Physics 222: Modern Physics for Engineers
Spring 2021

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Course objectives: To learn the physics of the 20th century
Course outcomes: Know the basic laws of relativity, quantum and atomic physics, nuclear physics ad solid state physics.

Text: Modern Physics for Scientists and Engineers
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CHAPTER 1

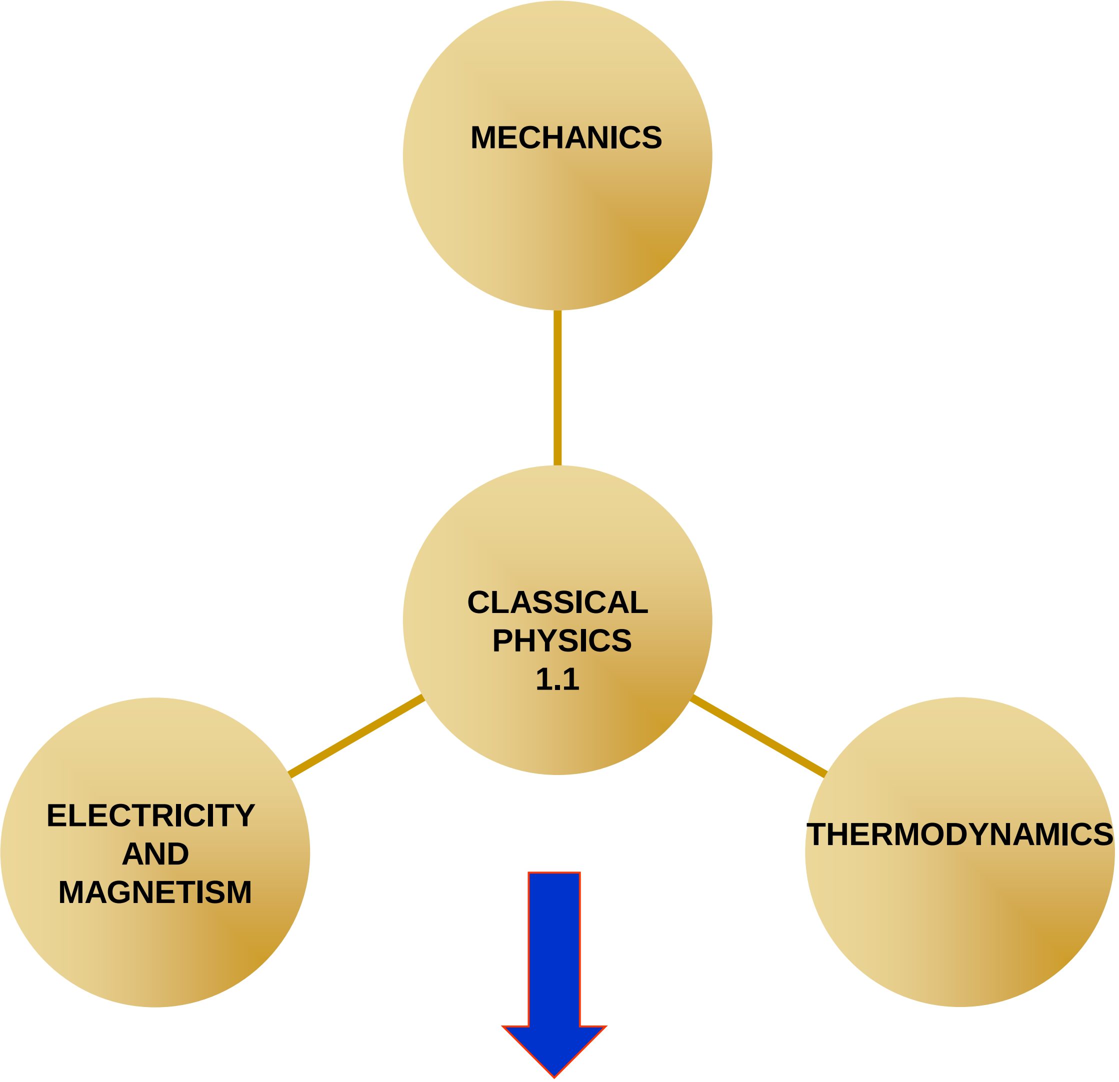
"The eternal mystery of the world is its comprehensibility.“
"Anyone who has never made a mistake has never tried anything new."

A. Einstein

- 1.1 Classical Physics of the 1890s
- 1.2 The Kinetic Theory of Gases
- 1.3 Waves and Particles
- 1.4 Conservation Laws and Fundamental Forces
- 1.5 The Atomic Theory of Matter
- 1.6 Unresolved Questions of 1895 and New Horizons

