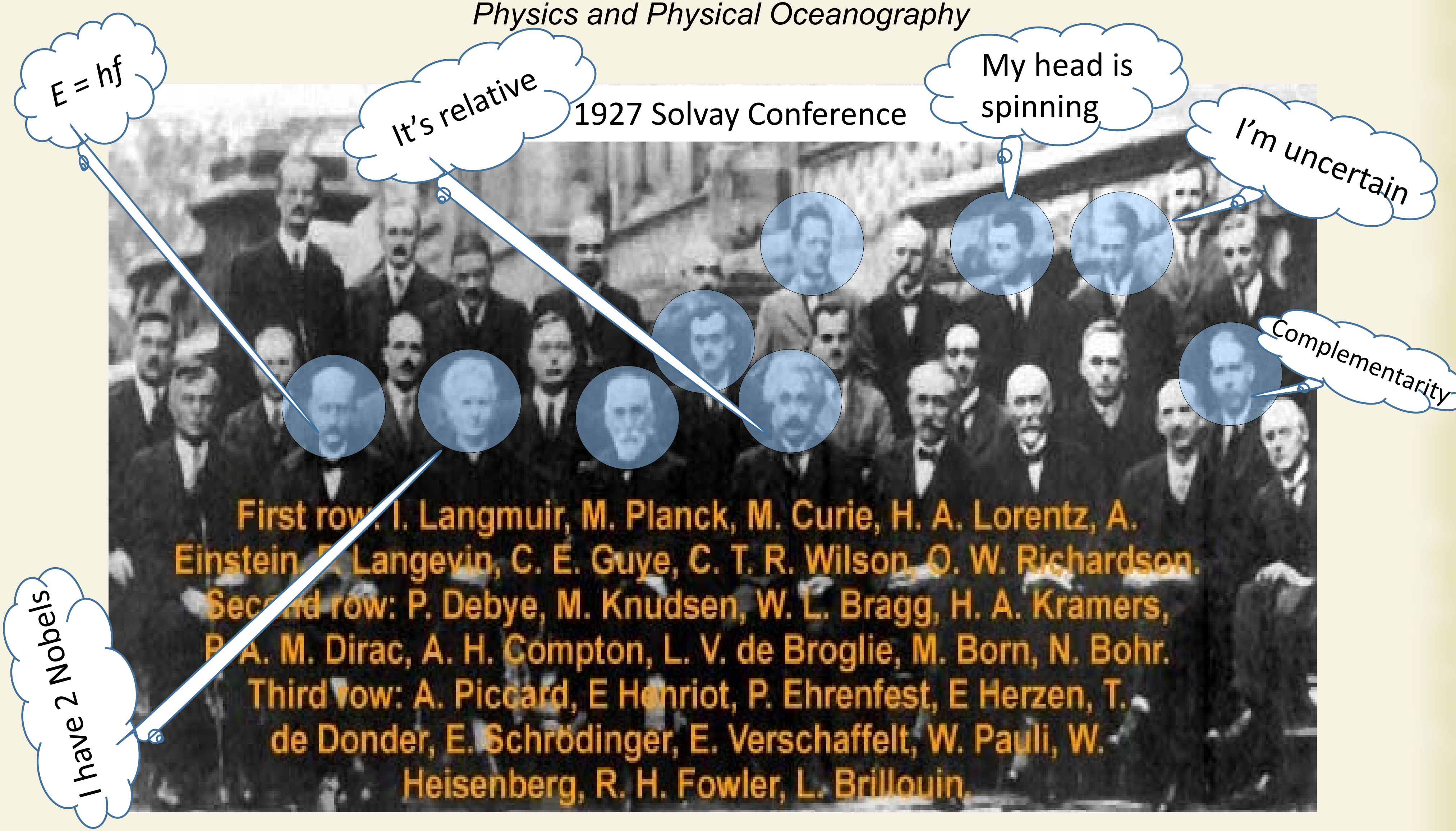
Introduction to Quantum Theory

Dr. Russell Herman
Physics and Physical Oceanography

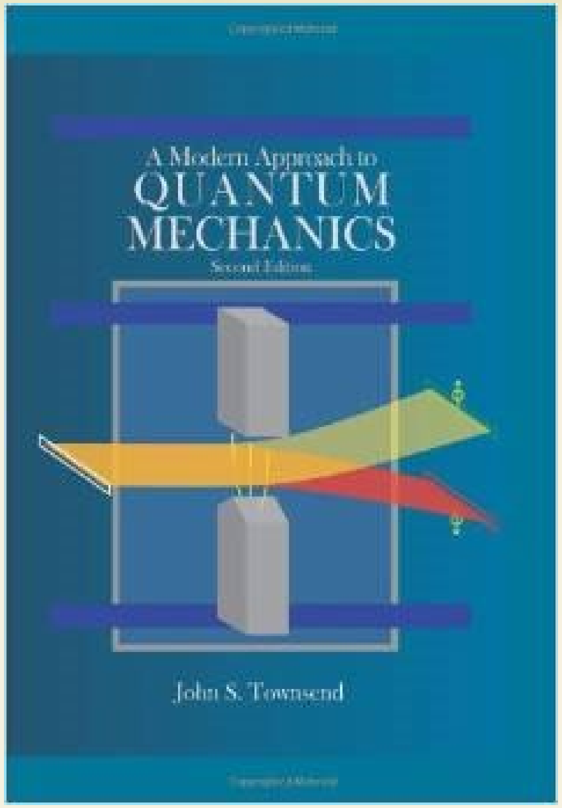


Syllabus

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

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

- Office Hours: MTWRF, 9:30-10:30 AM
  Sartarelli Hall 2007J



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

Artificial Intelligence Use Policy

Core Principles
Learning to use AI responsibly is an essential skill. You are encouraged to explore AI tools for brainstorming, idea generation, and research assistance while maintaining academic integrity and developing critical thinking skills.

Permitted Uses
- Small assignments: AI may be used for brainstorming, drafting, and iterative improvement
- Research projects: AI may assist with literature review, organizing ideas, and refining arguments
- All uses: Must be properly disclosed and attributed

Requirements and Responsibilities

Attribution: All AI use must be acknowledged at the end of your submission. Include:
- Which AI tool(s) you used and how
- Key prompts that generated useful content
- A brief description of how AI-generated material was incorporated or modified

Verification: You are responsible for fact-checking all AI outputs. AI systems frequently generate inaccurate information and fake citations. Cross-reference all claims with reliable sources.

Quality Control: Effective AI use requires skillful prompting and critical evaluation. Minimum-effort prompts produce low-quality results that may harm your work.

Prohibited Practices
- Submitting AI-generated work as your own without attribution
- Using AI-generated citations without verification
- Relying on AI for factual claims without independent confirmation

Academic Integrity
Failure to properly attribute AI use violates university honor code policies. While AI can enhance your work, it cannot replace your critical thinking, analysis, and original contribution to the assignment.

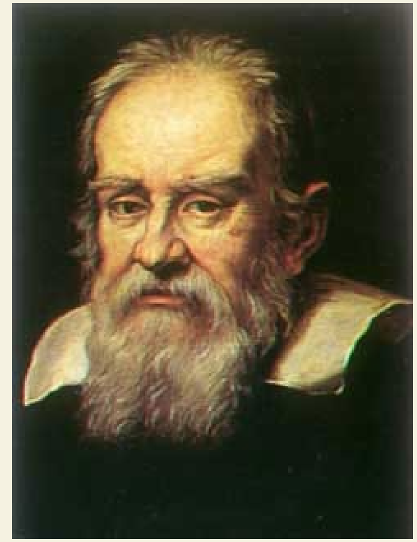
Time for Some Background

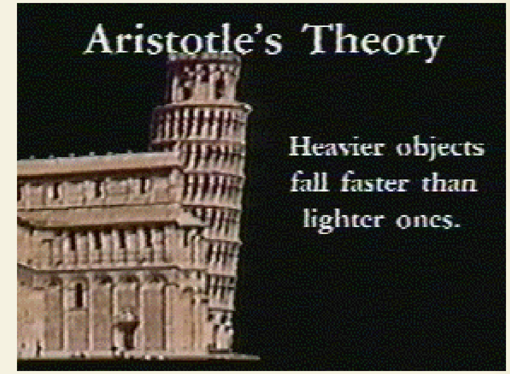
The Rise of Classical Physics

The Emergence of Physics - 1609

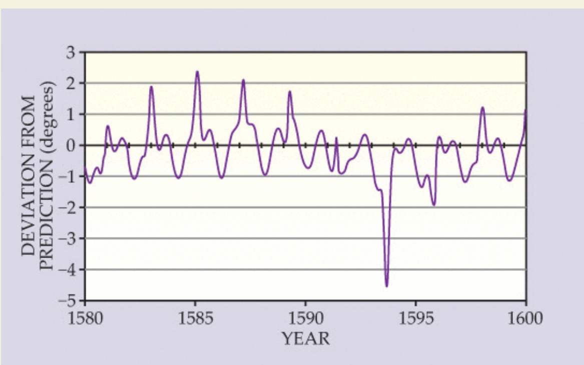
Nicolaus Copernicus (1773-1543)

Galileo Galilei (1564-1642)

