# *Your questions/comments*

**IMPORTANT ANNOUNCEMENT**:
James Scholar proposals due today, Oct. 20 by email!
Review session Tues. Oct. 21 from 6-8pm (180 Bevier) -> see website

“is it just me or am i more focused on trying to study for exam 2 material? so this mondays prelecture flew by me.”

“I'm really confused with polarization. It's hard to visualize/understand the different types of polarization: linear, circular and random.”

“Please discuss polarization and linear polarizers (and series of linear polarizers) (and how Intensity of light is affected).”

“This was A LOT of information to process. This was quite confusing and there seemed to be SO many concepts that weren't very related to anything we've done before.”

“I am confused about the different waves. Please explain the differences.”

# Phys 102 – Lecture 16

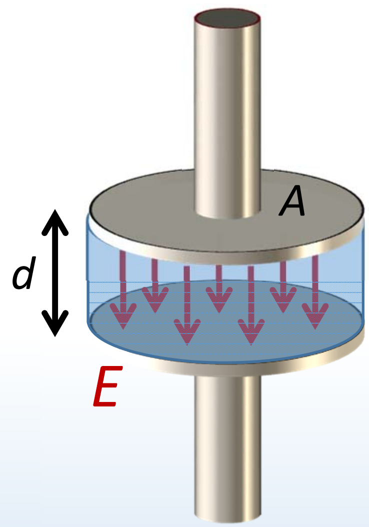
**Electromagnetic wave energy & polarization**

# *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

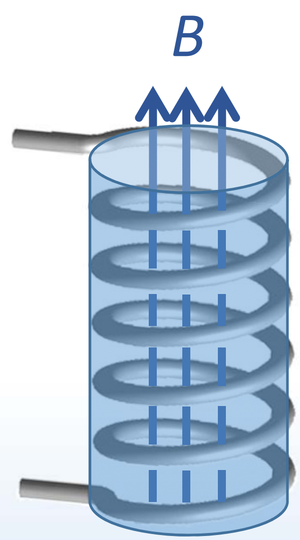
# *E & B field energy density*

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




Parallel plate capacitor

Recall Lect. 6




Solenoid

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

Volume containing *E* field

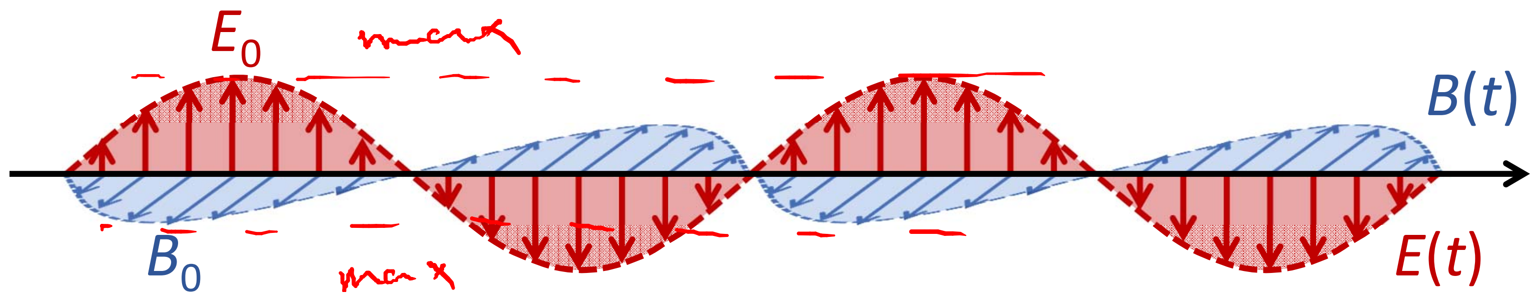
It is convenient to define *energy density* = energy per volume [$J/m^3$]

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

These expressions are correct for <u>*any*</u> *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*

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

E & B field amplitudes

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

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

Equal

Recall that

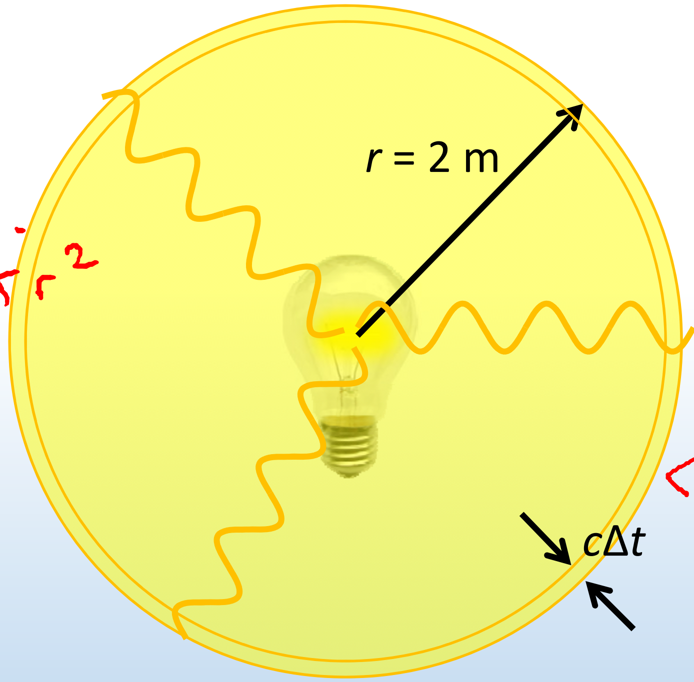
$$E(t) = cB(t)$$
$$c = 1\Big/\sqrt{\varepsilon_0\mu_0}$$

True for EM waves

# *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)

S.A. $4\pi r^2$




$\langle P \rangle = \langle u_{tot} \rangle A c$

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

What is rate of EM energy flow through surface?

