Light

- **What is light?**

- **To start, what are the observed properties of light? Describe the intrinsic properties of light — light by itself.**

- **Later, what are the interactions of light? What happens when light meets matter?**

Properties of light

Intensity, or brightness

COLOR

Speed (fast!)

The speed of light is different in different materials.

Direction of motion

Light does not always travel in straight lines.

Polarization

…first observed in the birefringence of calcite; discussed by Huygens and Newton.

Light moves! ➔an opaque object casts a shadow.

If light moves, how fast is it?

Galileo tried to measure the speed of light using signals from lanterns on two mountains. He was unsuccessful – light is too fast!

The first measurement of the speed of light was *astronomical,* made by Roemer in 1676 using the eclipses of the moons of Jupiter (which had been discovered by Galileo in 1610).

$c = 2.998 \times 10^8$ m/s

Use this number in the capa problems.

300,000 kilometers in one second

To explain the properties of light, we need a *theory*.

Question from history:
Is light composed of particles or waves?

Christian Huygens (1629-1695) developed a wave theory of light.

Isaac Newton (1642-1727) believed that light is a stream of particles.

Quantum theory (20th century) says that light has both wave and particle aspects.

Seems self-contradictory!

But that still doesn't answer the question.

What is light?

What is light made of?

Answer:

Light is an electromagnetic phenomenon.
Light is made of electric and magnetic fields.

James Clerk Maxwell…

…the second great theoretical physicist in the history of science (after Newton).

Maxwell's equations

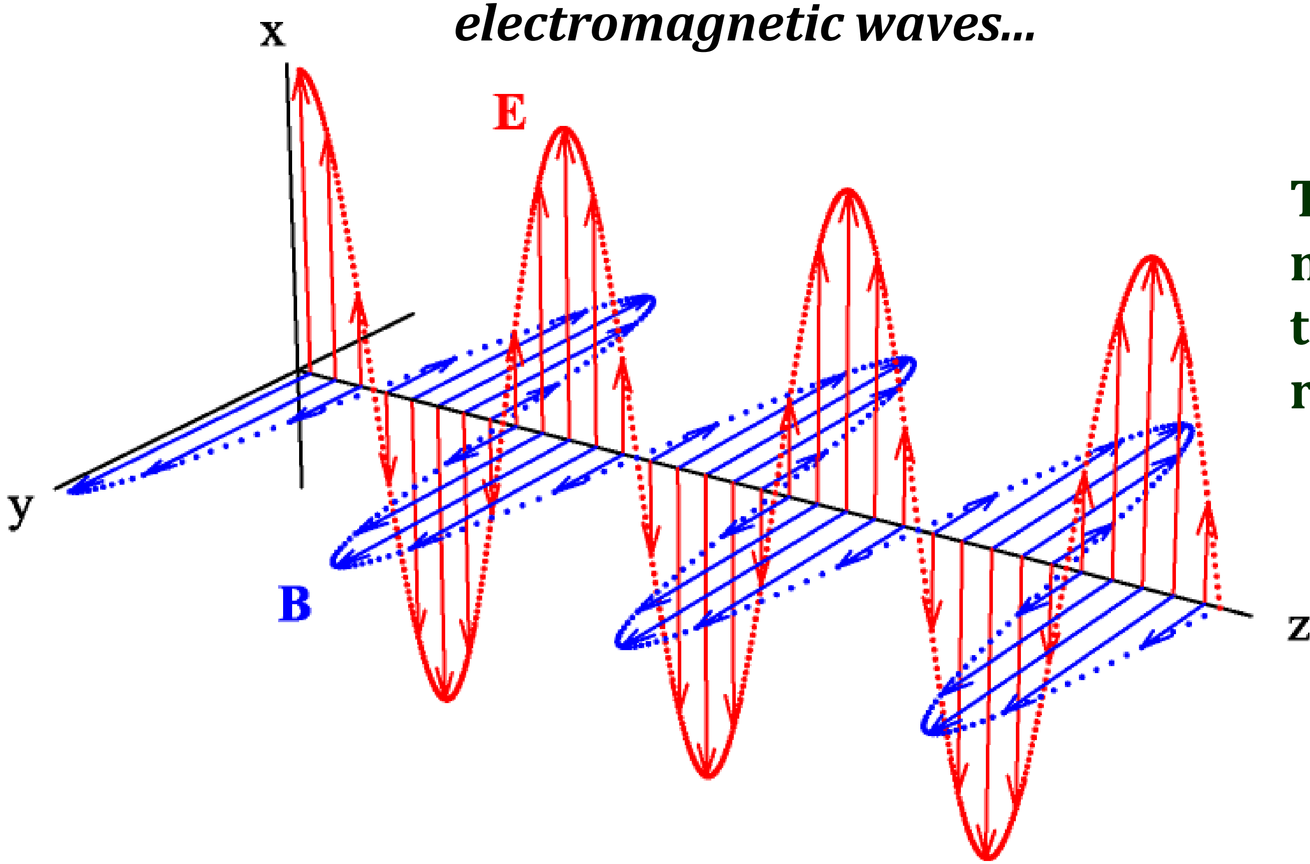
$$\nabla \cdot \mathbf{E} = \rho / \varepsilon_0 \quad \text{and} \quad \nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad \text{and} \quad \nabla \times \mathbf{B} = \mu_o \mathbf{j} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

Faraday Ampere Maxwell

These four equations describe all electromagnetic phenomena, if you know how to interpret them.

