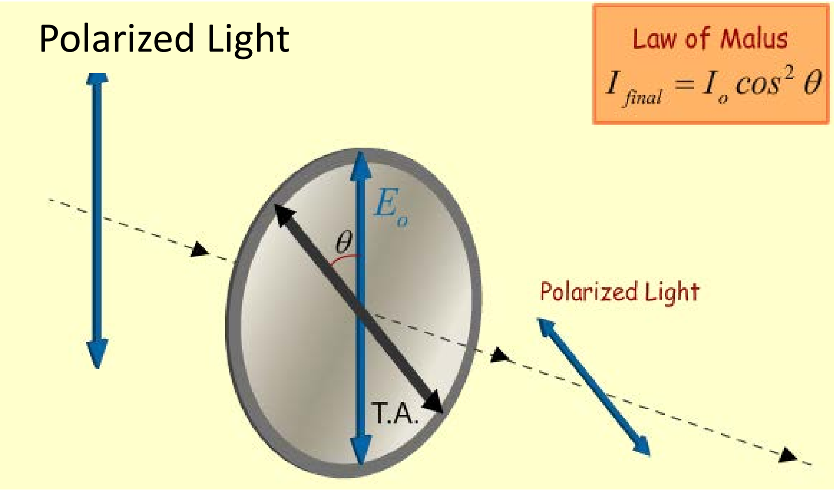
Case B:

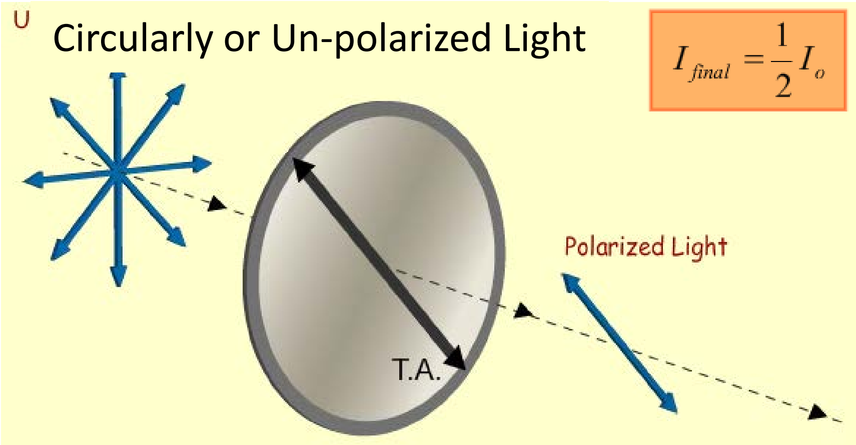
(E_x, E_y) phase changed

$$I_B = I_0$$

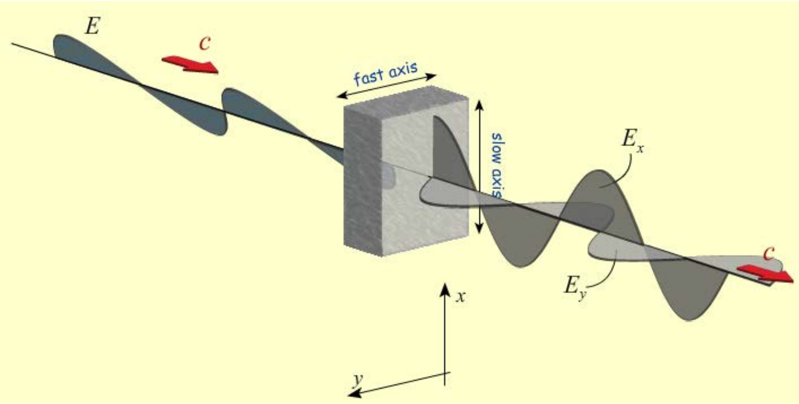
Executive Summary:

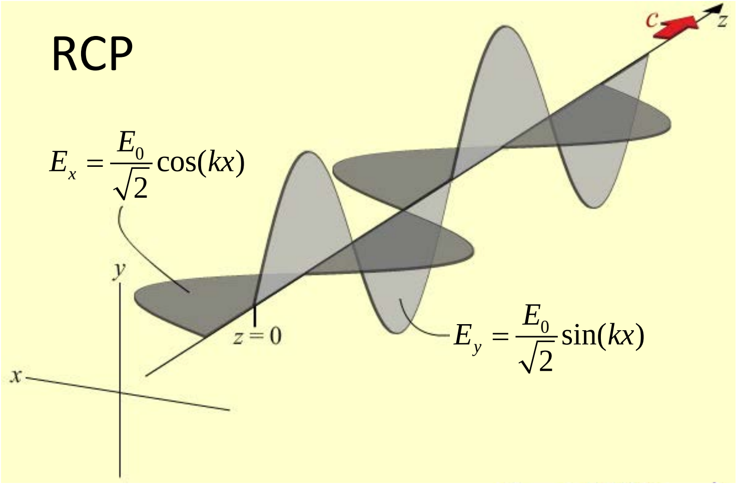
Polarizers & QW Plates:





Birefringence

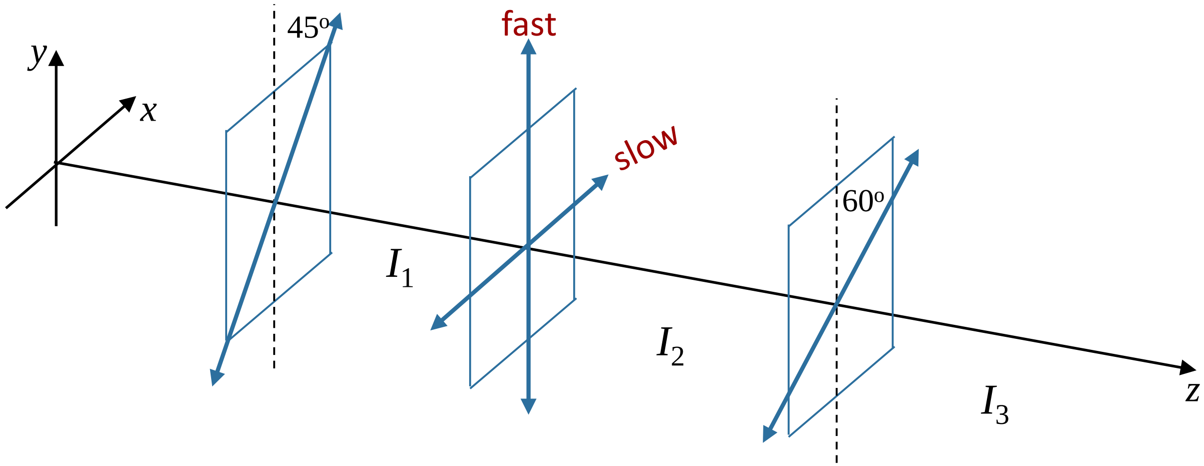




Calculation

Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.

What is the intensity I_3 in terms of I_1?



