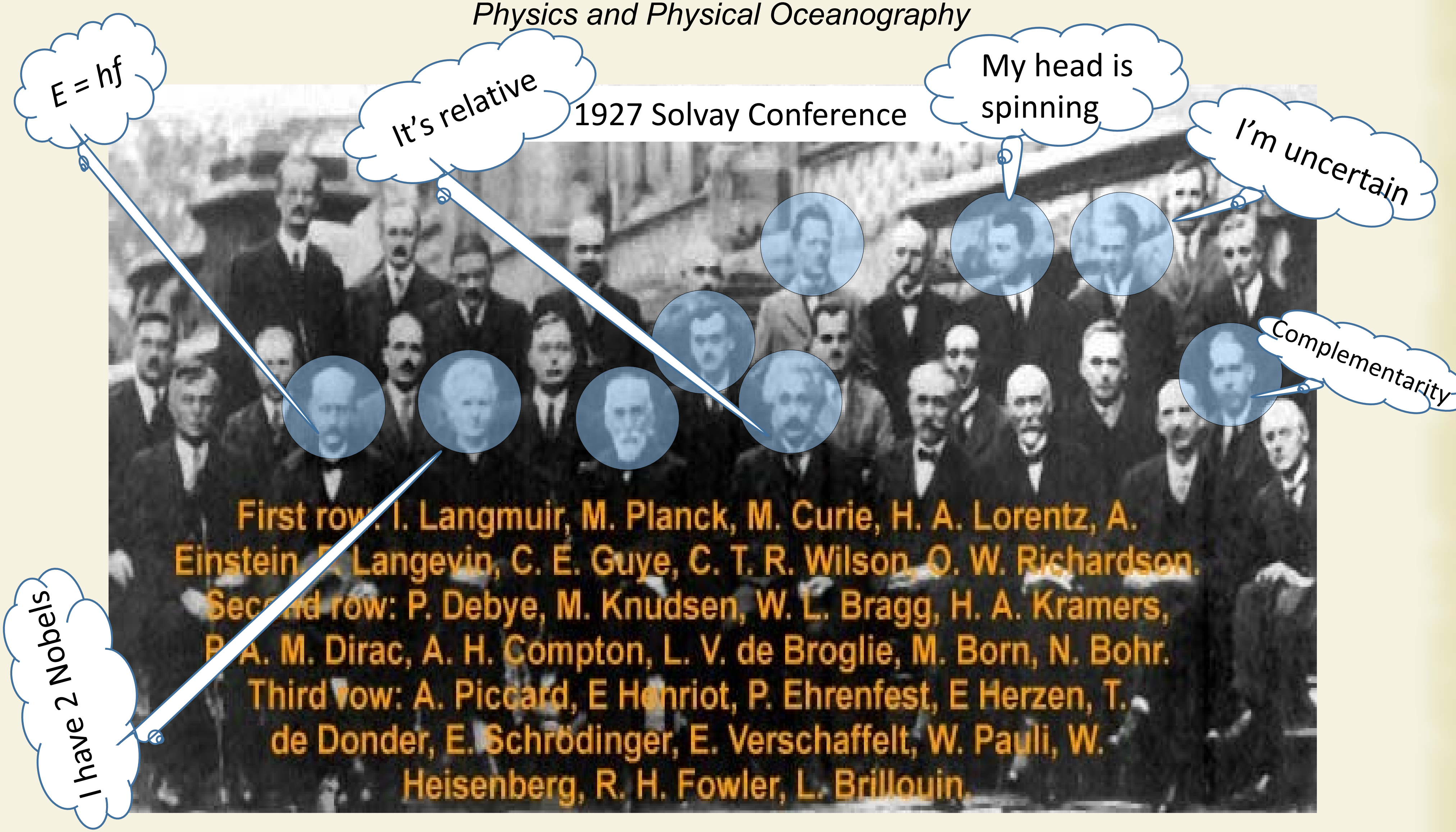
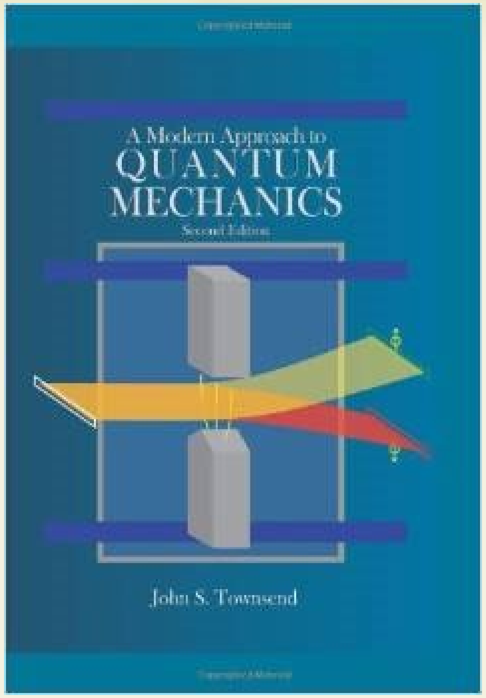
Introduction to Quantum Theory

Dr. Russell Herman
Physics and Physical Oceanography



Syllabus



- Website: http://people.uncw.edu/hermanr/qm/
- Grades

  Homework – 30%
  Papers – 10%
  3 Exams – 40%
  Final – 20%

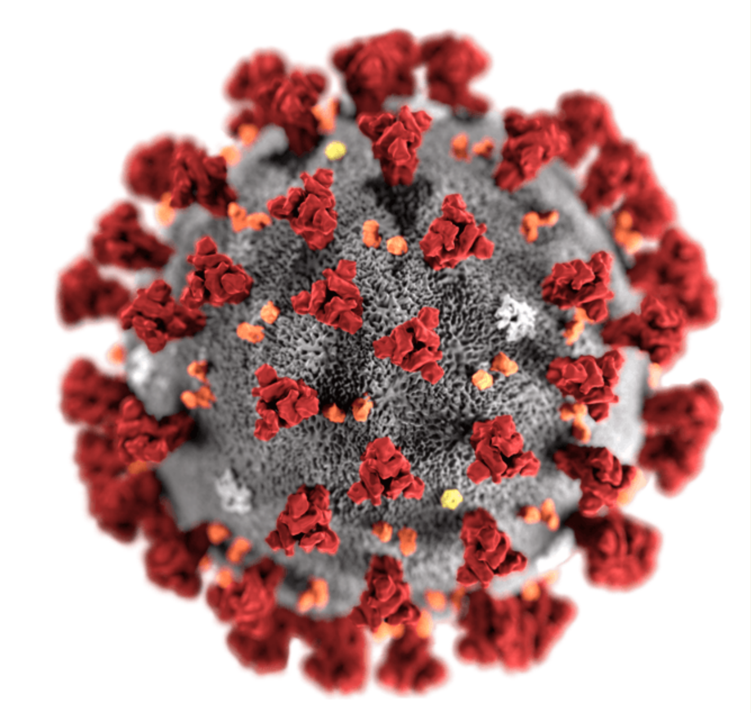
Required Text:
Townsend, *J. A Modern Approach to Quantum Mechanics*, 2nd Ed., 2012.

Other Readings:
Susskind, L. *Quantum Mechanics, The Theoretical Minimum*, 2014.
Feynman, R. C.,
The Feynman Lectures on Physics, Vol. III, 1965 and
QED: The Strange Theory of Light and Matter, 1988.

See also - http://people.uncw.edu/hermanr/booklist.htm

COVID-19

- Face to Face unless …
- https://uncw.edu/coronavirus/
  - Social Distancing
  - Face Coverings
  - Wash Hands
- Office Hours



Following CDC Guidelines, UNC System directives, and out of mutual respect as outlined in the UNCW Seahawk Respect Compact, all faculty, staff, and students will wear face coverings while inside buildings. Students who are unprepared or unwilling to wear protective face coverings will not be permitted to participate in face-to-face sessions and will need to leave the building. Noncompliant students will be referred to the Dean of Students for an Honor Code Violation. Any student who has a medical concern with wearing a face covering should contact the Disability Resource Center at (910) 962-7555.

