Phys 102 – Lecture 16

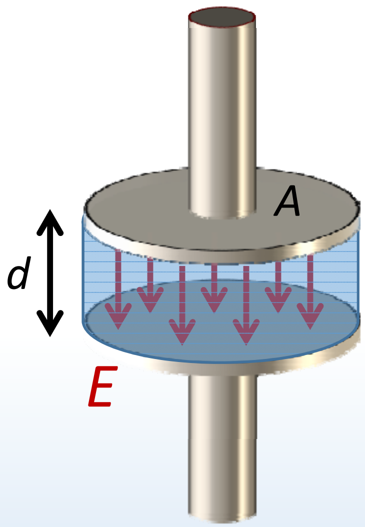
Electromagnetic wave energy & polarization

Today we will...

- Learn about properties of electromagnetic waves
  - Energy density & intensity
  - Polarization – linear, circular, unpolarized
- Apply those concepts
  - Linear polarizers
  - Optical activity
  - Circular dichroism

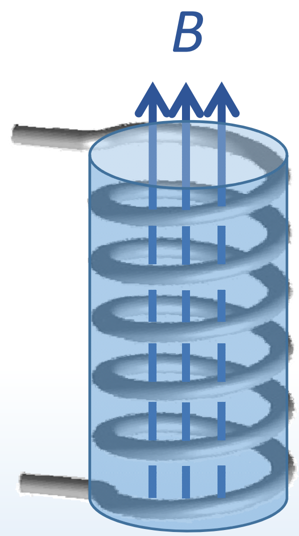
E & B field energy density

There is energy stored in an *E* & *B* field



Parallel plate capacitor

Recall Lect. 6



Solenoid

$$U_C = \frac{1}{2}CV^2 = \frac{1}{2}\frac{\varepsilon_0 A}{d}(Ed)^2 = \frac{1}{2}\varepsilon_0 E^2 Ad$$

Volume containing *E* field

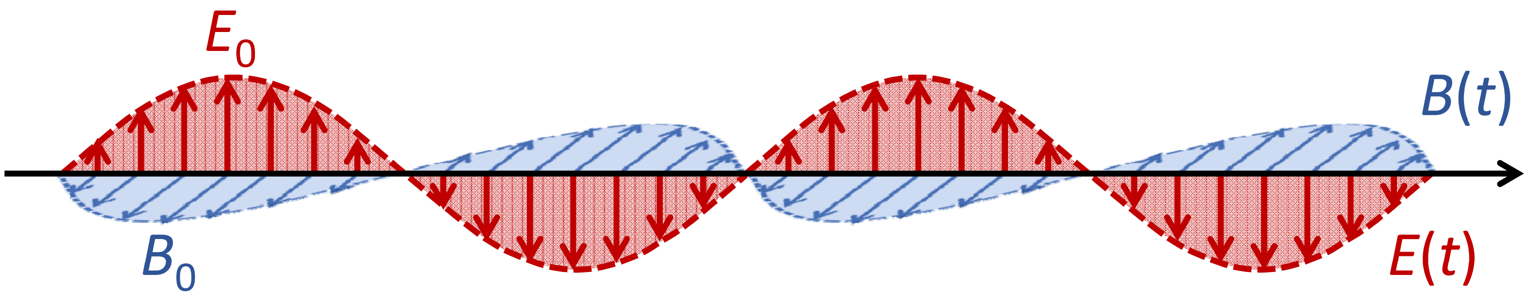
It is convenient to define *energy density* = energy per volume [J/m^3]

$$u_E = \frac{1}{2}\varepsilon_0 E^2 \qquad u_B = \frac{1}{2\mu_0}B^2$$

These expressions are correct for *any* *E* & *B* field in a vacuum

EM wave energy

There is energy stored in an EM wave in oscillating *E* & *B* fields



Since *E* and *B* oscillate, we measure the *average energy density*

$$\langle u_E \rangle = \frac{1}{2}\varepsilon_0 \langle E^2 \rangle = \frac{1}{2}\varepsilon_0 E_{rms}^2 \qquad E_{rms} = \frac{1}{\sqrt{2}} E_0$$

$$\langle u_B \rangle = \frac{1}{2\mu_0} \langle B^2 \rangle = \frac{1}{2\mu_0} B_{rms}^2 \qquad B_{rms} = \frac{1}{\sqrt{2}} B_0$$

E & *B* field amplitudes

$$\boxed{\langle u_{tot} \rangle = \frac{1}{2}\varepsilon_0 E_{rms}^2 + \frac{1}{2\mu_0} B_{rms}^2 = \varepsilon_0 E_{rms}^2 = \frac{B_{rms}^2}{\mu_0}}$$