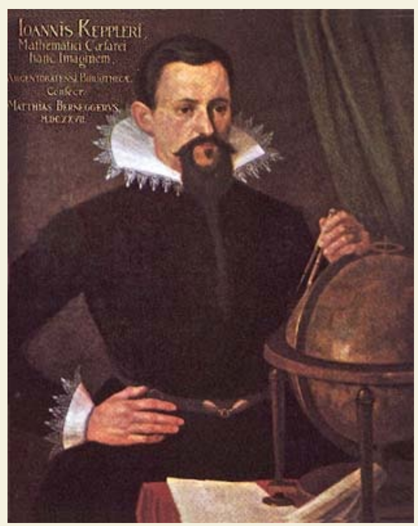


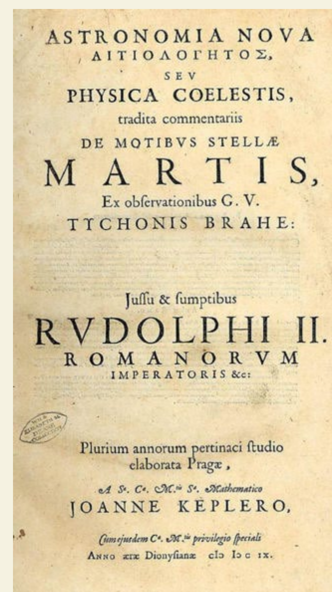


Tycho Brahe (1546-1601)



Johannes Kepler (1571-1630)





ASTRONOMIA NOVA
ΑΙΤΙΟΛΟΓΗΤΟΣ,
SEV
PHYSICA COELESTIS,
tradita commentariis
DE MOTIBVS STELLÆ
MARTIS,
Ex obſervationibus G. V.
TYCHONIS BRAHE:

Juſſu & ſumptibus
RVDOLPHI II.
ROMANORVM
IMPERATORIS &c:

Plurium annorum pertinaci ſtudio elaborata Pragæ,

JOANNE KEPLERO,

Anno æræ Dionyſianæ clɔ Iɔ c ix.

<u>The great Martian catastrophe and how Kepler fixed it</u>

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 (fluxions)

... Space and time are 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 $F = ma$

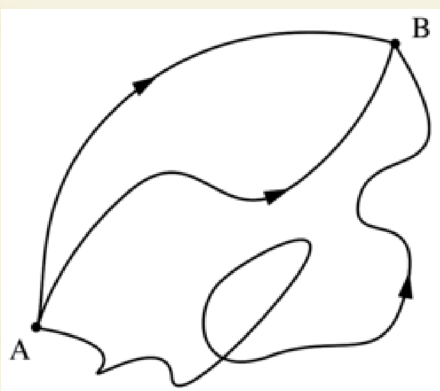
From Classical Dynamics

Euler (1707-1783) Variational Calculus

D'Alembert (1717-1783) Virtual Work

Lagrange (1736-1813) Lagrangian Mechanics

Hamilton (1805-1865) Hamiltonian Mechanics



Principles

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

Define the action

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

Require: $\delta S = 0.$

Then, $[F = ma]$

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

Optics	Vis viva	Action					Path Integrals
Fermat –	Leibniz vs	Maupertuis –	Euler –	Lagrange –	Hamilton –	..... -	Feynman
1662	1686	1744	1744	1788	1834		1948

Hamilton's Formulation

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

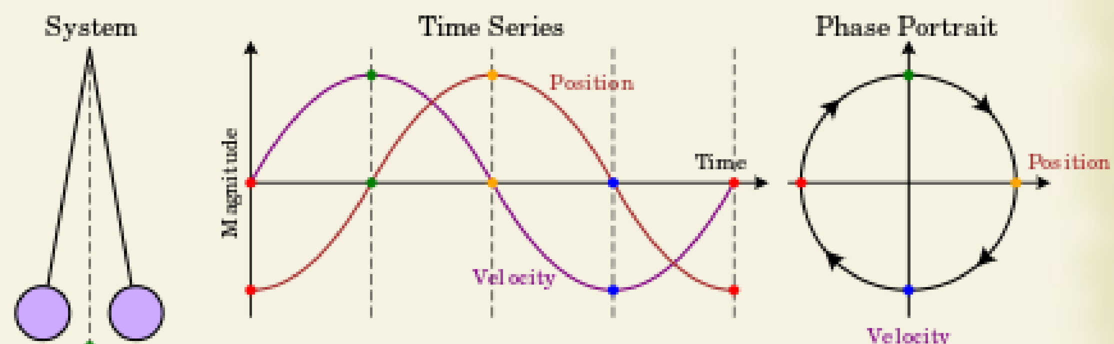
Initial (q, p) + 2nd Law => Motion for all t

Ex: Free particle, $p = \text{const}$

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

Energy Conservation $E = const$

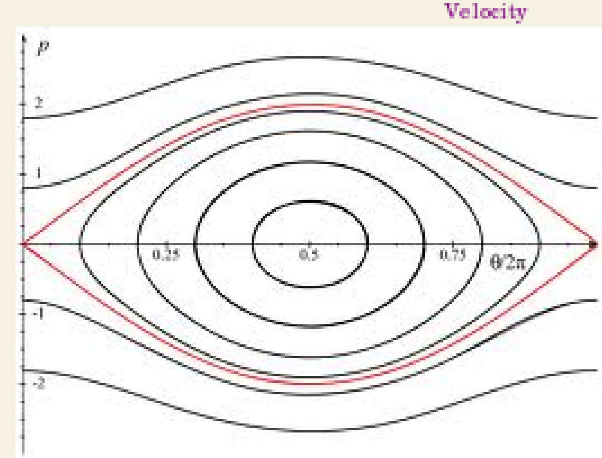
Hamiltonian $H(p,q) = T(p) + V(q)$



Hamilton's Eqns <=> Newton's Laws

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

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



Poisson: For F(p,q), $$\frac{d}{dt}F(p,q) = \frac{\partial F}{\partial q}\frac{\partial H}{\partial p} - \frac{\partial F}{\partial p}\frac{\partial H}{\partial q} = \{F,H\}$$

Electricity and Magnetism

Magnetism (Lode stones, Compasses)

Electricity (static, lightning)

William Gilbert (1544-1603)
(amber, elecktron, magnetic + electric forces different)

Thomas Browne (1605-1682) ("electricity")

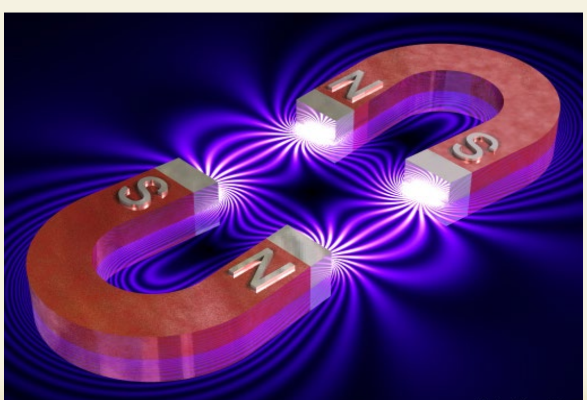
Benjamin Franklin (1706-1790) ("+/- electricity")

Henry Cavendish (1731-1810)

Charles-Augustin de Coulomb (1736-1806)

Luigi Galvani (1737-1798) (animal electricity)

Alessandro Volta (1745-1827) (electrochemical cell)



Electromagnetism

Hans Oersted (1777-1851)

1820 current deflects compass needles, made Al

André-Marie Ampère, (1775 - 1836)

“electrodynamics,” current carrying wires attract, telegraph

Georg Simon Ohm (1789-1854)

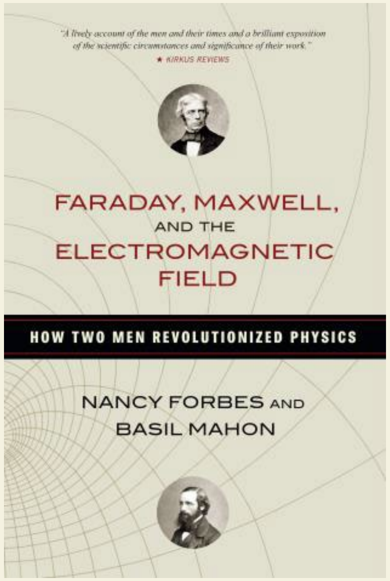
Ohm’s Law - 1827

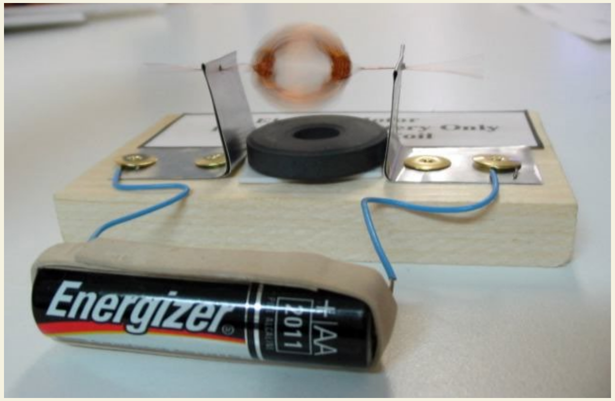
Joseph Henry (1797-1878)

electromagnetic induction, first motor, relays

Michael Faraday (1791-1867)

electrolysis, motors, induction coils, ...
Introduced concept of a field.