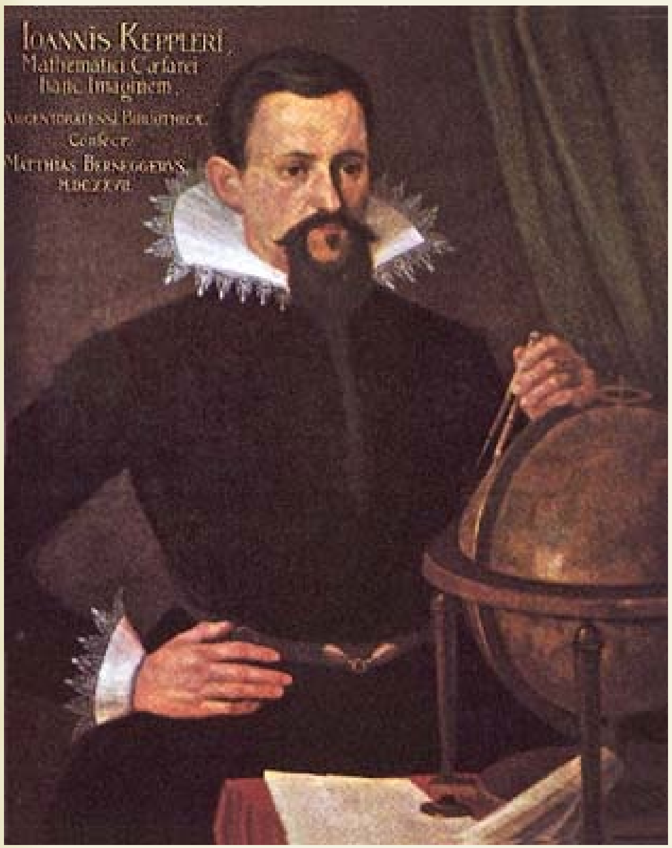
Students who experience COVID-19 symptoms should immediately contact the Abrons Student Health Center at (910) 962-3280.

The Rise of Classical Physics

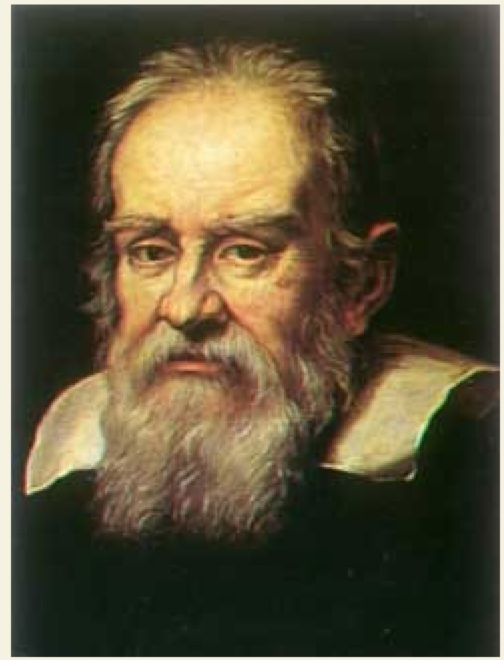
Scientific Deduction

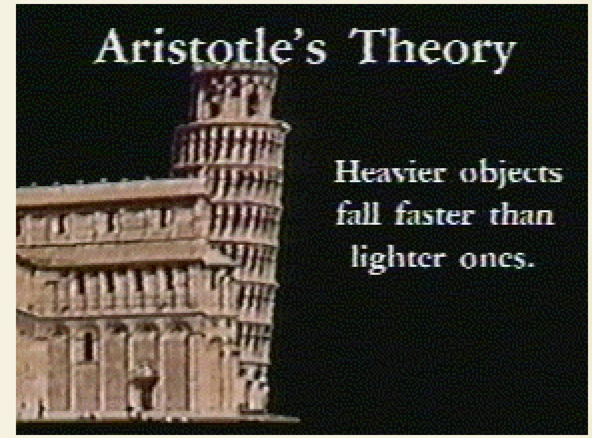
Tycho Brahe
(1546-1601)

Johannes Kepler
(1571-1630)



Galileo Galilei
(1564-1642)





The Clockwork Universe

Sir Isaac Newton (1642-1727)

Principia (1687)

Philosophiae Naturalis Principia Mathematica (Mathematical Principles of Natural Philosophy)

Laws of Motion $d\mathbf{p}/dt = \mathbf{F}$

Law of Gravitation

Kepler's Laws Explained

Calculus

... space is absolute ...

Determinism - Given **F**, predict **x** and **v**

Unification

... the force responsible for bodies falling on the Earth is the same as that causing the moon to follow its orbit.

Reformulations of $\boldsymbol{F = ma}$

Euler (1707-1783) Variational Calculus

D'Alembert (1717-1783) Virtual Work

Lagrange (1736-1813) Lagrangian Mechanics

Hamilton (1805-1865) Hamiltonian Mechanics

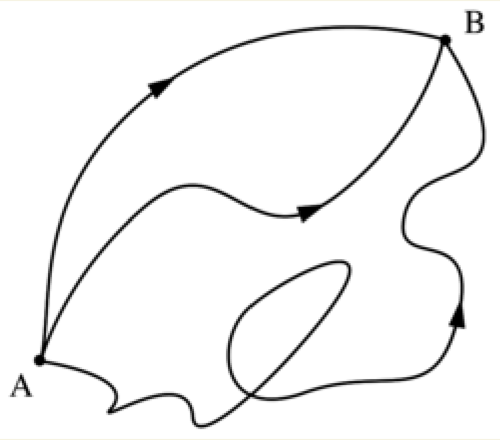
Define the action

$$S = \int_{t_1}^{t_2} L\,dt, \text{ for } L = T - V.$$

Require: $\delta S = 0.$

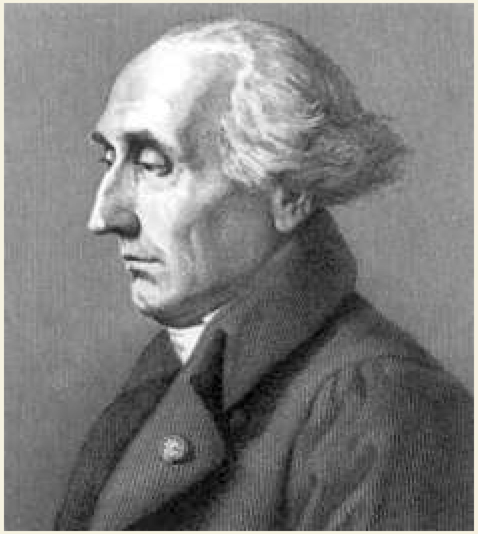
Then,

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{x}}\right) - \frac{\partial L}{\partial x} = 0.$$



Principles

Fermat's	least time
d'Alembert's	virtual work
Hamilton's	least action



Hamilton's Formulation

Phase Space (*q=x, p= m dx/dt*),

Initial *(q, p)* + 2nd Law => Motion for all *t*

Ex: Free particle, *p* = const

Harmonic Oscillator,

Energy Conservation *E=const*

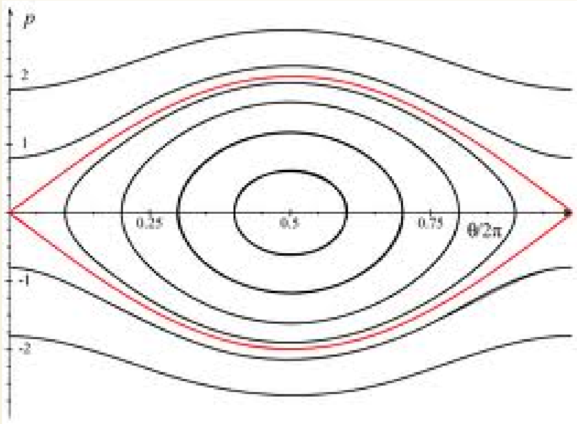
$$E = \frac{p^2}{2m} + \frac{1}{2}kq^2$$

Hamiltonian *H(p,q) = T(p) + V(q)*

Hamilton's Eqns <=> Newton's Laws

$$\frac{dq}{dt} = \frac{\partial H(q,p)}{\partial p}$$

$$\frac{dp}{dt} = -\frac{\partial H(q,p)}{\partial q}$$



Electricity and Magnetism

Magnetism

Lode stones

Compasses

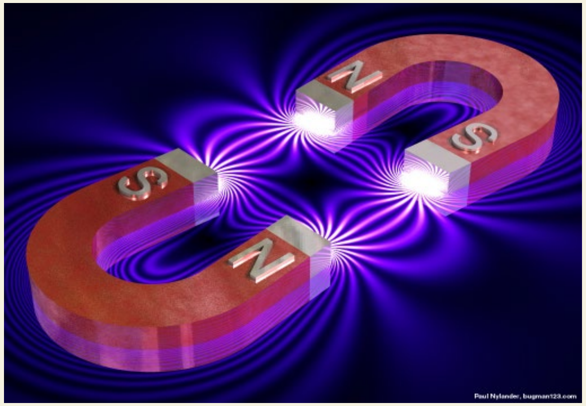
William Gilbert (1544-1603)

Thomas Browne (1605-1682)

Benjamin Franklin (1706-1790)

Luigi Galvani (1737-1798)

Alessandro Volta (1745-1827)



