Your questions/comments

IMPORTANT ANNOUNCEMENT:
Exam 2 on Lect. 6 – 12, Thurs. Mar. 19
Review session Tues. Mar. 17 from 6:30-8:30pm (141 Loomis) -> FA14 EX2

Study tips

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

"Oh my god.... What is going on?!?!? Please, please, please go over this stuff slowly. No idea what is going on with linear polarizers."

"Could you explain unpolarized light on polarizers"

"I found the concept of light intensity to be difficult."

"How do you physicists remember SO. MUCH. INFORMATION? This made my brain hurt!"

"I DON'T KNOW HOW TO PHYSICS."

Phys 102 – Lecture 16

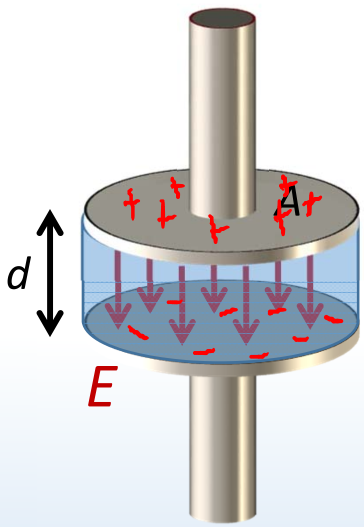
Electromagnetic wave energy & polarization

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

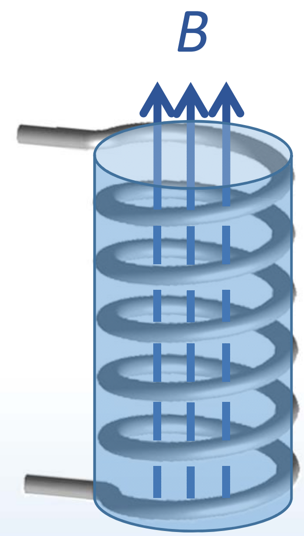
E & B field energy density

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

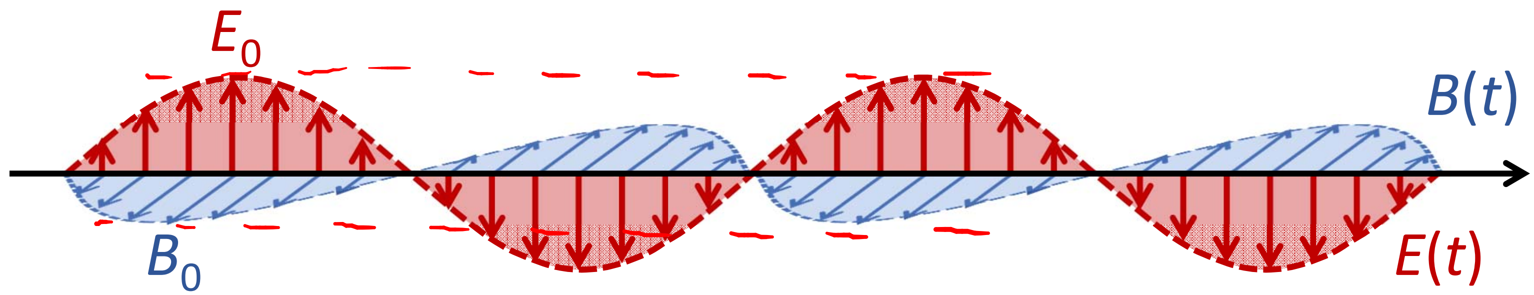
It is convenient to define *energy density* = energy per volume [J/m^3]

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

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*

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

Average over time

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

E & *B* field amplitudes

Maximum value

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

Equal

Recall that

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

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

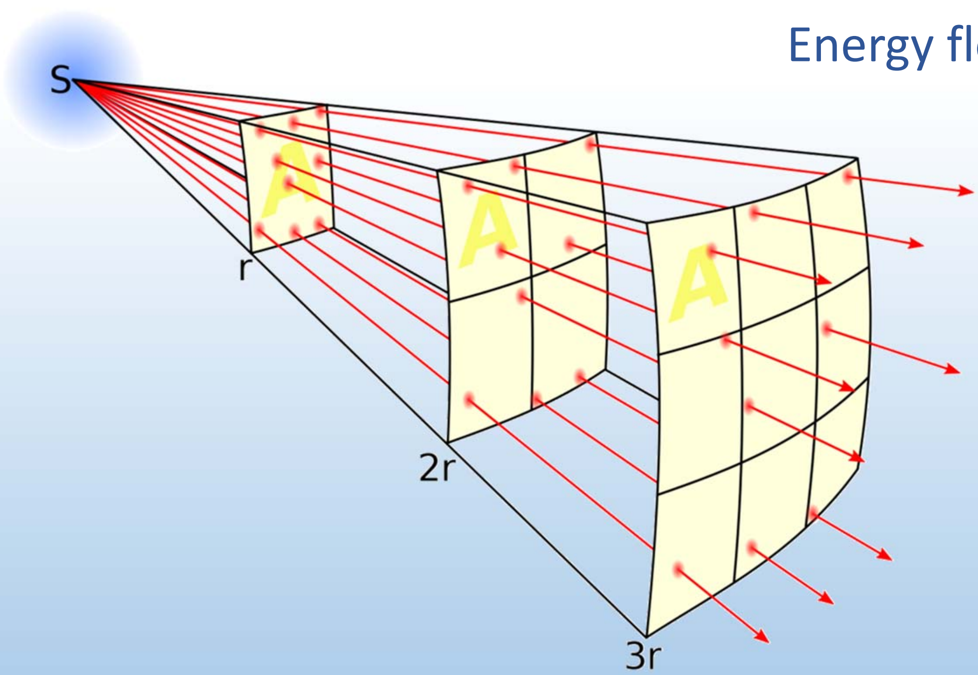
EM wave intensity

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*:

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

It is useful to define *intensity*:

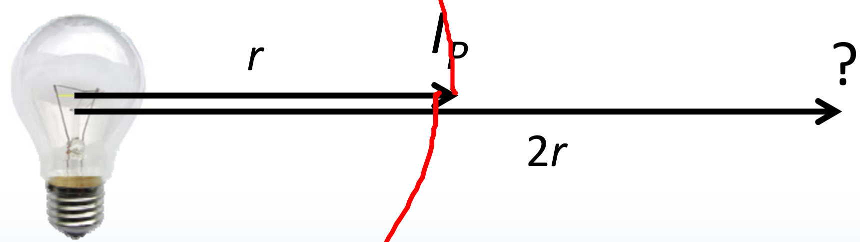
$$\boxed{I = S \equiv \frac{\langle P\rangle}{A} = \langle u_{tot}\rangle c}$$

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 $2r$?

A. $2I_P$

B. I_P

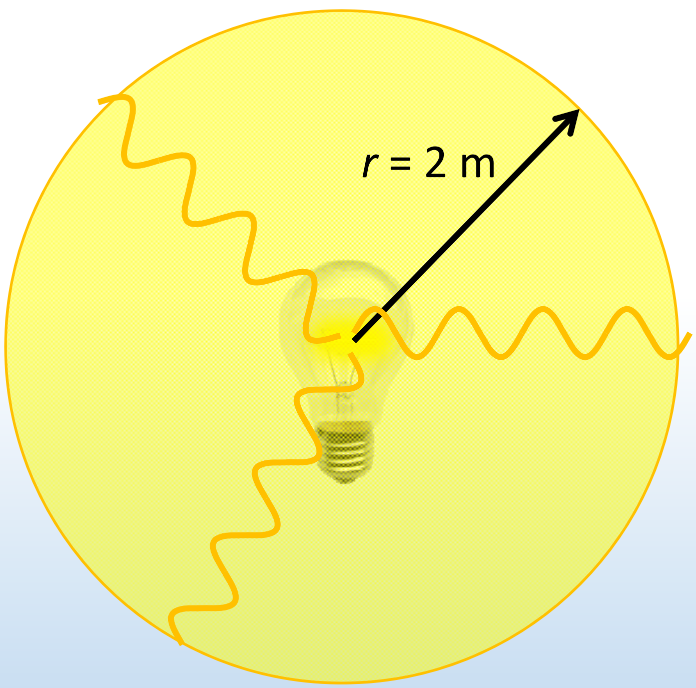
C. $I_P/2$

D. $I_P/4$

$$I = \frac{\langle P \rangle}{A} = \frac{\langle P \rangle}{4\pi r^2} \propto \frac{1}{r^2}$$

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

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

EM energy density

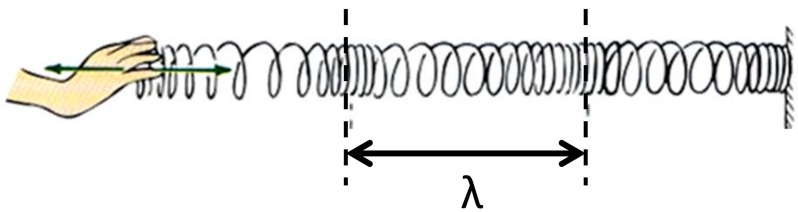
Area of surface through which EM energy flows

$$\langle u_{tot}\rangle = \varepsilon_0 E_{rms}^2 \quad \text{so} \quad E_{rms} = \sqrt{\frac{\langle P\rangle}{4\pi r^2 \varepsilon_0 c}} = \sqrt{\frac{60}{4\pi \cdot 8.85\times10^{-12}\cdot 2^2 \cdot 3\times10^8}} = 21.2\,\mathrm{V/m}$$

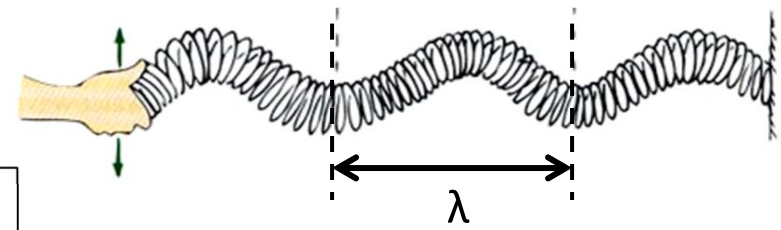
$$B_{rms} = \frac{E_{rms}}{c} = \frac{21.2}{3\times10^8} = 7.1\times10^{-8}\,\mathrm{T}$$