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

EM energy density

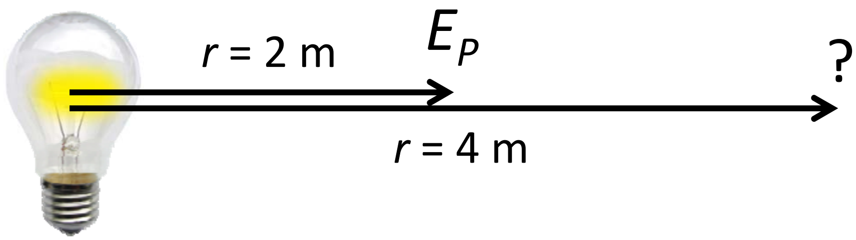
Volume of EM energy flowing into surface in time $\Delta t$

$$\langle u_{tot} \rangle = \varepsilon_0 E_{rms}^2 \quad \text{so} \quad E_{rms} = \sqrt{\frac{\langle P \rangle}{4\pi r^2 \varepsilon_0 c}} = \sqrt{\frac{60}{4\pi \cdot 8.85\times 10^{-12} \cdot 2^2 \cdot 3\times 10^8}} = 21.2\ \text{V/m}$$

$$B_{rms} = \frac{E_{rms}}{c} = \frac{21.2}{3\times 10^8} = 7.1\times 10^{-8}\ \text{T}$$

# 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. $E_P/2$

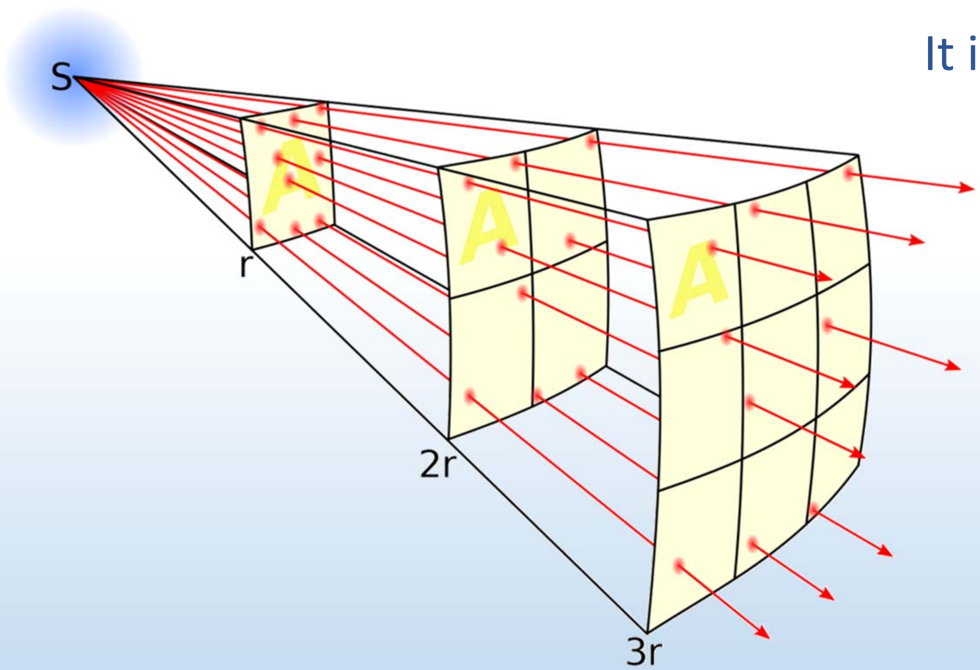
D. $E_P/4$

$$E_{rms} = \sqrt{\frac{\langle P \rangle}{4\pi r^2 \varepsilon_0 c}} \propto \frac{1}{r}$$

$$\langle u_{tot} \rangle \propto E_{rms}^2 \propto 1/r^2$$

# *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 $\langle P \rangle = \langle u_{tot} \rangle Ac$

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

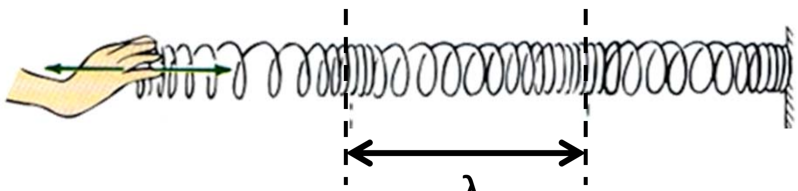
$\propto E_{rms}^2$

$\propto B_{rms}^2$

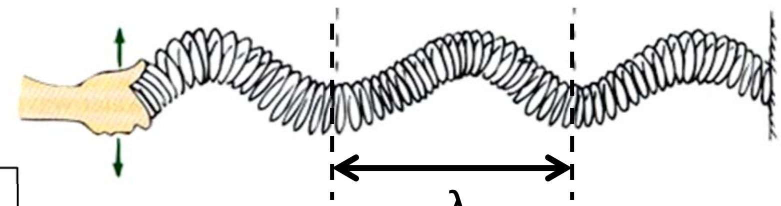
Intensity corresponds to "brightness" of light (light is dimmer the further from a point source)

