# What is Optics? Photonics?

- Think of optics as the science of light. It's a branch of physics that describes the behavior and properties of light and the interaction of light with matter. It's about what light is made of and how it behaves.
- Light allows us to see, but it also transmits sound, cuts things, and controls electrical circuits. That's where photonics comes in.
- Photonics is the science and technology of generating and harnessing light. This includes the emission, transmission, amplification, detection, modulation, and switching of light—much of which is centered around the use of lasers and photodetectors. Light sensors, telecommunications equipment, holographs, CDs, laser surgery, fiber optics, and the Internet are all based on photonics.

Among photonics-based technologies we take for granted today are:

- Barcode scanners, printers, remote control devices;
- Laser surgery, drilling, and surface modification;
- Range finding, navigation;
- Computer networking, circuit boards, and chips;
- CDs, DVDs; and
- Digital cameras.

# Example Applications

- Confocal microscopy
  - optical slicing
  - Fluorescence
  - two-photon
  - real-time
  - Holographic
  - Spectroscopic
  - bio-imaging, imaging through turbulence
- Super-resolution
  - apodizing filters
  - hybrid (optics+signal processing) approaches
  - information-theoretic viewpoint
  - meta-materials (invisible cloak?)
- Optical data storage
  - optical disks (CD's, DVD's, MO disks)
  - holographic memories

- Optical Communication
  - Fiber Optics
  - Optical switching and modulation
    - optical MEMS
    - electro-optics
    - acousto-optics
- Statistical optics
  - Coherence imaging (van Cittert-Zernicketheorem, radio astronomy)
  - Optical coherence tomography
  - X-ray tomography
- Lasers Spectroscopy
- Laser cooling of atoms/molecules
- Laser trapping (optical tweezers) of atoms/molecules

# What is Light?

And God said, “let there be light”, and there was light.

# And God said

$$\oint \overline{E} \bullet \overline{dl} = -\int \frac{\partial \overline{B}}{\partial \tau} \bullet \overline{ds}$$
$$\oint \overline{H} \bullet \overline{dl} = \int \left( \overline{J}_c + \frac{\partial \overline{D}}{\partial \tau} \right) \bullet \overline{ds}$$
$$\oint \overline{D} \bullet \overline{ds} = \int \nabla \bullet \overline{D}\, dv$$
$$\oint \overline{B} \bullet \overline{ds} = 0$$

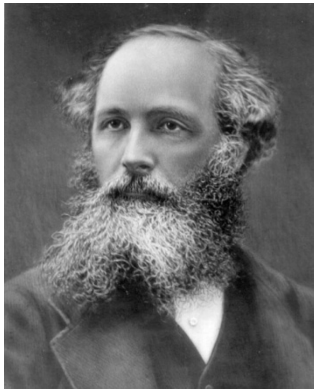
OR

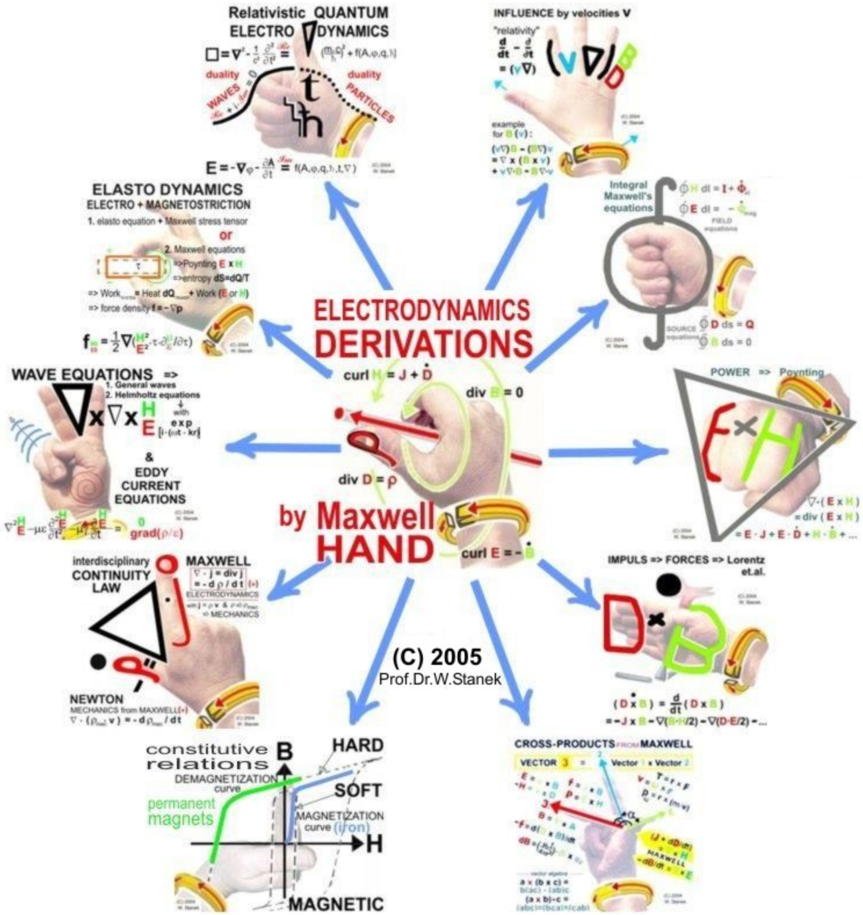
$$\nabla \times \overline{E} = -\mu \frac{\partial \overline{H}}{\partial \tau}$$
$$\nabla \times \overline{H} = \overline{J}_C + \varepsilon \frac{\partial \overline{E}}{\partial \tau}$$
$$\nabla \bullet \overline{D} = \rho_v$$
$$\nabla \bullet \overline{B} = 0$$

