# Phys 102 – Lecture 16

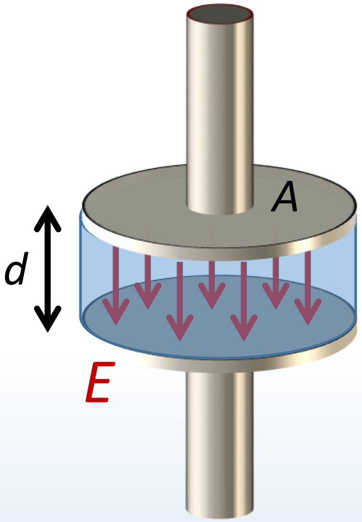
**Electromagnetic wave energy & polarization**

# *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

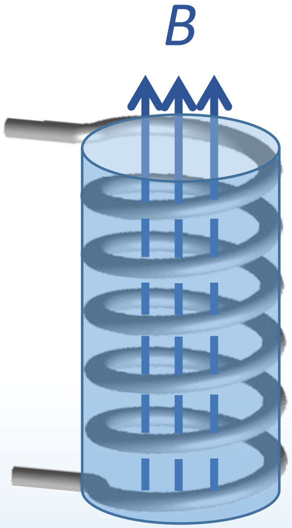
# *E* & *B* field energy density

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



Parallel plate capacitor

Recall Lect. 6



Solenoid

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

← Volume containing *E* field

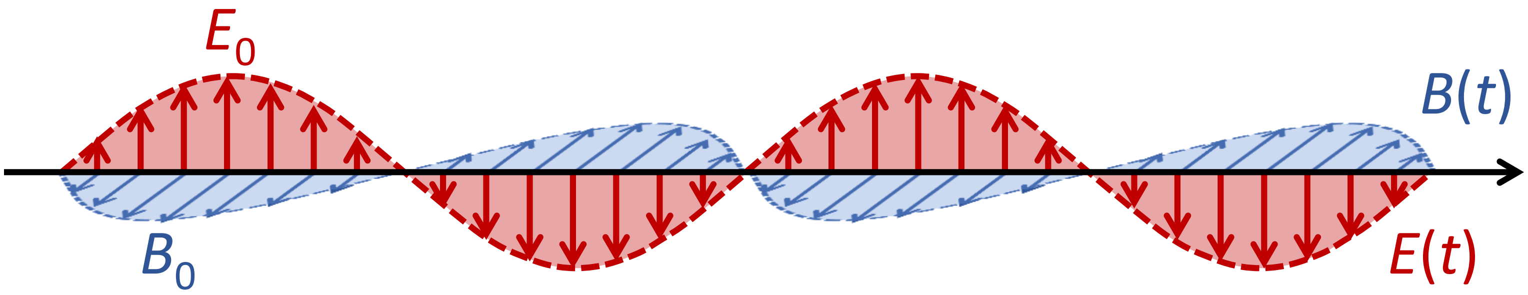
It is convenient to define *energy density* = energy per volume [$J/m^3$]

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

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*

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

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

*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

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

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

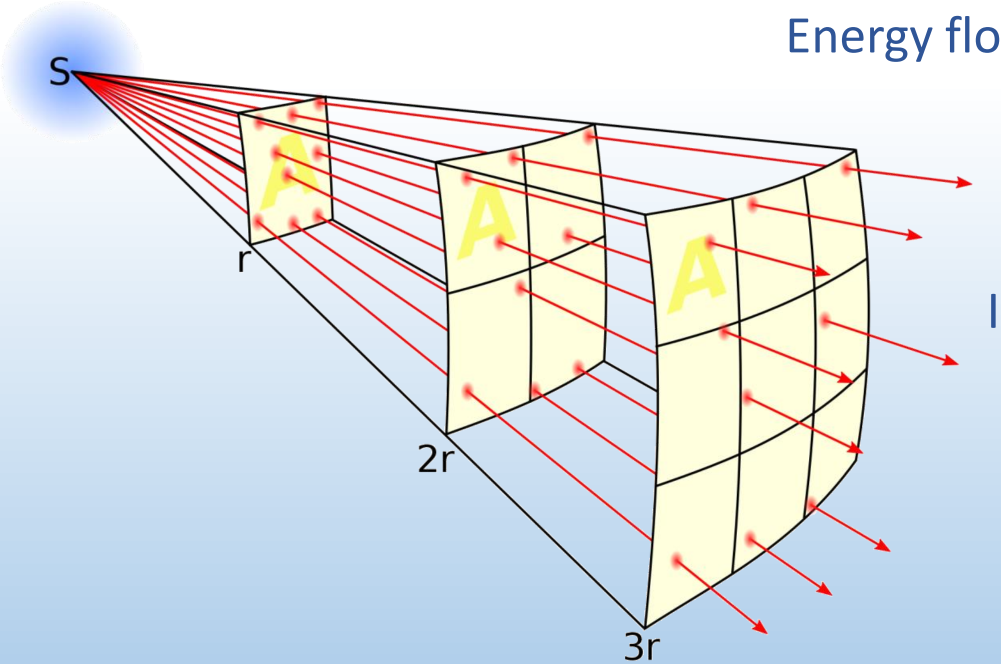
# EM wave intensity

A source of light emits EM energy at a rate given by the power *P*:

$$\langle P\rangle = \frac{\Delta\langle U\rangle}{\Delta t}$$

Units: W

Same energy flows through surfaces at larger distances, but spread over a larger surface area *A*.



