

Physics 24100

Electricity & Optics

Lecture 22 – Chapter 31 sec. 1-4,6

Fall 2012 Semester

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Question

- The magnetic field component of a radio wave is expressed:

$$B_y = B_0 \sin(kz - \omega t)$$

- In which directions do the Poynting vector and the $\vec{E}$ -field point?

(a) +z,+x

(b) +z,-x

(c) -z,+x

(d) -z,-x

(e) +y,+x

Question

- First, what is the direction of propagation?
 - General solution to the wave equation:

$$f(z, t) = f_+(z - vt) + f_-(z + vt)$$



Wave moving in the +z direction



Wave moving in the -z direction

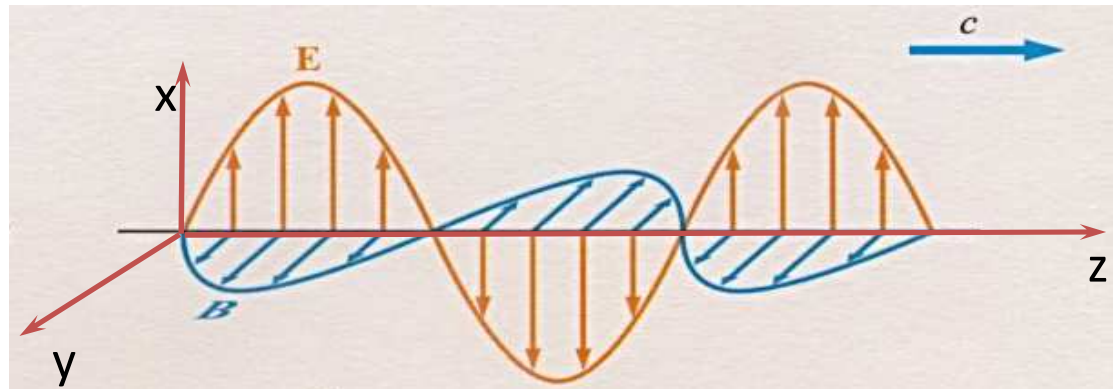
The equation for the wave we were given was

$$B_y = B_0 \sin(kz - \omega t)$$

It is moving in the +z direction.

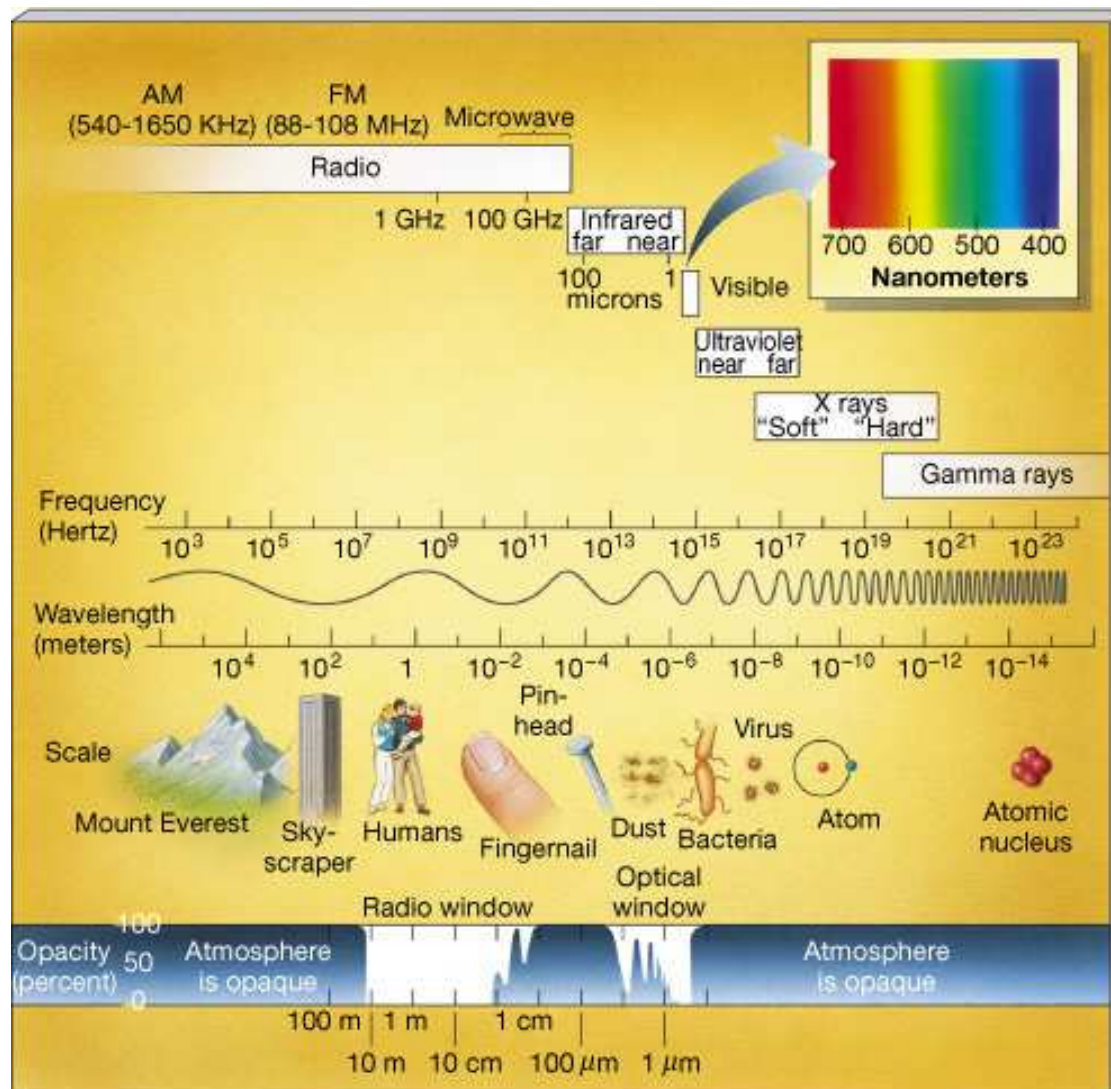
Question

- What is the direction of the $\vec{E}$ field?



- The Poynting vector, $\vec{S} = \frac{\vec{E} \times \vec{B}}{\mu_0}$, is in the direction of propagation.
- If $\vec{B}$ is in the +y direction and $\vec{S}$ is in the +z direction, then $\vec{E}$ must be in the +x direction.