Conceptual Analysis

Linear Polarizers: absorbs E field component perpendicular to TA

Quarter Wave Plates: Shifts phase of E field components in fast-slow directions

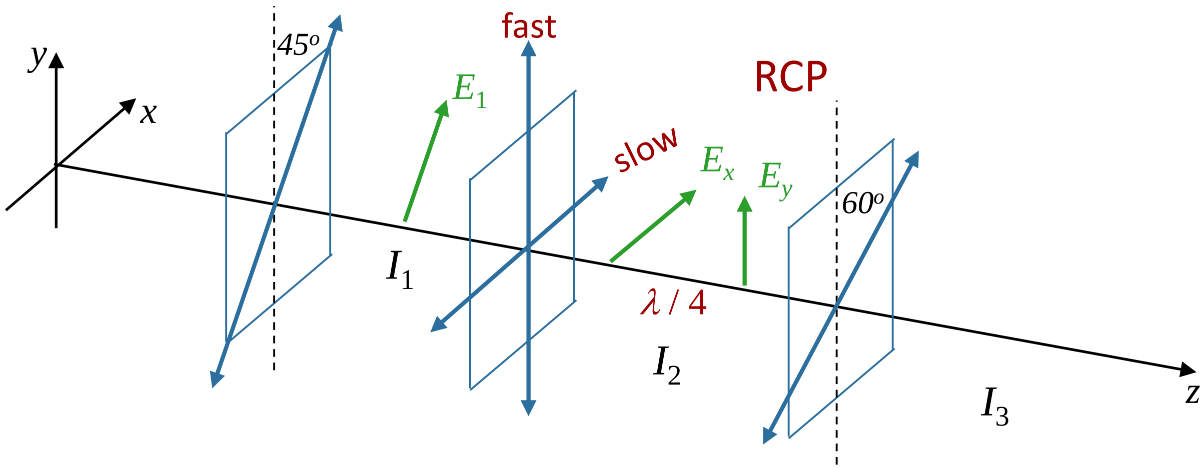
Strategic Analysis

Determine state of polarization and intensity reduction after each object

Multiply individual intensity reductions to get final reduction.

Calculation

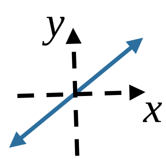
Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.

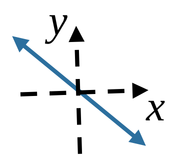


What is the polarization of the light after the QWP?

A) LCP

B) RCP

C) 

D) 

E) un-polarized

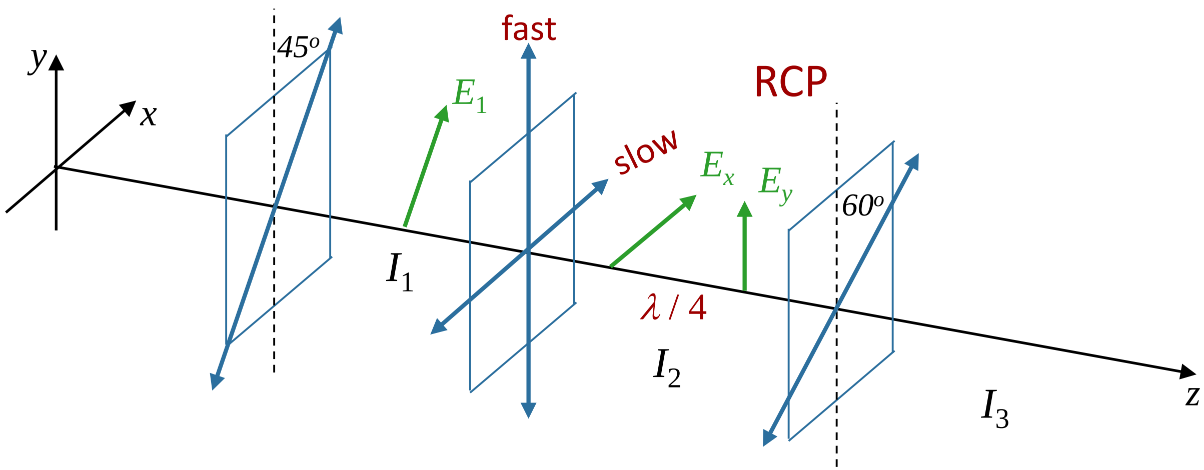
Light incident on QWP is linearly polarized at 45° to fast axis → Light will be circularly polarized after QWP

LCP or RCP? Easiest way: Right Hand Rule:

Curl fingers of RH back to front
Thumb points in dir of propagation
if right hand polarized. → RCP

Calculation

Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.



What is the intensity I_2 of the light after the QWP?

A) $I_2 = I_1$ B) $I_2 = ½\, I_1$ C) $I_2 = ¼\, I_1$

Before:

$$E_x = \frac{E_1}{\sqrt{2}}\sin(kz - \omega t)$$

$$E_y = \frac{E_1}{\sqrt{2}}\sin(kz - \omega t)$$

No absorption: Just a phase change!

$$I = \varepsilon_0 c\left[\left\langle E_x^2 \right\rangle + \left\langle E_y^2 \right\rangle\right]$$

Same before & after!