OR

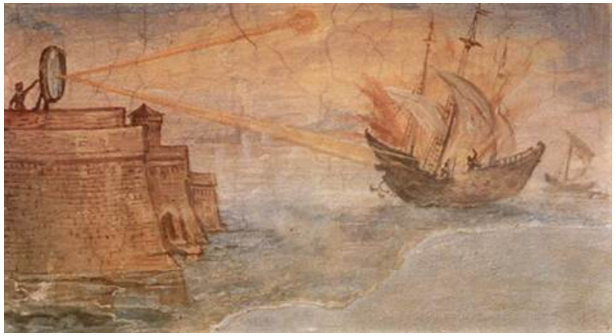
$$\nabla \times \overline{E} = -\mu \frac{\partial \overline{H}}{\partial \tau}$$
$$\nabla \times \overline{H} = J_c + \varepsilon \frac{\partial \overline{E}}{\partial \tau}$$
$$\nabla \bullet \overline{D} = \rho_v$$
$$\nabla \bullet \overline{B} = 0$$

# and there was light





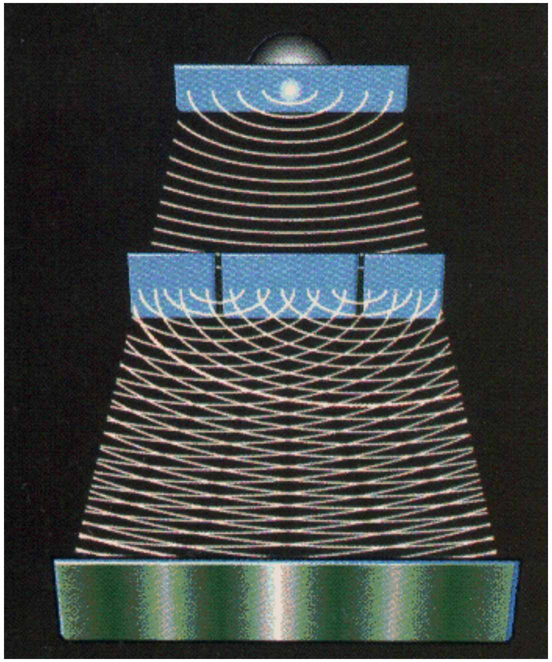
# Brief (*western-*)History of Optics



*A legend of Archimedes (no evidence)* link

- Ancient Greeks (~5-3 century BC)
  - Pythagoras (rays emerge from the eyes)
  - Democritus (bodies emit "magic" substance, simulacra)
  - Plato (combination of both of the above)
  - Aristotle (motion transfer between object & eye)
- Middle Ages
  - Alkindi, Alhazen defeat emission hypothesis (~9-10 century AD)
  - Lens is invented by accident (northern Italy, ~12thcentury AD)
  - Della Porta, da Vinci, Descartes, Gallileo, Kepler formulate geometrical optics, explain lens behavior, construct optical instruments (~15thcentury AD)
- Beyond the middle ages:
  - Newton (1642-1726) – "Particle"
  - Huygens (1629-1695) – "Wave"

# Brief History of Optics



- 18th –19th centuries
  - Fresnel, Young experimentally observe diffraction, question Newton's particle theory
  - Maxwell formulates electro-magnetic equations, Hertz verifies antenna emission principle (1899)
- 20th century
  - Quantum Mechanics (Black-body radiation, Plank's constant, photoelectric effects, atoms)
  - Quantum theory explains wave-particle duality Quantum Electrodynamics (QED)
  - Invention of holography (1948)
  - Invention of laser (1956)
  - Optical applications proliferate: computing, communications, fundamental science, medicine, manufacturing, entertainment.

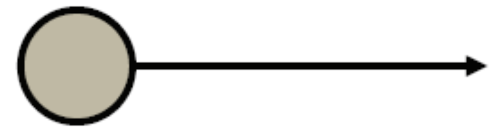
# Wave-Particle Duality of Light

"Light behaves like waves in its propagation and in the phenomena of interference and diffraction; however, it exhibits particle-like behavior when exchanging energy with matter, as in the Compton and photoelectric effects."

Pedrotti^3, p. 4

# Wave-Particle Duality of Light

Photon=elementary light particle



Energy $E=h\nu$

$h$=Planck's constant
$=6.6262\times10^{-34}$ J sec

$\nu$=frequency ($sec^{-1}$)
$\lambda$=wavelength (m)

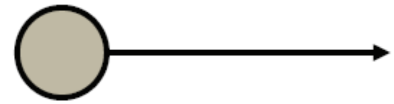
$$c=\lambda\nu$$

"Dispersion relation"

(holds in vacuum only)

# Particle Nature of Light

Photon=elementary light particle



Mass=0

Speed $c=3\times10^{8}$ m/sec

*According to Special Relativity, a mass-less particle travelling at light speed can still carry energy (& momentum)!*

Energy $E=h\nu$ → relates the dual particle & wave nature of light;

$h$=Planck's constant

$=6.6262\times10^{-34}$ J sec

$= 4.1357\times10^{-15}$ eV s

$\nu$ is the temporal oscillation frequency of the light waves

$$N\,[\#/\,s] = \frac{Power}{Energy\,/\,photon} = \frac{[Watt = J\,/\,s]}{[J]}$$

N is the number of photons per second.

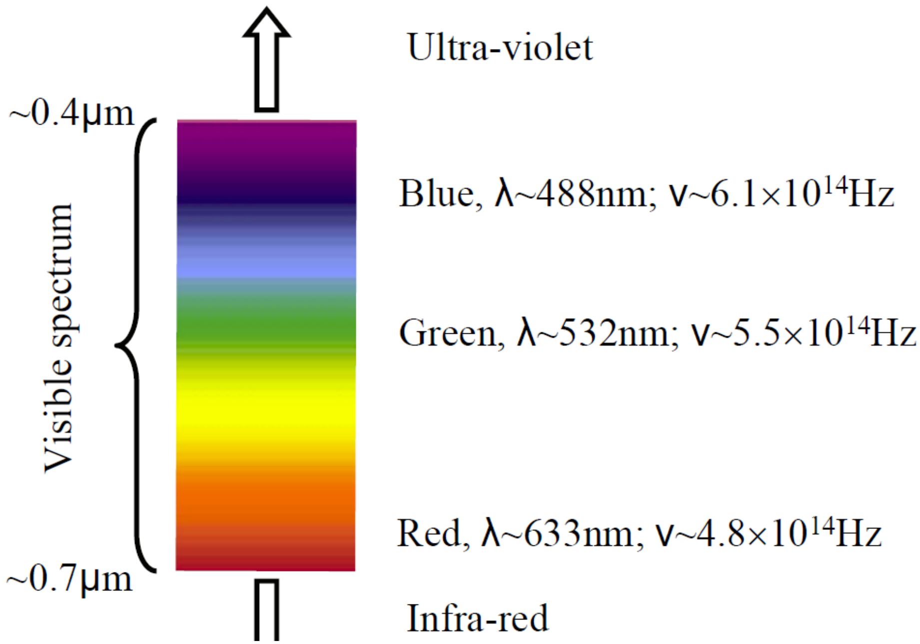
See Example 1-2, page 10 in Pedrotti[3].

