# A Journey Into Electromagnetics

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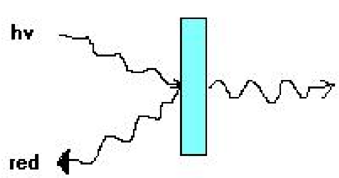
# Organization

- **Electromagnetics in day to day life**
- **The history of Electromagnetics**
- **Application base of Electromagnetics**
- **Present scenario**
- **What more can we do**

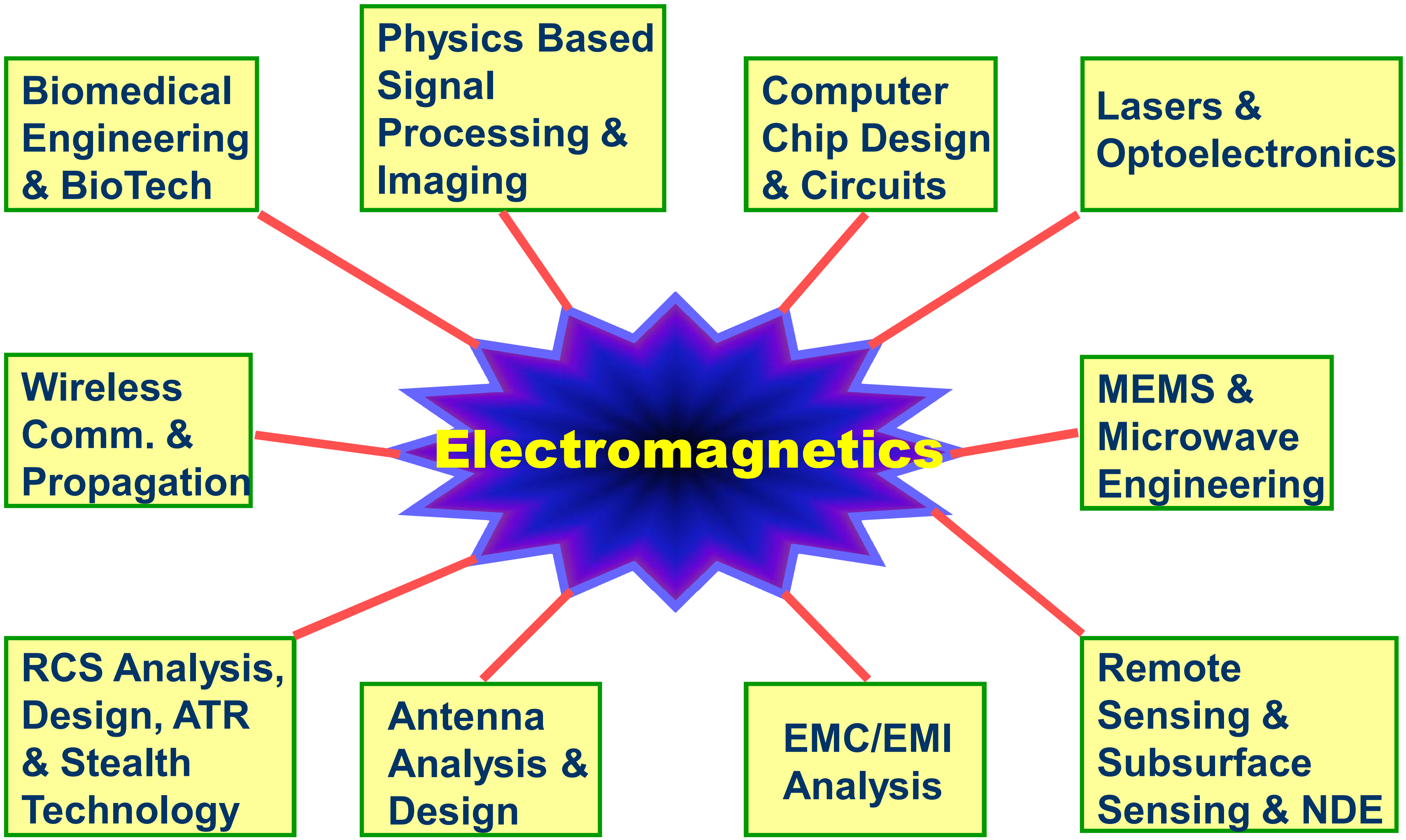
# Electromagentics in daily life

- Lighting
- Fans / motors
- Telephone / Fax/ Radio / TV
- Internet
- Mobile telephony
- Microwave cookers

Without Electromagetics – there is NO LIFE!



# Importance of Electromagnetics



# What is Electromagnetics (EM) ?

- **Electricity and Magnetism together is called EM**
- **Can light be electromagnetism?**
- **Can atom has electromagnetism?**
- **Can human body has electromagnetism?**
- **Clouds are electromagnetic?**
- **Can communication is electromagnetic?**
- **Is radio and Television  electromagnetic?**
- **Can a phone / mobile phone is electromagnetic?**

# Electricity and Magnetism

- Electric Charge and Electricity
  - Positive and negative charges, conductor vs. insulator.
  - Electric current, electric power, series & parallel circuits.
- Magnetism:
  - North and South poles, field lines around a magnet.
  - Make an electromagnet using electricity.

# Electric Charge: "Static" Electricity

"Rubbed" Balloon

*Figure from Serway*

objects
be tra
ject, i.e
an pro

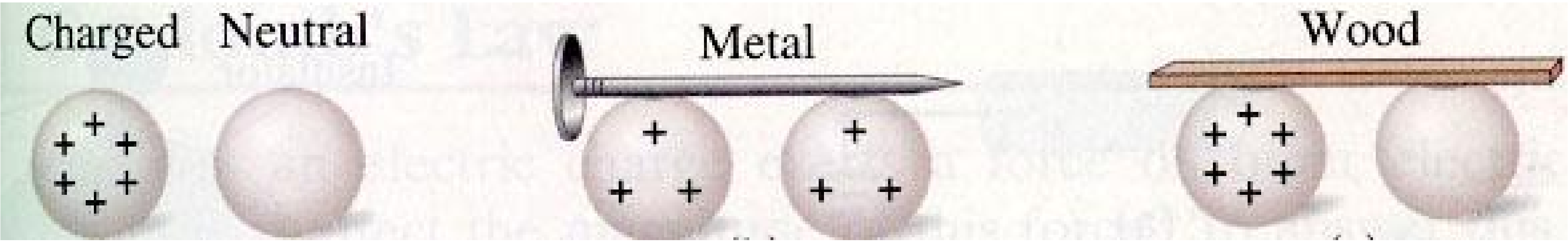
Van de Graaff Generator

- Charged objects c each other: Opposite charges attract (positive & negative) and like charges repel.

# Electric Charge: Conductor vs. Insulator

Step 1

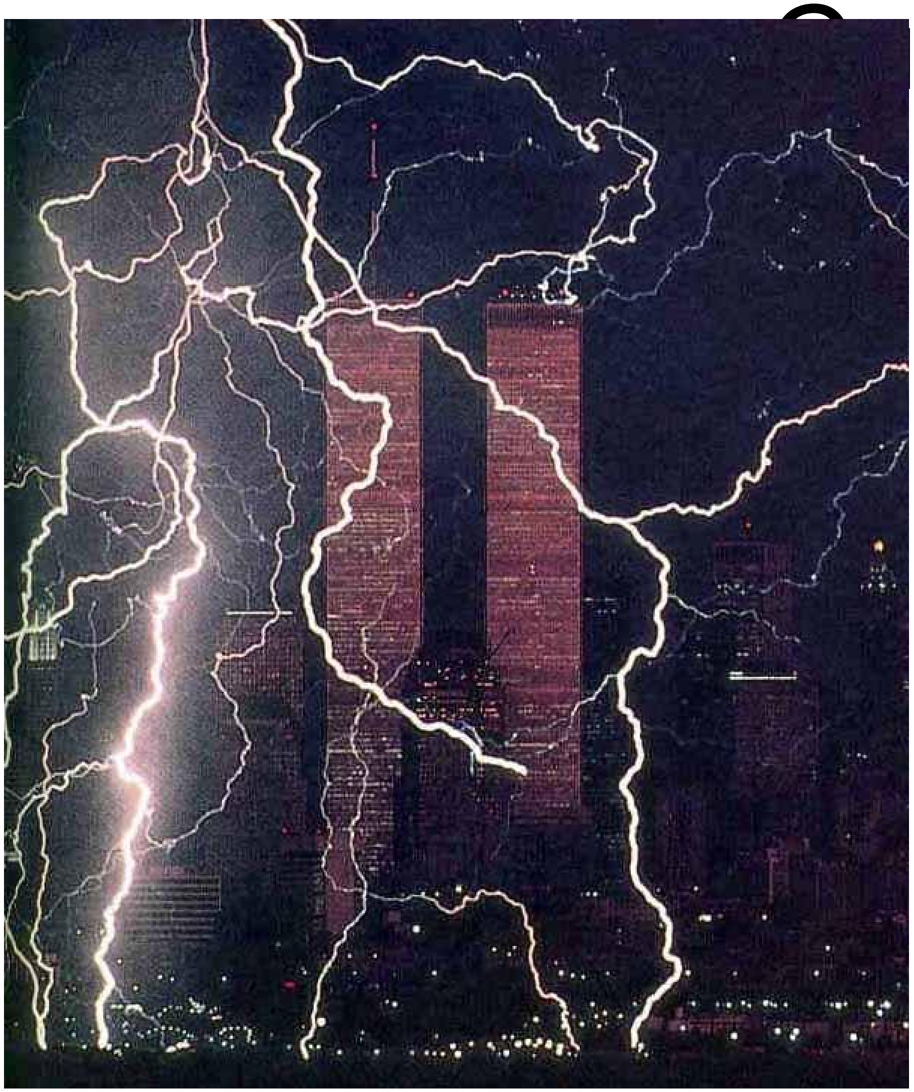
Step 2




- Electric charge can "flow" or travel through a metal <u>conductor</u>, but not through an <u>insulator</u> such as wood.
- It is negatively charged <u>electrons</u> that are traveling through a conductor (<u>not</u> the positive protons "stuck" inside the nucleus!)

*Figure from Giancoli*

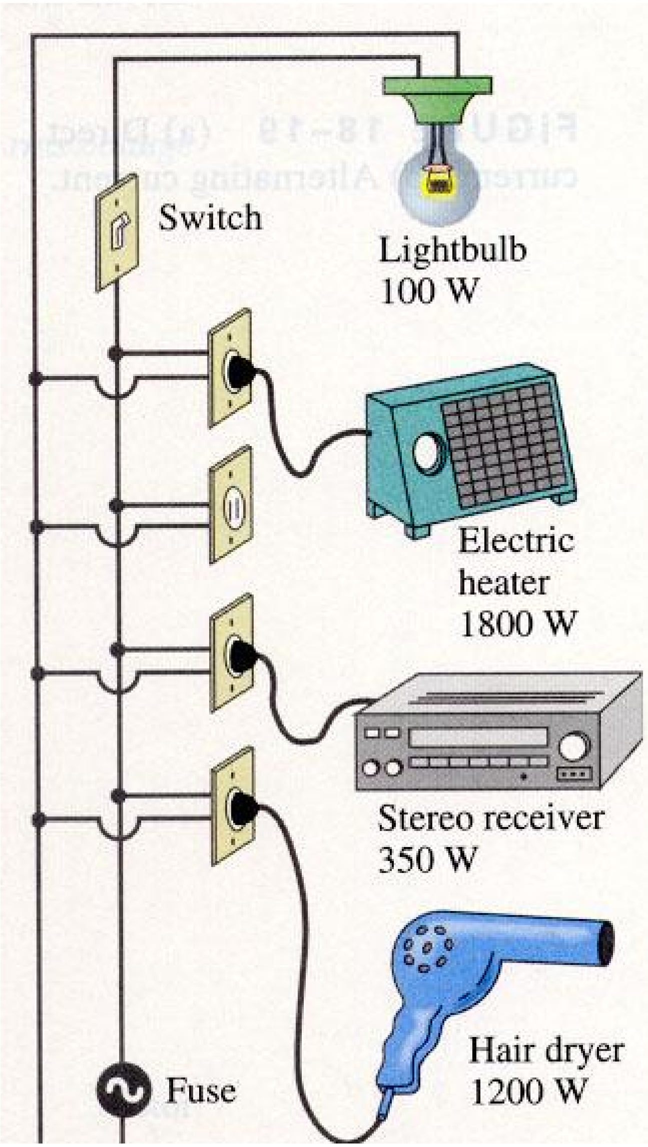
# Electricity: Lightning is Electrical Current



- Electrical current is the motion of charged particles such as electrons.
- For example, lightning is the result of electrons flowing from the clouds to the earth.
- In order for charge to flow between two points, there must be a build up

*Figure from Halliday, Resnick, & Walker*

# Power for Appliances

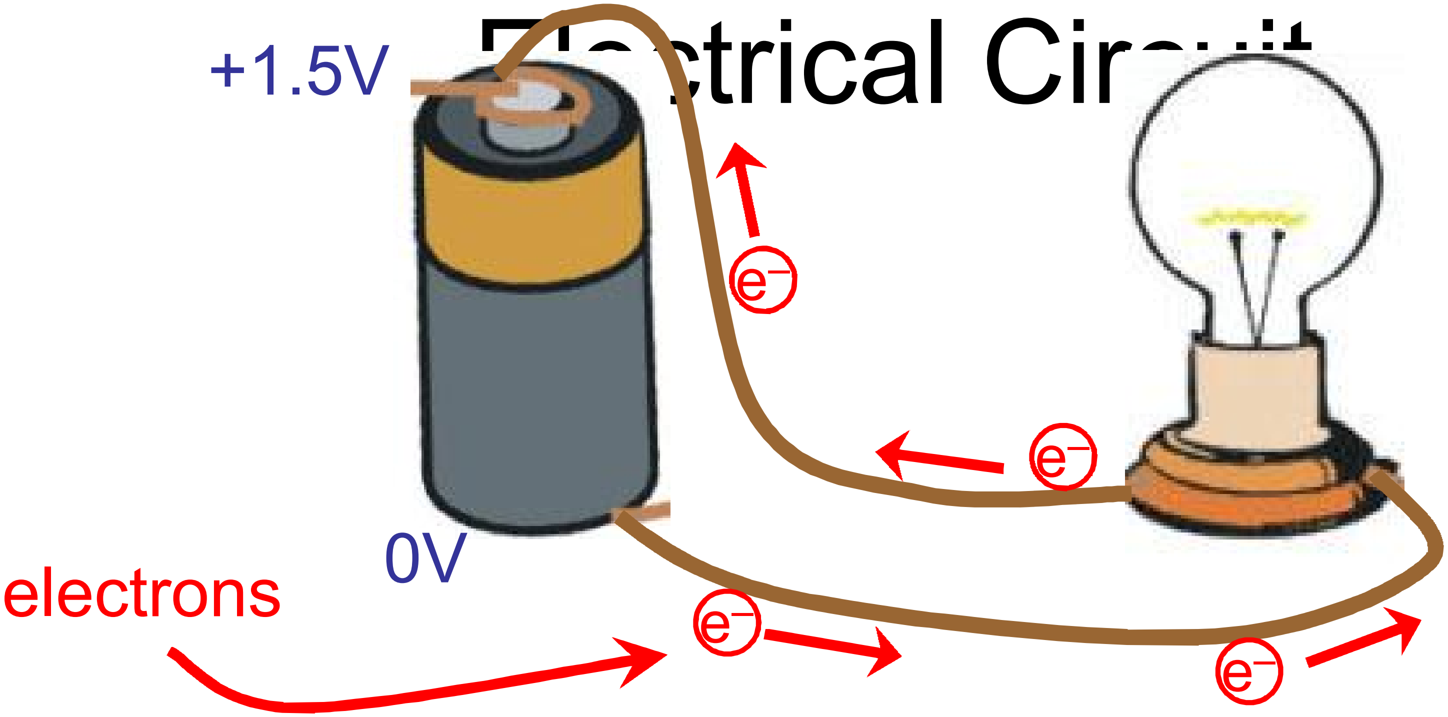



Oven ~ 6,000 W = 6 kW
Refrigerator = 800 W
TV = 100 W

- Power is the amount of energy used per unit time (Power = Energy / time).
  - Units of Watts (W) or Kilowatts ( kW = 1000 W)
- The energy used by an appliance is its power rating multiplied by the amount of time it is on (Energy = Power × time).
  - Units of Kilowatt-Hours (kW-hr)

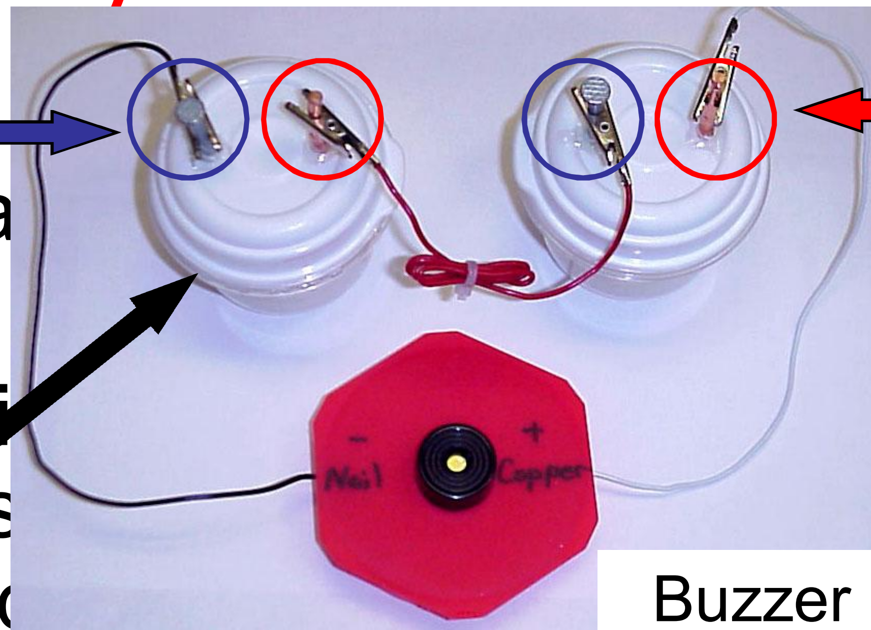
*Figure from Giancoli*

# Electrical Circuit




- An electrical circuit must have two things: 1) an energy (or voltage) source and 2) a circular path for moving electrons (or current) to flow through.
- Voltage = energy to separate positive and negative charges, such as in a battery (units of

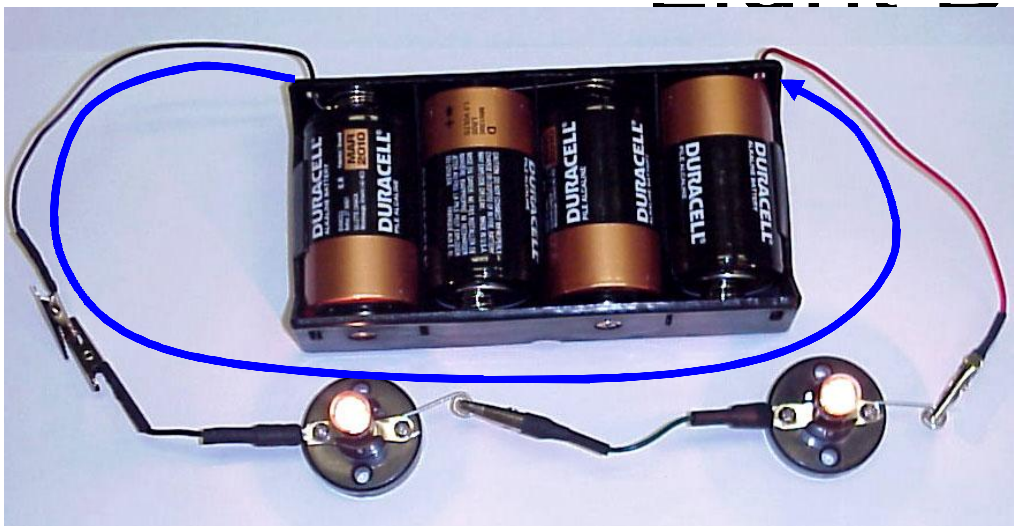
# Activity with Salt Battery




- Connect a … a circuit to make a …
- A battery i… ent metal electrodes … a conducting … .
- *Can you trace the <u>circular path</u> of the circuit above?*

# Activity with Series & Parallel

Series Circuit = one circular path | Parallel = two paths





- Bulbs look dimmer
  - Lower voltage on each bulb (3V).
- When one bulb is unscrewed, the other bulb goes off.
  - The circuit is now open!

- Bulbs look brighter
  - Higher voltage on each bulb (6V).
- When one bulb is unscrewed, the other bulb still stays lit.
  - A closed circuit still exists

# Magnetism: History

- More than 2,000 years ago, Greeks discovered that magnetite stone (iron oxide) attracted pieces of iron (Fe).

- In 1269, Pierre de Maricourt discovered that every permanent magnet has two poles: north and south.