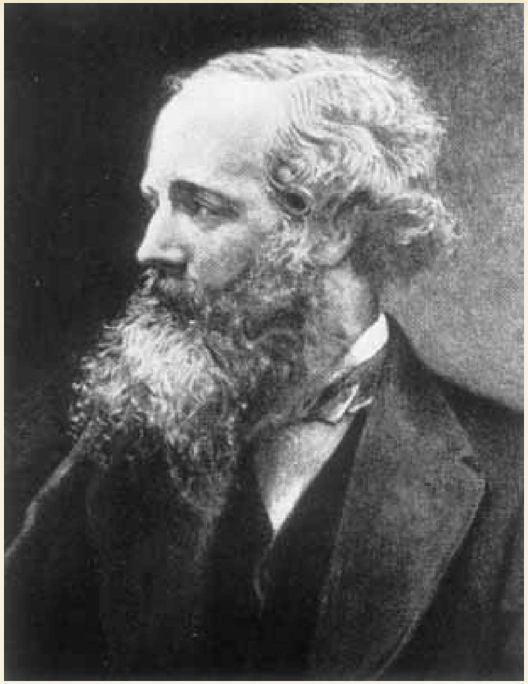




http://hilaroad.com/camp/projects/magnet.html

From experiment to theory ...

Electromagnetic Waves

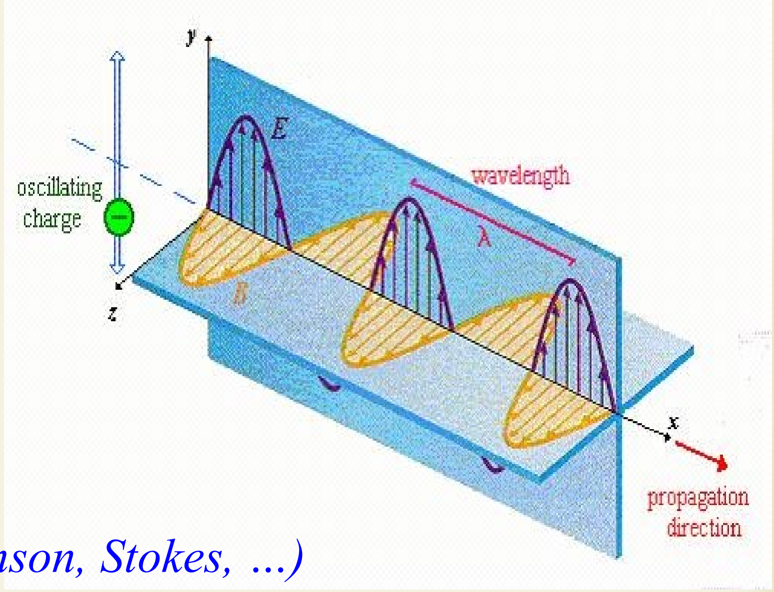


James Clerk Maxwell (1831-1879)

- Theory of electromagnetism – 1865.

  1873, Maxwell also used the quaternions of Hamilton (1843),
  1880s, Heaviside reduced the 20 PDEs –12 to 4,
  using symbolic vector calculus
  [independent of Josiah Gibbs, *Vector Analysis*, (1881-1884)]
  1890, Hertz presented other forms

- Predicted the electromagnetic waves - 1862.
  Electromagnetic waves travel: c = 299,792,458 m/s = 186,000 mi/s



The Maxwellians

George Francis FitzGerald (1851–1901),
Oliver Lodge (1851–1940) and Oliver Heaviside (1850)–1925)

Heinrich Hertz (1857-1894)

- Sent the first radio waves – 1888.
- Marconi (1874-1937), practical radio waves – 1897

What is the medium? - *Luminiferous Aether (supported by Thomson, Stokes, ...)*

Faraday, Thomson, and Maxwell: Lines of Force in the Ether – MIT OpenCourseWare lecture

Maxwell's Equations

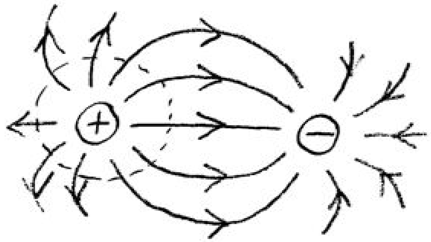
Not SI units!

JAMES CLERK MAXWELL'S EQUATIONS

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

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

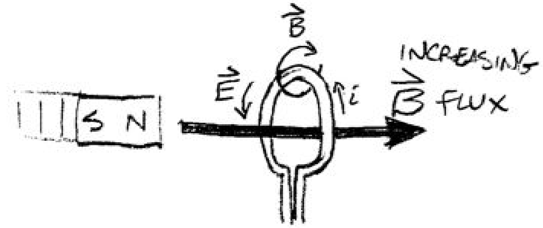
$\vec{E}$ DIVERGES OUT FROM POSITIVE CHARGES AND IN TOWARD NEGATIVE CHARGES. THE TOTAL FLUX OF $\vec{E}$ THROUGH ANY CLOSED SURFACE IS PROPORTIONAL TO THE CHARGE INSIDE.



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

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

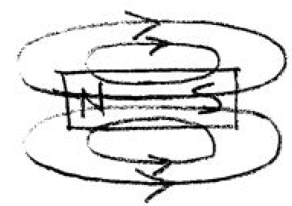
$\vec{E}$ CURLS AROUND CHANGING $\vec{B}$ FIELDS (FARADAY'S LAW) IN A DIRECTION THAT WOULD MAKE A CURRENT THAT WOULD PRODUCE A $\vec{B}$ FIELD TO OPPOSE THE CHANGE IN $\vec{B}$ FLUX (LENZ'S LAW).



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

DIVERGENCE OF $\vec{B}$

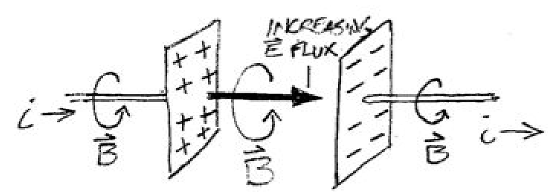
$\vec{B}$ NEVER DIVERGES. IT JUST LOOPS AROUND ON ITSELF.



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

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; $(\mu_0/\epsilon_0)^{1/2} \approx 377\Omega$

$$e^2 \text{ (Gaussian)} \rightarrow \frac{e^2}{4\pi\varepsilon_0} \text{ (SI)}$$

$$F_{\text{Coulomb}} = \frac{q_1 q_2}{r^2}$$

From ChatGPT 5

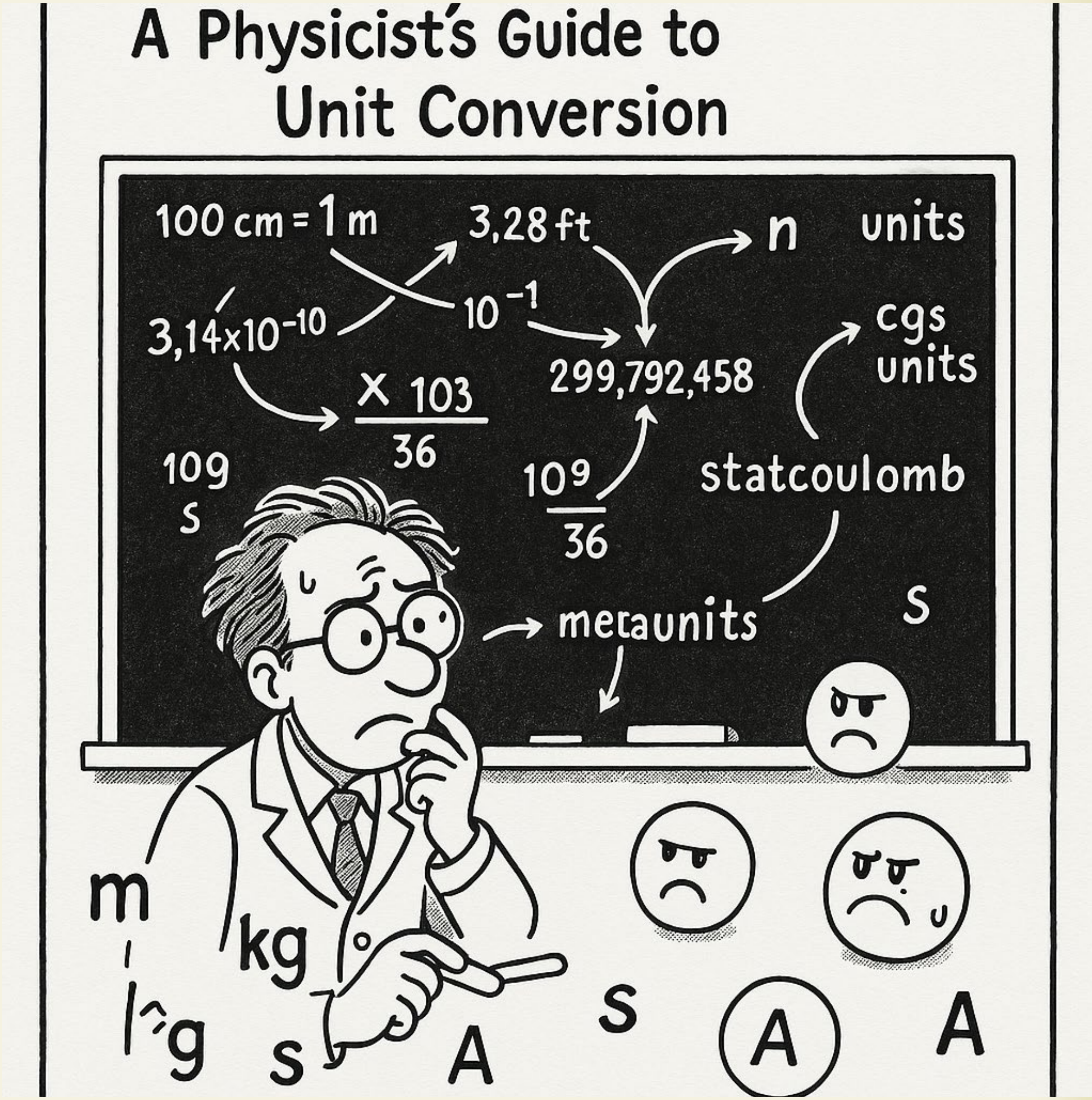
Prompt: Can you draw a cartoon based on the following?