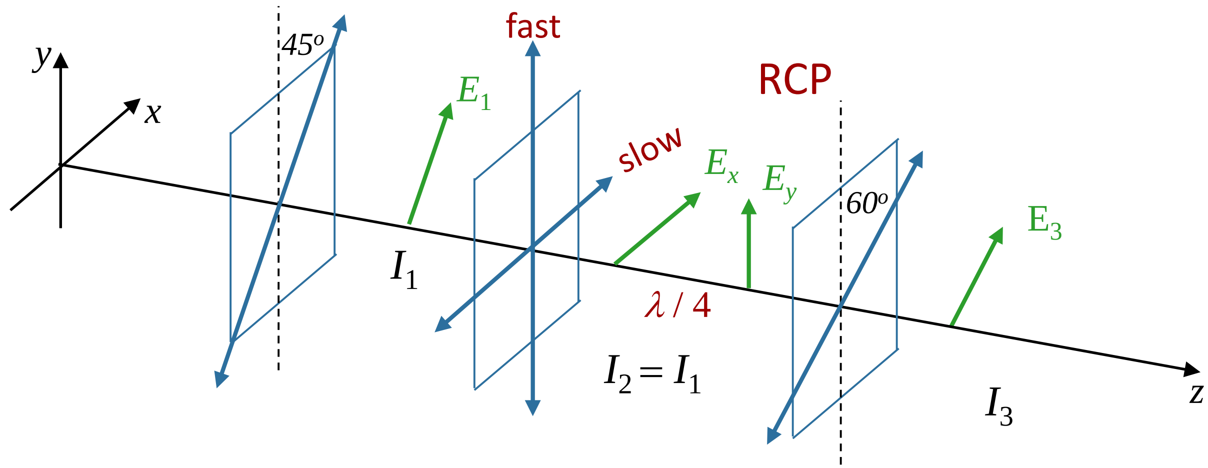
After:

$$E_x = \frac{E_1}{\sqrt{2}}\cos(kz - \omega t)$$

$$E_y = \frac{E_1}{\sqrt{2}}\sin(kz - \omega t)$$

Calculation

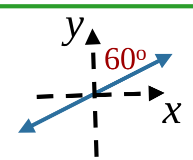
Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.

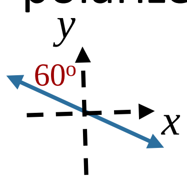


What is the polarization of the light after the 60° polarizer?

A) LCP

B) RCP

C) 

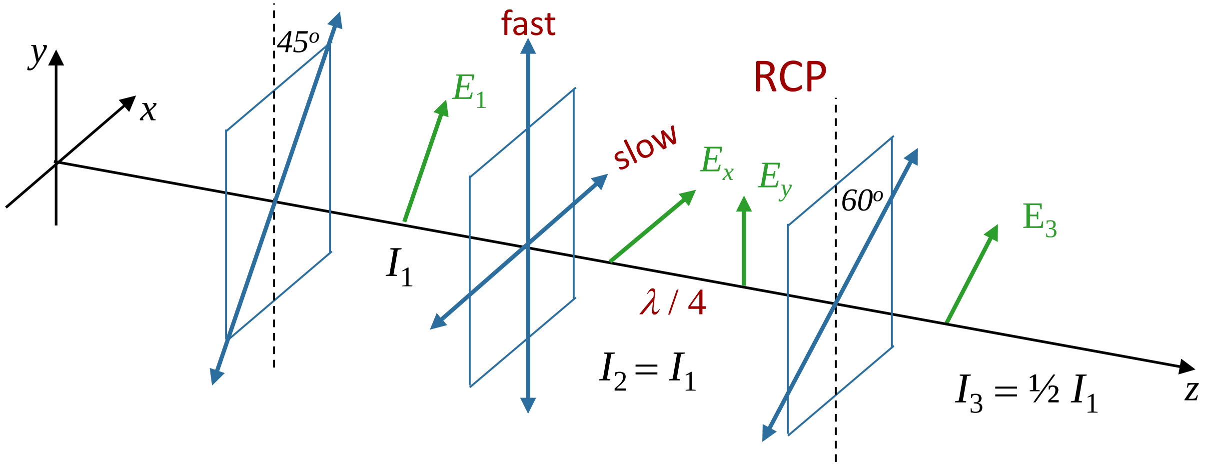
D) 

E) un-polarized

Absorption: only passes components of E parallel to TA ($\theta = 60^o$)

Calculation

Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.