Electromagnetic Spectrum



Speed of Light

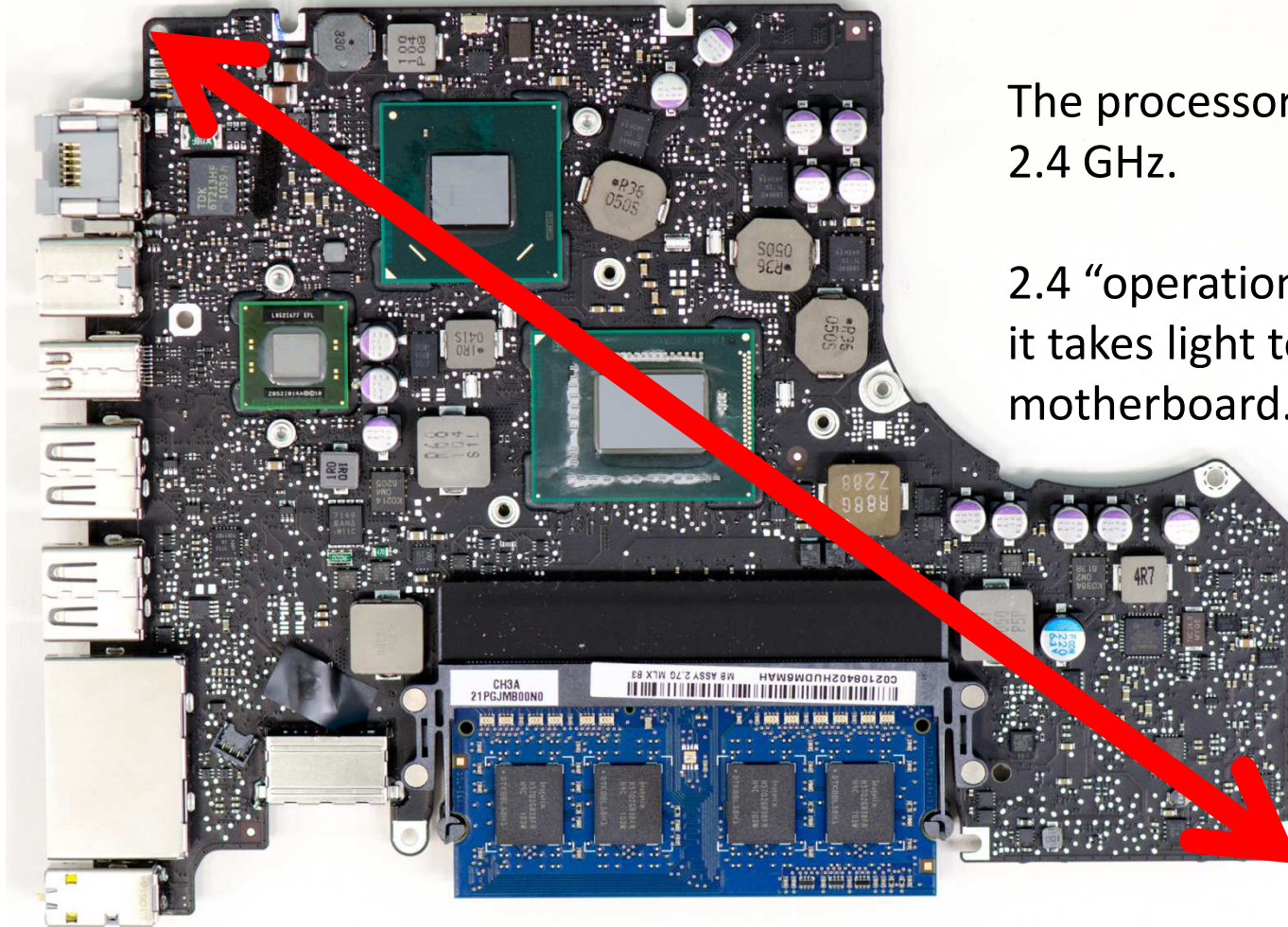
- How fast is $2.998 \times 10^8 \text{ m/s}$?
- One imperial foot is 30.48 cm .
- The speed of light is about 1 foot per ns.
 - Easy to remember
 - In 1675 this was quite fast
 - “Slow” by today’s standards...

Speed of Light

Motherboard is about 1 foot across.

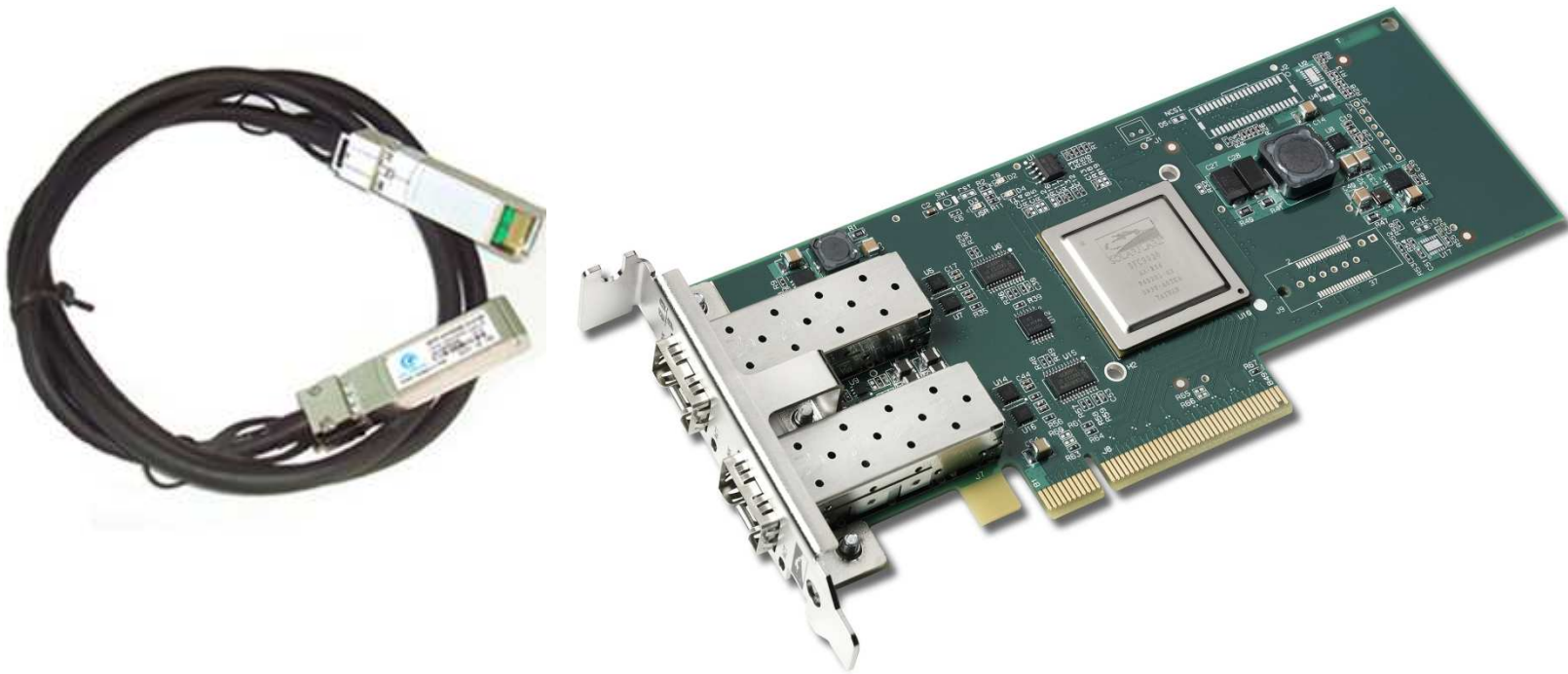
The processor operates at 2.4 GHz.