# *CheckPoint* 1.1–1.7

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

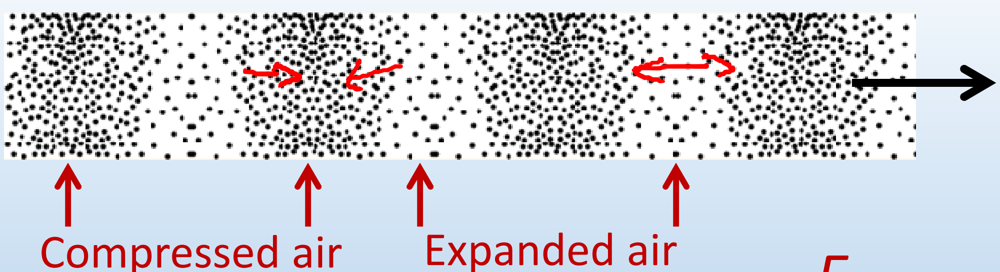



*Transverse* waves: oscillations are ⊥ to direction of propagation



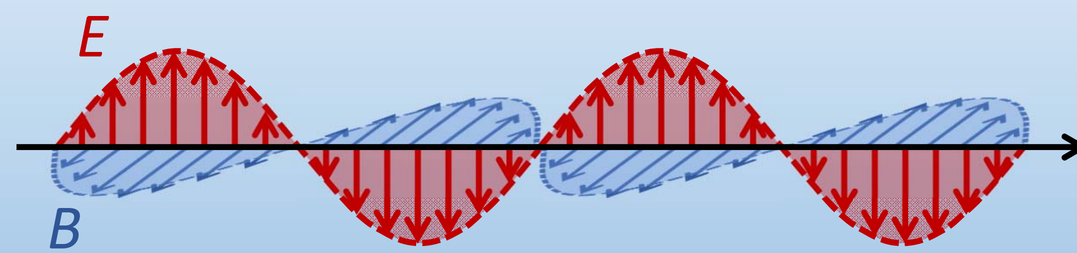

DEMO

Ex: Sound




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

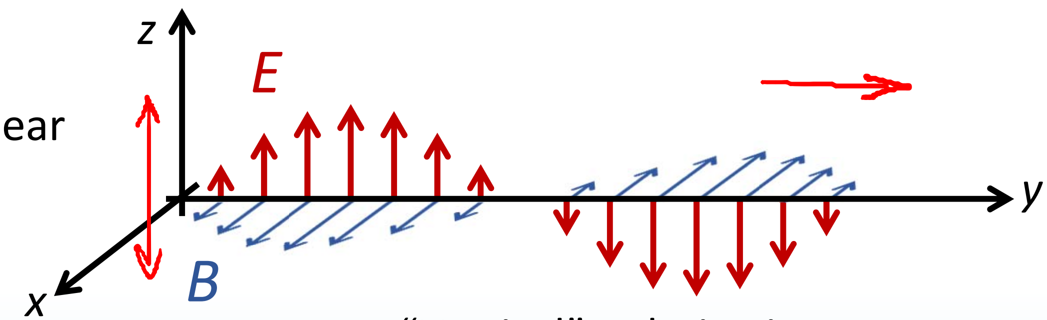
All EM waves!