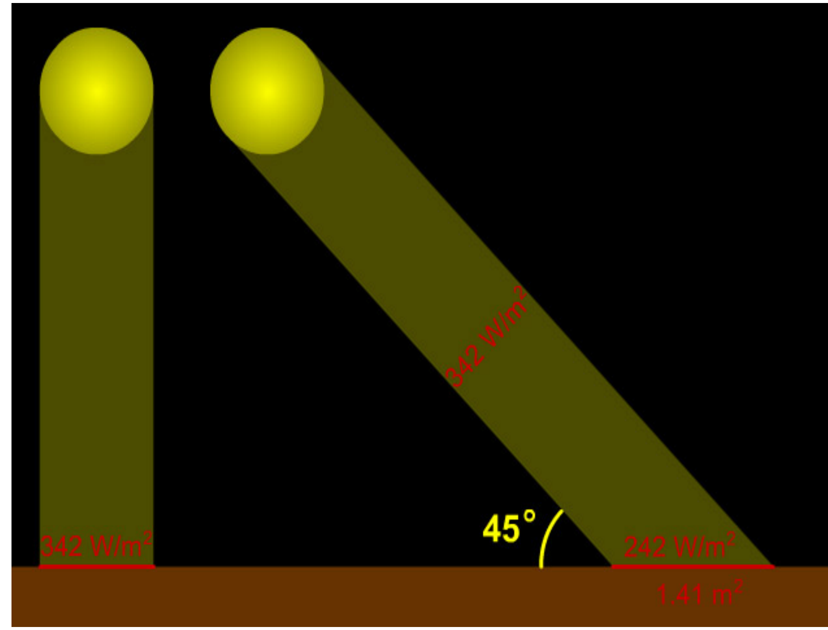
# Example 1-1

# What is light?

- Light is a form of **electromagnetic energy** – detected through its effects, e.g. heating of illuminated objects, conversion of light to current, mechanical pressure ("Maxwell force") etc.
- Light energy is conveyed through particles: "photons"
  - –ballistic behavior, e.g. shadows
- Light energy is conveyed through waves
  - –wave behavior, e.g. interference, diffraction
- Quantum mechanics reconciles the two points of view, through the "wave-particle duality" assertion

