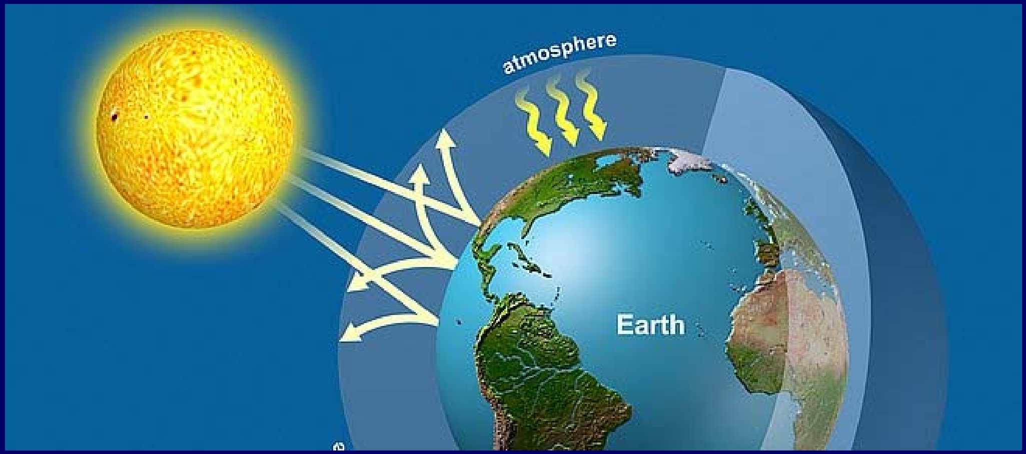
Physics 102: Lecture 15

Electromagnetic Waves

Energy & Polarization

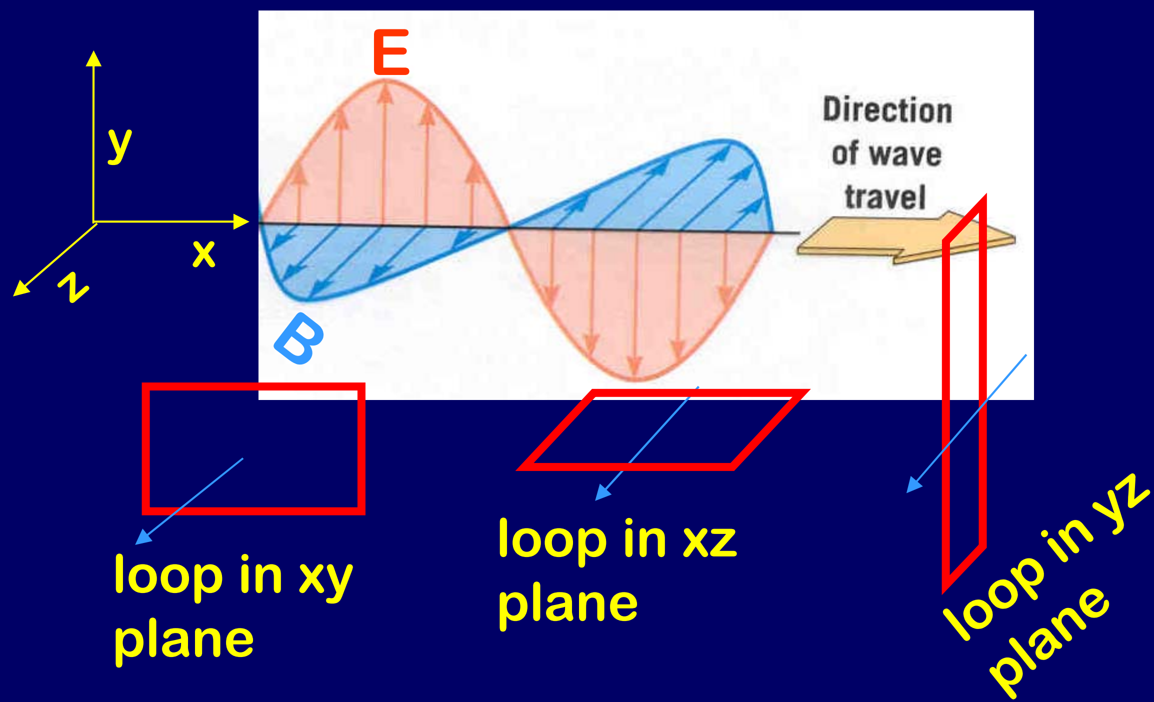


Material on exam 2!

James Scholar proposals due Oct. 20!!

Checkpoint 1.1, 1.2

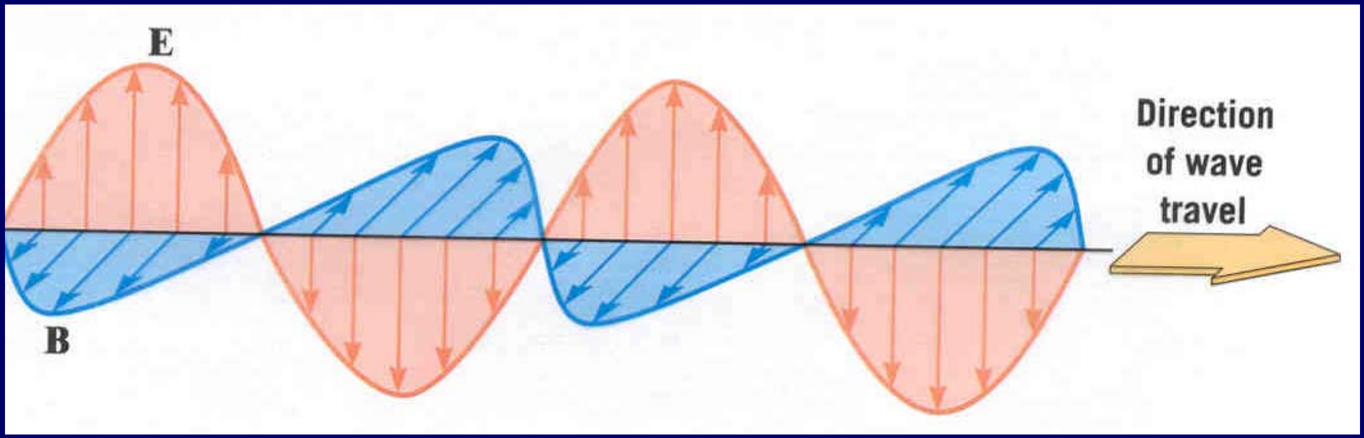
"In order to find the loop that detects the electromagnetic wave, we should find the loop that has the greatest flux through the loop."