1.1: Classical Physics of the 1890s

- Mechanics
- Electromagnetism
- Thermodynamics



MECHANICS

CLASSICAL
PHYSICS
1.1

ELECTRICITY
AND
MAGNETISM

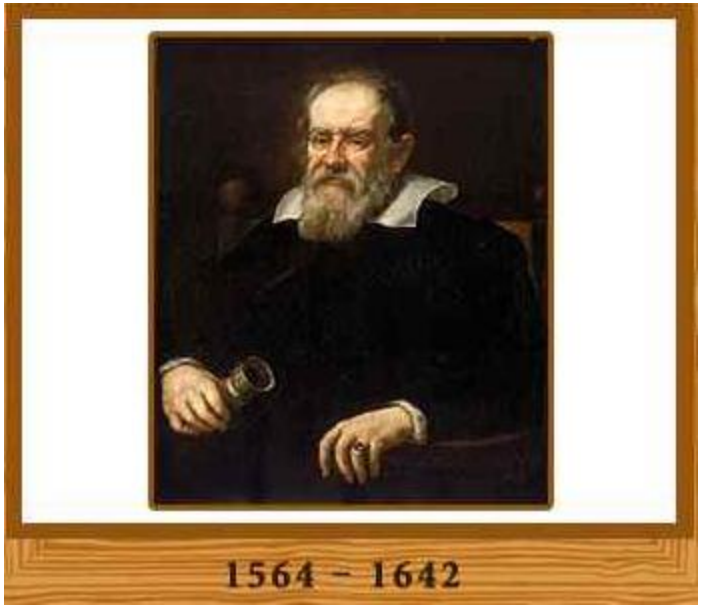
THERMODYNAMICS

CONSERVATION LAWS

Triumph of Classical Physics: The Conservation Laws

- **Conservation of energy**: The total sum of energy (in all its forms) is conserved in all interactions.
- **Conservation of linear momentum**: In the absence of external forces, linear momentum is conserved in all interactions.
- **Conservation of angular momentum**: In the absence of external torque, angular momentum is conserved in all interactions.
- **Conservation of charge**: Electric charge is conserved in all interactions.

Mechanics



- Galileo Galilei (1564-1642)
  - Great experimentalist
  - Principle of inertia
  - Established experimental foundations

Kinematics equations for constant acceleration

General formulas:

$$v = dx / dt$$

$$a = dv / dt = d^2 x / dt^2$$

$$v = v_o + at$$

$$x = x_0 + v_0 t + \frac{1}{2} a t^2$$

$$v^2 = v_0^2 + 2a(x - x_0)$$

$$x = x_0 + (\frac{v_0 + v}{2})t$$

Motion with const acceleration

$$a = \frac{v_2 - v_1}{t_2 - t_1} = \frac{v - v_0}{t - 0} \qquad \boxed{v = v_0 + at}$$

$$t = \frac{v - v_0}{a}$$

$$\left(\begin{array}{l} v_{av} = \dfrac{v_0 + v}{2} = \dfrac{v_0 + v_0 + at}{2} = v_0 + \dfrac{1}{2}at \\[2ex] v_{av} = \dfrac{x_2 - x_1}{t_2 - t_1} = \dfrac{x - x_0}{t - 0} \end{array}\right. \Rightarrow \boxed{x = x_0 + v_0 t + \frac{1}{2}at^2}$$

$$x = x_0 + v_0\left(\frac{v - v_0}{a}\right) + \frac{1}{2}a\left(\frac{v - v_0}{a}\right)^2 \Big| \cdot 2a$$

$$2a(x - x_0) = 2v_0(v - v_0) + (v - v_0)^2$$

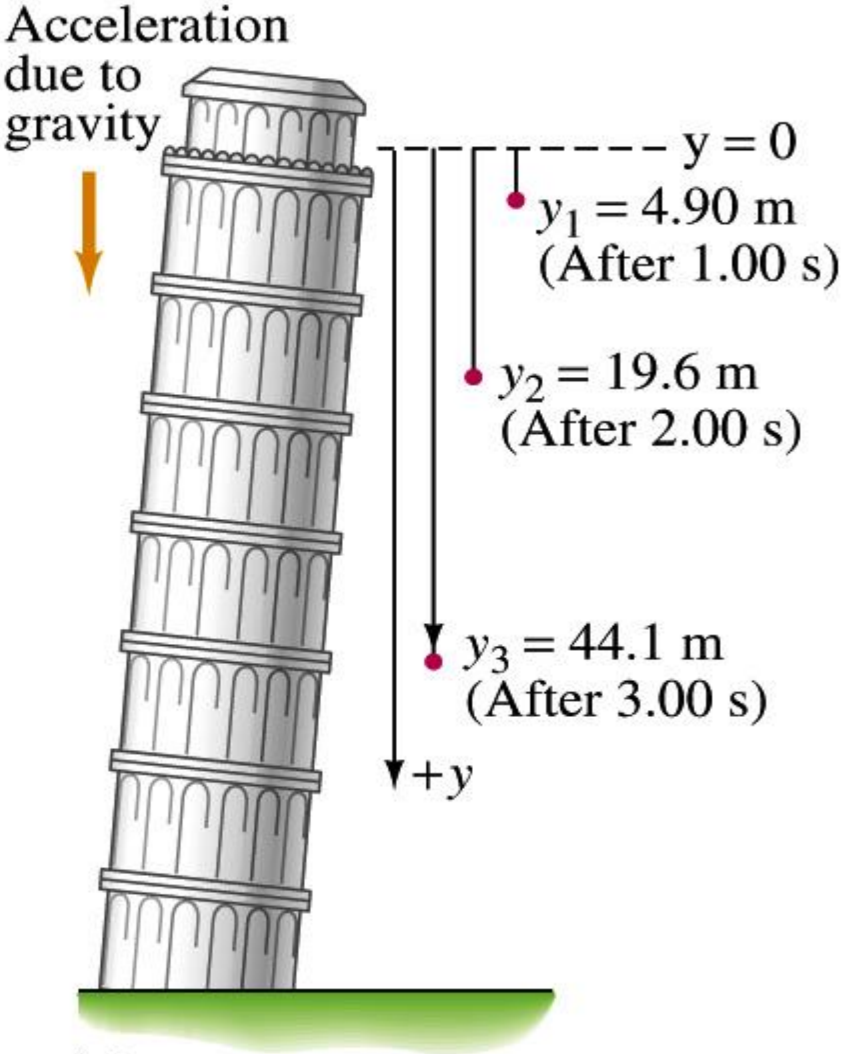
$$= \cancel{2v_0 v} - 2v_0^2 + v^2 + v_0^2 - \cancel{2vv_0}$$