- In 1600, William Gilbert discover
earth itself is a magnet with its m
near the geographic north and s
*(Today, the north pole is actually*
*magnetic pole, but that changes*
*centuries.)*

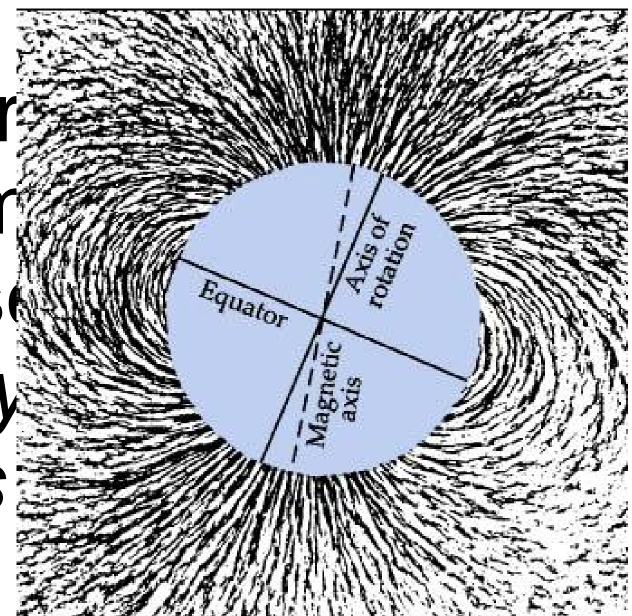
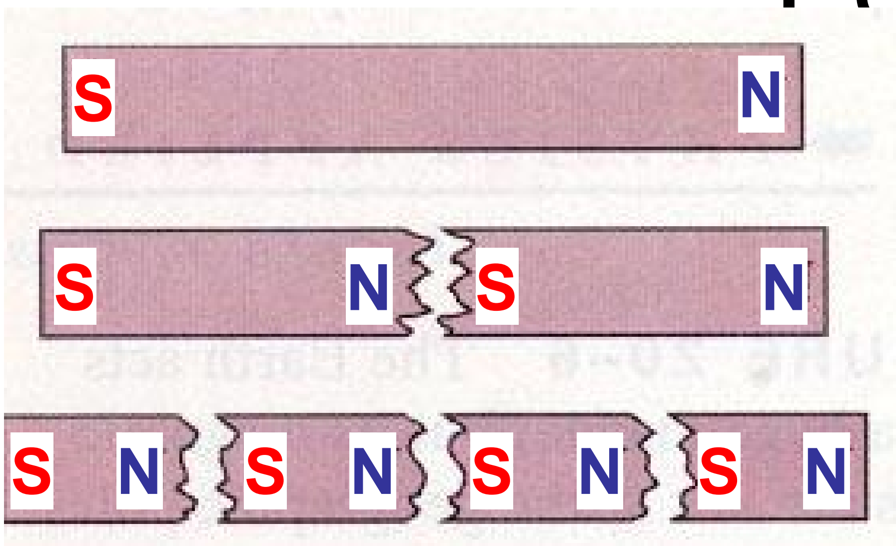
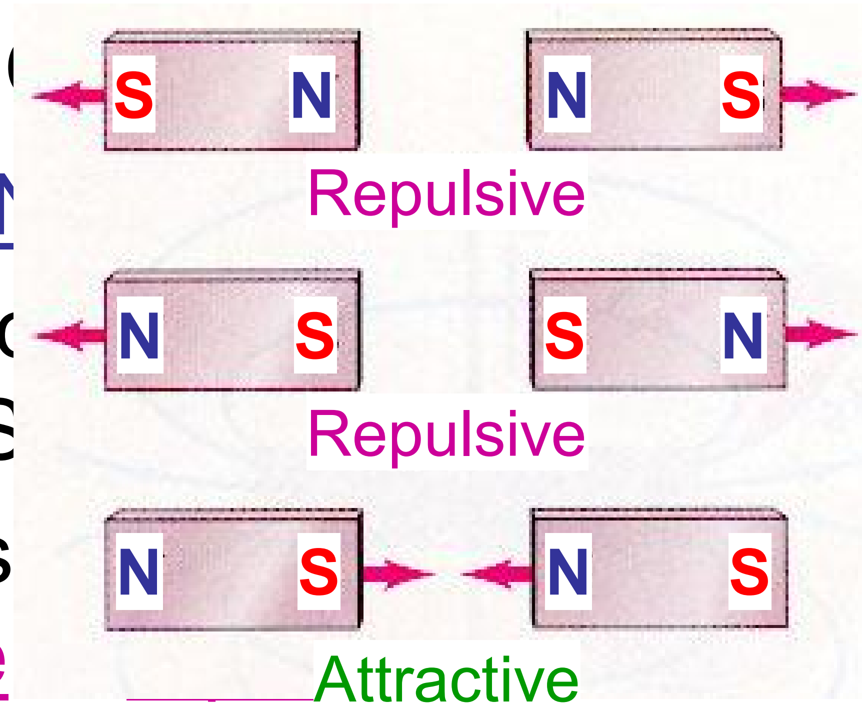



*Figure from Tipler*

- Magnets are present in numerous devices:
  - Refrigerator magnets, motors/generators, video/audio tapes, credit cards, hard disks, floppies, etc.

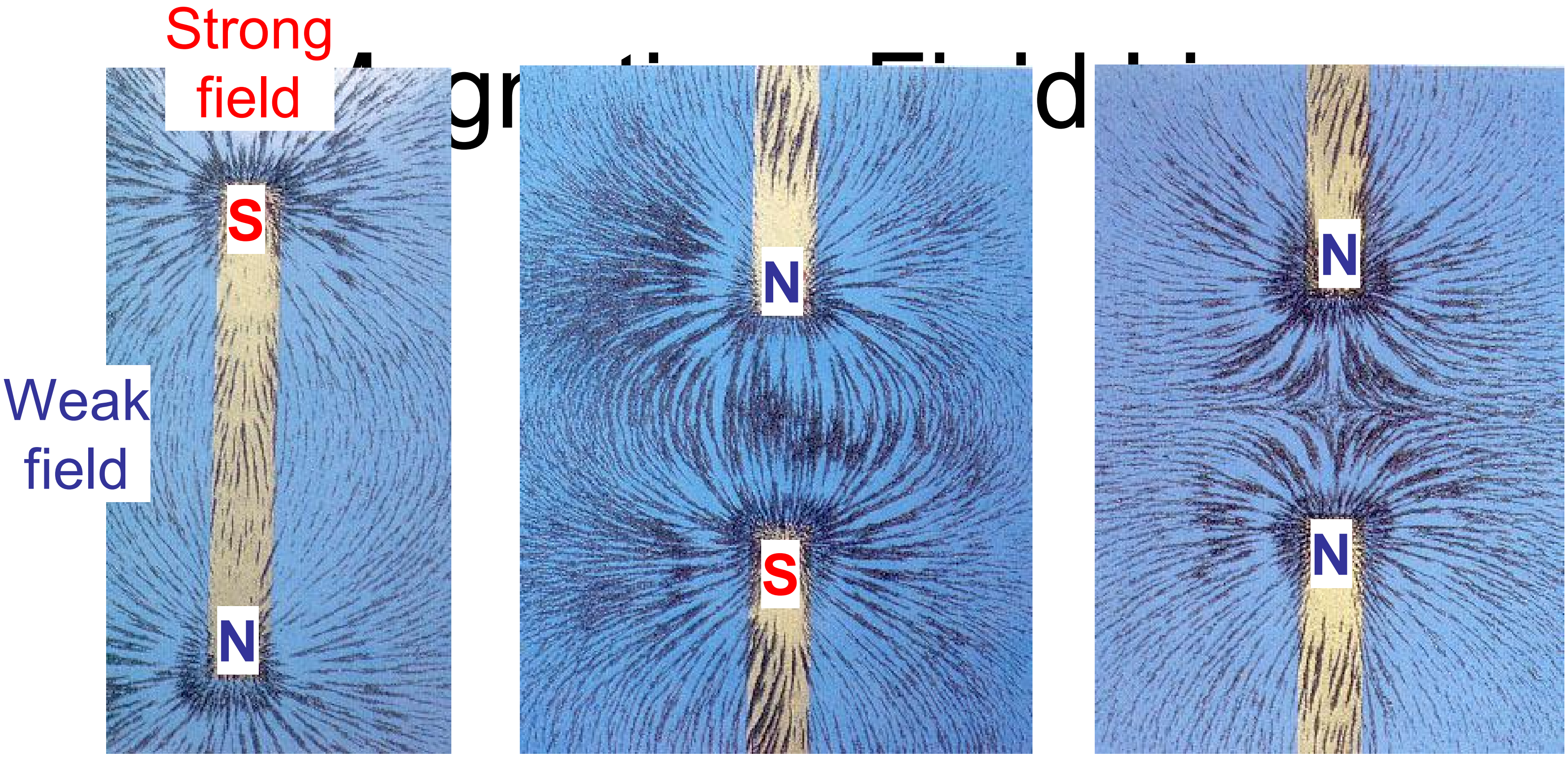
# Magnetism: North and South Pol




attract, and the same

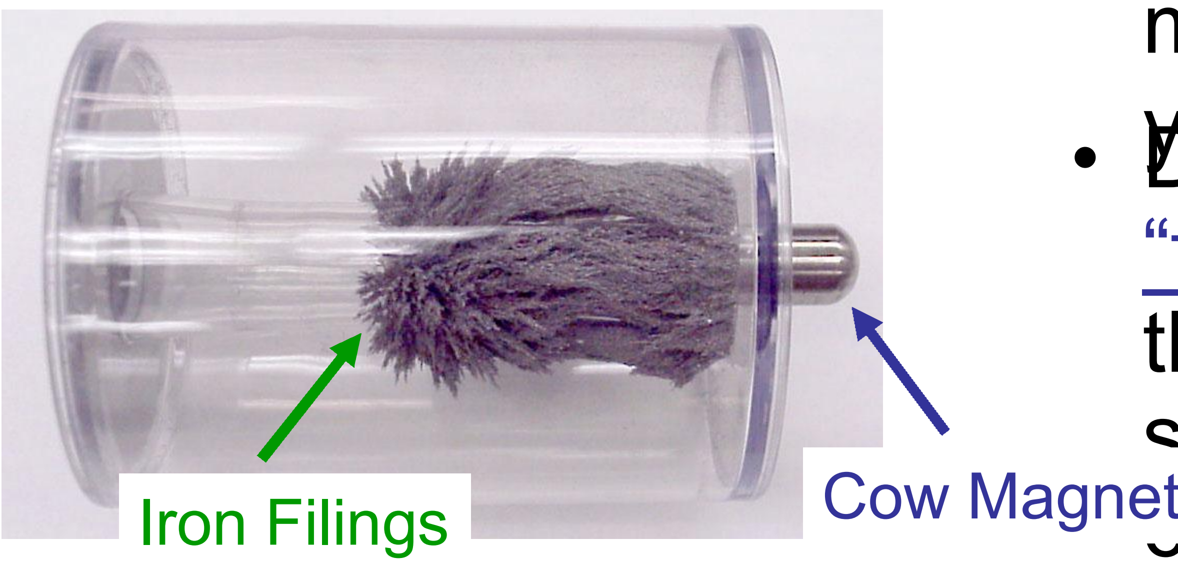
*Figure from Giancoli*




- We can “see” magnetic force field lines using iron particles.
- The density of these lines indicates the strength of the magnetic field, where denser lines indicate a stronger force.

*Figure from Serway*

# Activity with Magnets


- Predict whether the items in the plastic tub are magnetic or not.
- Use a cow magnet to test your predictions.
- Draw the magnetic “field” lines that the iron filings show around a cow magnet.

*Figure from Niculescu*

# Electromagnet: Electricity
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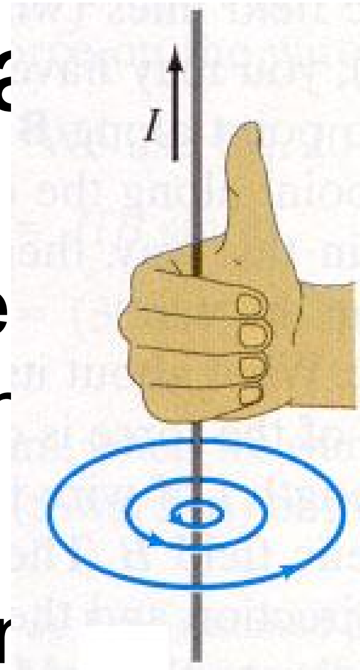
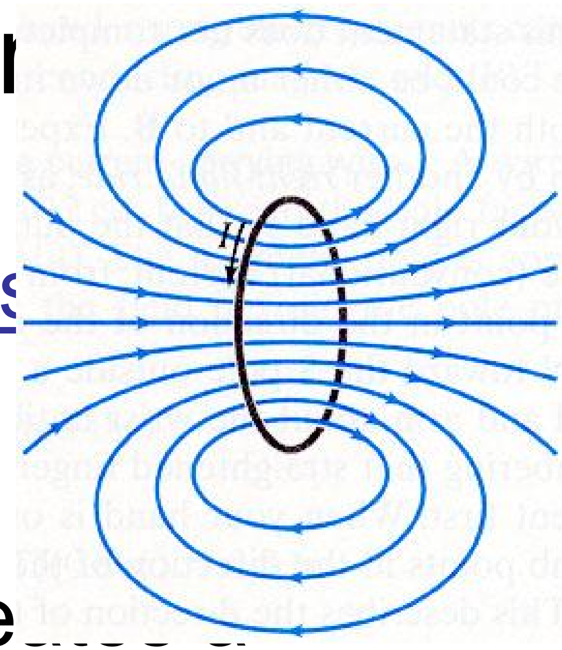
gr s that





Straight Wire





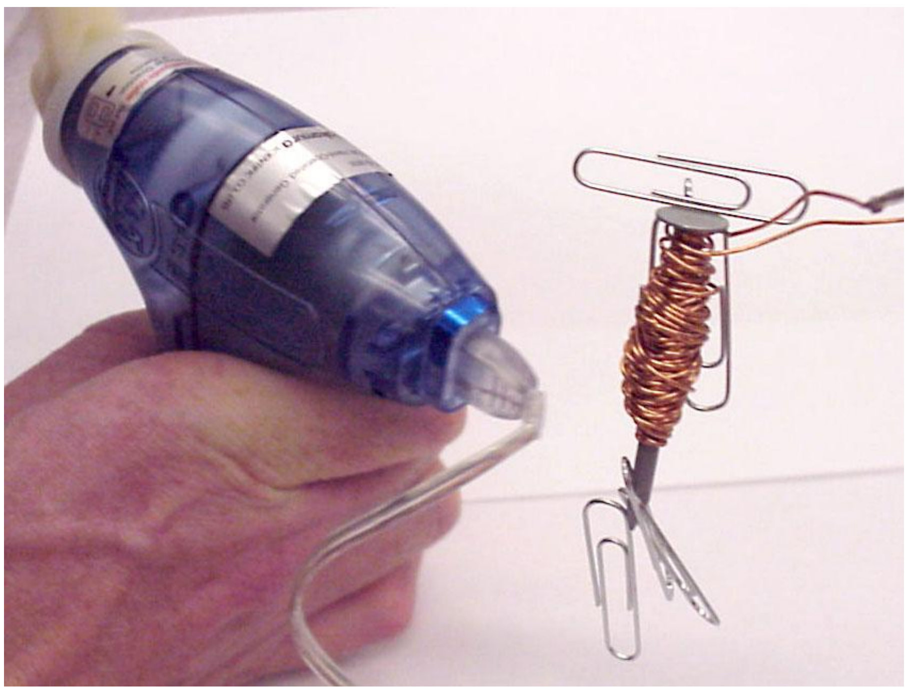
Looped Wire

- Current flowir op creates a magnetic field through the loop.

*Figures from Tipler & Giancoli*

# Activity making Electromagnet erator

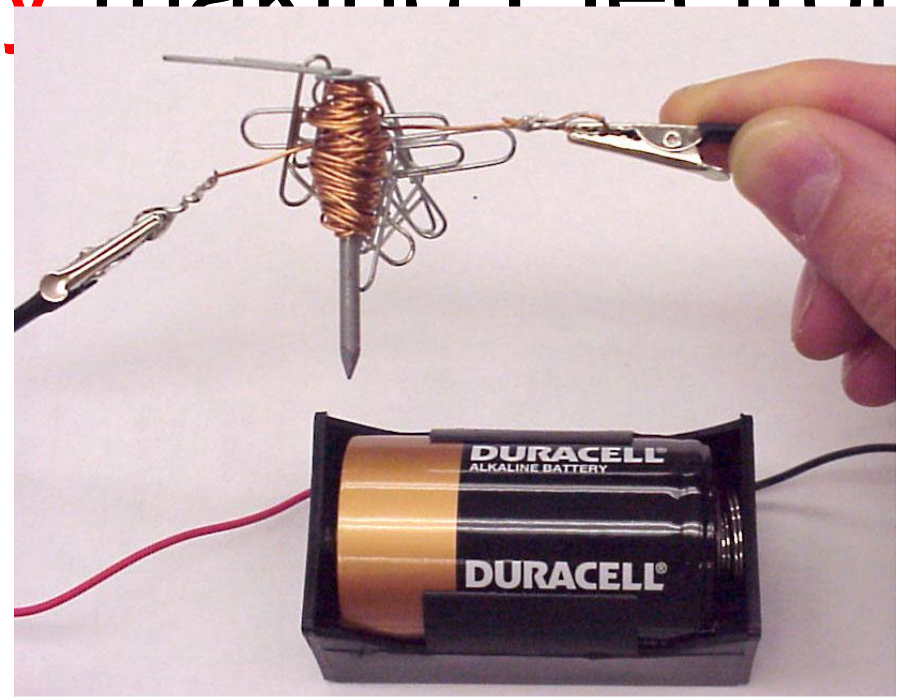

Show that a generator converts mechanical energy into electrical energy by cranking the generator handle and lighting a bulb .



Make an electromagnet by wrapping wire around a nail and connecting it to the generator.

When the generator is

# Activity making Electromagnet




- Make an electromagnet by wrapping wire around a nail and connecting the ends of the wire to a battery.
- Explore how the number of wire windings around the nail affect the strength of your magnet.

# Electromagnet Demonstration

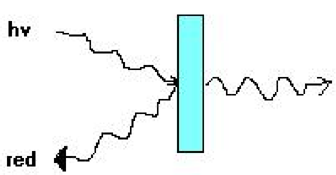
Electro-
magnet

- When turned on, a big electromagnet causes a metal ring around it to be launched. WHY?
  - The changing CURRENT in the big electromagnet creates CURRENT in the conducting ring.
    (This happens without them touching!!)
  - The current in the ring now makes a small electromagnet that is repelled from the big electromagnet.
  - When the ring is repelled, it flies into

# What we have learned in EM

- Charge when static:
  - **Like charges repel**
  - **Opposite charges attract**
- The tiny charge you can have is an electron
- Coulomb's law

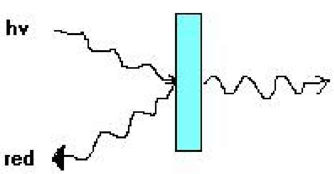
- When magnetic poles are static
  - **Like poles repel**
  - **Opposite poles attract**
- We cannot have a monopole
- Biot –Savart Law



# All Physics Problems are solved by

- Force methods:
  - **You must know all the forces acting on the system**
- The force due to FRICTION are NOT known
- Action at CONTACT
  - At a Distance

- Energy methods
  - **Every system in Nature tends to have Lowest Energy (at equilibrium)**
- Energy is a scalar

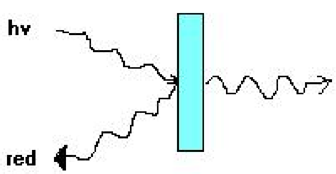


# In EM Theory

- We use concept of FIELDS (action at a distance)
- Classical Field Theory
- Quantum Field Theory

- We can also Use Energy methods:
- Calculation of Potential
- Potential and Fields are related by

  E = - grad V



# The approach

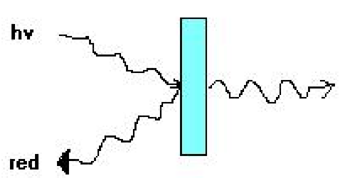
- When Charge is Static:

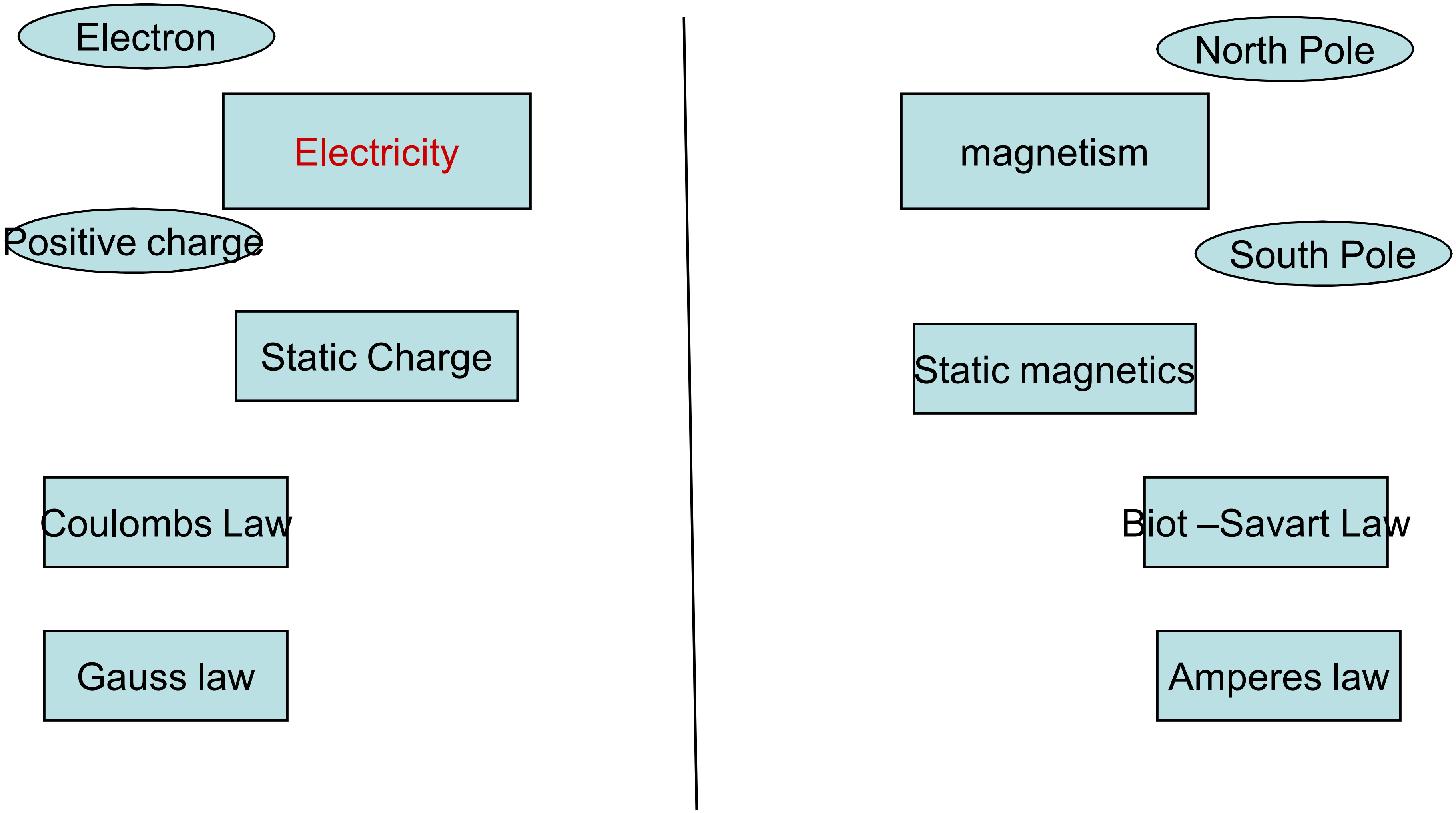
  -Electro statics

- When charge moves
  - **Electro Dynamics**
  - **Classical**
  - **Quantummechanical**

- When the two poles are staic
- Magneto statics

- When the magnetic dipoles are moving
  - Magneto dynamics




Electron
Electricity
Positive charge
Static Charge
Coulombs Law
Gauss law
North Pole
magnetism
South Pole
Static magnetics
Biot –Savart Law
Amperes law

