Ch07

Radiant Energy

Understanding Radiant Energy,

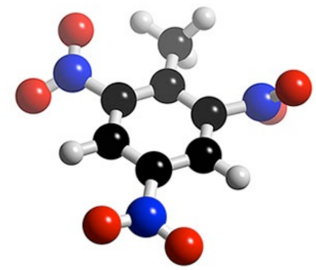
and the quantum processes by which it enters and leaves matter.

version 1.5

Ch07

Radiant Energy

- Radiant Energy (Radiation)
  - Wave Fundamentals
    - Understanding Waves
    - Measuring Waves
    - Interference & Diffraction
  - Electro-magnetic Radiation
    - The EM Spectrum
    - Fitting in Light
- Radiation & Matter: The Three Famous Puzzles
  - Blackbody Radiation solved by Max Planck
    - Radiant Energy from Matter.
  - The Photo-Electric Effect solved by Albert Einstein
    - Radiant Energy into Matter.
  - Line Spectra solved by Niels Bohr
    - What's happening inside the matter.
      - Do not underestimate the importance of these experiments!
- A Bohr model of the atom (planetary model).



What is a wave?

- Energy can be transmitted using particles or waves.
  - We can apply energy to an object, transfer the object to another location, and recover the energy at the new location.
  - The energy is transmitted by matter moving through empty space.
    - Example: Toss a baseball across the road and hit a window. The energy of the toss get's transmitted to the window.
  - We can apply energy to a media. The energy creates a disturbance. The disturbance moves through the media. The disturbance imparts energy at the other end.
  - The energy is transmitted from here to there – without accompanying matter leaving here and arriving there.
  - It's transmitted by a disturbance moving through a media.
    - Example: Sing a high note and crack a window with it. The energy of the disturbance get's transmitted to the window.
    - The energy of the singing disturbs the air. The air you exhale does not cross the road. A disturbance passing from one air molecule to another crosses the road.
  - Disturbances in matter are well described by a mathematical concept called a wave.

Newton's Cradle

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  - Classical mechanics models this motion with particles (chunks of matter).

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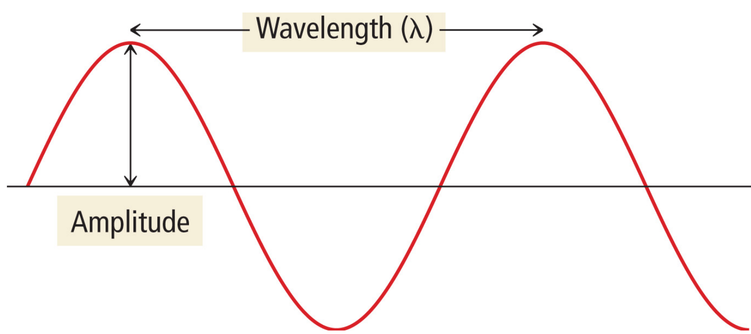
A

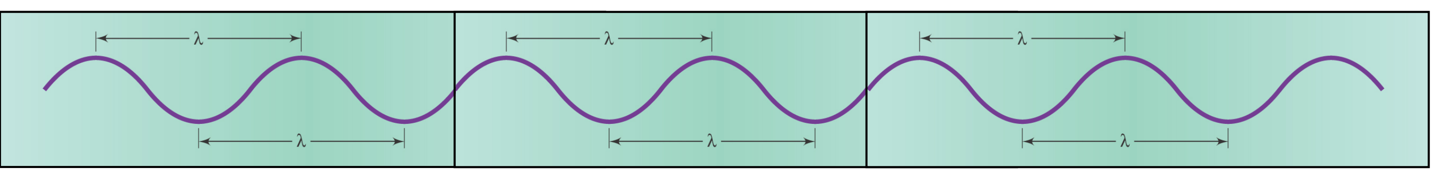
B

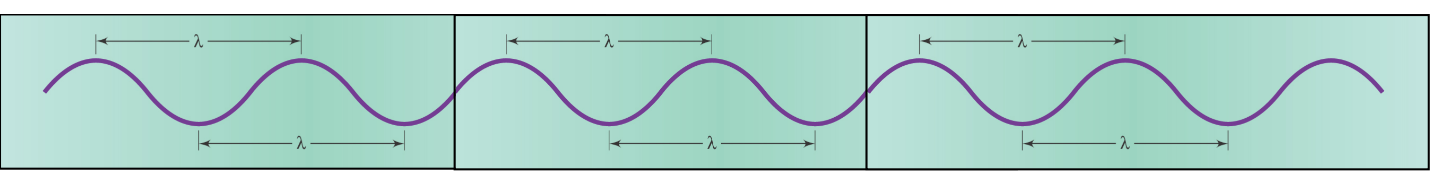
Quantifying Waves

- Waves can be defined structurally by their amplitude and wavelength.
- The wave transmission can be defined by speed, and frequency.
- Amplitude (A) is the height of a wave. It is sometimes measured from peak to peak and other times measured peak to midpoint. It can be negative or positive.
- Intensity (I) is proportional to amplitude squared, intensity is always positive.
- Wavelength (λ) is length of a wave, trough to through or peak to peak.
- Speed (s) is how fast waves move.
- Frequency (v) is how many waves pass a fixed point in one second
  -- frequency is measured in 1/s or s^{-1} also called Hertz (Hz).



$$s = \lambda\nu$$





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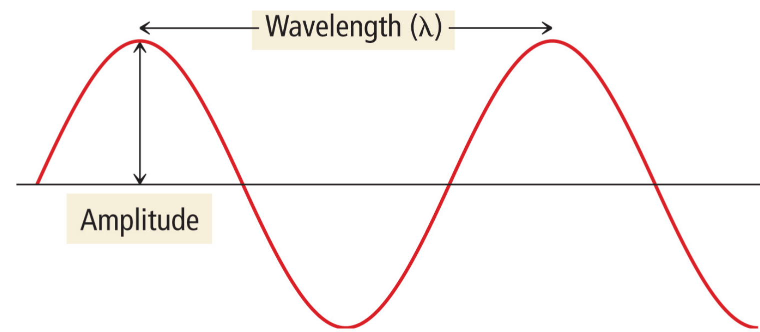

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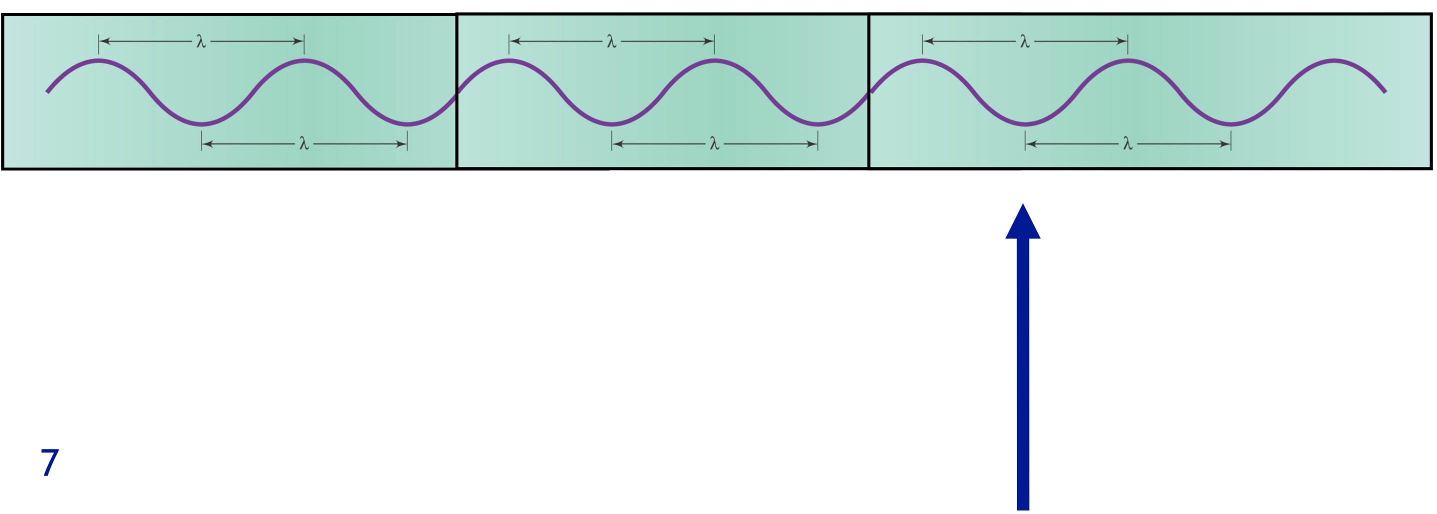
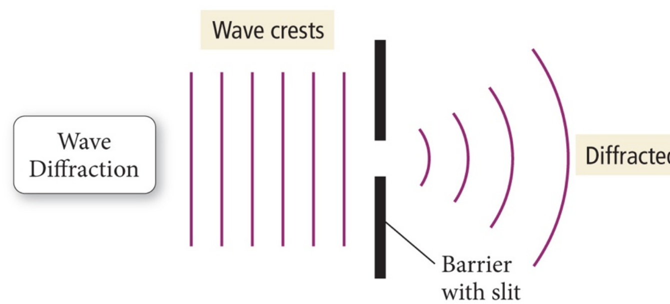
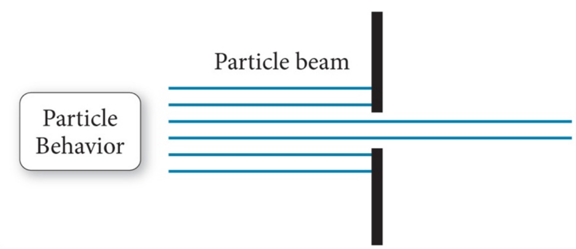


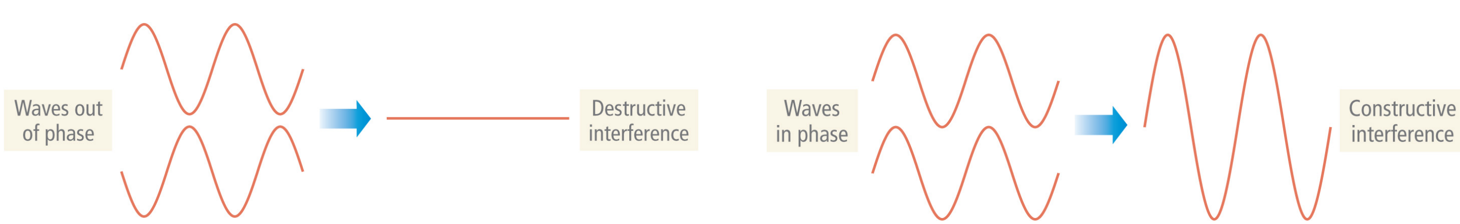
Wave Behavior

- Two waves traveling through the same media can interact with each other.
  - If they're "in phase" they reinforce each other. Constructive interference.
  - If they're "out of phase" they destroy each other. Destructive interference.