A scientist is shown with a complicated diagram of arrows and equations, trying to convert units between the two systems.

They might be surrounded by frustrated-looking unit symbols, some in SI (m, kg, s, A) and some in Gaussian (cm, g, s, statcoulomb).

The caption could be something like: "Lost in Translation: A Physicist's Guide to Unit Conversion".

8/12/25



New Questions

- Waves – What is the medium?
  Michelson-Morley (1887) - could not detect it.
- Spectroscopy – Why the spectral lines?
- Blackbody Spectrum – Describe the dependence on λ.
- Lorentz Invariance – Explain speed of light in moving media.

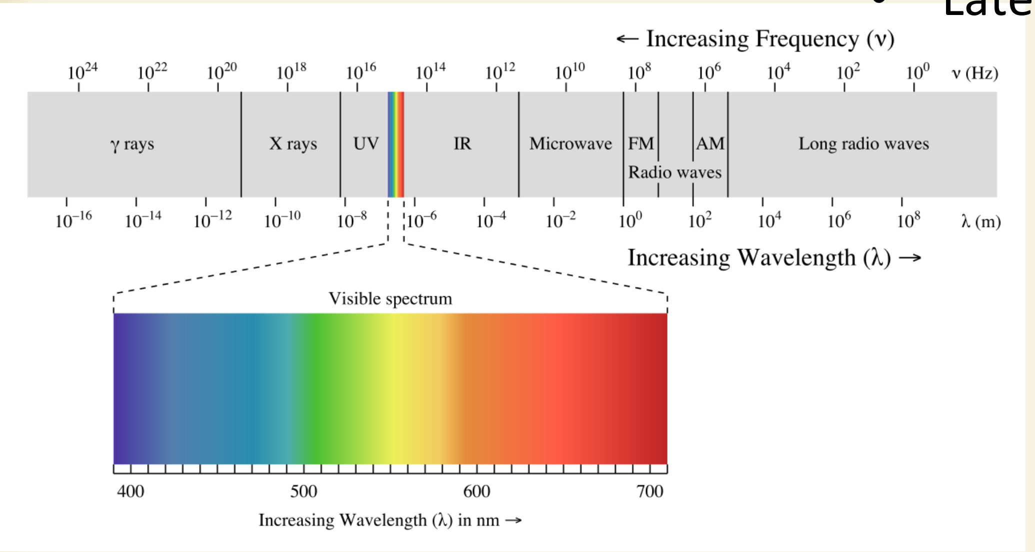
These led to Revolutions in Physics in the 1900s!

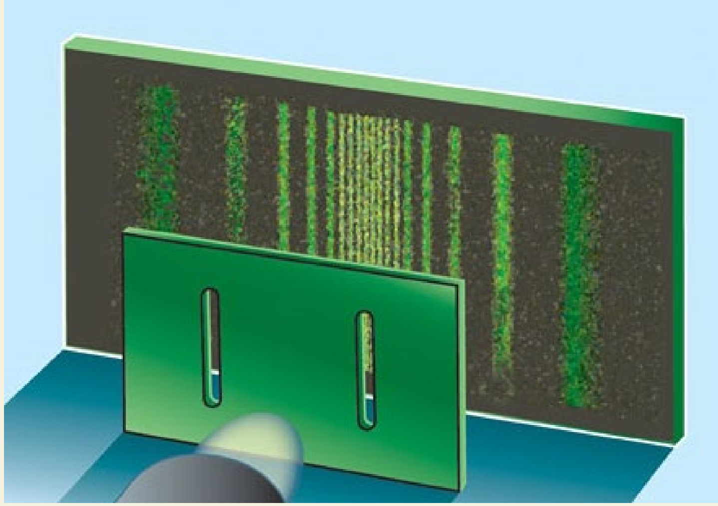
WAVES

What are waves?

- **Characteristics**
  - Wavelength, Frequency, Wavespeed
- **Behavior**
  - Superposition, Interference. Diffraction
  - Thomas Young, 1801, diffraction
  - 1817, the Académie des Sciences: diffraction would be the topic for the biannual physics *Grand Prix.* – proposed by corpuscular theorists.
  - Augustin-Jean Fresnel used Huygen's Principle, 1678.
  - Later – Airy, Stokes, Helmholtz, Kirchoff , and others.

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

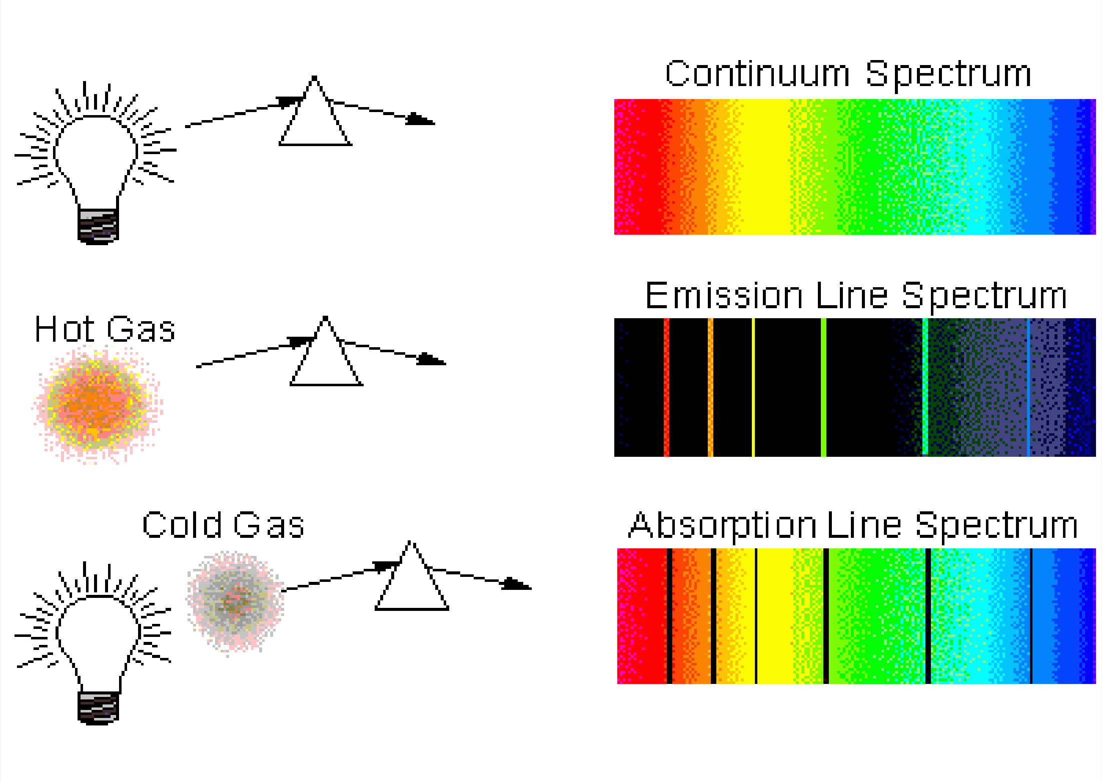




Spectroscopy

Robert Bunsen and Gustav Kirchhoff
developed the spectroscope, 1859.