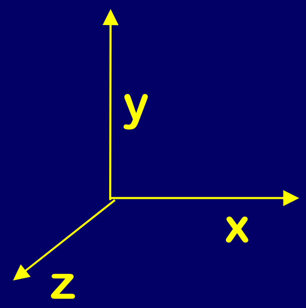


A 31% **B 30%** **C 39%**

Only the loop in the xy plane will have a magnetic flux through it as the wave passes. The flux will oscillate with time and induce an emf. (Faraday's Law!!!)

Propagation of EM Waves





- Changing B field creates E field
- Changing E field creates B field

$$\boxed{E = c\,B}$$ ← ONLY TRUE FOR EM WAVE

If you decrease E, you also decrease B!

CheckPoint 1.4

Suppose that the electric field of an electromagnetic wave decreases in magnitude. The magnetic field:

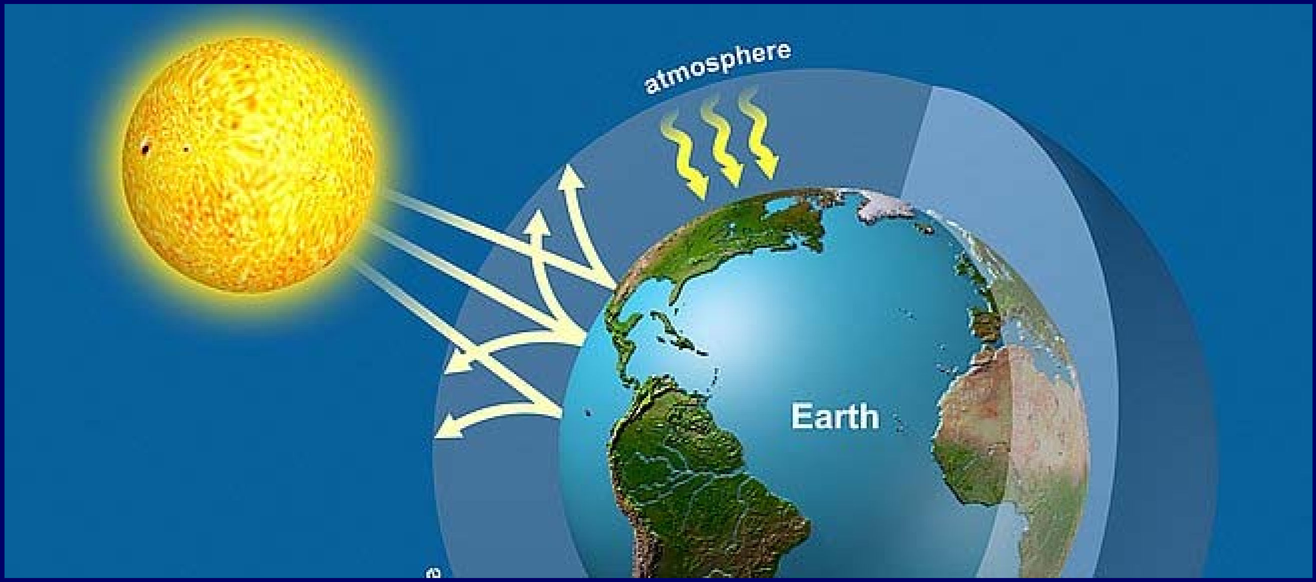
17% **1 increases**

71% **2 decreases** (circled)

12% **3 remains the same**

$$E = cB$$

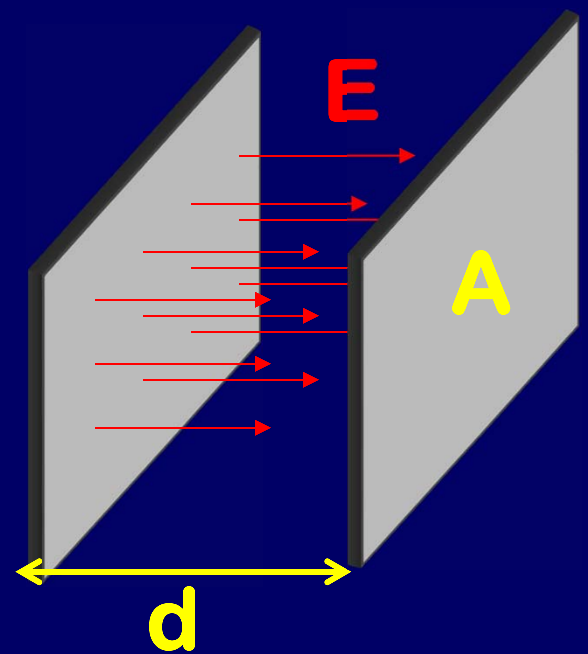
There is energy associated with electric and magnetic fields and electromagnetic waves!



WHY?