2.4 “operations” in the time it takes light to cross the motherboard.



Speed of Light

- Commercially available 10 Gb Ethernet:



- About 10 bits of data in the time it takes light to travel 1 foot.

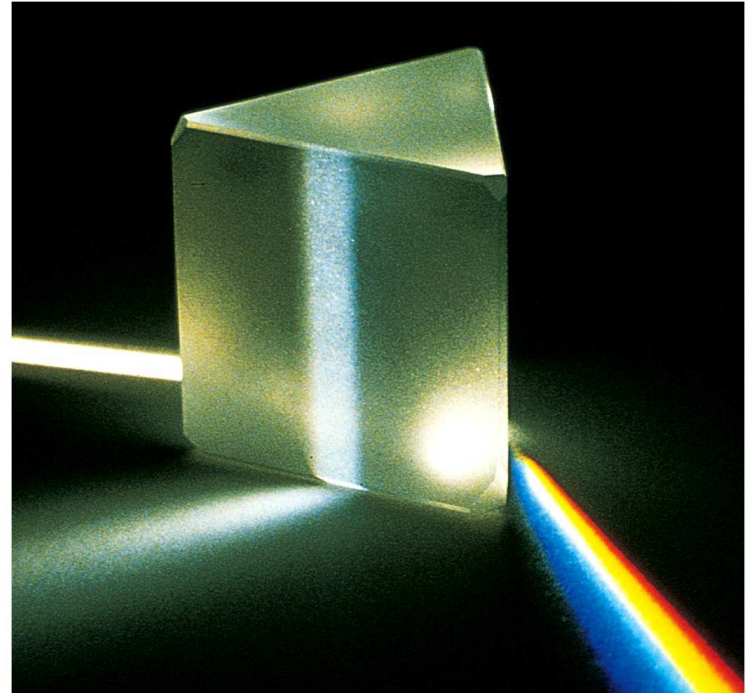
Measuring the Speed of Light

- Römer's method (1675): $c = d/t$
 - t is the period of Io's orbit around Jupiter
 - d is the distance the Earth moves in its orbit around the sun
- More recently (1960), $c = f\lambda$
 - Wavelength is one spectral line of a Krypton-86 discharge lamp
 - Precision limited by the definition of length
- Today (as of 1983), we *define* length in terms of the speed of light:
 - The meter is defined to be the distance light travels in $1/299,792,458$ of a second.

Properties of Light: Color

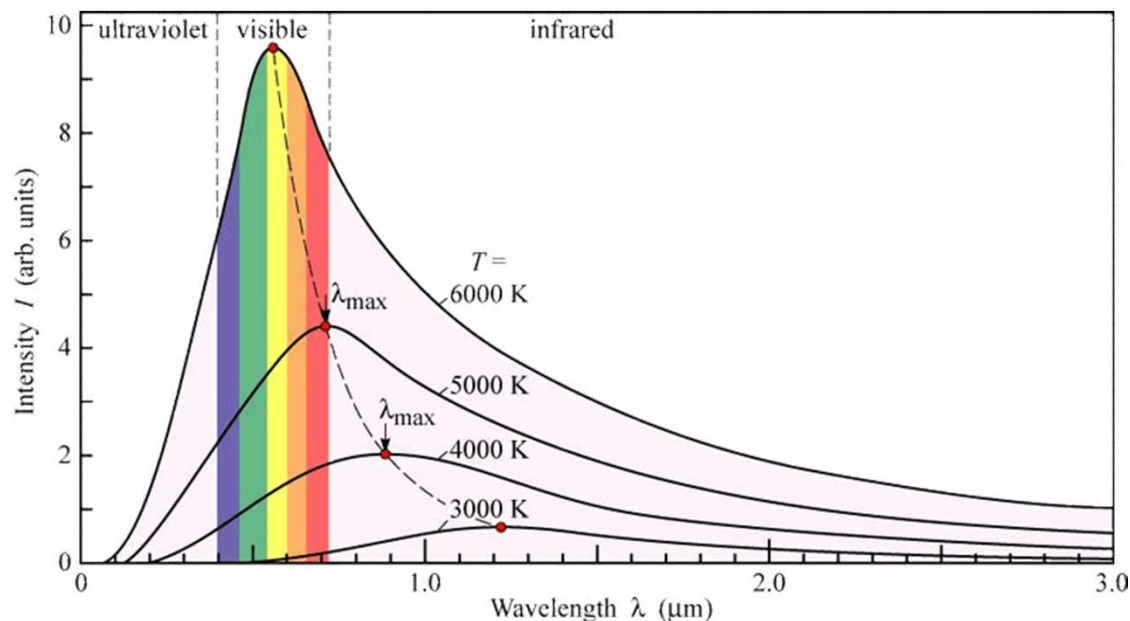


Isaac Newton – 1672.