## Coulomb's law

$$\mathbf{F} = q_1 q_2 / 4\pi\varepsilon_0 r^2$$

## Gauss' law

$$Q = {}_s\!\int E.ds$$

$$\nabla.E = \rho_v/\varepsilon_0$$

## Poisson's equation

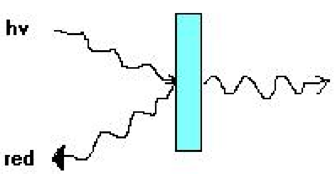
$$\nabla^2 V = - \rho_v / \varepsilon$$

## Laplace's equation

$$\nabla^2 V = 0$$

## Biot-savart law

$$dB = Idl \times r/4\pi r^3$$



A current carrying conductor has magnetic Field

Right hand Thumb Rule

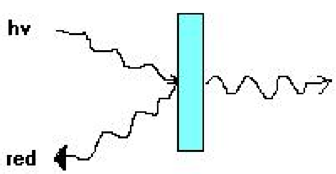
## Ampere

A Changing magnetic Flux

Produces Electro Motive Force

## Faraday

These Two Observations are Key to E M Theory



$$\int_{ClosedSurface} \bar{E} \cdot d\bar{S} = \frac{Q_{enclosed}}{\varepsilon_0}$$

$$\int_{ClosedSurface} \bar{B} \cdot d\bar{S} = 0$$

$$\int_{ClosedPath} \bar{E} \cdot d\bar{L} = -\frac{d\Phi_B}{dt}$$

$$\int_{ClosedPath} \bar{B} \cdot d\bar{L} = \mu_0 I + \mu_0 \varepsilon_0 \frac{d\Phi_E}{dt}$$

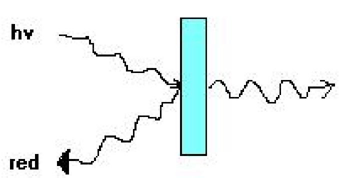
$$\nabla \cdot \vec{B} = 0,$$

$$\nabla \times \vec{E} + \partial \vec{B}/\partial t = 0,$$

$$\nabla \cdot \vec{D} = \rho,$$

$$\nabla \times \vec{H} - \partial \vec{D}/\partial t = \vec{J}.$$

$$\vec{D} = \varepsilon_0 \vec{E} + \vec{P} \quad \vec{H} = \vec{B}/\mu_0 - \vec{M}$$



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

**The Relation between Electricity and magnetism**

# Importance of Electromagnetics-Background

- Maxwell’s equations remains a fundamental law that drives electrical engineering, which is the study of the manipulation of electricity.
- Maxwell’s equations have strong predictive power.
- EM analysis is important in many engineering and scientific disciplines.
- Complete solution of Maxwell’s equations can expedite many design and analysis process

# Brief History of Analysis with Maxwell’s Theory

- Age of simple shapes: Scattering from spheres, cylinders, planes etc.
  - Sommerfeld, 1896,1949, Rayleigh, 1897, Mie, 1908, Debye, 1909, Chu & Stratton, 1938, 1941, Marcuvitz, 1951, Wait, 1955.
  - Bowman, Senior & Uslenghi, 1969.
- Age of approximations: Approximate solution methods, asymptotic and perturbation theory
  - Bremmer, 1951, Keller, 1956, Jones & Kline, 1958, Fock, 1965, Hanse, Lee & Deschamps, 1976, Felsen & Marcuvitz, 1973

# Scattering by Simple Shapes 1890s-1950s

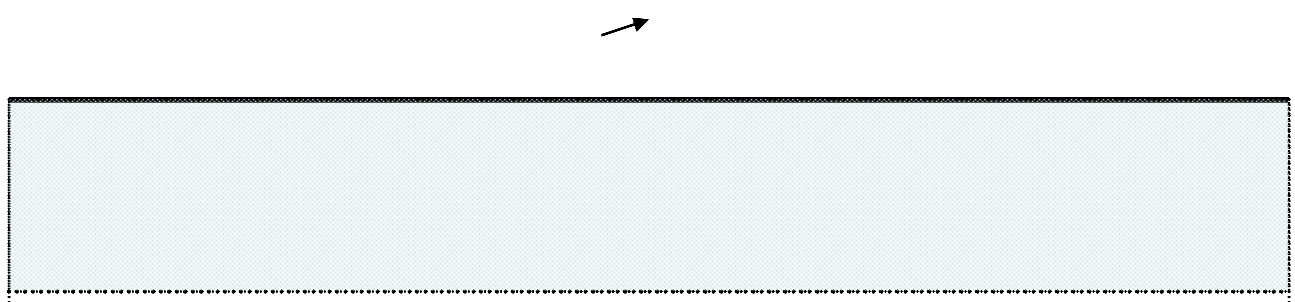
- EM theory was predated by theory of fluid and theory of sound.
- They were very rich in mathematics, with famous mathematicians such as Euler, Lagrange, Stokes, Gauss.
- Many mathematics of low-Reynold number flow and scalar wave theory of sound can be transplanted with embellishment to EM theory.

# Sommerfeld Half-Space Problem 1949

- Radiation of a Hertzian dipole on top of the half-space earth was solved in terms of Sommerfeld integrals.

$$\psi(\mathbf{r}) = \int_0^\infty dk_\rho J_n(k_\rho \rho)\left[ e^{ik_z|z-z'|} + R(k_\rho)e^{ik_z z} \right]$$

$$k_z = \left(k^2 - k_\rho^2\right)^{1/2}$$



# Approximate Scattering Theory 1950s-1970s

- Physical optics approximation, Kirchhoff approximation, geometrical optics approximation, geometrical theory of diffraction etc.
- Ansatz based:

$$\psi^{sca}(\mathbf{r}) \sim \frac{e^{ikr}}{r^{1+\alpha}}\left[a_0 + a_1\frac{1}{kr} + a_2\frac{1}{(kr)^2} + \cdots\right], \quad kr \to \infty$$

- The leading order coefficients are often obtained from canonical solutions such as the Sommerfeld half-plane problem, scattering by a sphere, Watson transformation, etc.

# Numerical Methods 1960s

- Method of moments (Harrington, 1960s)
  - Integral equation based.
  - Versatile geometry handling.
  - Small number of unknowns.
  - Cons: DENSE MATRIX SYSTEM.
- Finite Difference Time Domain Method (Yee, 1960s)
  - Differential equation based.
  - Simplicity (euphoric).
  - Sparse matrix system.

# Basic Physics Knowledge of a Student

- Modern physics
  - Understand the thought processes and abstractions that go on in the field of physics.
- Physics of classical electromagnetics
  - Fundamental solutions of simple shapes and geometries.
  - Physics that arises from approximate method, surface waves, creeping waves, lateral waves, Goubaud waves,

# Basic Math Knowledge of a Student

- Mathematical analysis:
  - Understand the finesse, care and precautions that mathematicians go through in their work.
  - Harmonic analysis, complex variables.
  - Perturbation and asymptotic methods.
  - Linear algebra, linear vector spaces.
- Modern demands:
  - Functional analysis.
  - PDE theory.
  - Approximation theory, error bounds.

# Computer Science Knowledge

- Knowledge of modern programming languages--object oriented programming paradigm.
- Parallel computing and large scale computing.
- Algorithms, fast algorithms.
- Computer architecture.
- Computational geometry.

**Galileo Galilei**

**Born: 15 Feb 1564 in Pisa**
**Died: 8 Jan 1642 in Arcetri**

**Robert Boyle**
**Born: 25 Jan 1627 in Lismore, County Waterford, Ireland**
**Died: 30 Dec 1691 in London, England**

writes *Experiments and Notes about the Mechanical Origine or Production of Electricity*

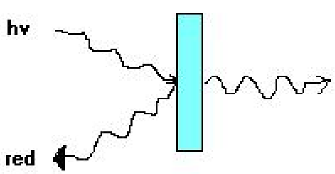
**Georg Simon Ohm**
**Born: 16 March 1789 in Erlangen, Germany)**
**Died: 6 July 1854 in Munich,**

formulates the relationship between current to electromotive force and electrical resistance

# Charles Augustin de Coulomb

**Born: 14 June 1736 in Angoulême, France**
**Died: 23 Aug 1806 in Paris, France**

independently invents the torsion balance to confirm the inverse square law of electric charges. He also verifies Michell's law of force for magnets and also suggests that it might be impossible to separate two poles of a magnet without creating two more poles on each part of the magnet.



## Johann Carl Friedrich Gauss

**Born: 30 April 1777 in Brunswick, Duchy of Brunswick (now Germany)**

**Died: 23 Feb 1855 in Göttingen, Hanover (now Germany)**

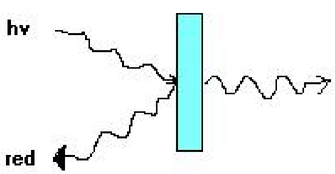
- formulates separate electrostatic and electrodynamical laws, including "Gauss's law." All of it remains unpublished until 1867.

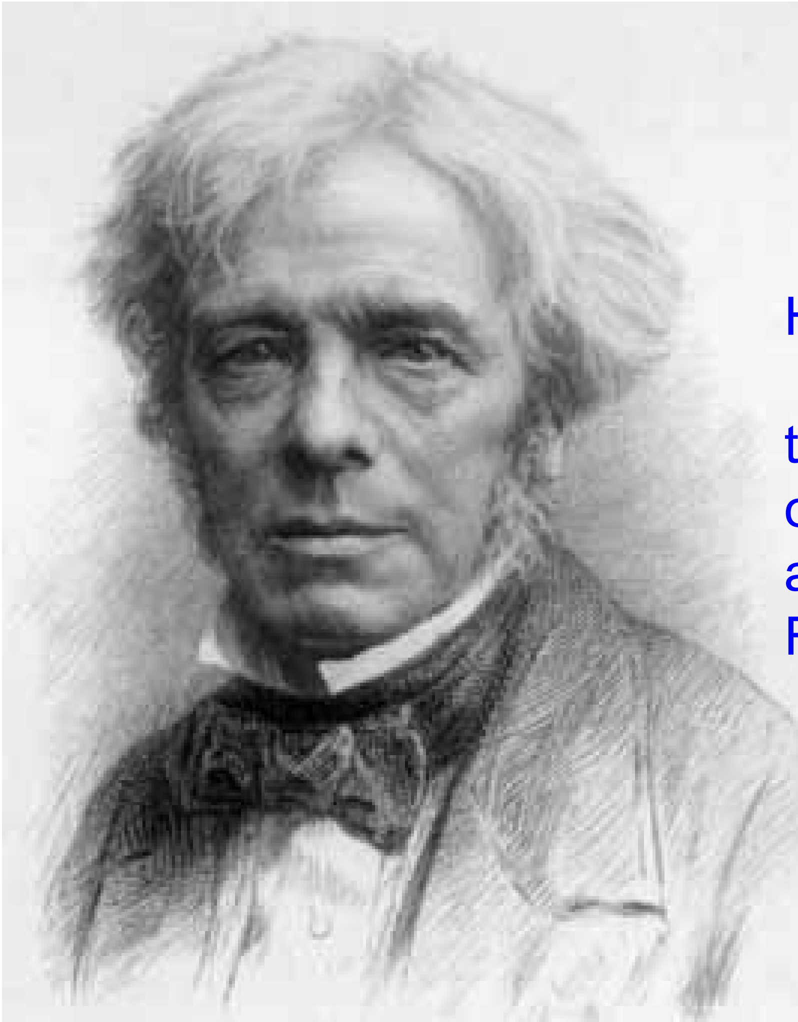
# Michael Faraday

**Born: 22 Sept 1791 in Newington Butts,
Surrey (now London) England**

**Died: 25 Aug 1867 in Hampton Court,
Middlesex, England**

explains electromagnetic induction, electrochemistry and formulates his notion of lines of force





He also estabishes a connection between light and electrodynamics by showing that the transverse polarization direction of a light beam was rotated about the axis of propagation by a strong magnetic Field (today known as "Faraday rotation").

# André Marie Ampère

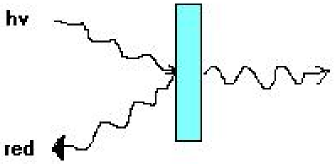
Born: 20 Jan 1775 in Lyon, France
Died: 10 June 1836 in Marseilles, France

He models magnets in terms of molecular electric currents. His formulation inaugurates the study of electrodynamics independent of electrostatics.

# James Clerk Maxwell

**Born: 13 June 1831 in Edinburgh, Scotland**
**Died: 5 Nov 1879 in Cambridge, Cambridgeshire, England**

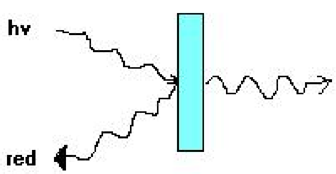
completes his formulation of the field equations of electromagnetism.
He established, among many things, the connection between the speed of propagation of an electromagnetic wave and the speed of light, and establishing the theoretical understanding of light.




## Heinrich Rudolf Hertz

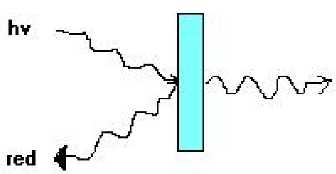
born in Hamburg on 22 February 1857
he died quite young, less than a month before his 37th birthday.

Fascinating facts about Heinrich Rudolf Hertz, who proved that electricity can be transmitted in electromagnetic waves which led to the development of wireless telegraph and the radio.



**Hertz's First Radiator**

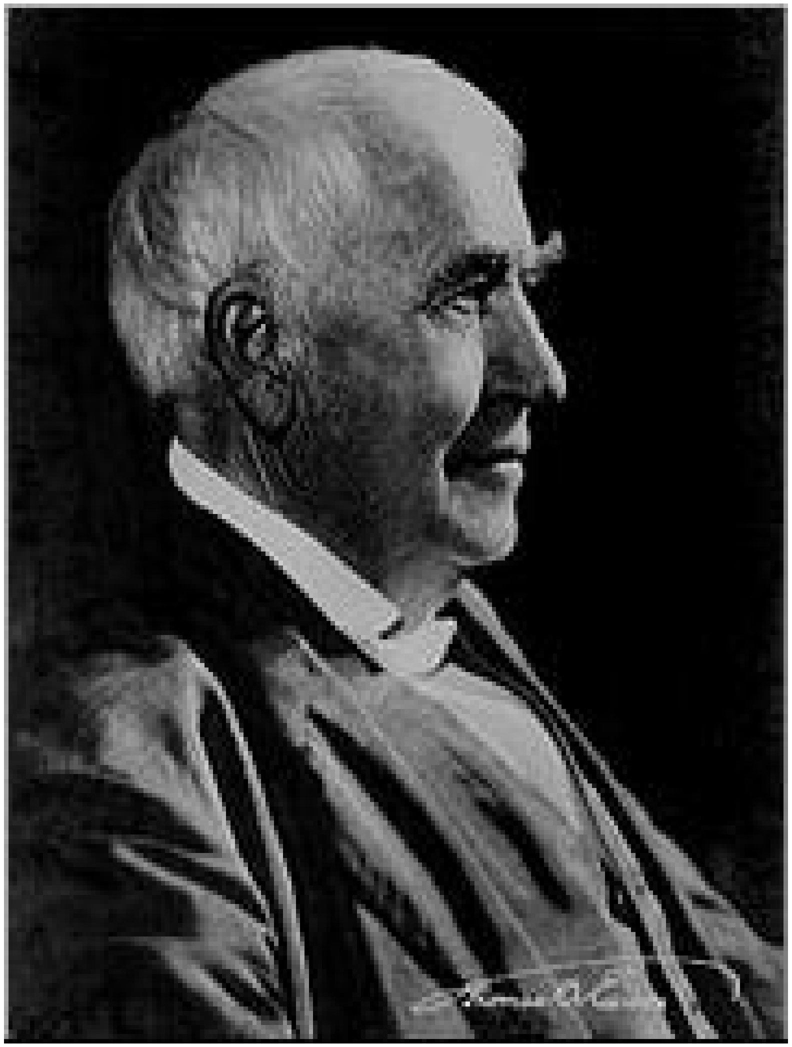
In his experiments, Hertz first employed a pair of one meter wires with a spark gap in the center connected to an induction coil. The large spheres at the ends were used to adjust the capacity of the circuit for resonance.



# Alexander Graham Bell

born on March 3, 1847 in
Edinburgh, Scotland
died in Baddek, Nova Scotia, on August 2, 1922.

**Bell's first telephone patent was granted on March 7, 1876**
**Bell Telephone Company, was founded on July 9, 1877.**



# Thomas Edison

born on February 11, 1847 in Milan, Ohio
dies on 18 October
in West Orange, New Jersey,
at the age of 84

**Edison obtained 1,093 United States patents, the most issued to any individual.**
**1931**

Thomas Edison listening to his
improved wax cylinder phonograph
after 72 hours of continuous work
on the mechanism (June 16, 1888).

# Hendrik Lorentz

**Born: 18 July 1853 in Arnhem, Netherlands**
**Died: 4 Feb 1928 in Haarlem, Netherlands**

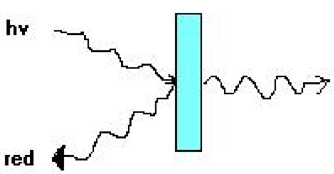
completes the description of Electrodynamics by clearly separating electricity and electrodynamic fields and formulating the equations for charged particles in motion

# Albert Einstein

Born: 14 March 1879 in Ulm, Württemberg, Germany

Died: 18 April 1955 in Princeton, New Jersey, USA

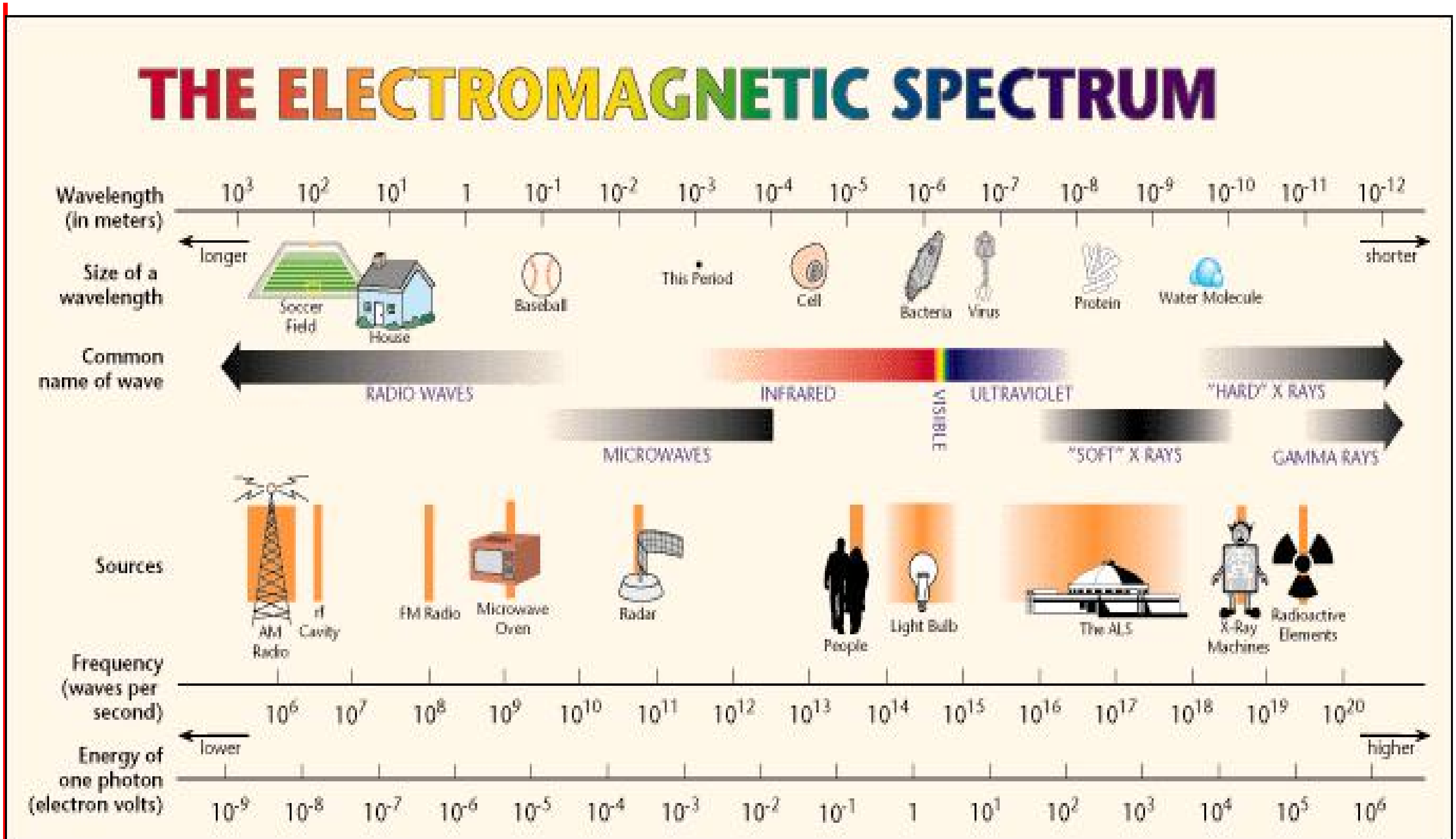
analyzes the phenomena of the photoelectric effect and theorizes that light may be taken to be made up of vast amounts of packets of electromagnetic radiation in discrete units

