# Poynting Vector

- ***Wave intensity I*** = time average over one or more cycle $\langle \sin^2(kx - \omega t) \rangle = 1/2$ then $\langle E^2 \rangle = E_{max}^2/2$ and $\langle B^2 \rangle = B_{max}^2/2$

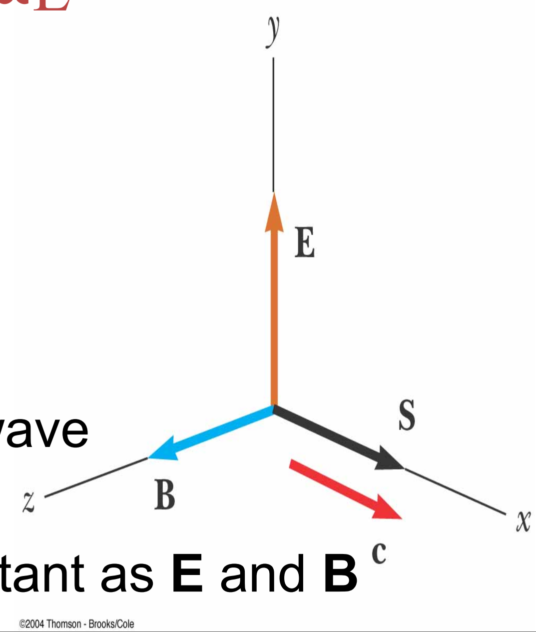
$$I_{av} = u_{av} c = \frac{E_{max} B_{max}}{2\mu_0}$$

- Define vector with magnitude= ***power per unit area*** ($J/s{\cdot}m^2 = W/m^2$)

Intensity$\propto E^2$

$$I = S_{av} = \frac{E_{max} B_{max}}{2\mu_o} = \frac{E_{max}^2}{2\mu_o c} = \frac{c B_{max}^2}{2\mu_o}$$

$$\mathbf{S} \equiv \frac{1}{\mu_o} \mathbf{E} \times \mathbf{B}$$




- Its direction is the direction of propagation of the EM wave
  - Its magnitude varies in time
  - Its magnitude reaches a maximum at the same instant as **E** and **B**

# Radiation Momentum and pressure

- EM waves transport **momentum**$\Rightarrow$ **pressure** on a surface
- **Complete absorption** on a surface: total transported energy $U$ in time interval $\Delta t \Rightarrow$ **total momentum $p = U / c$**
- Radiation Pressure = force per unit area

$$P = \frac{F}{A} = \frac{1}{A}\frac{dp}{dt} = \frac{1}{c}\frac{dU/dt}{A}$$

- S = $(dU/dt)/A$ and **$P = S / c$**
- **Perfectly reflecting surface**: momentum of incoming and reflected light p = U/c $\Rightarrow$ total transferred momentum **$p = 2U/c$ and $P = 2S/c$**
- Direct sunlight pressure ~5 x $10^{-6}$ N/m$^2$