$$\boxed{v^2 = v_0^2 + 2a(x - x_0)}$$

$$\left.\begin{array}{l} v_{av} = \dfrac{v_0 + v}{2} \\[2ex] v_{av} = \dfrac{x - x_0}{t} \end{array}\right\}$$

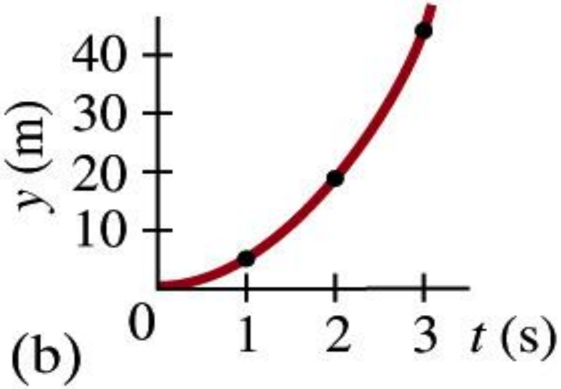
$$\boxed{x - x_0 = \left(\frac{v_0 + v}{2}\right)t}$$

Testing Kinetics for a=9.80m/s^2



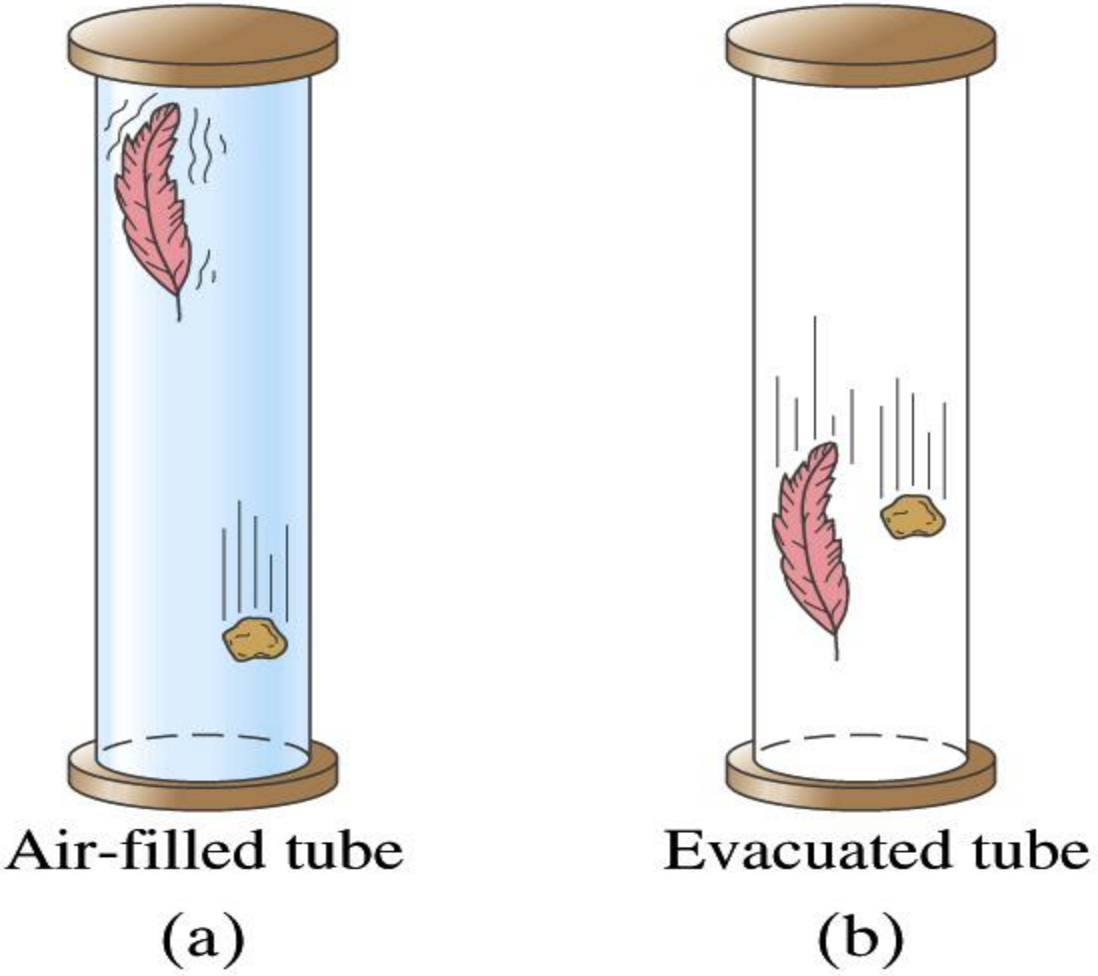
(a)