It takes work to create electric and magnetic fields…

Energy in E field



Electric Fields

- Recall Capacitor Energy:

  U = ½ C V²   Lect.4

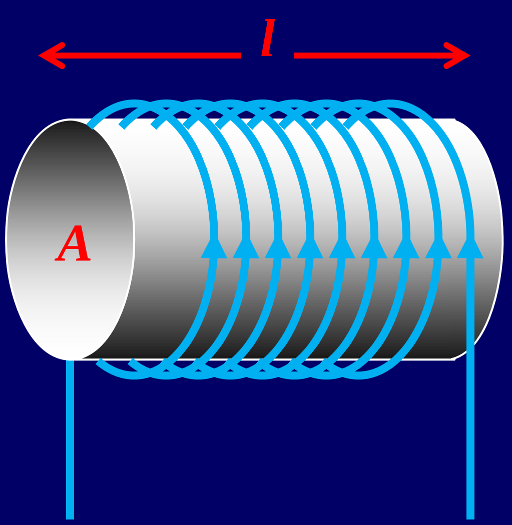
$$C = \frac{\varepsilon_o A}{d}$$

$$V = Ed$$

$$U = \tfrac{1}{2}CV^2 = \tfrac{1}{2}\frac{\varepsilon_0 A}{d}E^2 d^2 = \tfrac{1}{2}\varepsilon_0 E^2 Ad = \frac{1}{2}\epsilon_0 E^2 V$$

Ad = volume; V = Volume

Energy in B field



Magnetic Fields

- Recall Inductor Energy:

  $U = \frac{1}{2} L I^2$

Lect. 11

$$L = \mu_o n^2 l A$$

$$B = \mu_o n I$$

$$U = \tfrac{1}{2} L I^2 = \tfrac{1}{2}\left(\mu_0 n^2 l A\right)\frac{B^2}{\mu_0{}^2 n^2} = \tfrac{1}{2}\frac{B^2}{\mu_0} \underbrace{Al}_{\text{volume}} = \frac{1}{2}\frac{B^2}{\mu_0} V$$

Intensity (I or S) = Power/Area

- Energy (U) hitting flat surface in time t

  = Energy U in laser beam (red cylinder):

$$U = \left(\frac{1}{2}\epsilon_0 E^2 + \frac{1}{2}\frac{B^2}{\mu_0}\right)V = \left(\frac{1}{2}\epsilon_0 E^2 + \frac{1}{2}\frac{E^2}{c^2\mu_0}\right)V$$

$$\bar{U} = \epsilon_0 E_{rms}^2 A c t$$

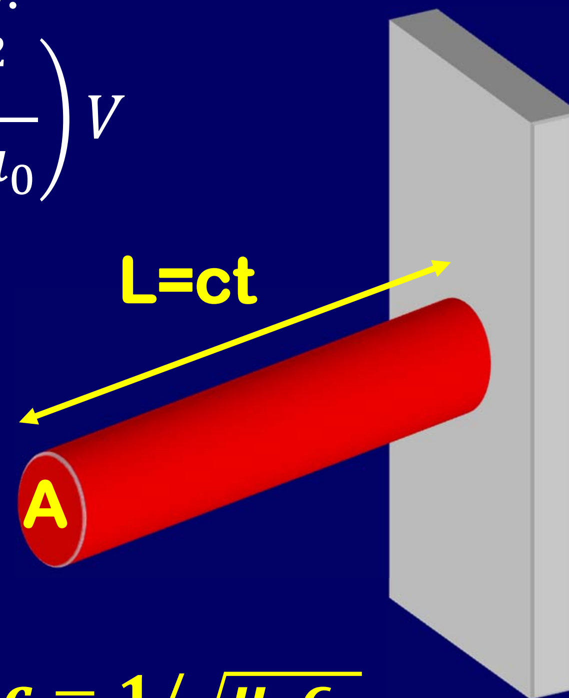
- Power (P):

$$\bar{P} = \bar{U}/t = \epsilon_0 E_{rms}^2 A c$$

- Intensity (I or S): = "brightness"

$$S = P/A \;\; [\mathrm{W/m^2}]$$

$$= c\varepsilon_0 E^2_{rms}$$



$B = E/c \qquad c = 1/\sqrt{\mu_0 \epsilon_0}$

U = Energy

A = Cross sectional area of laser beam

L = Length of laser beam

Example

The intensity of sunlight at the earth is approximately $1000 W/m^2$. A solar cooker collects light using a $1\ m^2$ area and focuses that light onto a pot of food. How much power is delivered to the food?

$$S = P/A \qquad P = S\,A = 1000 \times 1 = 1000W$$

What is the rms magnitude of the electric field of the light when it hits the solar cooker?

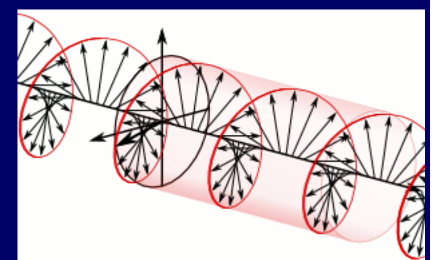
$$S = c\epsilon_0 E_{rms}^2 \qquad E_{rms} = \sqrt{S/c\epsilon_0}$$

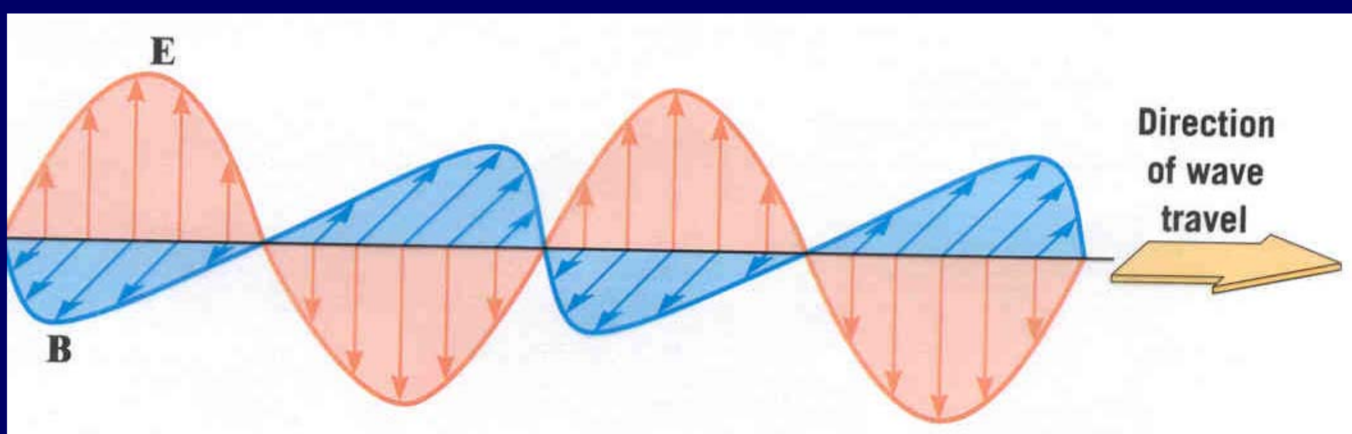
$$= \sqrt{1000/(3 \times 10^8 \times 8.85 \times 10^{-12})}$$