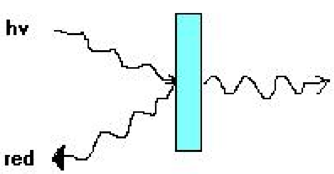


# Richard Phillips Feynman

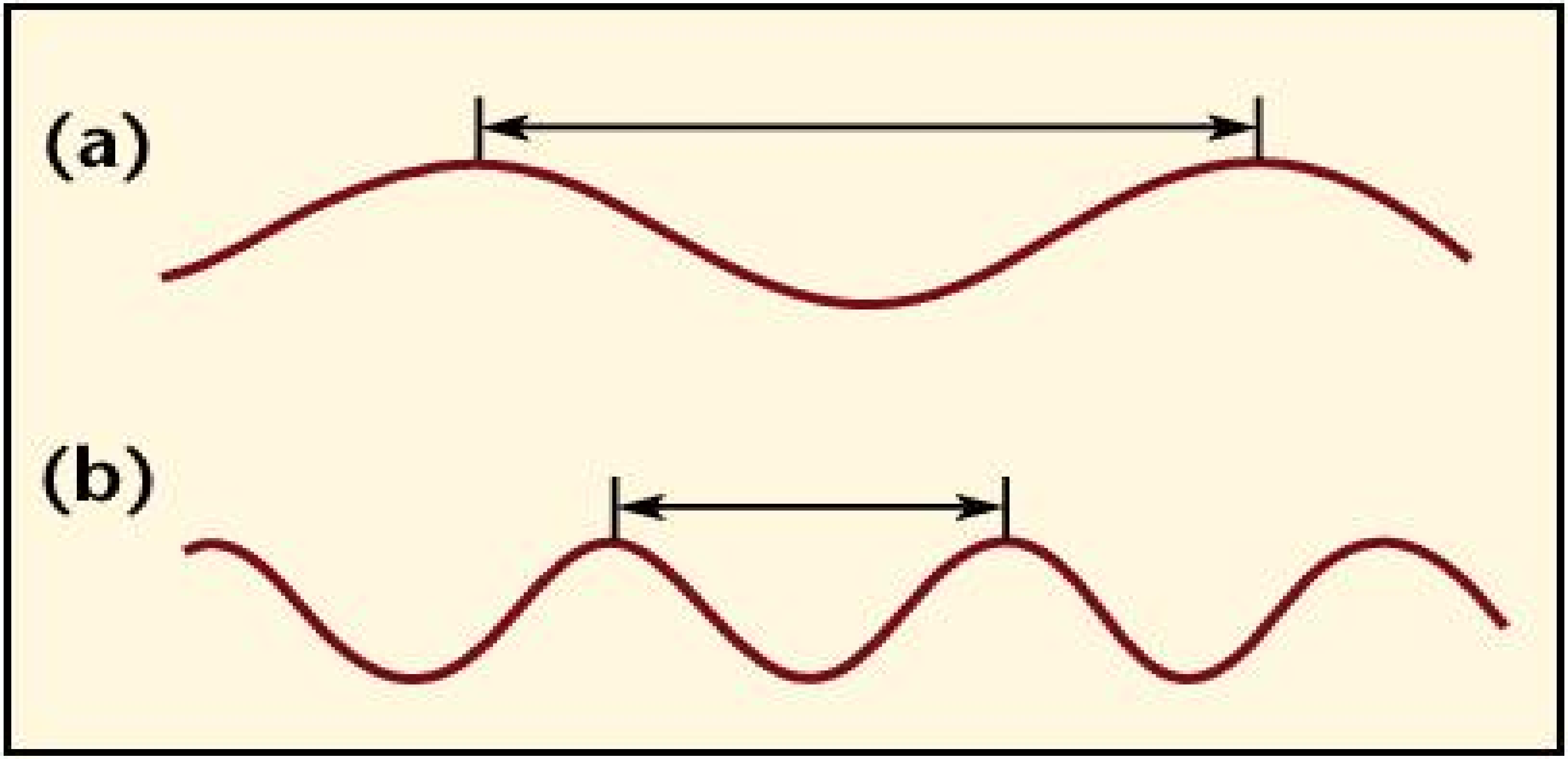
**Born: 11 May 1918 in Far Rockaway, New York, USA**

**Died: 15 Feb 1988 in Los Angeles, California, USA**

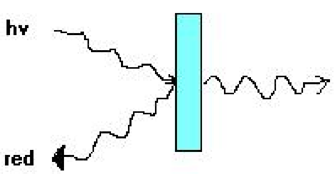


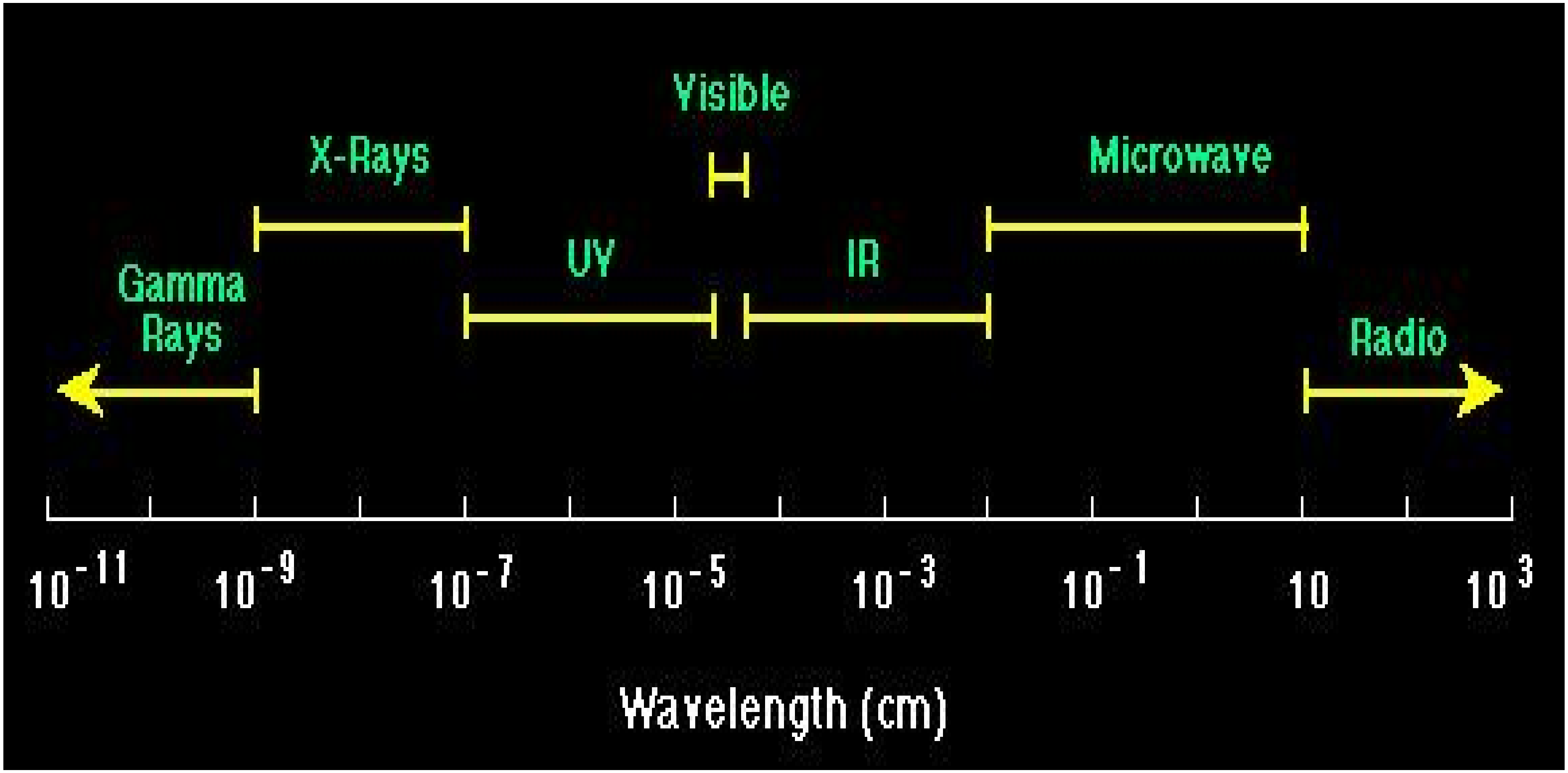



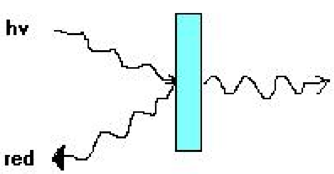

Semiconductor Laboratory, Dept.of Physics

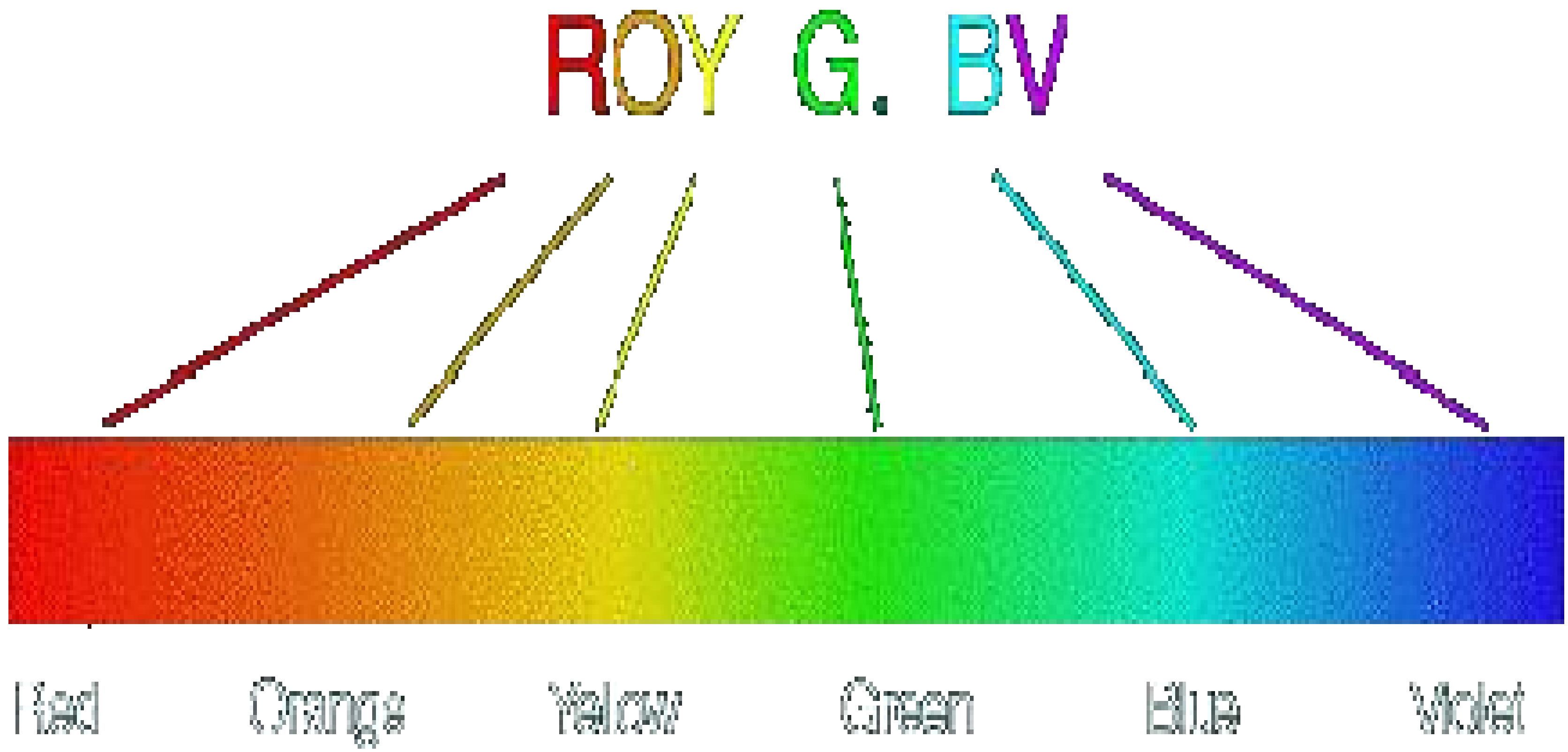


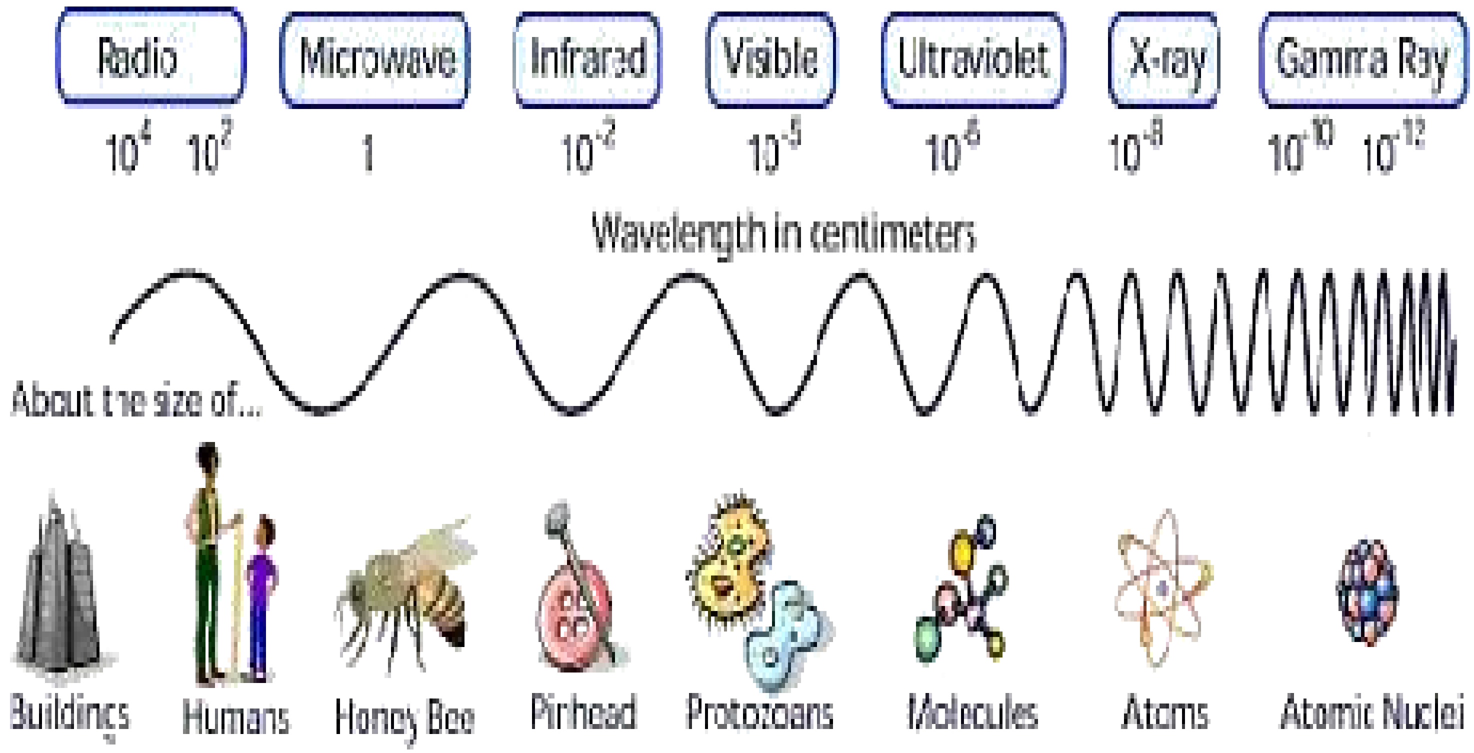

*(a) Longer wavelength; (b) shorter wavelength.*

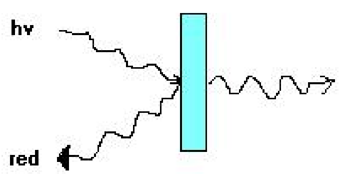



Visible
X-Rays
Microwave
UV
IR
Gamma Rays
Radio
$10^{-11}$
$10^{-9}$
$10^{-7}$
$10^{-5}$
$10^{-3}$
$10^{-1}$
10
$10^{3}$
Wavelength (cm)


hv
red

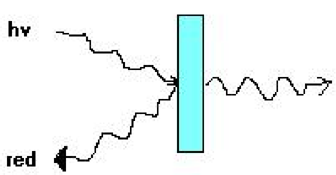

ROY G. BV
Red
Orange
Yellow
Green
Blue
Violet


Radio
Microwave
Infrared
Visible
Ultraviolet
X-ray
Gamma Ray
Wavelength in centimeters
About the size of...
Buildings
Humans
Honey Bee
Pinhead
Protozoans
Molecules
Atoms
Atomic Nuclei


hv
red

# Applications of EM

- Communications (optical fiber) including Space communication
- Entertainment electronics
- Medical Electronics (MRI, CT scans, Radiation Therapy)
- Material Characterization
- Internet and connectivity



# The Negative side of EM

- Biological Hazards
  - Video monitors emit radiations (10 MHs – 10 GHz)
  - Causes cancer
  - Microwaves kill cells

Now we are all immersed in EM Waves

# The challenges in EM

- EMI / EMC problems
- Military Electromagnetics
- E Bomb

What more comes I do not Know !!

Thanks for your attention

# Electromagnetic Waves

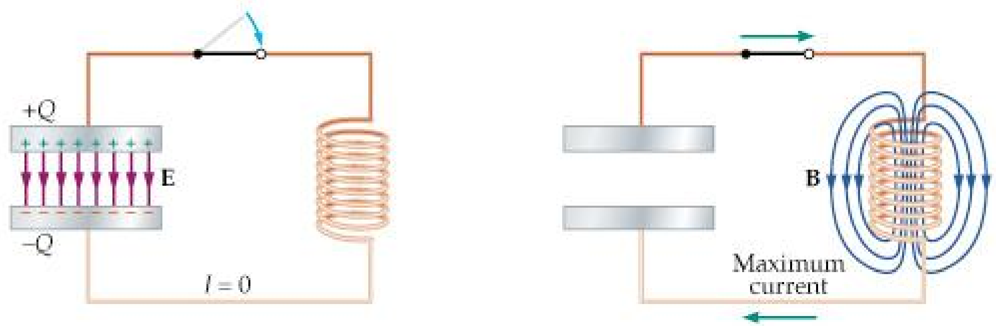
## Maxwell's Theory

In 1865, James Clerk Maxwell developed a theory about electricity and magnetism.

His *starting points* were:

- Electric field lines originate on positive charges and terminate on negative charges
- Magnetic field lines form closed loops
- A varying magnetic field induces an electric field
- A magnetic field is created by a current

# LC Circuit
# Oscillating
# E & B fields




- Current in wire creates magnetic field
- EMF = $-\Delta\Phi_M/\Delta t$
- EMF produces electric field in wire
- Charge on Capacitor generates electric field in gap
- Maxwell: Changing electric field in gap acts like a current and produces a magnetic field.

Bottom Line:

- Changing magnetic fields produce electric fields
- Changing electric fields produce magnetic fields
- Electromagnetic Waves travel through space without need for the wires of the circuit.

Maxwell’s theory is a mathematical formulation that relates electric and magnetic phenomena.

His theory, among other things, predicted that electric and magnetic fields can travel through space as waves.

The uniting of electricity and magnetism resulted in the Theory of Electromagnetism.

# Maxwell's Predictions

- A changing electric field produces a magnetic field
- Accelerating charges will radiate electromagnetic waves
- Electromagnetic waves travel at the speed of light c:

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

- The electric and magnetic fields in the wave are fluctuating

# EM Waves and Hertz

In 1887, Heinrich Hertz generated and detected electromagnetic waves in his lab.

The waves radiated from a transmitter circuit and were detected in a receiver circuit.

Hertz used the fact that electrical circuits have resonant frequencies just like

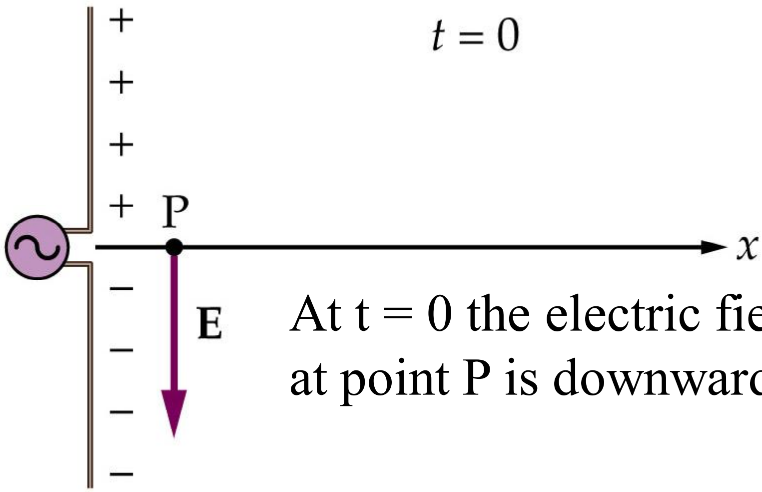
# Producing EM Waves

Electromagnetic waves will be produced when a **charge undergoes acceleration**.

If an ac voltage is applied to an antenna, the charges will be accelerated up and down and radiate EM waves.

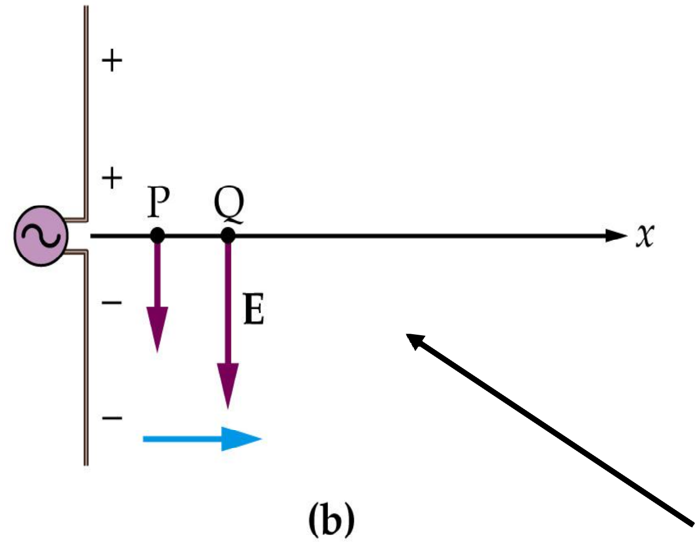
The radiated waves are made up of electric and magnetic fields.

# A traveling electromagnetic wave produced by an ac generator attached to an antenna.



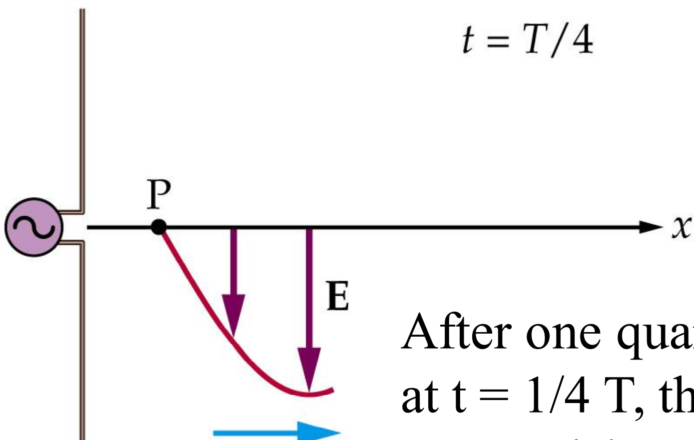

At t = 0 the electric field at point P is downward.