Electromagnetism

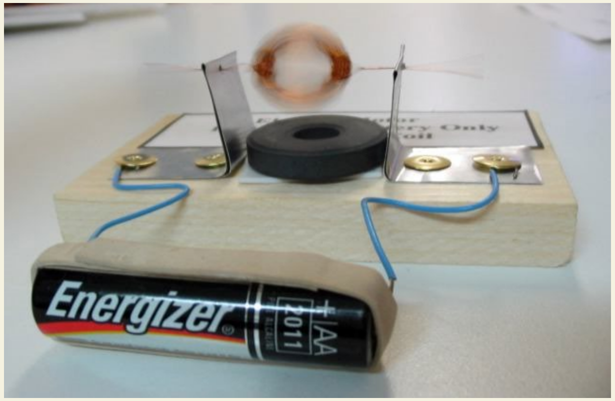
André-Marie Ampère, (1775 - 1836)

Hans Oersted (1777-1851)
  current deflects compass needles

Georg Simon Ohm (1789-1854)

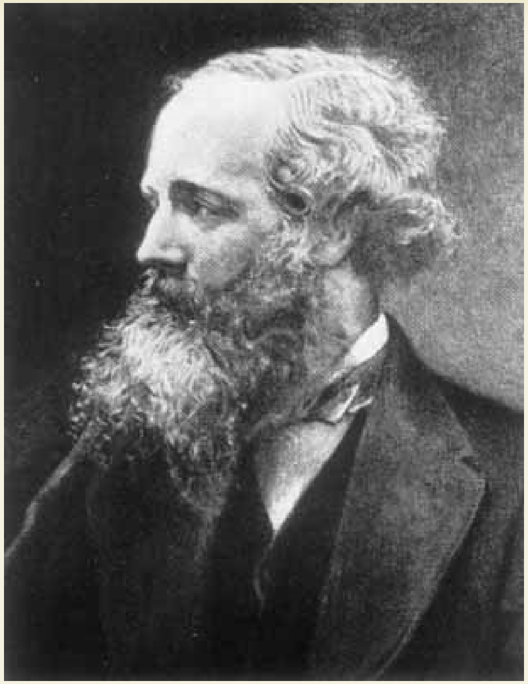
Joseph Henry (1797-1878)
  electromagnetic induction, first motor, telegraph

Michael Faraday (1791-1867)
  electrolysis, motors, induction coils, ...



http://hilaroad.com/camp/projects/magnet.html

Electromagnetic Waves



James Clerk Maxwell (1831-1879)

- Theory of electromagnetism.
- Predicted the electromagnetic waves.
- Electromagnetic waves travel at

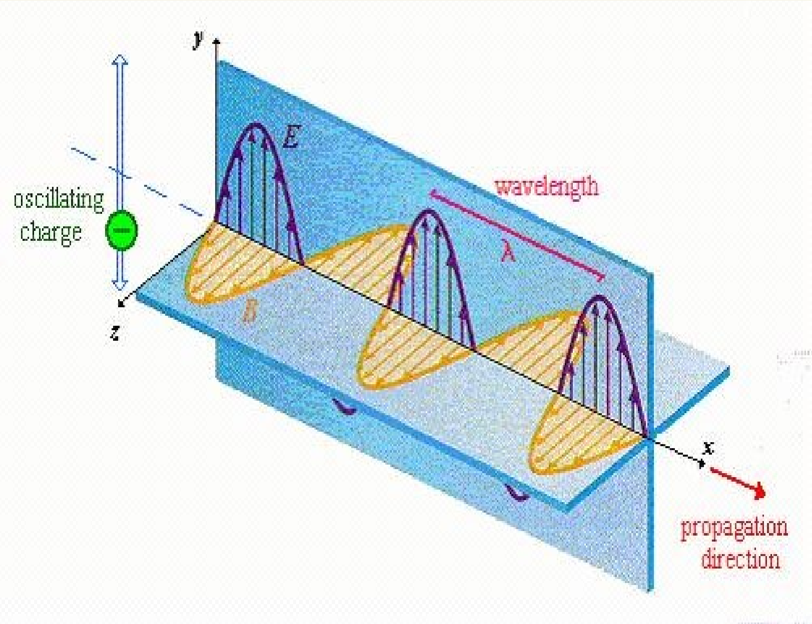
$$c = 299{,}792{,}458 \text{ m/s} = 186{,}000 \text{ mi/s}$$

Heinrich Hertz (1857-1894)

- sent the first radio waves (1888)

What is the medium?

Luminiferous Aether



Michelson-Morley (1887)

- could not detect it.

Maxwell's Equations

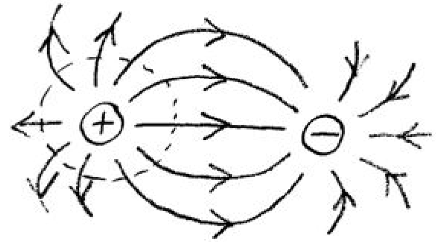
Not SI units!

JAMES CLERK MAXWELL'S EQUATIONS

$$\nabla\cdot\vec{E} = 4\pi\rho$$

DIVERGENCE OF $\vec{E}$ — CHARGE DENSITY

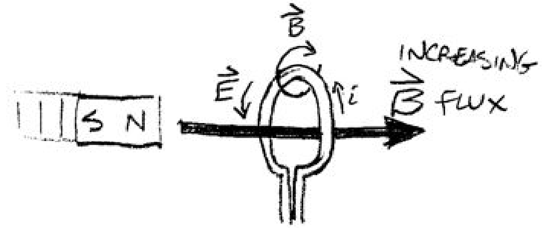
$\vec{E}$ DIVERGES OUT FROM POSITIVE CHARGES AND IN TOWARD NEGATIVE CHARGES. THE TOTAL FLUX OF $\vec{E}$ THROUGH ANY CLOSED SURFACE IS PROPORTIONAL TO THE CHARGE INSIDE.



$$\nabla\times\vec{E} = -\frac{1}{c}\frac{d\vec{B}}{dt}$$

CURL OF $\vec{E}$ — SPEED OF LIGHT — RATE $\vec{B}$ IS CHANGING

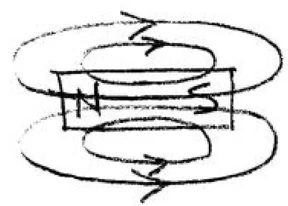
$\vec{E}$ CURLS AROUND CHANGING $\vec{B}$ FIELDS (FARADAY'S LAW) IN A DIRECTION THAT WOULD MAKE A CURRENT THAT WOULD PRODUCE A $\vec{B}$ FIELD TO OPPOSE THE CHANGE IN $\vec{B}$ FLUX (LENZ'S LAW).



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

DIVERGENCE OF $\vec{B}$

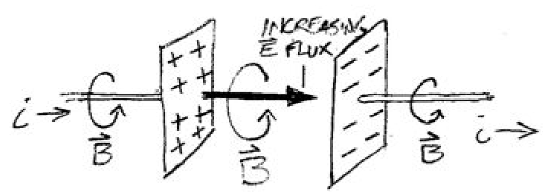
$\vec{B}$ NEVER DIVERGES. IT JUST LOOPS AROUND ON ITSELF.



$$\nabla\times\vec{B} = \frac{4\pi}{c}\vec{J} + \frac{1}{c}\frac{d\vec{E}}{dt}$$

CURL OF $\vec{B}$ — SPEED OF LIGHT — CURRENT DENSITY — RATE $\vec{E}$ IS CHANGING

$\vec{B}$ CURLS AROUND CURRENTS AND CHANGES IN $\vec{E}$ FIELDS



Gaussian Units

Unit Conversions

		Conversion	SI
Distance	cm	10^{-2}	m
Mass	g	10^{-3}	kg
Time	s	1	s
Force	dyne	10^{-5}	N
Energy	erg	10^{-7}	J
Power	erg/s	10^{-7}	W
Charge	esu	3.336×10^{-10}	C
Electric Potential	statvolt	299.79	V
Magnetic Field	Gauss	10^{-4}	T

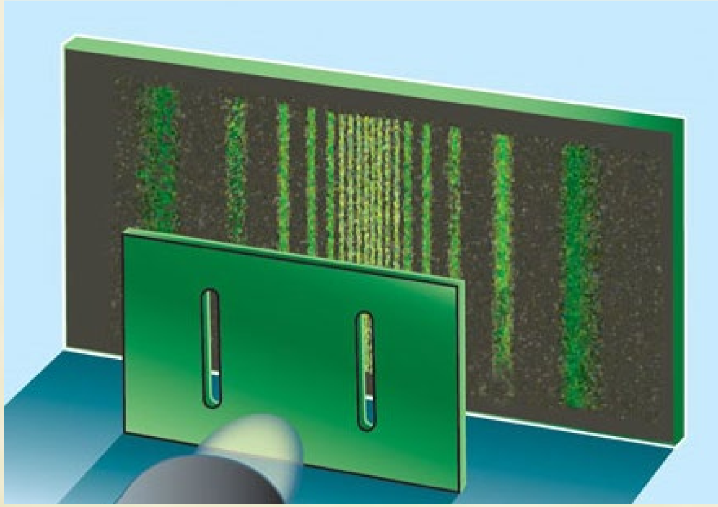
- 1 eV $= 1.6022 \times 10^{-12}$ erg $= 1.602 \times 10^{-19}$ J
- 1 Ry = 13.6057 eV (ionization energy of hydrogen)
- 1 C $= 2.9979 \times 10^{9}$ esu, 1 statcoul = 1 esu
- 1 Å $= 10^{-10}$ m
- 1 eV/c^2 $= 1.7827 \times 10^{-36}$ kg
- $(\mu_0\epsilon_0)^{-1/2} = 299,792,458$ m/s; $(\mu_0/\epsilon_0)^{1/2} \approx 377\Omega$