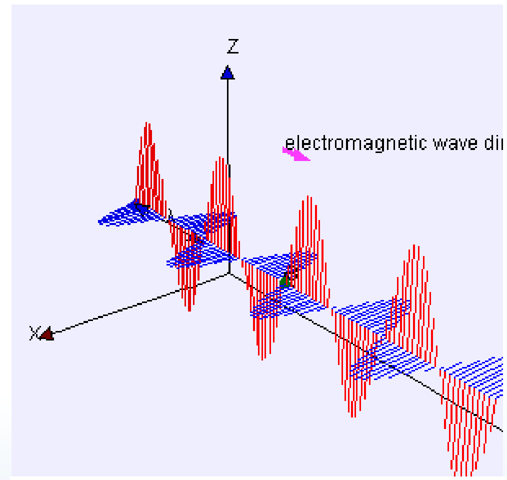
# *Polarization*

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

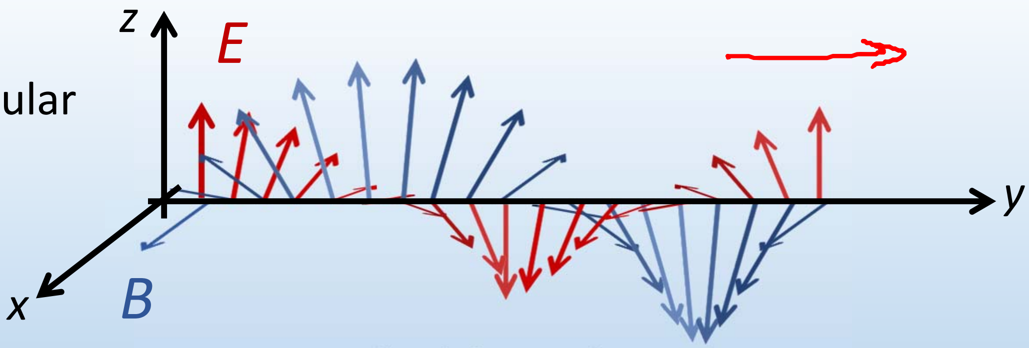
Linear



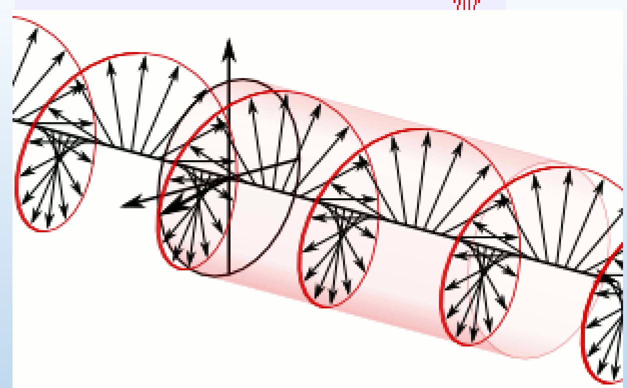

Ex: “Vertical” polarization




Circular




Ex: “Left” circular polarization



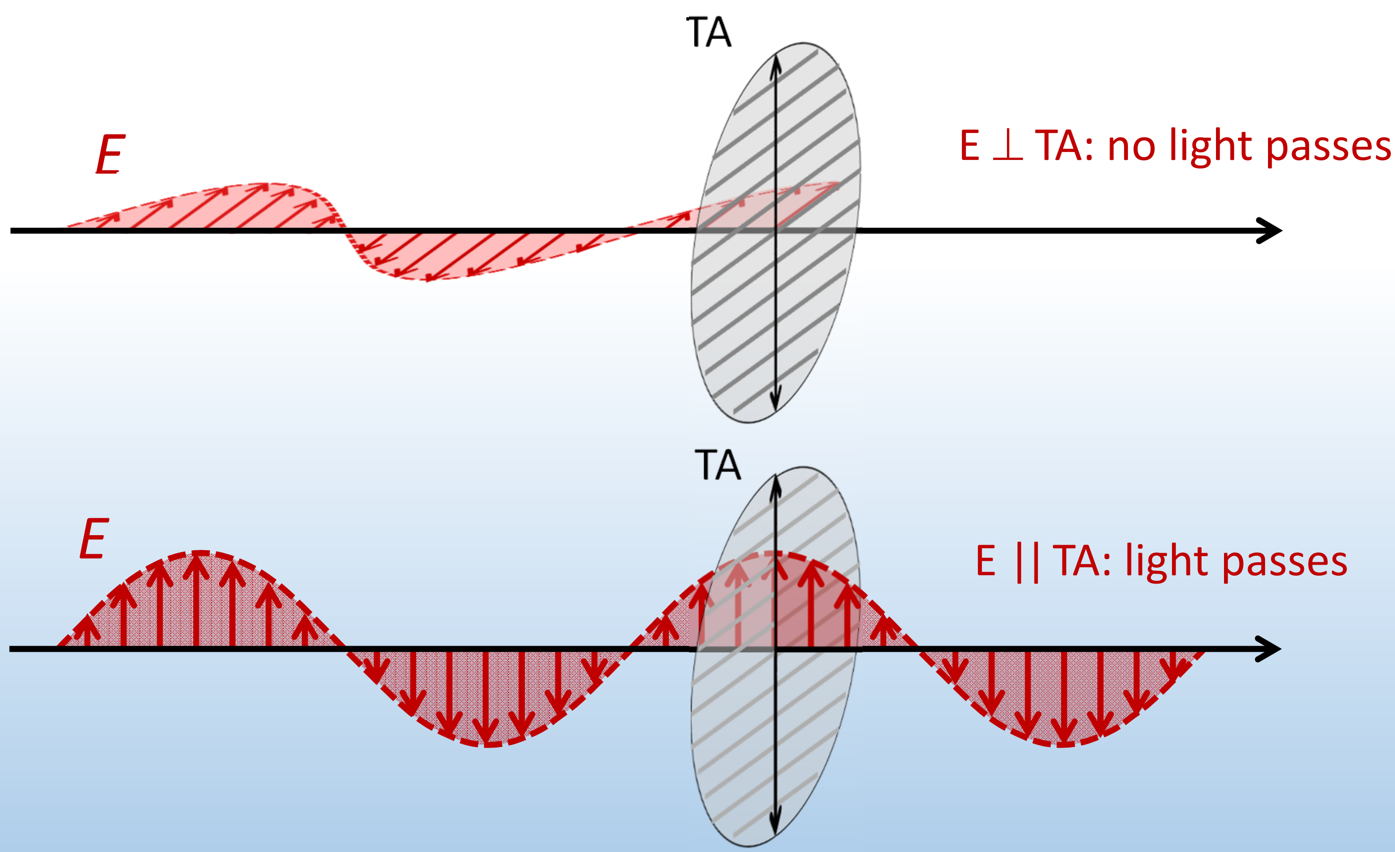
Unpolarized – direction is *random*

For convenience we will stop showing the *B* field

# ***Linear polarizers***

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

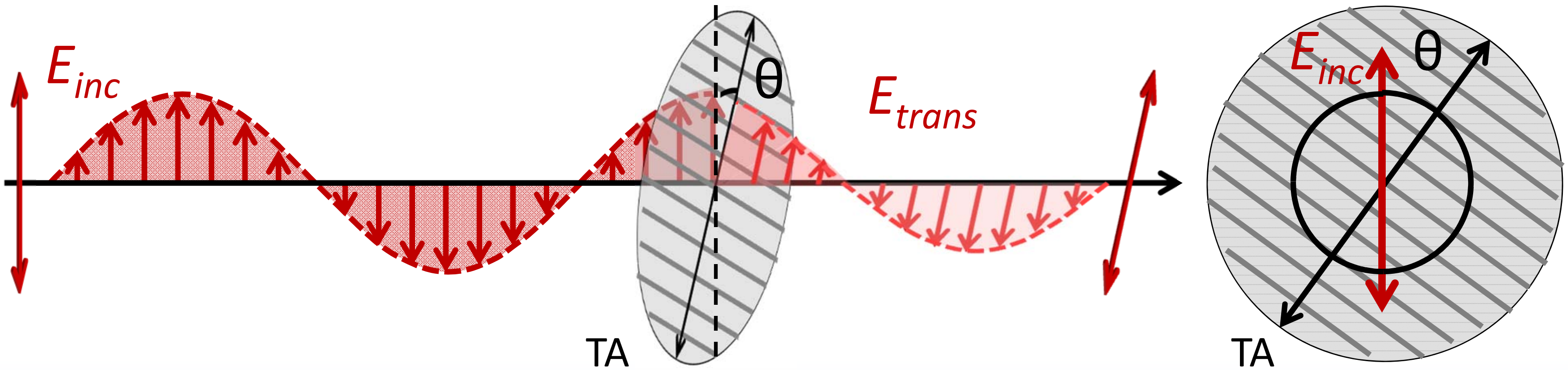
*Transmission axis* (TA) is defined in direction that *E* field passes



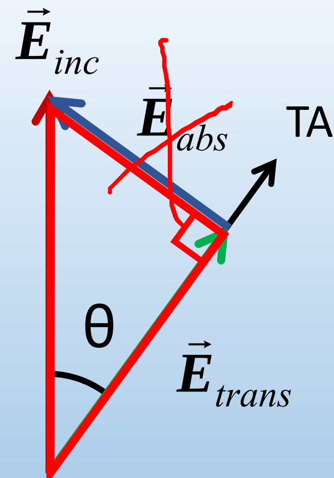

What happens for other angles between polarization and TA?