Ionized gas gives off radiation



Johann Balmer 1885

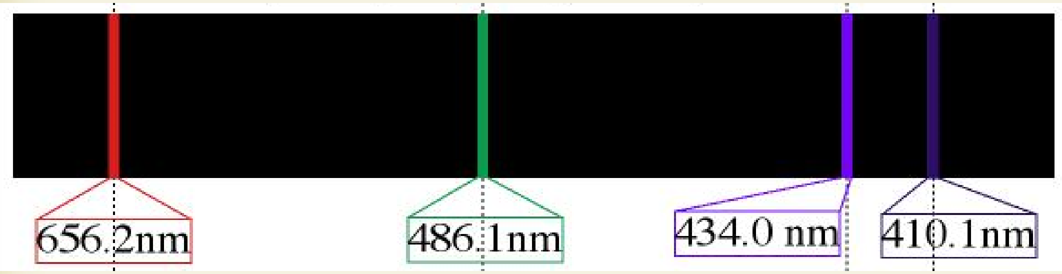
Spectral Lines: Hydrogen
410, 434, 486, 656 nm

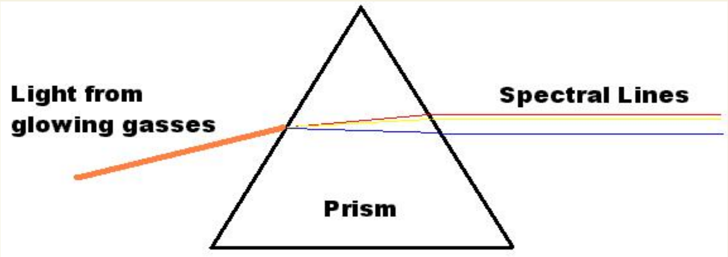
Derived Empirical Formula:

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

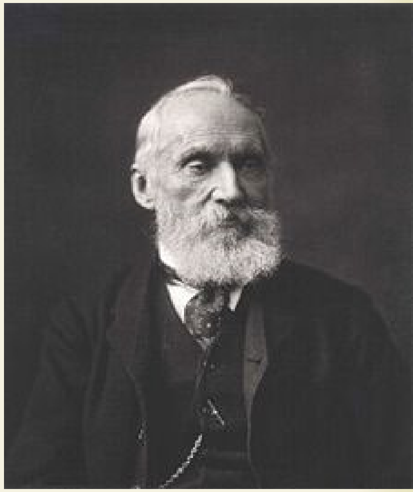
Predicted 5th-7th lines

Lyman Series (1906-1914), ultraviolet
Paschen Series (1908), infrared





Laws of Thermodynamics



Engine: Carnot (1824), Clapeyron – heat converted to work
James Joule (1843) Mechanical Equivalent of Heat
Second law, Clausius, Thomson – "thermo-dynamics" -1850s

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)

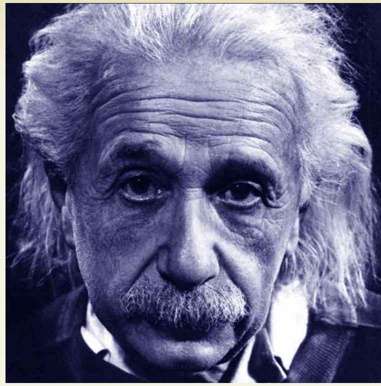
Joseph Stefan (1835-1893) and **Ludwig Boltzmann (1844-1906)**

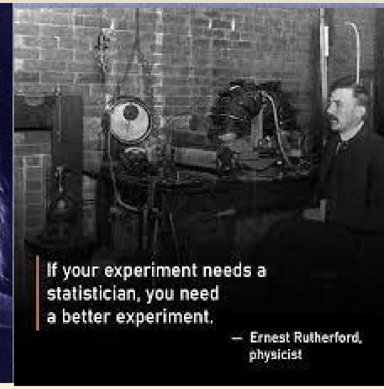
Heated bodies Radiate - Stefan-Boltzmann Law
Radiation from blackbody proportional to T^4.

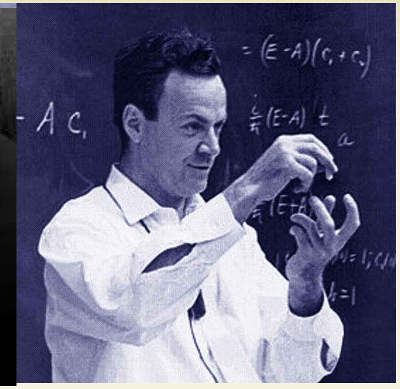
$$P = e\sigma A T^4$$

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

Energeticism (Helm, Ostwald) vs atomism (Boltzmann, Klein).



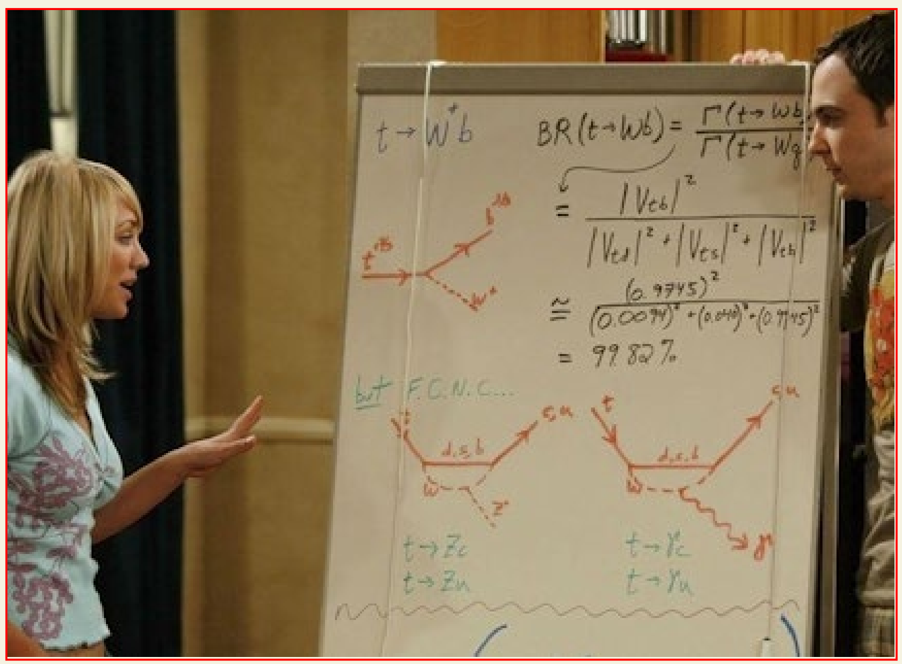


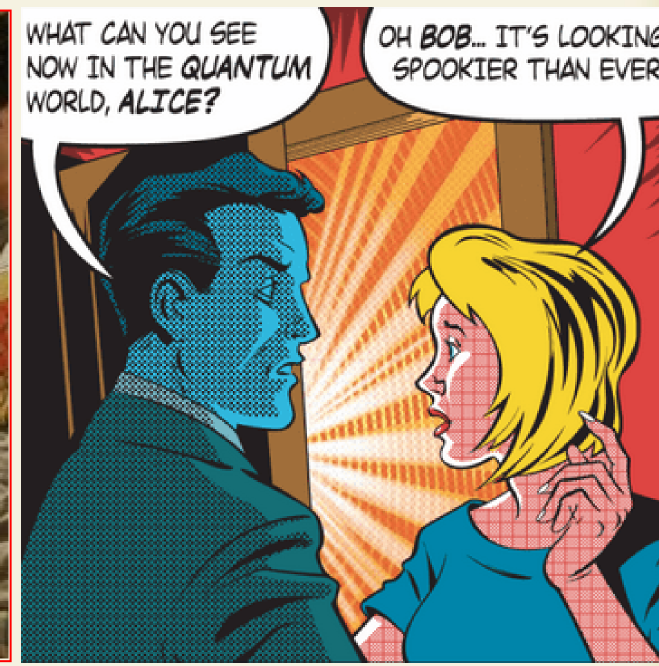


$$H\left|\psi\right\rangle = i\hbar\frac{\partial}{\partial t}\left|\psi\right\rangle$$

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

This is not your grandfather's physics



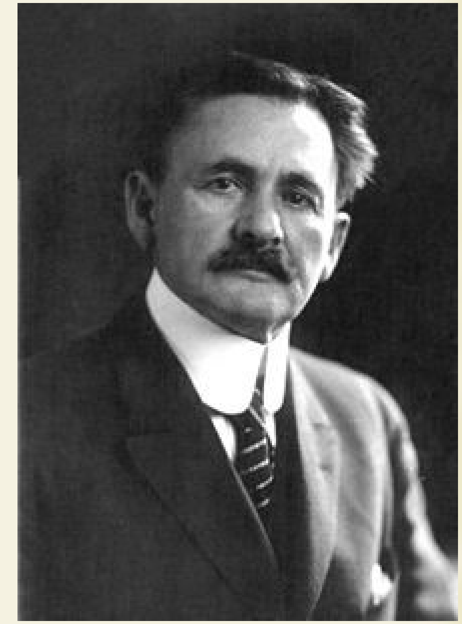


$$\left[i\hbar\gamma^{\mu}\partial_{\mu} - mc\right]\psi = 0$$

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

Physics Revolutions

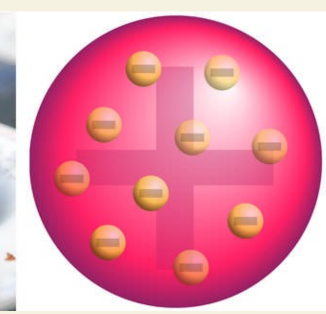
Albert A. Michelson, NP 1907 (1852 – 1931)



"it seems probable that most of the grand underlying principles have been firmly established and that further advances are to be sought chiefly in the rigorous application of these principles ." - 1894