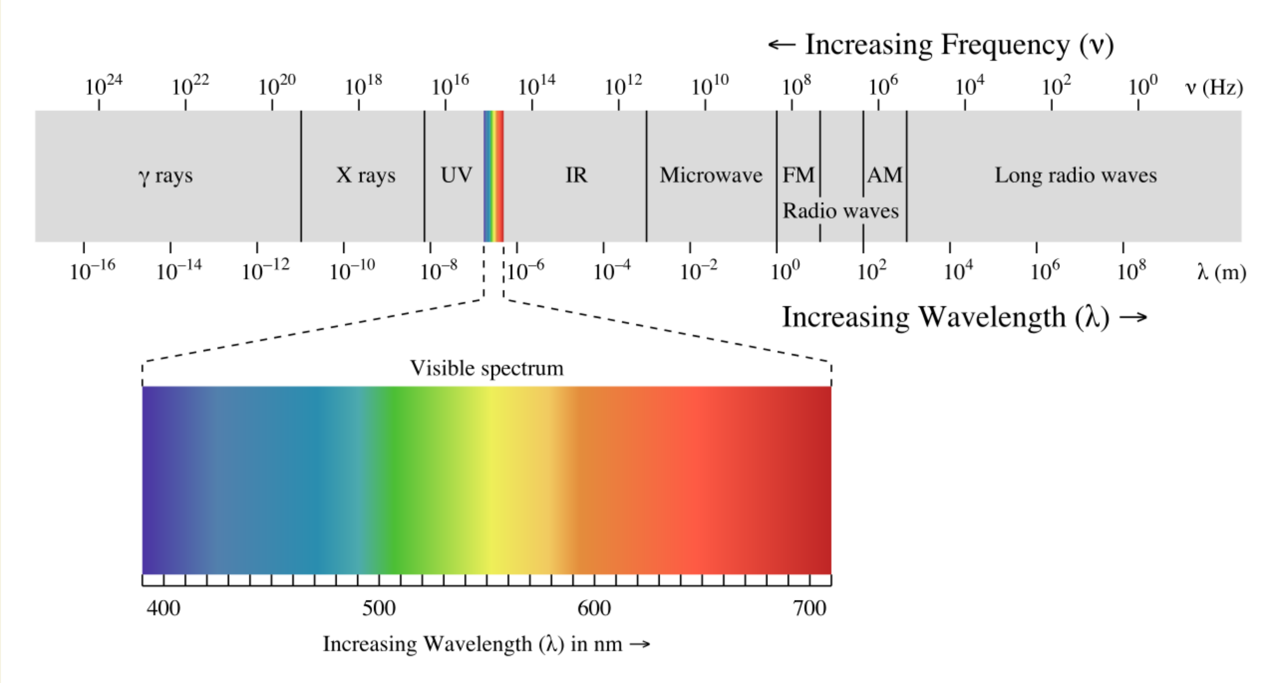
WAVES

What are waves?

- **Characteristics**
  - Wavelength, Frequency, Wavespeed
- **Behavior**
  - Superposition, Interference. Diffraction

$$\frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} = \nabla^2 E$$





Spectroscopy

Ionized gas gives off radiation

Johann Balmer 1885

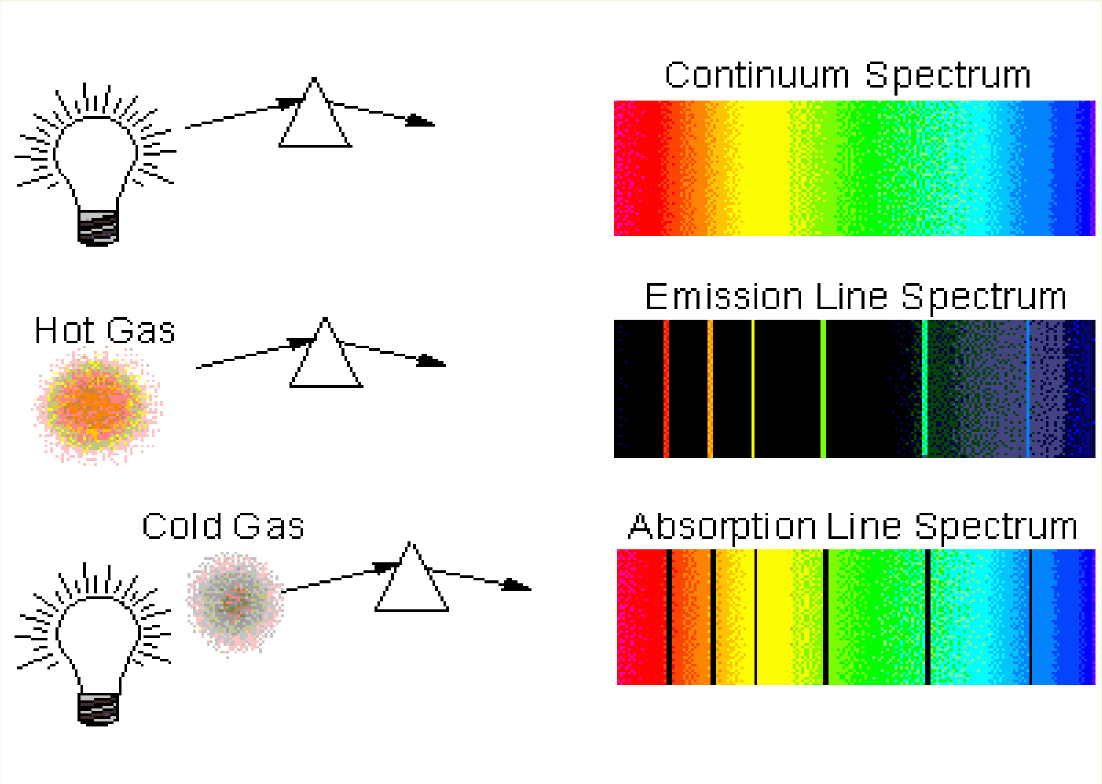
Spectral Lines: Hydrogen
410, 434, 486, 656 nm

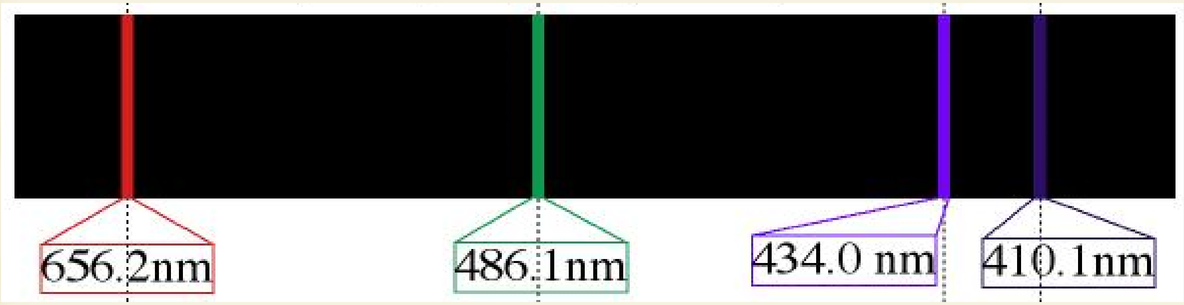
Empirical Formula:

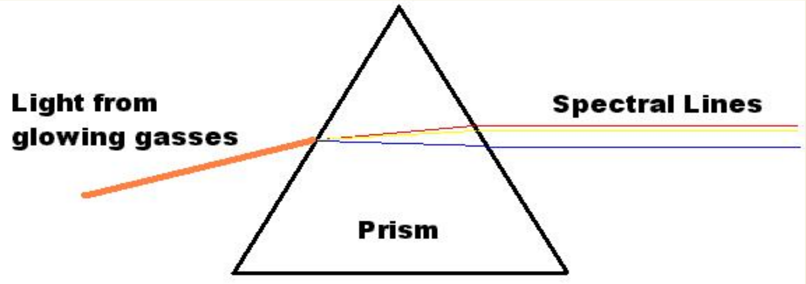
$$\lambda = R\,(1/4 - 1/n^2)$$

Predicted 5th-7th lines

Lyman and Paschen Series







Laws of Thermodynamics

Engines: Watt, Carnot, Kelvin, Clausius, Carnot

James Joule (1818-1889)