Energy flowing through surface in time Δ*t*:

$$\Delta\langle U\rangle = \langle u_{tot}\rangle Ac\Delta t$$

It is useful to define *intensity*:

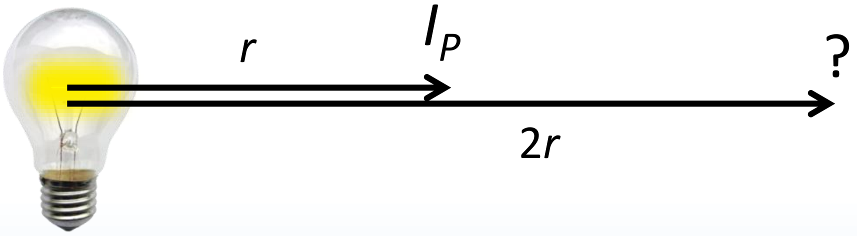
$$\boxed{I = S \equiv \frac{\langle P\rangle}{A} = \langle u_{tot}\rangle c}$$

Units: W/m$^2$

Intensity corresponds to "brightness" of light

# ACT: EM wave intensity

$I_P$ is the light intensity at a point *P* a distance *r* from a point source, a 60 W light bulb. (Assume all electric power goes into EM wave)

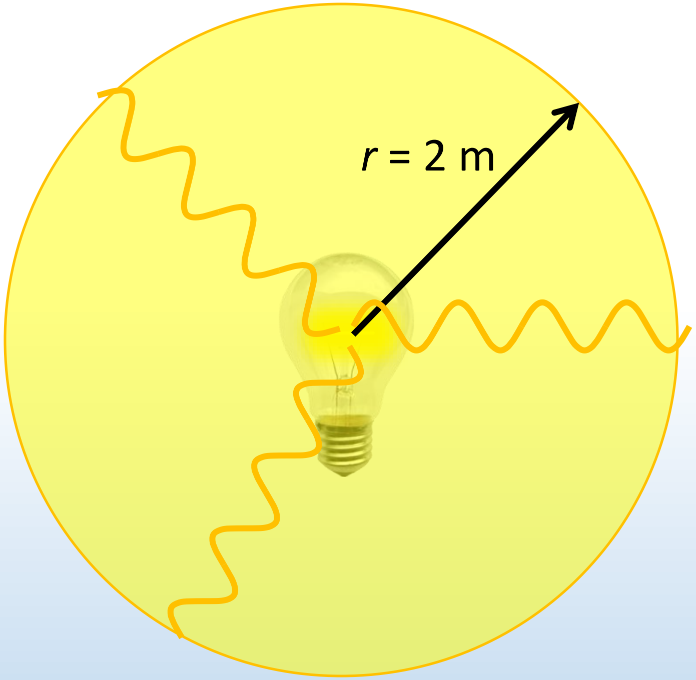


What is the light intensity at a distance 2*r*?

A. $2I_P$
B. $I_P$
C. $I_P/2$
D. $I_P/4$

# 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)



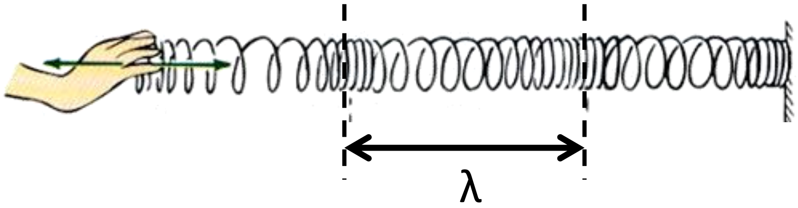
By energy conservation, power emitted = power through spherical surface at $r$ = 2 m

$$\langle P \rangle = IA = \langle u_{tot} \rangle c\, 4\pi r^2$$

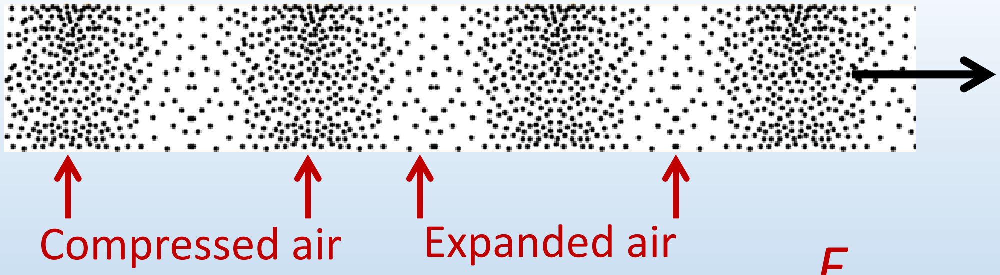
$$\langle u_{tot} \rangle = \varepsilon_0 E_{rms}^2$$