CheckPoint 1.1–1.7

Longitudinal waves: oscillations are || to direction or propagation



Transverse waves: oscillations are ⊥ to direction of propagation



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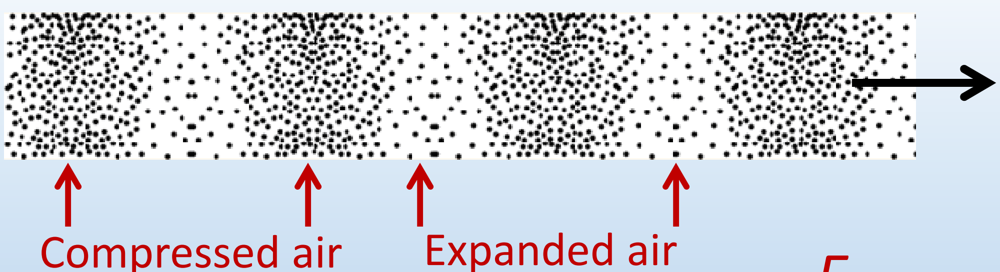
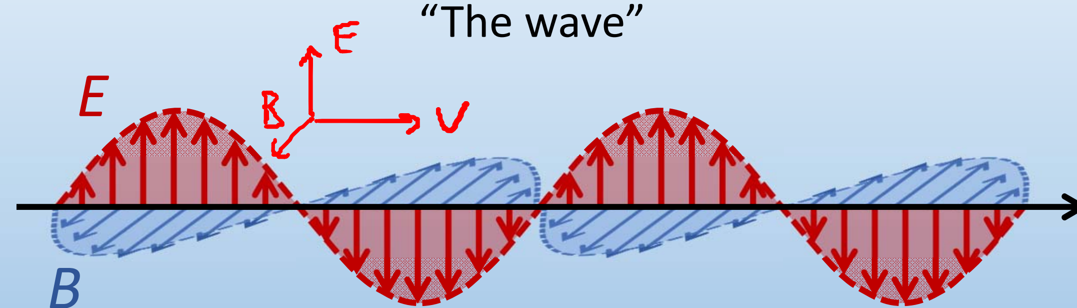
Ex: Sound



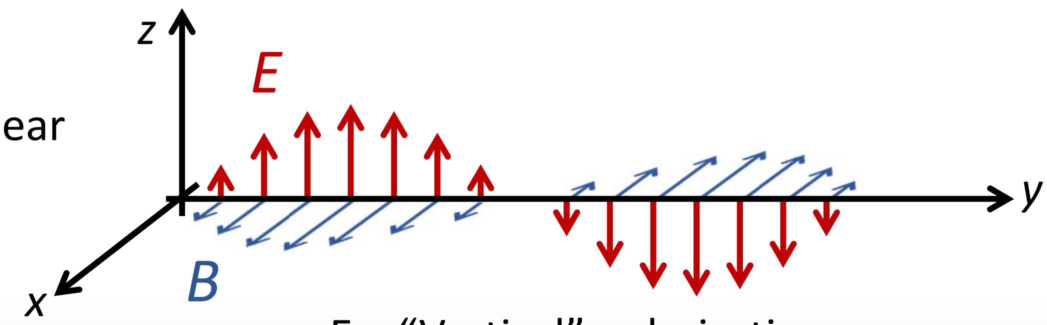
Ex: Light
Radio waves
X-rays
Microwaves
Water waves
"The wave"

All EM waves!



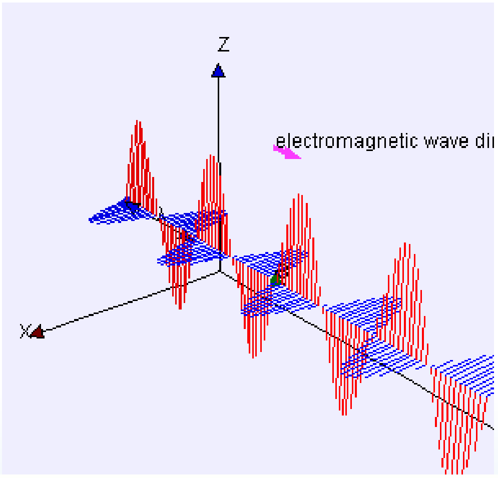
Polarization

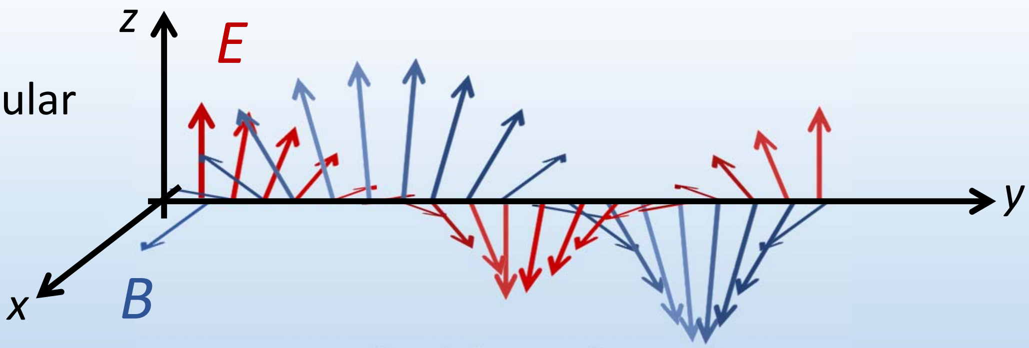
EM waves are transverse and have *polarization* – by convention, the direction of the *E* field oscillation