Maxwell noted that the field equations can be satisfied by ***electromagnetic waves...***



The electric and magnetic fields go together, in a fixed ratio.

Propagation in the direction of ExB

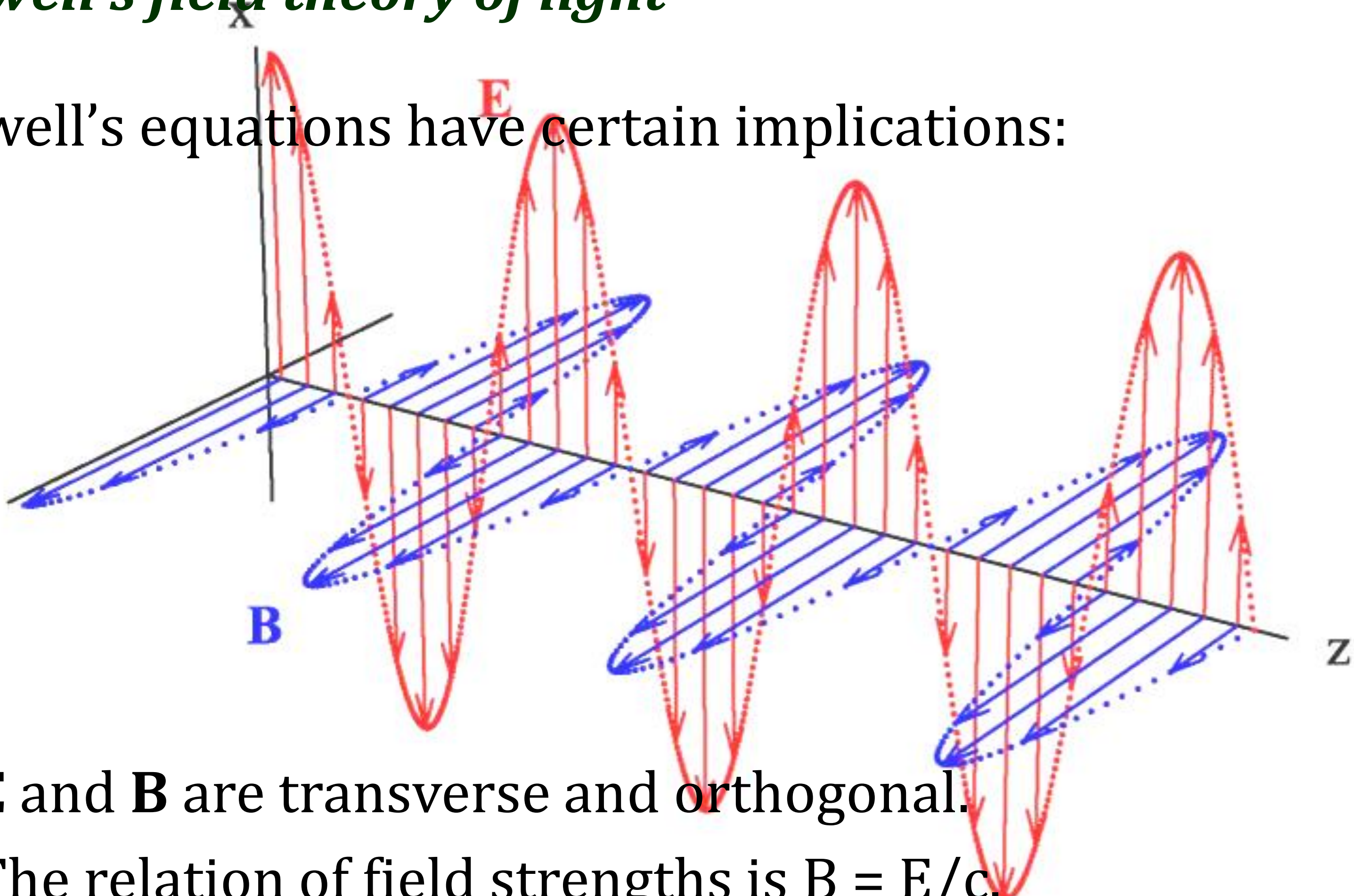
... and the wave speed is

$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} =$$

use the measured values

Maxwell's field theory of light

Maxwell's equations have certain implications:



- **E** and **B** are transverse and orthogonal.
- The relation of field strengths is B = E/c.
- The speed of light is $c = 1/\sqrt{\mu_0\varepsilon_0}$, independent of wavelength, in vacuum.