# CheckPoint 1.1–1.7

*Longitudinal* waves: oscillations are || to direction or propagation



Ex: Sound



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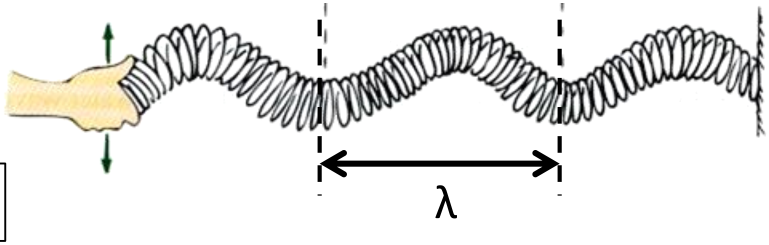
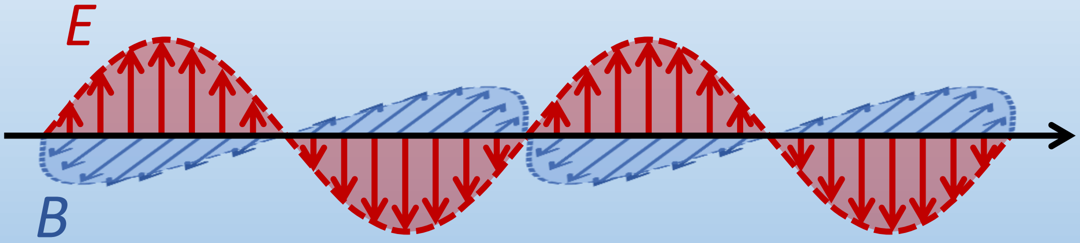
*Transverse* waves: oscillations are ⊥ to direction of propagation



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

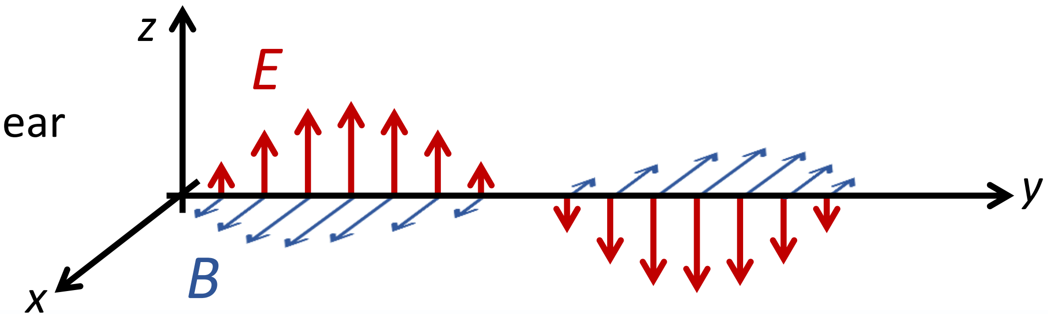
All EM waves!