1897 **Joseph (J.J.) Thomson** measures electron, NP 1906

"plum-pudding" model of atom"



Nobel Prizes covered five fields: physics, chemistry, physiology or medicine, literature, and peace. - Tuesday, 7 October, 11:45 CEST

Radioactivity and the Atom

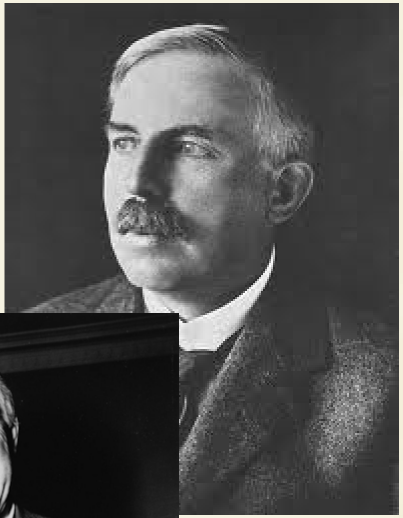
1892 - Cathode ray tube, Philipp Lenard [NP 1905]

1895 - Wilhelm Röntgen discovers X-rays. [NP 1901],

1896 - Henri Becquerel discovers radioactivity [NP 1903]

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

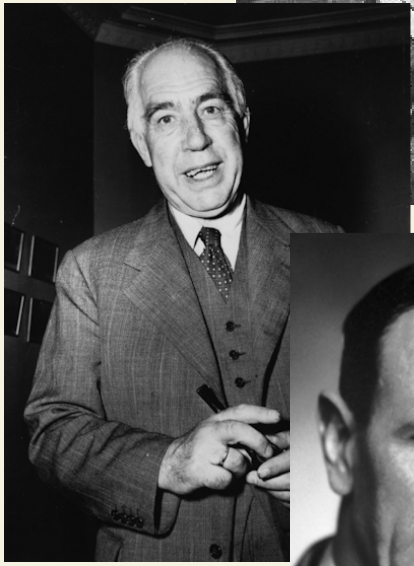
1898 - Marie and Pierre Curie discover the first radioactive elements: radium and polonium [NP 1903].



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.

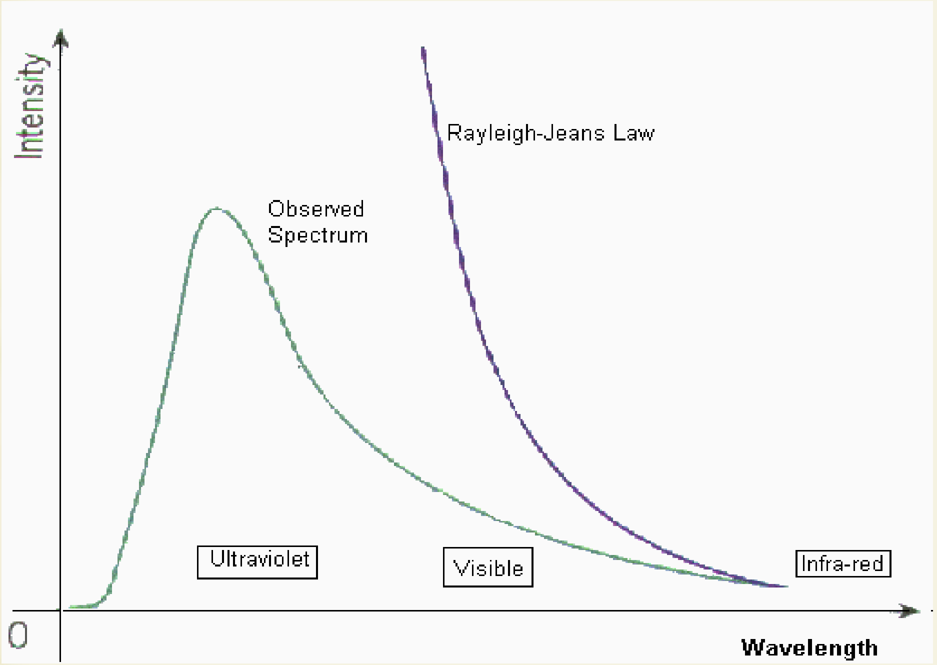
1920 - Ernest Rutherford discovered and named the proton.

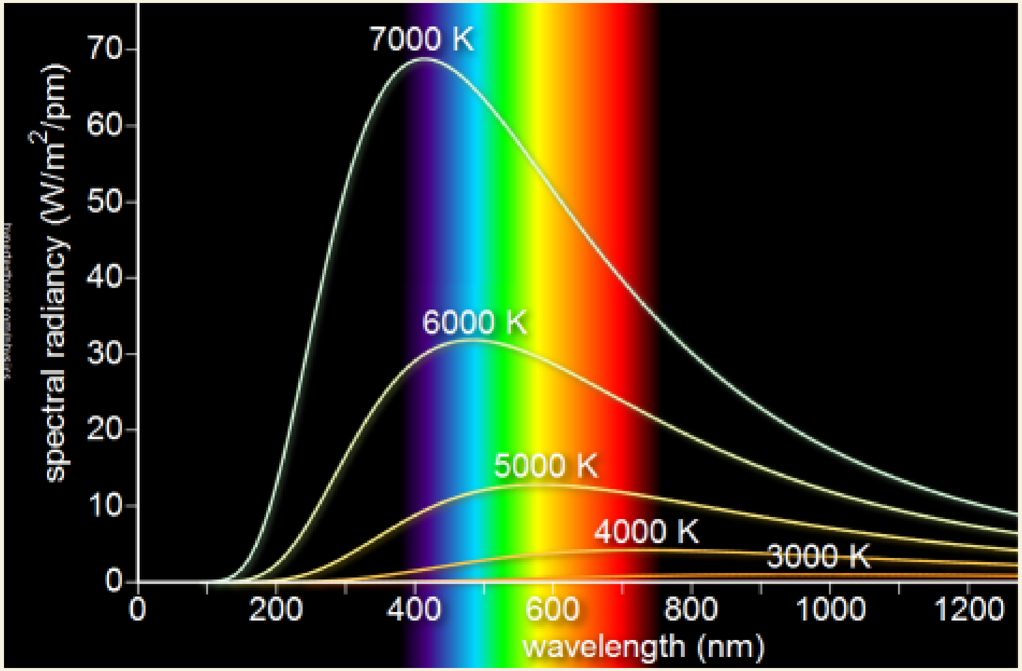
1932 - James Chadwick discovers the neutron. [NP 1935]

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** (1900/1905)





Ultraviolet (Rayleigh–Jeans) 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."

For fixed T, monochromatic energy density becomes infinite at infinitely small wavelengths!

Progress on BB Radiation

"**A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it.**" – Max Planck

Practical problem – efficient street lighting for Berlin in late 1800s

Planck not concerned with UV Catastrophe … didn't believe in atoms …

1859 Kirchoff challenge – derive blackbody formula
1889 Planck succeeds Kirchhoff
1896 Wien's distribution Law
1899 Planck derives Wien's Law using electrodynamics
1900 Measurement contradiction at low frequency
1900 Planck's formula (from the entropy of a resonator) matches experiment

See Boltzmann's grave!

$$S = k \log W$$

Quantum Theory

Max Planck NP 1918

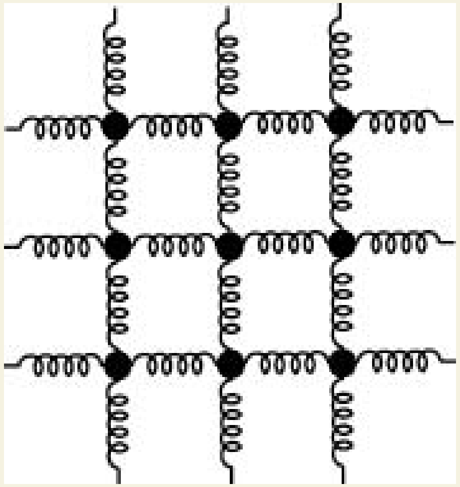
(Karl Ernst Ludwig Max Planck 1858-1947)

What makes hot solids glow different colors?

Nov. 1900 – he used Boltzmann's theory.

oscillators can only vibrate at discrete frequencies:

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



Thus, the energy difference

$$\Delta E = hf,$$

where Planck's constant is given by

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

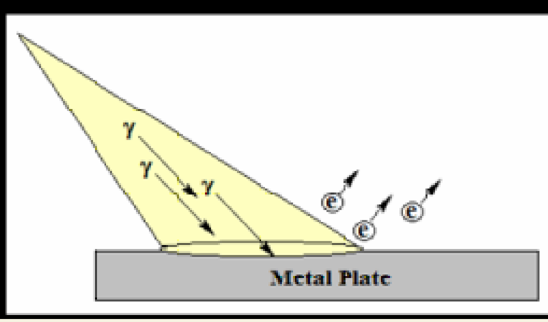
Albert Einstein - 1905

Received 18 March and published 9 June,

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.