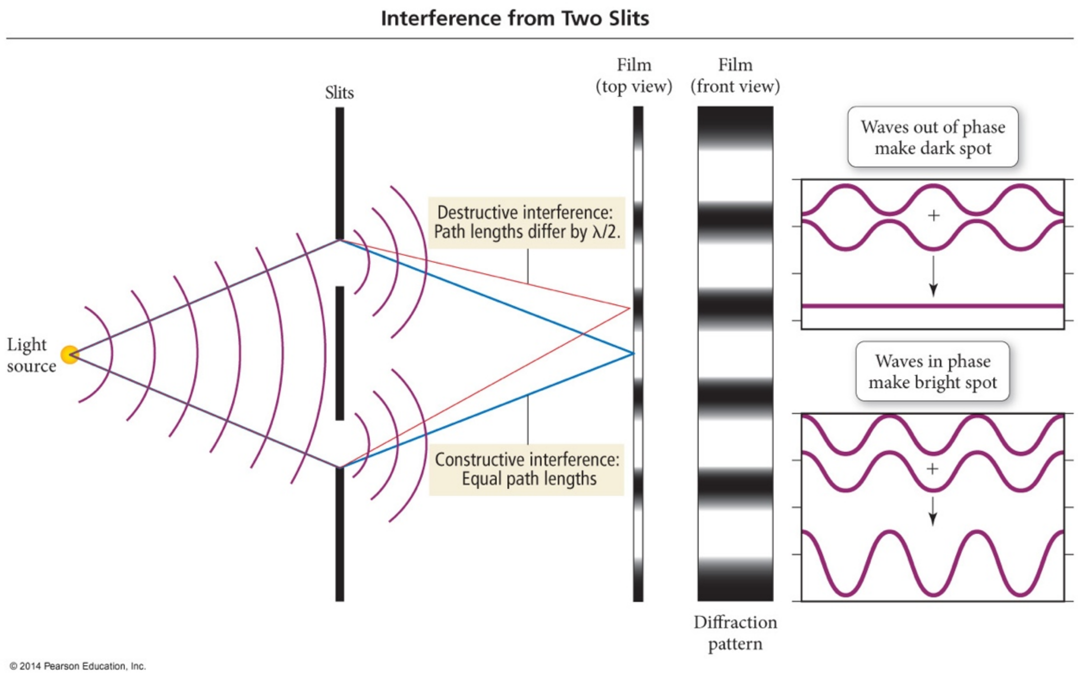
- Particles passing through an opening continue on their trajectory.
- Waves passing through a narrow opening experience diffraction.
  - The media near the slit edges is less conductive, so the edges of the wave move more slowly than the center.
  - Waves passing through a narrow opening curve and spreads out.





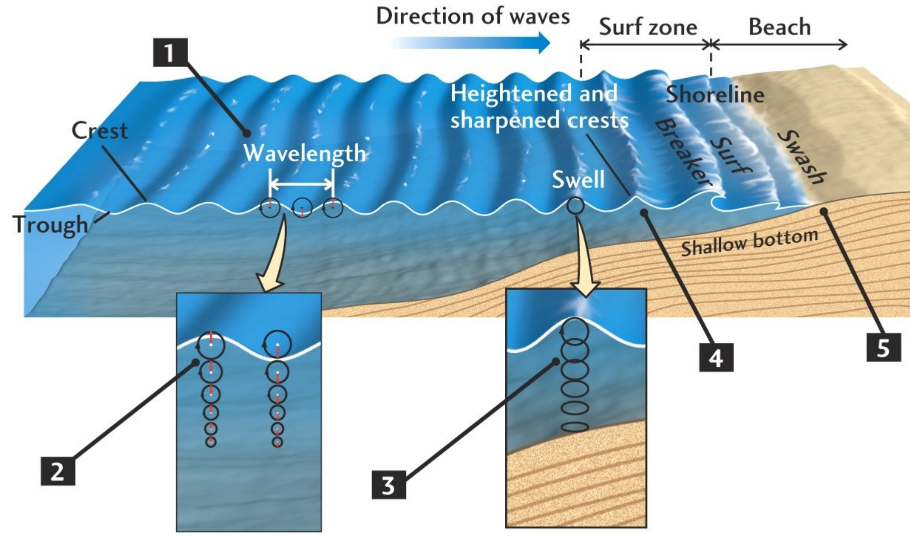
Wave Behavior

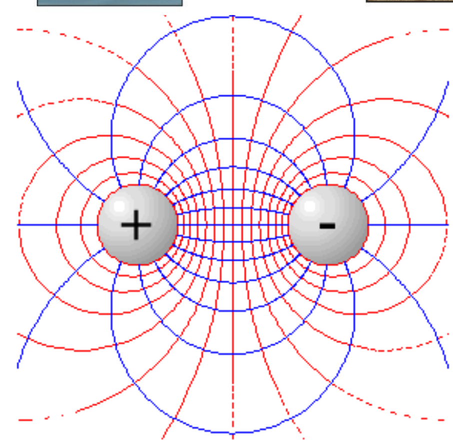
- A diffraction grating is a thin barrier with slots about the same size as the wavelength of the radiation it's designed for.
- Waves passing through it are diffracted, the diffracted waves create interference.
- Constructive interference creates intense bands.
- Destructive interference creates gaps.

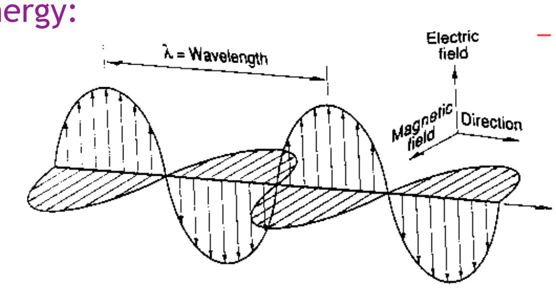


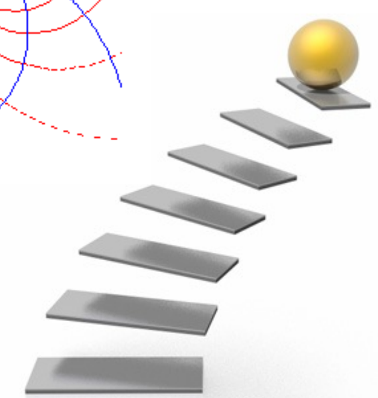
Radiant Energy

- Waves can be transmitted through different media.
  - Ocean waves are disturbances in the ocean water.
  - Sound waves are disturbances in air molecules.
- E-M Fields
  - Magnetic fields are empty space in which a magnetic particle feels a force (the space around a magnet for example).
  - Electric fields are empty space in which charged particles feel a force (like the space around a proton or electron).
  - There are protons and electrons everywhere.
  - There are electric fields everywhere.
  - Electric fields create magnetic fields (and vice versa)
  - We are surrounded by electromagnetic fields.
- E-M waves are disturbances in E-M fields.
  - E-M waves are radiant energy.
    - Unlike ocean waves or sounds waves, the media *contains no matter* — only energy.
  - There are different types of radiant energy:
    - Light
    - X-Rays
    - Microwaves
    - Radio Waves



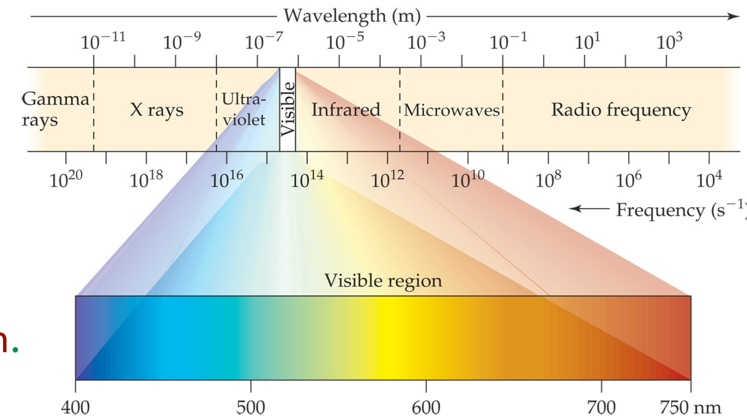






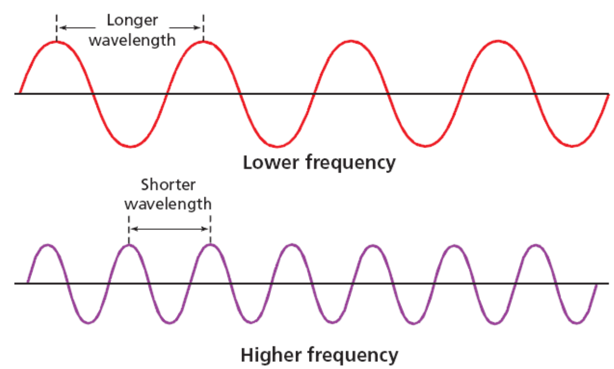
Radiant Energy

- All Radiant Energy moves at the speed of light (c) in a vacuum.
  - Radiant energy moves at exactly 299,792,458 m/s (don't memorize)
  - We generally use the measurement 3.00×10^8 m/s instead of the exact value.
- If all e-m waves move at the same speed:
  - those with higher frequency must have shorter wavelength.
  - those with lower frequency must have longer wavelength.



memorize this

$$c = \lambda \nu$$



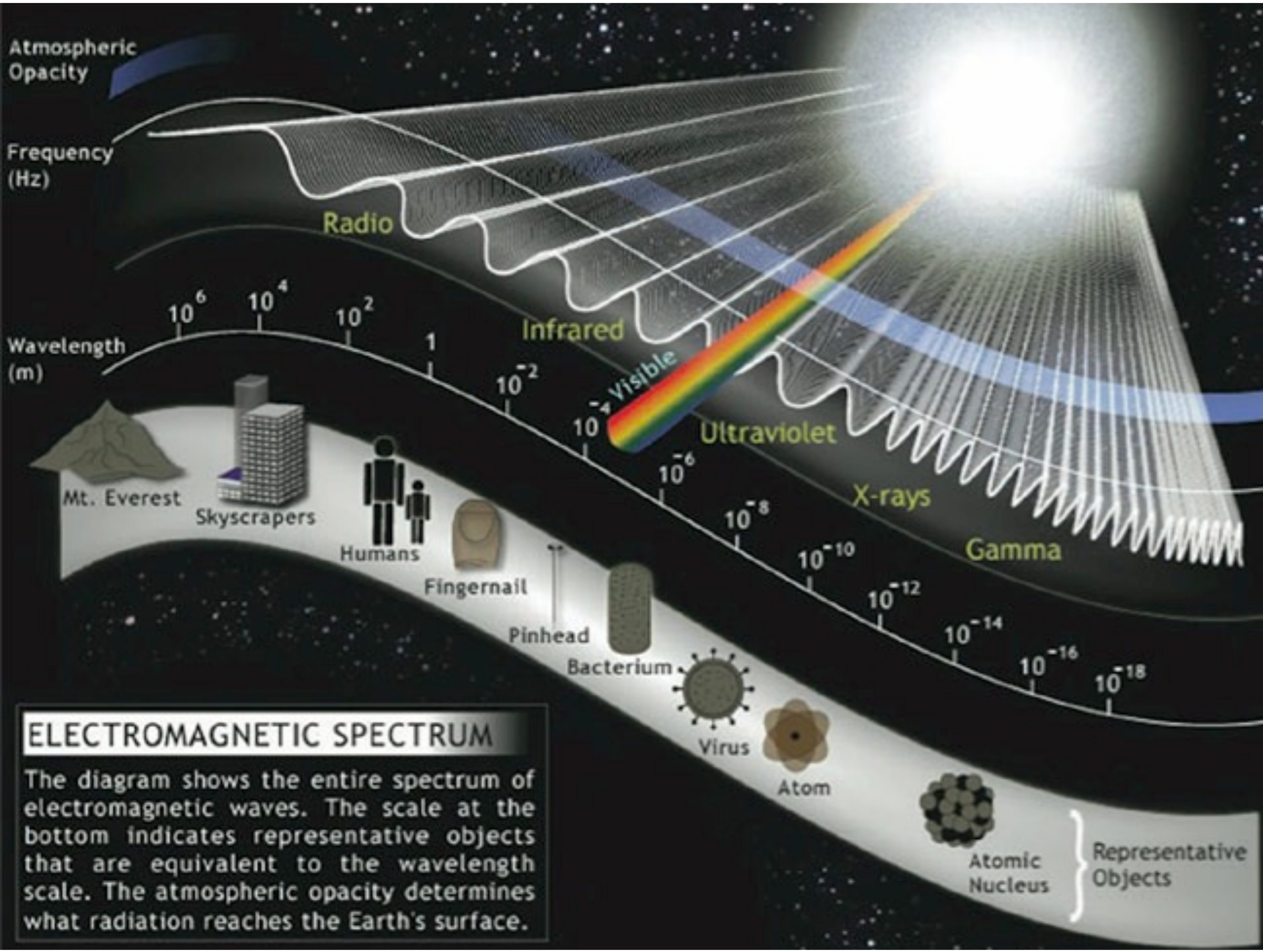
- The speed of e-m radiation in a vacuum is 3.00×10^8 m/s