Mechanical Equivalent of Heat

Laws of Thermodynamics

1. Adding heat energy or doing work on a body increases internal energy. (Energy conservation)
2. A body will not spontaneously get hotter. (Entropy and the Arrow of Time)

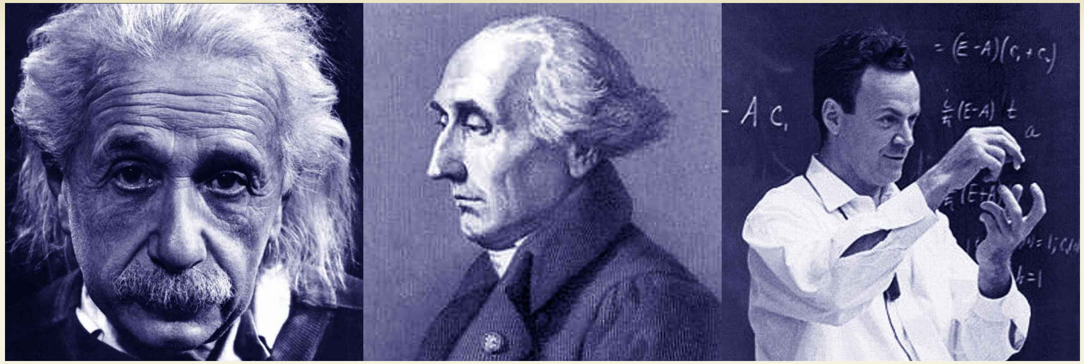
Joseph Stefan (1835-1893) and **Ludwig Boltzmann (1844-1906)**

Heated bodies Radiate - Stefan-Boltzmann Law

Radiation from blackbody proportional to T^4.

$$P = e\sigma A T^4$$

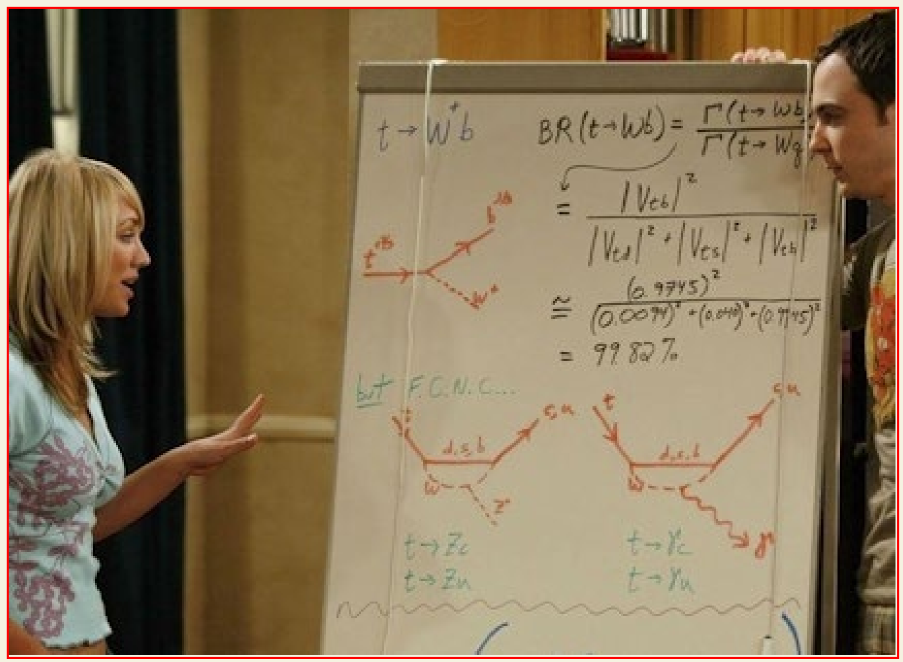
Maxwell-Boltzmann Statistical Mechanics – ***Bah Humbug!***

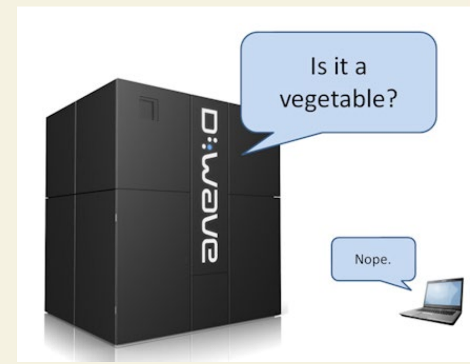


$$H\left|\psi\right\rangle = i\hbar\frac{\partial}{\partial t}\left|\psi\right\rangle$$

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

This is not your grandfather's physics





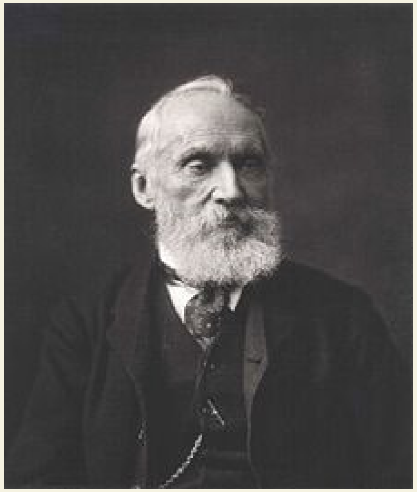
$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

$$\left[i\hbar\gamma^{\mu}\partial_{\mu} - mc\right]\psi = 0$$

Physics Revolutions

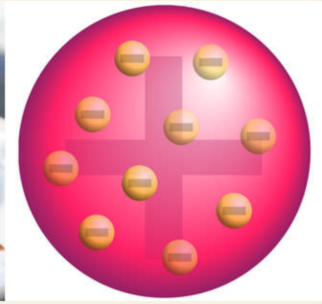
William Thomson, (1824 – 1907)
1st Baron Kelvin (**Lord Kelvin**)

"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement." - 1900

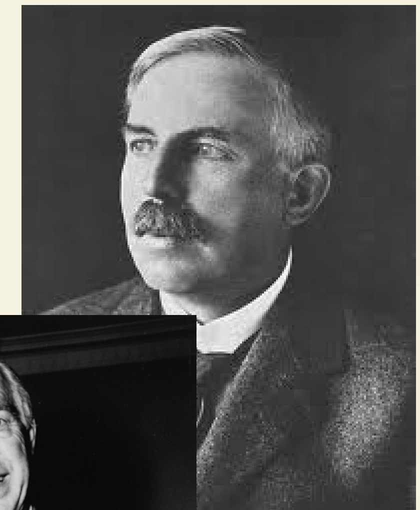


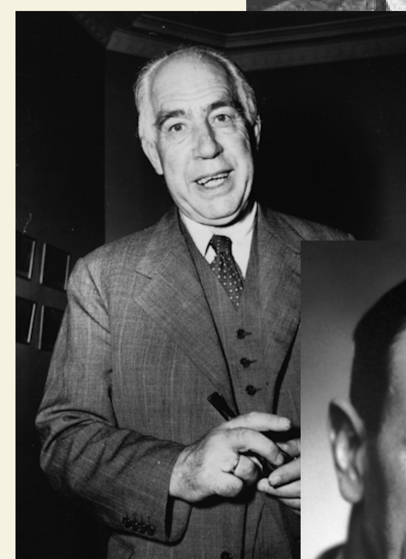
1895 **Wilhelm Röntgen** discovers X-rays. NP 1901
1896 **Henri Becquerel** discovers radioactivity NP 1903
1898 **Marie and Pierre Curie** separate radioactive elements NP 1903
1897 **Joseph (J.J.) Thomson** measures electron, NP 1906

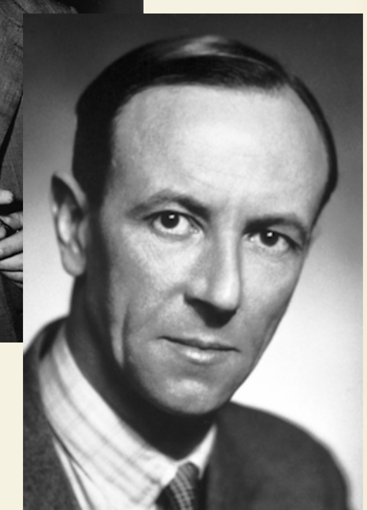
"plum-pudding" model of atom"



Radioactivity and the Atom







1897 - J.J. Thomson discovers the electron [NP 1906].

1898 - Marie and Pierre Curie discover the first radioactive elements: radium and polonium [NP 1903].

1899 - Ernest Rutherford divided radiation into alpha and beta rays [NP 1908].

1900 - Pierre Curie observes gamma rays.

1911 - Ernest Rutherford discovers the atomic nucleus

1913 - Niels Bohr introduces the first atomic model, [NP 1922] the mini solar system.

1913 - Hans Geiger invents counter for measuring radioactivity.