(a)




(b)

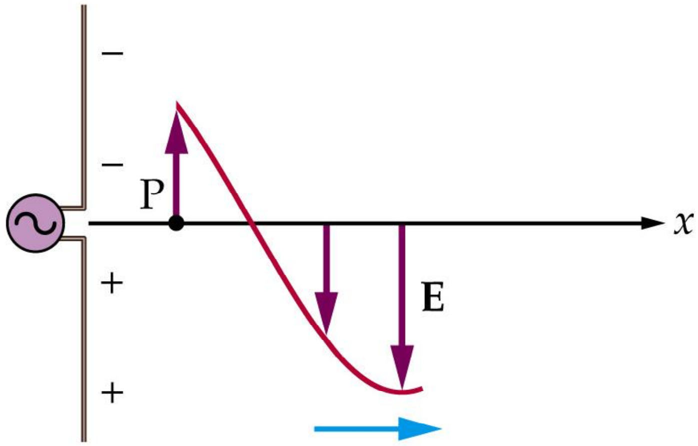
A short time later the electric field at P is still downward, but now with a reduced magnitude. Note that the field created at t = 0 has moved to point Q.
The decreasing electric field at point P creates a magnetic field at point Q pointing into the viewgraph




After one quarter of a cycle, at t = 1/4 T, the electric field at P vanishes.

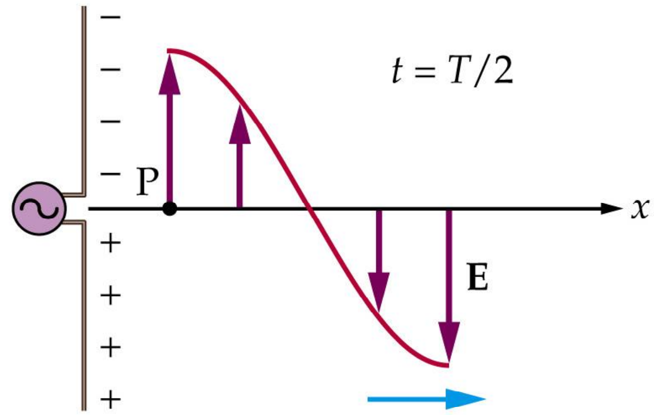
(c)

# A traveling electromagnetic wave produced by an ac generator attached to an antenna.



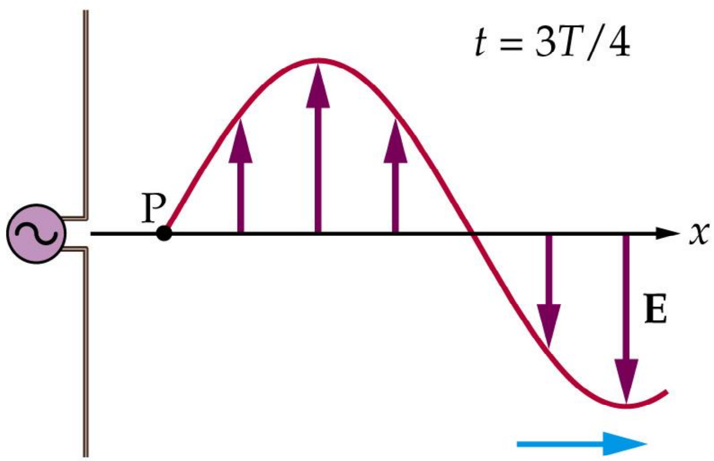

(d)

The charge on the antenna has reversed polarity now, and the electric field at P points upward.




(e)

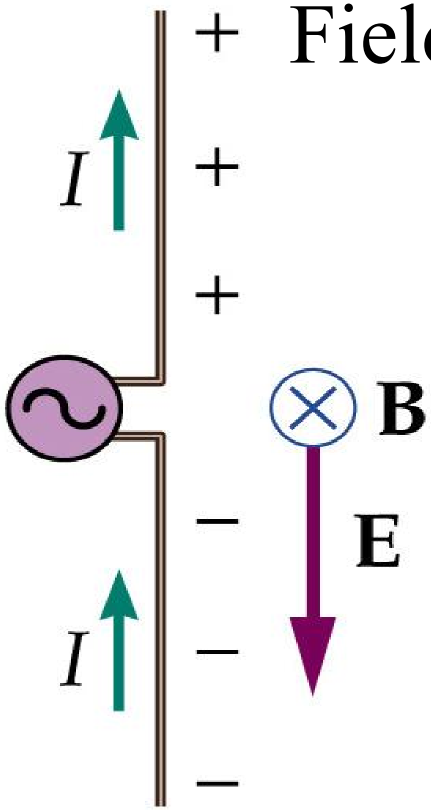
When the oscillator has completed half a cycle, t = 1/2 T, the field at point P is upward and of maximum magnitude.

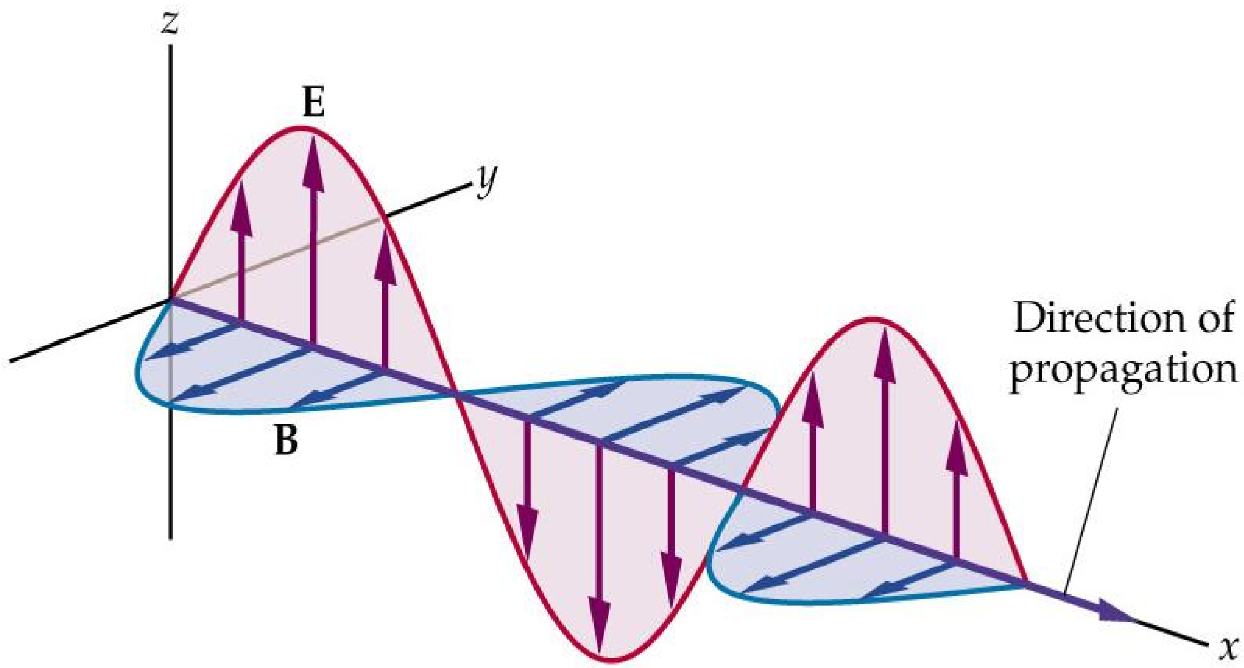



(f)

At t = 3/4 T the field at P vanishes again. The fields produced at earlier times continue to move away from the antenna.

# Field directions in an electromagnetic wave




At a time when the electric field produced by the antenna points downward, the magnetic field points into the page. In general, the electric and magnetic fields in an electromagnetic wave are always at right angles to each other.

An electromagnetic wave propagating in the positive x direction. Note that E and B are perpendicular to each other and in phase. The direction of propagation is given by the thumb of the right hand, after pointing the fingers in the direction of E and curling them toward B (palm towards B).

# Properties of EM Waves

The radiated EM waves have certain properties:

- EM waves all travel at the speed of light c.

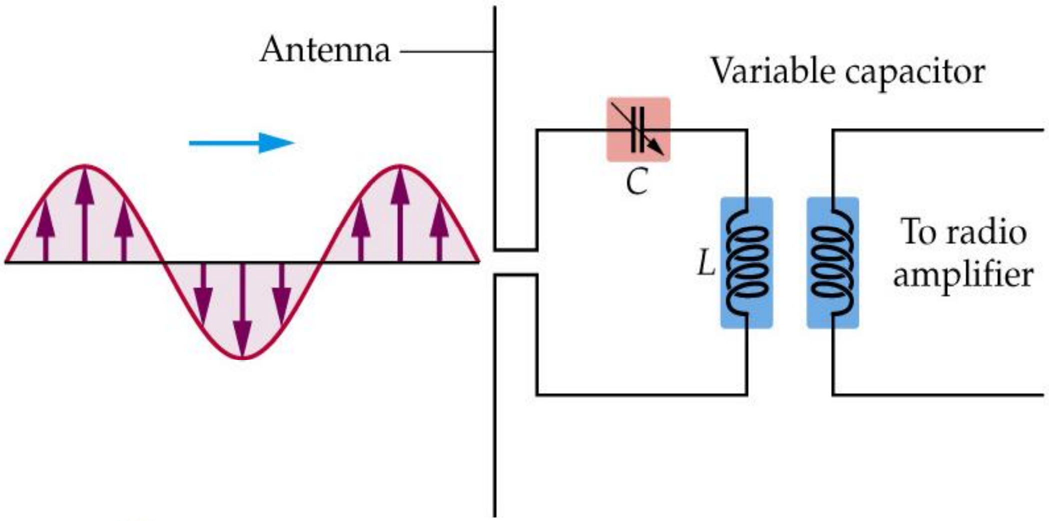
  $c^2 = 1/(\varepsilon_0 \mu_0)$

- the E and B fields are perpendicular to each other

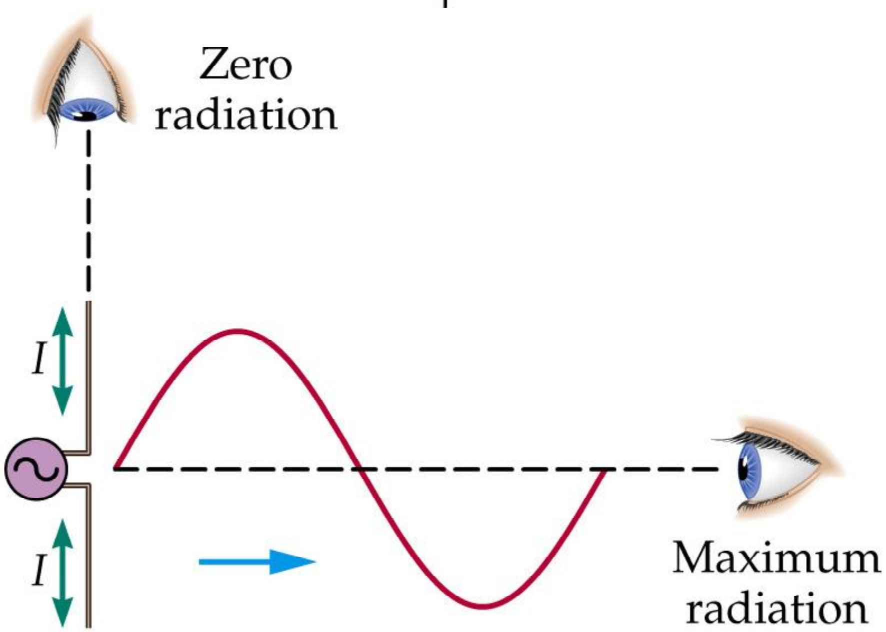
- the E and B fields are in phase (both reach a maximum and minimum at the same time)

- The E and B fields are perpendicular to the direction of travel (transverse waves)

# Receiving radio waves




Basic elements of a tuning circuit used to receive radio waves. First, an incoming wave sets up an alternating current in the antenna. Next, the resonance frequency of the LC circuit is adjusted to match the frequency of the radio wave, resulting in a relatively large current in the circuit. This current is then fed into an amplifier to further increase the signal.




Electromagnetic radiation is greatest when charges accelerate at right angles to the line of sight. Zero radiation is observed when the charges accelerate along the line of sight. These observations apply to electromagnetic waves of all frequencies.

# Plane Waves

EM waves in free space are plane waves. That means that the E and B fields are confined to a plane and uniform within the plane at all time.

As we said, EM waves travel at the speed of light. Light speed can be derived from two other quantities we have already used:

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

# Light

## Light is an electromagnetic wave

$c = \lambda f = 3 \times 10^8$ m/s

As light waves travel through space they:

» **transport energy**

» **transport momentum**

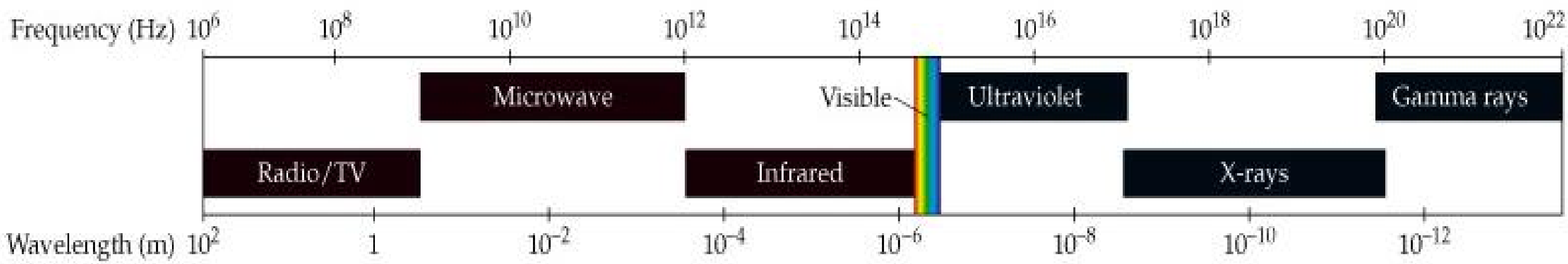
The energy density, $u$, of an electromagnetic wave:

$$u = \tfrac{1}{2}\varepsilon_0 E^2 + \tfrac{1}{2\mu_0}B^2 = \varepsilon_0 E^2 = \tfrac{1}{\mu_0}B^2$$

$$E = cB$$

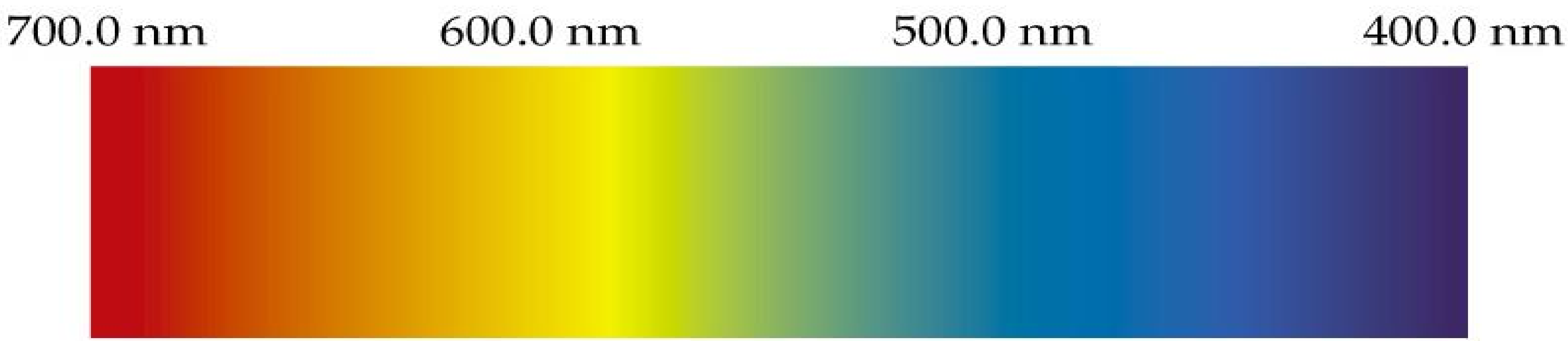
EM waves can be generated in different frequency bands:

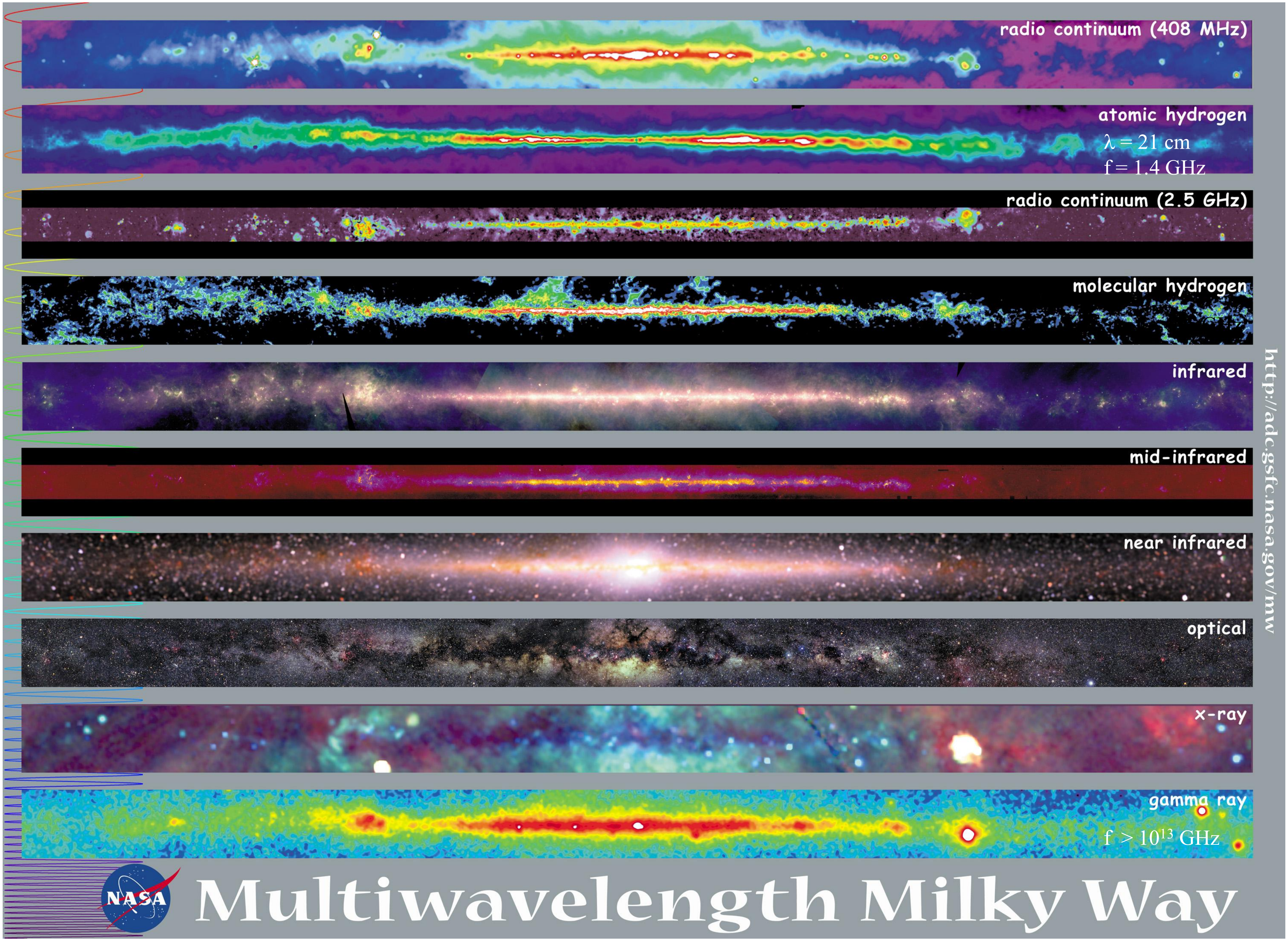
radio, microwave, infrared, visible, ultraviolet, x-rays, gamma rays



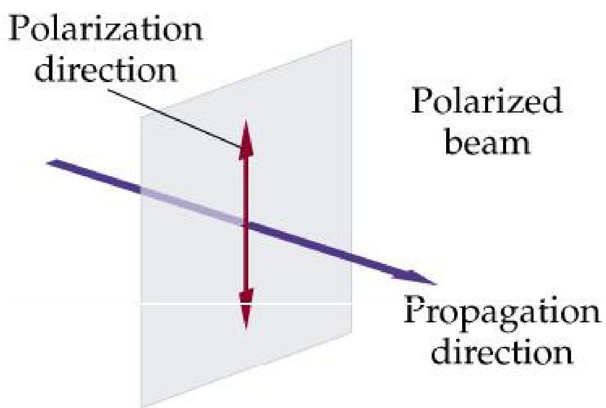

Note that the visible portion of the spectrum is relatively narrow.

The boundaries between various bands of the spectrum are not sharp, but instead are somewhat arbitrary.

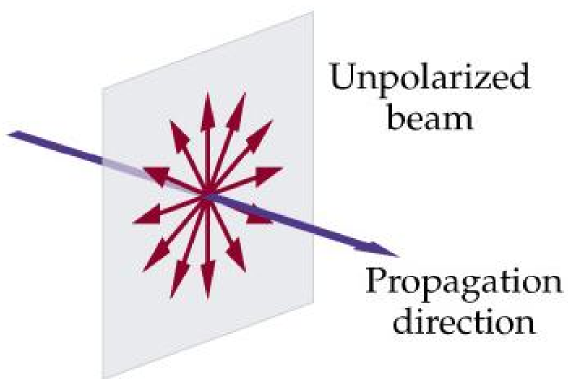



radio continuum (408 MHz)
atomic hydrogen
λ = 21 cm
f = 1.4 GHz
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
f > 10^13 GHz
http://adc.gsfc.nasa.gov/mw
NASA
Multiwavelength Milky Way

# Polarization




(a)




(b)

When light is polarized, the electric field always points in the same direction.

A beam of light that is:

(a) polarized in the vertical direction (the electric field points in the vertical direction).

(b) unpolarized: = Superposition of many beams, approximately parallel, but each with random polarization. Every atom in the filament of an incandescent bulb radiates a separate wave with random phase and random polarization.

# Topic 2: Particle/Wave Duality I

**PART I**

- Electrons as discrete Particles.
  - Measurement of ***e*** (oil-drop expt.) and ***e/m*** (e-beam expt.).
- Photons as discrete Particles.
  - Blackbody Radiation: Temp. Relations & Spectral Distribution.
  - Photoelectric Effect: Photon "kicks out" Electron.
  - Compton Effect: Photon "scatters" off Electron.

**PART II**

- Wave Behavior: Interference and Diffraction.