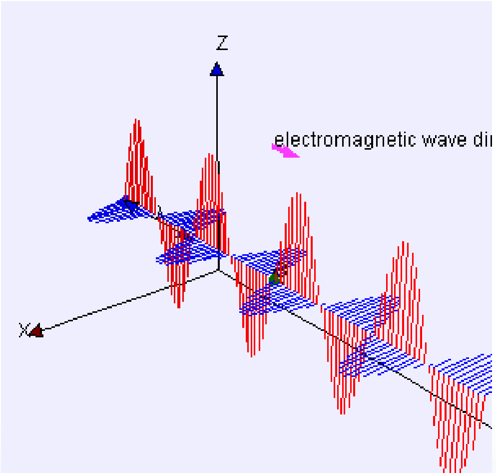
# *Polarization*

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

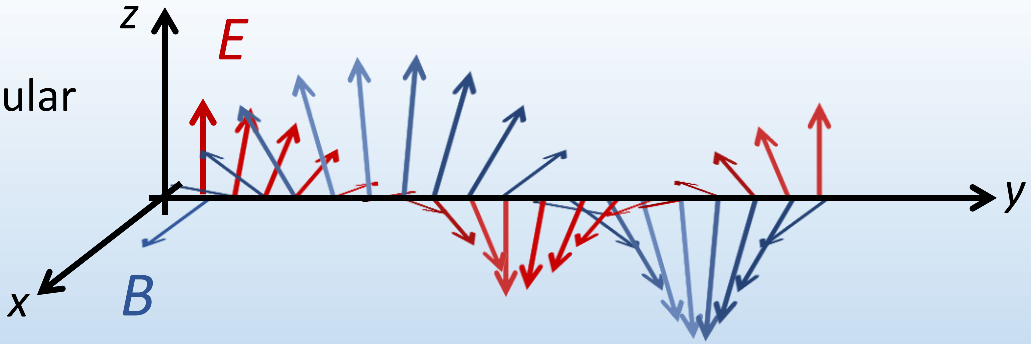
Linear



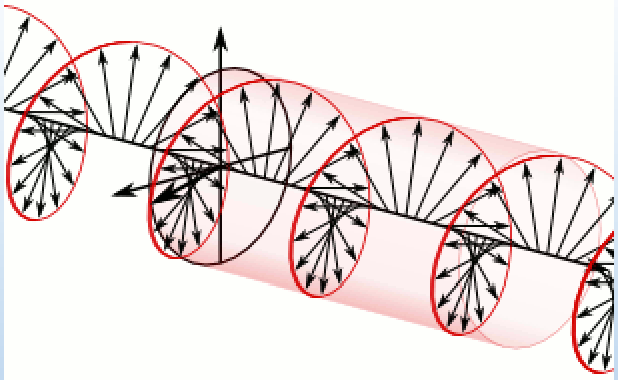
Ex: “Vertical” polarization



Circular



Ex: “Left” circular polarization



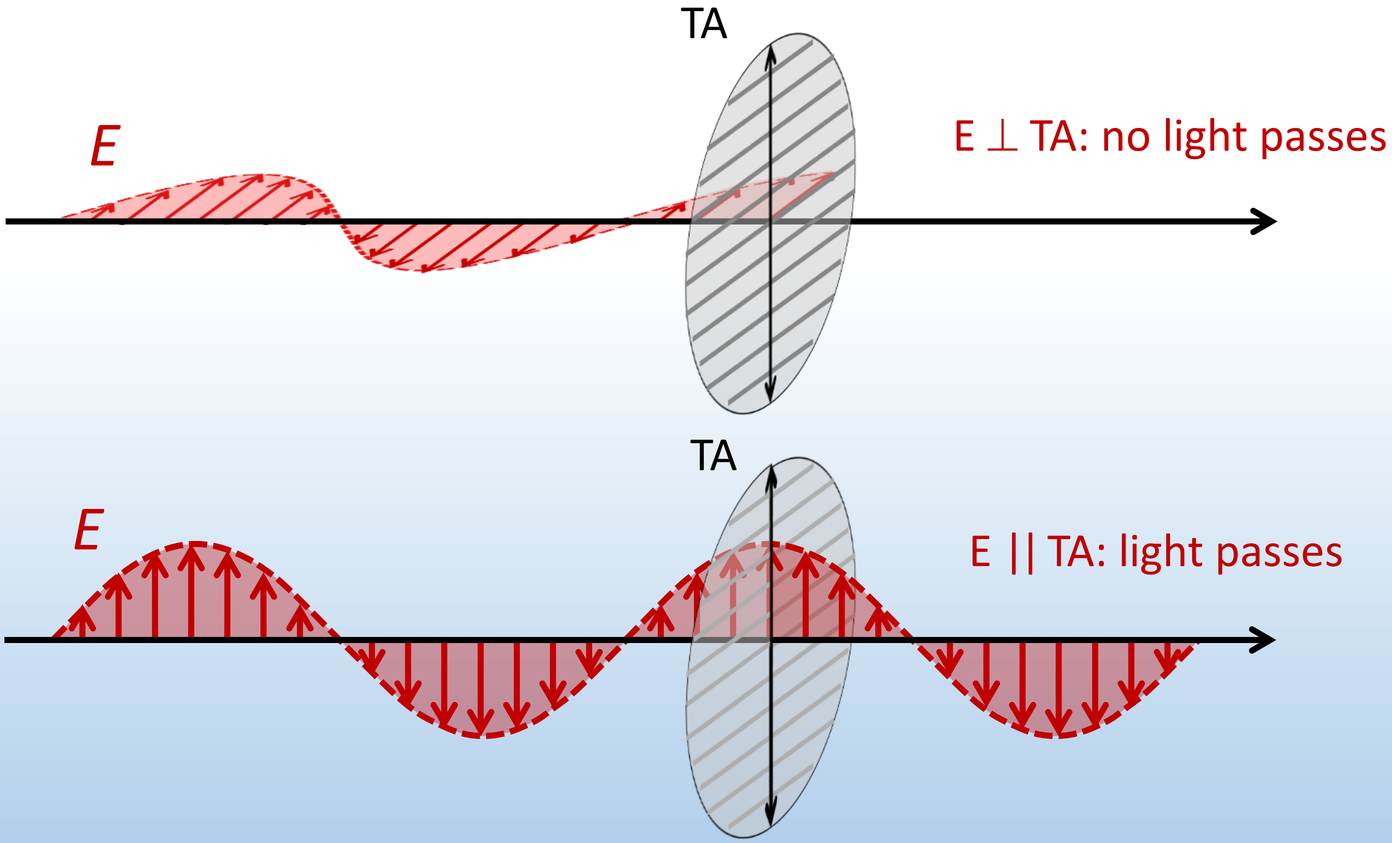
Unpolarized – direction is *random*

For convenience we will stop showing the *B* field

# *Linear polarizers*

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

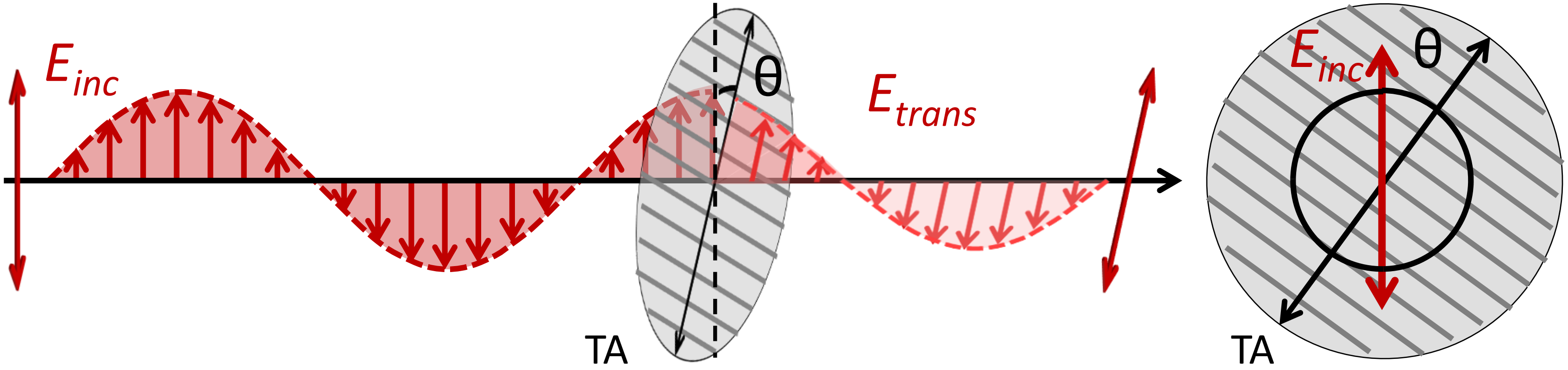
*Transmission axis* (TA) is defined in direction that *E* field passes