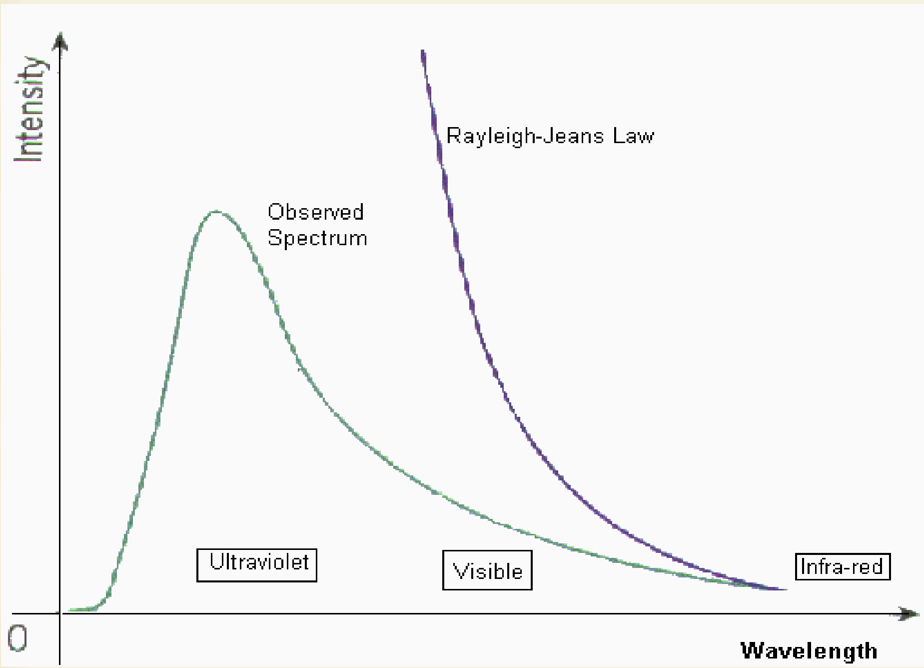
1920 - Ernest Rutherford discovered and named the proton.

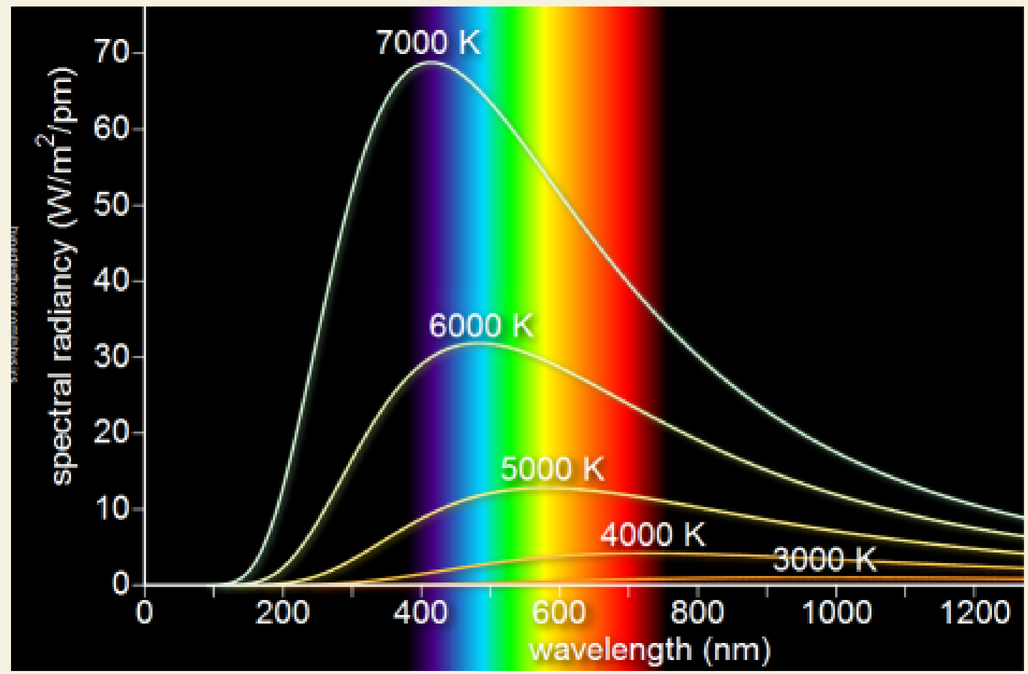
1932 - James Chadwick discovers the neutron. [NP 1935]

Blackbody Spectrum

Blackbody - a theoretical object that absorbs 100% of the radiation that hits it.

Wien's Law (1896) NP 1911 and **Rayleigh** NP 1904 **- Jeans Law** (1900)





Ultraviolet Catastrophe "... when you turn on your toaster, you are instantly fried by a massive gamma ray burst, since your little blackbody toaster should emit infinite energy at the shortest wavelengths."

Quantum Theory

Max Planck NP 1918

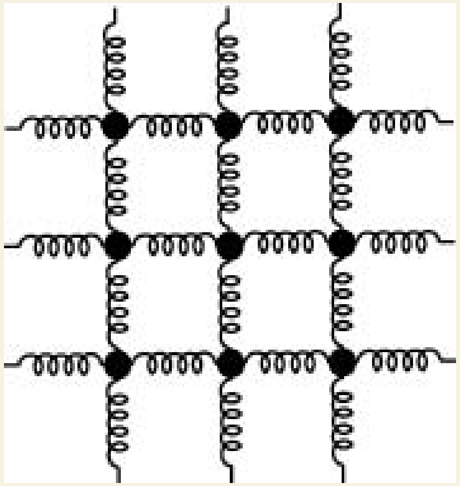
(Karl Ernst Ludwig Max Planck 1858-1947)

oscillators can only vibrate at discrete frequencies:

$$E_n = n(hf),\ n = 1,2,3 \ldots.$$

Thus, the energy difference

$$\Delta E = hf,$$



where Planck's constant is given by

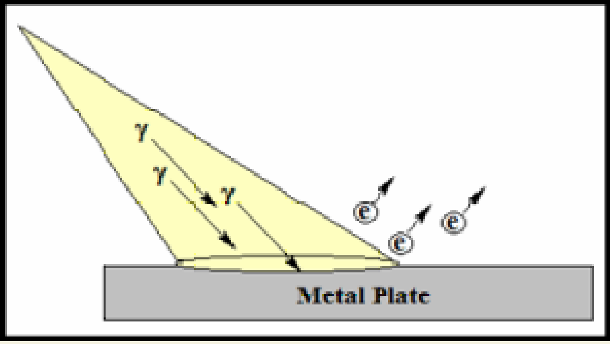
$$h = 6.63 \times 10^{-34}\ Js$$

Albert Einstein - 1905

Photoelectric Effect

Light can cause currents

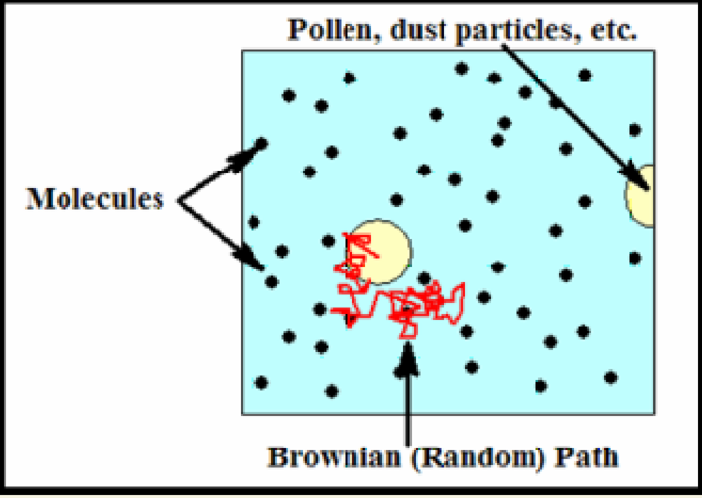
- **Electrons can be ejected from irradiated metal plates.**
- **Light can be act like either particles (quanta) or waves.**
- **Extended Planck's ideas of energy quantization.**
- **Lead to explanation of electromagnetic spectra,**
- **Lead to the development of lasers, transistors and other applications.**