Wavelength, frequency, and wave speed

$$\lambda f = c$$

That holds for all "harmonic" waves; simply,

$$\frac{\text{distance}}{\text{time}} = \text{speed}$$

Properties of light

Intensity, or brightness

COLOR

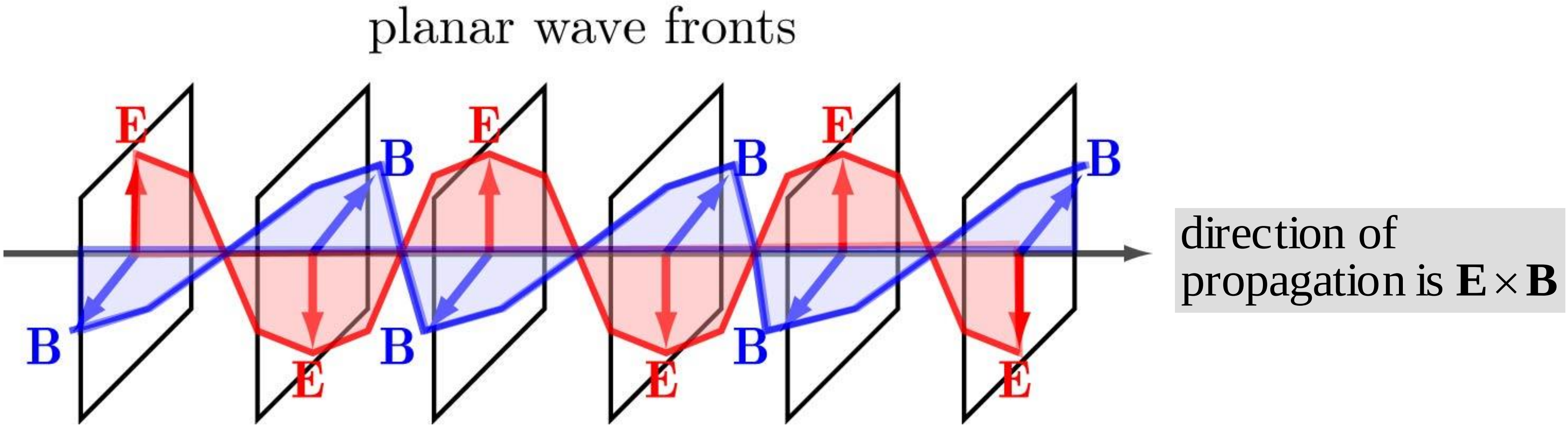
Speed (fast!) — The speed of light is different in different materials.

Direction of motion — Light does not always travel in straight lines.

Polarization — …observed in birefringence of calcite; discussed by Huygens and Newton.

How are these properties explained by the electromagnetic field theory?

Intensity, or brightness



E_0 = amplitude of electric field oscillations

B_0 = amplitude of magnetic field oscillations

$B_0 = E_0/c$ where $c^2 = 1/\varepsilon_0\mu_0$

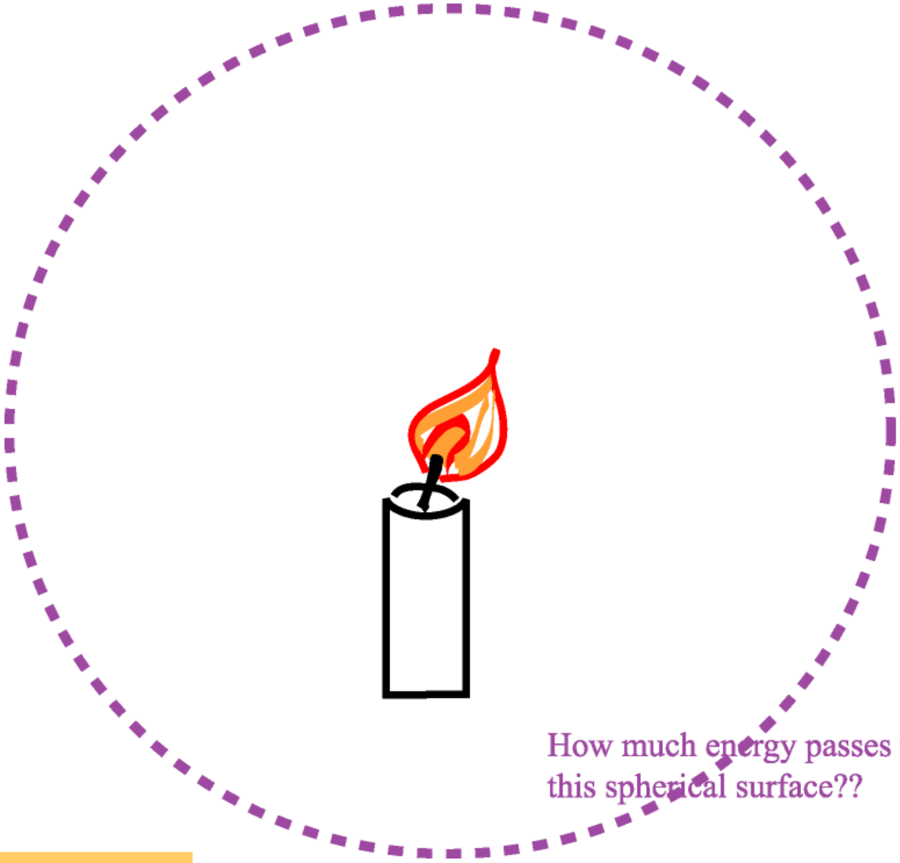
$$\text{energy flux} = \frac{\text{radiant power}}{\text{area}} = c\varepsilon_0 E_0^2$$

Example: The intensity decreases with distance as $1/r^2$ for a point-like source†.