# *Law of Malus*

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



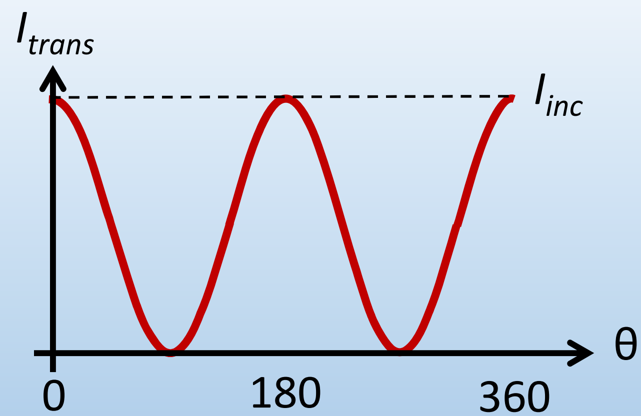

Component of *E* field ⊥ to TA axis is absorbed:




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

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

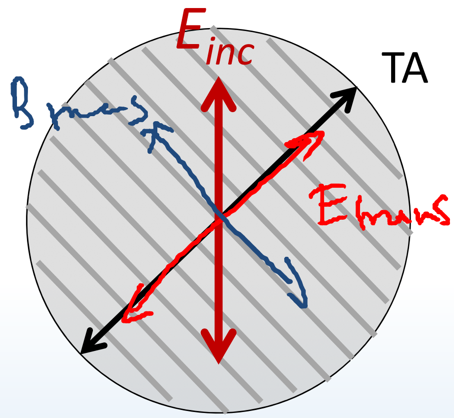
$$\boxed{I_{trans} = I_{inc} \cos^2\theta}$$




Light emerges with polarization || to TA axis

# *ACT: polarizer*

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




Transmitted light is polarized along TA
*B* field oscillates ⊥ to *E* field

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

A. ↕

B. ↖↘

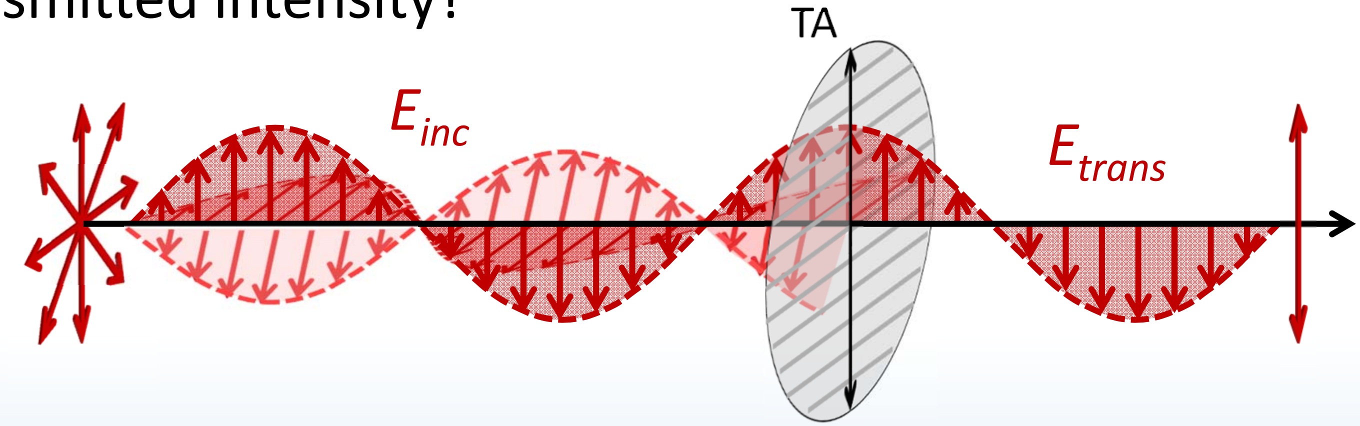
C. ↗↙

D. ↔

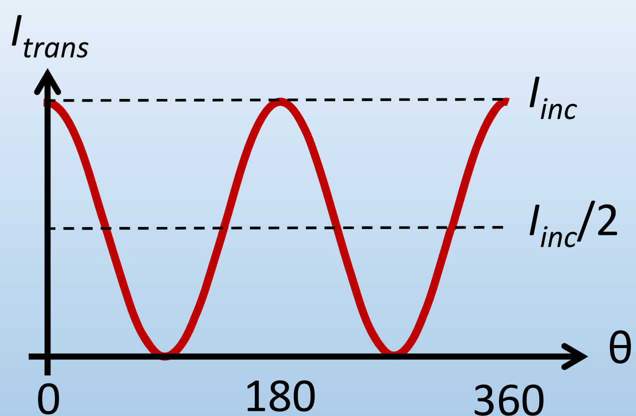
What is the magnitude? $B = E/c$ so $B_{trans} = B_{inc}\cos(45) = 0.707 B_{inc}$