Brownian Motion

the random movement of particles suspended in a fluid

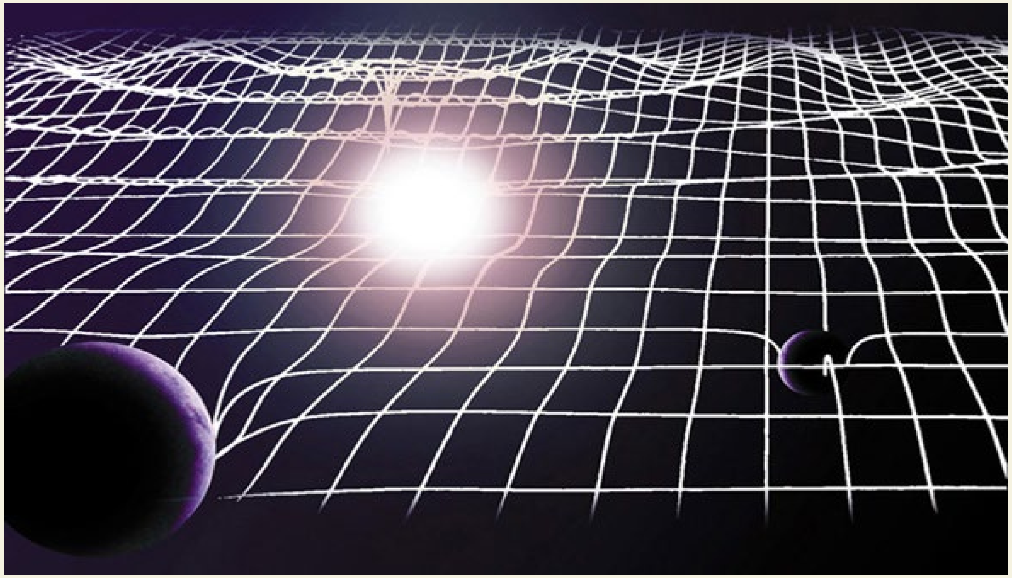
- **Explained the observations credited to Robert Brown, 1827**
- **Predicted molecular motion and size through the effects of collisions with larger particles**
- **Einstein's work lead to an acceptance of molecular theory**



Paradigm Shifts

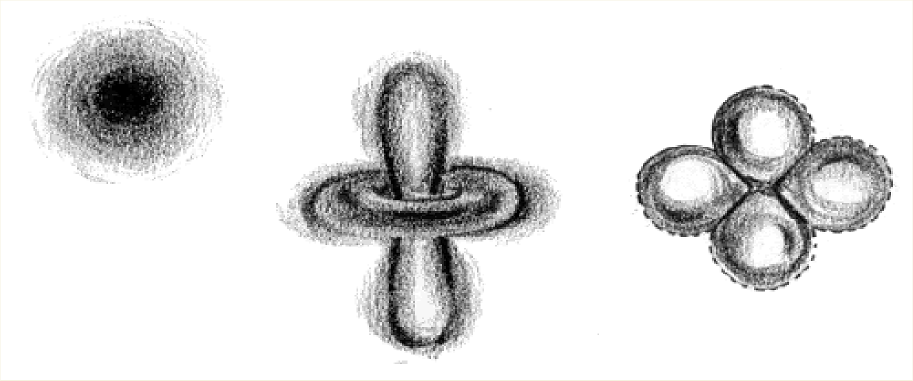
Relativity

Space and Time not absolute, not Euclidean



Quantum Mechanics

Loss of Determinism



http://www.zamandayolculuk.com/cetinbal/AE/Deformation.jpg

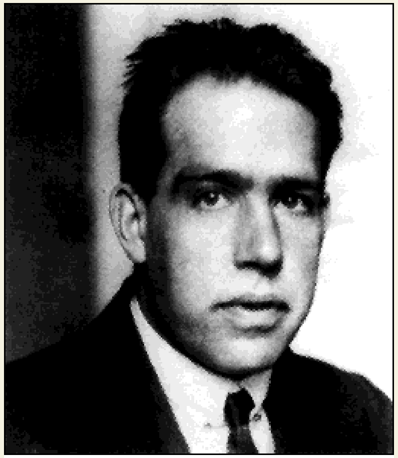
Bohr's Atom - 1913

Niels Bohr (1885-1962)

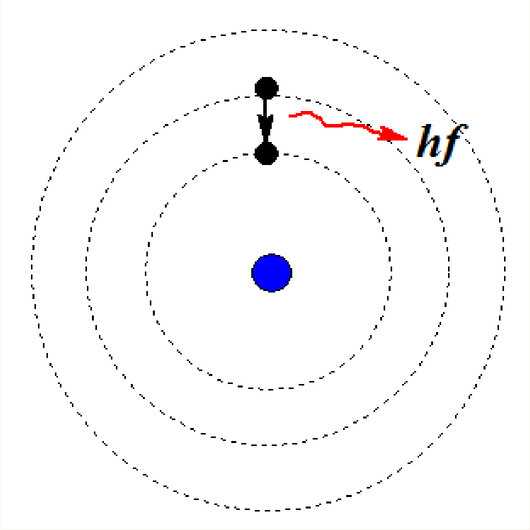
Accelerating electrons radiate at specific energies.

Are atoms stable?

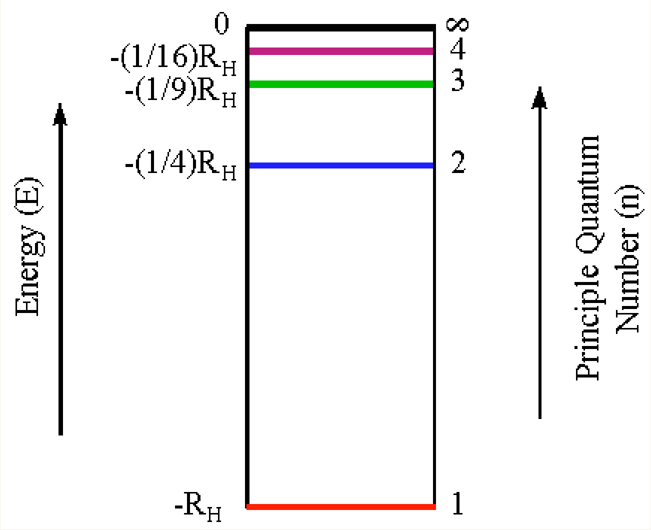
Assume angular momentum is quantized.



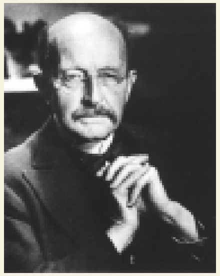
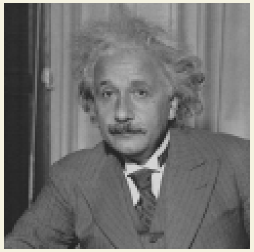
Neils Bohr



$$E_n = R_H\left(\frac{1}{m^2} - \frac{1}{n^2}\right)$$

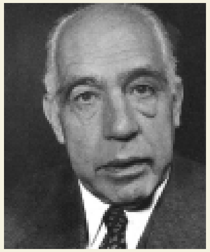


Early History - Quantum Mechanics

1900 - Planck Explains Blackbody Radiation [NP 1906]

1905 - Einstein - the Photoelectric Effect, Photons [NP 1921]



1913 - The Bohr Model for Hydrogen [NP 1922]

1916 - Confirmation of photon, Millikan [NP 1923]

1922 – Stern-Gerlach Experiment [NP 1943]

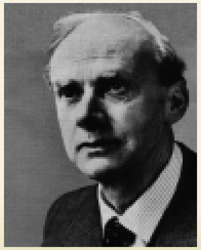

1923 - Compton [NP 1927] Effect – X-Ray Scattering

1924 – de Broglie [NP 1929] - Particles Behave Like Waves

1925 - Matrix Mechanics – Heisenberg [NP 1932], Born [NP 1954], Jordan
- Pauli Principle [NP 1935]

1926 - Wave Mechanics - Schrödinger [NP 1933]

1927 - The Uncertainty Principle – Heisenberg
- Davisson [NP 1937] –Germer, Thomson [NP 1937] - Verified de Broglie's idea



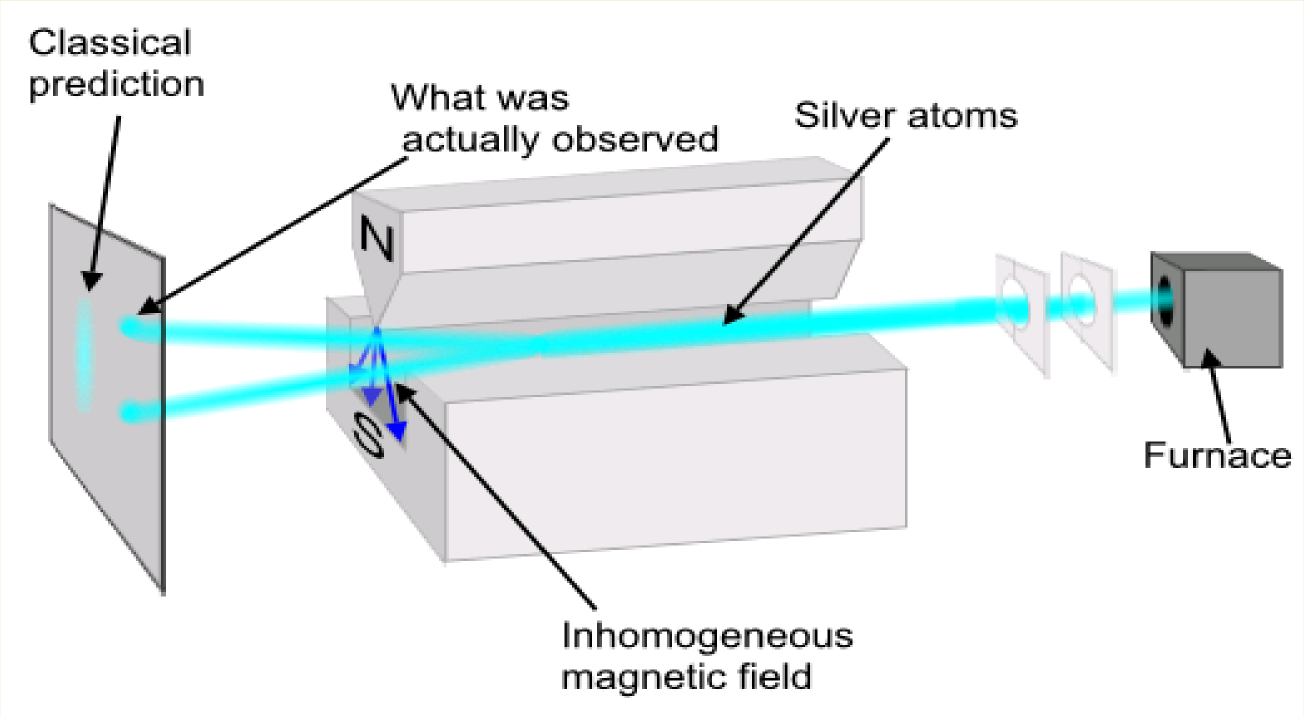
1928 - Relativistic Quantum Mechanics - Dirac [NP 1933]