Reason: Conservation of energy.

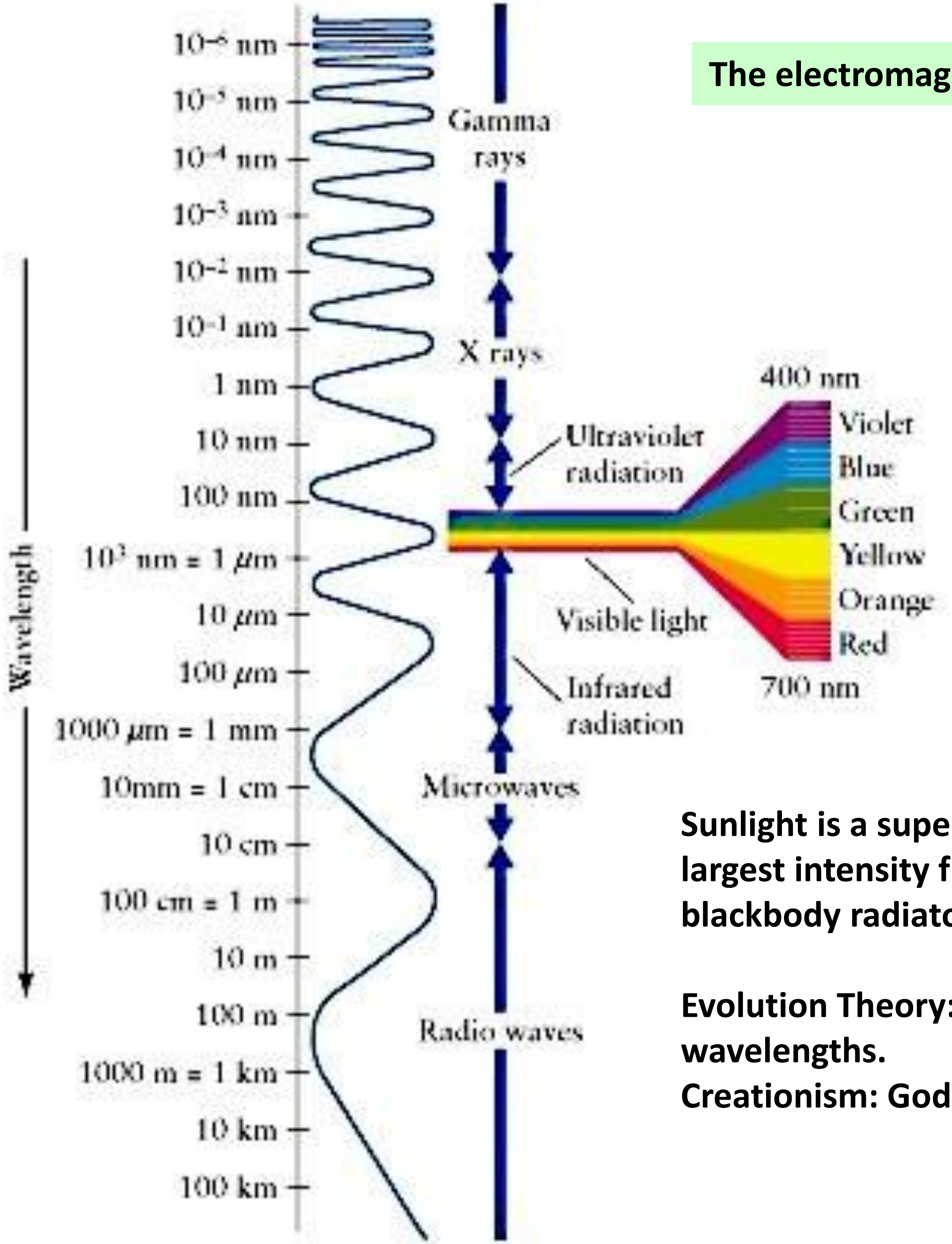
$$I(r) = \frac{P}{A}$$

$$\text{where} \quad A = 4\pi r^2$$



† defining "intensity" as energy flux

The electromagnetic spectrum



Electromagnetic waves exist with any wavelength.

What is so special about visible light?