memorize this

$$c = 3.00 \times 10^8 \text{ m/s}$$

(a measurement)

- Visible light is just a small part of the e-m spectrum.
- Visible light has wavelengths of 400 nm (blue) to 750 nm (red)


Atmospheric Opacity
Frequency (Hz)
Wavelength (m)
Radio
Infrared
Visible
Ultraviolet
X-rays
Gamma
10^6
10^4
10^2
1
10^-2
10^-4
10^-6
10^-8
10^-10
10^-12
10^-14
10^-16
10^-18
Mt. Everest
Skyscrapers
Humans
Fingernail
Pinhead
Bacterium
Virus
Atom
Atomic Nucleus
Representative Objects
ELECTROMAGNETIC SPECTRUM
The diagram shows the entire spectrum of electromagnetic waves. The scale at the bottom indicates representative objects that are equivalent to the wavelength scale. The atmospheric opacity determines what radiation reaches the Earth's surface.

When Radiation & Matter Collide

- Radiant energy is energy moving independent of matter.
- What happens when the radiation interacts with matter?
    - How does matter absorb radiant energy?
    - How does matter emit radiant energy?
    - How is matter changed by these processes?
  - What does understanding these processes tell us about the structure of matter?
- Solving three famous chemical puzzles unlocked the answers to these questions.

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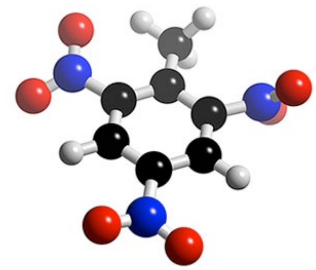
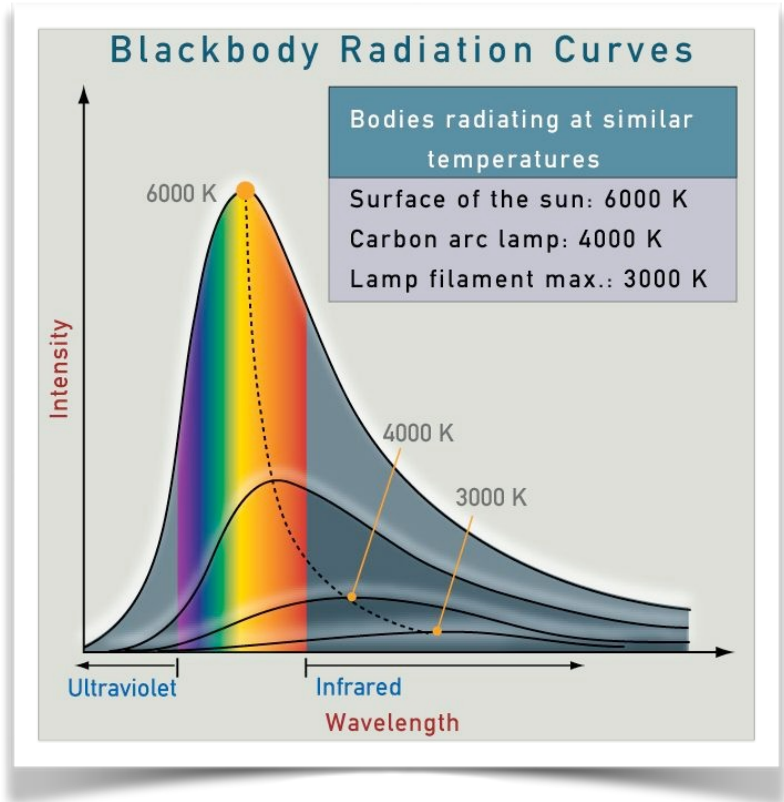


Blackbody Radiation

- Blackbody objects are objects that do not not reflect radiation.
- There is no perfect blackbody. All objects reflect some radiation.
- We call the non-reflected portion of radiation from any object blackbody radiation.
- All matter emits blackbody radiation at temperatures above absolute zero.
- Blackbody radiation is determined solely by the equilibrium temperature, it does not depend upon the substance, shape or structure of the body.
- As you increase it's temperature:
  - the frequency increases, the wavelength decreases.
- The total energy emitted at any single frequency does not increase smoothly with temperature.
- The energy emitted at any given frequency only comes out in multiples of that frequency.
- Max Planck discovered that blackbody radiation will always come out of an object as a multiple of a whole number, times the frequency, times 6.626×10^{-34} J-s — Planck's Constant (h).
- Max suggested that this means energy must be released from matter only in packets with a minimum size of 6.626×10^{-34} J-s.
- He named these packets quanta.
- He showed for all radiant energy:

$$E = h\nu$$

memorize this



Light & Heat

- Heat comes out of black bodies in any quantity.
- Light only comes out in packets of a certain size (hν)
- And therefore certain colors

(note: e-m radiation, particularly infrared radiation can cause heat, but it is not heat.)

→ 102.2578 kJ

→ 3.479 J

→ any number is possible

heat

· ·

light

→ 1 x hν J

→ 2 x hν J

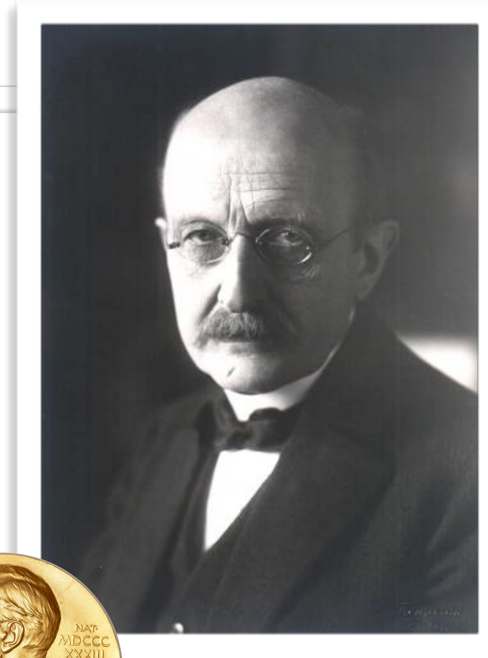
→ n x hν J

only!

$$E = h\nu$$

memorize this

Max Planck



- Radiant energy is emitted from matter in packets.
- These packets have a size equal to the frequency of the energy times 6.626×10^{-34} J-s — Planck's Constant (h).
- These packets of energy are called quanta.
- The Nobel Prize in Physics 1918 was awarded to Max Planck "in recognition of the services he rendered to the advancement of Physics by his discovery of energy quanta".

memorize this

$$c = 3.00 \times 10^{8} \frac{\text{m}}{\text{s}}$$

$$E = h\nu$$

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

$$h = 6.626 \times 10^{-34}\ \text{Js}$$

$$c = \lambda\nu$$

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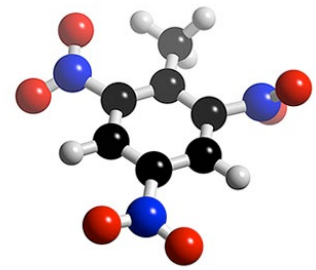
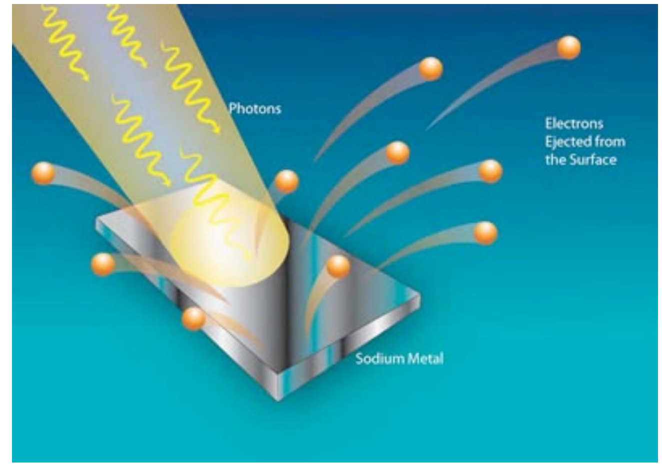
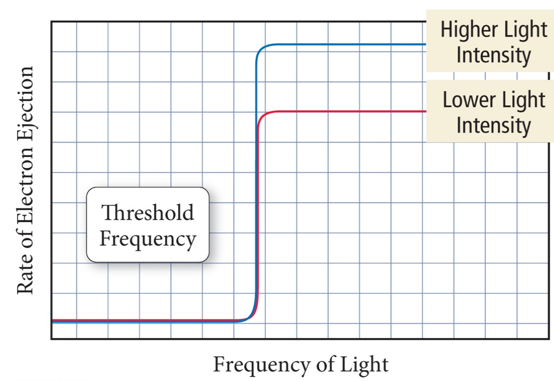


The Photo Electric Effect

- If you shine light on alkali metal, electrons fly off it.
- The light must have a minimum frequency or nothing happens.
- Once you reach that threshold frequency, increasing the frequency does not effect the number of electrons released.
- It's like hitting a switch, on or off — all or nothing.