What is the intensity I_3 of the light after the 60° polarizer?

A) $I_3 = I_1$

B) $I_3 = \frac{1}{2} I_1$

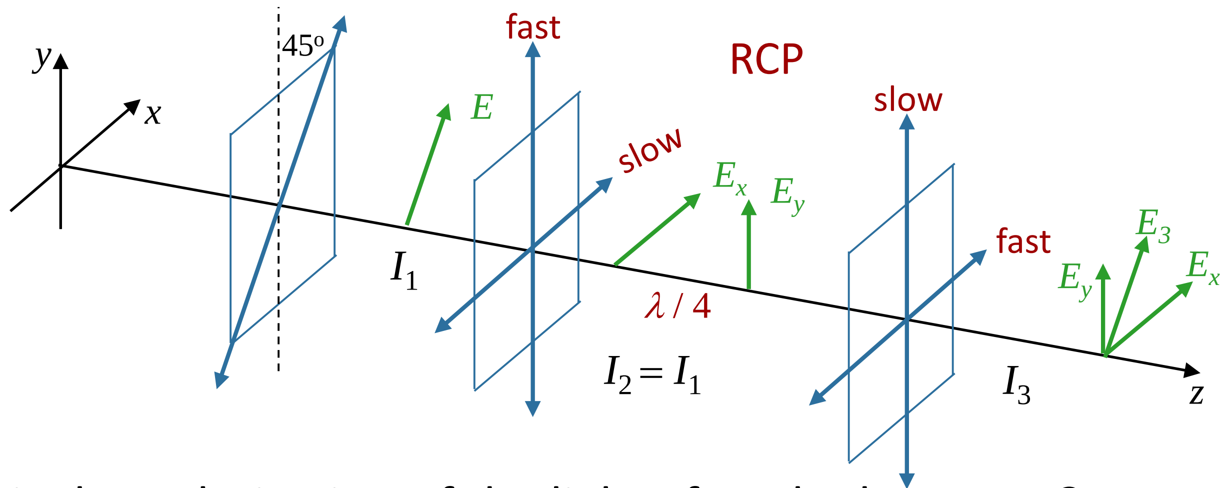
C) $I_3 = \frac{1}{4} I_1$

Circularly polarized light through linear polarizer cuts intensity by ½. ➡ $I_3 = \frac{1}{2} I_1$

NOTE: This does not depend on θ !

Follow-Up 1

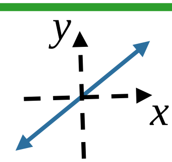
Replace the 60º polarizer with another QWP as shown.

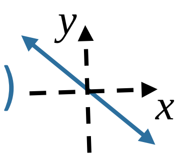


What is the polarization of the light after the last QWP?

A) LCP

B) RCP

C) 

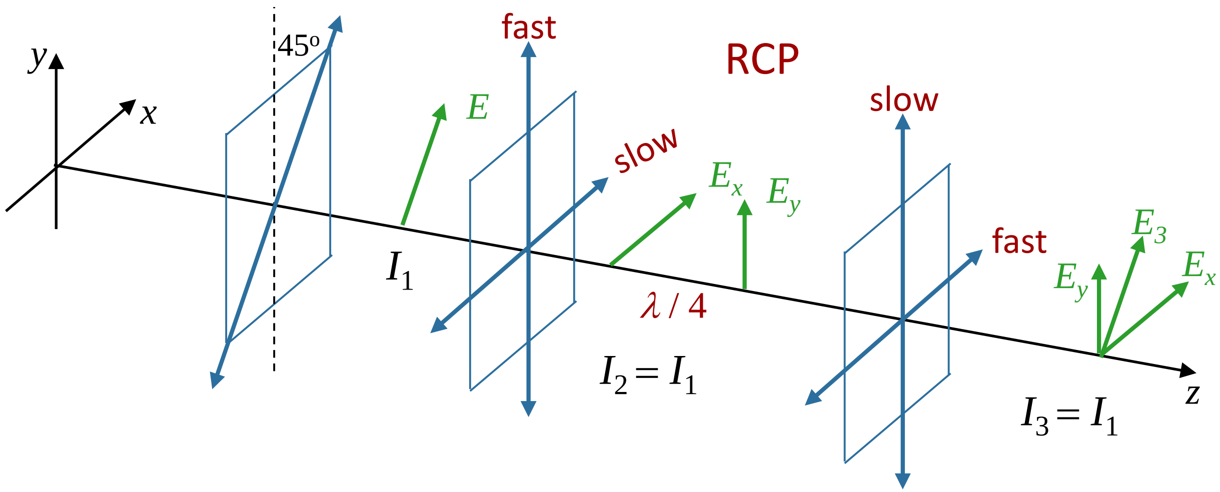
D) 