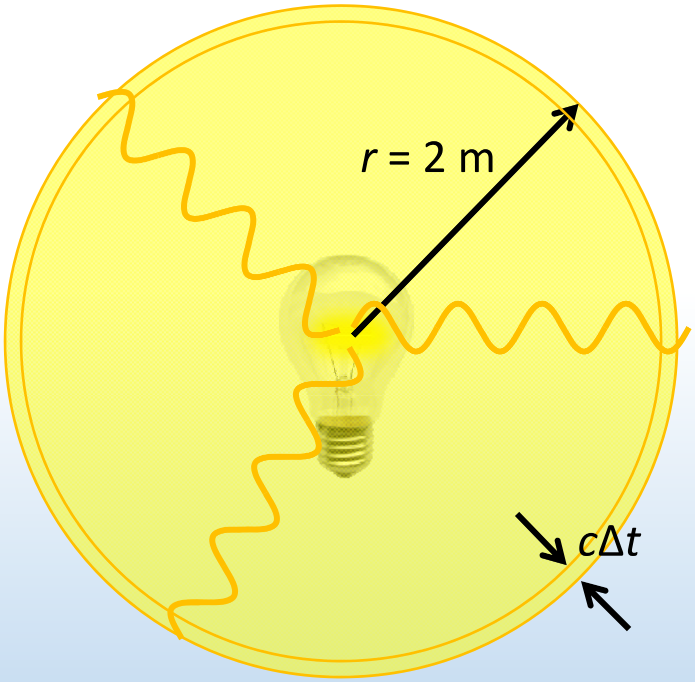
Recall that

$$E(t) = cB(t)$$

$$c = 1\big/\sqrt{\varepsilon_0 \mu_0}$$

Calculation: EM power

A light bulb emits an average 60 W of power. Calculate E_{rms} & B_{rms} at a distance r = 2 m from bulb. (Assume all electric power goes into EM wave)



By energy conservation, power emitted = power through spherical surface at r = 2 m

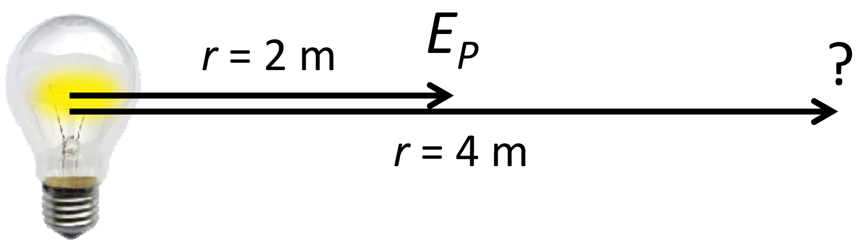
What is rate of EM energy flow through surface?

$$\langle P \rangle = \frac{\Delta \langle U \rangle}{\Delta t} = \frac{\langle u_{tot} \rangle 4\pi r^2 c\Delta t}{\Delta t}$$

$\langle u_{tot} \rangle = \varepsilon_0 E_{rms}^2$ so

ACT: EM wave E field

E_P is the rms E field at a distance r = 2m from the 60W light bulb.



What is the rms E field at a distance r = 4m?

A. $4E_P$

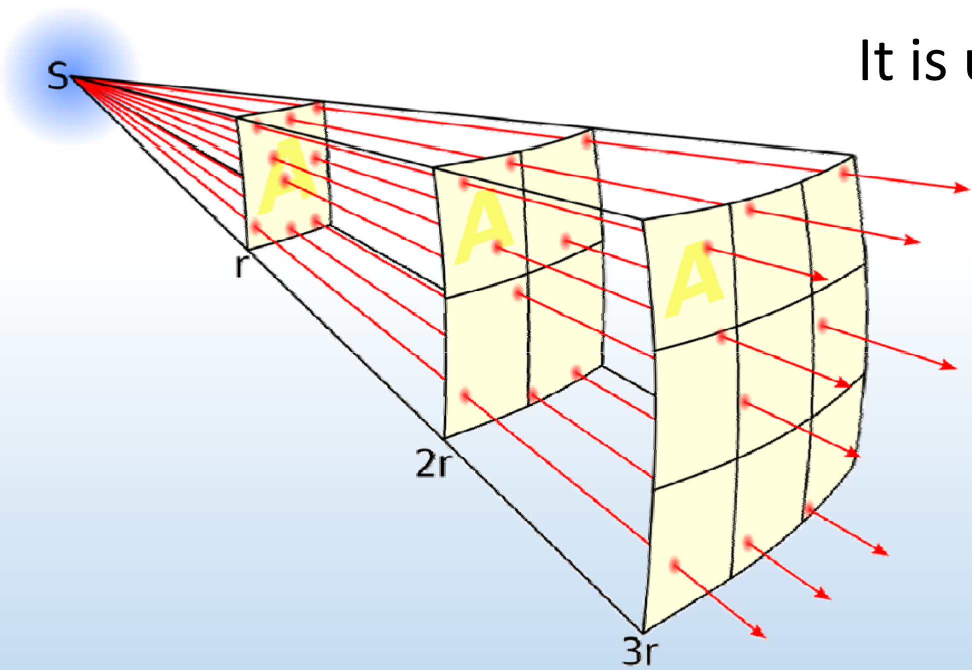
B. $2E_P$

C. $E_P/2$

D. $E_P/4$

EM wave intensity

The same power from point source of light flows through surfaces at larger distances, but spread over a larger surface area *A*.



It is useful to define intensity (*I* or *S*):

$$I = S \equiv \frac{\langle P \rangle}{A}$$ Units: W/m^2

Since $\langle P \rangle = \langle u_{tot} \rangle Ac$

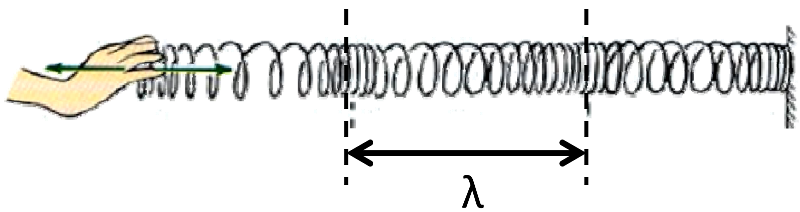
$$\boxed{I = S = \langle u_{tot} \rangle c}$$

Intensity corresponds to "brightness" of light (light is dimmer the further from a point source)