Properties of Light: Blackbody Radiation

- Hot objects (eg, light bulbs, stars) emit light that has a continuous spectrum of wavelengths:



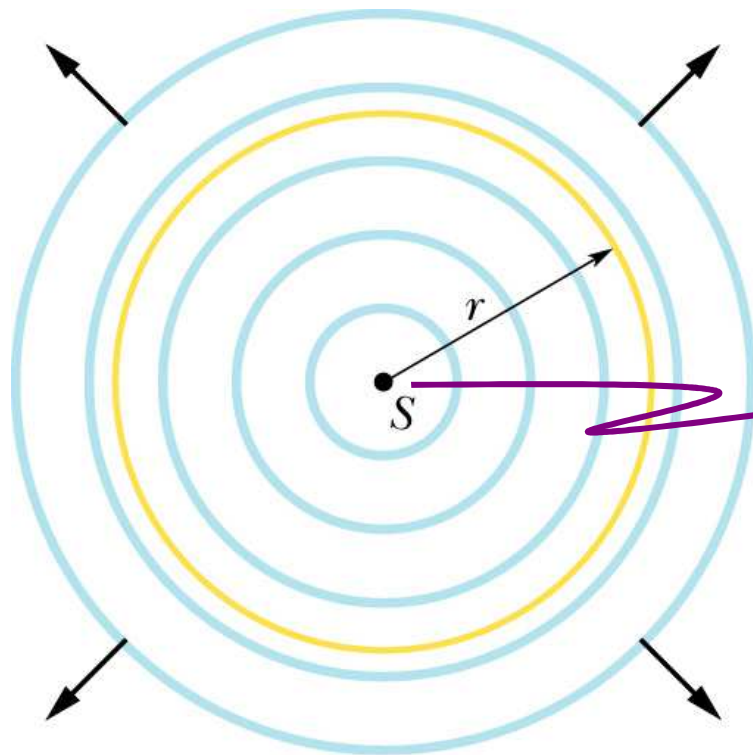
- Stefan-Boltzmann law: $P \propto T^4$
- Wein's displacement law: $\lambda_{\text{max}} \propto 1/T$

Radiation Pressure

- Light carries energy: Poynting vector is $\vec{S} = \frac{\vec{E} \times \vec{B}}{\mu_0}$
- Light also carries momentum: $p = \frac{E}{c}$
- Intensity: $I = \langle S \rangle = \frac{E_0 B_0}{2\mu_0}$ since $\langle E \rangle = \frac{E_0}{\sqrt{2}}$, $\langle B \rangle = \frac{B_0}{\sqrt{2}}$
 - This is the energy per unit area per unit time (W/m²)
- Radiation pressure: $P_r = \frac{I}{c}$

Radiation Intensity

- When light is emitted uniformly in all directions, the intensity falls as $1/r^2$:



Power, P_{av}

Surface area is

$$A = 4\pi r^2$$

Intensity is

$$I = P_{av} / 4\pi r^2$$

Question

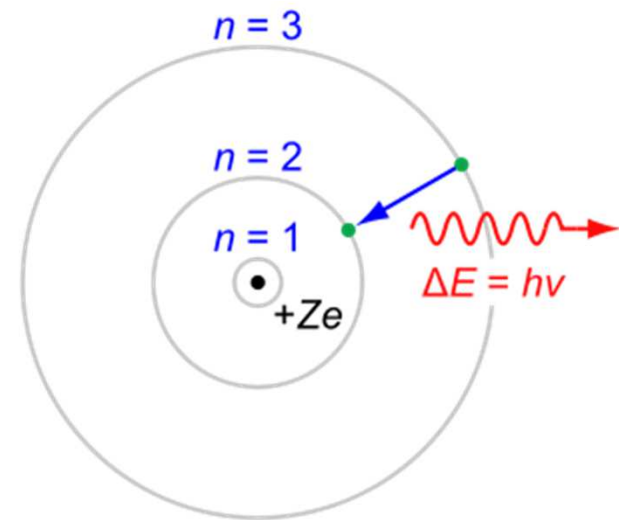
Light of uniform intensity shines perpendicularly on a surface. If the area of the surface is increased, which of the following is true?

- (a) The radiation pressure on the surface increases
- (b) The radiation pressure on the surface stays the same
- (c) The radiation pressure on the surface decreases