# Momentum and Energy: Get it

- Momentum and Energy DEFINITIONS

$$p = \frac{h}{\lambda} = \hbar k$$

$$E = hf = \hbar\omega$$

- Energy vs. Momentum RELATIONSHIPS

$$E(\text{photon}) = pc = \frac{hc}{\lambda}$$

$$E(\text{particle}) = \frac{p^2}{2m} = \frac{(hc)^2}{2(mc^2)\lambda^2}$$

# Electrons: Quantized Charged Particles

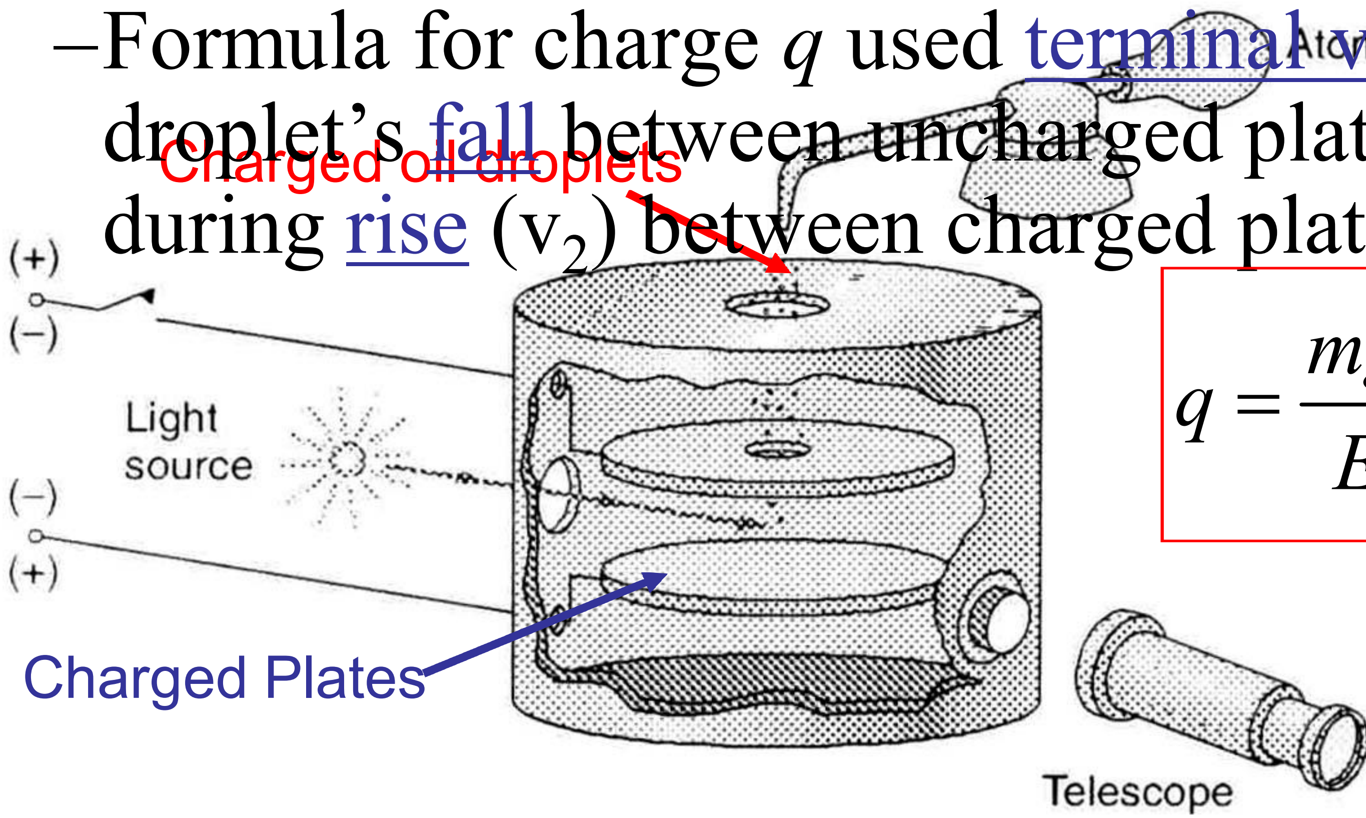
- In the late 1800's, scientists discovered that electricity was composed of discrete or quantized particles (electrons) that had a measurable charge.

- Found defined amounts of charge in electrolysis experiments, where F (or Farad) = $N_A$ e.
  - One Farad (96,500 C) always decomposes one mole ($N_A$) of monovalent ions.

- Found charge *e* using Millikan oil-drop experiment

# Electrons: Millikan's Oil-drop Expt.

- Millikan measured quantized charge values for oil droplets, proving that charge consisted of quantized electrons.
  - Formula for charge $q$ used terminal velocity of droplet's fall between uncharged plates ($v_1$) and during rise ($v_2$) between charged plates.




$$q = \frac{mg}{E}\left(\frac{v_2}{v_1} + 1\right)$$

Scope to measure droplet terminal velocity.

# Electron Beam e/m : Motion in E and B Fields

$$\boldsymbol{F}_E = q\boldsymbol{E}$$

$$\boldsymbol{F}_B = q\boldsymbol{v} \times \boldsymbol{B}$$

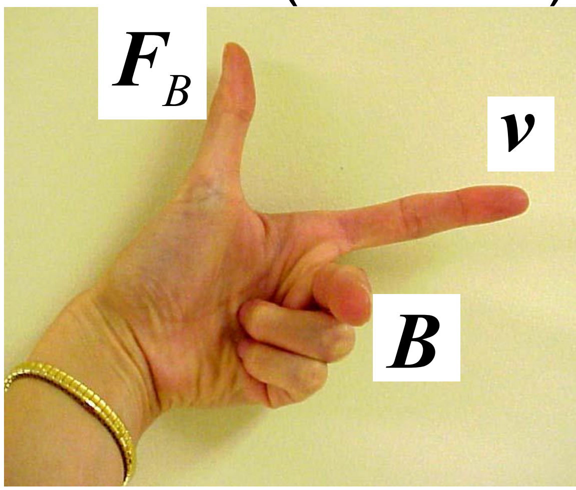
Circular Motion of electron in B field:

$$\frac{mv^2}{r} \ (or\ \boldsymbol{F}_{centrip}) = qvB \ \ (or\ \boldsymbol{F}_B)$$

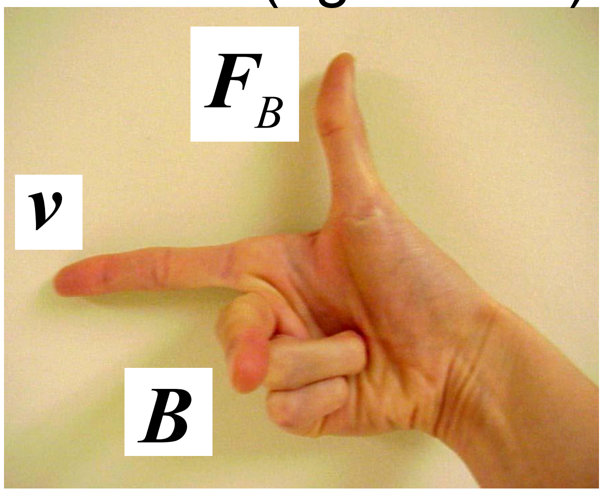
$$r = \frac{mv}{qB} \propto \frac{m}{q}$$

⇒ Larger $q/m$ gives smaller $r$, or larger deflection.

Electron (left hand)



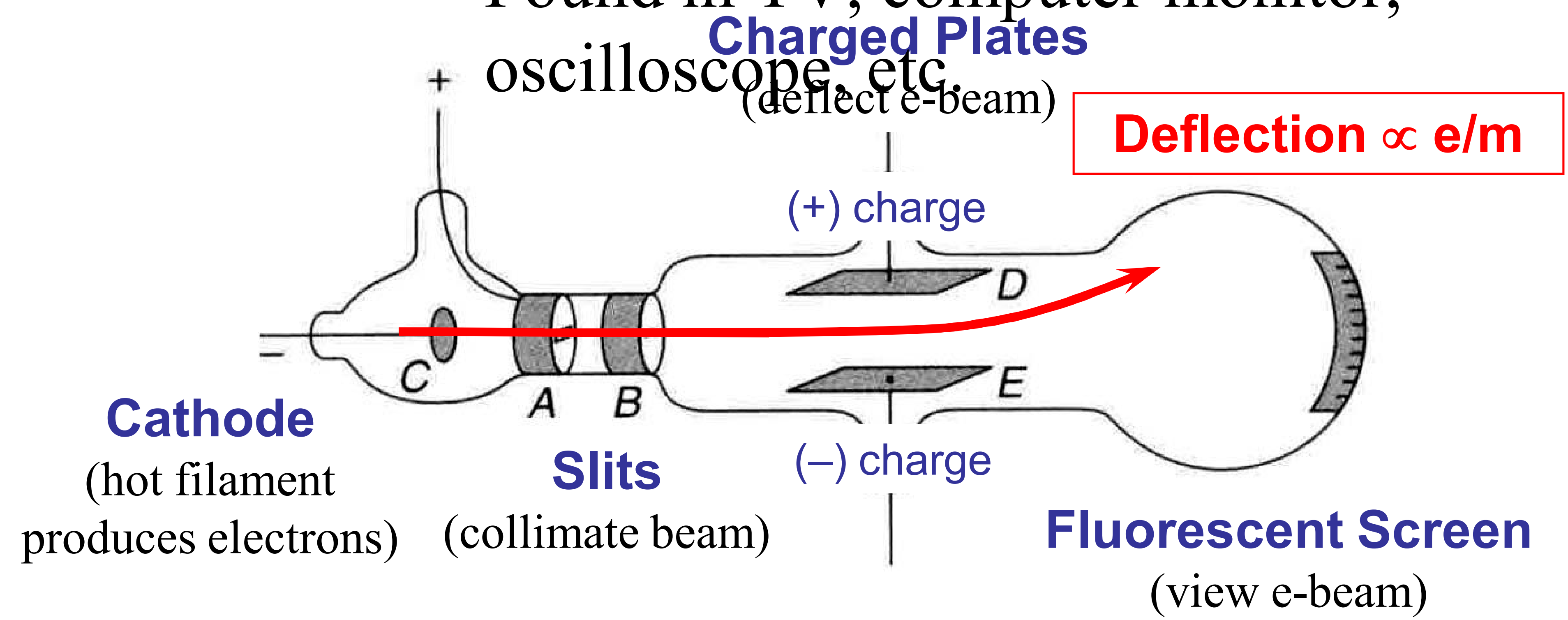

Proton (right hand)



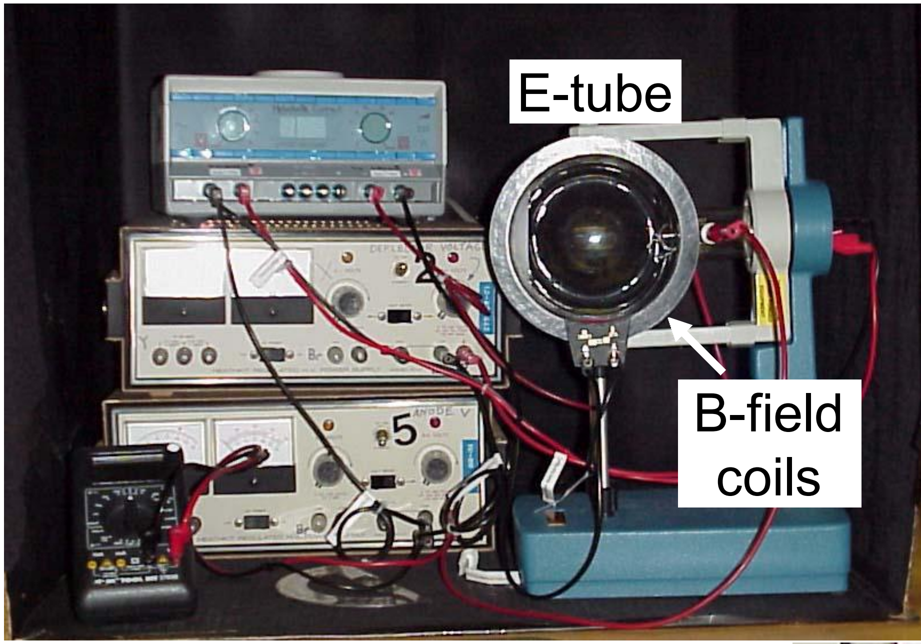
# Electron Beam e/m: Cathode Ray Tube (CRT)

J.J. Thomson

- Tube used to produce an electron beam, deflect it with electric/magnetic fields, and then measure e/m ratio.
- Found in TV, computer monitor, oscilloscope, etc.

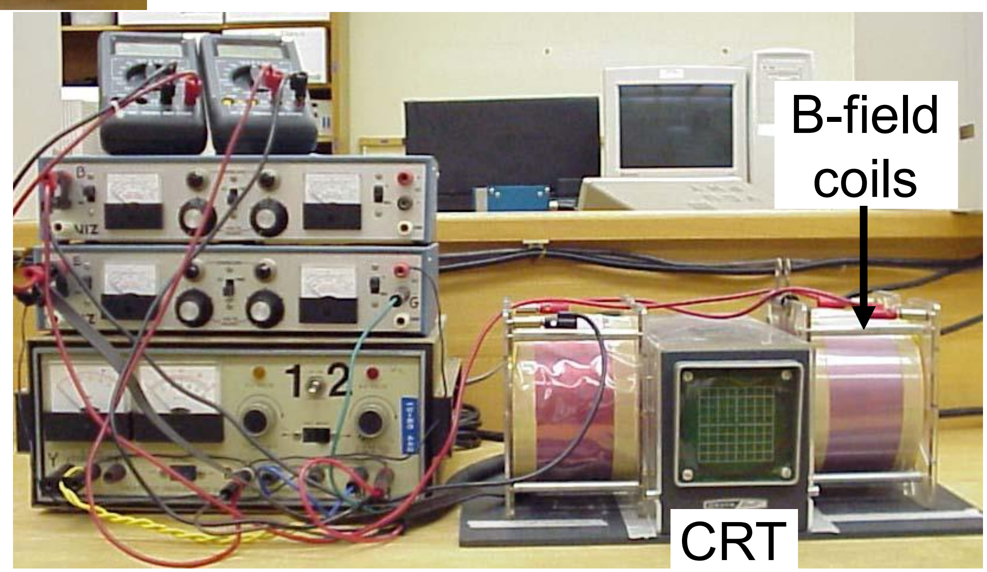


# Electron Beam e/m: Modern
s Lab




e/m with Electron Tube

(observe e-beam in gas tube)




Cathode Ray Tube

(study effects of E and B)

# Ionized Beam q/m: Mass Spectrometer

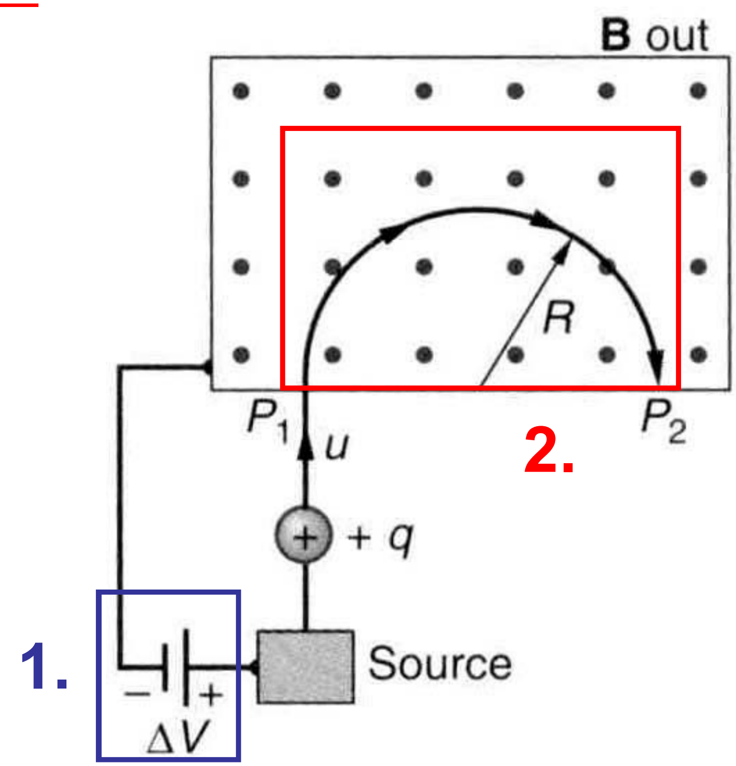
- Mass spectrometer measures q/m for unknown elements.

1. $$\frac{mv^2}{2} = qV \quad \Rightarrow \quad v^2 = \frac{2qV}{m}$$ Ions accelerated by E field.

2. $$R = \frac{mv}{qB}$$ Ion path curved by B field.

$$R^2 = \frac{m^2v^2}{q^2B^2} = \frac{m^2}{q^2B^2}\left(\frac{2qV}{m}\right)$$

$$\therefore \frac{q}{m} = \frac{2V}{B^2R^2}$$



# Photons: Quantized Energy Particle

- Light comes in discrete energy "packets" called photons.

Energy of Single Photon

$$E = hf = \frac{hc}{\lambda} = \frac{1240\text{ eV nm}}{\lambda(\text{nm})}$$

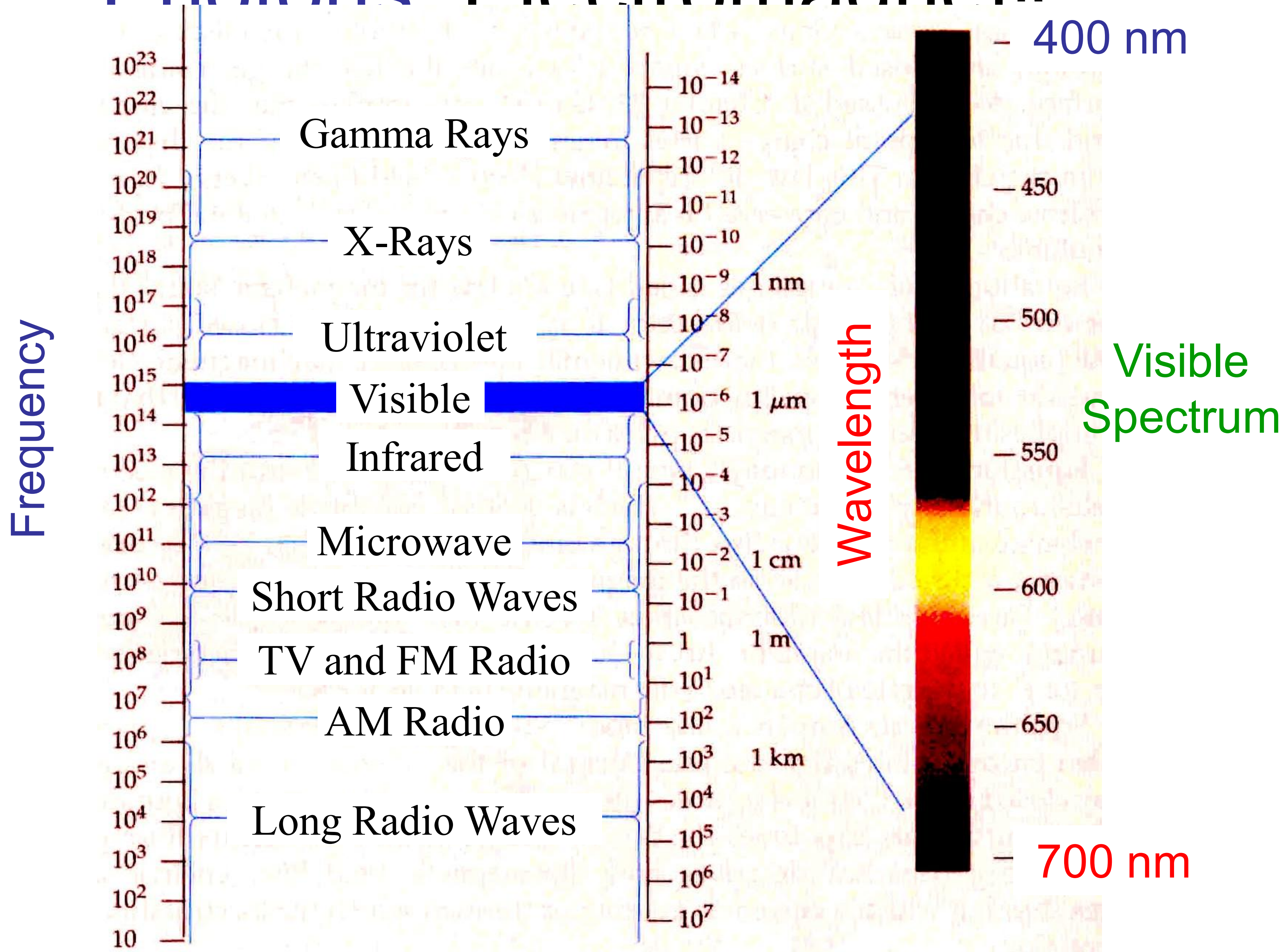
Momentum of Single Photon

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

From Relativity: $E^2 = (pc)^2 + (mc^2)^2 \longleftarrow$ Rest mass

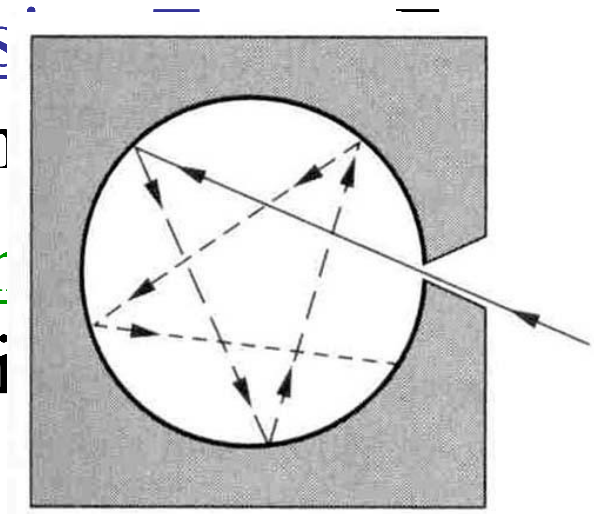
For a Photon (m = 0): $E^2 = (pc)^2 + 0 \Rightarrow \boxed{E = pc}$

# Photons: Electromagnetic



# Blackbody Radiation: Photons from "hot" object

- Temperature of a body is proportional to its average translational kinetic energy.
  - Emitted Energy = Thermal Radiation (red ~ 500 $^{o}$C)
  - Increasing Temp: Energy (or photons) absorbed via oscillating atoms.
  - Decreas… y emitted via oscillating electron…
  - Constan… tes of energy absorption and emi…
- Ideal Bla… ALL incident radiation and re-emits it.