# The EM Spectrum

Gamma rays: $\lambda \sim 10^{-14} - 10^{-10}$ m

Source: radioactive nuclei

cause serious damage to living tissues

X-rays: $\sim 10^{-12} - 10^{-8}$ m

source: deceleration of high-energy electrons striking a metal target

Diagnostic tool in medicine

UV $\lambda \sim 6 \times 10^{-10} - 4 \times 10^{-7}$ m

Most UV light from the sun is absorbed in the stratosphere by ozone

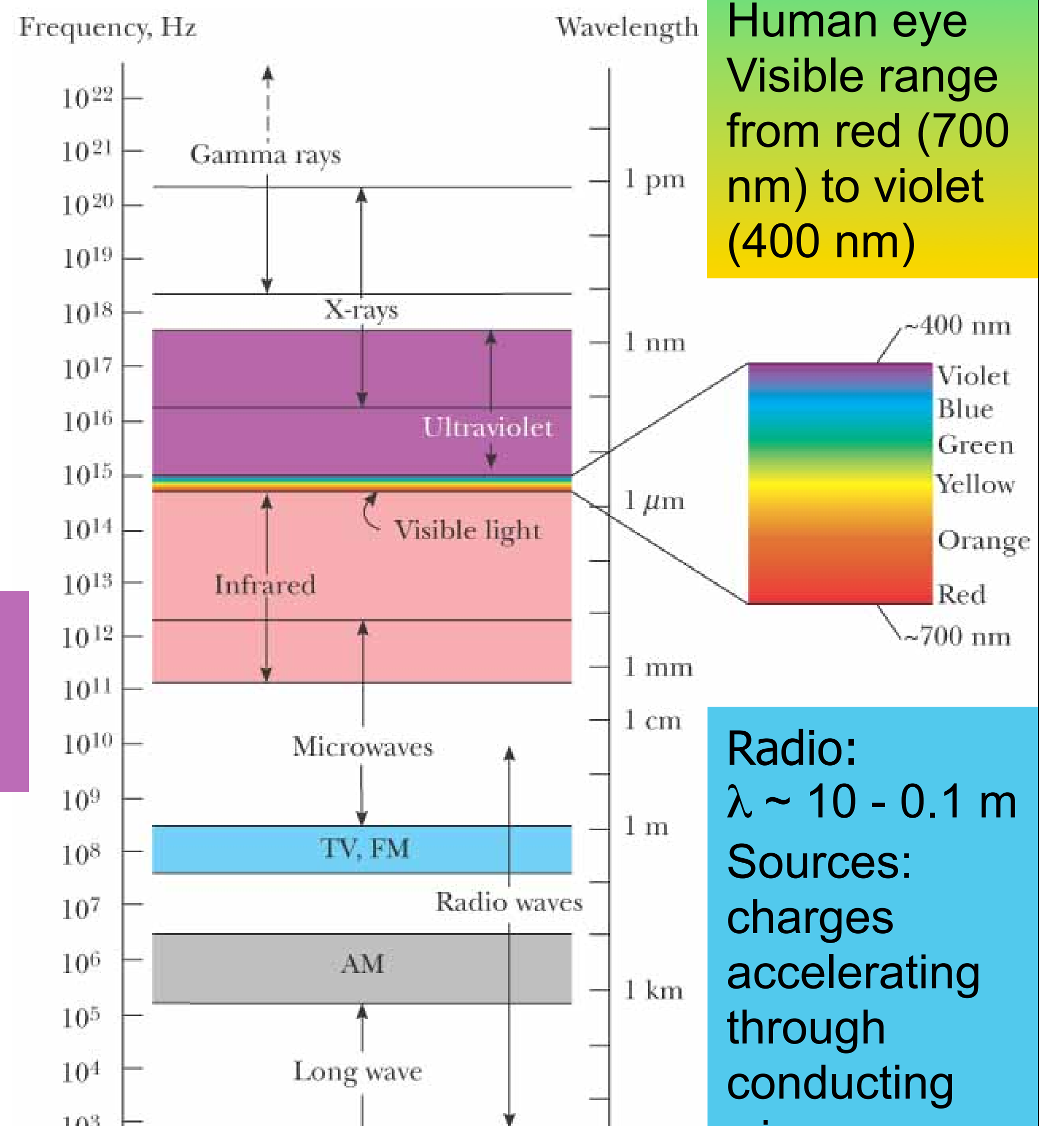
Infrared: $\lambda \sim 7 \times 10^{-7} - 10^{-3}$ m

Sources: hot objects and molecules

Microwaves: $\lambda \sim 10^{-4} - 0.3$ m

sources: electronic devices

radar systems, MW ovens




Source: atoms and molecules

Human eye Visible range from red (700 nm) to violet (400 nm)

Radio:

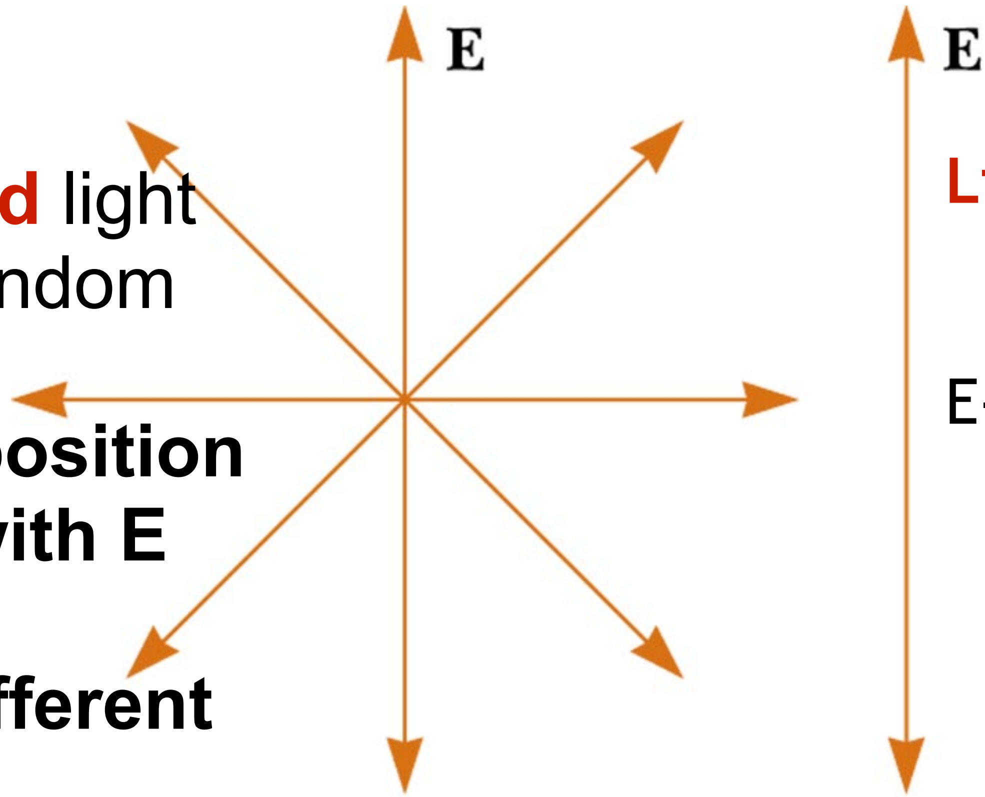
$\lambda \sim 10 - 0.1$ m

Sources: charges accelerating through conducting wires

Radio and TV

# Polarization of Light Waves (Sec 31.7)

- **Linearly polarized waves: E-field** oscillates at all times in the **plane of polarization**
- Any two waves can be superposed to make a third, or a single wave decomposed into two.