Linear

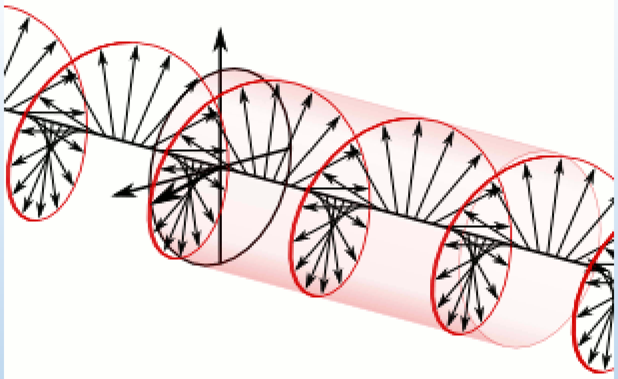
Ex: "Vertical" polarization





Circular

Ex: "Left" circular polarization



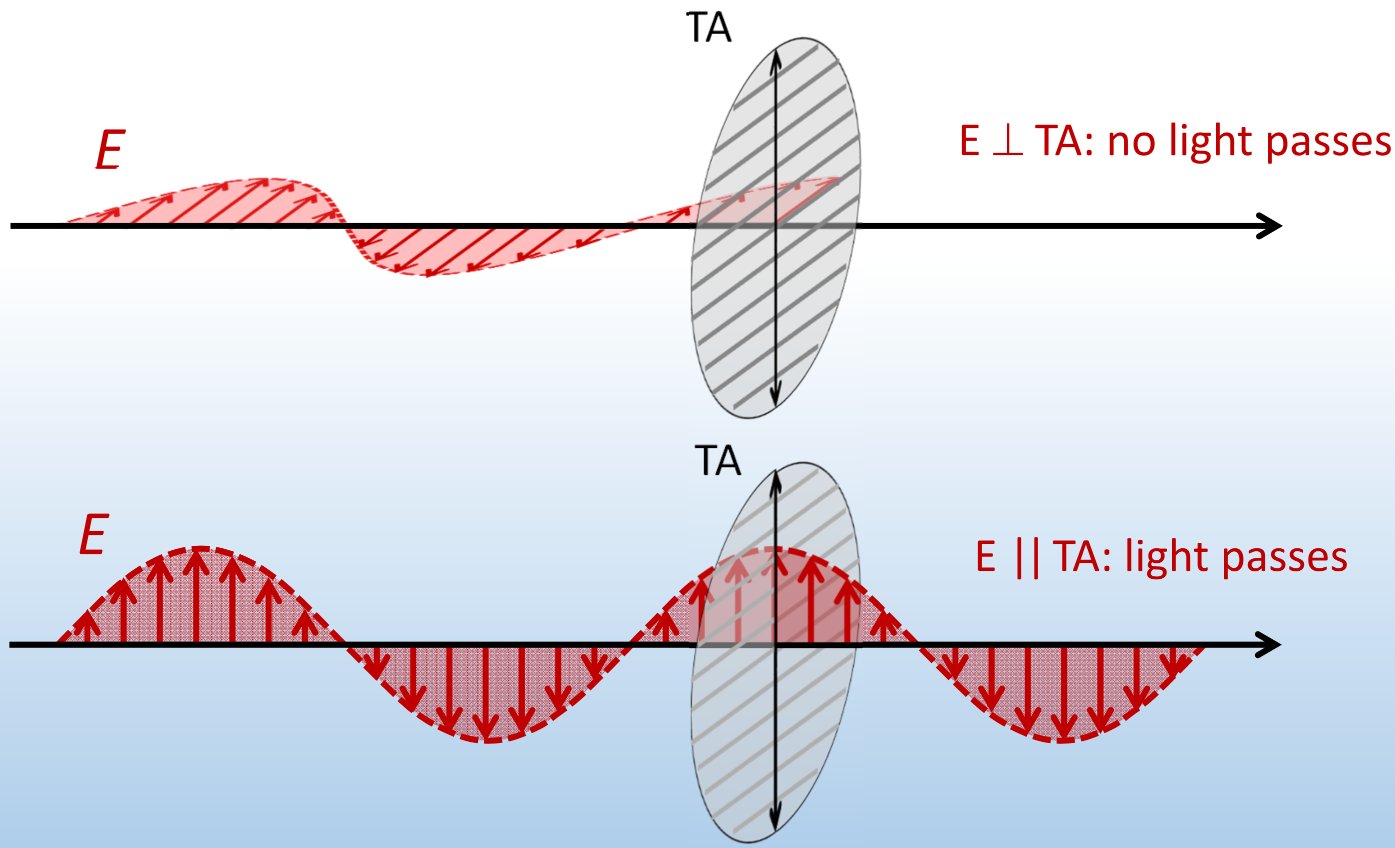
Unpolarized – direction is *random*

For convenience we will stop showing the *B* field

Linear polarizers

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

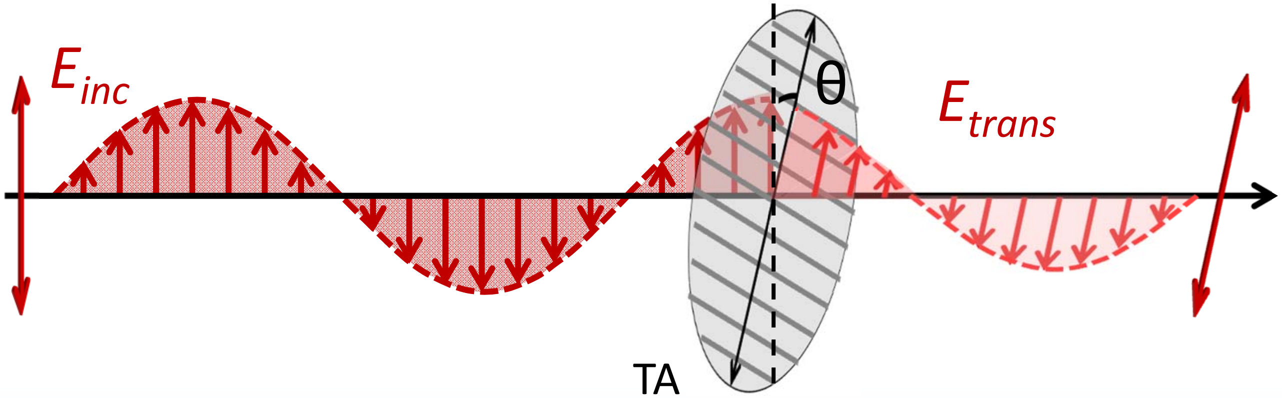
Transmission axis (TA) is defined in direction that *E* field passes

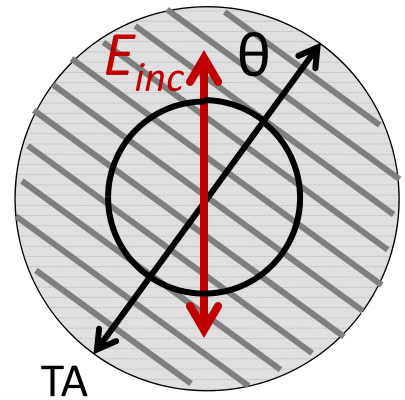


What happens for other angles between polarization and TA?