I decreases as 1/r^2

CheckPoint 1.1–1.7

Longitudinal waves: oscillations are || to direction or propagation



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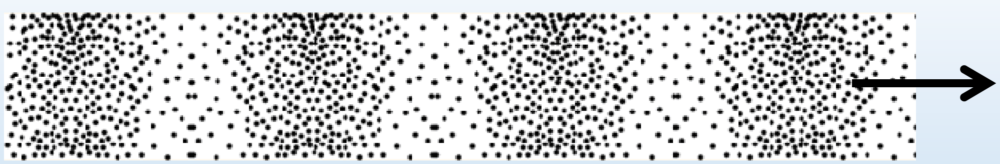
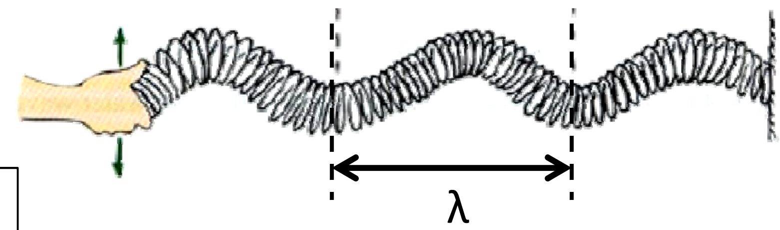
Ex: Sound



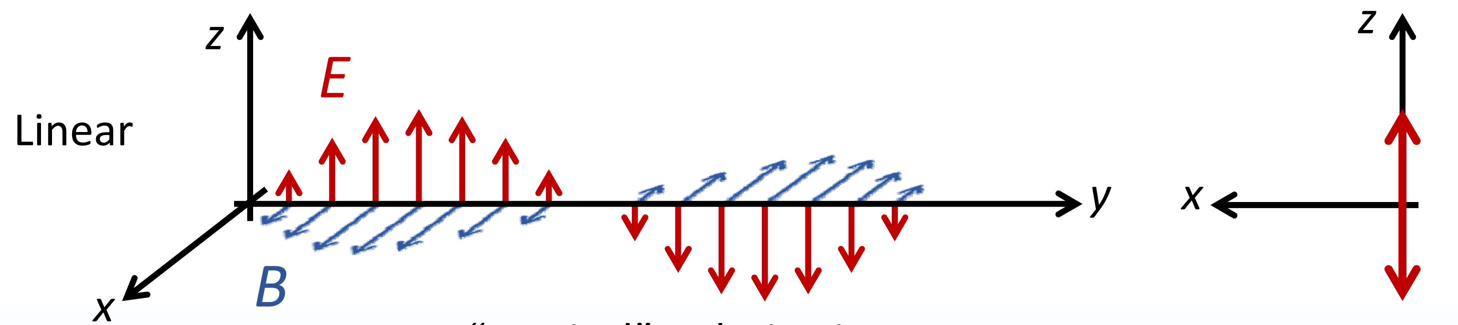
Transverse waves: oscillations are ⊥ to direction of propagation



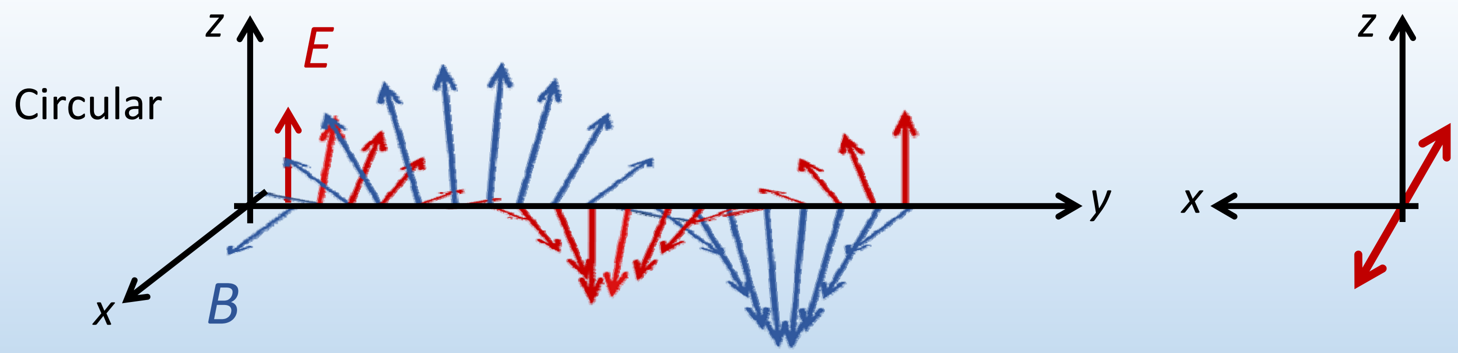
Ex: Light
Radio waves
X-rays
Microwaves
Water waves
"The wave"

Polarization

EM waves are transverse and have *polarization* – by convention, the direction of the *E* field oscillation