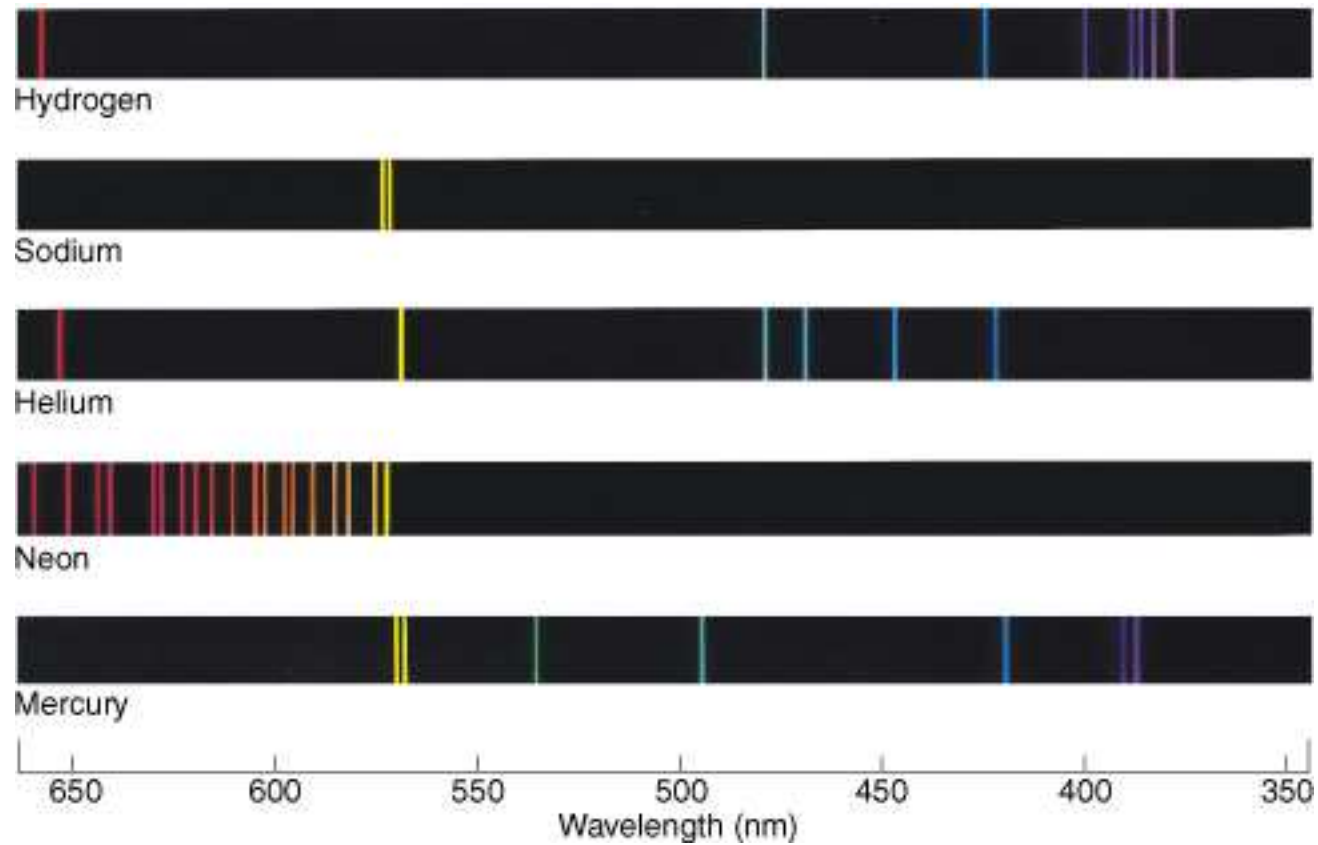
Properties of Light: Spectral Lines

- Electrons in atoms have discrete energies.
- An electron that moves to a lower energy state emits a photon.
- An electron that moves to a higher energy state absorbs a photon.
- The color (wavelength) is related to the energy difference:

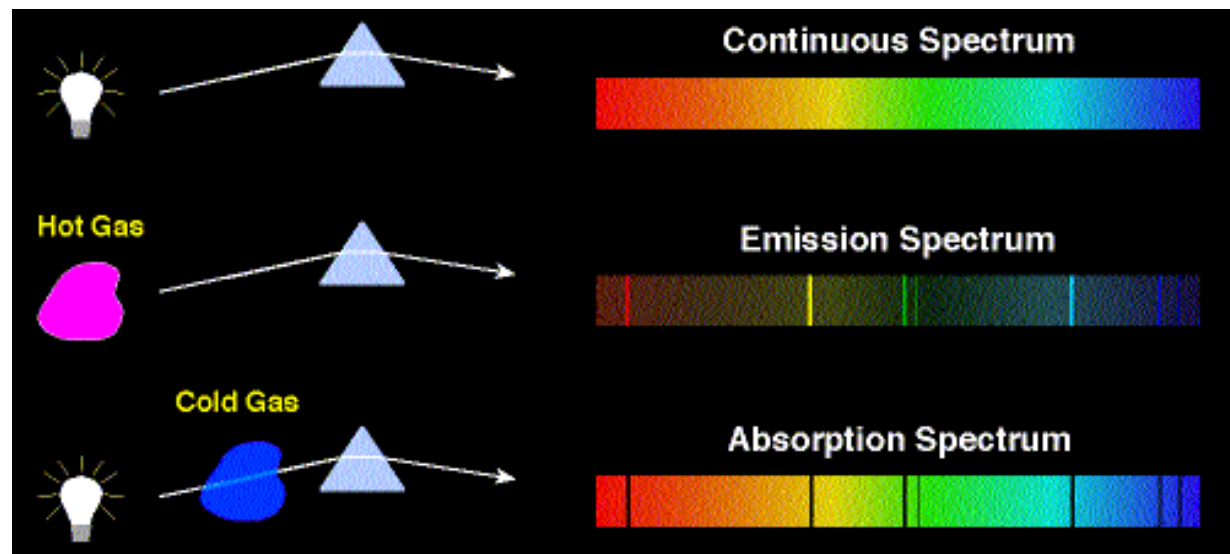
$$\lambda \propto \frac{1}{\Delta E}$$



Spectral Lines



Emission and Absorption Spectra



- Light is absorbed by a gas, but only when it has the same wavelengths as the emission lines.
 - Emitted/absorbed $\lambda \propto \frac{1}{(E_2 - E_1)}$

Propagation of Light

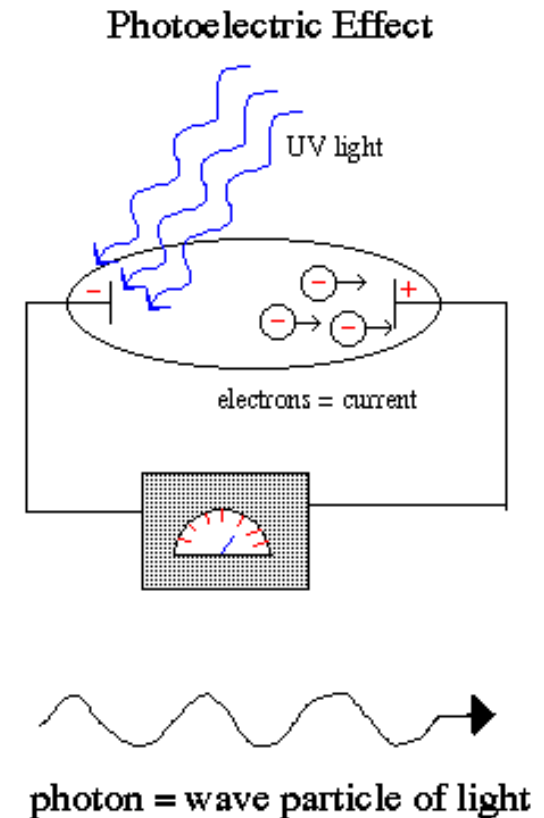
- Christian Huygens: *light is a wave*
- Isaac Newton: *light moves in straight lines*
- Thomas Young/Augustin Fresnel: *diffraction of light*
 - Rejected because it disagreed with Newton
 - Experimentally confirmed
- Maxwell: *wave theory of light from E&M*
- Albert Einstein: *particle theory of light to explain photoelectric effect*
- *Quantum Mechanics naturally accounts for both of these effects, not just for light but for all forms of matter.*