# 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



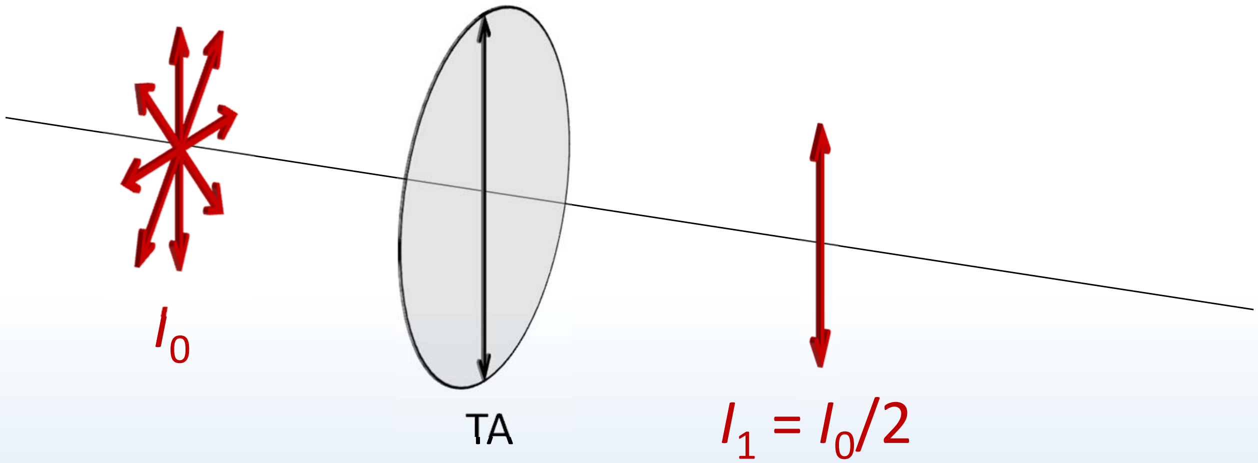

$I_{trans} = I_{inc} \cos^2\theta$ average over all θ:

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

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 8%

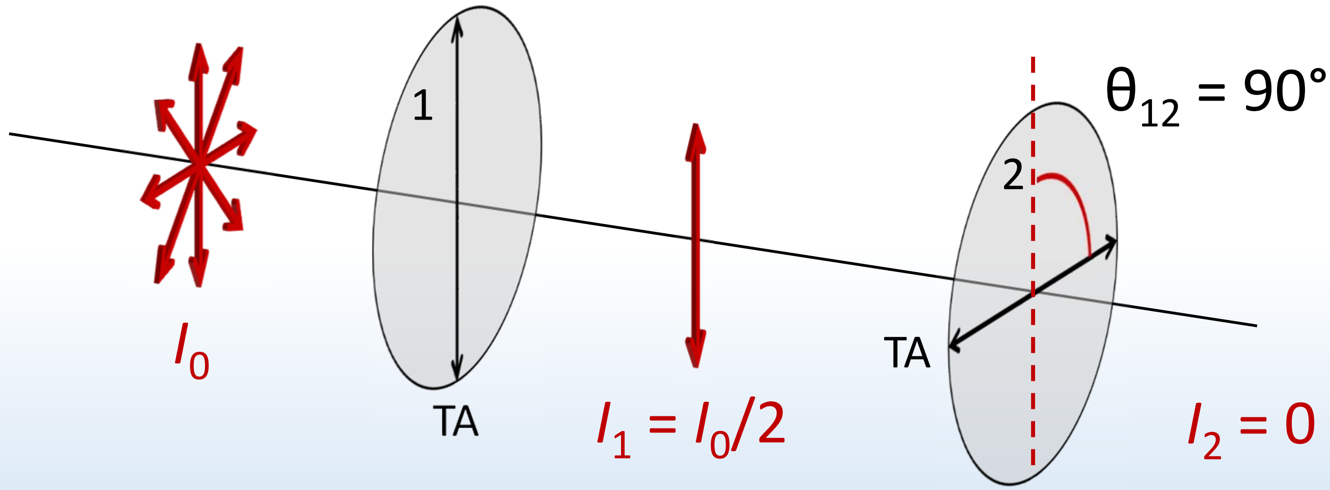
B. 1/2 what it was before 53%

C. 1/4 what it was before 14%

D. 1/3 what it was before 6%

# *ACT: CheckPoint 2.2*

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

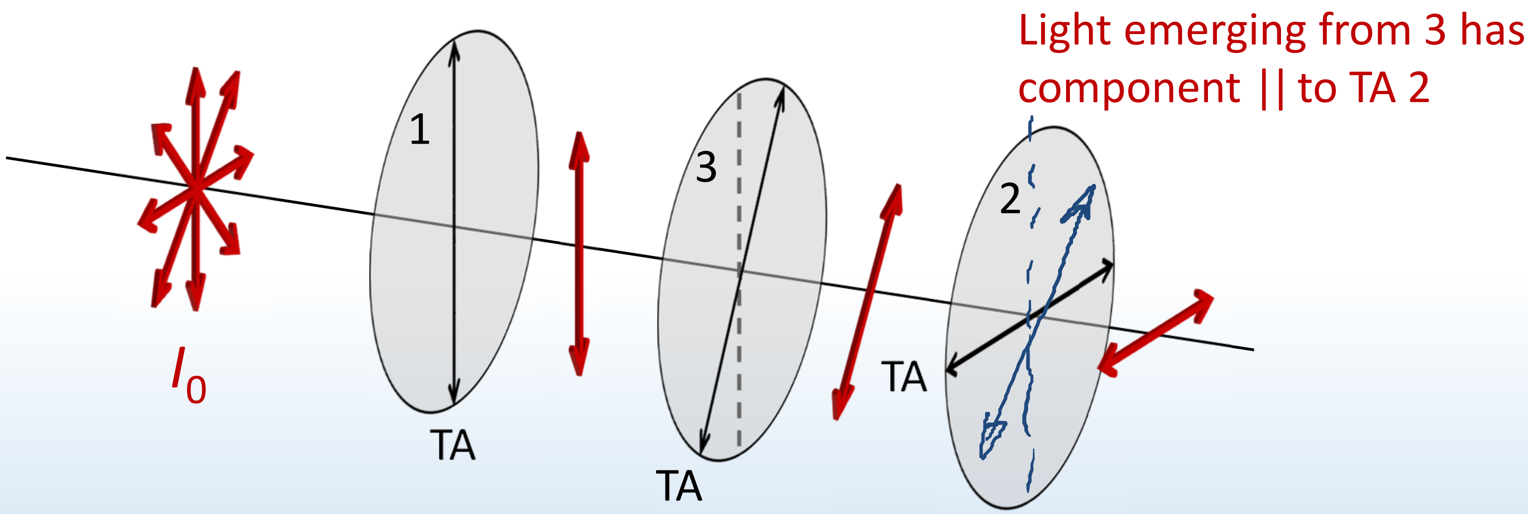



What is the intensity of light when it emerges?