$$y = \frac{1}{2} a t^2$$

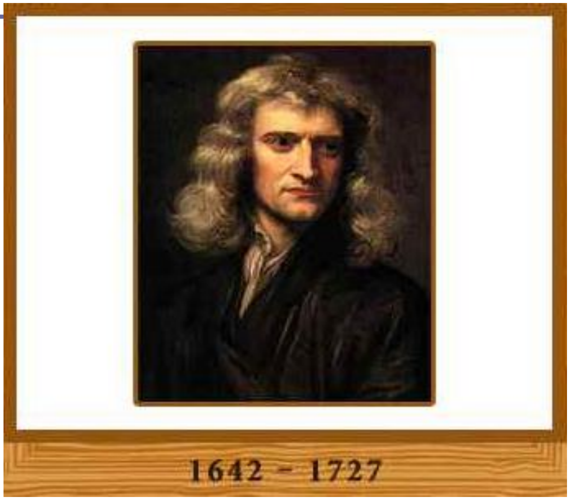


(b)

All objects fall with the same constant acceleration!!



Isaac Newton (1642-1727)



Three laws describing the relationship between mass and acceleration.

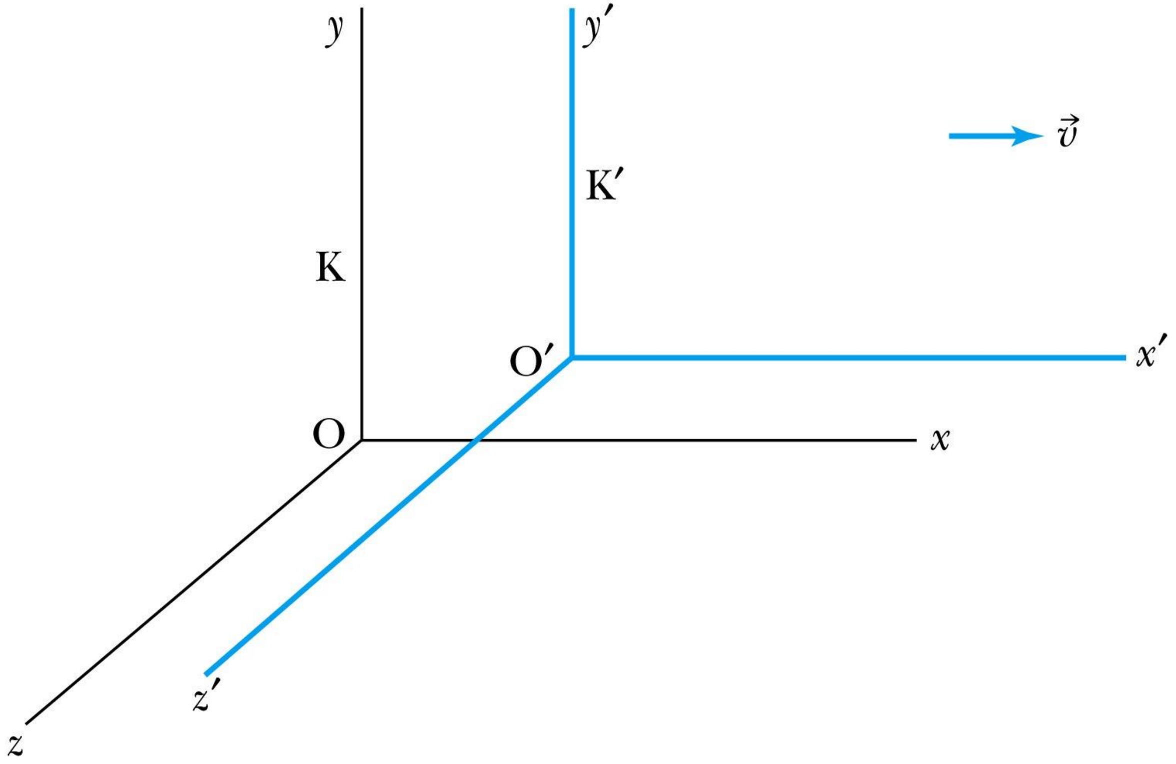
- **Newton's first law** (*law of inertia*): An object in motion with a constant velocity will continue in motion unless acted upon by some net external force.
- **Newton's second law**: Introduces force (F) as responsible for the change in linear momentum (p):

$$\vec{F} = m\vec{a} \quad \text{or} \quad \vec{F} = \frac{d\vec{p}}{dt}$$

- **Newton's third law** (*law of action and reaction*): The force exerted by body 1 on body 2 is equal in magnitude and opposite in direction to the force that body 2 exerts on body 1.

$$\vec{F}_{21} = -\vec{F}_{12}$$

Inertial Frames K and K’