# What is Light?

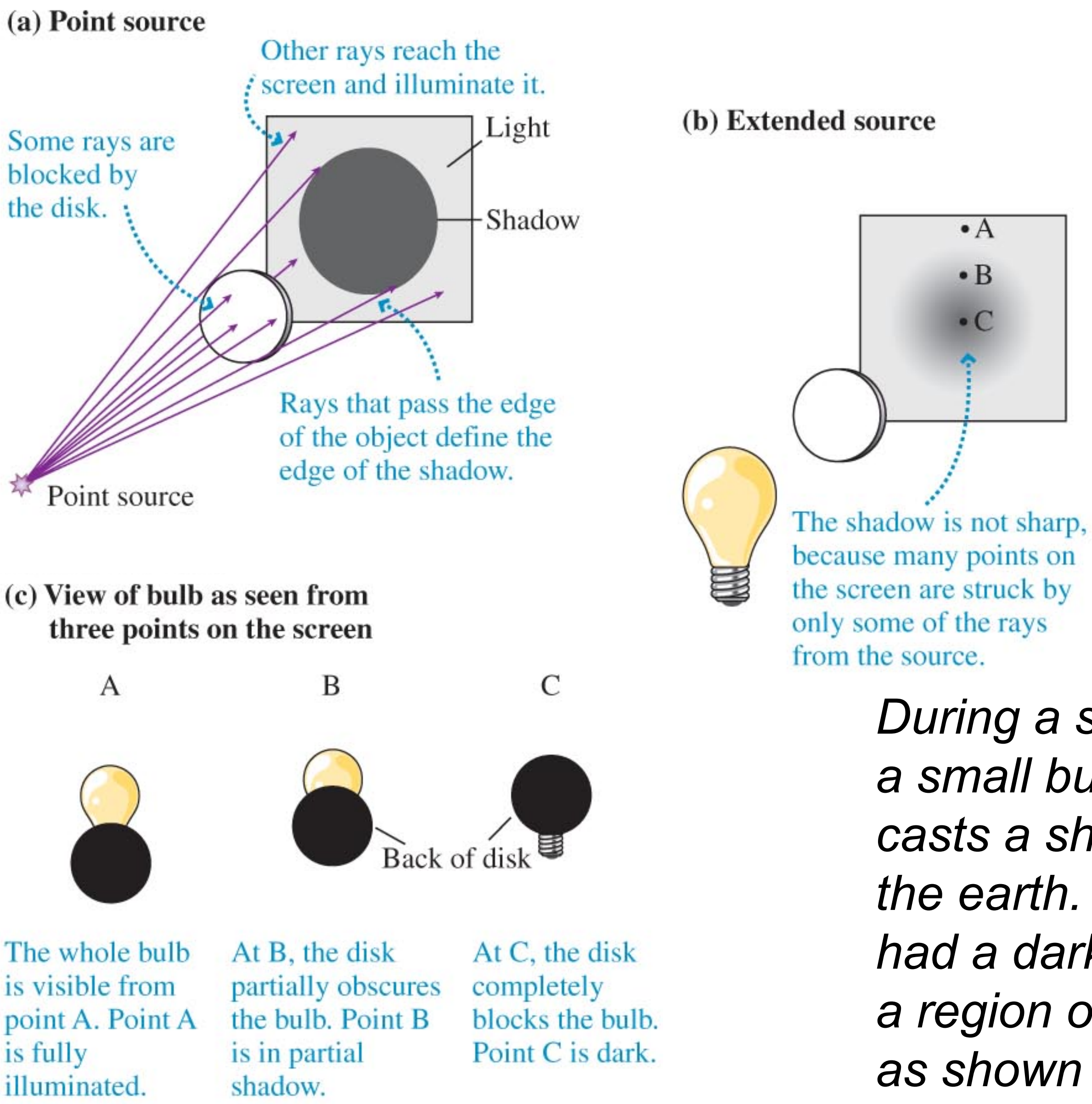



When the Sun is directly overhead, its rays strike Earth perpendicular to the ground and so deliver the maximum amount of energy. When the Sun is lower in the sky, a sunbeam strikes the ground at an angle (in the example above, 45°) and so its energy is "spread out" over a larger area... thus "diluting" its energy. In this example, the energy is spread over an area of 1.41 square meters (instead of 1 square meter when the Sun is directly overhead), so the energy per unit area is reduced from 342 W/m2 to 242 W/m2 (342 ÷ 1.41 = 242).
Credit: Artwork by Randy Russell.

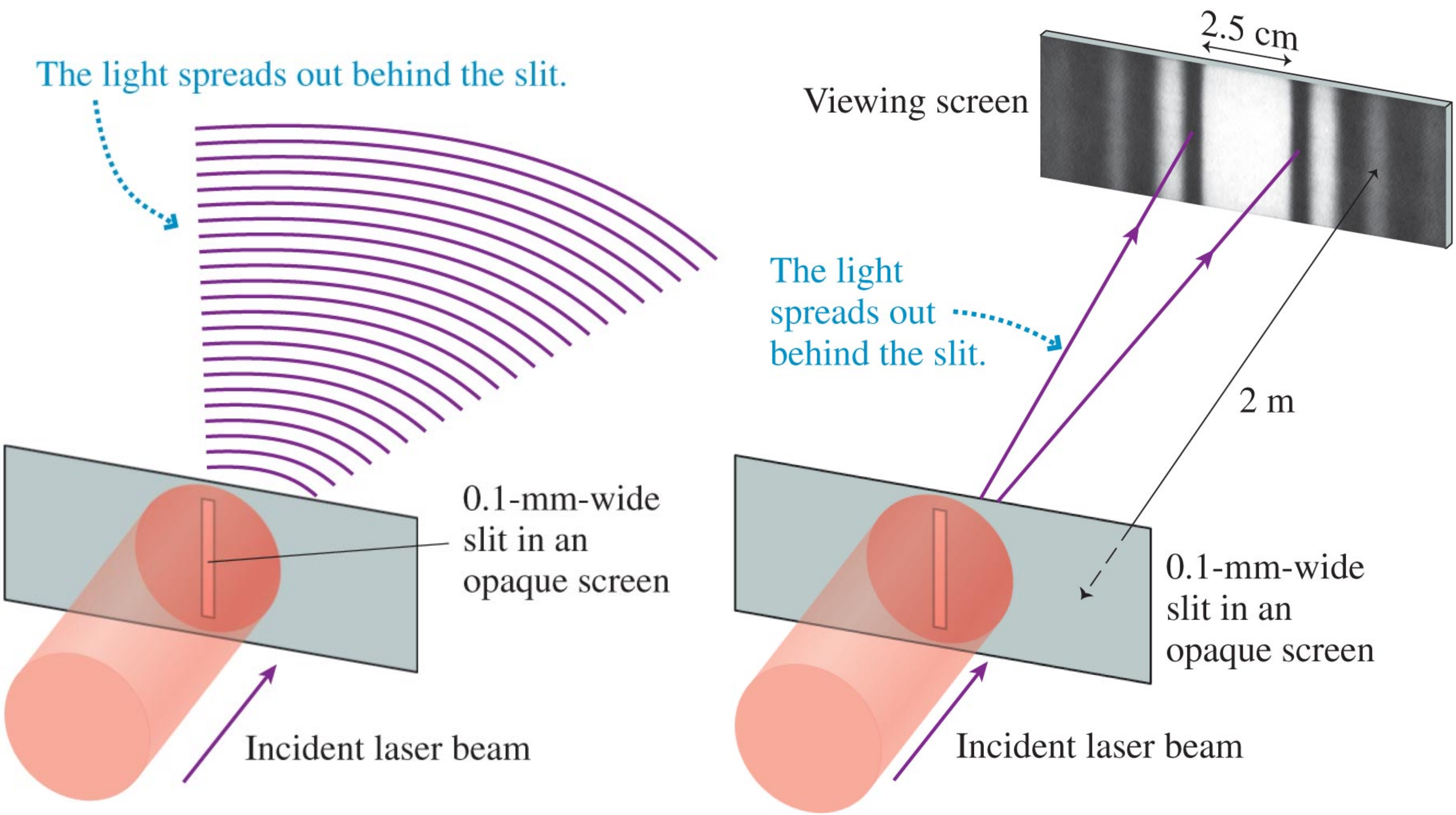
http://www.windows2universe.org/earth/climate/sun_radiation_at_earth.html

# Shadows




*During a solar eclipse, the sun – a small but extended source – casts a shadow of the moon on the earth. The moon's shadow had a dark center surrounded by a region of increasing brightness as shown in (b).*