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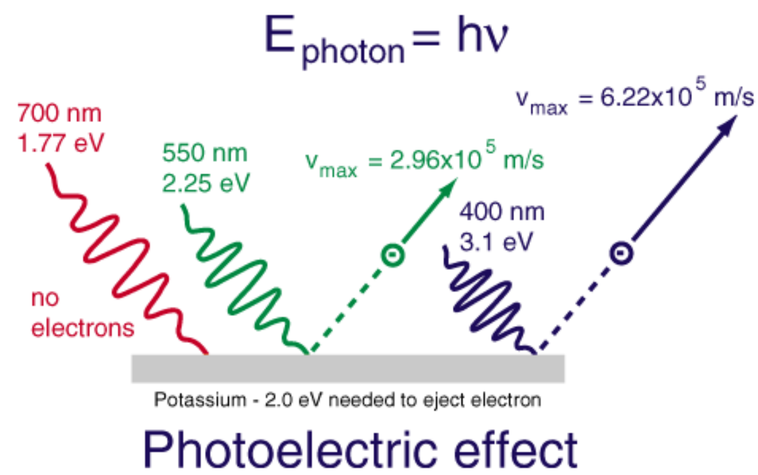
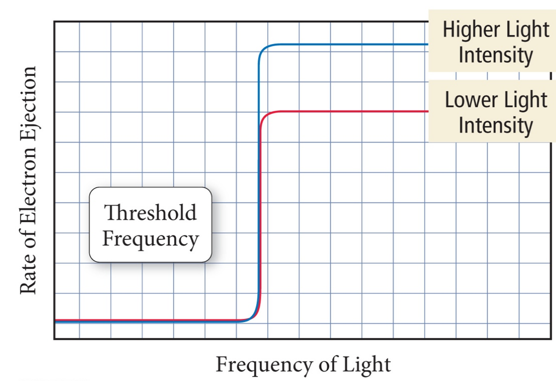
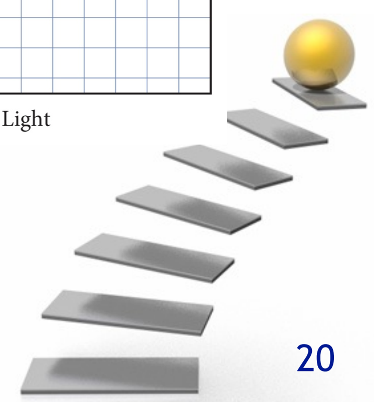
- Albert Einstein used Max Planck's idea of quanta to explain the photo electric effect.
- Einstein suggested that there is a minimum energy needed to liberate an electron.
- That the electron was only ejected if it was hit by a packet of light who's quantum energy was sufficient to eject it.
- Like kicking a ball over a fence, if the kick didn't have enough energy to clear the fence — nothing happened.
- If the kick was strong enough, the ball goes free.
- If you kick it harder, you still get ***only one ball*** over.







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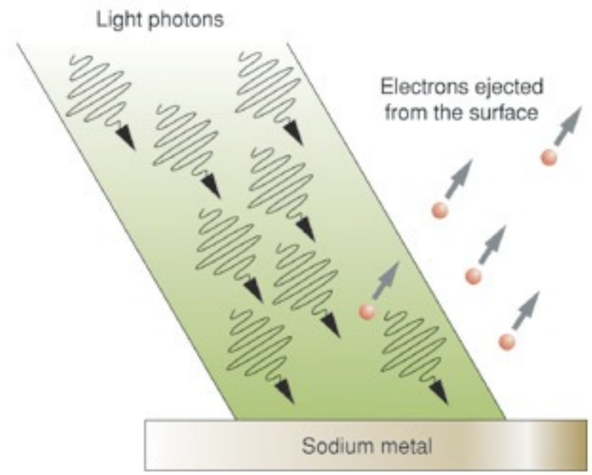
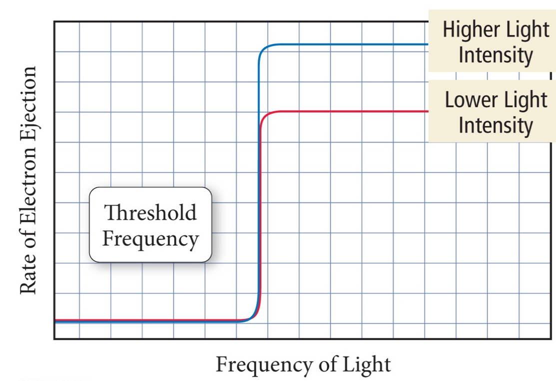
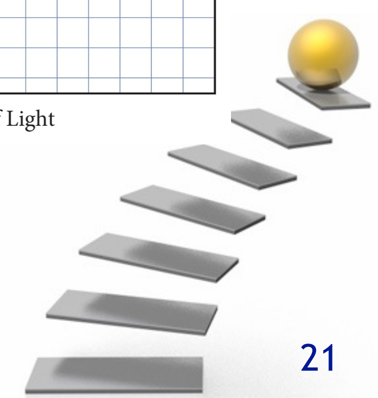
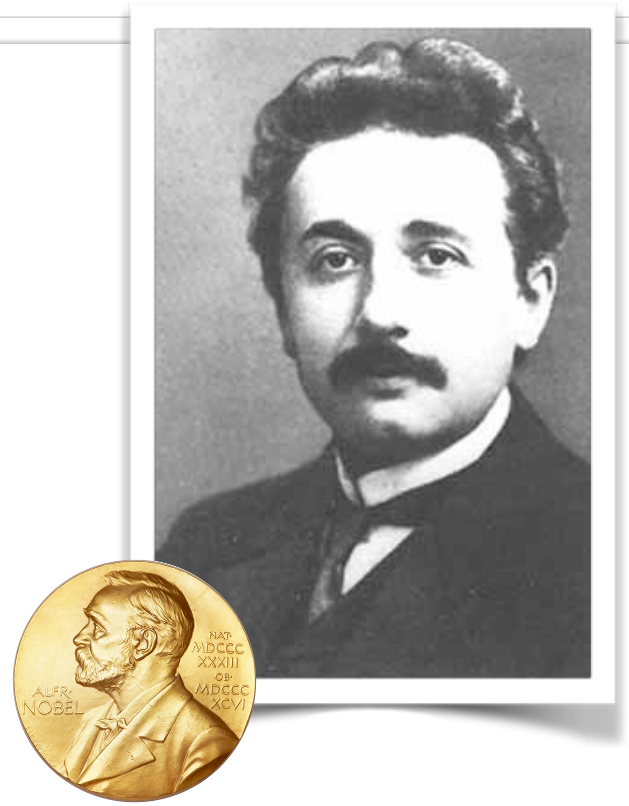
- Like kicking a ball over a fence, if the kick didn't have enough energy to clear the fence — nothing happened.
- If the kick was strong enough, the ball goes free.
- If you kick it harder, you still get only one ball over.
- Einstein argued that light, which has no mass, should in many cases, be thought of a particle.
- Einstein called these imaginary light particles photons.
- Light is not a particle, it has no mass. It's just useful to think of it that way.
- Because it let's you think of all light as granular, with each grain of light, each photon, having one quanta of energy.



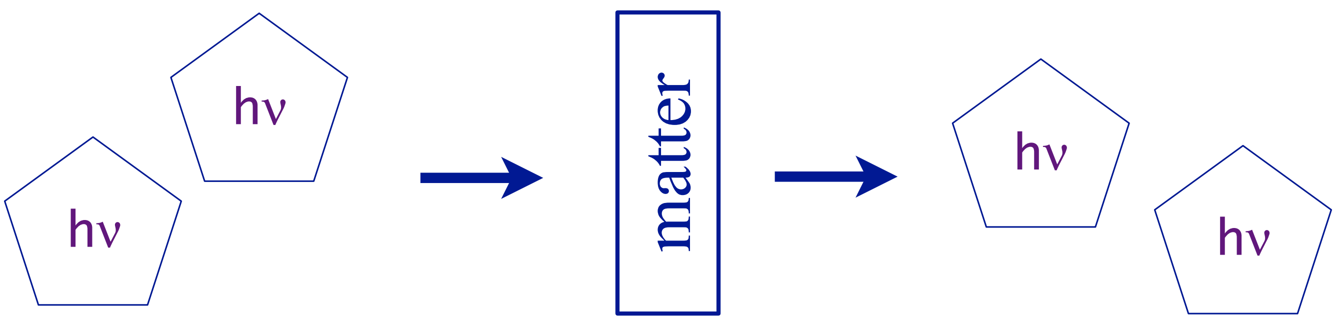




Albert Einstein



- Energy is absorbed by matter in packets.
- Light is not matter.
- But if we think of radiant energy as a stream of particles, it solves many problems of how energy interacts with matter.
- It gives us a better understanding how e-m energy interacts with matter.
- We call these imaginary particles photons.
- Photons don't exist, they're just a trick we use to describe particle like behavior of light.
- Albert Einstein was not given a nobel prize for relativity.
- The Nobel Prize in Physics 1921 was awarded to Albert Einstein "for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect".
- Planck and Einstein created a new field of science based on the hypothesis of quanta. One that provided tremendous new insights into the nature of matter.
- Quantum Mechanics explained many things about chemistry that Classical Mechanics could not.



Frequency, Wavelength & Energy

- Red light has a wavelength of about 703 nm.
  - (a) What is it's frequency?

$$\lambda = 703\,nm \cdot \frac{10^{-9}\,m}{nm} = 7.03 \times 10^{-7}\,m$$

$$c = \lambda \nu$$

$$\nu = \frac{c}{\lambda} = \frac{3.00 \times 10^{8}\,m/s}{7.03 \times 10^{-7}\,m} = \boxed{4.27 \times 10^{14}\ 1/s\ (\text{or } Hz)}$$

  - (b) Calculate the energy of one photon of red light.

$$E = h\nu = 6.626 \times 10^{-34}\,J\,s \cdot 4.27 \times 10^{14}\,1/s$$

$$= \boxed{2.83 \times 10^{-19}\,J}$$

  - (c) Purple light as a wavelength of 450 nm. Would a photon of purple light have more or less energy than a photon of red light?

$$E = h\nu \qquad \nu = \frac{c}{\lambda}$$

$$E = h\frac{c}{\lambda}$$

as wavelength goes down, energy goes up.

Purple light has more energy than red.