| | | |
|---|---|---|
| A. | zero | 40% |
| B. | 1/2 what it was before | 23% |
| C. | 1/4 what it was before | 23% |
| D. | 1/3 what it was before | 5% |

# *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?

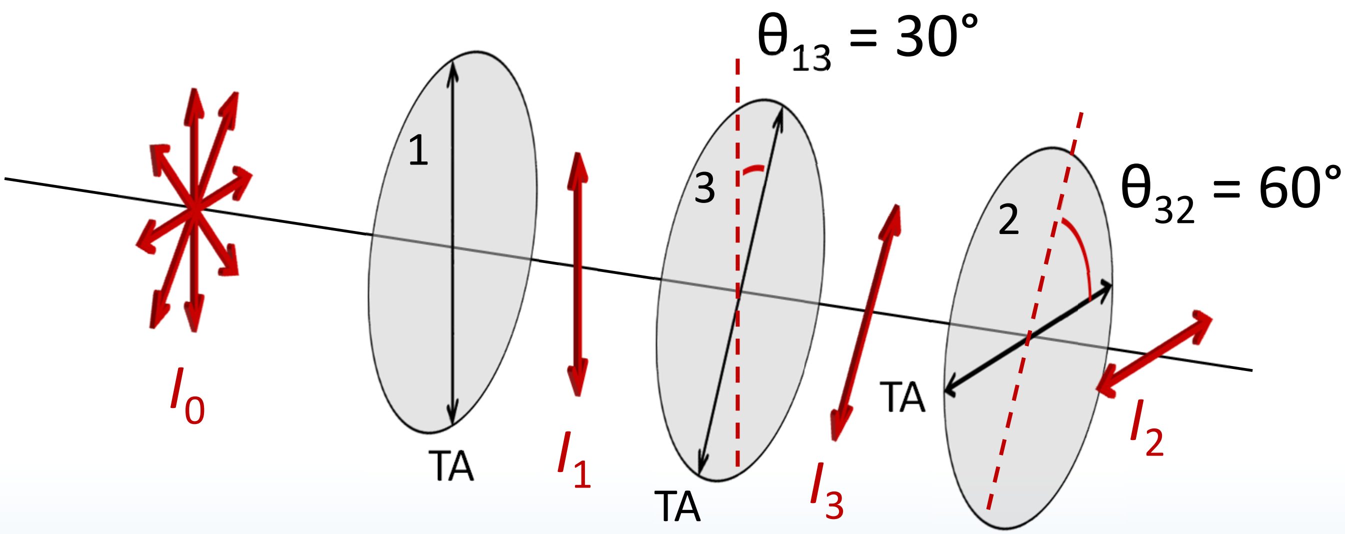
DEMO

A. zero, same as before

B. more than what it was before

C. need more information

# *Calculation: 3 polarizers*




Light transmitted through polarizer 1 is vertically polarized. Angle between polarizer 3 and incident light is $\theta_{13}$ = 30°.

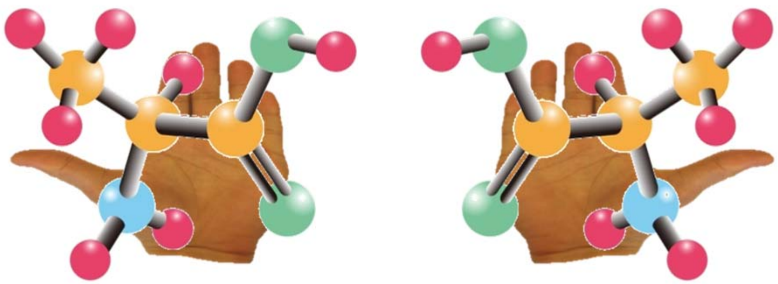
$$I_1 = \tfrac{1}{2} I_0 \qquad I_3 = I_1 \cos^2\theta_{13} = \tfrac{1}{2} I_0 \cos^2(30)$$

Light transmitted through polarizer 3 is polarized 30° from vertical. Angle between polarizer 3 and incident light is $\theta_{32}$ = 60°.

$$I_2 = I_3 \cos^2\theta_{32} = \tfrac{1}{2} I_0 \underbrace{\cos^2(30)}_{3/4}\,\underbrace{\cos^2(60)}_{1/4} = \tfrac{3}{32} I_0$$

# *Chirality & optical activity*

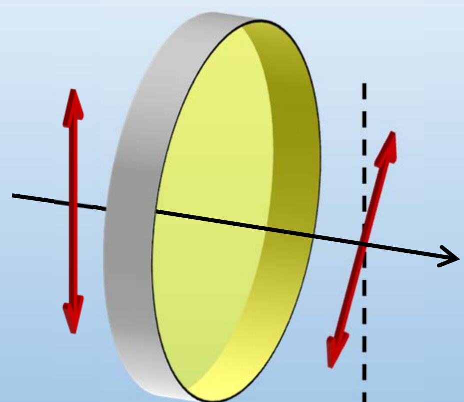
Many organic molecules are *chiral* – they have "handedness"



L-alanine D-alanine (unnatural enantiometer)