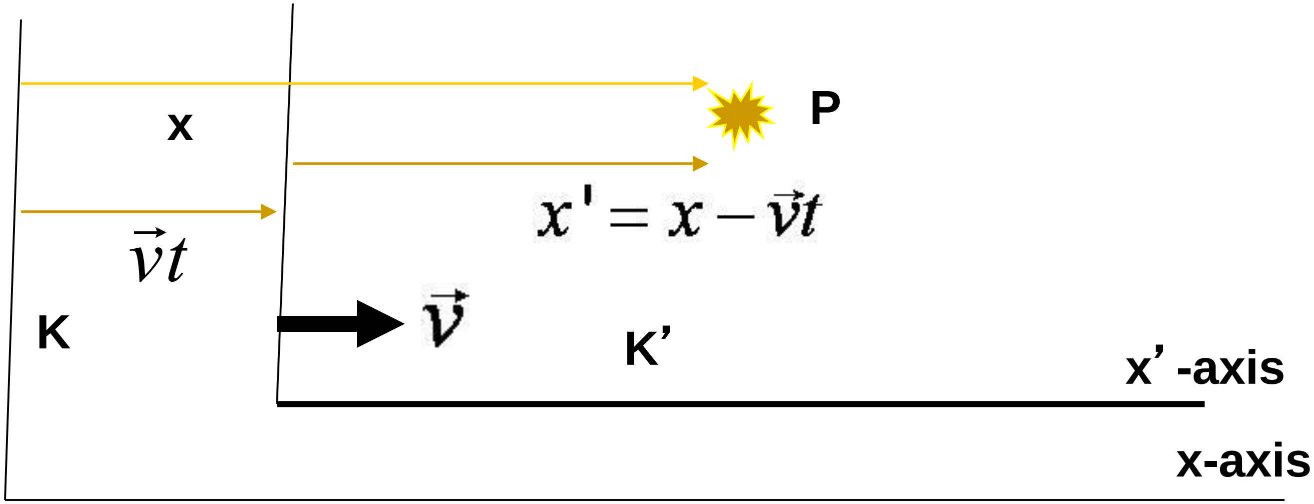


- K is at rest and K’ is moving with constant velocity
- Axes are parallel
- K and K’ are said to be *INERTIAL COORDINATE SYSTEMS*

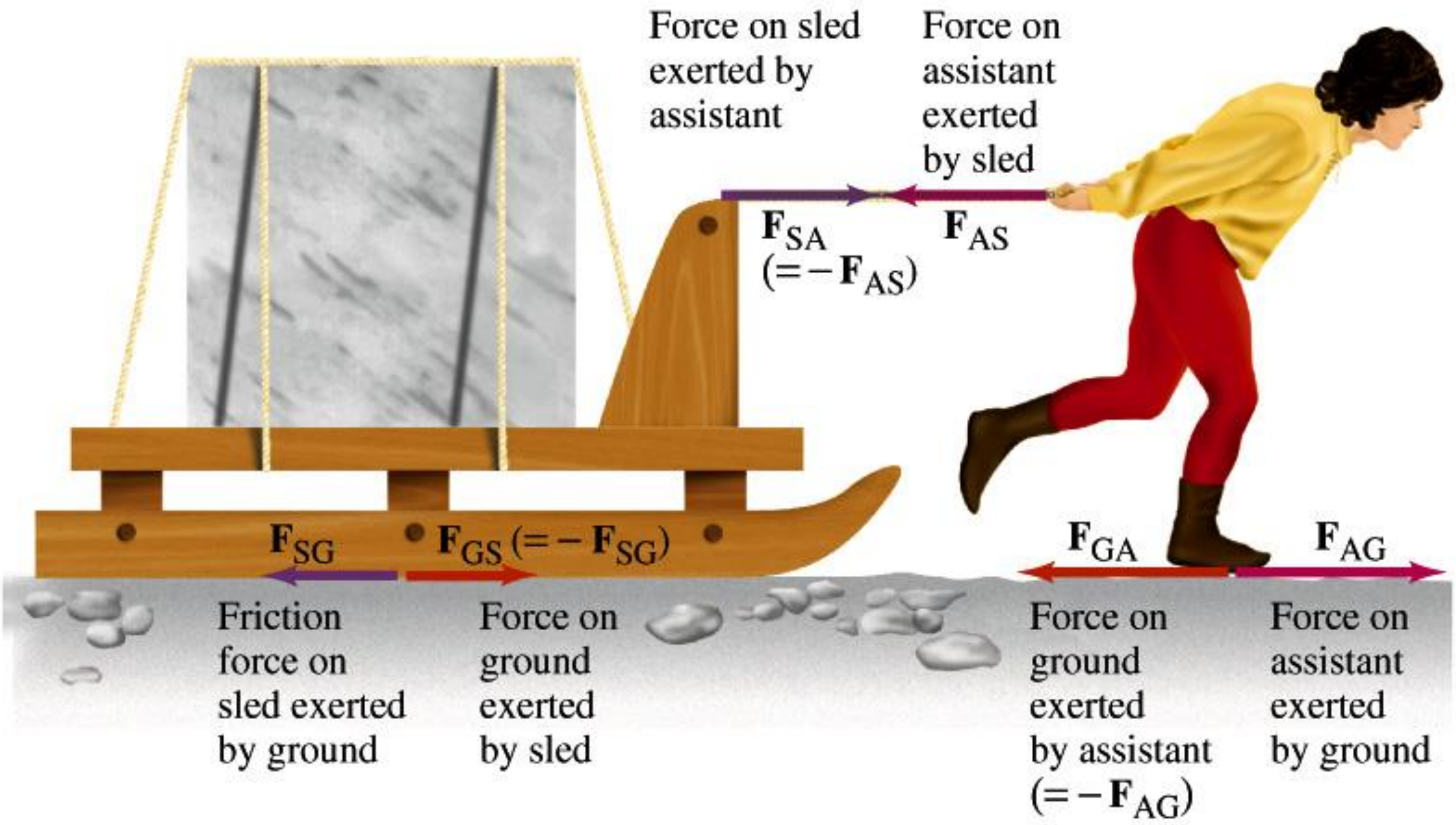
The Galilean Transformation

For a point P

- In system K: P = (x, y, z, t)
- In system K' : P = (x' , y' , z' , t')