Ex: "Vertical" polarization



Ex: "Left" circular polarization

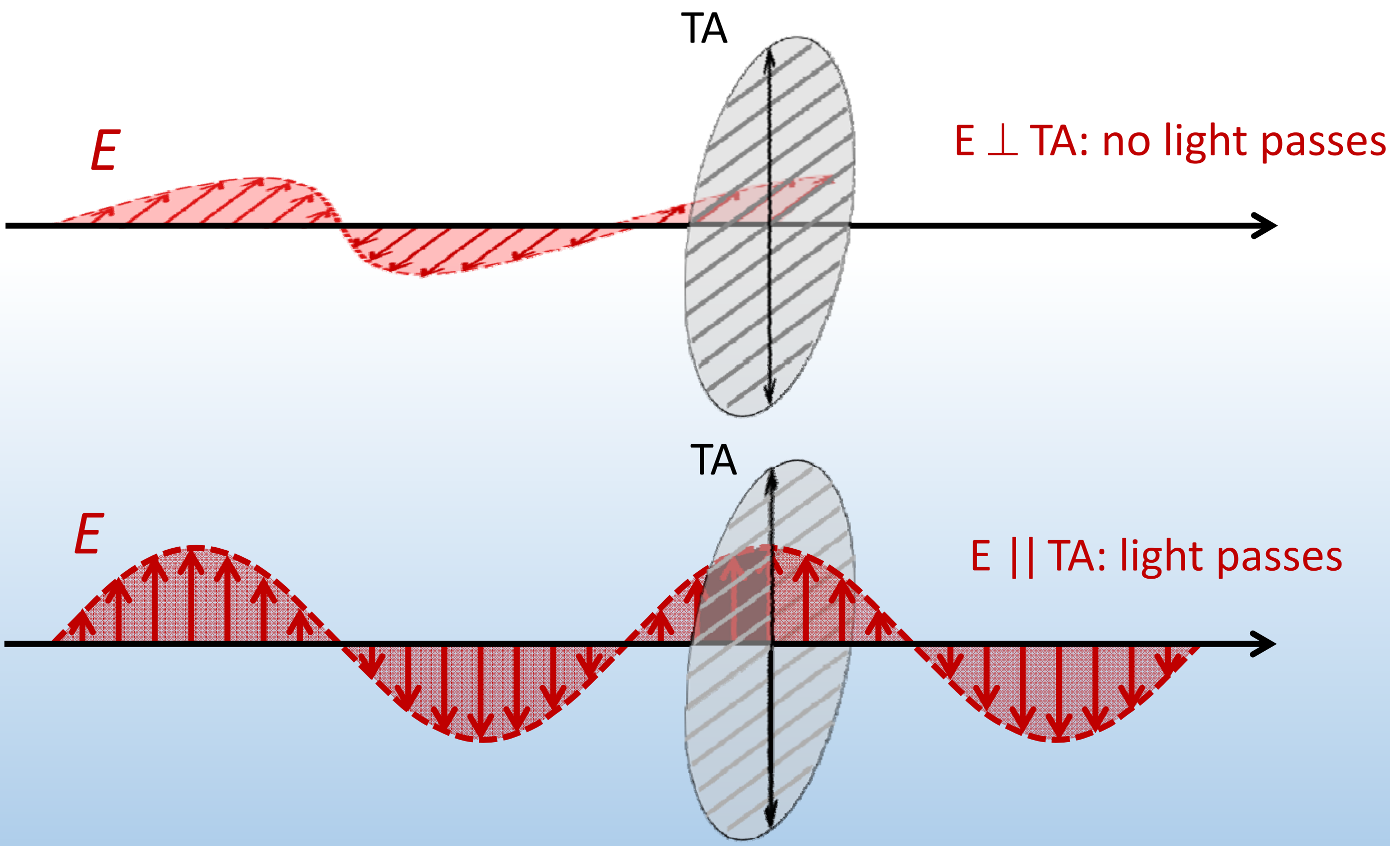
Unpolarized – direction is *random*

For convenience we will stop showing the *B* field

Linear polarizers

Linear polarizers consist of || metal lines that absorb || *E* field.

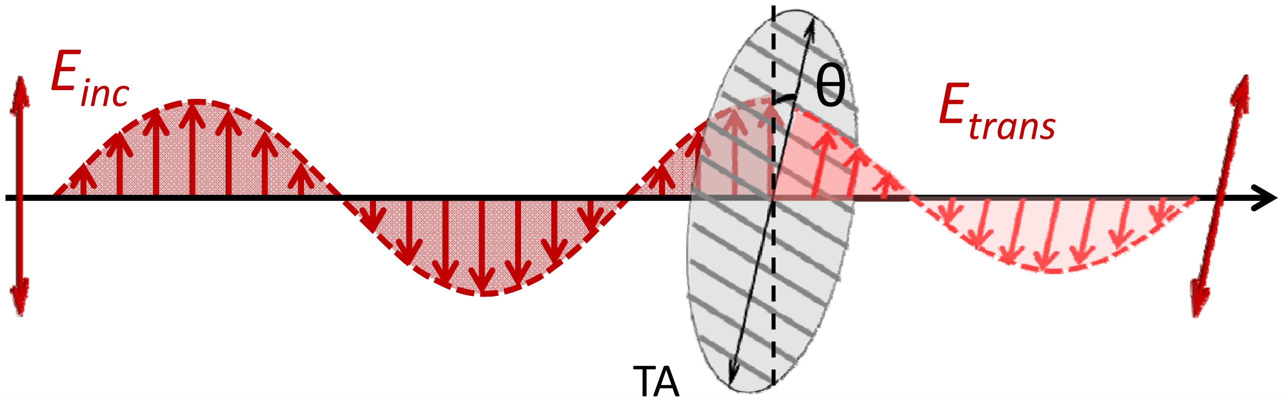
Transmission axis (TA) is defined in direction that *E* field passes

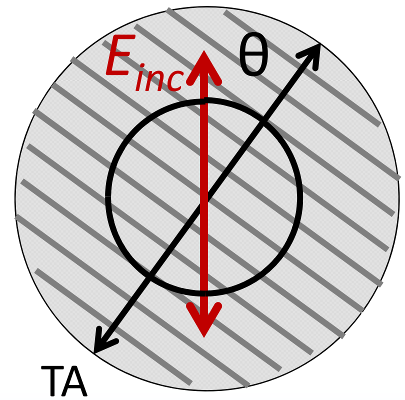


What happens for other angles between polarization and TA?