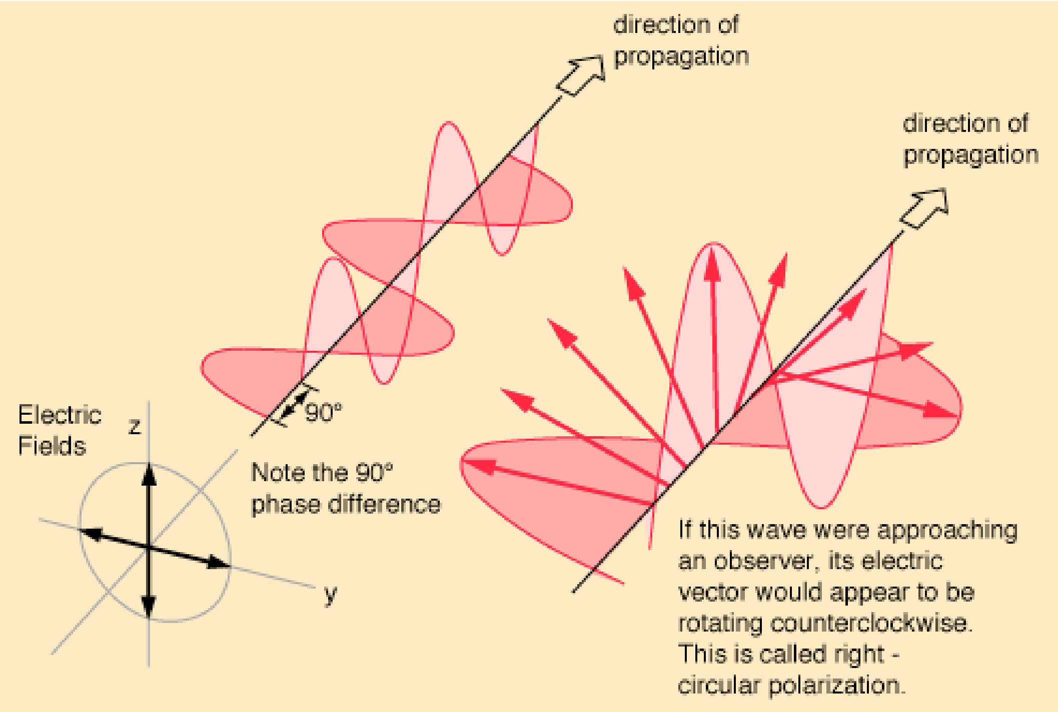



**Unpolarized** light
E-field in random directions
Is a **superposition of waves with E vibrating in many different directions**

**Linearly polarized** light
E-field has one spatial orientation

# Circular and elliptical polarization

- **Circularly polarized light:** superposition of 2 waves of equal amplitude with orthogonal linear polarizations, and 90˚ out of phase. The tip of **E** describes a circle (counterclockwise = RH and clockwise=LH depending on y component ahead or behind)
- The electric field rotates in time with constant magnitude.
- If amplitudes differ ⇒ **elliptical polarization**

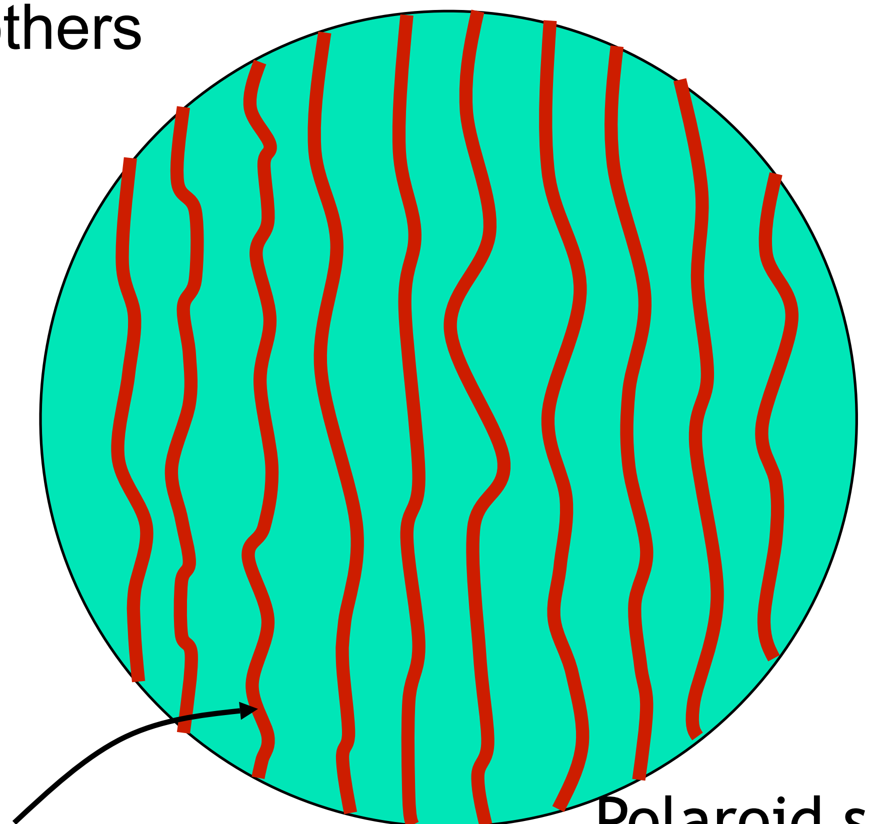


# Producing polarized light

- Polarization by **selective absorption**: material that transmits waves whose E-field vibrates in a plain parallel to a certain direction and absorbs all others