Photoelectric Effect

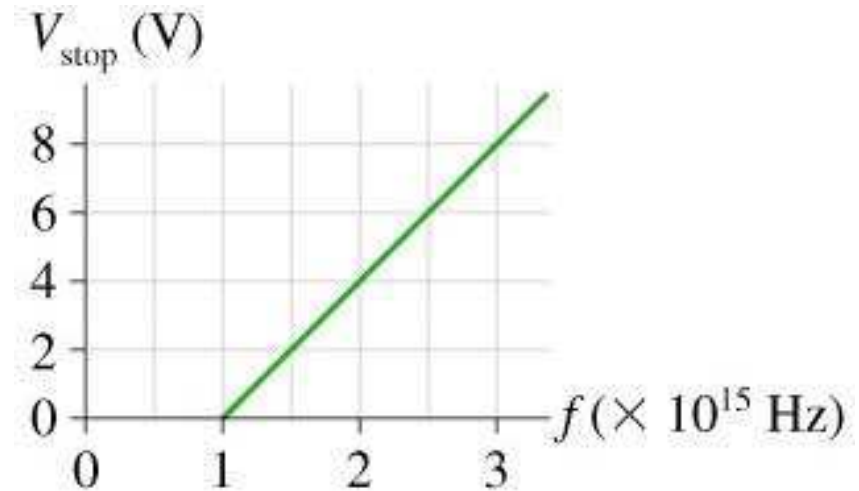
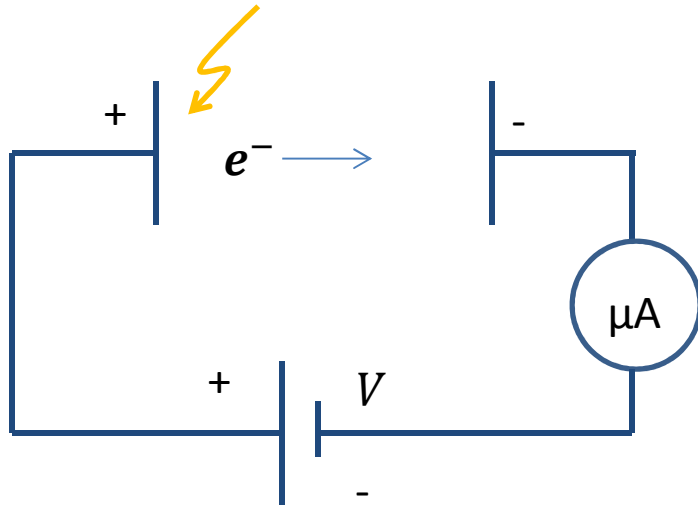
- Removing an electron from the surface of a metal requires a certain energy.
- Light with a low frequency produces no current in the circuit.
- Light with a greater frequency produces a current.
- Current depends on wavelength, not intensity.
- Energy is proportional to frequency:

$$E = hf = \frac{hc}{\lambda}$$

- Planck's constant: $h = 6.626 \times 10^{-34} \text{ J} \cdot \text{s}$
- *"Wave particle duality"*

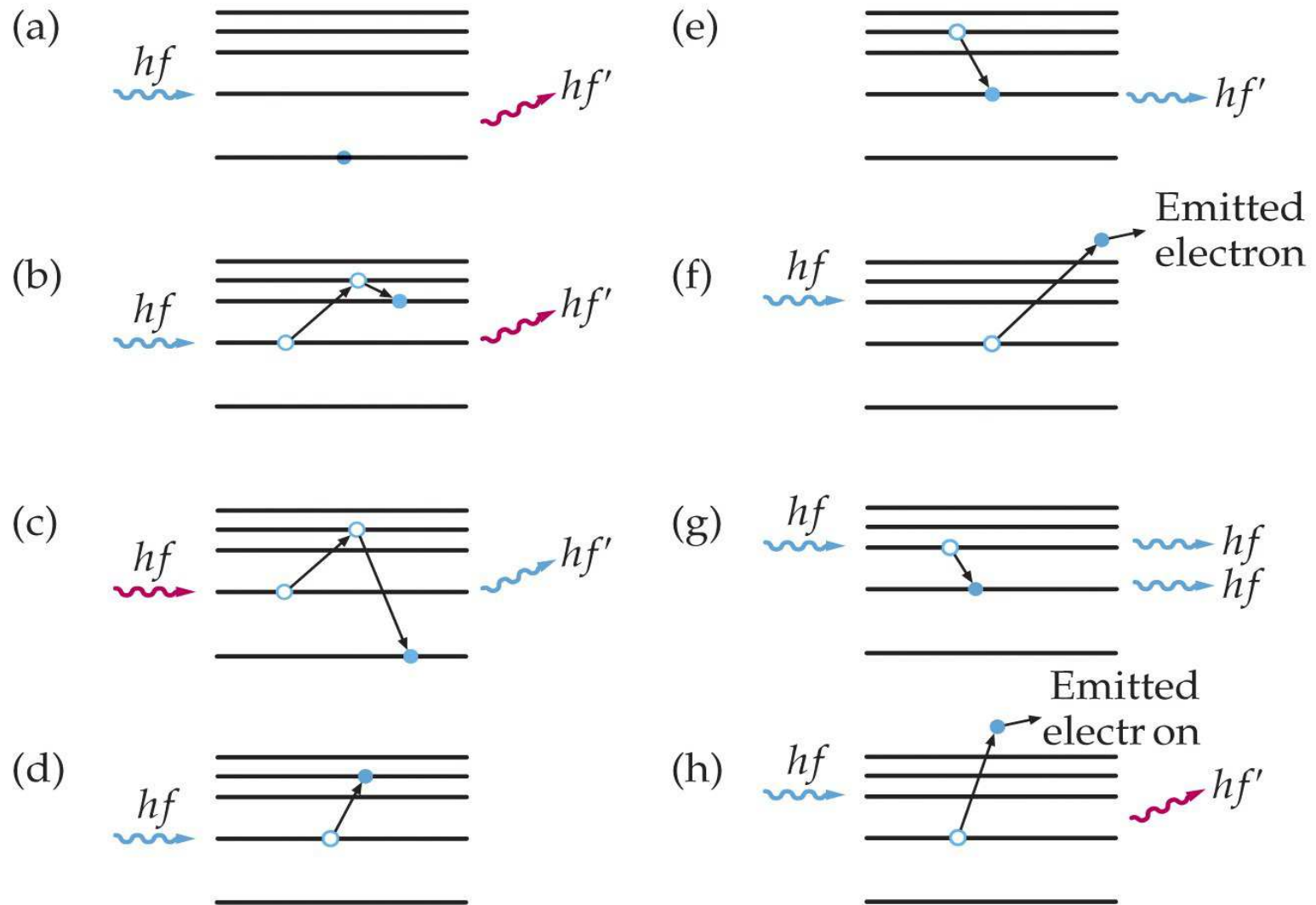


Photoelectric Effect



- Photon energy, $E = hf$.
- Work function of the metal: $W \sim$ few electron volts
- An electron must be emitted with an energy of at least $E = hf - W$ if it is to reach the anode.
- Current depends on the light intensity.
- V_{stop} is independent of light intensity.