# Light waves also spread out behind a very narrow slit




Will come back to the single slit case in a bit

# Wave Nature of Light

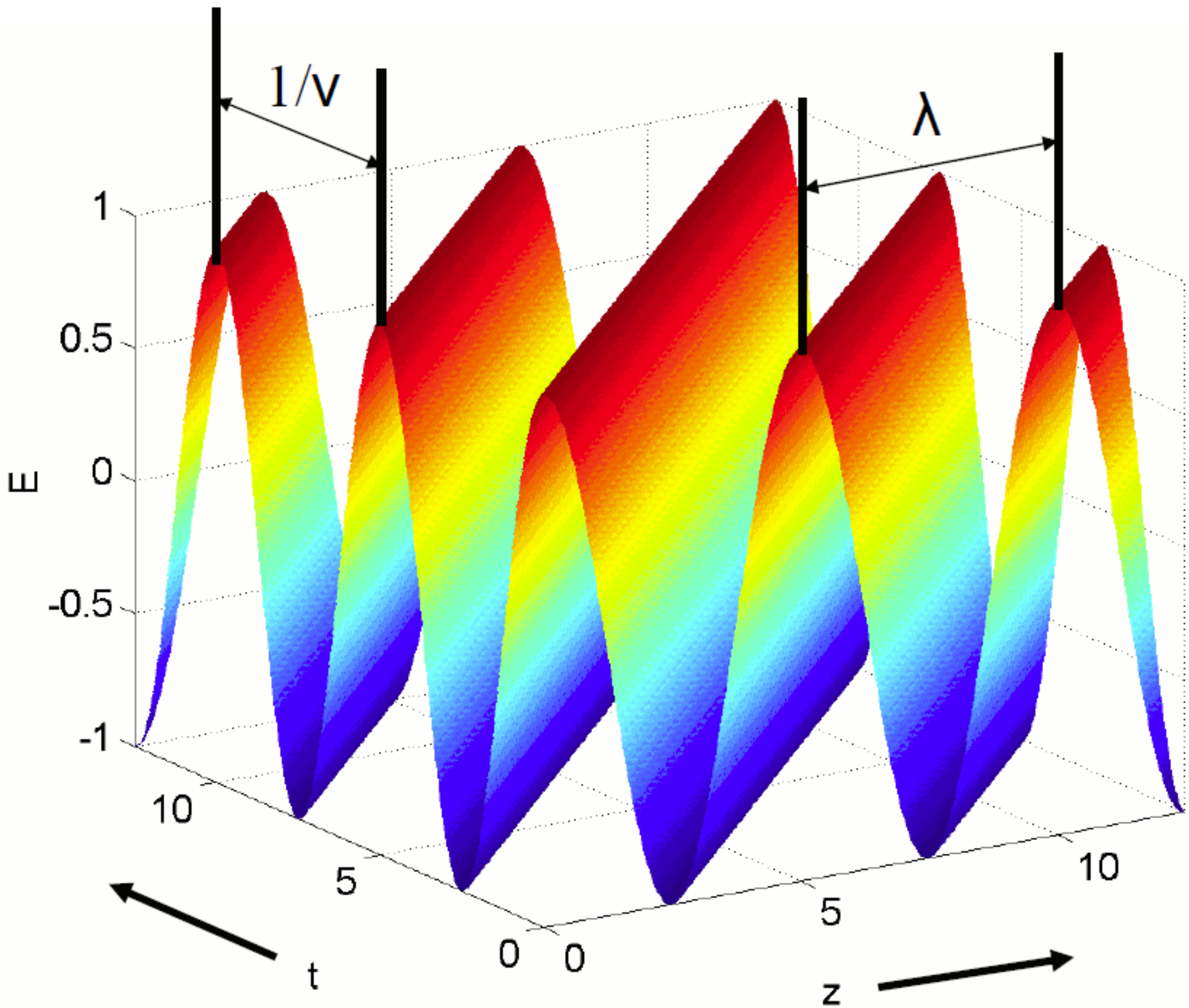
λ: **wavelength**
(spatial period)

$k=2\pi/\lambda$
wavenumber

ν: temporal
**frequency**

$\omega=2\pi\nu$
angular frequency

E: electric
field

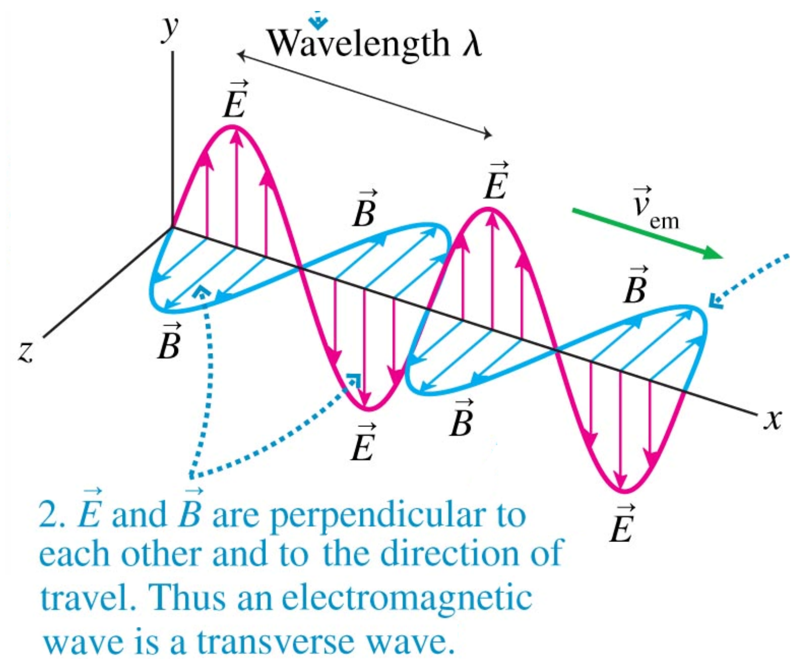


# Maxwell's theory

- Maxwell showed that E and B fields could sustain themselves (free from charges or currents) if they took the form of an electromagnetic (EM) wave.
- Maxwell's theory predicted that an EM wave would travel with speed:

$$v_{em} = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$

$$v_{em} = c = \text{ speed of light}$$




**Light is an electromagnetic wave!**

Animation http://www.walter-fendt.de/ph14e/emwave.htm

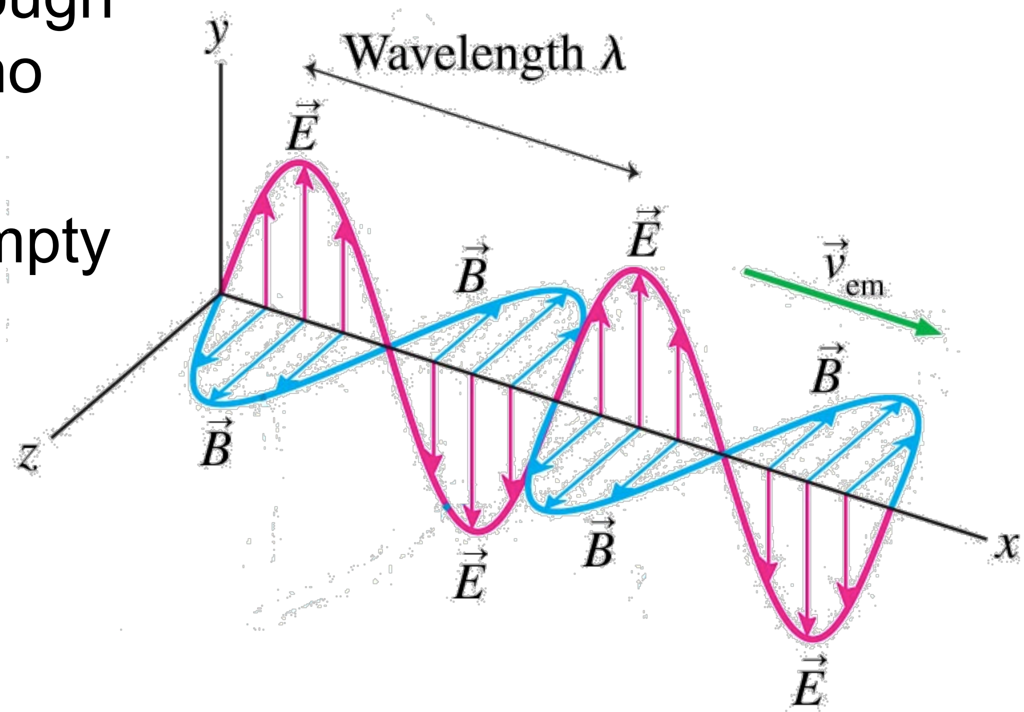
# Electromagnetic (EM) Waves

- EM waves can travel through empty space (vacuum); no medium is necessary!
- The speed of light **c** in empty space is

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

$$= 299{,}792{,}458 \text{ m/s}$$

**$c = 3\text{x}10^8$ m/s**




- EM waves carry energy and momentum
- The **speed is constant** so the frequency f is determined by the wavelength λ and speed of light c:

$$f = c / \lambda$$

# Intensity of an Electromagnetic Wave

$$I = \frac{P}{A} = \frac{1}{2} c \epsilon_0 E_0^2 = \frac{1}{2} \frac{c}{\mu_0} B_0^2$$

Intensity of an electromagnetic wave with field amplitudes $E_0$ and $B_0$

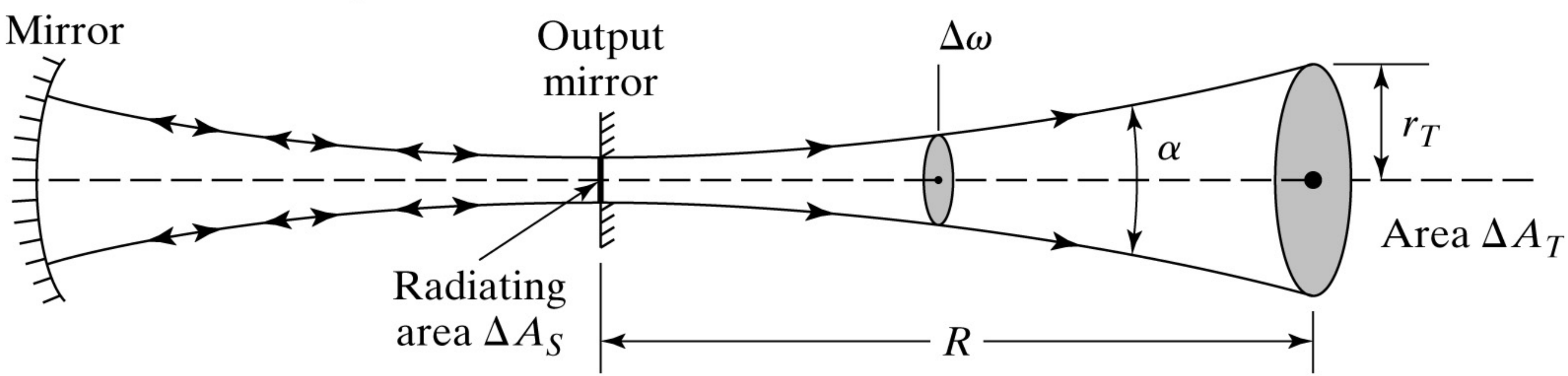
We will discuss in details in Ch. 4-8.