"Ideal" Blackbody

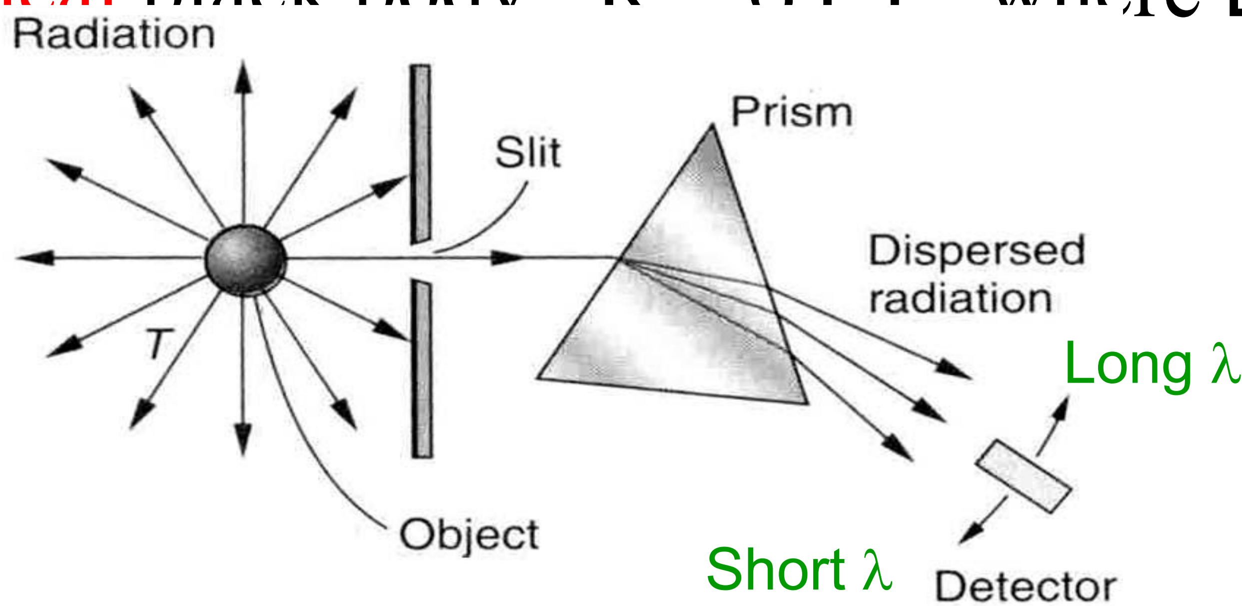
Only absorbed and emitted radiation, no reflected radiation

# Blackbody Radiation : Stefan-Boltzmann Relation

$$R\ (\mathrm{J/m^2 s}) = \sigma T^4 \propto T^4$$

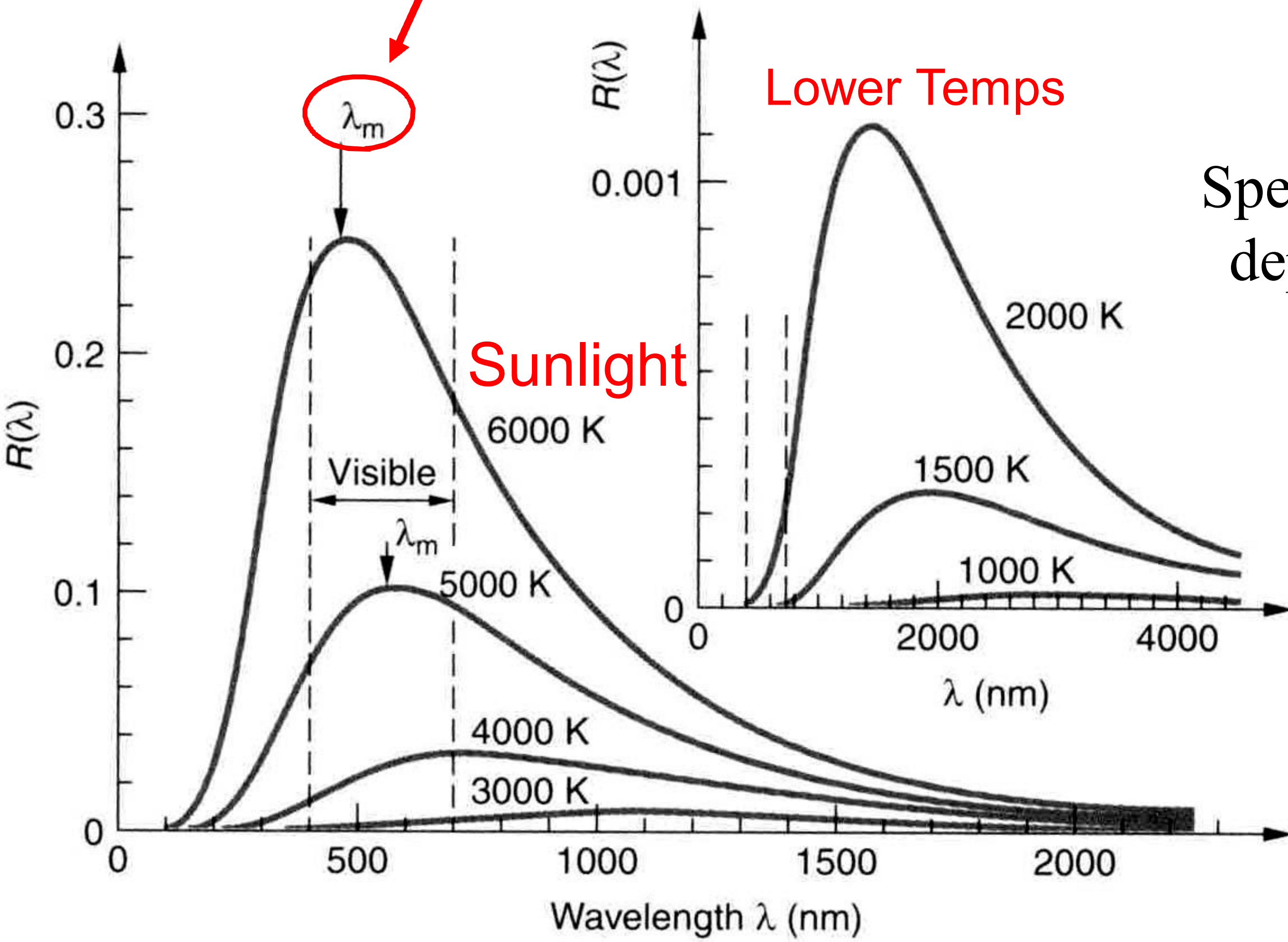
- R = Radiation intensity, T = Temp. in Kelvin, σ = $5.67 \times 10^{-8}\ \mathrm{W/m^2K^4}$
- For non-ideal black body, $R = \sigma T^4 E$, where E = emissivity

Experimental Spectral Distribution



# Blackbody Radiation : Wien's Law

$$\lambda_{peak} = \frac{2.9\times10^{-3}(\text{mK})}{T(\text{K})} \propto \frac{\mathbf{1}}{\boldsymbol{T}}$$




Spectral Distribution depends ONLY on Temperature.

# Blackbody Spectrum: Rayleigh-Jeans Equation

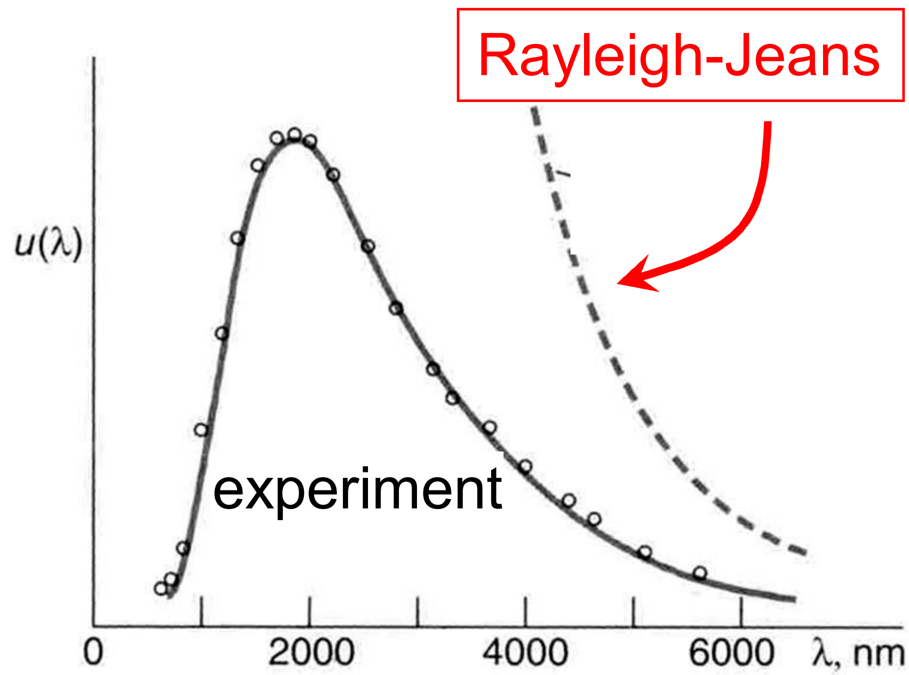
Energy Density: $u(\lambda) = E_{ave}\, n(\lambda) = kT\left(8\pi\lambda^{-4}\right)$

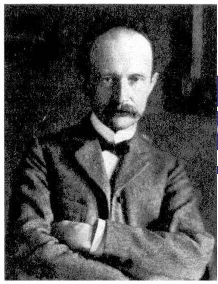
where $E_{ave}$ = average energy per "mode" = kT from Boltzmann distribution

$n(\lambda)$ = number of oscillation modes of cavity

- Raleigh-Jeans equation behaves well at long λ (low energy).
- BUT, explodes to infinity for short λ (high energy).

⇒ UV catastrophe!





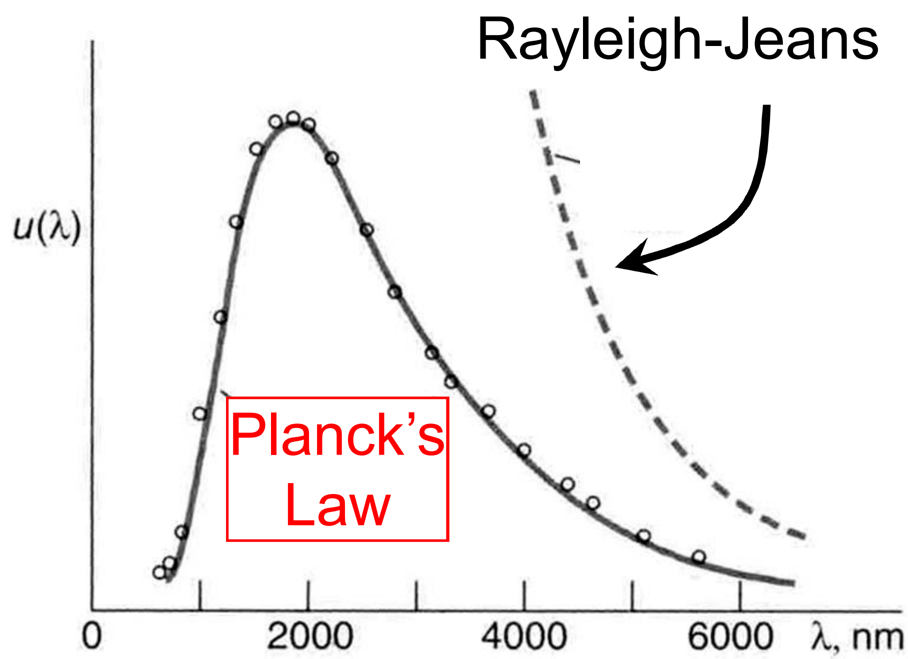
# Blackbody Spectrum: Planck's

$$u(\lambda) = E_{ave}\, n(\lambda) = \left[\frac{hc/\lambda}{e^{hc/\lambda kT} - 1}\right]\left(8\pi\lambda^{-4}\right)$$

where $E_{ave}$ is given by Bose-Einstein distribution using

$$E = hc/\lambda$$

- Planck's Law was initially found empirically (trial and error!)
- Derived from quantization of radiation, i.e. existence



# Spectral Blackbody: Derivation of $E_{ave}$

- OLD method uses a continuous energy distribution $f(E)$ and integrates to find $E_{ave}$ for the Raleigh-Jeans equation

$$\boxed{E_{ave}} = \int E\, f(E)\, dE = \int E\left(Ae^{-E/kT}\right) dE = \boxed{kT}$$

- NEW method uses a discrete energy distribution $f_n(E_n)$ and uses a summation to find $E_{ave}$ for Planck's Law

$$E_{ave} = \sum E_n f_n(E_n) = \sum E_n \left(Ae^{-E_n/kT}\right) \text{ where } E_n = \frac{nhc}{\lambda}$$

$$\boxed{E_{ave}} = \boxed{\frac{hc/\lambda}{e^{hc/\lambda kT} - 1}}$$

- Assumption of Energy Quantization is CRITICAL !

# Photoelectric Effect: "Particle Behavior" of Photon

PHOTON IN → ELECTRON OUT

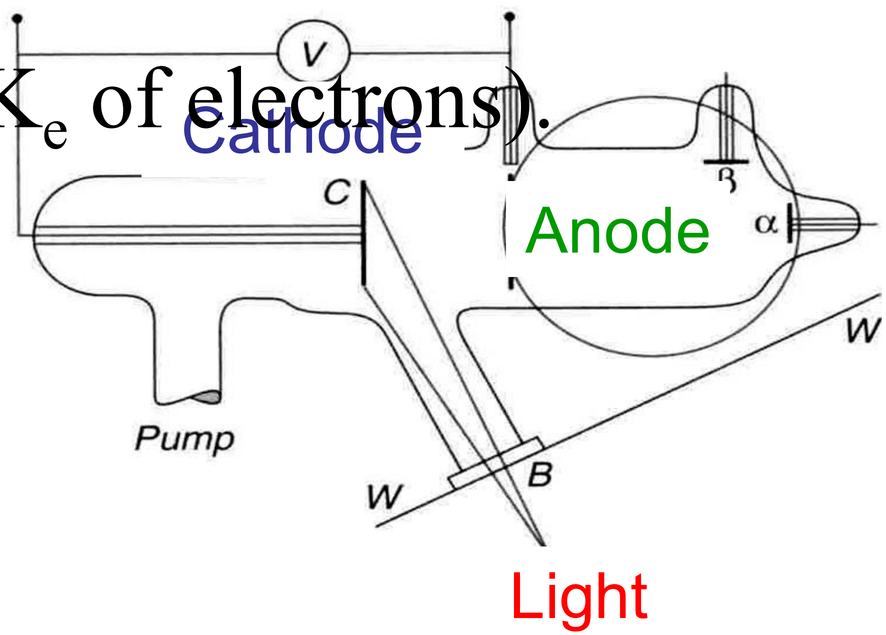
- Photoelectric effect shows quantum nature of light, or existence of energy packets called photons.
  - *Theory by Einstein and experiments by Millikan.*

- A single photon can eject a single electron from a material only if it has the minimum energy necessary (or work function $\phi$).
  - *A 1 eV (or larger) photon can eject an electron with a 1 eV work function.*

- Electron ejection occurs instantaneously → photons

# Photoelectric Effect: Apparatus

- Photons hit metal cathode and eject electrons with work function $\phi$.
- Electrons travel from cathode to anode against retarding voltage $\mathbf{V_R}$ (measures kinetic energy $K_e$ of electrons).
- Electrons collected as "photoelectric" current at anode.
- Photocurrent becomes zero when retarding voltage $V_R$ equals stopping voltage $\mathbf{V_{stop}}$,

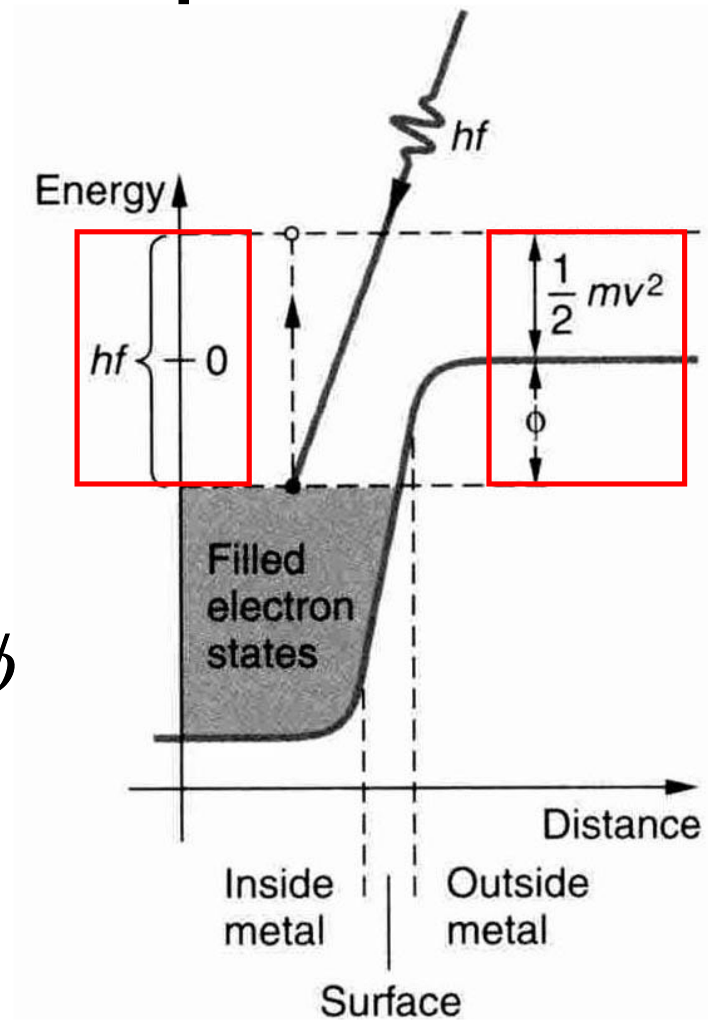


# Photoelectric Effect: Equations

- Total photon energy = $e^-$ ejection energy + $e^-$ kinetic energy.

$$\frac{hc}{\lambda} = \phi + \frac{mv^2}{2} = \phi + eV_{stop}$$

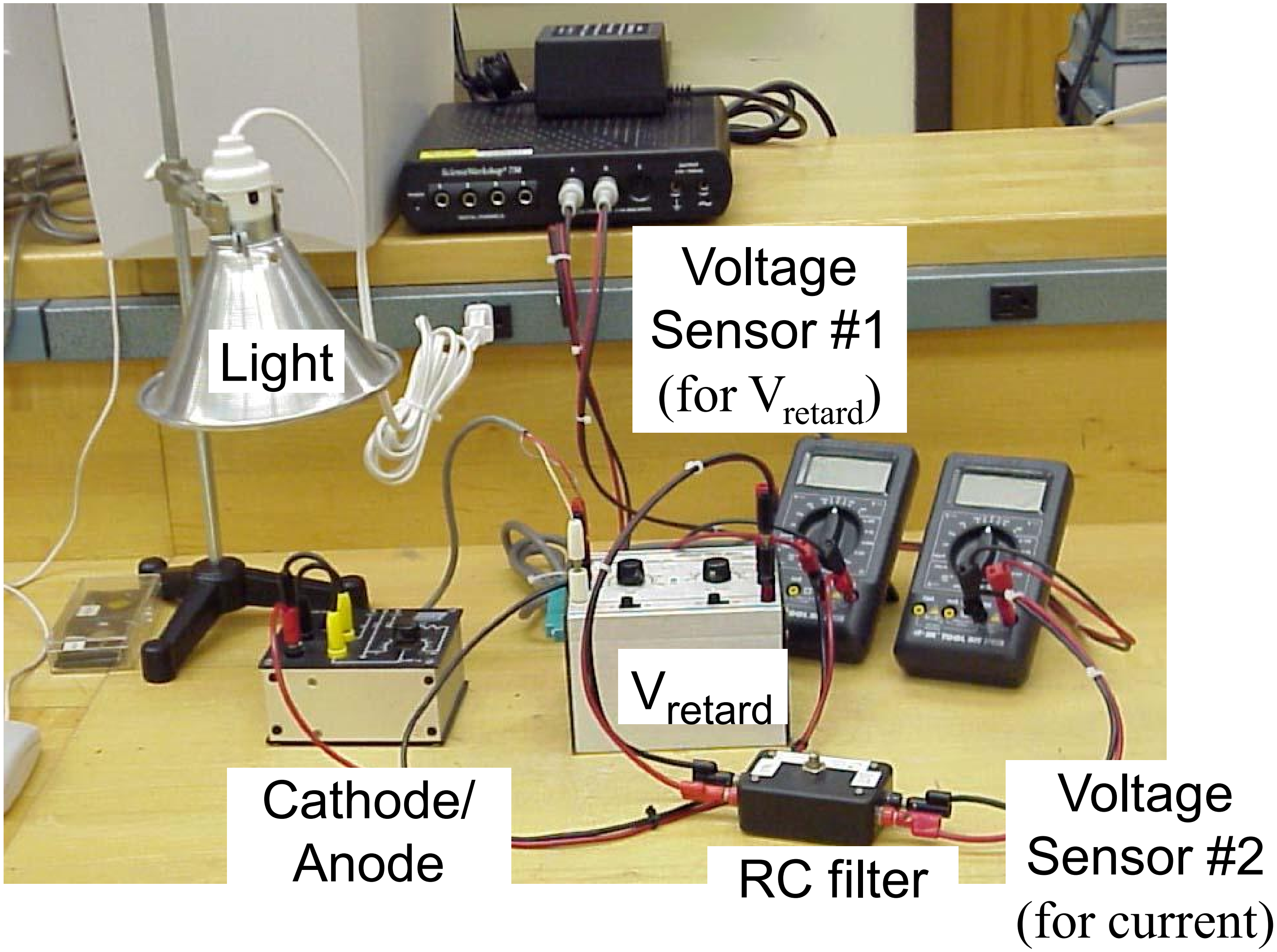
  – where $hc/\lambda$ = photon energy, $\phi$ = work function, and $eV_{stop}$ = stopping energy.




$$E_{min} = \frac{hc}{\lambda_{min}} = \phi$$

- Special Case: No kinetic energy ($V_o$ = 0).