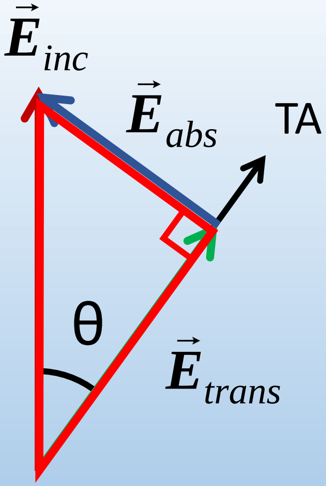
What happens for other angles between polarization and TA?

# *Law of Malus*

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



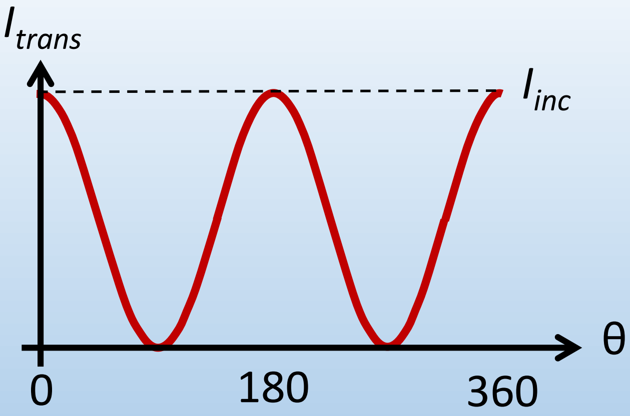
Component of *E* field ⊥ to TA axis is absorbed:



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

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

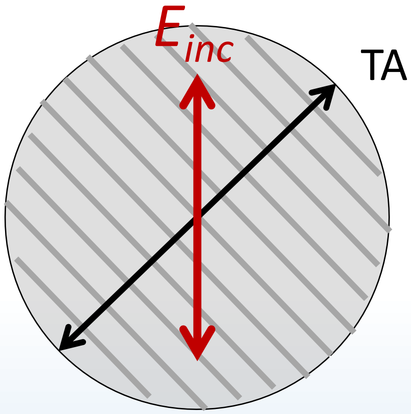
$$\boxed{I_{trans} = I_{inc} \cos^2\theta}$$



Light emerges with polarization || to TA axis

# ACT: polarizer

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

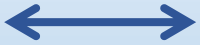


What is the direction of the *B* field after the polarizer?

A. 

B. 

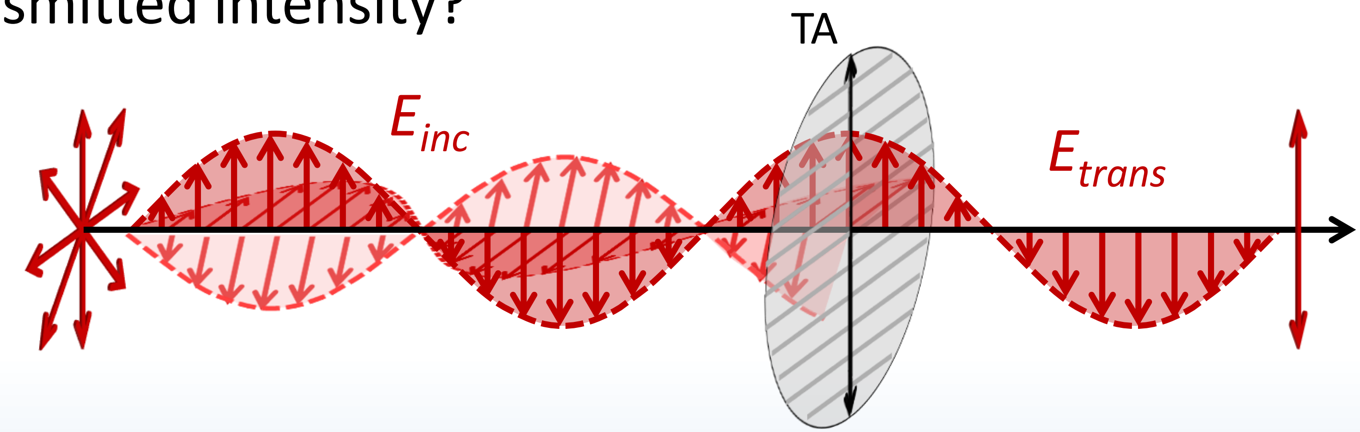
C. 

D. 