pulling a sled, Michelangelo’s assistant



For forward motion: $F_{AG} > F_{AS}$ $F_{SA} > F_{SG}$

Gravitation

Newton's Law of Gravitation

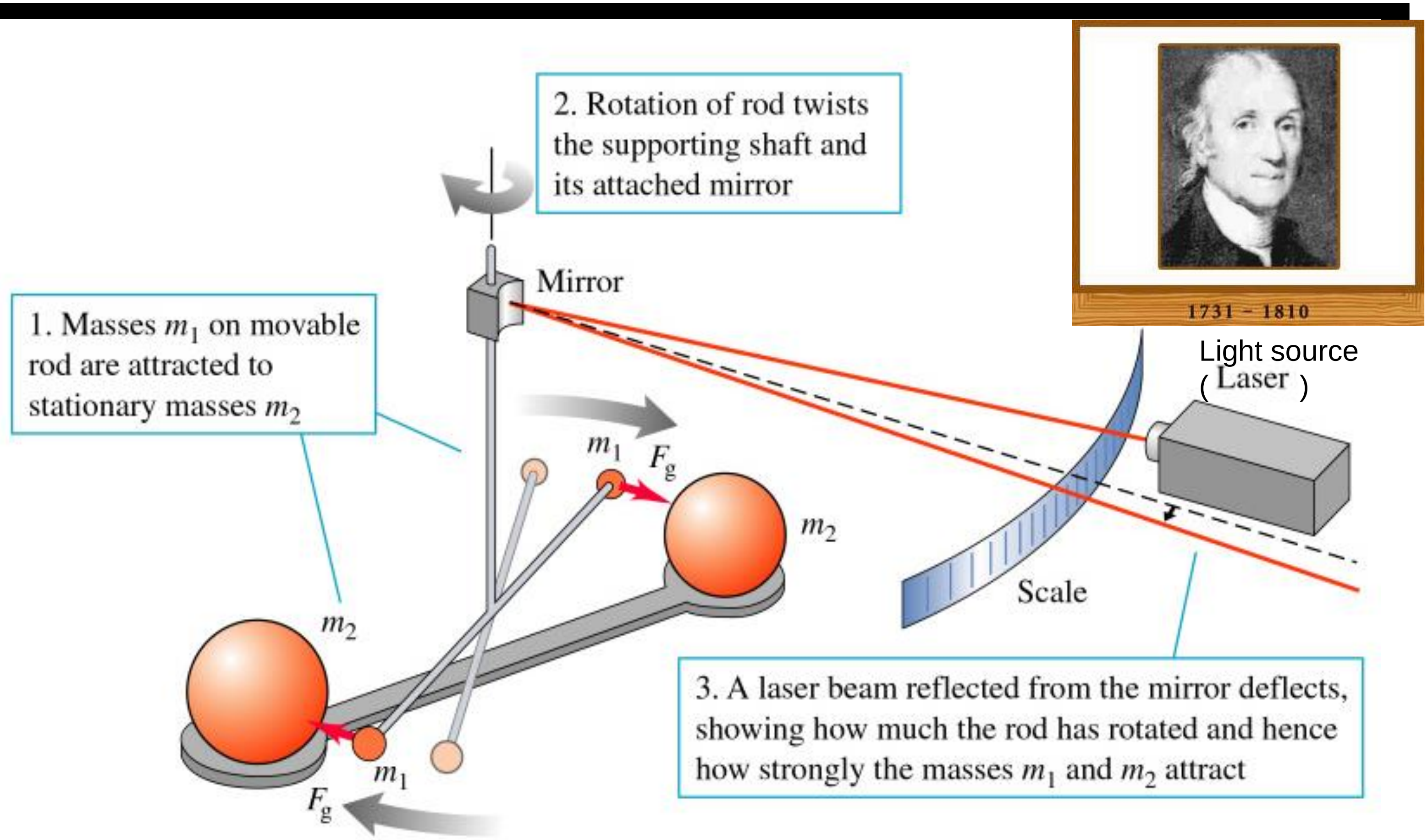
$$F_g = \frac{Gm_1 m_2}{r^2}$$

G=gravitational constant $= 6.673(10) \times 10^{-11} Nm^2 / kg^2$

Note: The weight ω of a body of mass m on the earth's surface with radius R_E *is*

$$\omega = mg = \frac{Gm_E \cdot m}{R_E^2} \quad \text{or} \quad g = \frac{Gm_E}{R_E^2}$$

Cavendish balance



2. Rotation of rod twists the supporting shaft and its attached mirror

1. Masses m_1 on movable rod are attracted to stationary masses m_2

3. A laser beam reflected from the mirror deflects, showing how much the rod has rotated and hence how strongly the masses m_1 and m_2 attract

Henry Cavendish(1798) announced that he has weighted the earth.