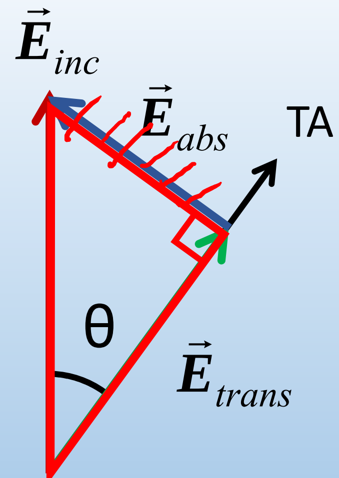
Law of Malus

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





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

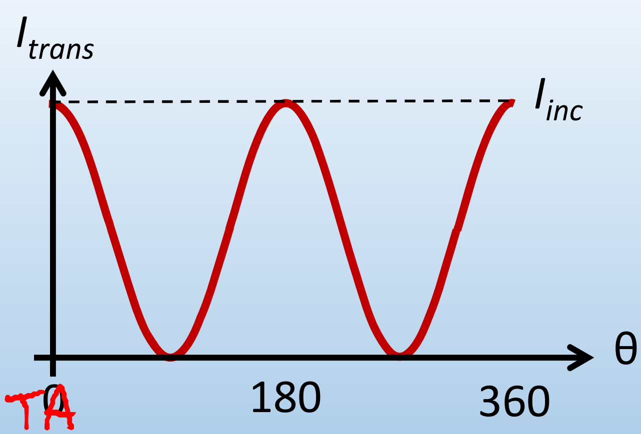


$$\left|\vec{E}_{trans}\right| = \left|\vec{E}_{inc}\right| \cos\theta$$

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

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

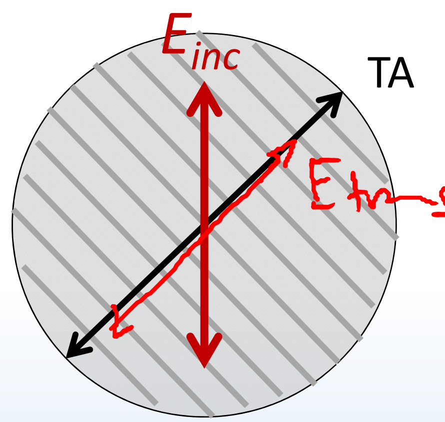
between E_{inc} and TA



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

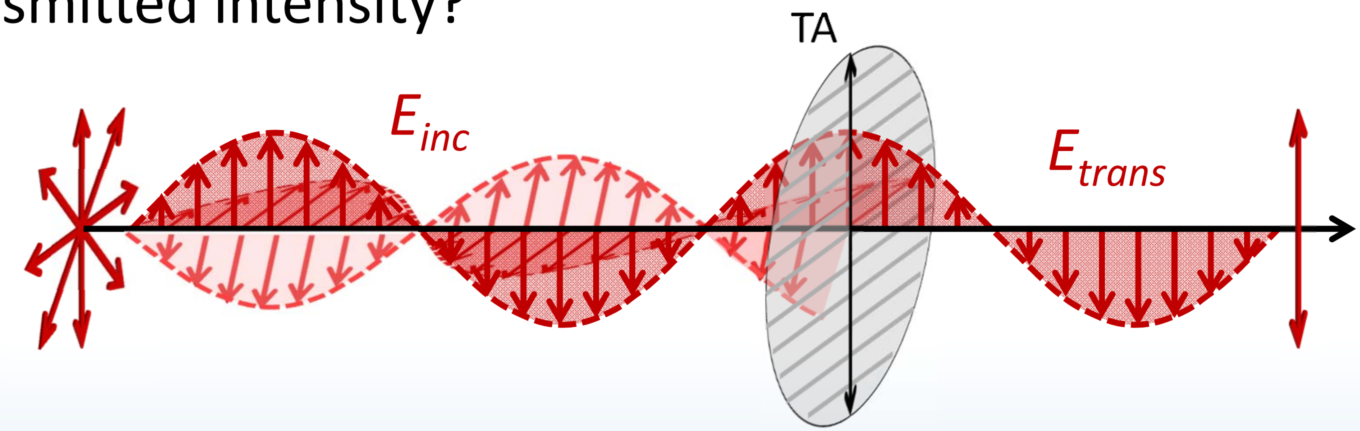
B field oscillates ⊥ to *E* field

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

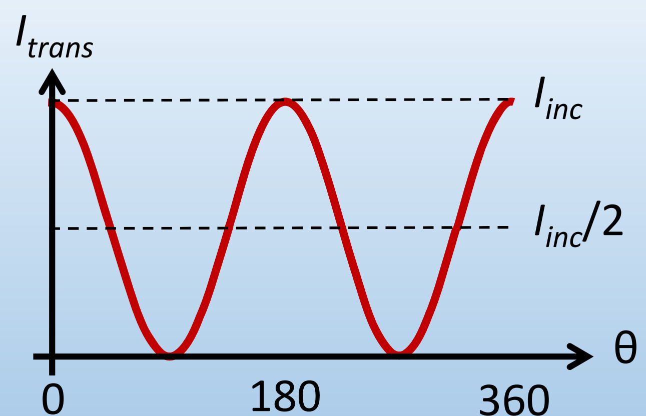
What is the magnitude? $B = E/c$ so $B_{trans} = B_{inc}\cos(45) = 0.707 B_{inc}$

