Photon Model
The **photon model** of light consists of three basic postulates:

1. Light consists of discrete, massless units called *photons*. A photon travels in vacuum at the speed of light.

2. Each photon has energy:

   \[ E_{\text{photon}} = hf \]

   where \( f \) is the frequency of the light and \( h = 6.63 \times 10^{-34} \) J s is Planck’s constant. In other words, the light comes in discrete “chunks” of energy \( hf \).

3. The superposition of a sufficiently large number of photons has the characteristics of a classical light wave.
Both Particle and Wave Properties are Displayed

- Individual photons strike the target individually and are detected as tiny spots.
- Individual photons still follow an interference pattern – but at random.
- The intensity of an EM wave only tells us the probability of finding a photon at a particular place.
Double-Slit Experiment with Photons
The energy of a photon of red light is ____ the energy of a photon of blue light.

A. larger than
B. the same as
C. smaller than
Photons are sometimes visualized as wave packets.

The electromagnetic wave shown in the figure has a wavelength and a frequency, yet it is also discrete and fairly localized.

- Photons are sometimes visualized as wave packets.
The Photon Rate

- Light consists of a stream of photons.
- For monochromatic light of frequency \( f \), \( N \) photons have a total energy \( E_{\text{light}} = Nh \). 
- The power of the light, or the rate (in joules per second, or watts) at which the light energy is delivered is:

\[
P = \frac{dE_{\text{light}}}{dt} = \frac{dN}{dt} hf = Rhf
\]

where \( R = dN/dt \) is the rate at which photons arrive or, equivalently, the number of photons per second.
A beam of light has wavelength $\lambda$. The light’s intensity is reduced without changing the wavelength. Which is true after the intensity is reduced?

A. The photons are smaller.
B. The photons travel slower.
C. The photons have less energy.
D. There are fewer photons per second.
E. Both B and D
Points 1 and 2 are 5 $\mu$m apart. Light with a wavelength of 1 $\mu$m travels from point 1 to point 2. Which is the trajectory followed by the photons?

A

B

C

D None of these

Light travels in straight lines.
Foothold Ideas:
The Photon Model

• When it interacts with matter, light behaves as if it consisted of packets (photons) that carry both energy and momentum according to:

\[ E = hf = \frac{hc}{\lambda} \quad \text{and} \quad p = \frac{E}{c} = \frac{h}{\lambda} \]

with \( hc = 1234 \text{ eV-nm} \).

– These equations are somewhat peculiar. The left side of the equations look like particle properties and the right side like wave properties.
The most important tool for measuring the wavelengths of light is the spectrometer.

Making the diffraction grating slightly curved focuses the spectrum onto the photodetector.
A hot, self-luminous object, such as the filament of an incandescent lightbulb, forms a rainbow-like **continuous spectrum** in which light is emitted at every possible wavelength.
The heat energy $Q$ radiated in a time interval $\Delta t$ by an object with surface area $A$ and absolute temperature $T$ is given by:

$$\frac{Q}{\Delta t} = e\sigma A T^4$$

where $\sigma = 5.67 \times 10^{-8}$ W/m² K⁴ is the Stefan-Boltzmann constant.

- The parameter $e$ is the *emissivity* of the surface.
- A perfectly absorbing—and thus perfectly emitting—object with $e = 1$ is called a *blackbody*, and the thermal radiation emitted by a blackbody is called **blackbody radiation**.
A brass plate at room temperature (300 K) radiates 10 W of energy. If its temperature is raised to 600 K, it will radiate

A. 10 W  
B. 20 W  
C. 40 W  
D. 80 W  
E. 160 W  

Radiated power $\propto T^4$
If we measure the spectrum of a blackbody at three temperatures, 3500 K, 4500 K, and 5500 K, the data appear as shown.

These continuous curves are called *blackbody spectra*. 

A hotter object has a much greater intensity, peaked at shorter wavelengths.
All blackbodies at the same temperature emit exactly the same spectrum.

Increasing the temperature increases the radiated intensity at all wavelengths.

Increasing the temperature causes the peak intensity to shift toward shorter wavelengths.

The wavelength corresponding to the peak of the intensity graph is given by Wien’s Law:

$$\lambda_{\text{peak}}(\text{in nm}) = \frac{2.90 \times 10^6 \text{ nm K}}{T}$$

where $T$ must be in Kelvin.
A brass plate at room temperature (300 K) radiates 10 W of energy. If its temperature is raised to 600 K, the wavelength of maximum radiated intensity

A. increases.
B. decreases.
C. remains the same.
D. Not enough information to tell

\[ \lambda_{\text{peak}} \propto \frac{1}{T} \]
Line Spectra
Michael Faraday sealed metal electrodes into a glass tube, lowered the pressure with a vacuum pump, and then attached an electrostatic generator.

When he started the generator, the gas inside the tube began to glow with a bright purple color!

Faraday's device, called a gas discharge tube, is shown.
If light from a gas discharge tube is passed through a spectrometer, it produces a spectrum like the one shown below.

This is called a **discrete spectrum** because it contains only discrete, individual wavelengths.

Further, each kind of gas emits a unique spectrum—a spectral fingerprint—that distinguishes it from every other gas.
- Not only do gases emit discrete wavelengths, they also absorb discrete wavelengths.

- The top figure shows the spectrum when white light passes through a sample of gas.