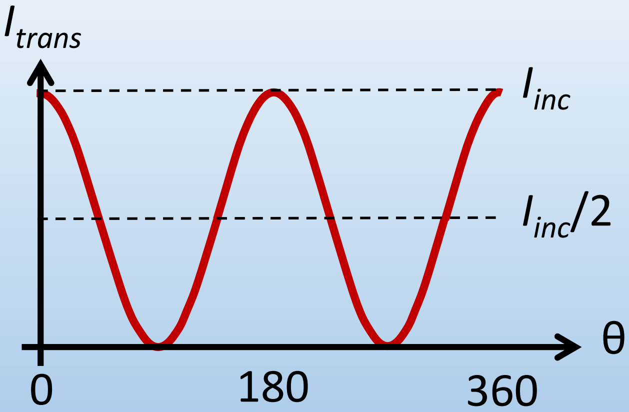
What is the magnitude?

# 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



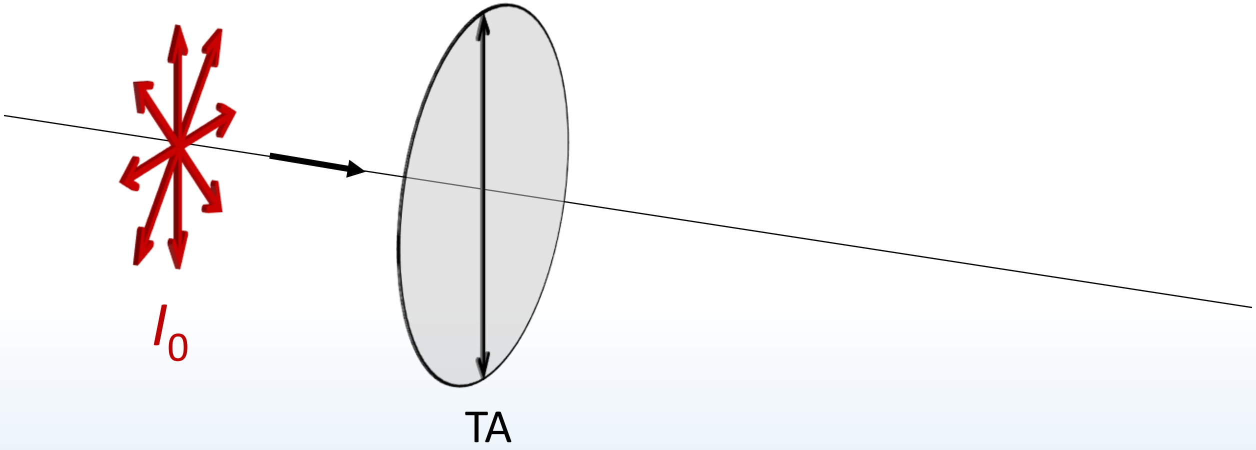
$I_{trans} = I_{inc} \cos^2 \theta$ average over all θ:

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

Light emerges with polarization || to TA axis

# ACT: CheckPoint 2.1

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

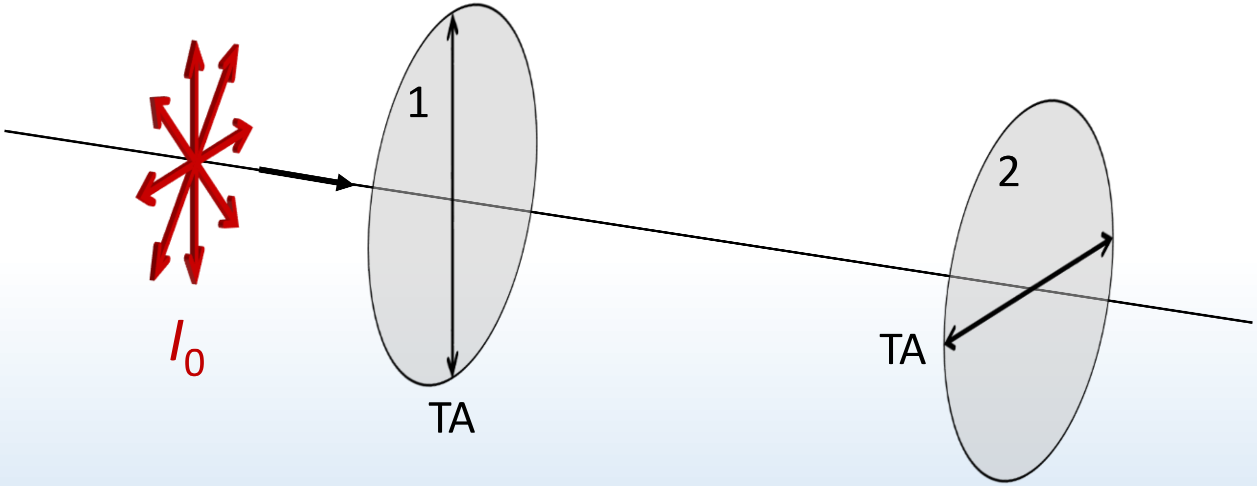


What is the intensity of light when it emerges?

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.