$$a_{earth} = 9.81 \frac{m}{s^2}$$

$$a_{moon} = 1.67 \frac{m}{s^2}$$

$$a_{sun} = 274 \frac{m}{s^2}$$

$$a_{gr} = g = G\frac{M}{R^2}$$

The Foucault pendulum in Aggieland

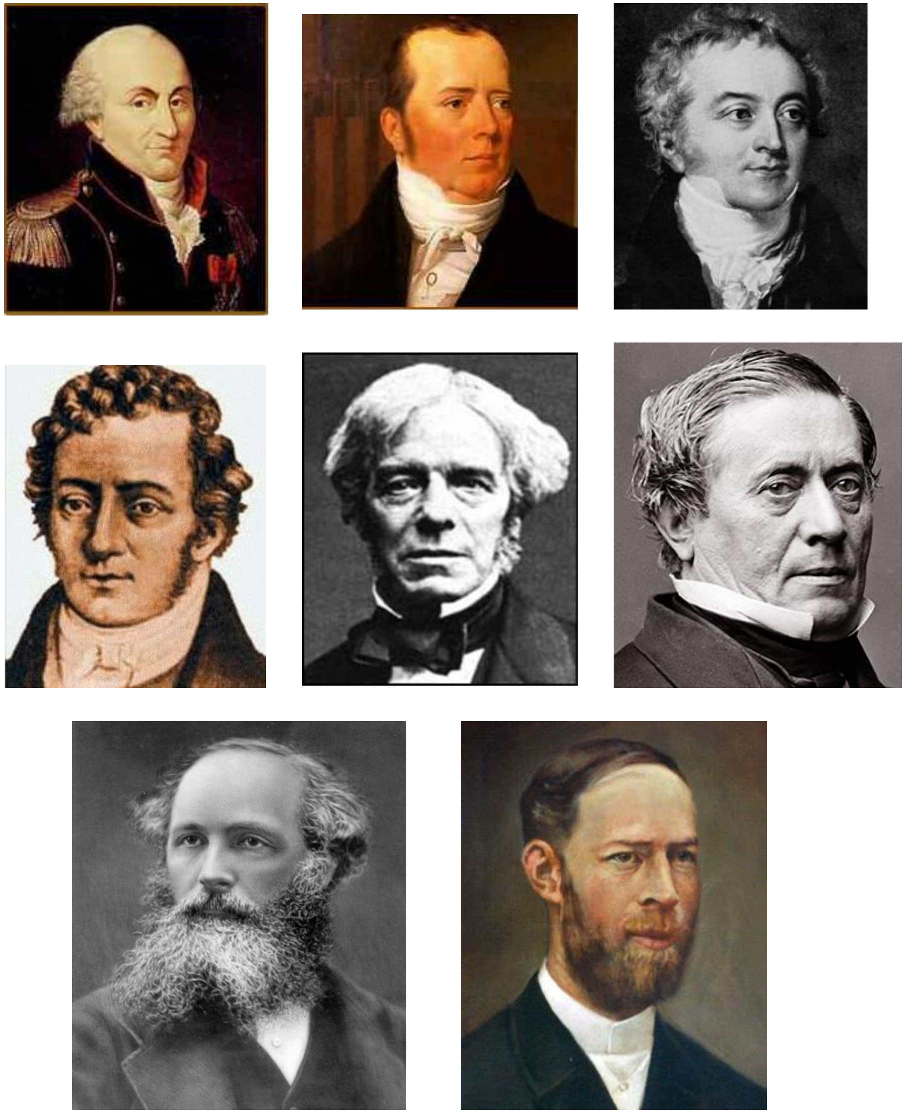
What does it show?? Seeing is believing

T=10 sec   how long is it??

Electromagnetism: 18th-19th centuries

Contributions made by:

- Coulomb (1736-1806)
- Oersted (1777-1851)
- Young (1773-1829)
- Ampère (1775-1836)
- Faraday (1791-1867)
- Henry (1797-1878)
- Maxwell (1831-1879)
- Hertz (1857-1894)



Culminates in Maxwell's Equations

Gauss (1777 –1855)

- Gauss's law (Φ_E): (electric field)

$$\oint \vec{E} \cdot d\vec{A} = \frac{q}{\varepsilon_0}$$

- Gauss's law (Φ_B): (magnetic field)

$$\oint \vec{B} \cdot d\vec{A} = 0$$

- Faraday's law:

$$\oint \vec{E} \cdot d\vec{s} = -\frac{d\Phi_B}{dt}$$

- Ampère's law: (Generalized)

$$\oint \vec{B} \cdot d\vec{s} = \mu_0 \varepsilon_0 \frac{d\Phi_E}{dt} + \mu_0 I$$

- Lorentz law: (force)

$$\bar{F} = q\bar{E} + q\bar{v} \times \bar{B}$$

Thermodynamics

Contributions made by:

- Benjamin Thompson (1753-1814) (frictional heat) (Count Rumford)
- Sadi Carnot (1796-1832) (heat engine and Carnot cycle)
- James Joule (1818-1889) (mechanical equivalent of heat))
- Rudolf Clausius (1822-1888) (heat can never pass from a colder to a warmer body without some other change)
- William Thompson (1824-1907) (Lord Kelvin) (proposed absolute temperature scale)

Primary Results

- Deals with temperature, heat, work, and the internal energy of systems
- Introduces thermal equilibrium
- The first law establishes heat as energy and expresses conservation of energy
- Introduces the concept of internal energy and considers temperature as a measure of internal energy
- Introduces limitations of the energy processes that can or cannot take place

The Laws of Thermodynamics

- **First law**: The change in the internal energy ΔU of a system is equal to the heat Q added to a system plus the work W done on the system

$$\Delta U = Q + W$$

- **Second law**: It is not possible to convert heat completely into work without some other change taking place.