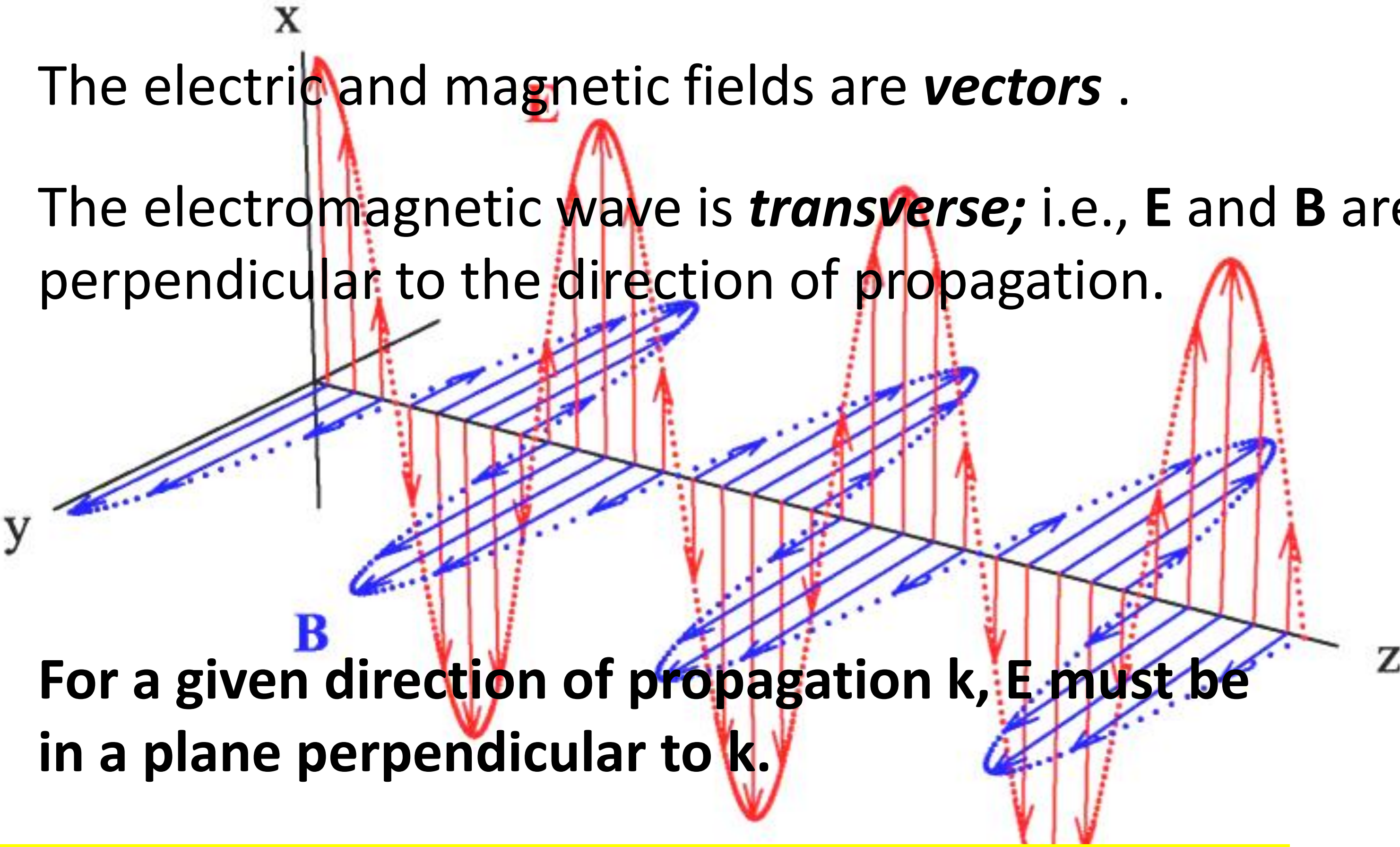
Sunlight is a superposition (mixture) of wavelengths – with largest intensity from 400 to 700 nm - because the sun is a blackbody radiator at about 5800 K.

Evolution Theory: Our eyes evolved to perceive these wavelengths.
Creationism: God made our eyes to see these wavelengths.

Polarization of light

The electric and magnetic fields are ***vectors*** .

The electromagnetic wave is ***transverse;*** i.e., **E** and **B** are perpendicular to the direction of propagation.



For a given direction of propagation k, E must be in a plane perpendicular to k.

For ***<u>polarized light</u>****, the electric field oscillates in only one direction in the transverse plane.*

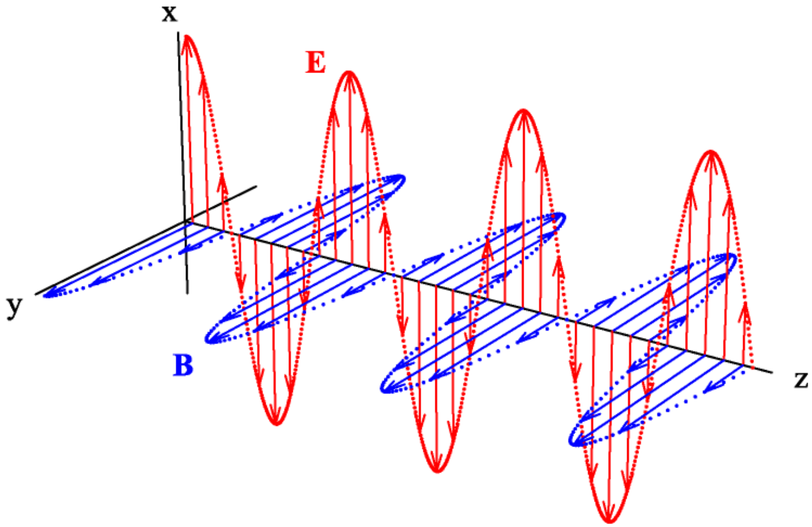
Why do fishermen wear polarized sunglasses?