- Any wavelengths absorbed by the gas are missing, and the film is dark at that wavelength.
Although the emission and absorption spectra of a gas are both discrete, there is an important difference.

Every wavelength absorbed by the gas is also emitted, but *not* every emitted wavelength is absorbed.

The wavelengths in the absorption spectrum are a subset of those in the emission spectrum.

All the absorption wavelengths are prominent in the emission spectrum, but there are many emission wavelengths for which no absorption occurs.
These spectra are from the same element. Which is an emission spectrum, which an absorption spectrum?

A. Top is emission; bottom absorption.

B. Top is absorption; bottom emission.

C. Either could be emission (or absorption), depending on the conditions with which they were made.

D. Can’t tell without knowing the element.
The emission spectrum of hydrogen, seen below, is very simple and regular.

The spectral lines extend to the series limit at 364.7 nm.

Hydrogen emission spectrum

656.5 nm  486.3 nm  434.2 nm  410.3 nm
In 1885 a Swiss schoolteacher named Johann Balmer discovered a formula which accurately describes every wavelength in the emission spectrum of hydrogen:

\[ \lambda = \frac{91.18 \text{ nm}}{\left( \frac{1}{m^2} - \frac{1}{n^2} \right)} \quad m = 1, 2, 3, \ldots \quad n = m + 1, m + 2, \ldots \]

This result is called the **Balmer formula**.

Balmer’s original version only included \( m = 2 \).

When first discovered, the Balmer formula was *empirical knowledge*; it did not rest on any physical principles or physical laws.
Line Spectra

• When energy is added to gases of pure atoms or molecules by a spark, they give off light, but not a continuous spectrum.

• They emit light of a number of specific colors — *line spectra*.

• The positions of the lines are characteristic of the particular atoms or molecules.
Foothold Ideas: Light interacting with Matter

- Atoms and molecules naturally exist in states having specified energies. EM radiation can be absorbed or emitted by these atoms and molecules.

- When light interacts with matter, both energy and momentum are conserved.

- The energy of radiation either emitted or absorbed therefore corresponds to the difference of the energies of states.
Energy Level Diagrams

Absorption:

\[ E_1 = hf + E_0 \]

Emission:

\[ E_i = hf + E_f \]
A molecule has the energy levels shown in the diagram at the right. We begin with a large number of these molecules in their ground states. We want to raise a lot of these molecules to the state labeled $E_2$ by shining light on it. What energy photon should we use?

A. 0.7 eV  
B. 1.1 eV  
C. 1.4 eV  
D. 1.8 eV  
E. 2.1 eV  
F. 3.2 eV  
G. Something else
A molecule has the energy levels shown in the diagram at the right. We have a large number of these molecules in the state $E_2$. The state decays by emitting photons. What might we expect about the wavelength of the emitted photons?

A. They will be the same as the wavelength of the photons that were used to pump the molecules up to state $E_2$.

B. Some might be the same wavelength, but some might be shorter.

C. Some might be the same wavelength, but some might be longer.

D. You only expect to see shorter wavelength 2.1 eV

E. You only expect to see shorter wavelength

F. You will see longer, shorter, and the same wavelengths.
A molecule has the energy levels shown in the diagram at the right. We have a large number of these molecules in the state $E_2$. The state decays by emitting photons. What energy photons might we expect to see?

1. B D F
2. B D
3. C
4. C E
5. A C E
6. Some other set

A. 0.7 eV
B. 1.1 eV
C. 1.4 eV
D. 1.8 eV
E. 2.1 eV
F. 3.2 eV
In the transitions you found in the last slide, which corresponds to the longest wavelength? (and what is it)

A. 0.7 eV
B. 1.4 eV
C. 2.1 eV

\[ E = hf \]
\[ f\lambda = c \]
\[ hc = 1234 \text{ eV-nm} \]
\[ c = 3 \times 10^8 \text{ m/s} \]
Foothold Ideas: The Probability Framework

- It’s clear that both the wave model and the photon have an element of truth. Here’s the way we reconcile it:
  - Maxwell’s equations and the wave theory of light yield a function – the electric field – whose square (the intensity of the light) is proportional to the probability of finding a photon.
  - No theory of the exact propagation of individual photons exist. This is the best we can do: a theory of the probability function for photons.
Foothold Ideas:
The Probability Framework for electrons

• Quantum mechanics gives us a wave function of an electron, whose square gives us the probability of finding an electron
  
  — Schrödinger’s equation is the wave theory of matter. Its solution yields the wave function whose square is proportional to the probability of finding an electron.

  — No theory of the exact propagation of individual electrons exist. This is the best we can do: a theory of the probability function for electrons.
In 1924 French graduate student Louis-Victor de Broglie wondered, “If light waves can have a particle-like nature, why shouldn’t material particles have some kind of wave-like nature?”

In other words, could matter waves exist?

de Broglie thought about an analogy with light, and postulated that if a material particle of momentum \( p = mv \) has a wave-like nature, then its wavelength must be given by:

\[
\lambda = \frac{h}{p} = \frac{h}{mv}
\]

where \( h \) is Planck’s constant.

This is called the de Broglie wavelength.
The Wave Model of Matter

- The image to the right shows the intensity pattern recorded after 50 keV electrons passed through two slits separated by 1.0 mm.
- The pattern is clearly a double-slit interference pattern.
- Electrons, neutrons, atoms, and even molecules exhibit all the behavior we associate with waves.