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



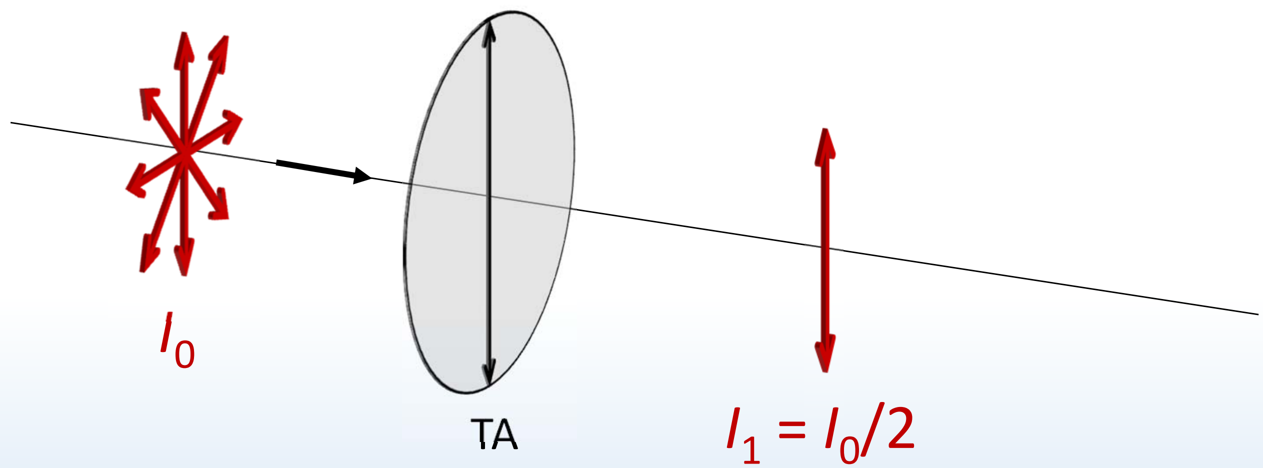
$I_{trans} = I_{inc} \cos^2 \theta$ average over all θ:

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

Light emerges with polarization || to TA axis

ACT: CheckPoint 2.1

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

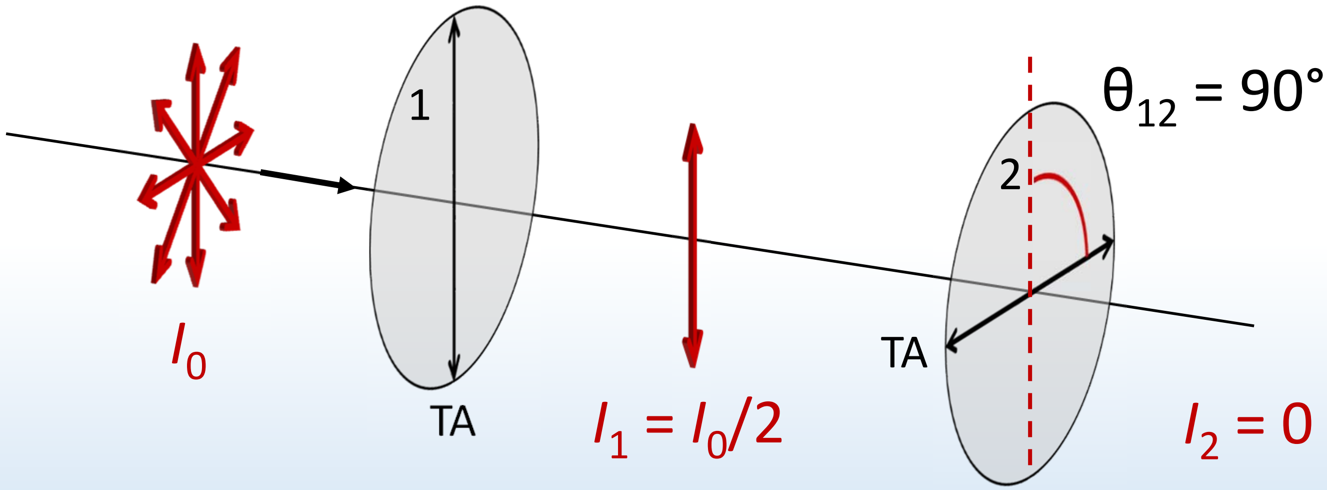


What is the intensity of light when it emerges?