This polarization **absorbed**

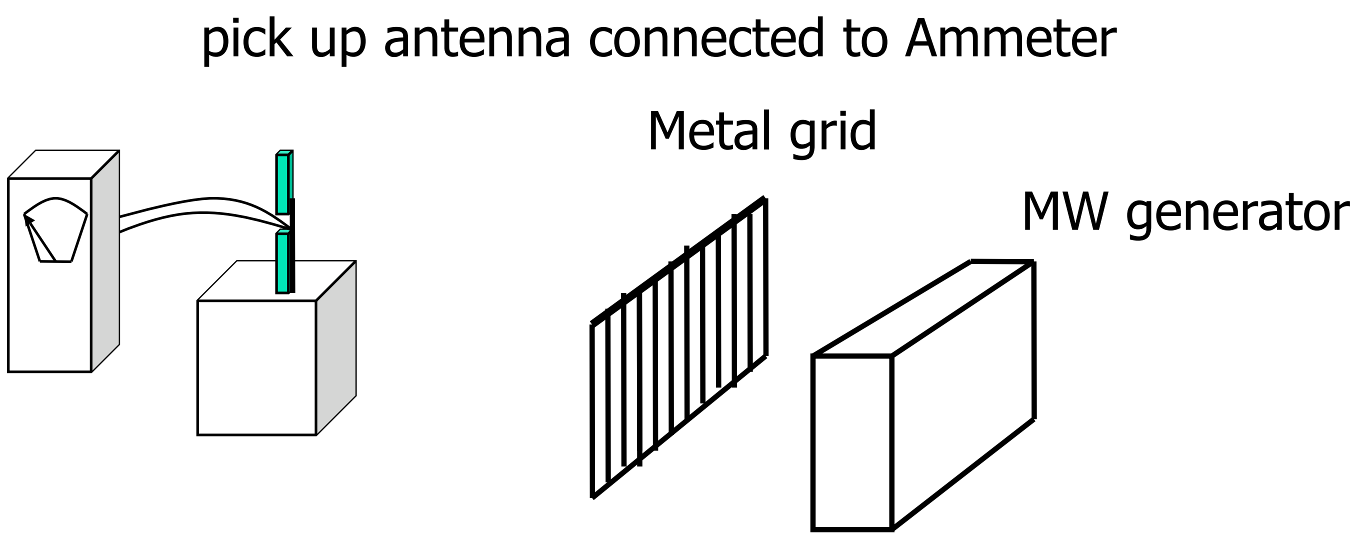
This polarization **transmitted**
**transmission axis**



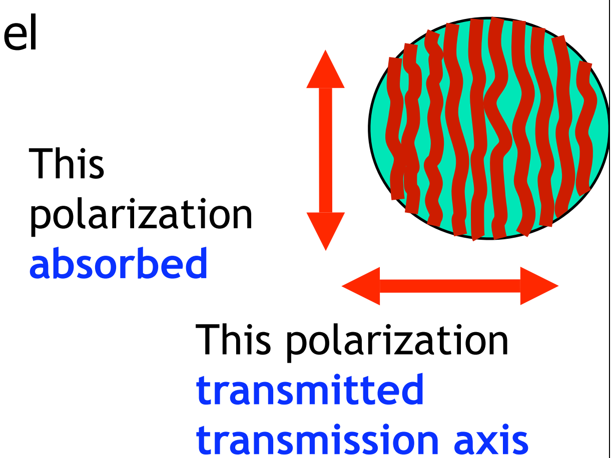
Long-chain hydrocarbon molecules

Polaroid sheet
(Land 1938)