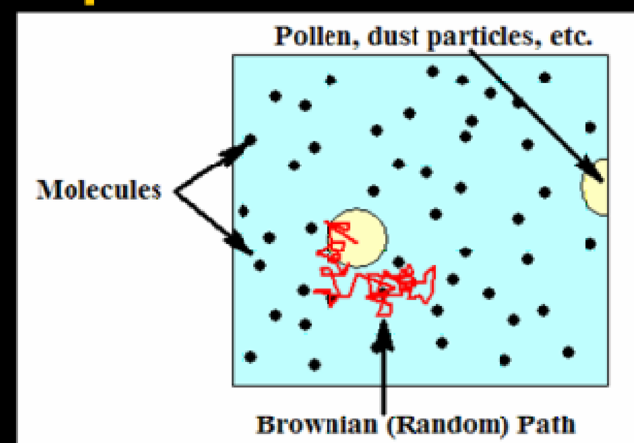


Received 11 May and published 18 July

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



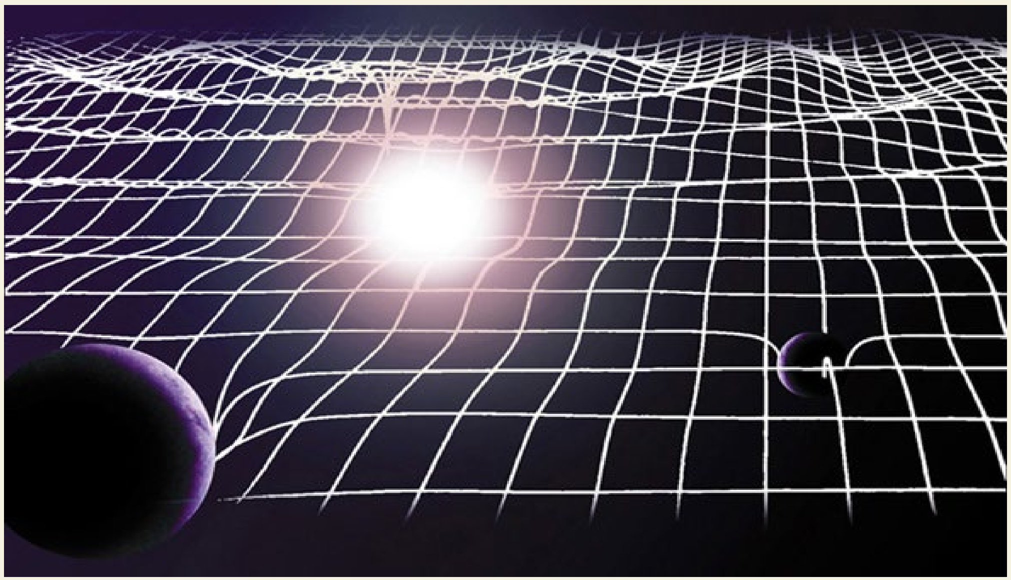
Special Relativity: received on 30 June and published 26 September

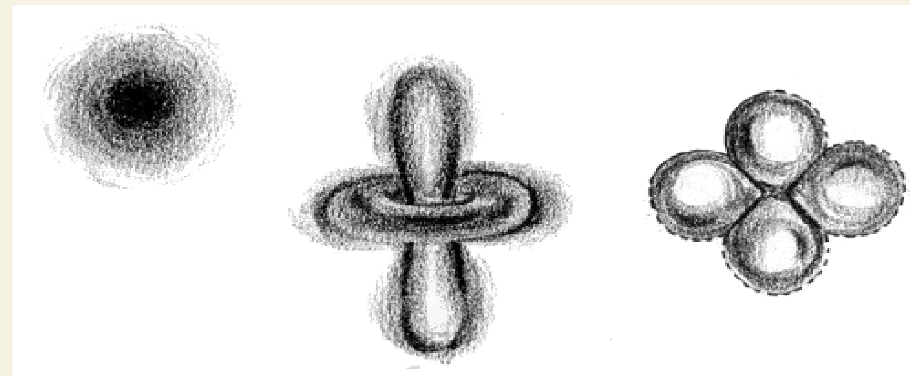
Mass-Energy Equivalence: received September 27 and published 21 November

Paradigm Shifts – *in progress*

Relativity

Space and Time are not absolute, there is no preferred frame.
and not Euclidean





$$\Delta t = \gamma \Delta \tau$$

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

Quantum Mechanics

Loss of Determinism:

Determinism: If we knew all of the initial conditions, we couldn't predict the exact position and velocity of an electron.

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

Bohr's Atom - 1913

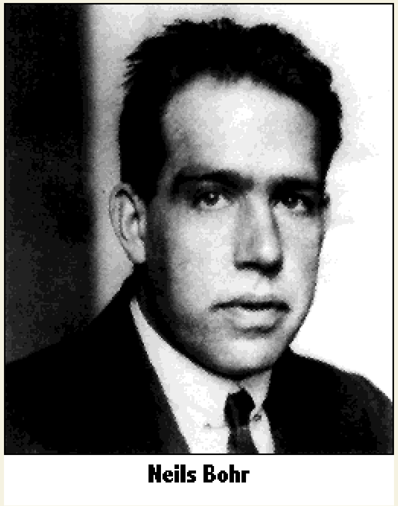
Niels Bohr (1885-1962)

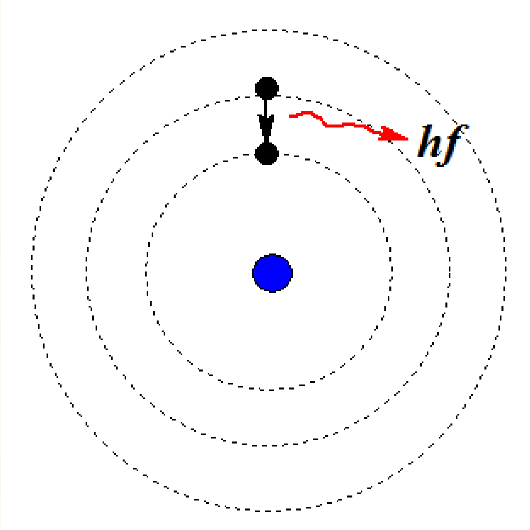
Accelerating electrons radiate at specific energies.

Are atoms stable?

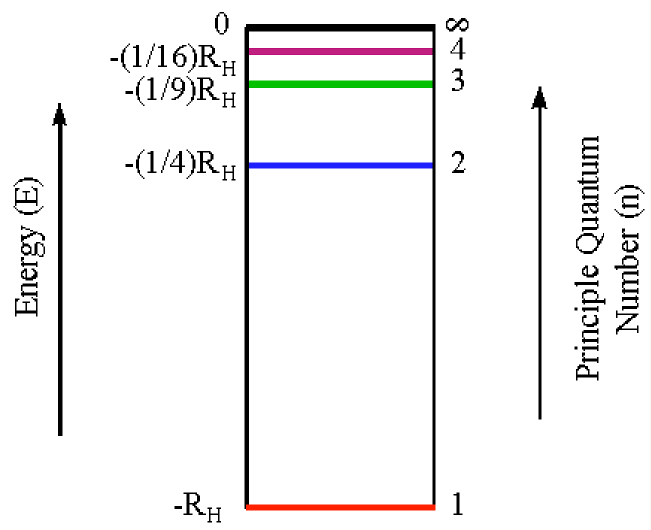
Assume angular momentum is quantized.

Derived Balmer's formula (1884) $\frac{m^2}{m^2-2^2}\times 3645.6\ \text{Å}\ \ m = 3,4,5,\ldots.$





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



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

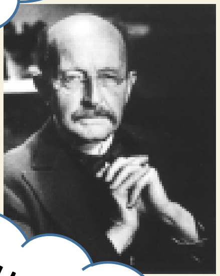
1924 – de Broglie NP 1929 - Particles Behave Like Waves

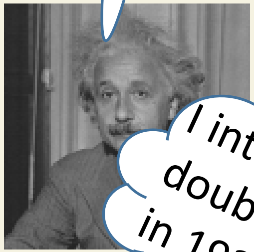
1925 - Matrix Mechanics – Heisenberg NP 1932, Born NP 1954, Jordan
- Pauli Principle NP 1935
- Uhlenbeck and Goudsmit, spinning particles

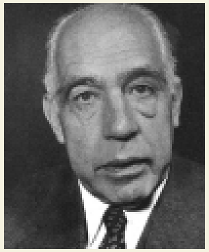
1926 - Wave Mechanics - Schrödinger NP 1933

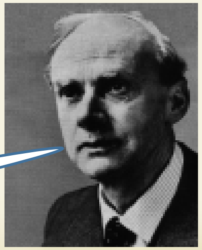
1927 - The Uncertainty Principle – Heisenberg
- Davisson NP 1937 –Germer, Thomson NP 1937 - Verified de Broglie's idea