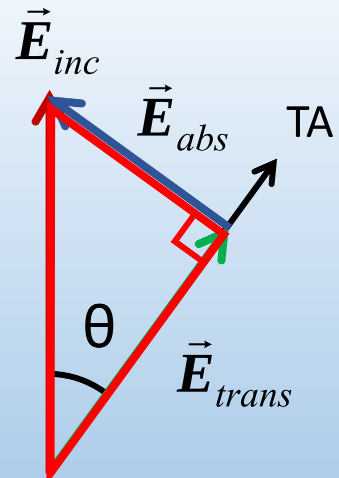
Law of Malus

Given angle θ between TA and polarization of incident EM wave:





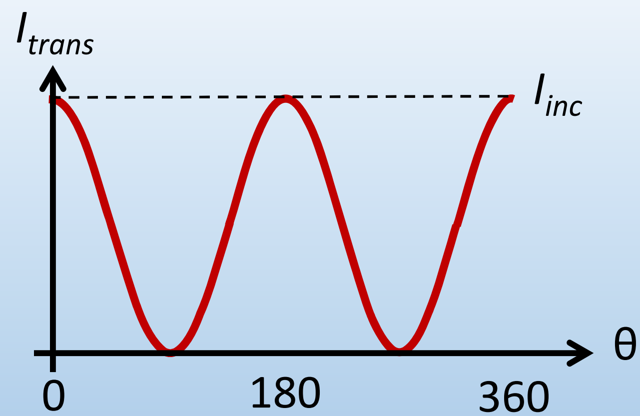
Component of E field $\perp$ to TA axis is absorbed:



$$\left|\vec{E}_{trans}\right| = \left|\vec{E}_{inc}\right| \cos\theta$$

Since $I = \langle u_{tot} \rangle c \propto E^2$

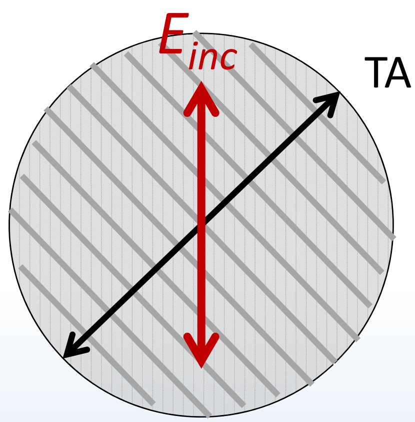
$$\boxed{I_{trans} = I_{inc} \cos^2 \theta}$$



Light emerges with polarization || to TA axis

ACT: polarizer

A vertically polarized EM wave passes through a linear polarizer with TA at 45°



What is the direction of the *B* field after the polarizer?

A. 

B. 

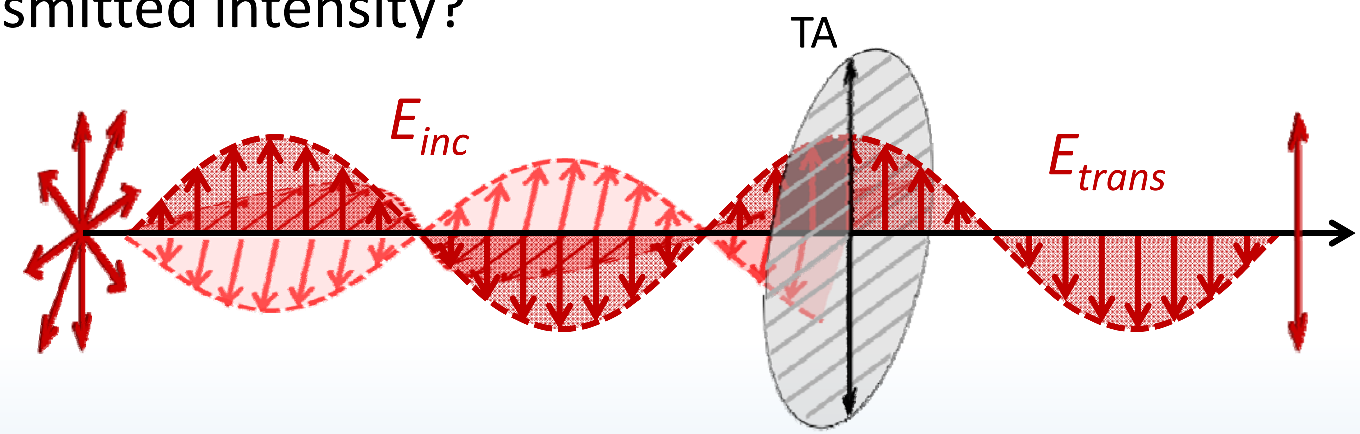
C. 

D. 

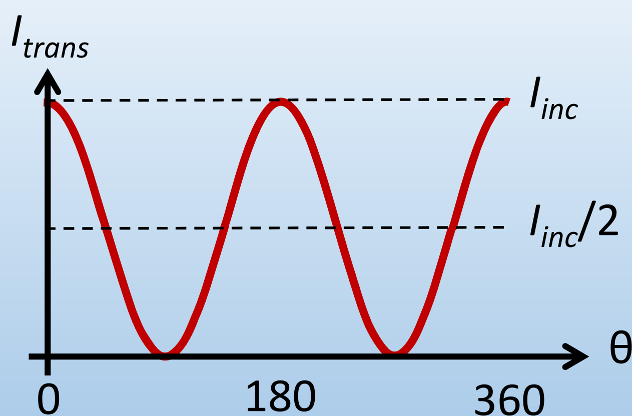
What is the magnitude?