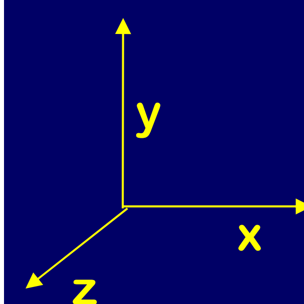
$$= 614\ V/m$$

Polarization

- Transverse waves have a polarization
  - (Direction of oscillation of E field for light)
- Types of Polarization
  - Linear   (Direction of E is constant)
  - Circular (Direction of E rotates with time)
  - Unpolarized (Direction of E changes randomly)

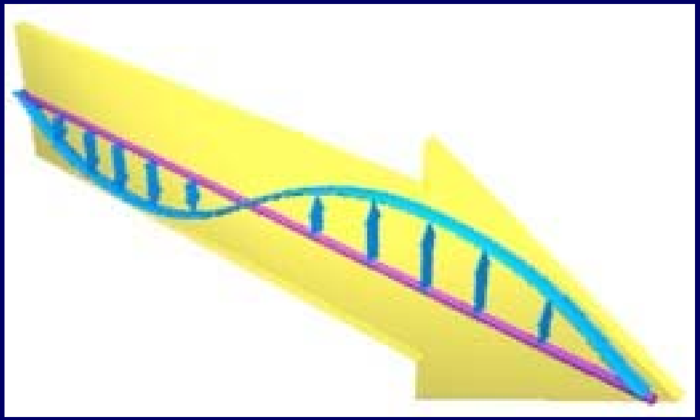


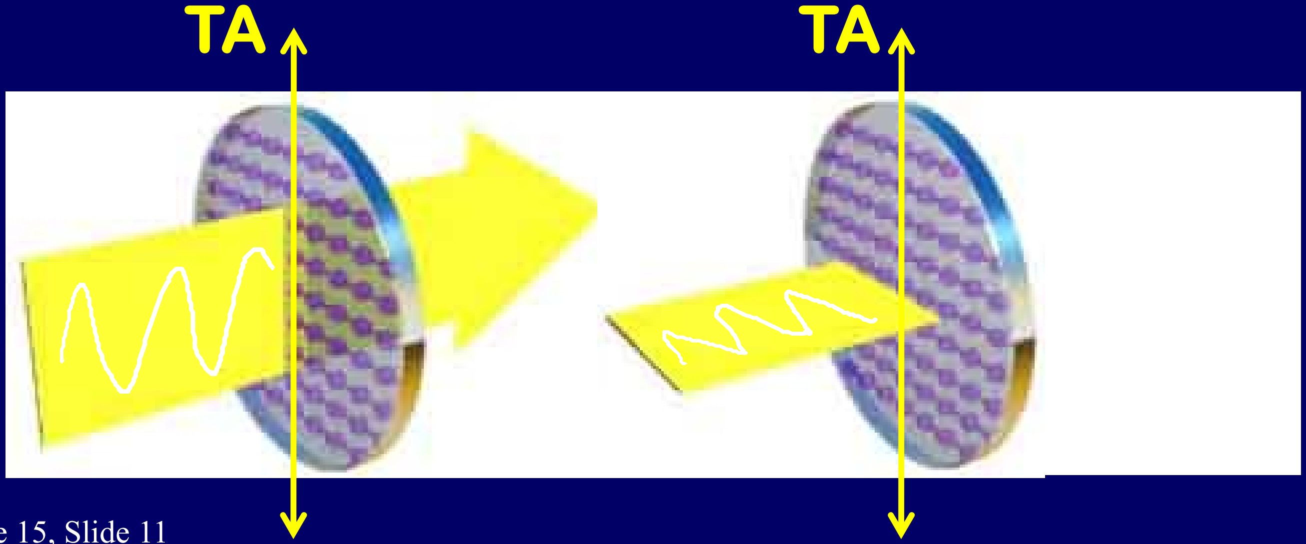




Linear Polarizers

- Linear Polarizers absorb all <u>electric fields</u> perpendicular to their transmission axis (TA)