# DEMO with MW generator and metal grid

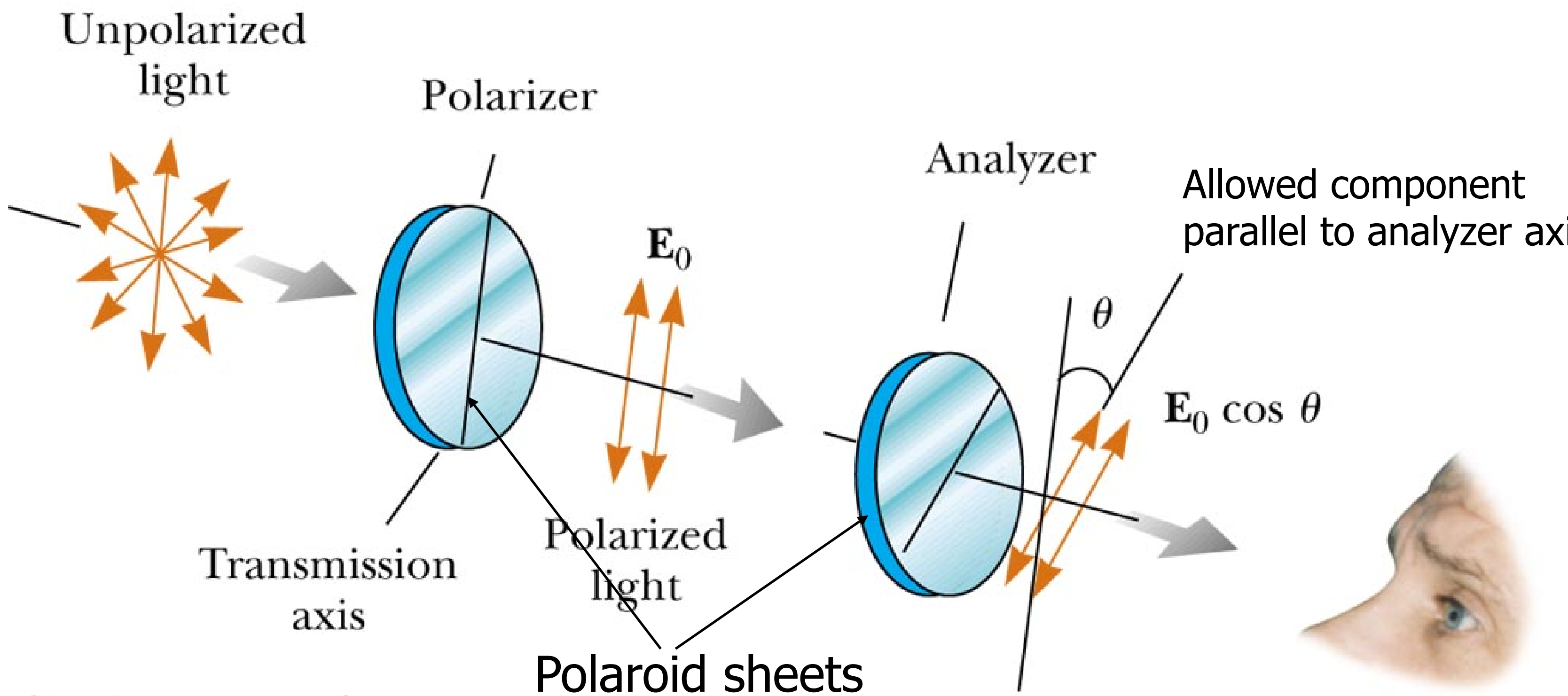



If the wires of the grid are parallel to the plane of polarization the grid absorbs the E-component (electrons oscillate in the wire).
The same thing happens to a polaroid: the component parallel to the direction of the chains of hydrocarbons is absorbed.
If the grid is horizontal the Ammeter will measure a not null current since the wave reaches the antenna pick-up



# Detecting polarized light

- Ideal polarizer transmits waves with E parallel to transmission axis and absorbs those with E ⊥ axis
- Relative orientation of axis of polarizer and analyzer determines intensity of transmitted light.
- Transmitted intensity: $I = I_0\cos^2\theta$  $I_0$ = intensity of polarized beam on analyzer (Malus' law)