Sunlight reflects from the water surface. The reflected waves are significantly polarized, having stronger horizontal vibrations of E than vertical.

The sunglasses are designed to absorb the horizontal vibrations.

Velocity of light (speed and direction)

- Electromagnetic waves in vacuum



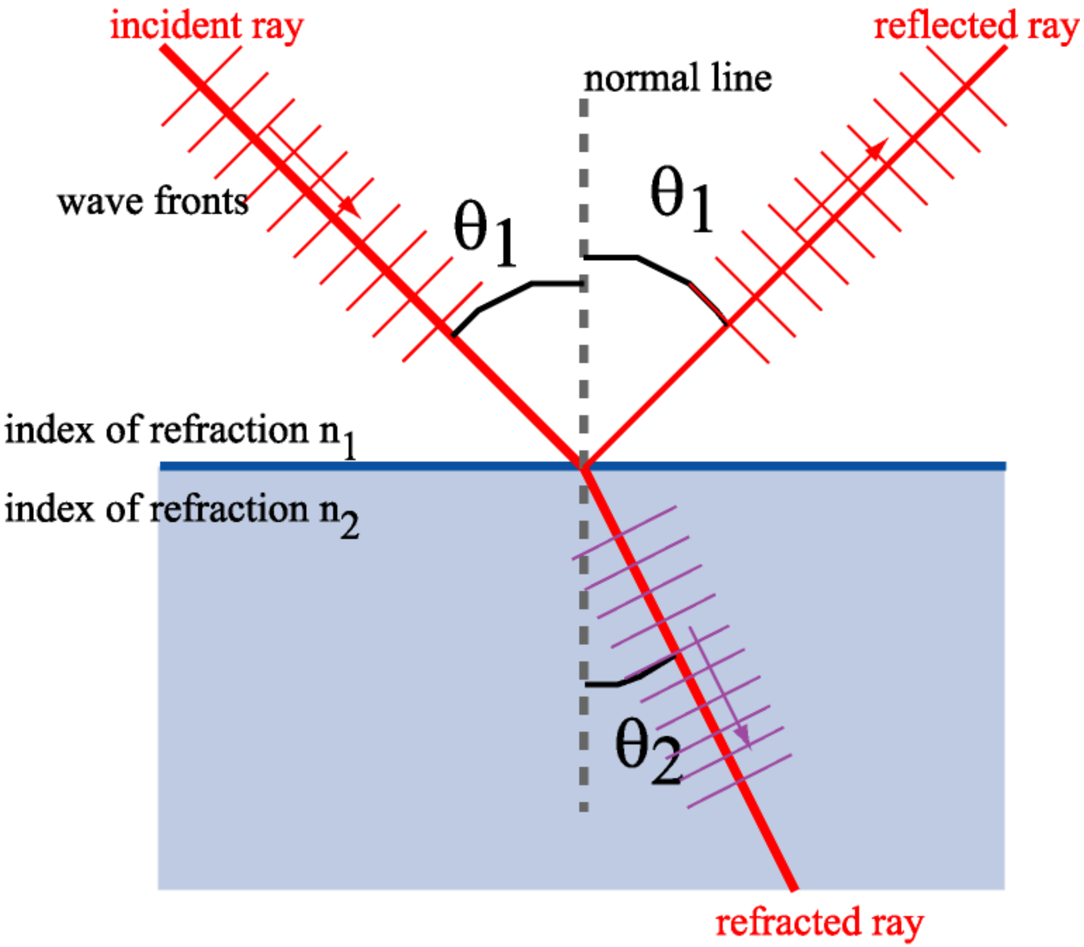
Imagine this wave moving to the right.
As the magnetic field changes there is an induced electric field (Faraday).
As the electric field changes there is an induced magnetic field (Maxwell).
The wave propagates as a whole.

- Electromagnetic waves in a dielectric (air, water, glass, etc)

The fields polarize the atoms (mainly electric polarization and a little bit of magnetic polarization) and the polarized atoms modify the fields. So, the wave propagates at a slower speed.

REFLECTION AND REFRACTION

Reflection and refraction



These materials are dielectrics.