E) un-polarized

Easiest way:
E_{fast} is λ / 4 ahead of E_{slow} → Brings E_x and E_y back in phase!

Follow-Up 2

Replace the 60° polarizer with another QWP as shown.



What is the intensity I_3 of the light after the last QWP?

A) I_1

B) ½ I_1

C) ¼ I_1

Before:

$$E_x = \frac{E_1}{\sqrt{2}}\cos(kz - \omega t)$$

$$E_y = \frac{E_1}{\sqrt{2}}\sin(kz - \omega t)$$

No absorption: Just a phase change!

Intensity $= \langle E^2 \rangle$

$$I_{before} = \frac{E_1^2}{2} \quad \longleftrightarrow \quad I_{after} = \frac{E_1^2}{2}$$

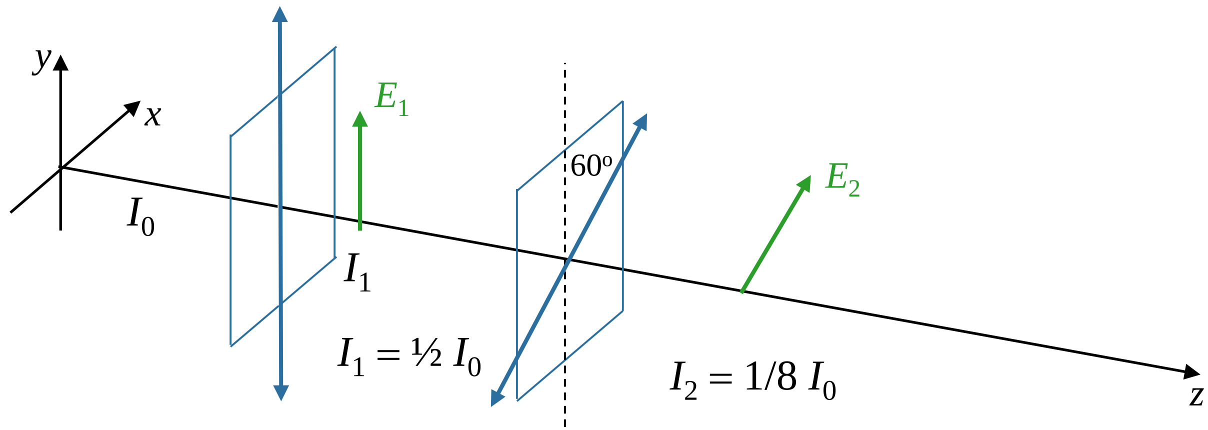
After:

$$E_x = \frac{E_1}{\sqrt{2}}\cos(kz - \omega t)$$

$$E_y = \frac{E_1}{\sqrt{2}}\cos(kz - \omega t)$$

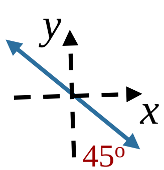
Follow-Up 3

Consider light incident on two linear polarizers as shown. Suppose $I_2 = 1/8\, I_0$



What is the possible polarization of the input light?

A) LCP

B) 

C) un-polarized

D) all of above

E) none of above

After first polarizer: LP along y–axis with intensity I_1

After second polarizer: LP at 60° wrt y–axis

Intensity: $I_2 = I_1 \cos^2(60°) = ¼\, I_1$

$I_2 = 1/8\, I_0$ Þ $I_1 = ½\, I_0$

Question is: What kind of light loses ½ of its intensity after passing through vertical polarizer?

Answer: Everything except LP at θ other than 45°