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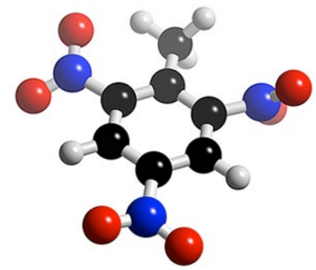
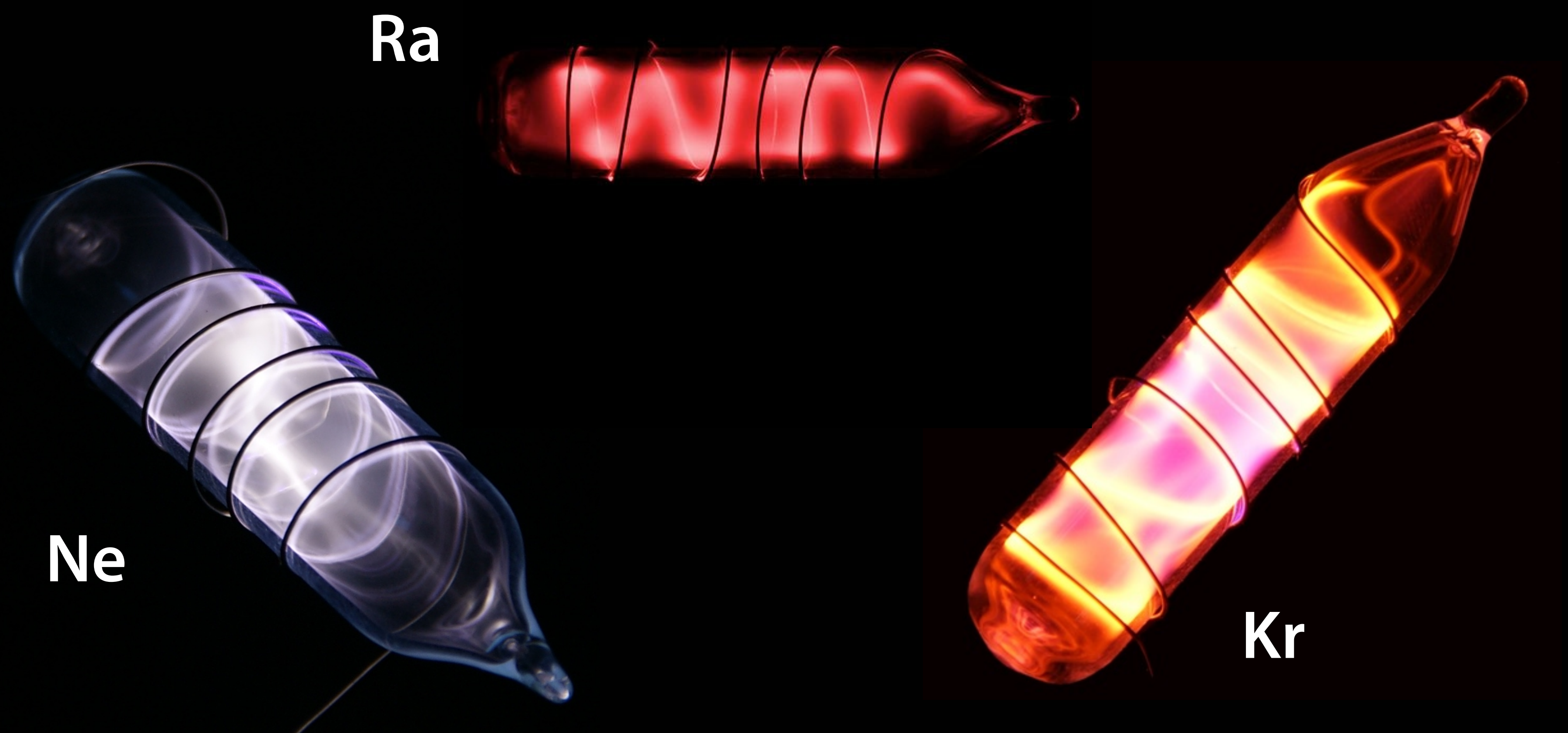
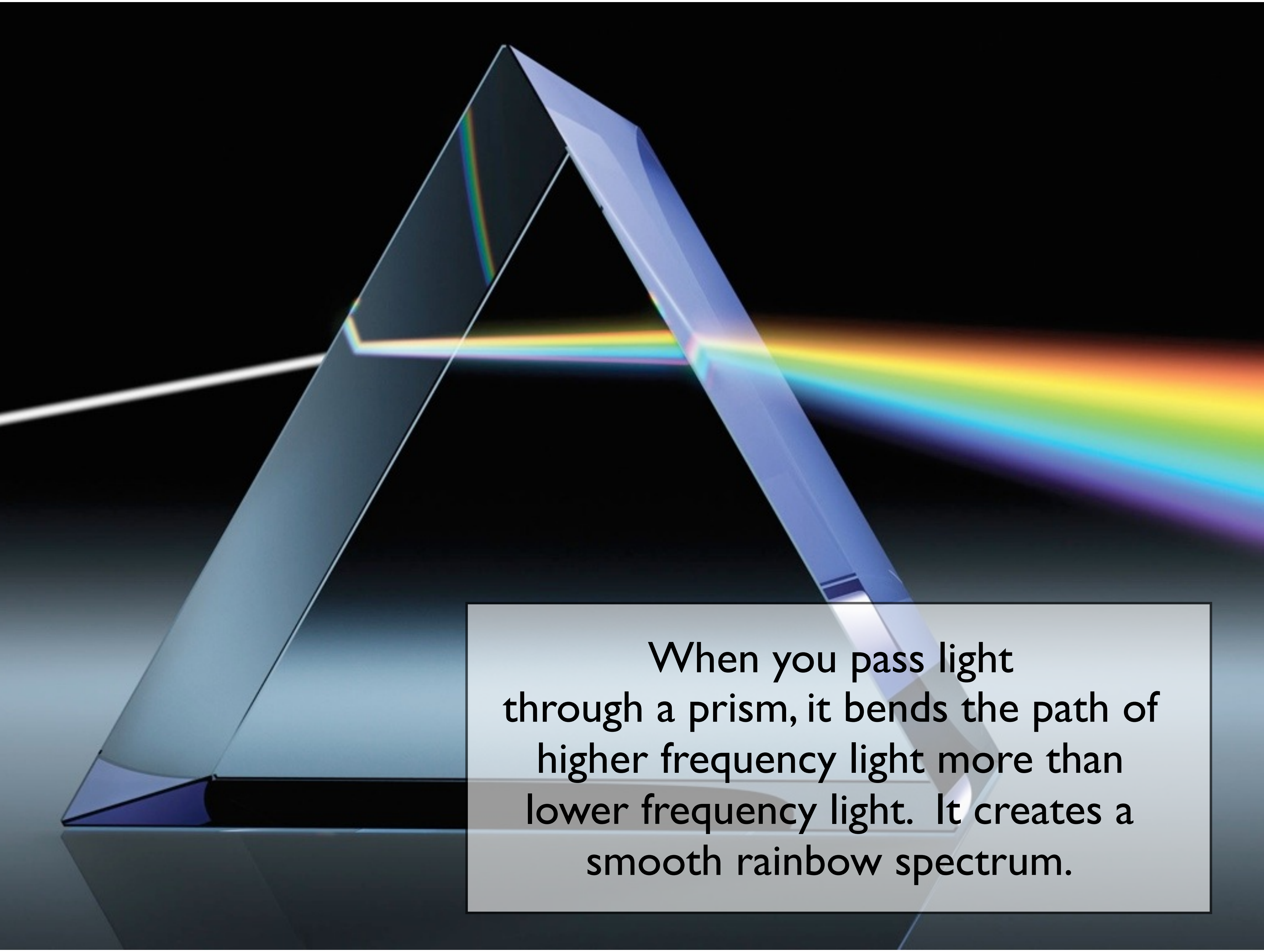
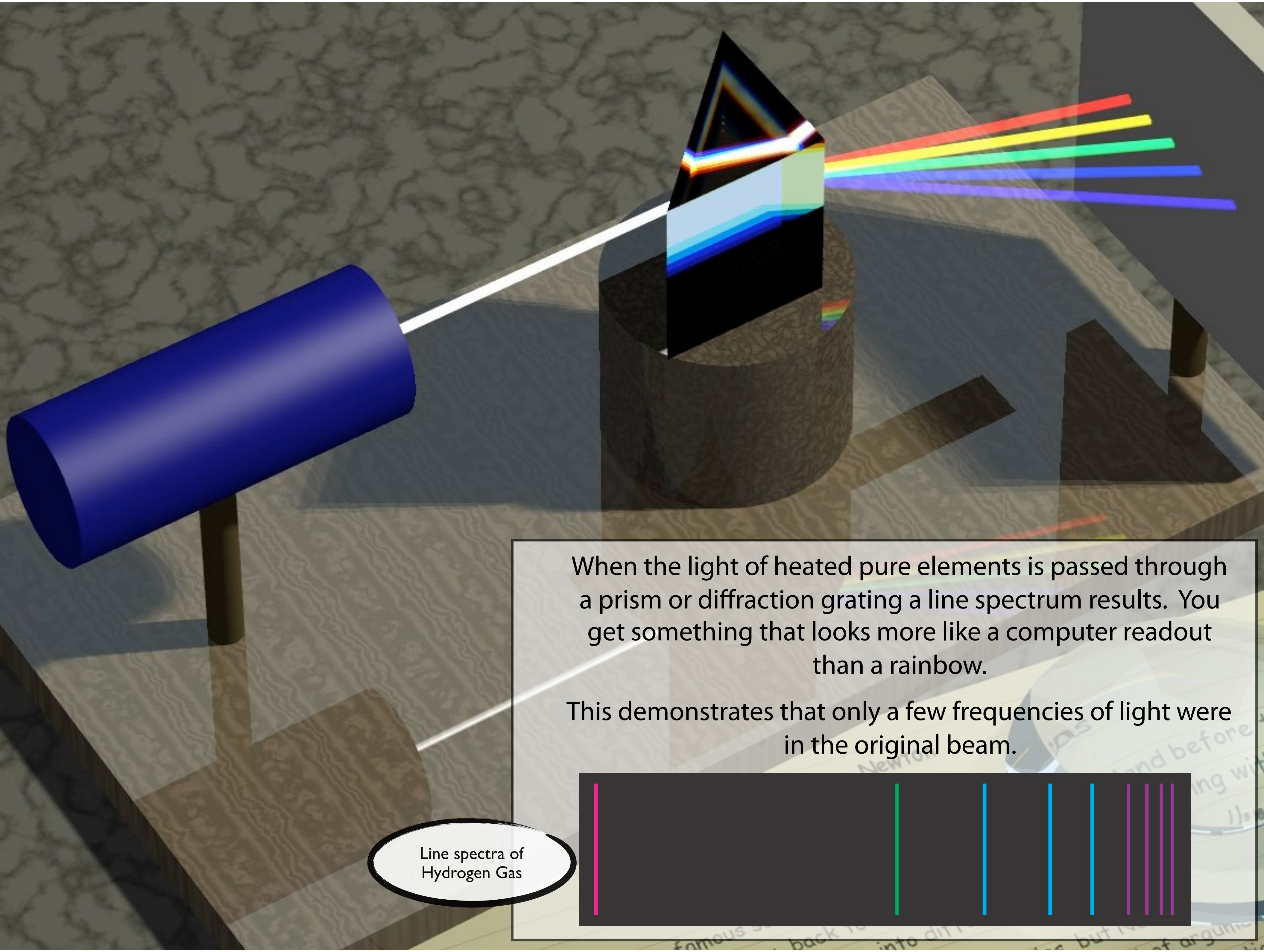


At high temperatures or voltages, pure elements in the gaseous state emit light of different colors.

There is something special about this light.




When you pass light
through a prism, it bends the path of
higher frequency light more than
lower frequency light. It creates a
smooth rainbow spectrum.