A. zero 14%
B. 1/2 what it was before 52%
C. 1/4 what it was before 16%
D. 1/3 what it was before 4%

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 33%

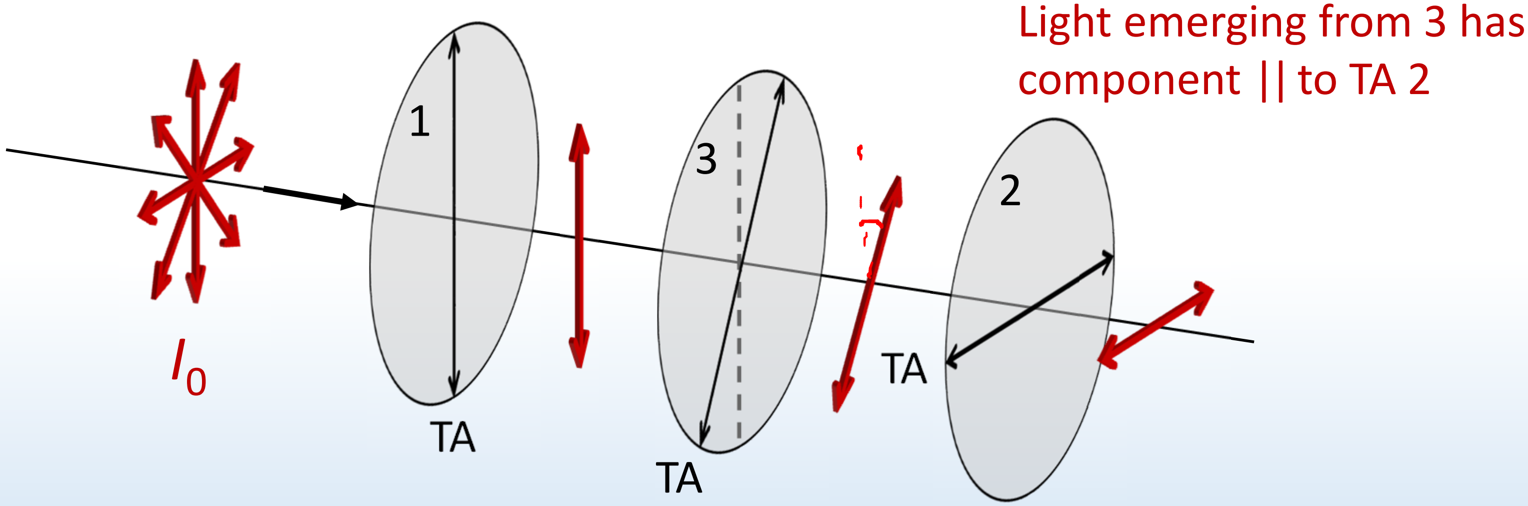
B. 1/2 what it was before 24%

C. 1/4 what it was before 26%

D. 1/3 what it was before 8%

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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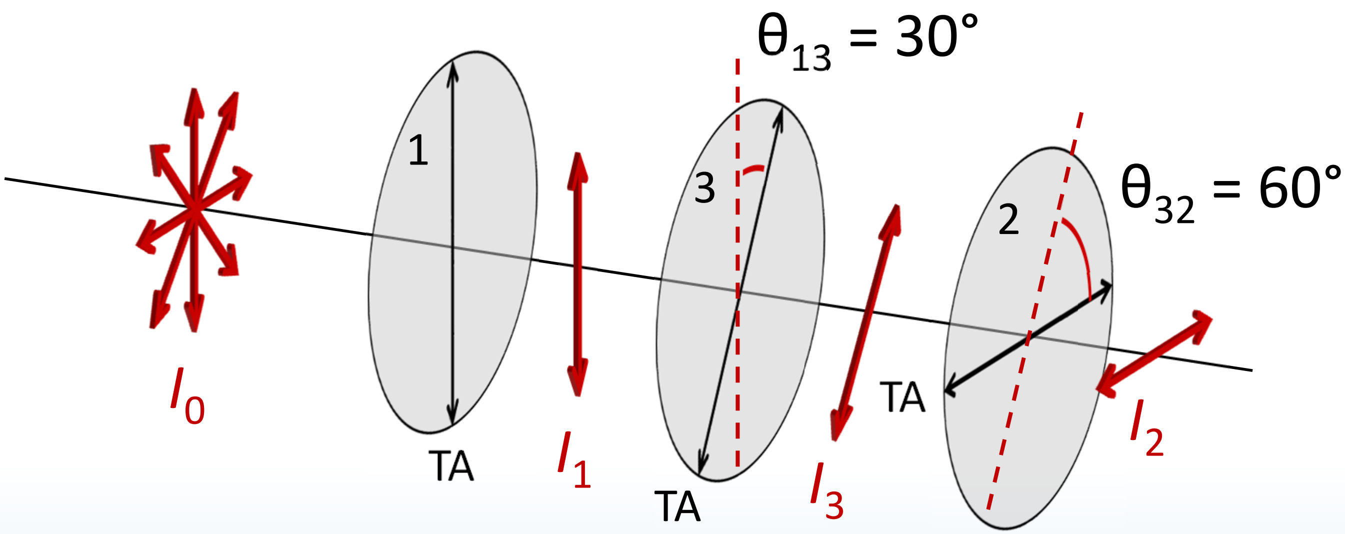
A. zero, same as before

B. more than what it was before

C. need more information

Calculation: 3 polarizers



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

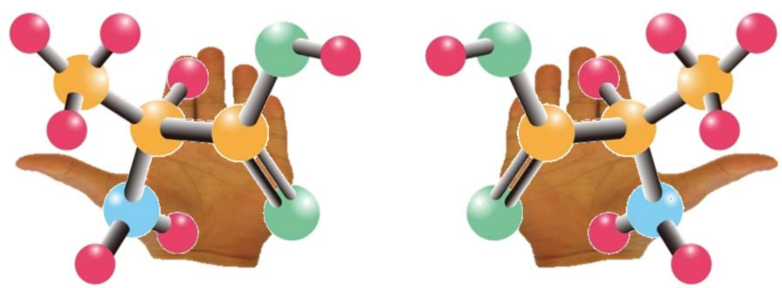
$$I_1 = \tfrac{1}{2} I_0 \qquad I_3 = I_1 \cos^2\theta_{13} = \tfrac{1}{2} I_0 \cos^2(30)$$

Light transmitted through polarizer 3 is polarized 30° from vertical. Angle between polarizer 2 and incident light is θ_{32} = 60°.