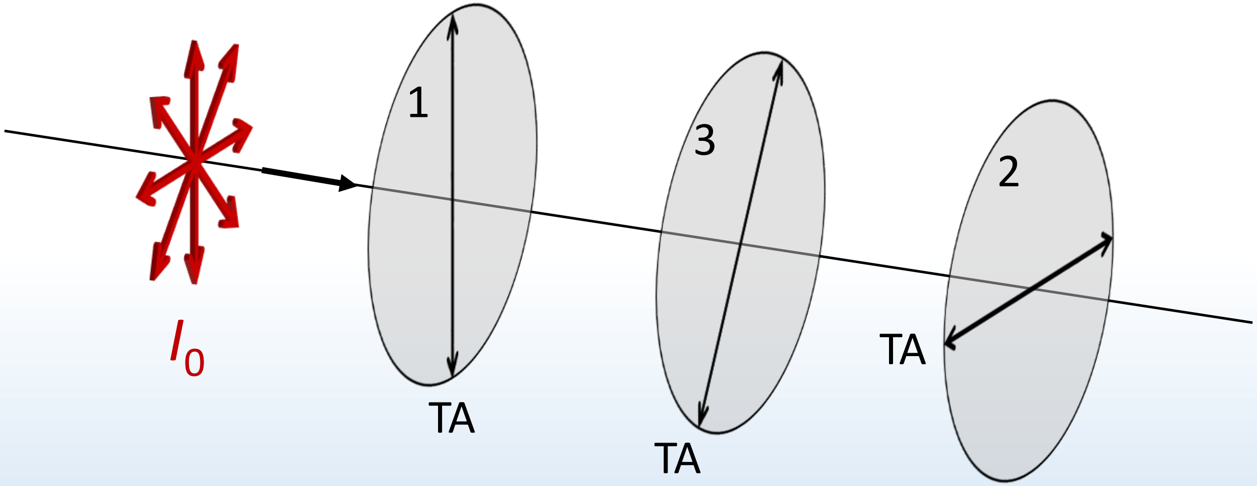


What is the intensity of light when it emerges?

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?

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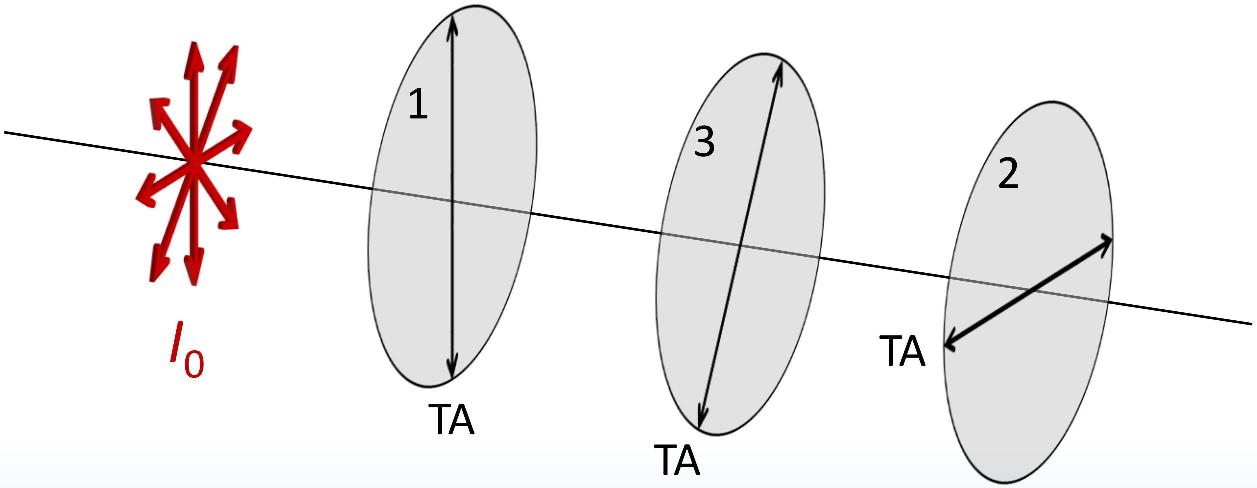
A. zero, same as before

B. more than what it was before

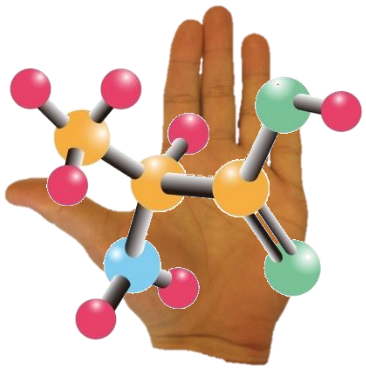
C. need more information

# Calculation: 3 polarizers



# *Chirality & optical activity*

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

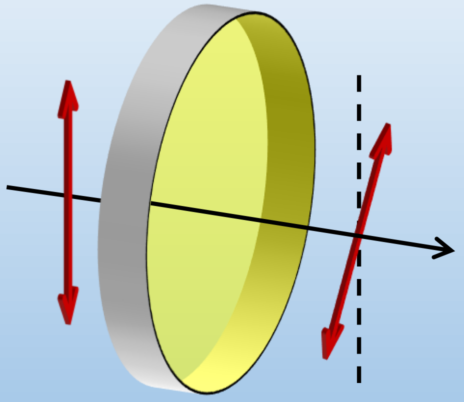


L-alanine

D-alanine (unnatural enantiometer)