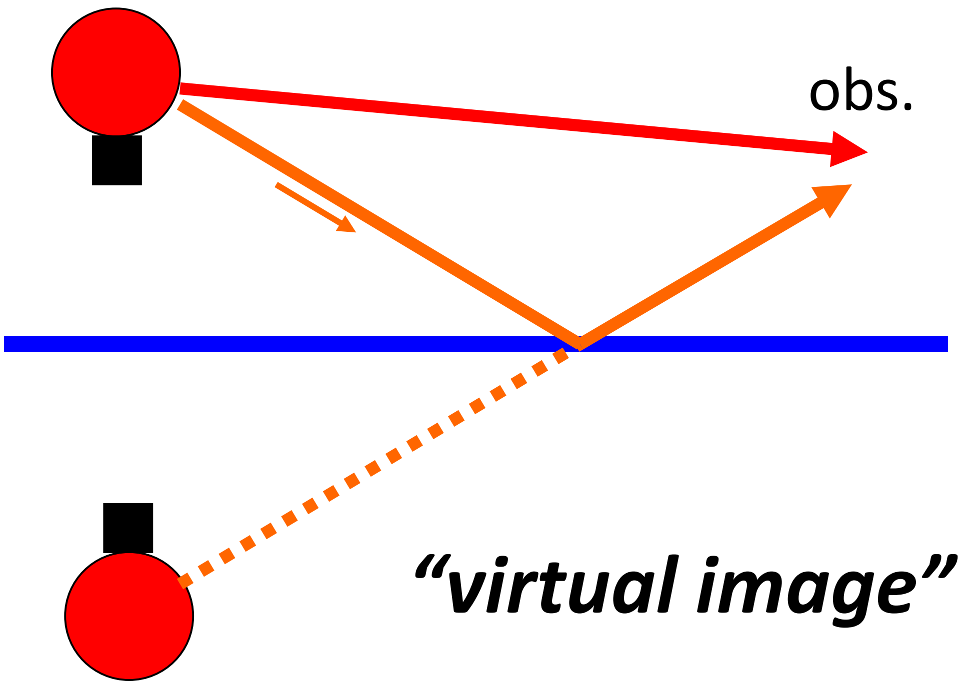
Define ***index of refraction*** ***n by***
n = c/v.

Law of reflection: equal angles

Law of refraction (Snell):