Calculation: unpolarized light

Unpolarized light is incident on a linear polarizer. What is the transmitted intensity?



Unpolarized light has an equal mixture of all possible θ's



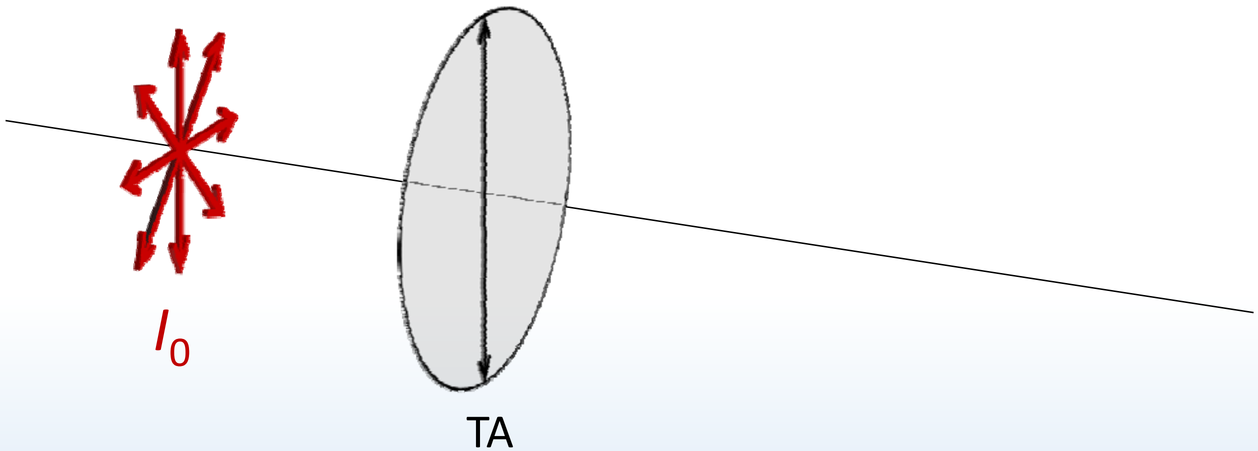
$I_{trans} = I_{inc} \cos^2 \theta$ average over all θ:

$$\boxed{I_{trans} = \frac{1}{2} I_{inc}}$$

Light emerges with polarization || to TA axis

ACT: CheckPoint 2.1

Unpolarized light passes through a linear polarizer with a vertical TA.

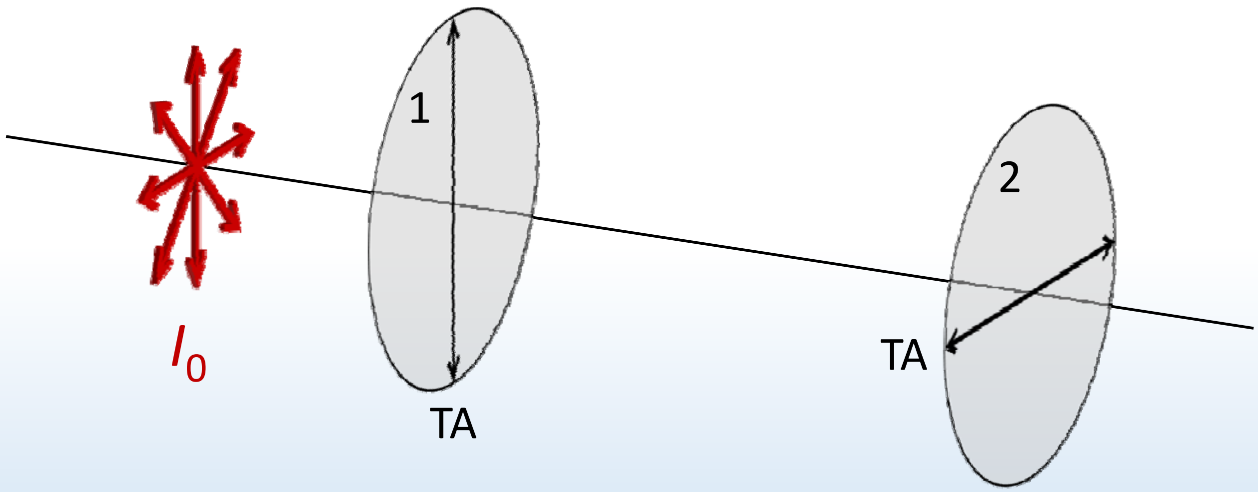


What is the intensity of light when it emerges?

A. zero
B. 1/2 what it was before
C. 1/4 what it was before
D. 1/3 what it was before

ACT: CheckPoint 2.2

Now the light that emerged from the previous polarizer passes through a second linear polarizer with a horizontal TA.



What is the intensity of light when it emerges?