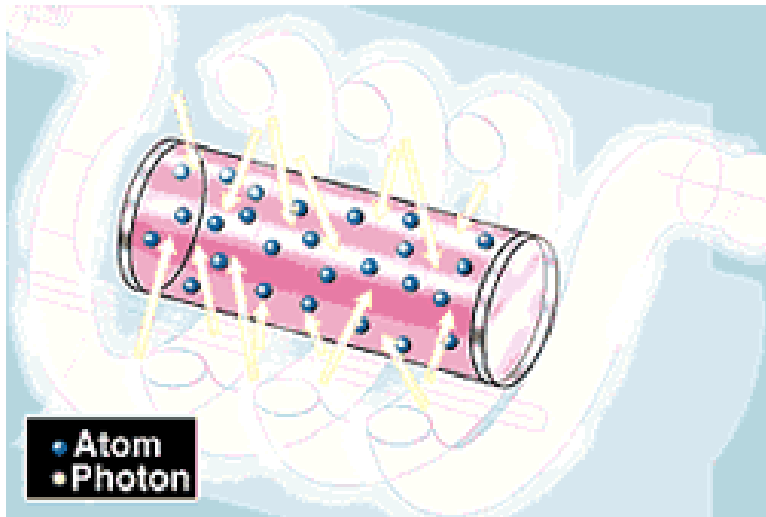
Interactions with Matter



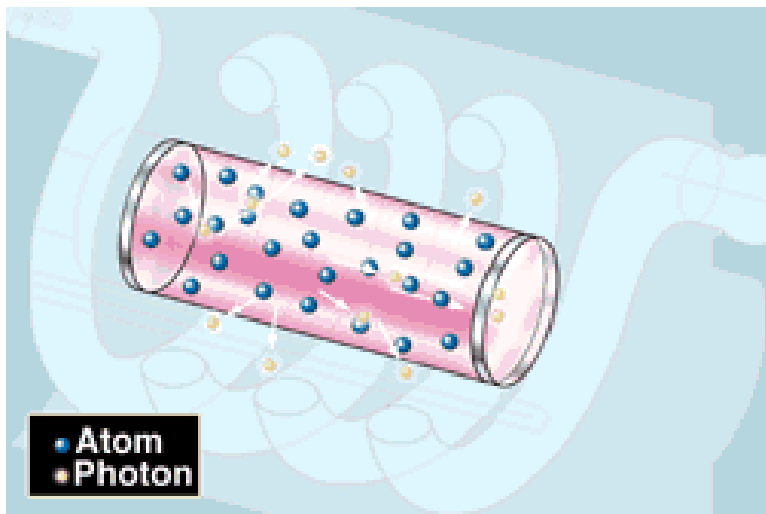
Stimulated Emission

- Suppose an electron was in an excited state with energy E_1 .
- If a photon has energy $E = E_1 - E_0$, it can cause the electron to make a transition to a state with energy E_0 .
 - The electron emits another, identical photon (same energy, direction, phase)
 - Same phase: **coherent**
Outgoing $\vec{E}$ -field component: $\vec{E}(z, t) = 2\vec{E}_0 \sin(kz - \omega t)$
 - Random phase: **incoherent**
Outgoing $\vec{E}$ -field component:
 $\vec{E}(z, t) = \vec{E}_0 \sin(kz - \omega t) + \vec{E}_0 \sin(kz - \omega t + \varphi)$

Ruby Laser (Light Amplification by stimulated emission)

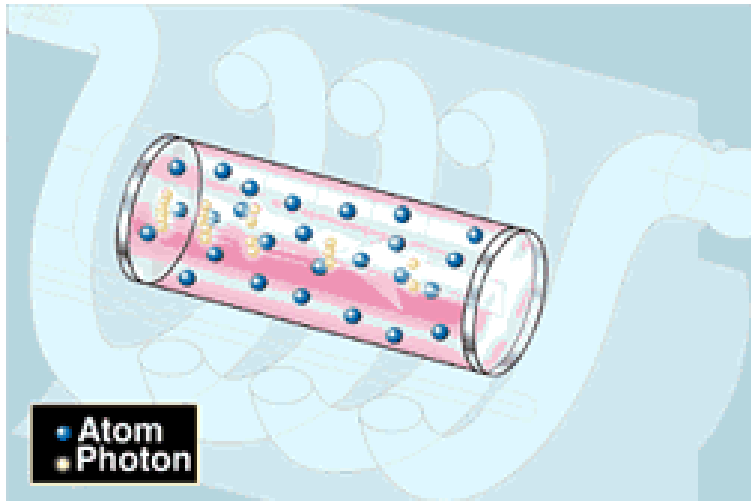


1. High-voltage electricity causes the quartz flash tube to emit an intense burst of light, exciting some of the atoms in the ruby crystal to higher energy levels.

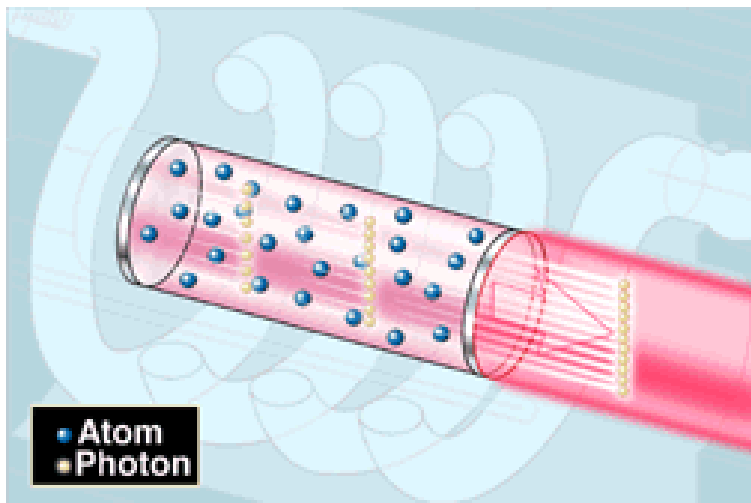


2. At a specific energy level, some atoms emit photons. At first, photons are emitted in all directions. Photons from one atom stimulate emission of photons from other atoms and the light intensity is amplified.