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

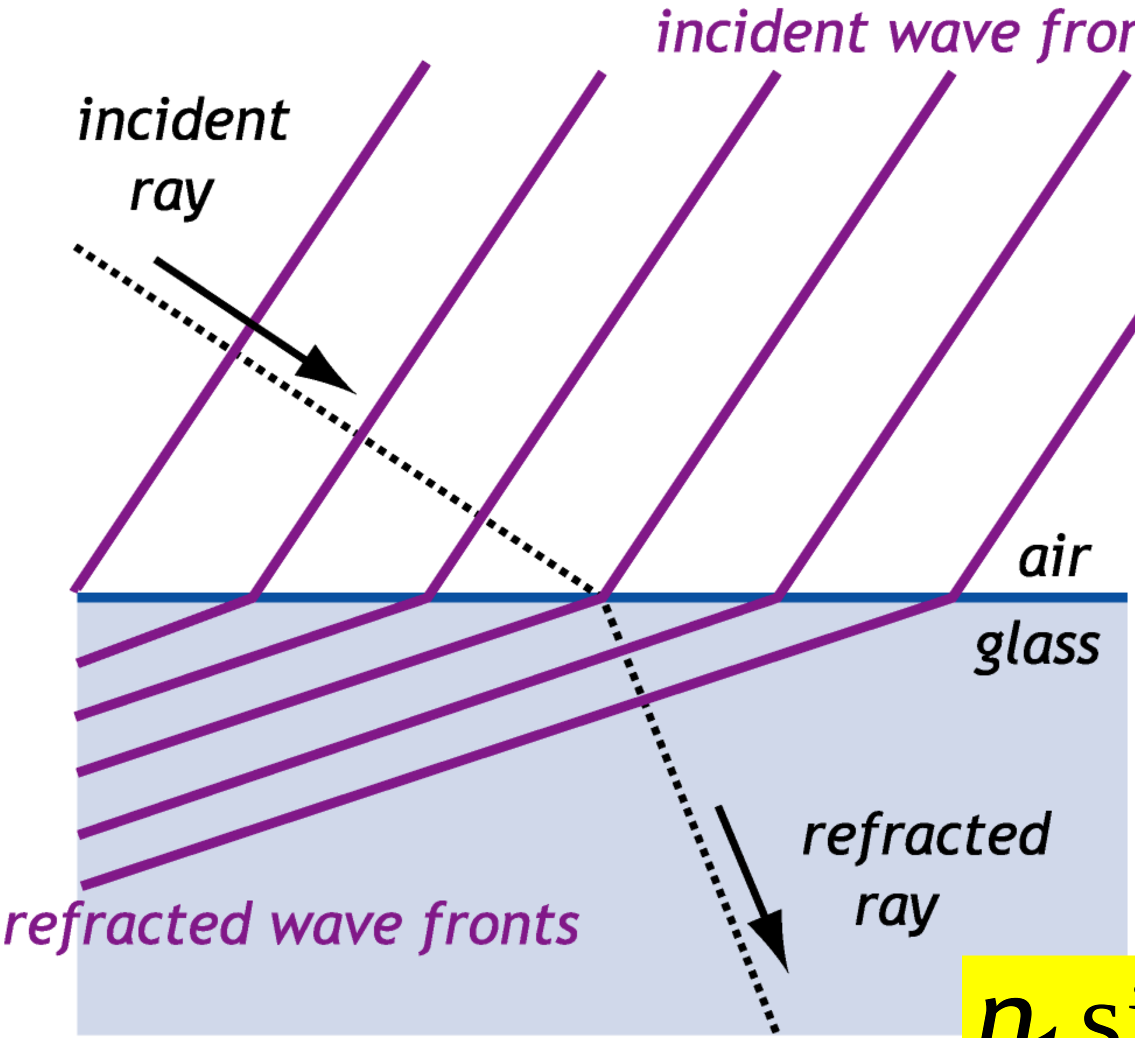
Mirror images



When you look at an object in an ideal mirror, the "image" is the same as if a copy were facing you from an equal distance behind the mirror.

Reflection – The Law of Equal Angles

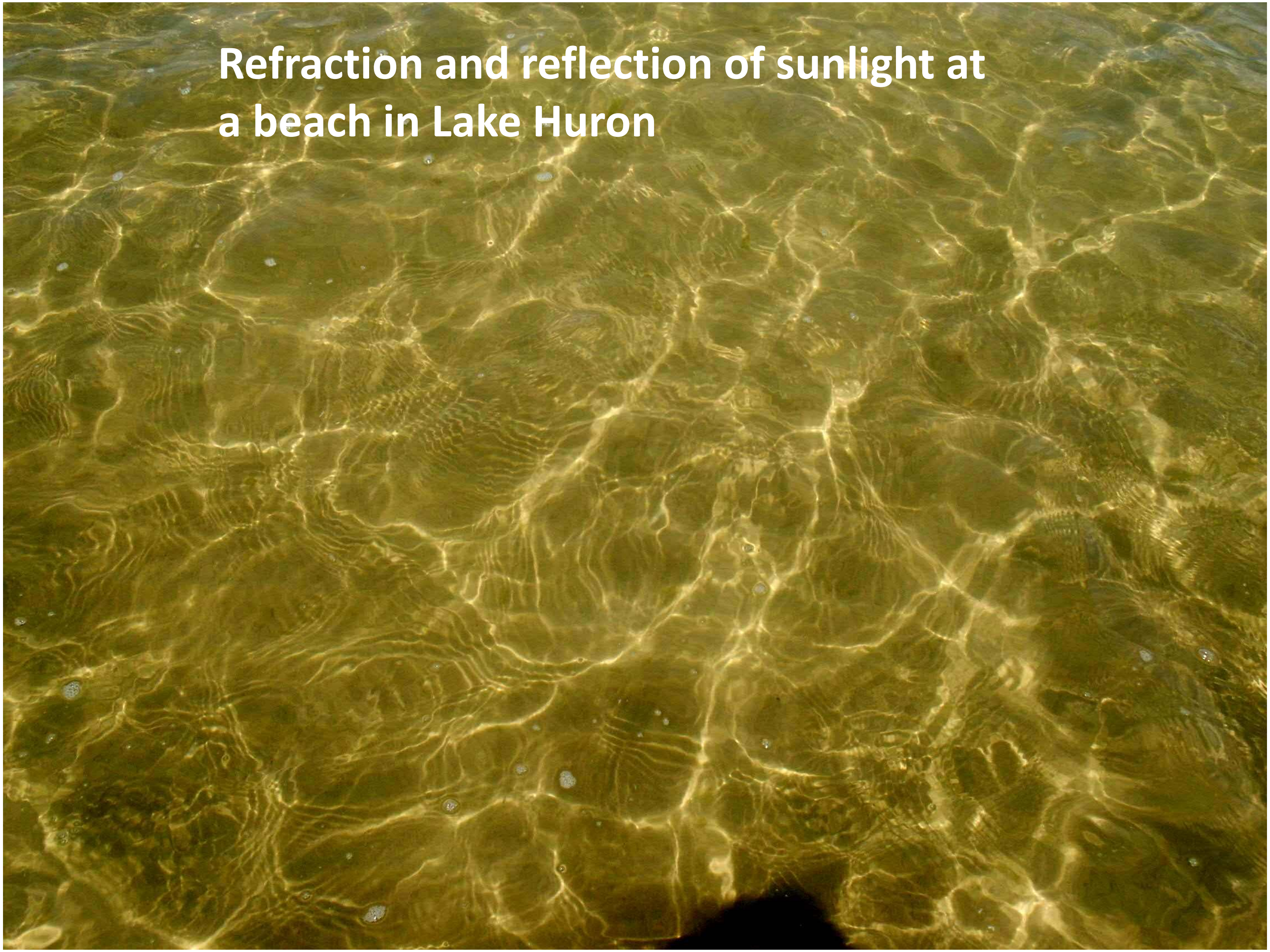
Refraction: The wave slows down so it changes direction.



$$n = c/v$$

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

Why does it look bent?


Refraction and reflection of sunlight at a beach in Lake Huron