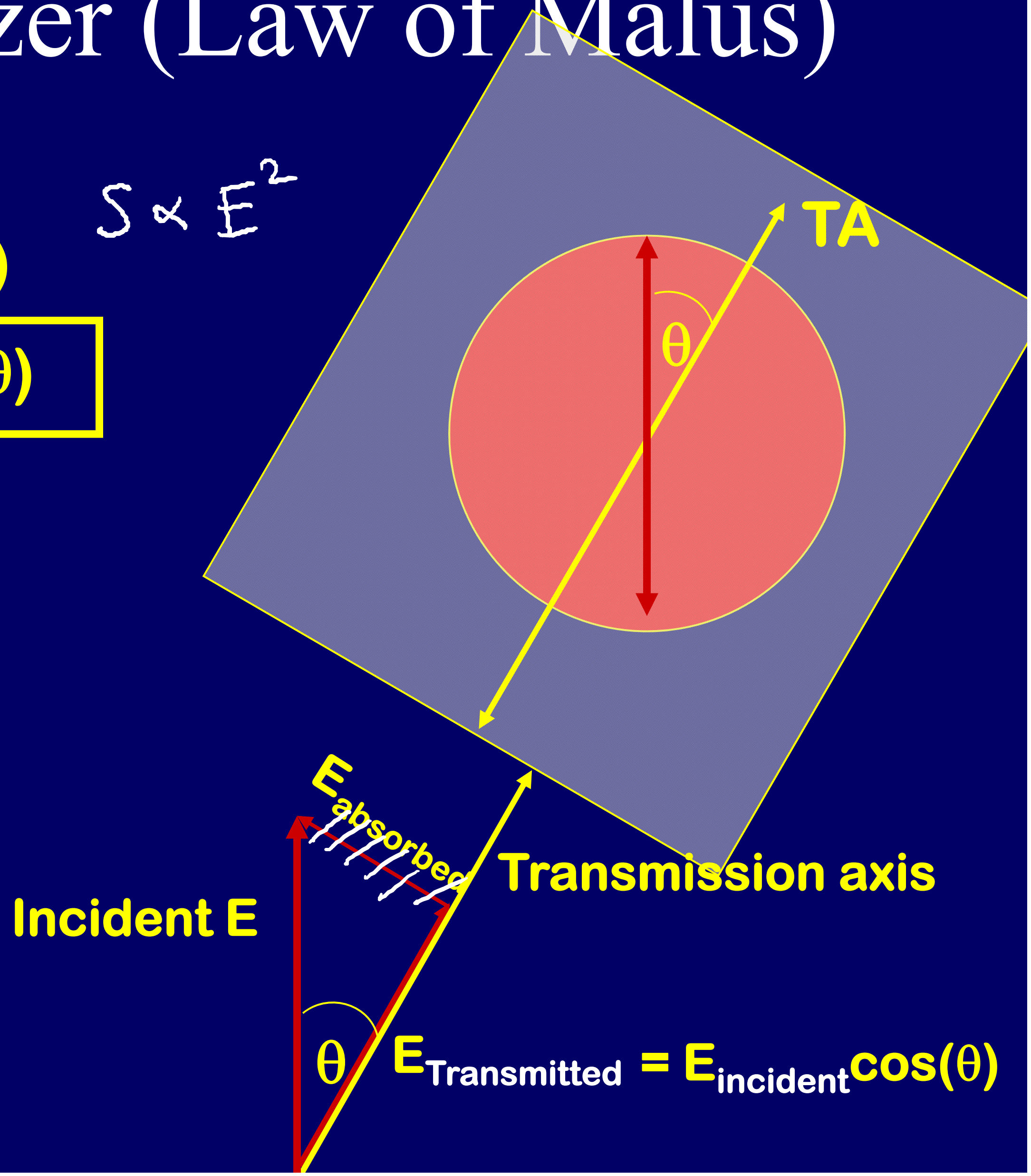
Linearly Polarized Light on Linear Polarizer (Law of Malus)

$S \propto E^2$

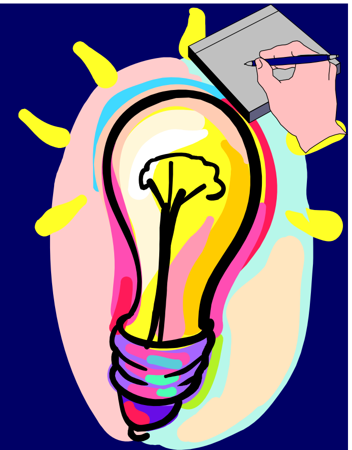
$E_{transmitted} = E_{incident} \cos(\theta)$

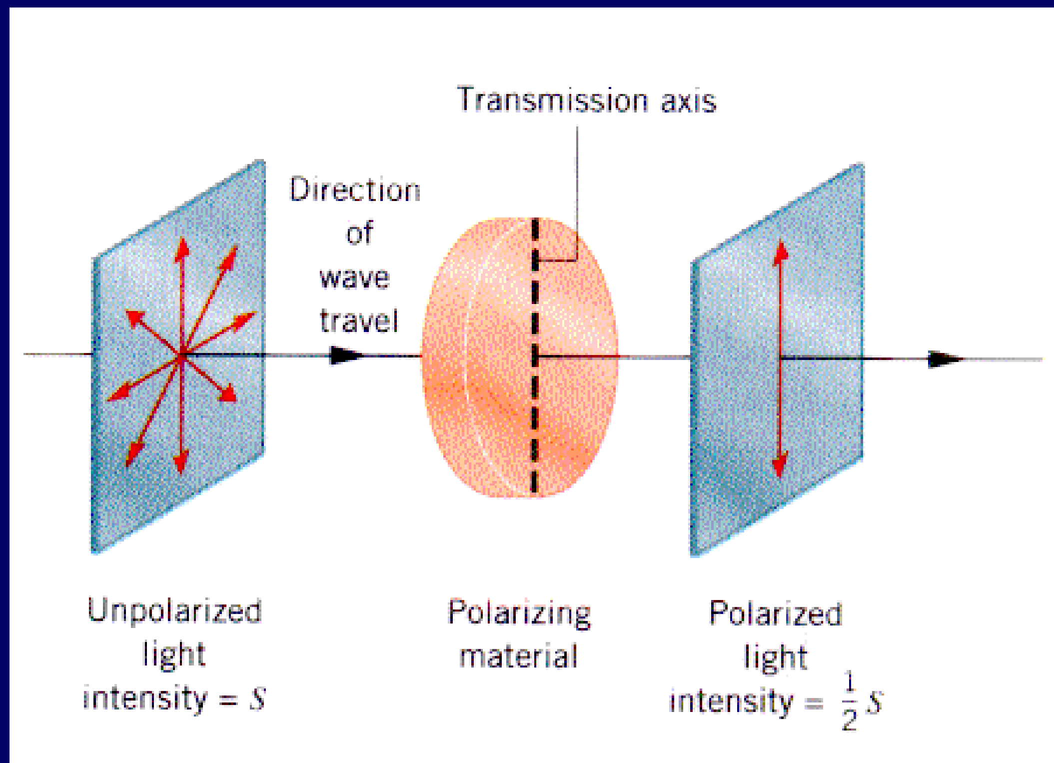
$S_{transmitted} = S_{incident} \cos^2(\theta)$

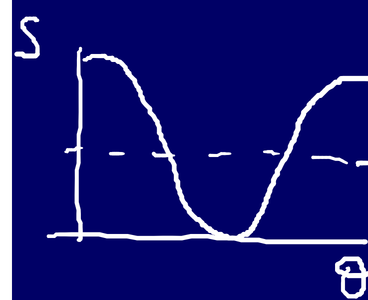
θ is the angle between the incoming polarization and the transmission axis



Unpolarized Light on Linear Polarizer







- Most light comes from electrons accelerating in random directions and is unpolarized.
- Averaging over all directions: $S_{transmitted} = ½\ S_{incident}$

Always true for unpolarized light!