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

Chirality & optical activity

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

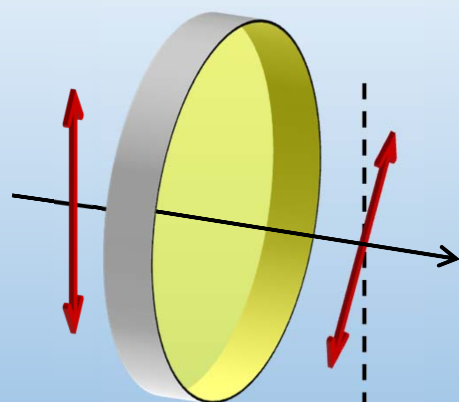


L-alanine

D-alanine (unnatural enantiometer)

Chiral molecules rotate linearly polarized light – *optical activity*

DEMO



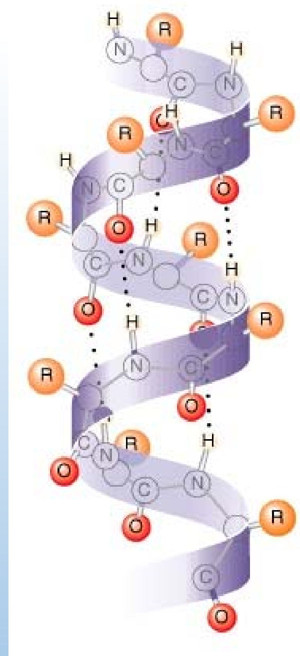
“Dextrorotary” CW rotation
“Levorotary” CCW rotation

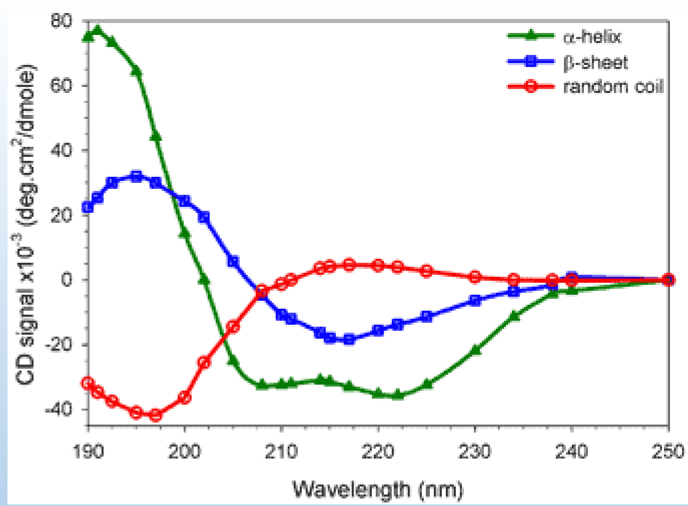
Circular dichroism

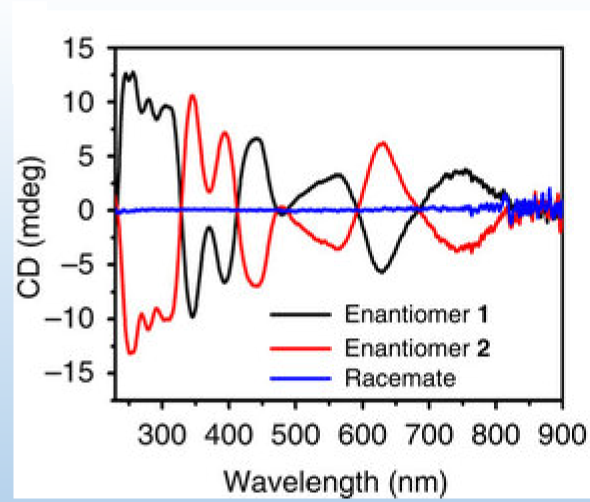
Chiral molecules also absorb left vs. right circularly polarized light differently

Circular dichroism (CD) measures difference in absorption

Tool to distinguish chiral features in biomolecules



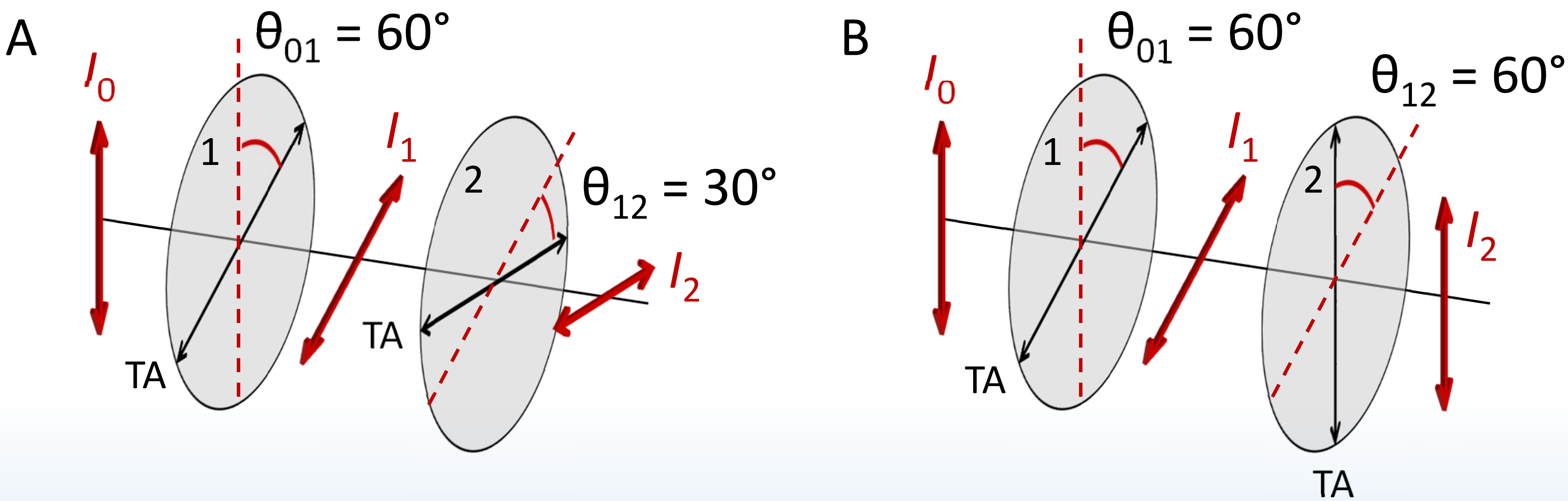




CD spectra

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