A. zero

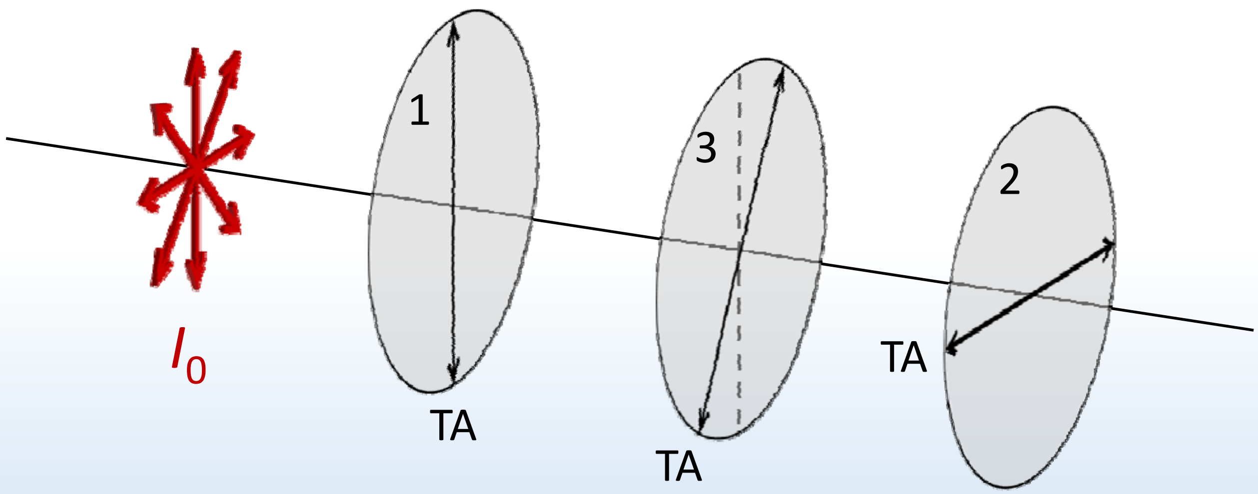
B. 1/2 what it was before

C. 1/4 what it was before

D. 1/3 what it was before

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?

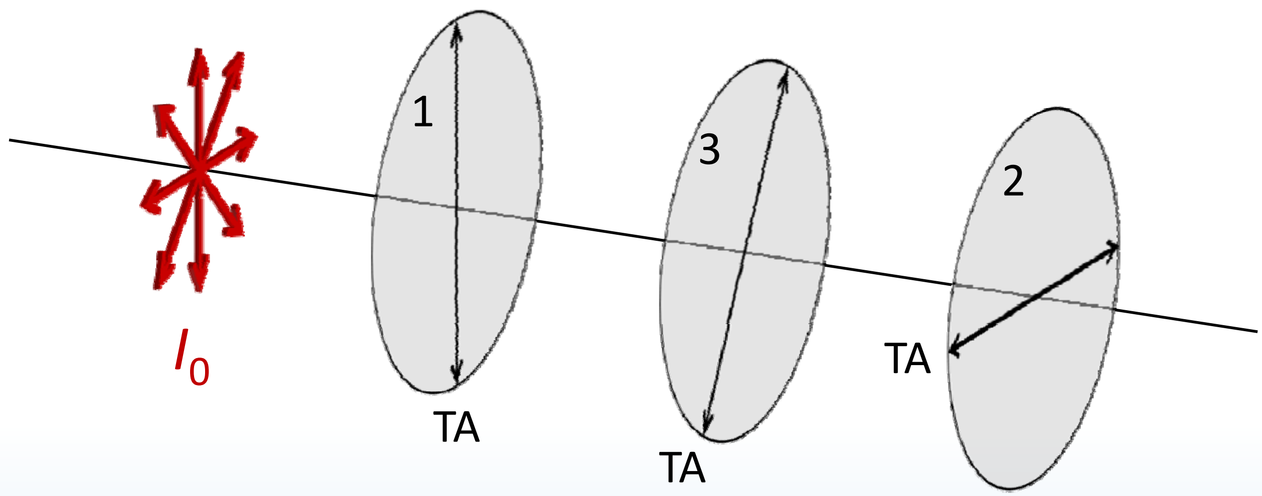
DEMO

A. zero, same as before

B. more than what it was before

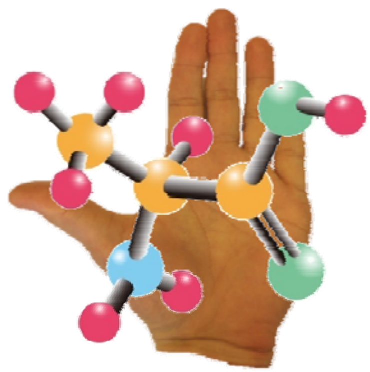
C. need more information

Calculation: 3 polarizers



Chirality & optical activity

Many organic molecules are *chiral* – they have “handedness”

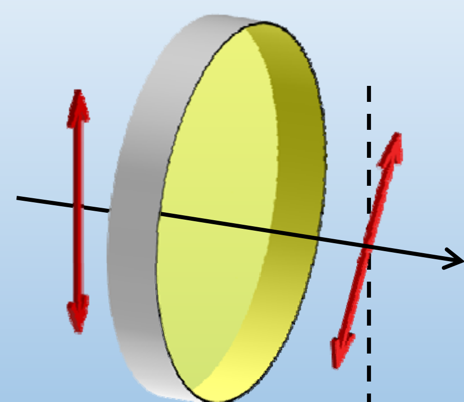


L-alanine

D-alanine (unnatural enantiometer)