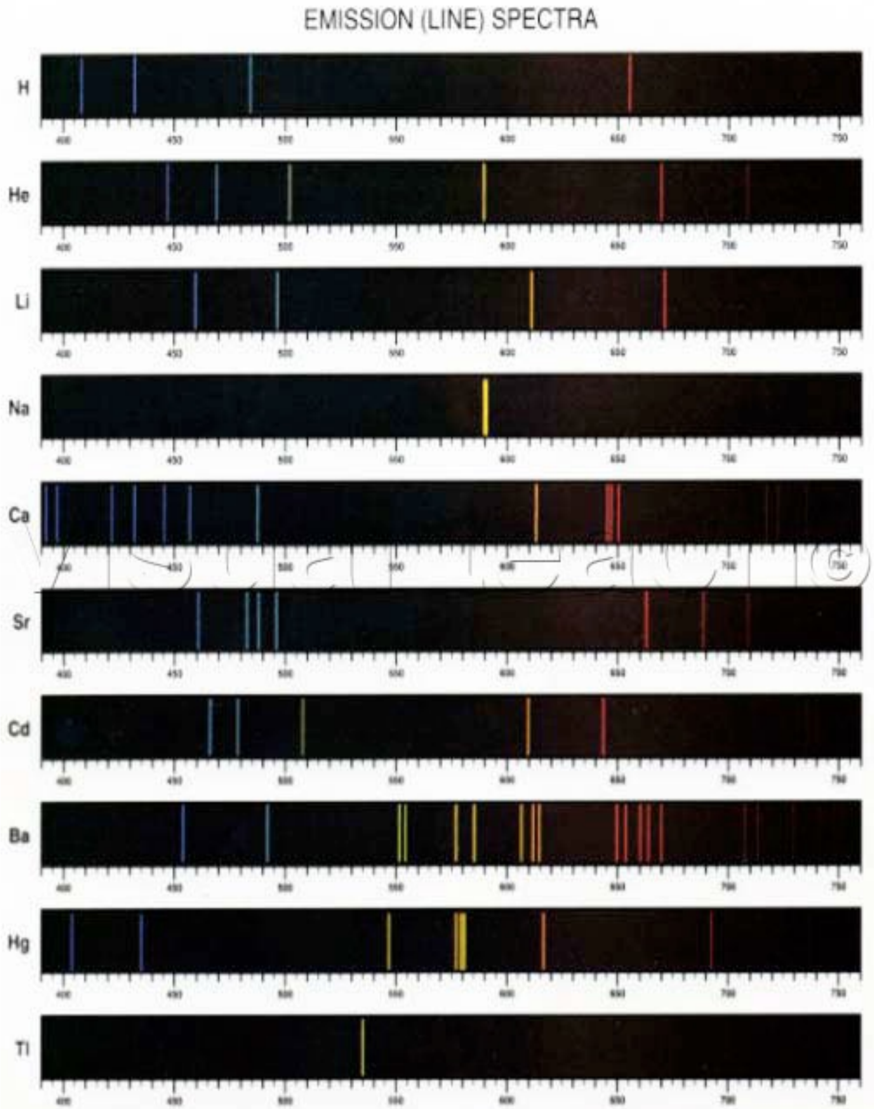


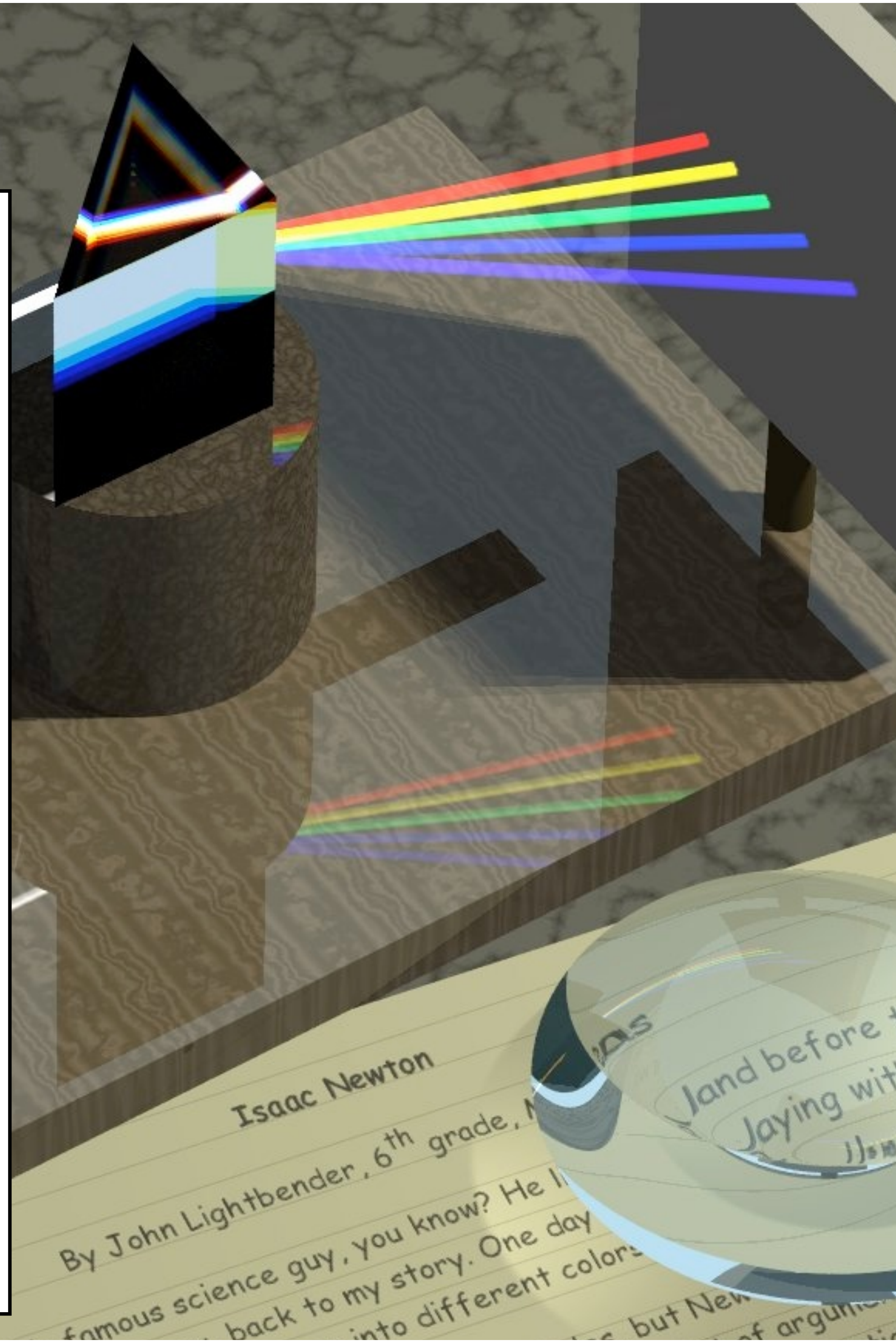
When the light of heated pure elements is passed through a prism or diffraction grating a line spectrum results. You get something that looks more like a computer readout than a rainbow.

This demonstrates that only a few frequencies of light were in the original beam.

Line spectra of Hydrogen Gas

Each element has a different unique set of spectral emissions that distinguish it from the other elements.





Radiant Energy

- Radiant Energy
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    - What's happening inside the matter.
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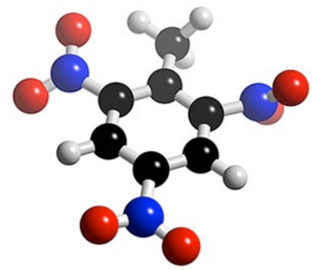
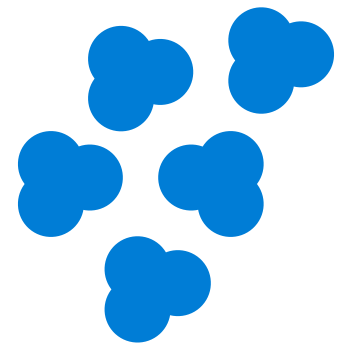


A Bohr model of the atom (planetary model).

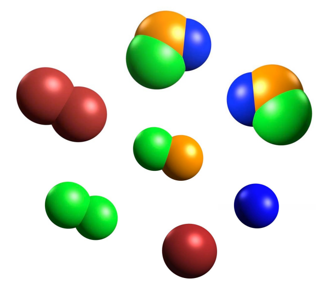
Up to the Nuclear Age

A Brief History of Atomic Theory

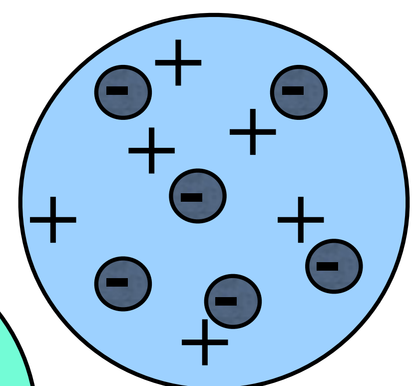


Greeks were the first to suggest that matter is made up of atoms

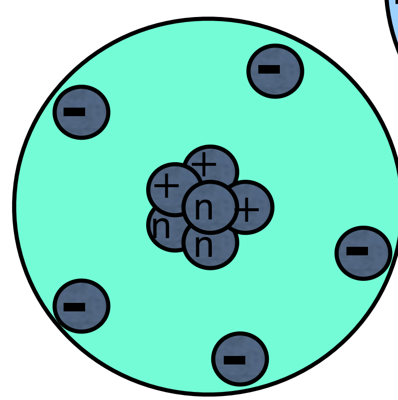
Early chemists performed experiments



Their experiments led to Dalton's Atomic Theory



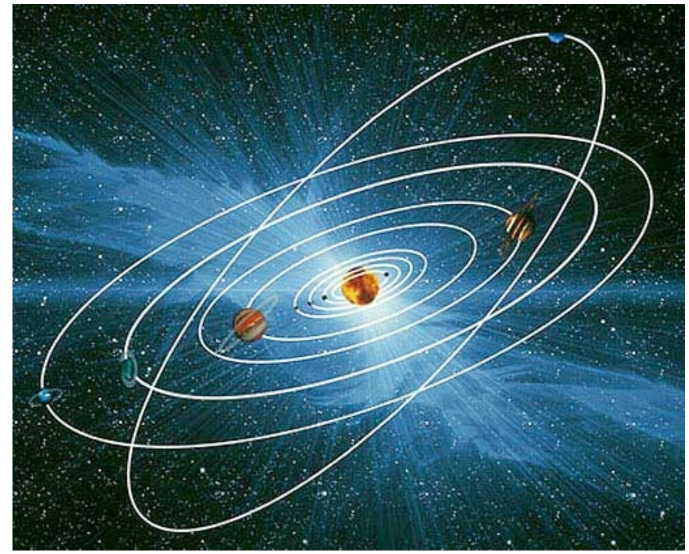
Limitations of Dalton's model led to the Thompson and Rutherford models of the atom.

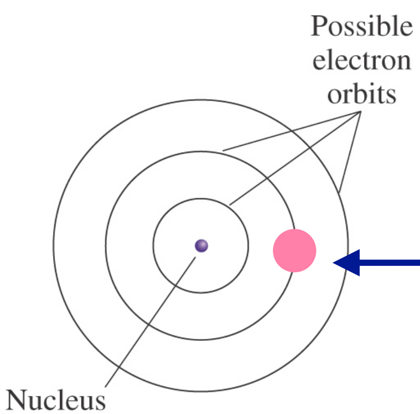


While these models work reasonably well their limitatons have led to more modern theories as to the nature of the atom.

Line Spectra of the Elements

- At high temperature or voltages, elements in their pure state emit light
  - That light is special.
- Unlike most sources of light, it contains only discrete frequencies.
- Each element emits light with a unique set of frequencies.
- Niels Bohr started with Rutherford's model that electrons floated around a heavy positively charged nucleus.
- He postulated that much the same way planets orbit the sun in only orbits of a fixed distance, that electrons are also constrained to orbits of a fixed distance from the nucleus.
- There are reasons why planets must maintain those fixed orbits, those reasons don't apply to negatively charged electrons orbiting a positive nucleus. Bohr knew his hypothesis had this hole in it.