ACT/CheckPoint 15.6

Unpolarized light (like the light from the sun) passes through a polarizing sunglass (a linear polarizer). The intensity of the light when it emerges is

1. zero
2. 1/2 what it was before
3. 1/4 what it was before
4. 1/3 what it was before
5. need more information

$S_{transmitted} = ½\ S_{incident}$ **for unpolarized light**

ACT/CheckPoint 15.7

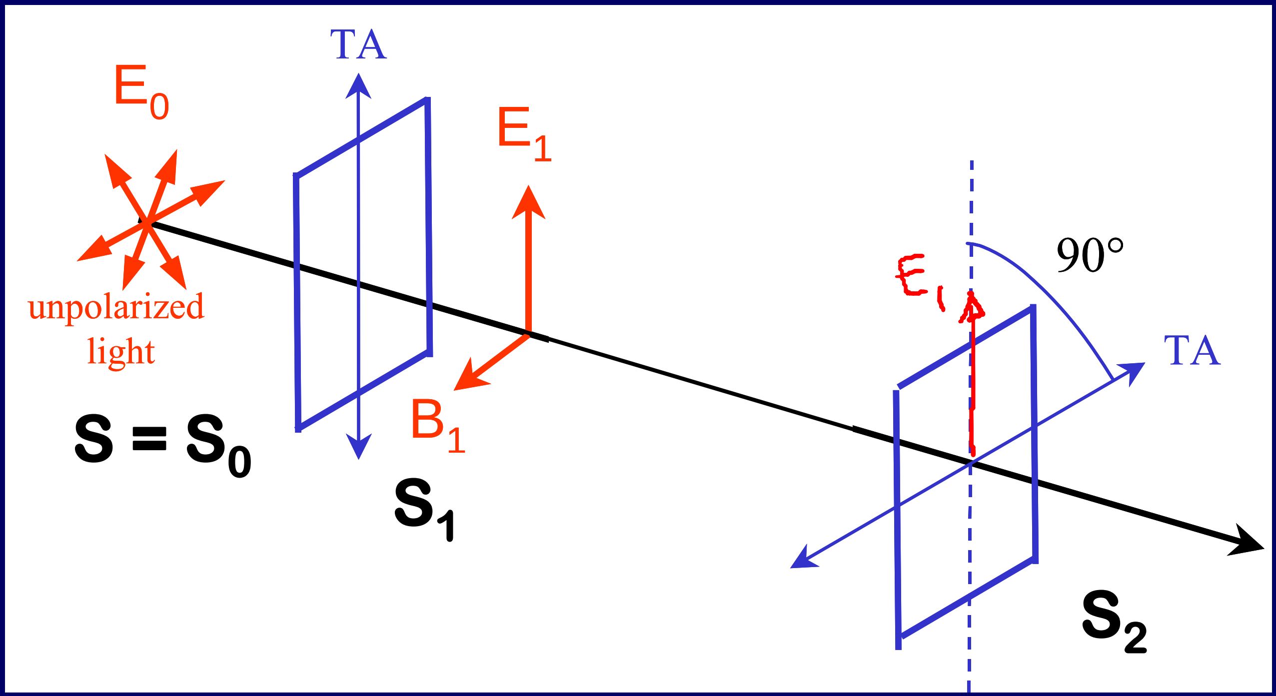
Now, horizontally polarized light passes through the same glasses (which are vertically polarized). The intensity of the light when it emerges is

1. zero
2. 1/2 what it was before
3. 1/4 what it was before
4. 1/3 what it was before
5. need more information