1928 - Relativistic Quantum Mechanics - Dirac NP 1933









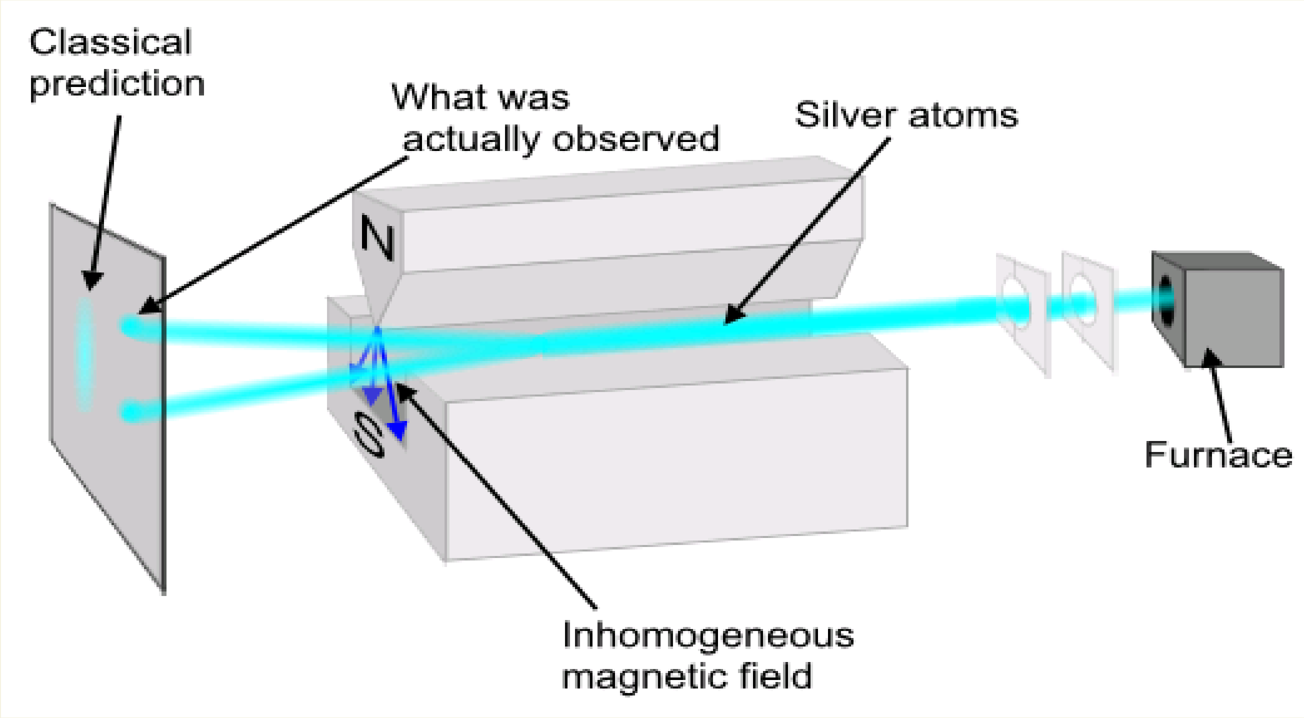
Stern-Gerlach Experiment - 1922

Otto Stern (1888-1969)

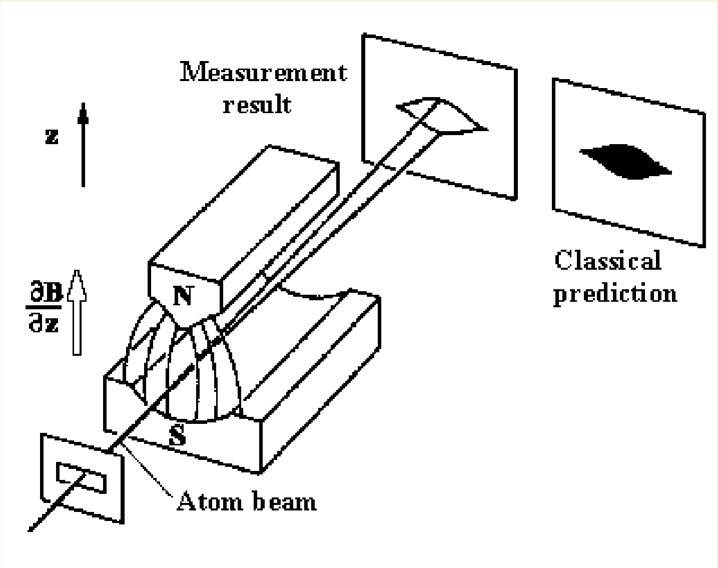
Walther Gerlach (1889-1979) – Was it the cigar?

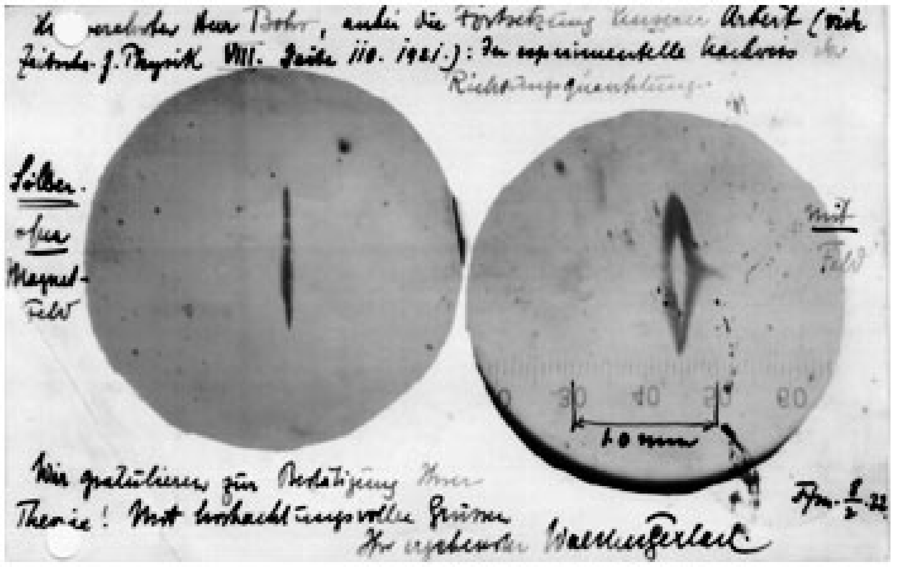
Ag atoms sent through inhomogenous magnetic field.

Demonstration of space quantization.



Stern-Gerlach Results





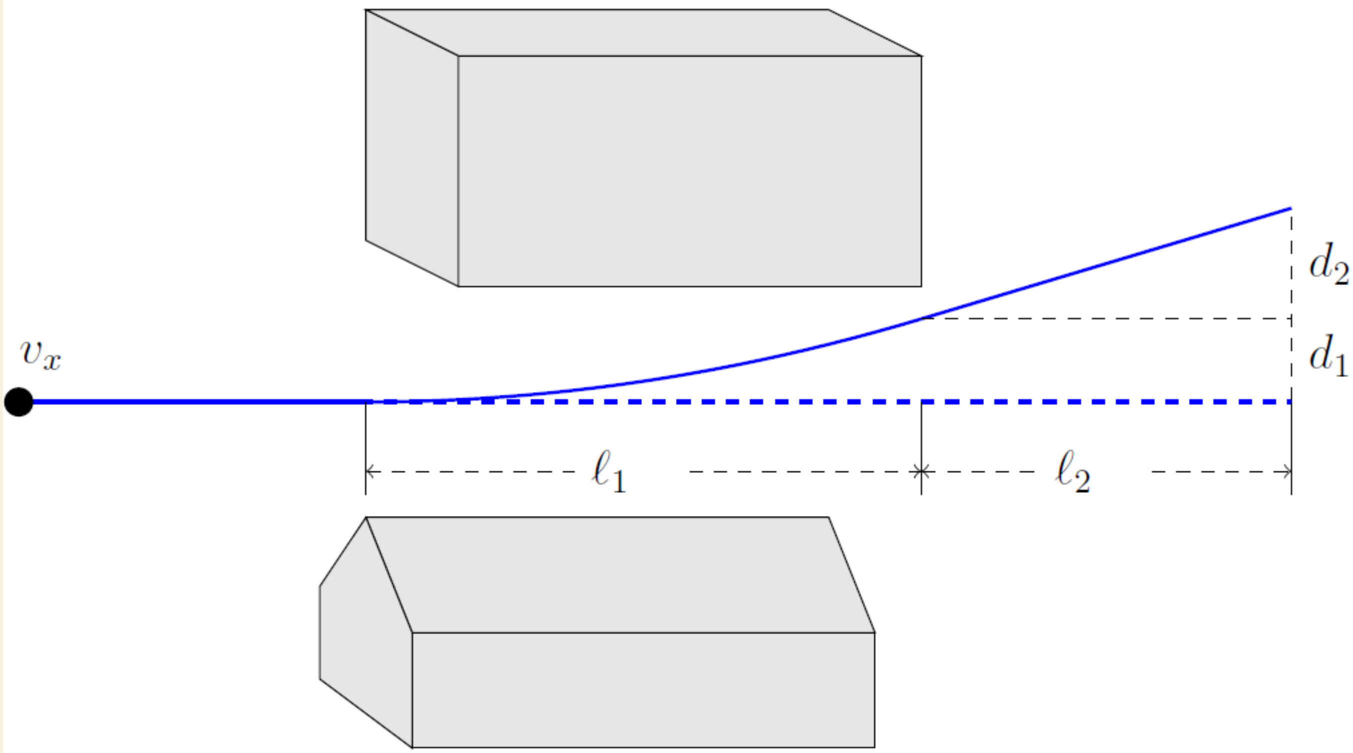
Test of classical vs quantum theory of angular momentum (**L**).

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