Ruby Laser (Light Amplification by stimulated emission)

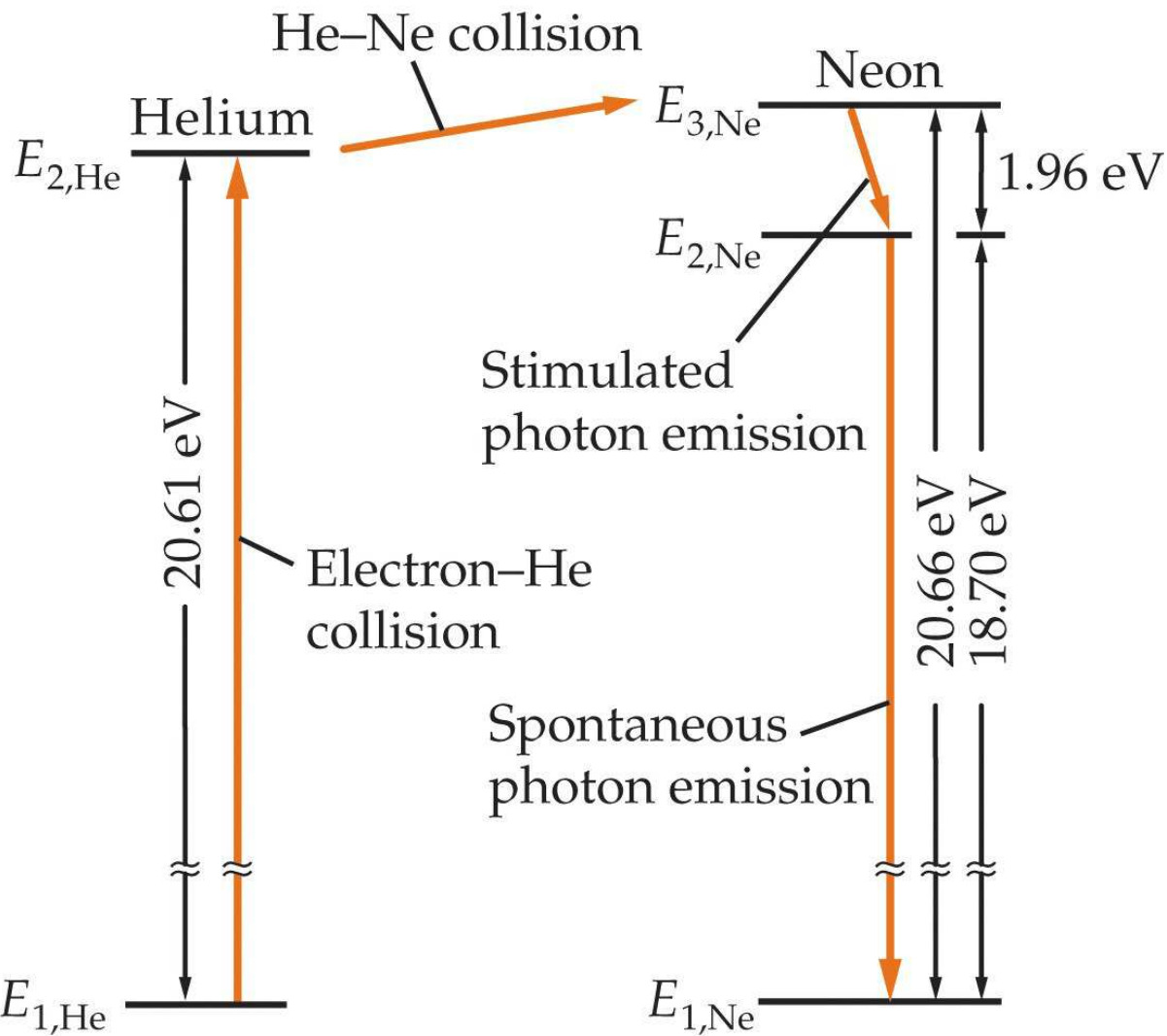


3. Mirrors at each end reflect the photons back and forth, continuing this process of stimulated emission and amplification.

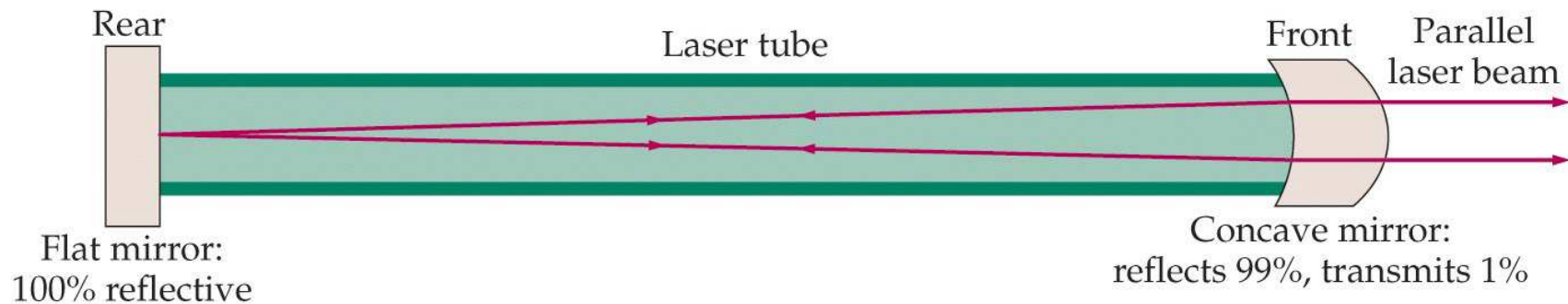


4. The photons leave through the partially silvered mirror at one end. This is laser light.

Helium-Neon Laser Energy Levels



Helium-Neon Laser



15% helium, 85% neon

$\lambda = 632.8 \text{ nm}$ ($E = 1.96 \text{ eV}$)

Characteristics of laser beams: coherent (photons have the same frequency in phase, and the same direction of propagation), very small angular divergence, intense.

Clicker Question

- The intensity of sunlight at the distance of Earth's orbit is about 1.4 kW/m^2 .
- The orbit of Mars is roughly twice the distance from the sun as Earth's orbit.
- With what intensity does sunlight arrive on the surface of Mars?
 - (a) 1.4 kW/m^2
 - (b) 2.8 kW/m^2
 - (c) 0.70 kW/m^2
 - (d) 0.35 kW/m^2
 - (e) Not enough information