$S_{transmitted} = S_{incident} \cos^2(\theta)$ $\theta = 90^\circ$

Law of Malus – 2 Polarizers

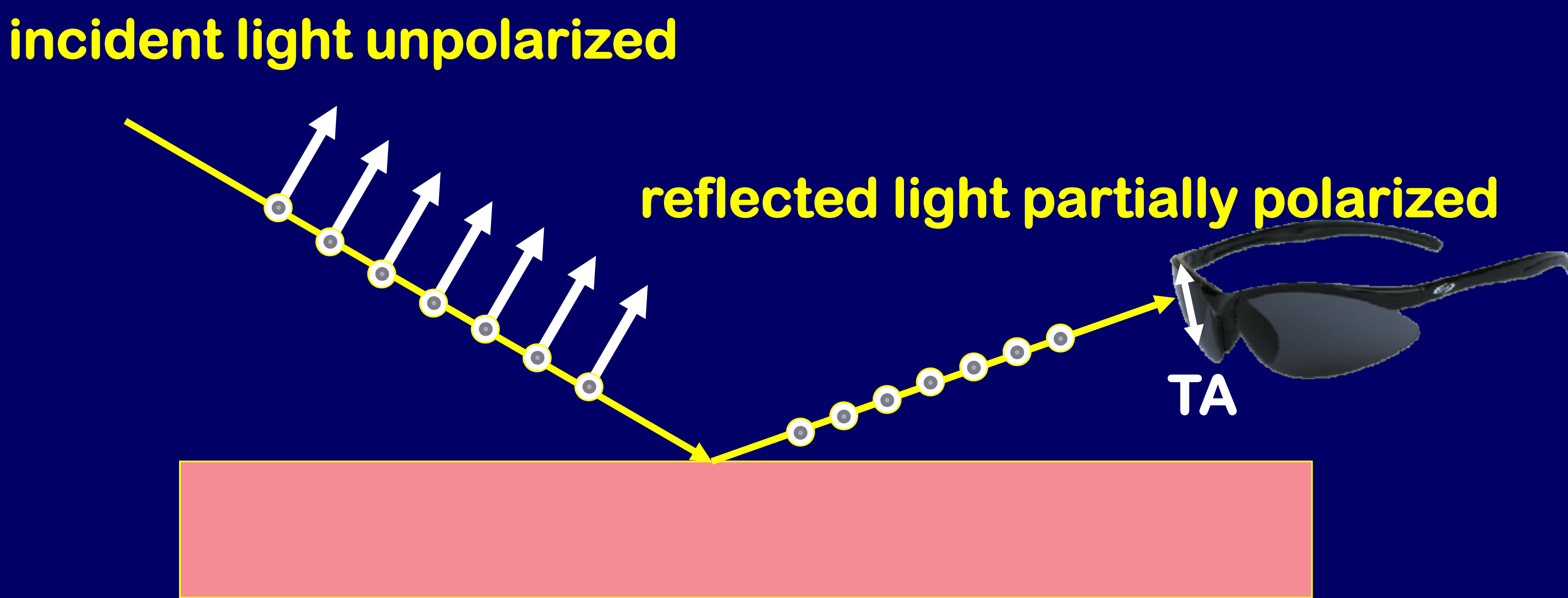
Example



1) Intensity of unpolarized light incident on linear polarizer is reduced by ½ . $S_1 = ½\, S_0$

2) Light transmitted through first polarizer is vertically polarized. Angle between it and second polarizer is θ=90°. $S_2 = S_1 \cos^2(90°) = 0$

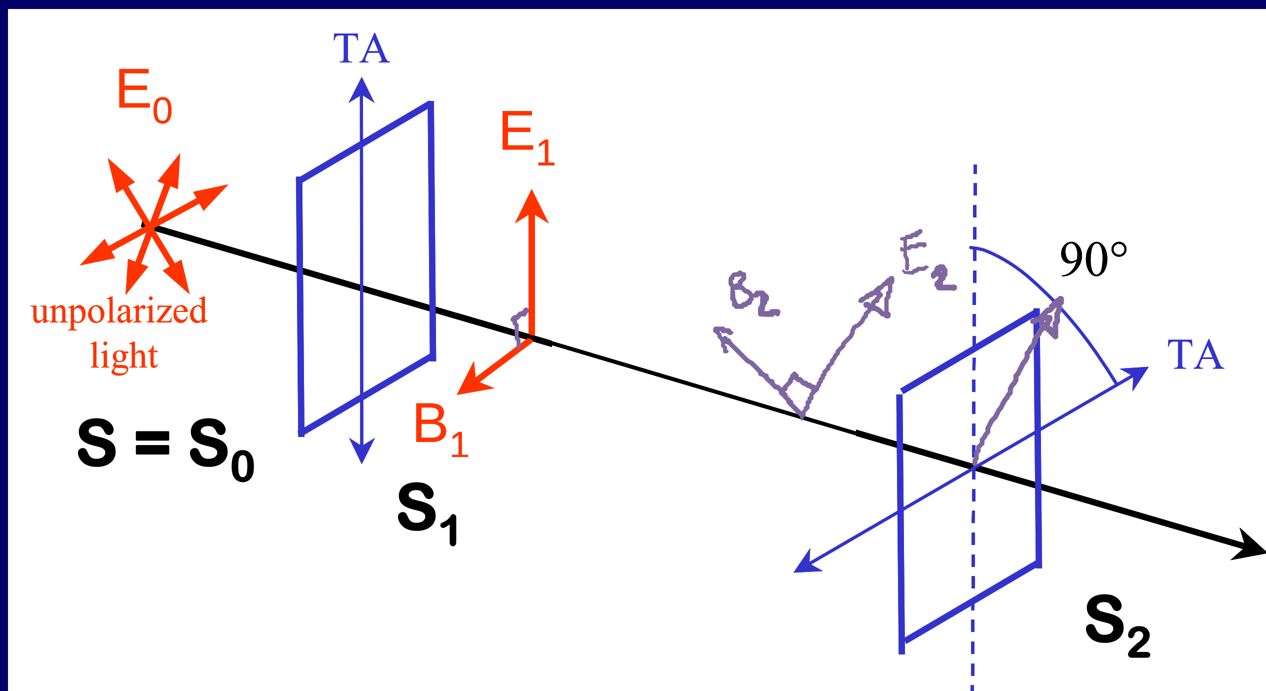
How do polarized sunglasses work?



the sunglasses reduce the glare from reflected light

ACT: 3 polarizers

Now suppose we add a third polarizer between the two outer polarizers. The polarizer TA is tilted from vertical. What is the intensity of the light that emerges?