Chiral molecules rotate linearly polarized light – *optical activity*

DEMO



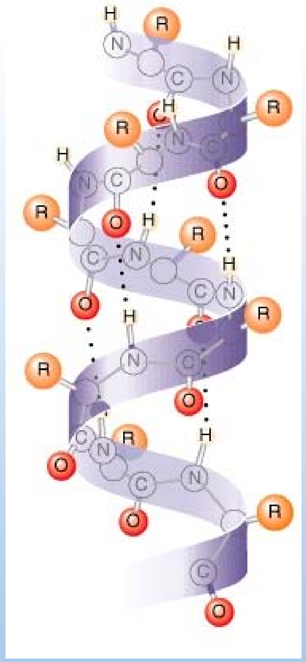
"Dextrorotary" CW rotation
"Levorotary" CCW rotation

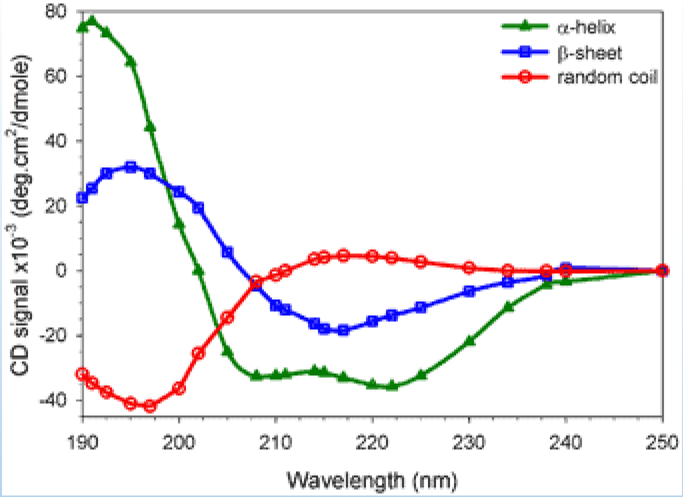
# *Circular dichroism*

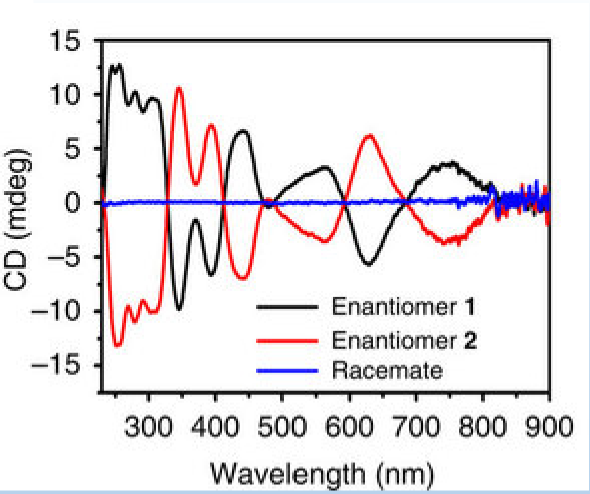
Chiral molecules also absorb left vs. right circularly polarized light differently

Circular dichroism (CD) measures difference in absorption

Tool to distinguish chiral features in biomolecules



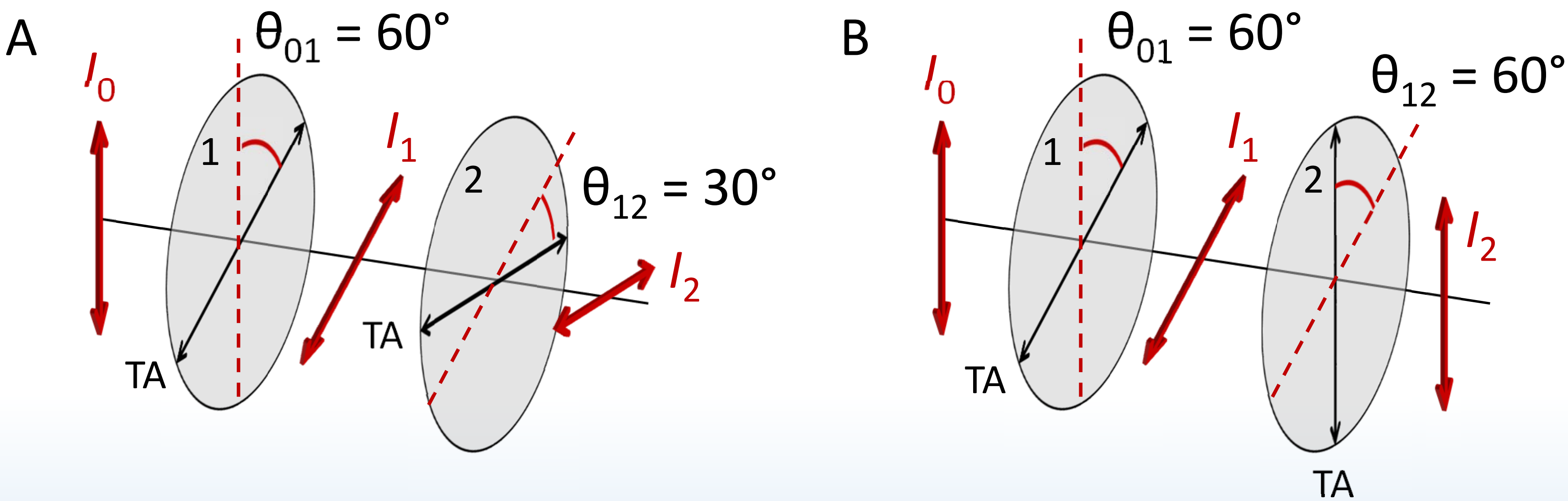




CD spectra

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. $I_2^A < I_2^B$

$$I_1^A = I_0 \cos^2\theta_{01} = I_0 \cos^2(60) \quad = I_1 = \quad I_1^B = I_0 \cos^2\theta_{01} = I_0 \cos^2(60)$$

$$I_2^A = I_1 \cos^2\theta_{12} = I_1 \cos^2(30) = \tfrac{3}{4} I_1 \quad > \quad I_2^B = I_1 \cos^2\theta_{12} = I_1 \cos^2(60) = \tfrac{1}{4} I_1$$

# *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