Electrons revolve around the nucleus in orbits that are located at fixed distances from the nucleus.

An electron has a discrete energy when it occupies an orbit.

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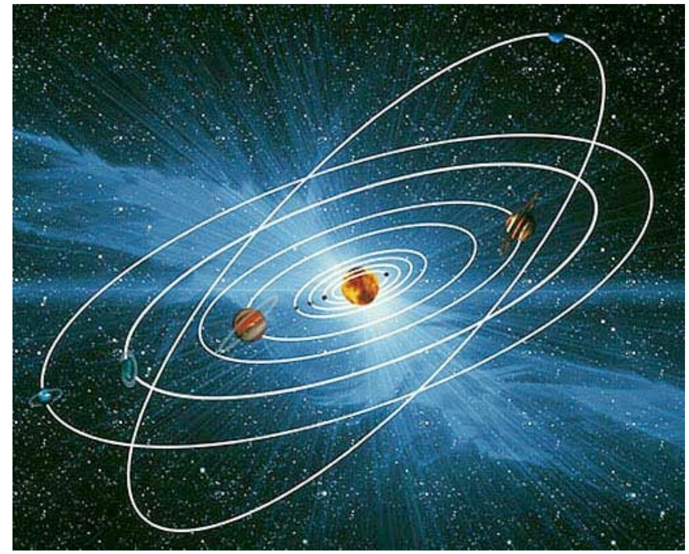
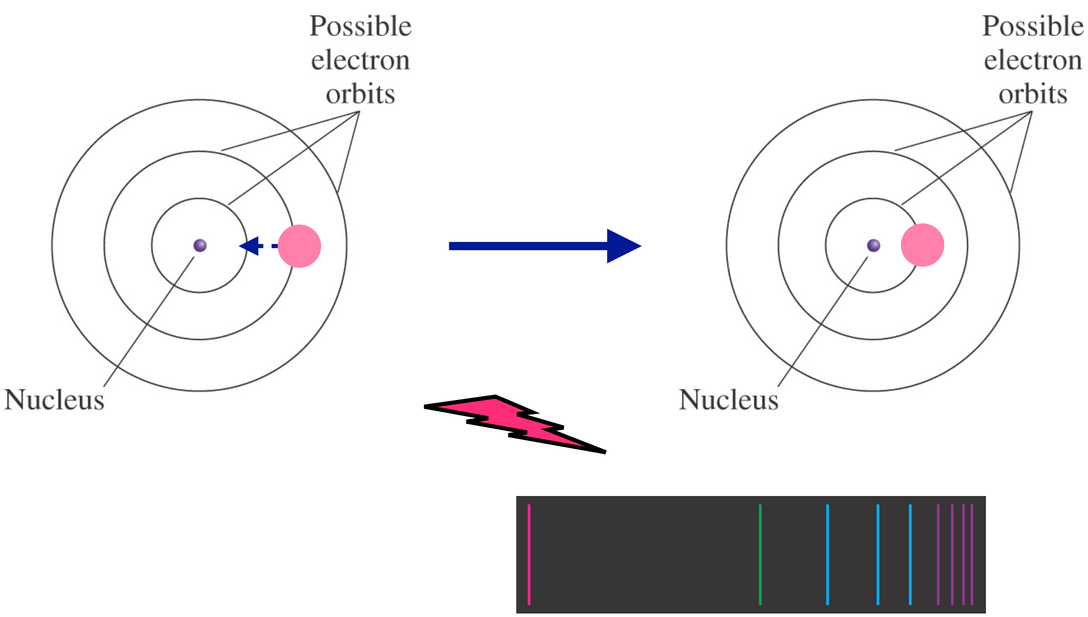
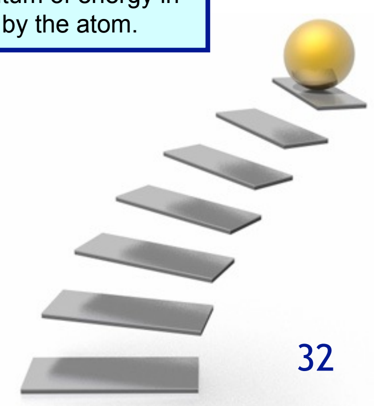




When an electron falls from a higher energy level to a lower energy level a quantum of energy in the form of light is emitted by the atom.



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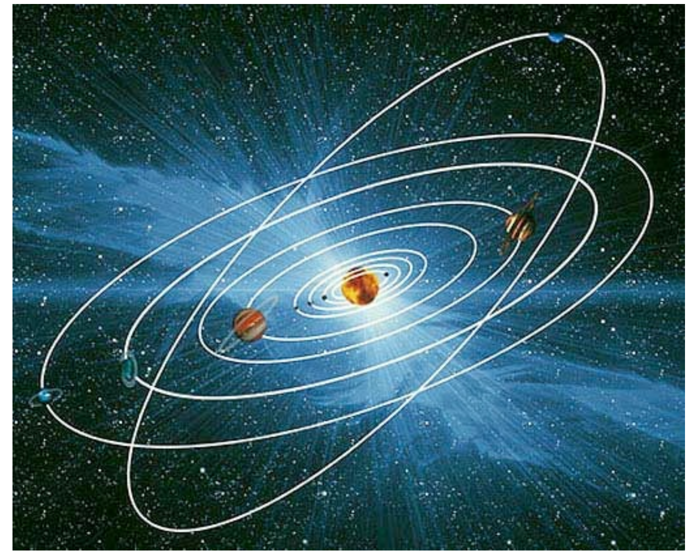
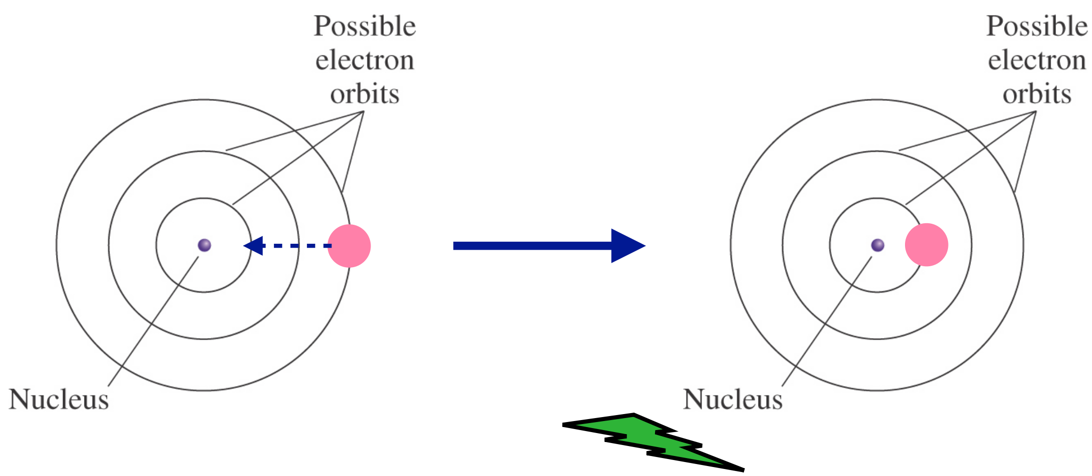
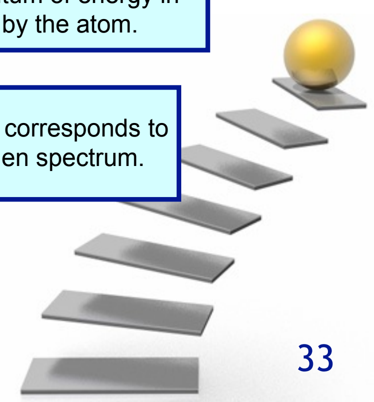




$$E = h\nu$$

When an electron falls from a higher energy level to a lower energy level a quantum of energy in the form of light is emitted by the atom.

The color of the light emitted corresponds to one of the lines of the hydrogen spectrum.



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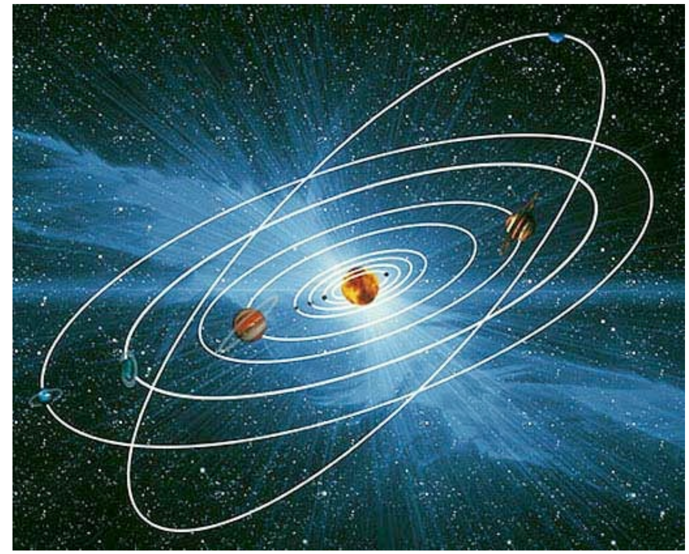

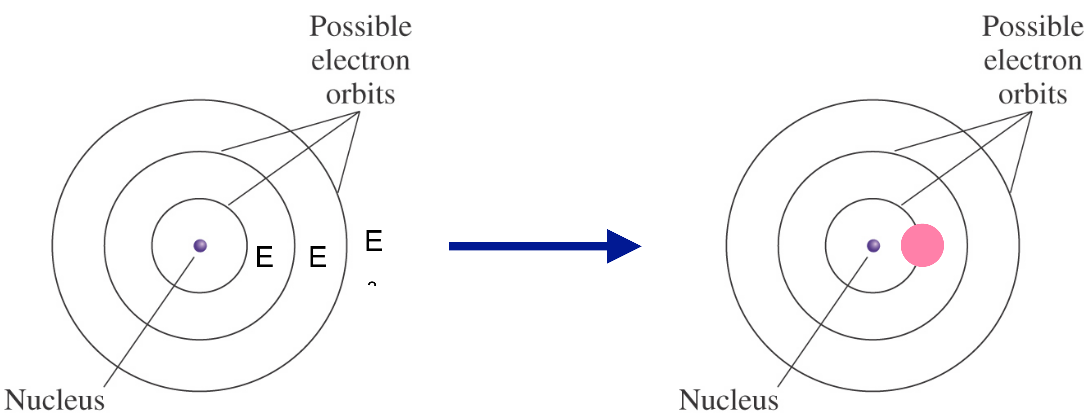

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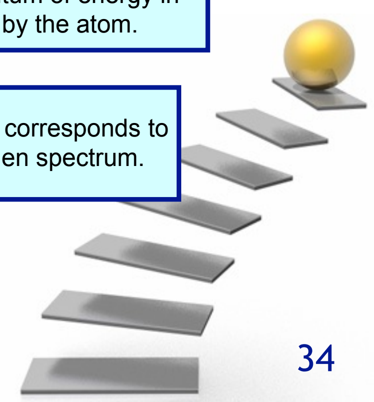