# Example 1-3

**TABLE 1-1** RADIOMETRIC TERMS

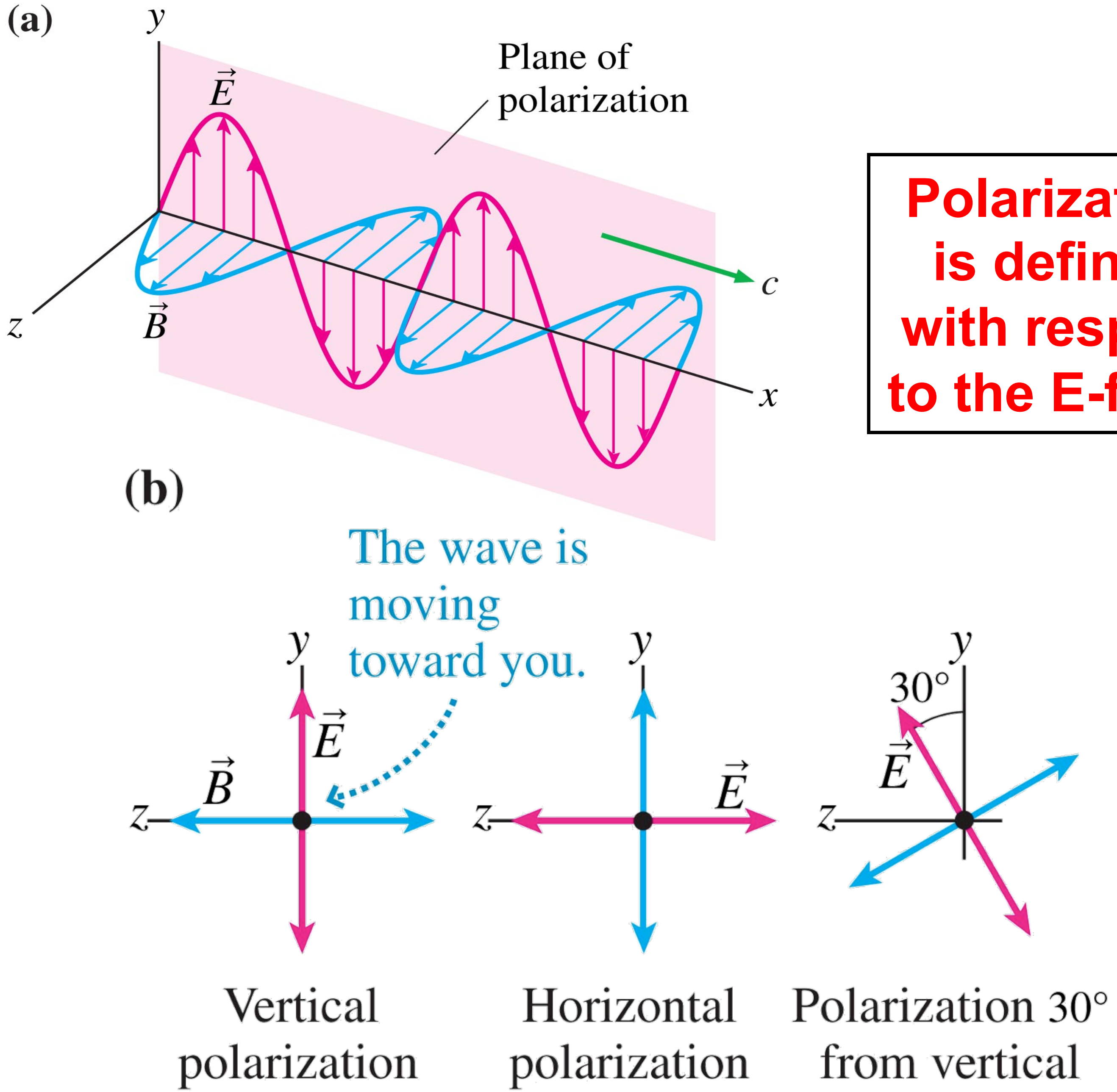
| Term | Symbol (units) | Defining equation |
|---|---|---|
| Radiant energy | $Q_e(\mathrm{J} = \mathrm{W} \cdot \mathrm{s})$ | — |
| Radiant energy density | $w_e(\mathrm{J/m^3})$ | $w_e = dQ_e/dV$ |
| Radiant flux, Radiant power | $\Phi_e(\mathrm{W})$ | $\Phi_e = dQ_e/dt$ |
| Radiant exitance | $M_e(\mathrm{W/m^2})$ | $M_e = d\Phi_e/dA$ |
| Irradiance | $E_e(\mathrm{W/m^2})$ | $E_e = d\Phi_e/dA$ |
| Radiant intensity | $I_e(\mathrm{W/sr})$ | $I_e = d\Phi_e/d\omega$ |
| Radiance | $L_e\left(\dfrac{\mathrm{W}}{\mathrm{sr} \cdot \mathrm{m}^2}\right)$ | $Le = dI_e/dA\cos\theta$ |

Abbreviations: J, joule; W, watt; m, meter; sr, steradian.