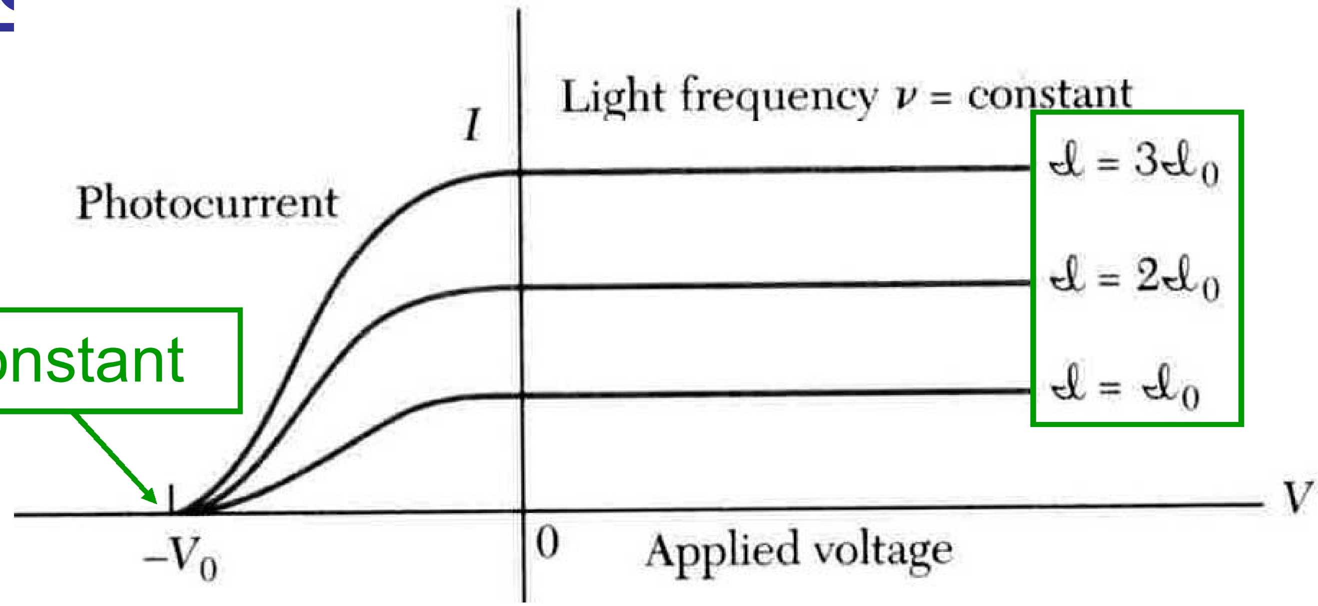
# Photoelectric Effect: Modern



# Photoelectric Effect: IV Curve

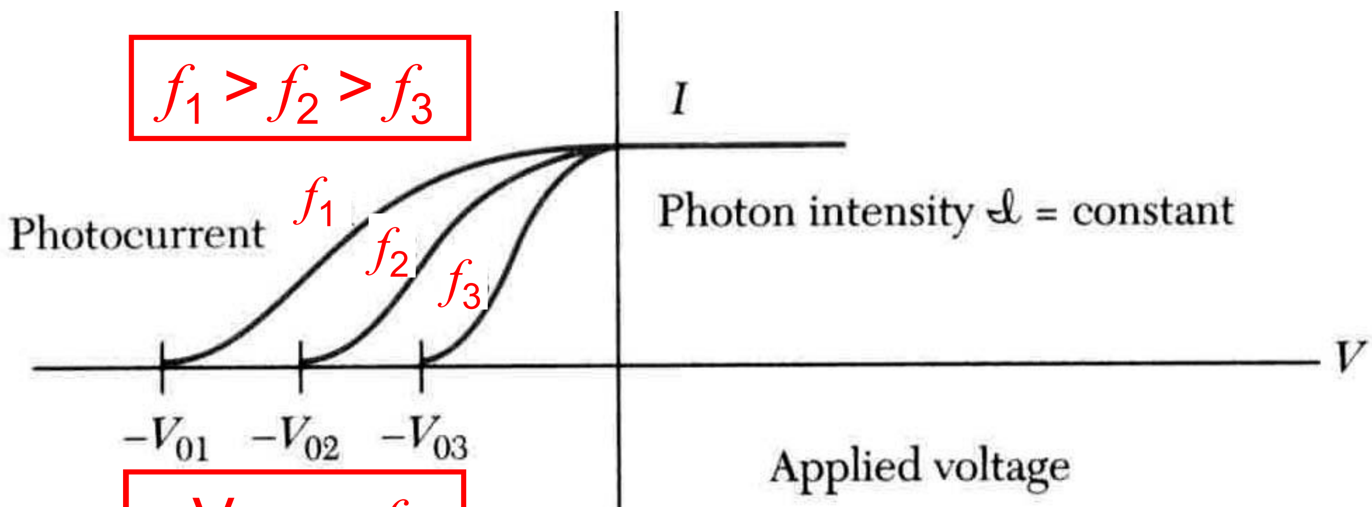
Intensity $I$ dependence

$V_{stop}$ = Constant




Frequency $f$ dependence

$f_1 > f_2 > f_3$

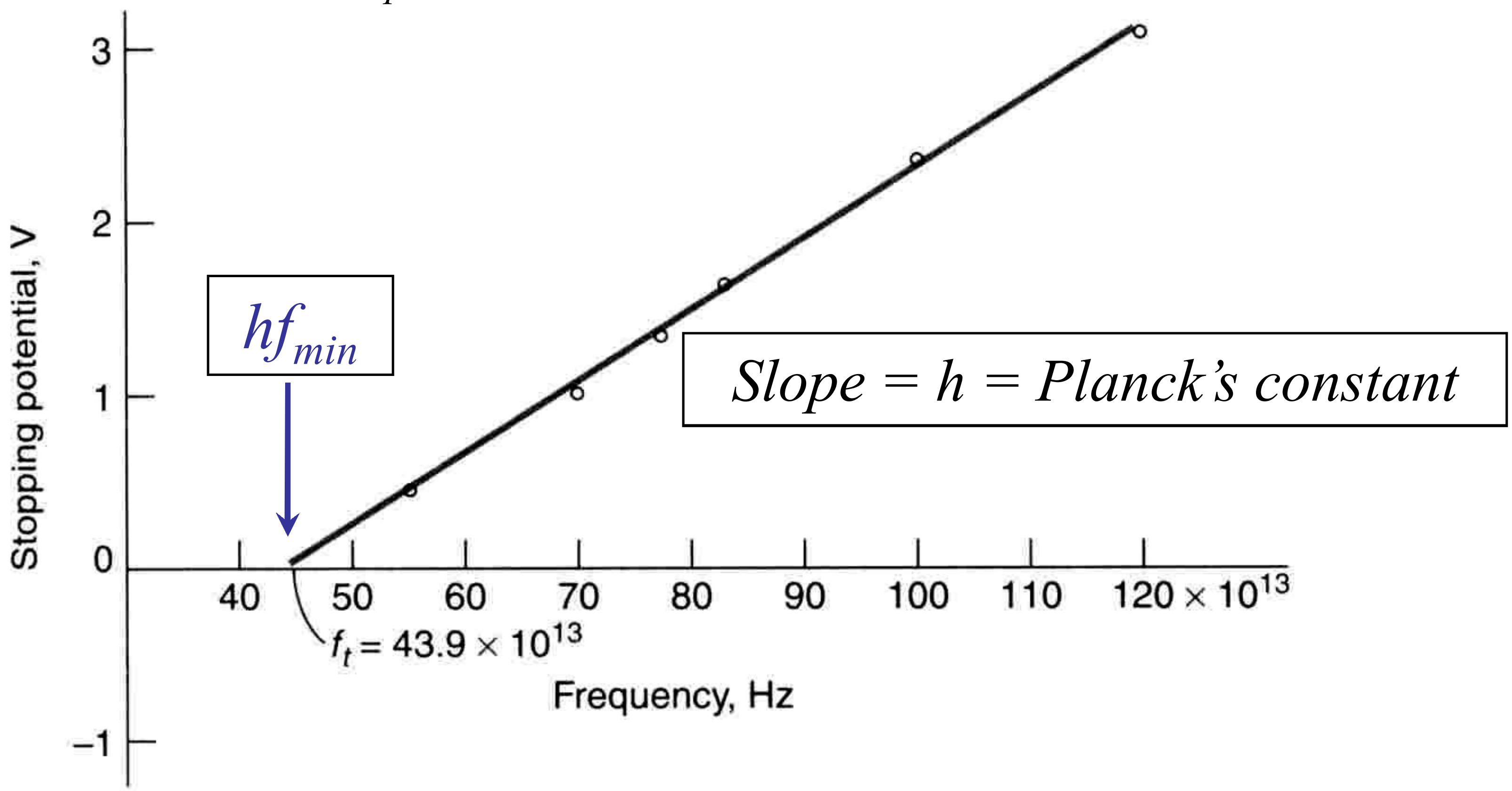



$V_{stop} \propto f$

# Photoelectric Effect: $V_{stop}$ vs. Frequency

$$eV_{stop} = hf - \phi$$

$$V_{stop} = 0 \quad \Rightarrow \quad hf_{min} = \phi$$



# Photoelectric Effect: Threshold Energy Problem

If the work function for a metal is $\phi = 2.0$ eV, then find the threshold energy $E_t$ and wavelength $\lambda_t$ for the photoelectric effect. Also, find the stopping potential $V_o$ if the wavelength of the incident light equals $2\lambda_t$ and $\lambda_t /2$.

*At threshold, $E_k = eV_o = 0$ and the photoelectric equation reduces to:*

$$\boxed{E_t} = \phi = \boxed{2\ eV} \qquad and \qquad \boxed{\lambda_t} = \frac{hc}{E_t} = \frac{1240eVnm}{2\ \ eV} = \boxed{620\ \ nm}$$

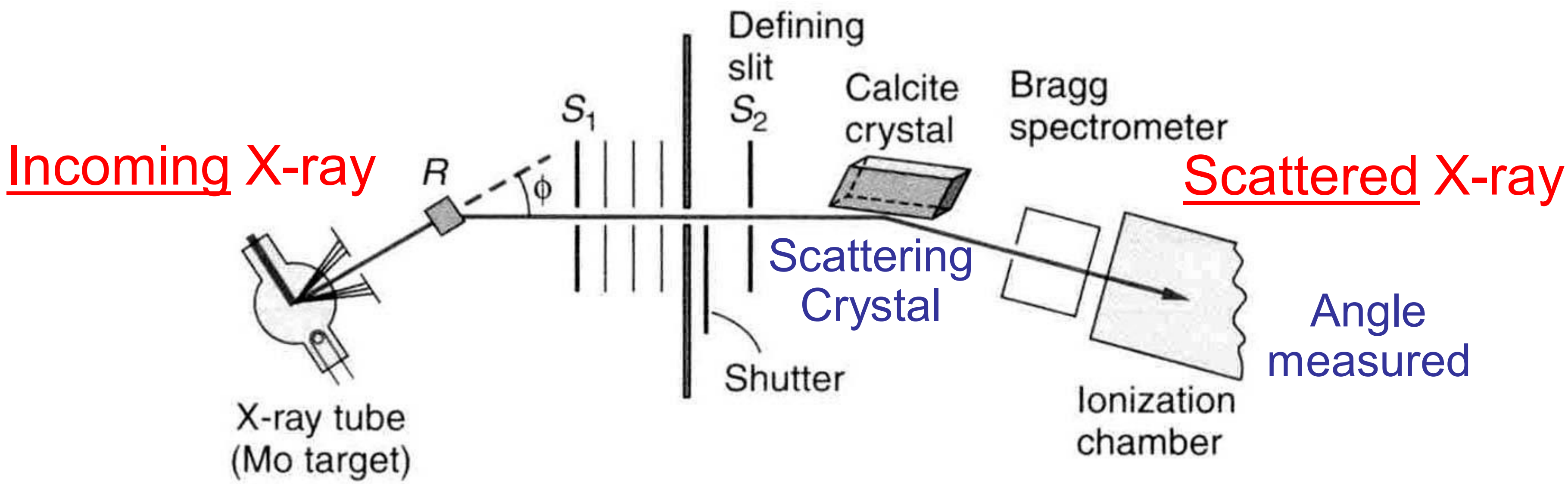
For $2\lambda_t$, the incoming light has twice the threshold wavelength (or half the threshold energy) and therefore does not have sufficient energy to eject an electron. Therefore, the stopping potential Vo is meaningless because there are no photoelectrons to stop!

For $\lambda_t/2$, the incoming light has half the threshold wavelength (or twice the threshold energy) and can therefore eject an electron with the following stopping potential:

$$For\ \ \lambda = \frac{\lambda_t}{2}\ \ (or\ E = 2E_t), \qquad \boxed{eV_o} = \frac{hc}{\lambda} - \phi\ =\ 2E_t - \phi\ =\ 2(2) - 2\ \ eV = \boxed{2\ \ eV}$$

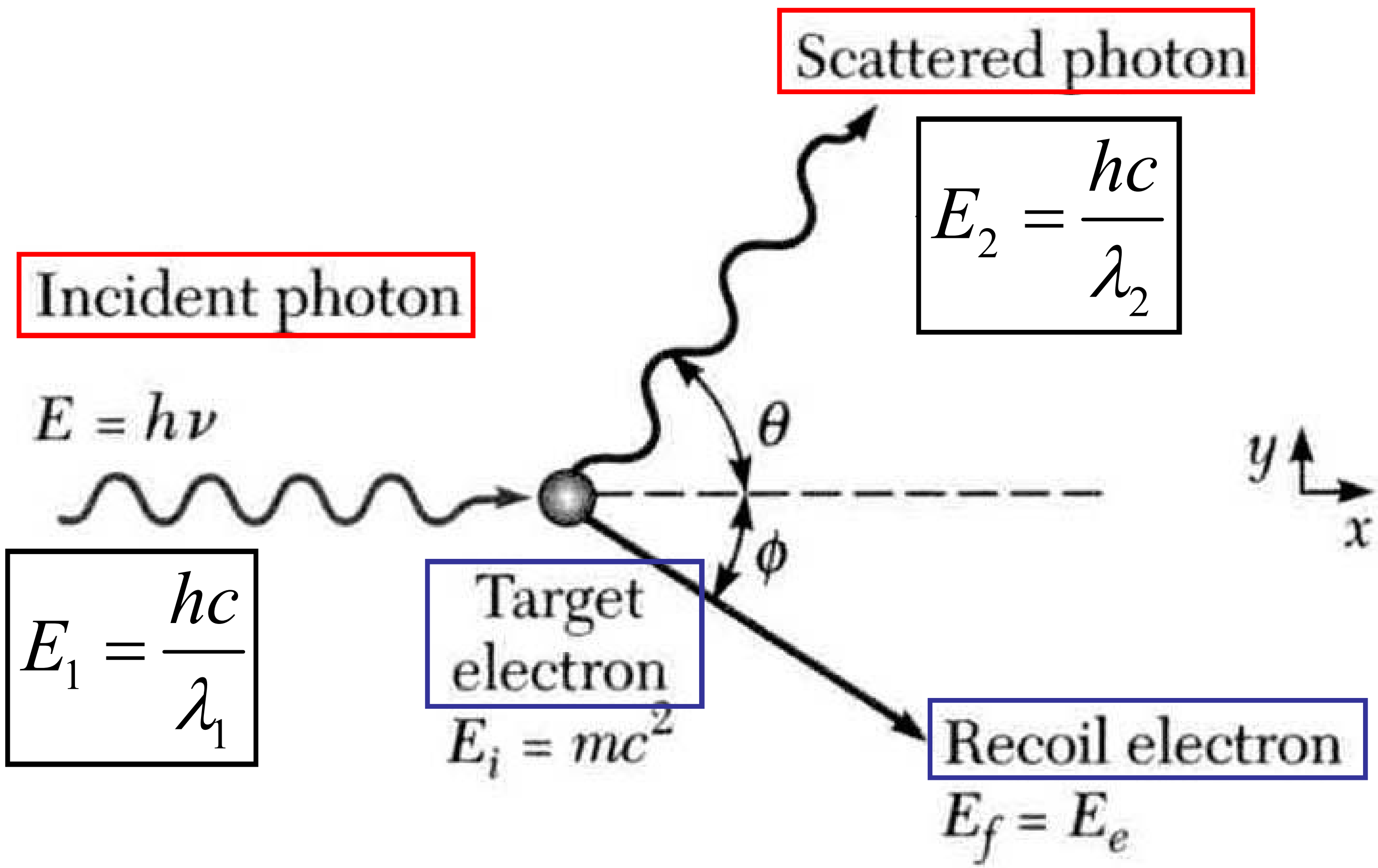
# Compton Scattering: "Particle-like" Behavior of Photon

- An incoming photon (E$_1$) can inelastically scatter from an electron and lose energy, resulting in an outgoing photon (E$_2$) with lower energy ($E_2 < E_1$).
- The resulting energy loss (or change in wavelength $\Delta\lambda$) can be calculated from the scattering angle $\theta$.



# Compton Scattering: Schematic

PHOTON IN → PHOTON OUT (inelastic)



# Compton Scattering: Equation

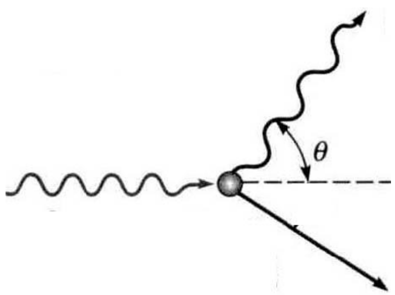
Photon OUT

Scattering Angle

$$\Delta\lambda = \lambda_2 - \lambda_1 = \left(\frac{h}{mc}\right)(1-\cos\theta)$$

Photon IN

Critical $\lambda_c$= 0.0024 nm for $e^-$




- Limiting Values
  - No scattering: $\theta = 0^o \rightarrow \cos 0^o = 1 \rightarrow$ **$\Delta\lambda = 0$**
  - Bounce Back: $\theta = 180^o \rightarrow \cos 180^o = -1 \rightarrow$ **$\Delta\lambda = 2\lambda_c$**
- Difficult to observe unless $\lambda$ is small (i.e. $\Delta\lambda/\lambda$

# Compton Scattering: Wavelength/Energy Problem

If a 0.511-MeV photon from a positron-electron annihilation scatters at θ = 180° from a free electron, then find the wavelength and energy of the Compton scattered photon.

$$\lambda_2 - \lambda_1 = \lambda_C\left(1-\cos\theta\right) = (0.00243\ \ nm)\left(1-\cos 180^o\right) = 4.86\times 10^{-3}\,nm$$

$$\lambda_1 = \frac{hc}{E_1} = \frac{1240\ \ eV\cdot nm}{0.511\times 10^6\,eV} = \underline{2.43\times 10^{-3}\,nm}$$

$$\boxed{\lambda_2} = \lambda_1 + \Delta\lambda = 2.43\times 10^{-3}\,nm + 4.86\times 10^{-3}\,nm = \boxed{7.29\times 10^{-3}\,nm}$$

$$\boxed{E_2} = \frac{hc}{\lambda_2} = \frac{1240\ \ eV\cdot nm}{7.29\times 10^{-3}\,nm} = \boxed{1.70\times 10^5\,eV\ \ \text{or } 0.17\ \ MeV}$$

# A (very) Little about Einstein and Relativity

A very contracted account.

# What is Relativity?

- General relativity is a theory of GRAVITY.

- Recall Newton's theory of gravity:
  - $F = G M_1 M_2 / d^2$
    - G = Universal gravitational constant
    - M1 and M2 are the masses of the objects
    - d = the center to center distance

- Newton’s theory was highly successful and was refined and reworked by several prominent scientists and mathematicians such as Euler, Lagrange, Hamilton, Jacobi, Clairaut, Laplace, and Poisson.

- There was little reason to question Newton’s theory except its failure to explain how the two bodies knew each other were there.

- James Clark Maxwell, developer of our classical laws of electricity and magnetism is quoted as saying:

*"After tracing to the action of the surrounding medium both the magnetic and the electric attractions and repulsions, and finding them to depend on the inverse square of the distance, we are naturally led to inquire whether the attraction of gravitation, which follows the same law of the distance, is not also traceable to the action of a surrounding medium."* JCM

# Problem?

- Following Maxwell's logic, if gravitation were like electro-magnetism and dependant upon the medium through which it operated, then the presence of mass must reduce the energy of the medium.
  - *"As I am unable to understand in what way a medium can possess such properties, I cannot go further in this direction in searching for the cause of gravitation." JCM*

# Special Relativity

- Special relativity is a study in the consequences of holding simultaneously to the principal of the constancy of the speed of light and the *principle of relativity*
  - "Who would imagine that this simple law has plunged the conscientiously thoughtful physicist into the greatest intellectual difficulties?" A.E.

# Principle of Relativity

If, relative to *K*, *K′* is a uniformly moving co-ordinate system devoid of rotation, then natural phenomena run their course with respect to *K′* according to exactly the same general laws as with respect to *K*. This statement is called the *principle of relativity* (in the restricted sense).

# Postulates

- Formally special relativity can be derived from four postulates.
- The first two concern the nature of space-time.
- The second two form the heart of special relativity.

# #1 - **The Geometry of Space-time**

- Space and time form a 4 dimensional continuum.
  - This is a continuation and generalization of the Galilean concept of 3 dimensional space + 1 separate dimension of time.

# #2 - **The Existence of Globally Inertial Frames**

- There exist global space-time frames with respect to which unaccelerated objects move in straight lines at constant velocity

# #3-**The Speed of Light is Constant**

- The speed of light *c* is a universal constant, the same in any inertial frame

# #4 - **The Principle of Special Relativity**

- The laws of physics are the same in any inertial frame, regardless of position or velocity
  - There is no absolute reference frame, only relative positions and velocities are meaningful.

# “the happiest thought of my life” A.E.

- In 1907 Einstein proposed the “Equivalence principle”
  - *“... we shall therefore assume the complete physical equivalence of a gravitational field and the corresponding acceleration of the reference frame. This assumption extends the principle of relativity to the case of uniformly accelerated motion of the reference frame.”*

# Toward a General Theory of Relativity

- The notion of the equivalence principle set Einstein as well as others on the path toward a more complete and generalized theory of gravitation.
- Einstein realized the problem:

  *"If all accelerated systems are equivalent, then Euclidean geometry cannot hold in all of them."* A.E

- 1913 “*As an older friend I must advise you against it for in the first place you will not succeed, and even if you succeed no one will believe you.*”

M. Planck

# …and finally

- Eventually, with much advice and assistance from other very notable scientists and mathematicians Einstein was able to publish the correct field equations for general relativity in 1915.
  - "*That fellow Einstein suits his convenience. Every year he retracts what he wrote the year before.*" A.E

$$R_{ij} - (1/2)g_{ij}R = T_{ij}$$

**$R_{ij}$** (= h(ihj ) - j(hhi ) + hhl  ilj - ilh  jhl , with m = /xm defined for notational convenience) is the contracted Riemann-Christoffel curvature tensor (Riss j , a.k.a. the Ricci tensor)

**R** is the associated scalar gi jRi

**$g_{i\ j}$** is the fundamental tensor

**$T_{i\ j}$** is the stress-energy tensor

# Results

- Although the basic theory is attributable to Einstein he did not follow through on examining many of the consequences of dynamical models of the universe.
- Much of this work was initiated by A. Freidmann and was only brought to the attention of the world after Hubble's observations of an expanding universe.

# Further reading…

- For a text by Einstein on G.R. (remarkably readable.) http://www.bartleby.com/173/
- For a nice demo of some weird aspects of special relativity.

  http://casa.colorado.edu/~ajsh/sr/paradox.html
- For a neat demo of near light speed travel try

  http://hexadecimal.uoregon.edu/relativity/index.html
- For a nice "fan site" with some interesting stuff.

  http://www.geocities.com/einstein_library/index.htm