Chiral molecules rotate linearly polarized light – *optical activity*

DEMO



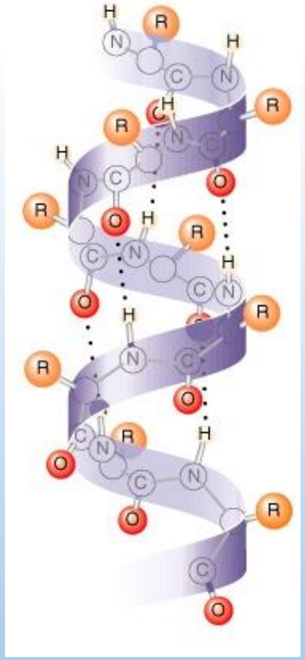
“Dextrorotary” CW rotation
“Levorotary” CCW rotation

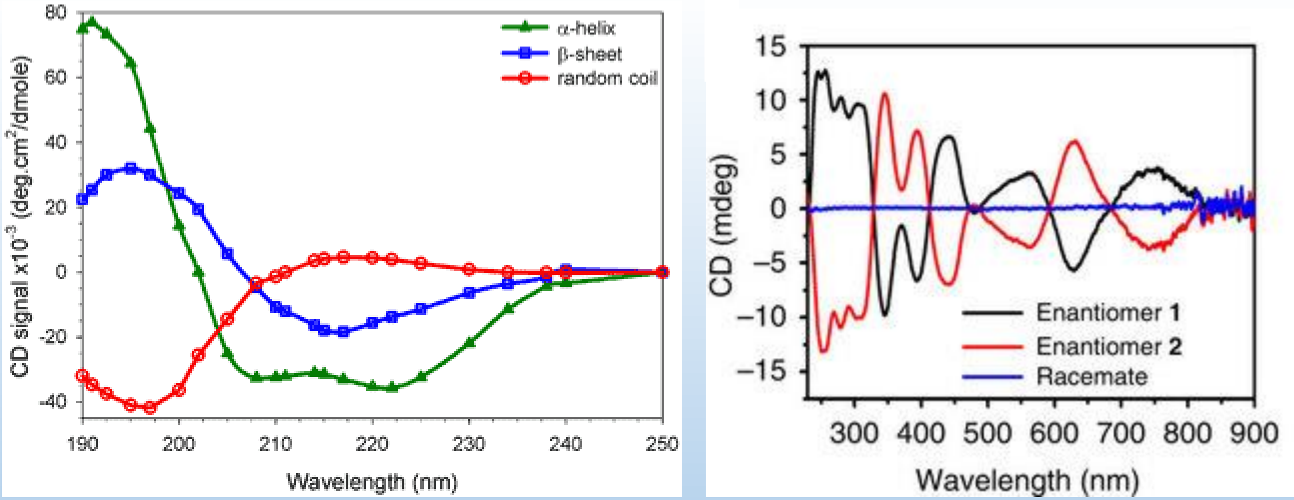
# Circular dichroism

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

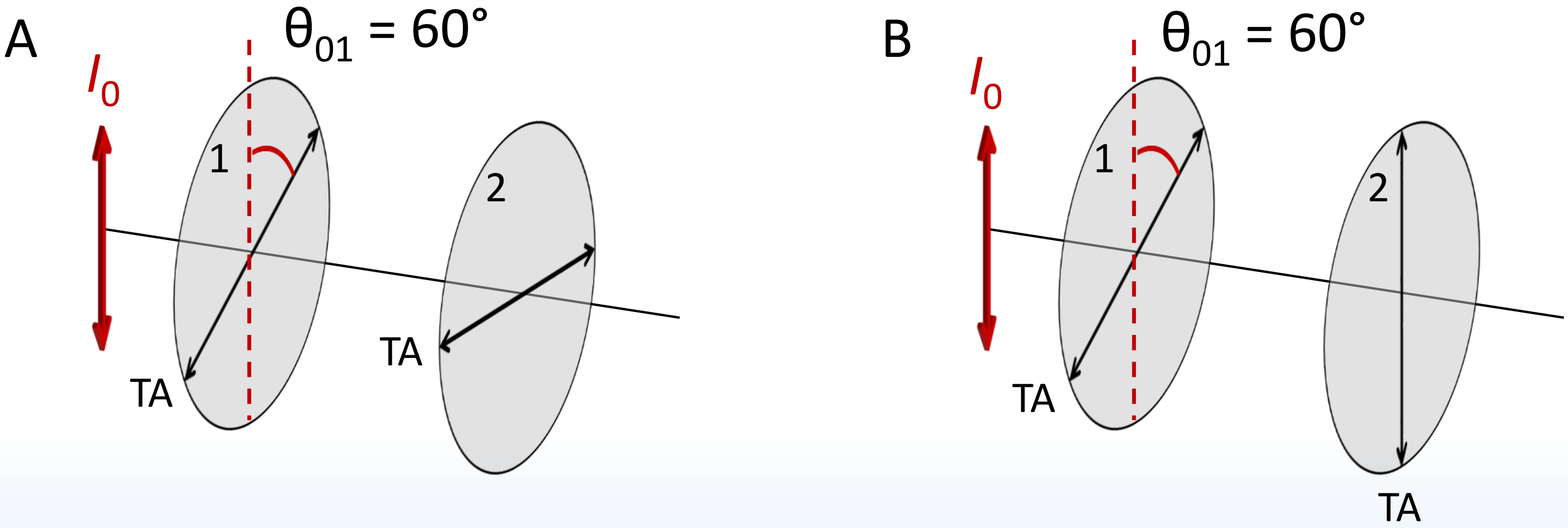




CD spectra

α-helix (right-handed helix)

# ACT: Law of Malus



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