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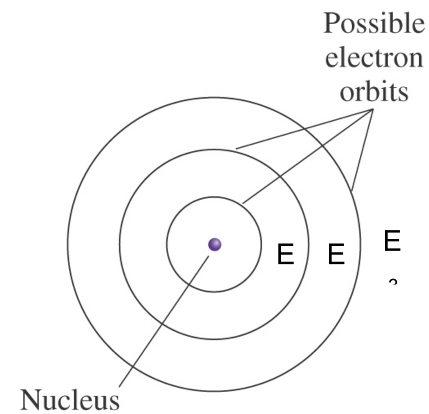
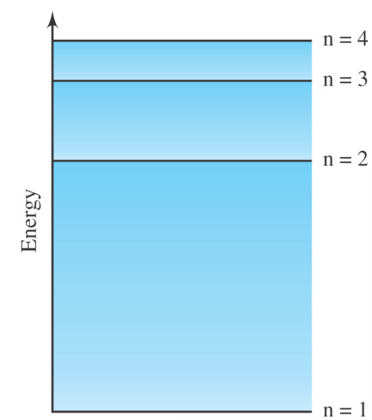
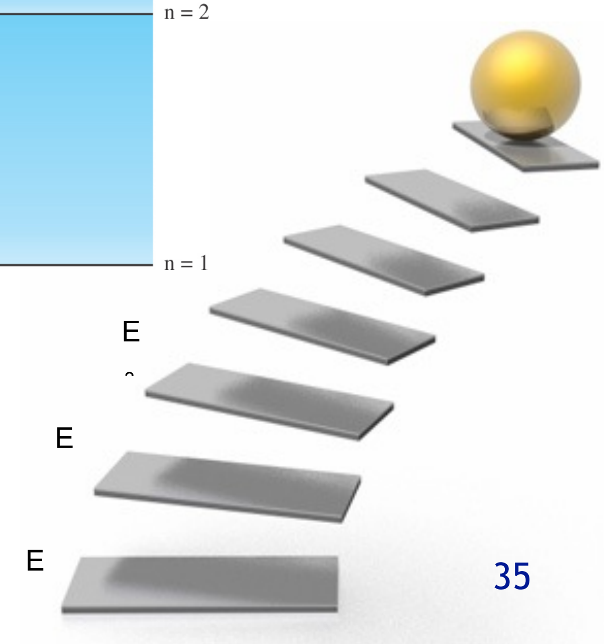
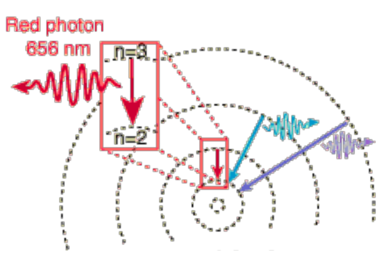
- He suggested that when an electron falls from a higher orbit to a lower energy orbit, it emits a photon.
- The color of that light depends on the wavelength, which depends on the energy difference between the two levels.
- With this model, only photons of with energy that equals the difference between levels can be emitted.
- This would explain why only discrete colors are seen in the line spectra.









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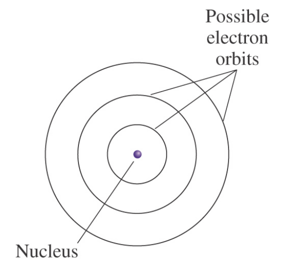
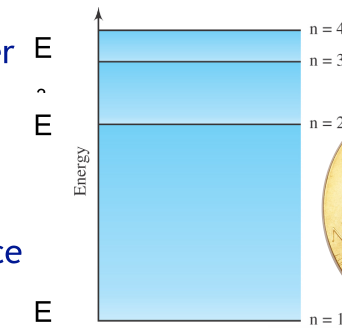
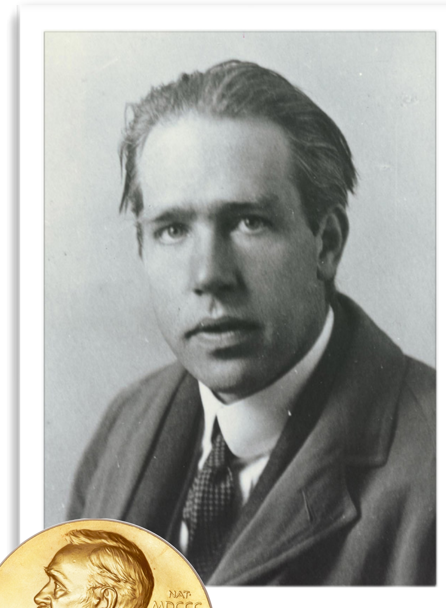
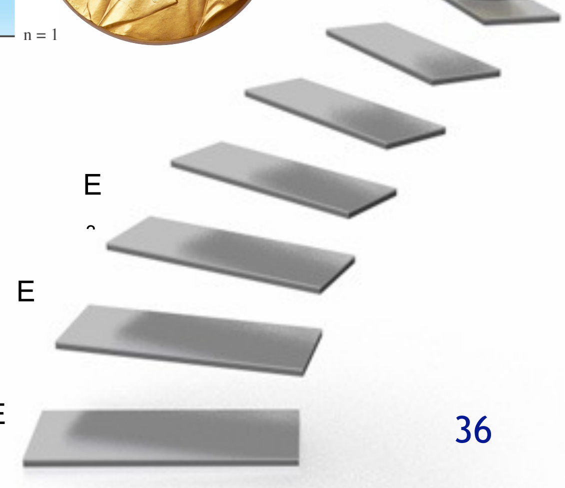
- The Nobel Prize in Physics 1922 was awarded to Niels Bohr "for his services in the investigation of the structure of atoms and of the radiation emanating from them".









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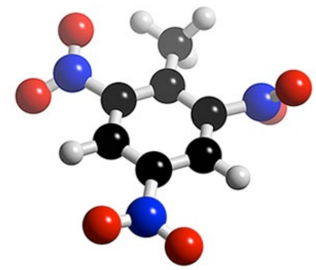
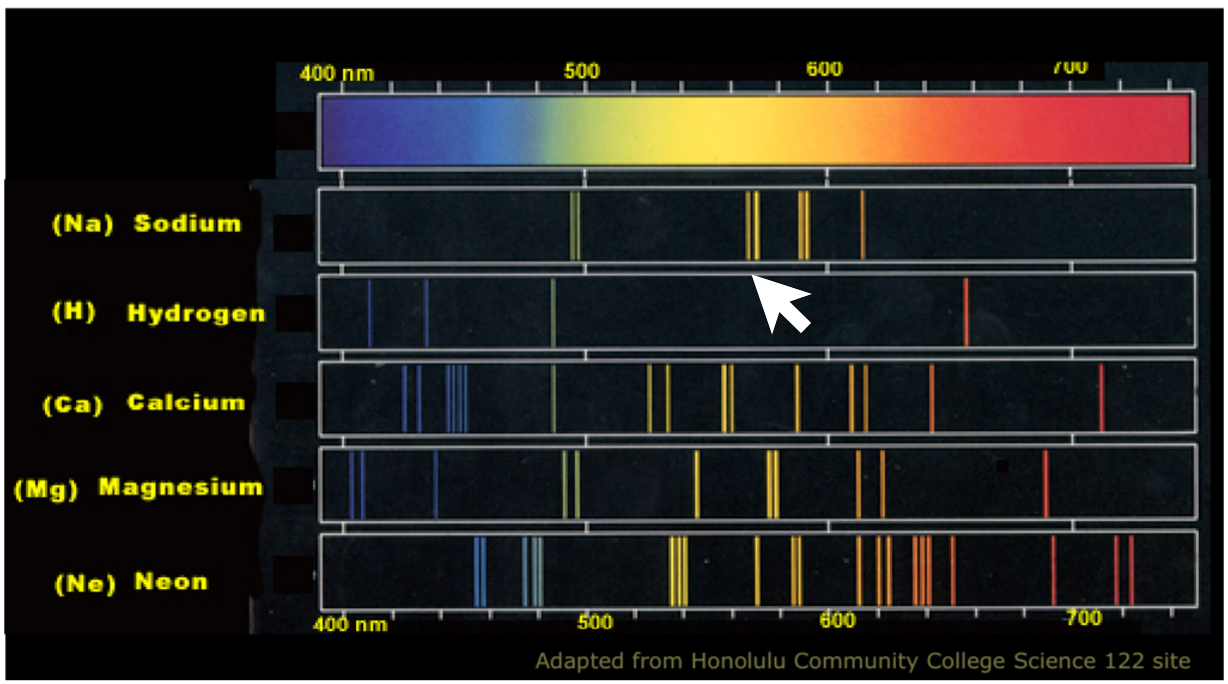


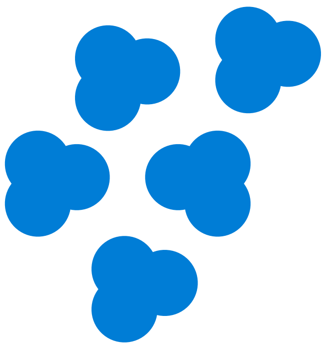
Problems with the Bohr Model

- The Bohr model was a huge step forward in atomic theory.
- It explained the line spectra and gave us insight into how electrons were arranged inside the atom.
- Bohr knew it was an incomplete model.
- His postulate that only certain orbits were allowed was unexplained.
- His model only predicted line spectra perfectly for the hydrogen atom.
- The line spectra of other elements showed splitting that wasn't explained by the Bohr model.



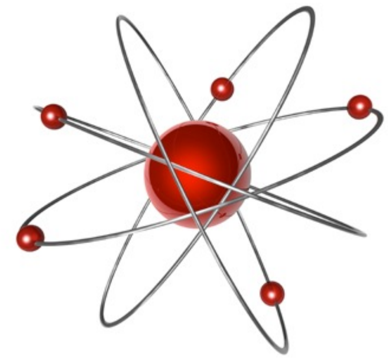
Adapted from Honolulu Community College Science 122 site

Evolution of the atom.

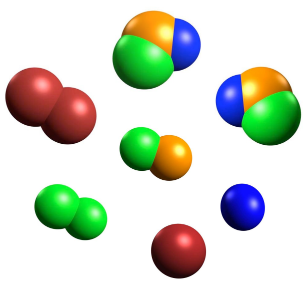


Atomos.

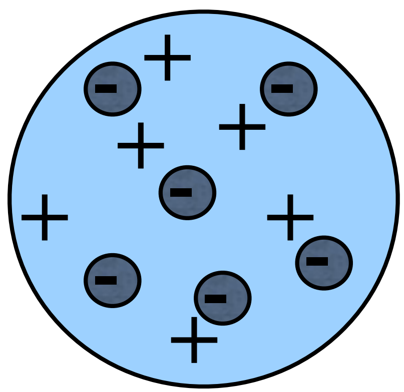
The next atom?



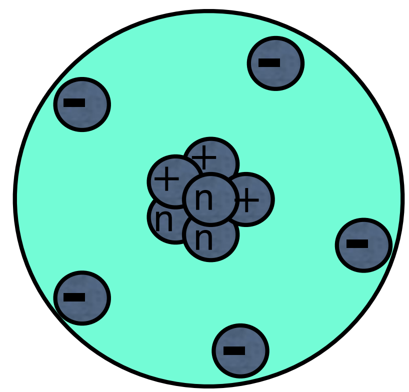
The planetary model.



Molecules & Compounds.
Elements, flavors of the atom.



The plum pudding model.



The nuclear atom.

Questions?