Chiral molecules rotate linearly polarized light – *optical activity*

DEMO



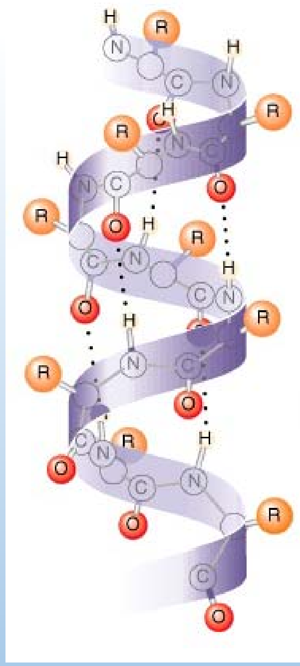
“Dextrorotary” CW rotation
“Levorotary” CCW rotation

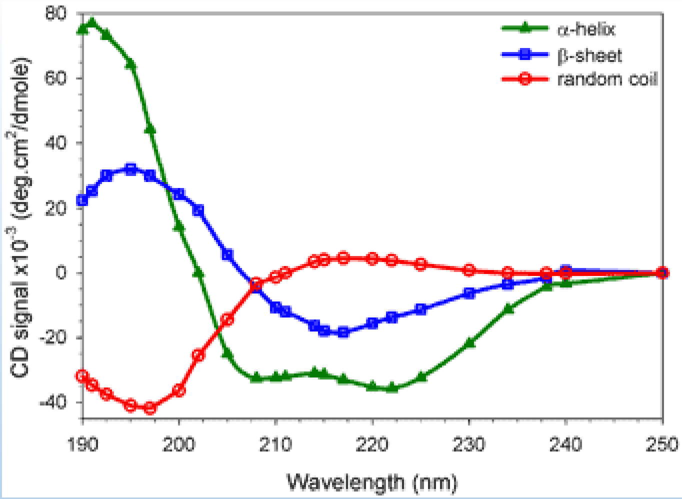
Circular dichroism

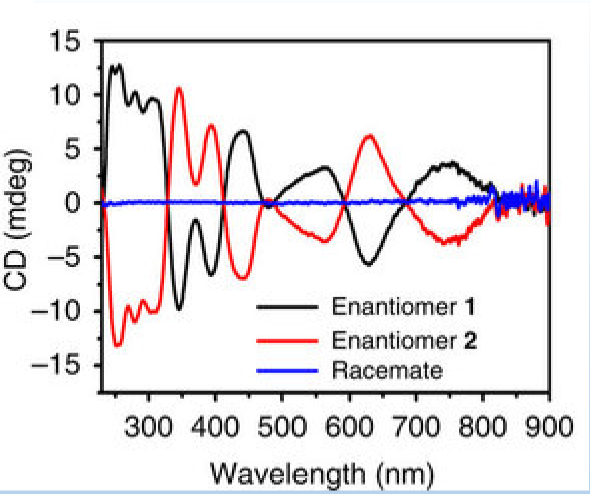
Chiral molecules also absorb left vs. right circularly polarized light differently

Circular dichroism (CD) measures difference in absorption

Tool to distinguish chiral features in biomolecules





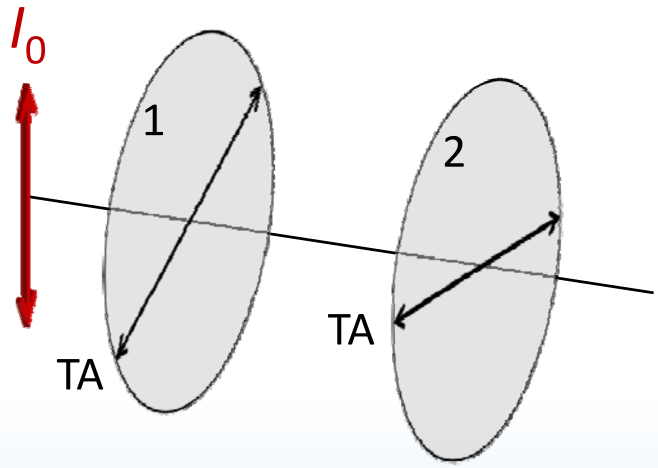


CD spectra

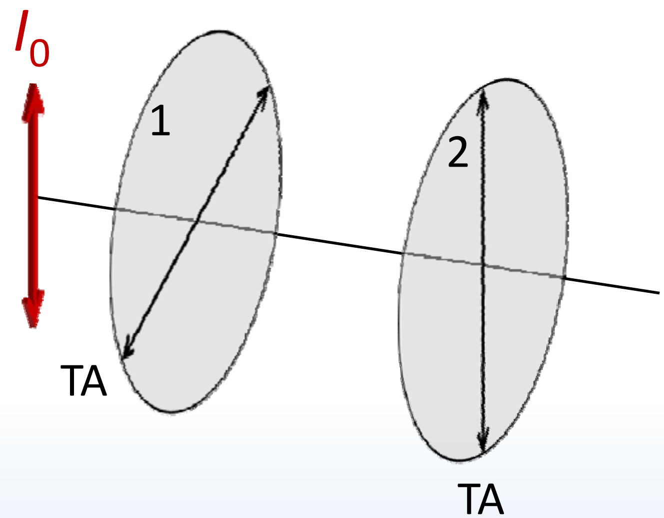
α-helix (right-handed helix)

ACT: Law of Malus

A



B



Compare the light emerging from the two polarizers in A and B:

A. $I_2^A > I_2^B$

B. $I_2^A = I_2^B$

C. $I_2^A < I_2^B$

Summary of today's lecture

- Electromagnetic waves
  - Carry energy in E and B fields – energy density & intensity
  - Are transverse & polarized – linear, circular, unpolarized
- Applications
  - Linear polarizers – Law of Malus
  - Optical activity
  - Circular dichroism