Stern-Gerlach Experiment - 1922

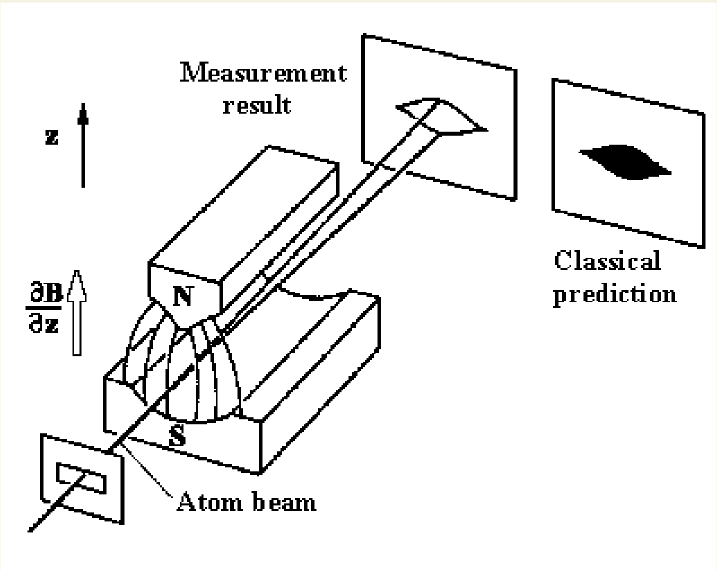
Otto Stern (1888-1969)

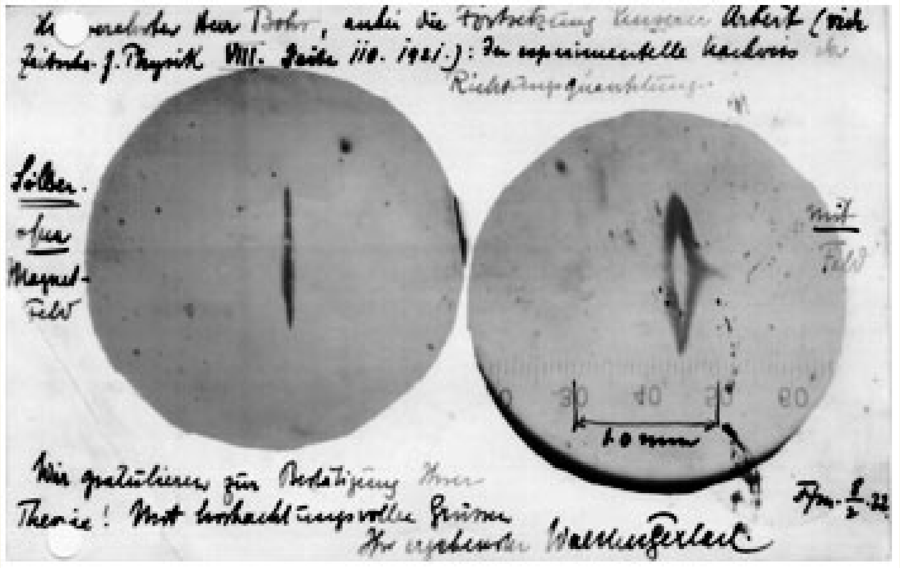
Walther Gerlach (1889-1979) – Was it the cigar?

Ag atoms sent through inhomogenous magnetic field.



Stern-Gerlach Results





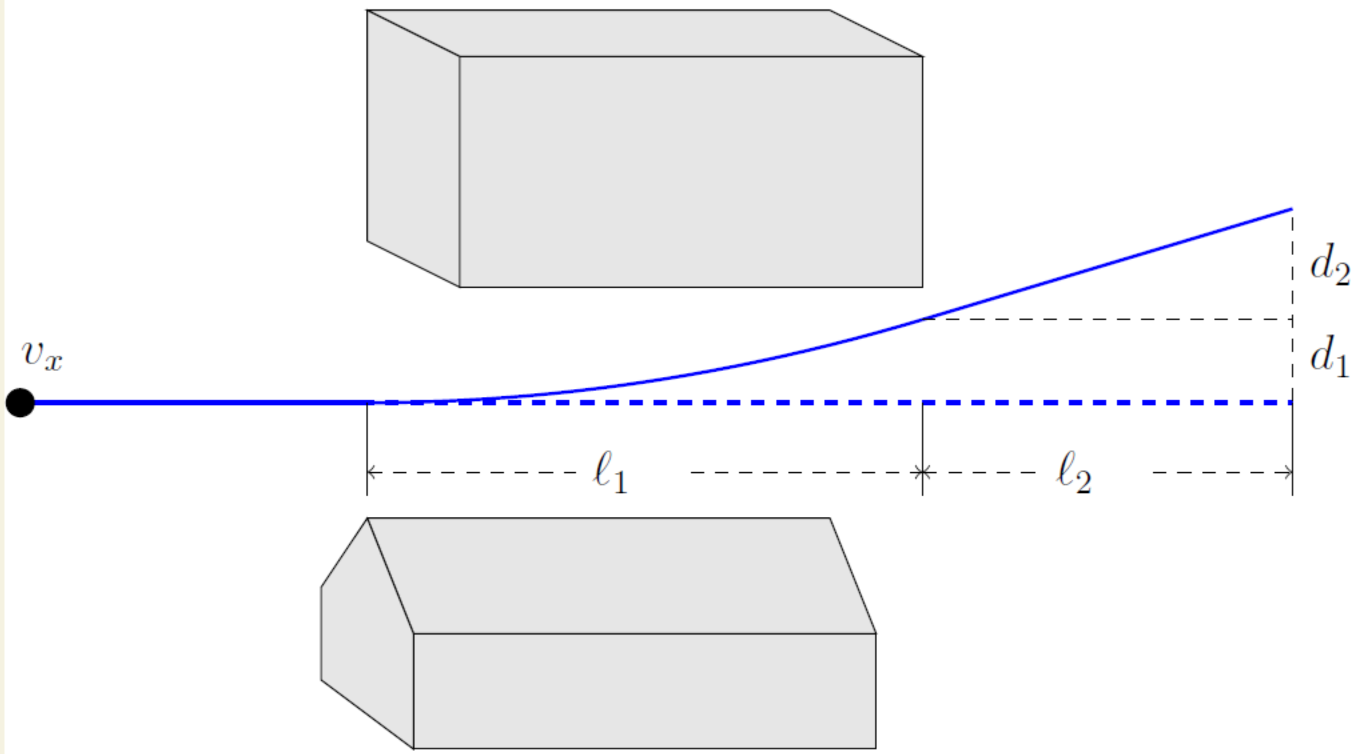
Test of classical vs quantum theory of angular momentum (**L**).

L = 0 or *L = 1*   – No splitting for *L = 0*?

Uhlenbeck and Goldsmit (1925,1926) proposed intrinsic spin.
  - to explain the anomalous Zeeman effect,
          (the splitting of spectral lines in a magnetic field).

Stern-Gerlach Particle Path – Problem 1

$$a_z = \frac{\mu_B}{M}\frac{\partial B_z}{\partial z} \qquad \tfrac{1}{2}Mv_x^2 = 2k_BT$$



$$x = v_x t_1 = \ell_1 \qquad x = v_x t_2 = \ell_2$$

$$z = \tfrac{1}{2}a_z t_1^2 = d_1 \qquad z = v_z t_2 = d_2$$

Stern-Gerlach Thought Experiments

1

2

3