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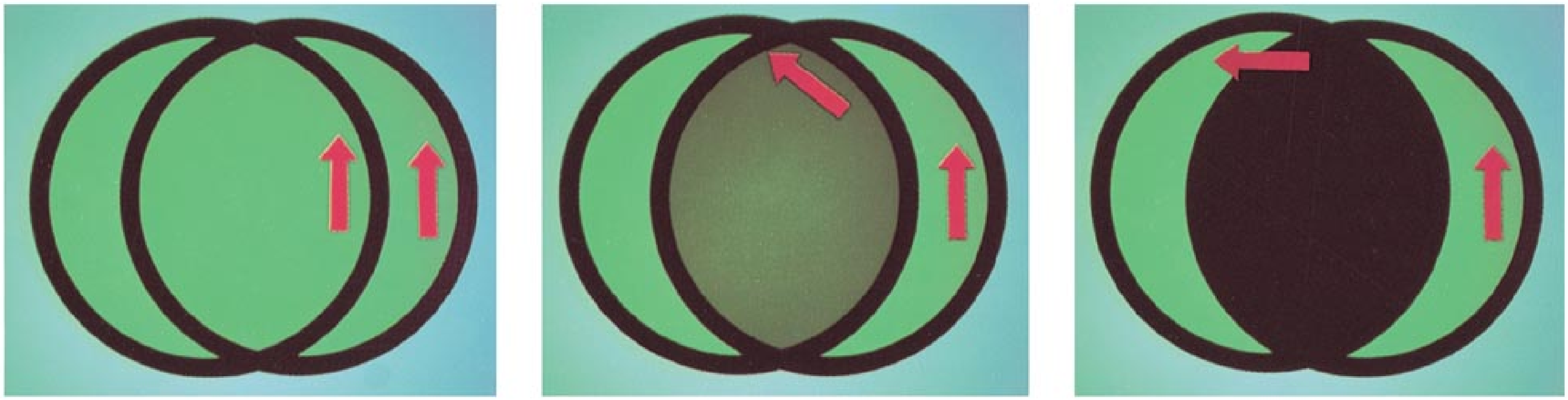
# Relative orientation of polarizers



(a) (b) (c)

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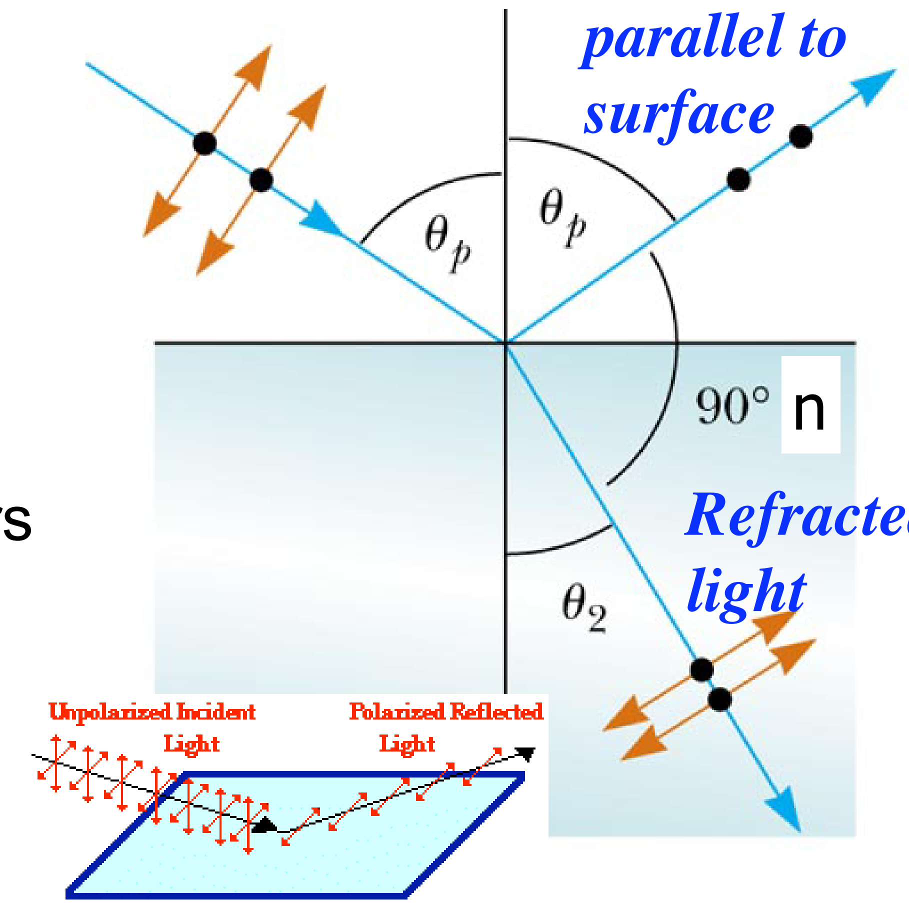
- Transmitted amplitude is $E_o\cos\theta$ *(component of polarization along polarizer axis)*
- Transmitted intensity is $I_o\cos^2\theta$ ( *square of amplitude)*
- Perpendicular polarizers give zero intensity.