# Polarization

From Chapter 25

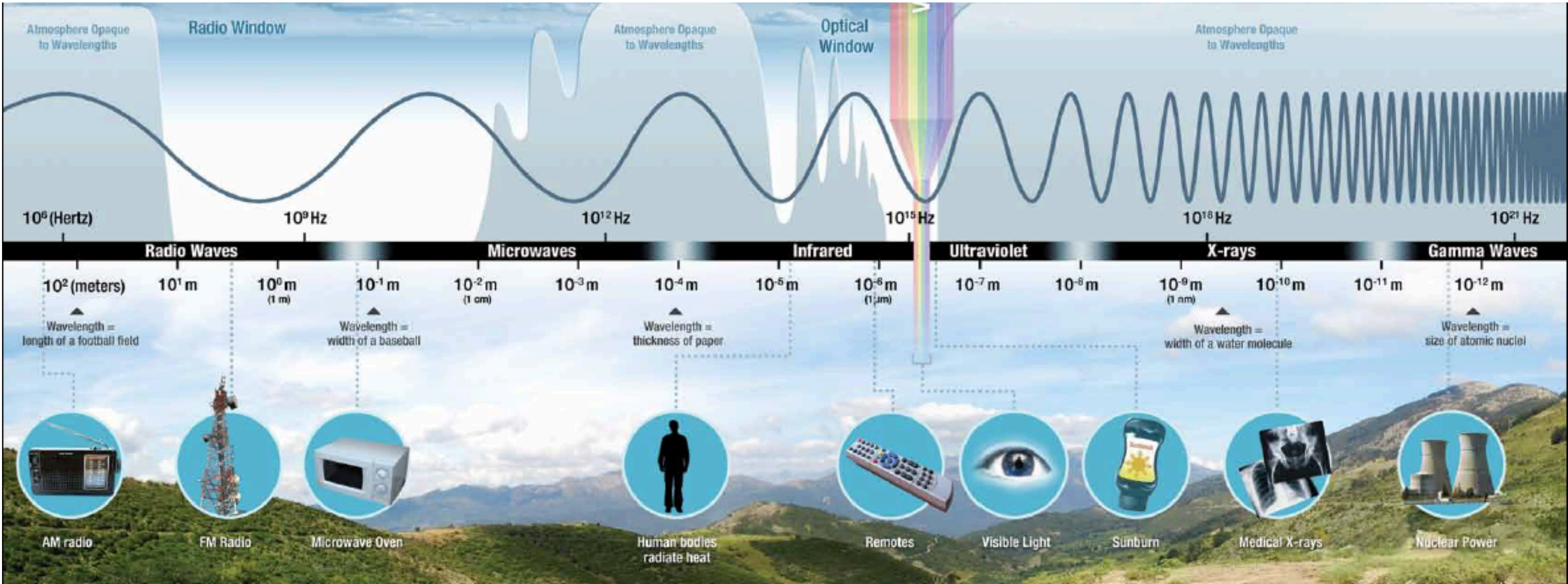



**Polarization is defined with respect to the E-field.**

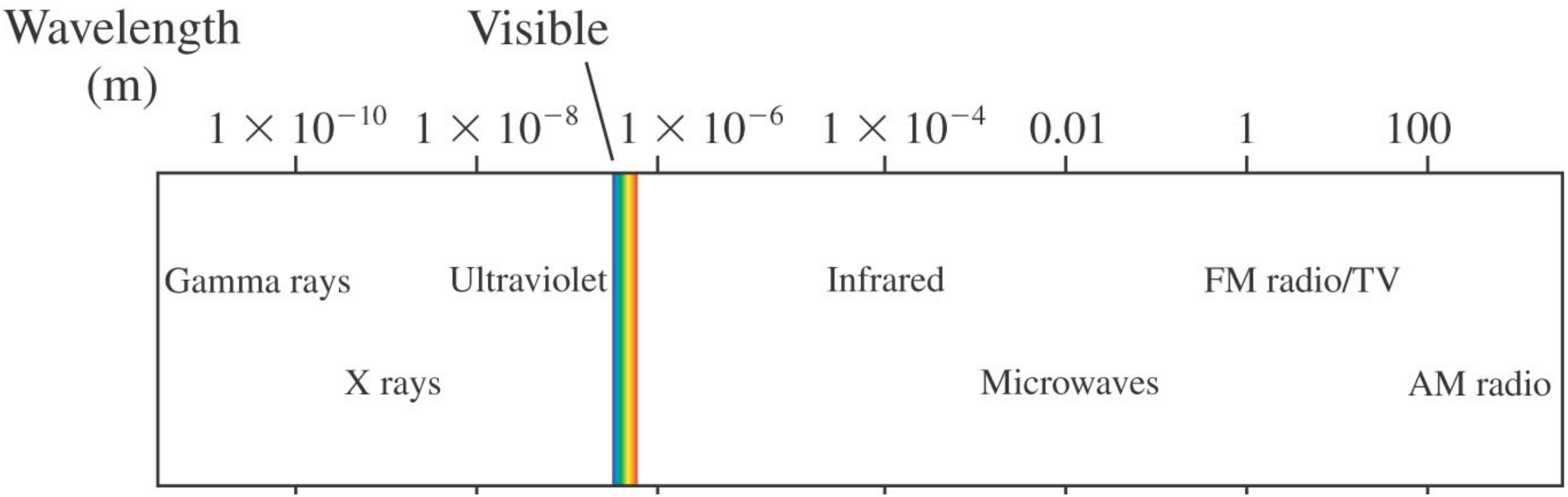
# Tour of the Electromagnetic Spectrum

A 5-min video tour
http://missionscience.nasa.gov/ems/emsVideo_01intro.html

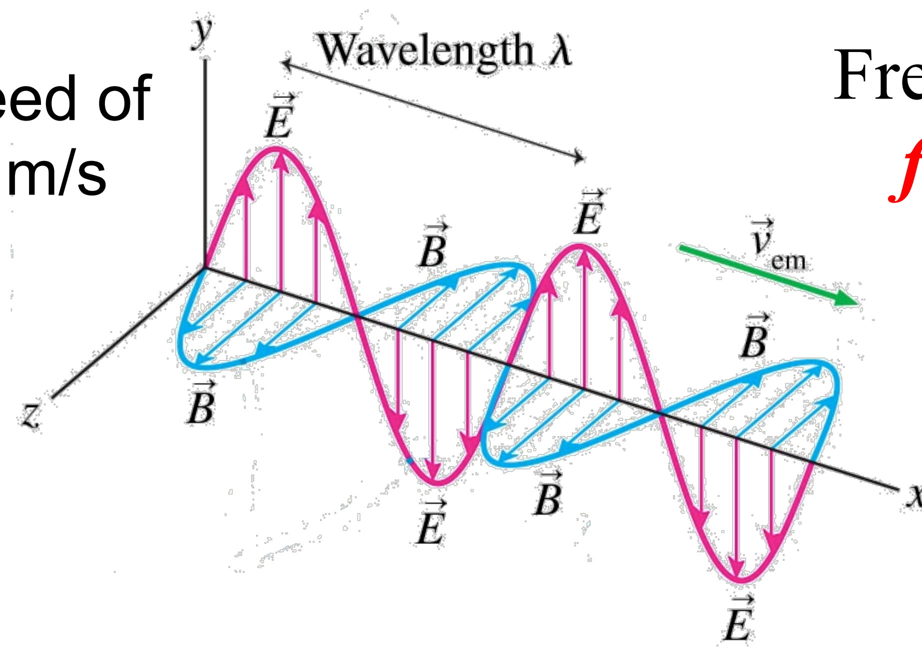
Introductions to various part of the EM spectrum
http://missionscience.nasa.gov/ems/index.html



# Remember the EM Spectrum




In a vacuum, speed of light is $c = 3x10^8$ m/s




Frequency,
$f = c/\lambda$

# The Electromagnetic Spectrum