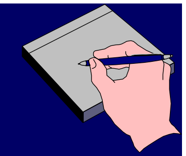
A. zero, same as before

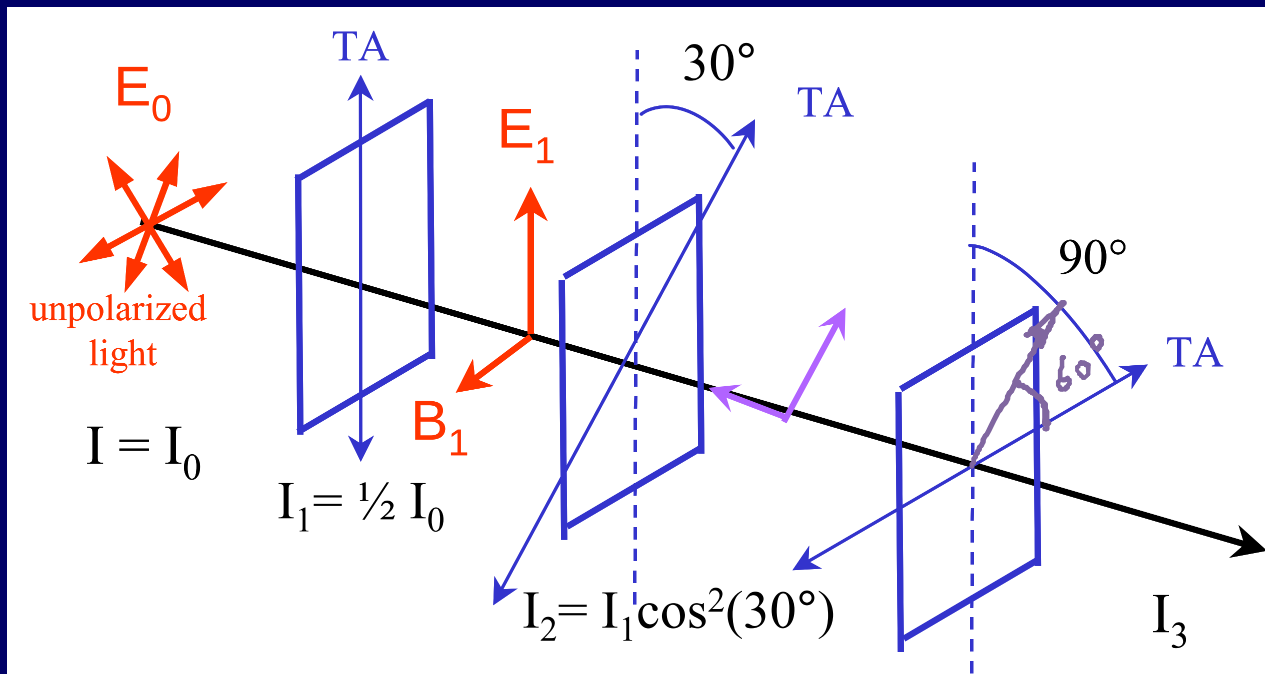
B. more than what it was before

C. need more information

Example

Law of Malus – 3 Polarizers





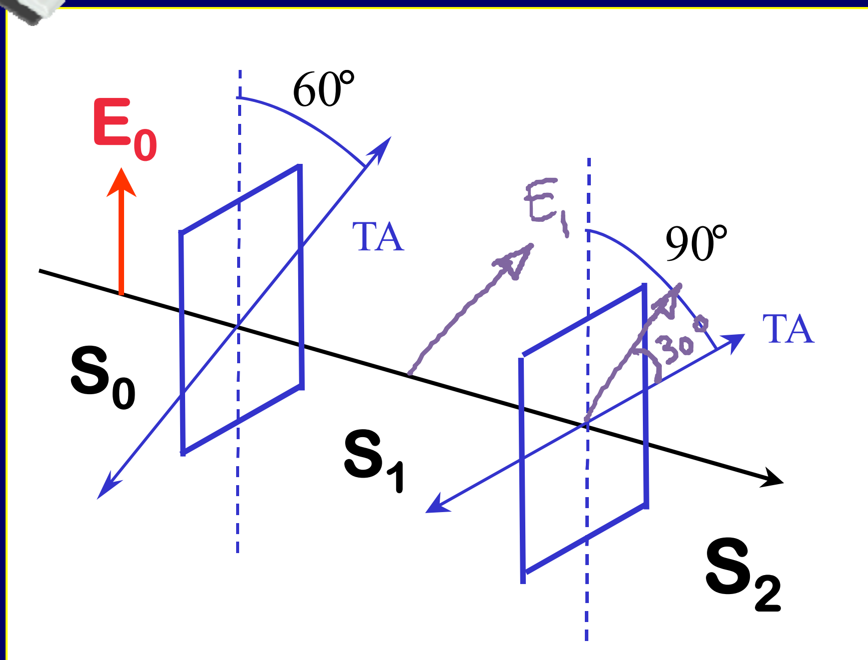
2) Light transmitted through first polarizer is vertically polarized. Angle between it and second polarizer is $\theta = 30^{\circ}$.

$I_2 = I_1 \cos^2 (30^{\circ}) = ½ I_0 \cos^2 (30^{\circ})$

3) Light transmitted through second polarizer is polarized 30° from vertical. Angle between it and third polarizer is $\theta = 60^{\circ}$.

$I_3 = I_2 \cos^2 (60^{\circ}) = ½ I_0 \cos^2 (30^{\circ}) \cos^2 (60^{\circ}) = 0.09375\ I_0$

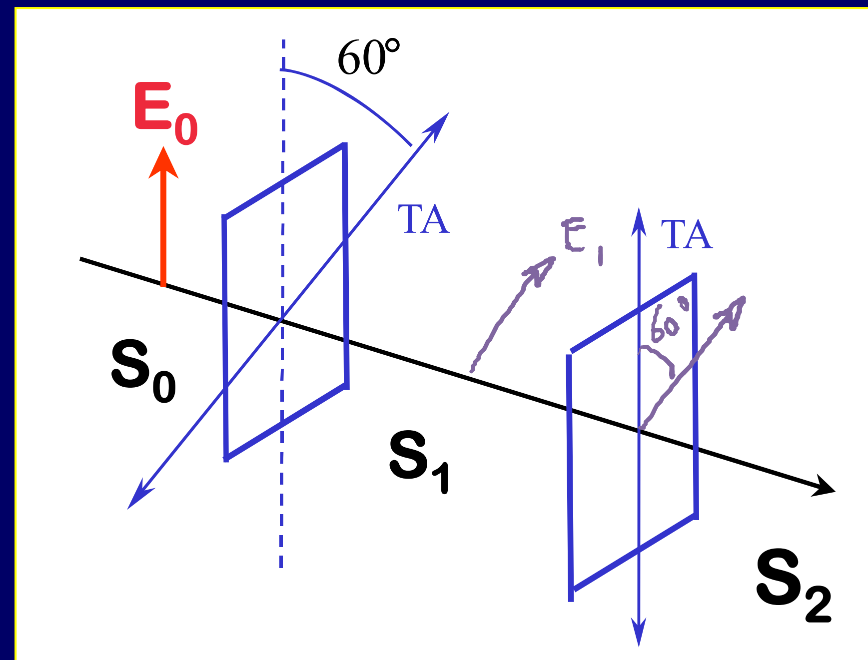
ACT: Law of Malus



A

$S_1 = S_0\cos^2(60)$

$S_2 = S_1\cos^2(30) = S_0\cos^2(60)\cos^2(30)$



B

$S_1 = S_0\cos^2(60)$

$S_2 = S_1\cos^2(60) = S_0\cos^4(60)$

1) $S_2^A > S_2^B$ 2) $S_2^A = S_2^B$ 3) $S_2^A < S_2^B$

See You Monday!