# Polarization by reflection

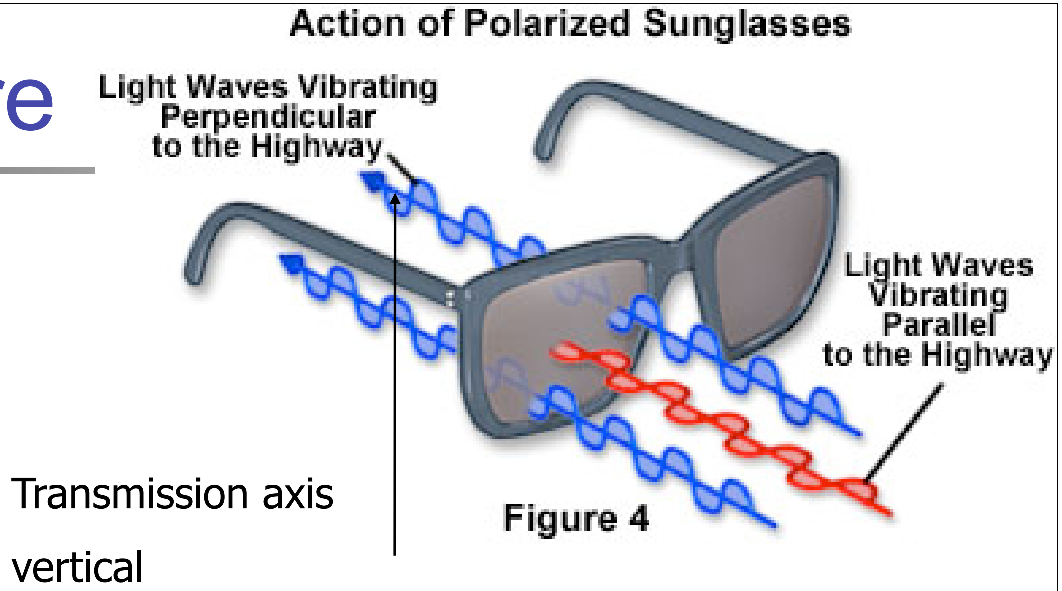
- Unpolarized light reflected from a surface becomes partially polarized
- Degree of polarization depends on angle of incidence
- If reflected and refracted beams are orthogonal complete polarization occurs




Reflection of light off of non-metallic surfaces results in some degree of polarization parallel to the surface.

# Reducing glare

A polarizer can substantially reduce intensity of reflections, since the reflections are partially polarized.




Sunlight reflected from water, glass, snow is partially polarized. If surface is horizontal the E-field vector of reflected light has strong horizontal component.
Polarized glasses: vertical transmission axis absorbs strong horizontal component
Reflected light can be eliminated!

# Polarization by scattering

When light hits a material **electrons absorb and reradiate part of the light.**

The sky appears blue due to scattering of light on air and resulting partially polarized light.

Short wavelengths (blue) are scattered more intensely than red.

Looking far from the Sun we see mainly scattered light $\Rightarrow$blue sky

Looking towards the Sun the light that survives is weighted towards red because most of the blue light has been scattered

So different directions relative to Sun have different polarizations. Some insects can detect this polarization and use it to navigate.

# Tips for the final

- about 35% of new material: B-fields, B produced by a current, forces between currents, torque on a loop, inductance and RL circuits, Ampere and Ampere-Maxwell's law (time dependent fields), EM waves, Poynting vector, energy density in E and B field, radiation pressure
- 65% Electric Fields, Potential, Potential energy, Gauss' law, DC circuits, Resistance and capacitance, RC and R circuits, Joule law and Joule heating, wave functions and probability, Schoredinger equation, atom, general relativity, gravity
- see http://icecube.wisc.edu/%7eshiu/PHY248_S07/Syllabus.html, see grading policy