- **The "zeroth" law**: Two systems in thermal equilibrium with a third system are in thermal equilibrium with each other.

- **Third law**: It is not possible to achieve an absolute zero temperature.

1.2: The Kinetic Theory of Gases

Contributions made by:

- Robert Boyle (1627-1691)
- Jacques Charles (1746-1823)
- Joseph Louis Gay-Lussac (1778-1823)

- Culminates in the **ideal gas equation** for *n* moles of a "simple" gas:

$$pV = nRT$$

(where *R* is the ideal gas constant, 8.31 J/(mol · K)

Additional Contributions

- Amedeo Avogadro (1776-1856) (number of molecules in a mole and their weights)
- John Dalton (1766-1844) (atomic theory of elements)
- Daniel Bernoulli (1700-1782) (kinetic theory of gases)
- Ludwig Boltzmann (1844-1906) (kinetic theory of gases, entropy as log() of probability)
- James Clerk Maxwell (1831-1879) (velocity distribution)
- J. Willard Gibbs (1939-1903) (thermodynamic and chemical potentials)

Primary Results

- Average molecular kinetic energy directly related to absolute temperature
- **Internal energy** *U* directly related to the average molecular kinetic energy
- Internal energy equally distributed among the number of degrees of freedom (*f*) of the system containing n moles of substance

$$U = nN_A \langle K \rangle = \frac{f}{2} nRT$$

($N_A = 6.022 \times 10^{23}$ mol^{-1}

Avogadro's number: number of molecules in 1 mole)

Other Primary Results

2. Maxwell derives a relation for the molecular speed distribution *f* (*v*):

$$f(v) = 4\pi N \left(\frac{m}{2\pi kT} \right)^{3/2} v^2 e^{-mv^2/2kT}$$

3. Boltzmann contributes to determine the *root-mean-square* of the molecular speed

$$v_{rms} = \sqrt{\langle v^2 \rangle} = \sqrt{\frac{3kT}{m}}$$

Thus relating energy to the temperature for an ideal gas

Molecular speeds in an ideal gas

$$K_{av}(molecule) = \frac{1}{2} m v_{ev}^2 = \frac{3}{2} kT$$

$$\boxed{v_{rms} = \sqrt{v_{av}^2} = \sqrt{\frac{3kT}{m}} = \sqrt{\frac{3RT}{M}}}$$

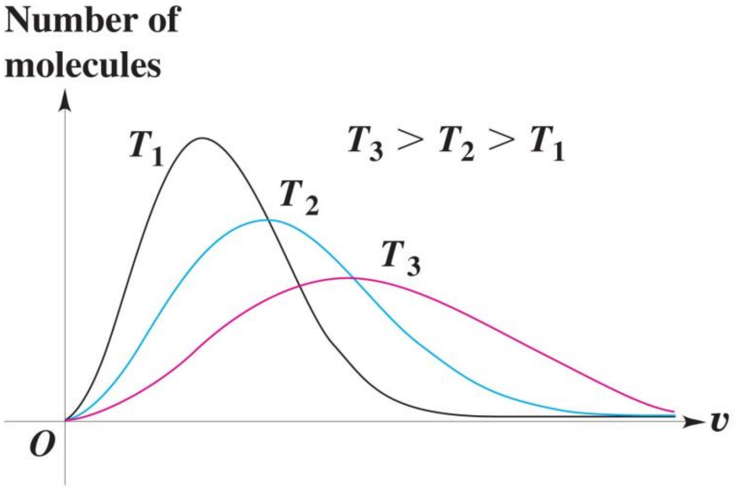
Consider O_2 as an ideal gas at 27°C. Find K_{av} and K_{tr}

$27^{0}C = 300\,K$

$\uparrow$ per molecule $\quad$ $\uparrow$ per mole

$$K_{av} = \frac{1}{2} m v_{av}^2 = \frac{3}{2} kT = \frac{3}{2}(1.38 \times 10^{-23})(300) = 6.21 \times 10^{-21}\ J$$

$$K_{tr} = \frac{3}{2} RT = \frac{3}{2}(1\,mol)\, \underset{[J/mol \cdot K]}{\underset{\uparrow}{8.3}} \cdot 300\,K = 3740\,J$$



1.3: Waves and Particles

Two ways in which energy is transported:

1) Point mass interaction: transfers of momentum and kinetic energy: *particles*
2) Extended regions wherein energy transfers by way of vibrations and rotations are observed: *waves*

Particles vs. Waves

- Two distinct phenomena describing physical interactions
    - Particles in the form of point masses and waves in the form of perturbation in a mass distribution, i.e., a material medium
    - The distinctions are observationally quite clear; however, not so for the case of visible light
    - Thus by the 17th century begins the major disagreement concerning the nature of light

The Nature of Light

Contributions made by:

- Isaac Newton (1642-1742)
- Christian Huygens (1629 -1695)
- Thomas Young (1773 -1829)
- Augustin Fresnel (1788 – 1829)

The Nature of Light

- Newton suggested the corpuscular (particle) theory
  - Particles of light travel in straight lines or rays
  - Explained sharp shadows
  - Explained reflection and refraction

The Nature of Light

- Christian Huygens promoted the wave theory
  - Light propagates as a wave of concentric circles from the point of origin
  - Explained reflection and refraction
  - Did not explain sharp shadows

The Wave Theory Advances…

- Contributions by Huygens, Young, Fresnel and Maxwell
- Double-slit interference patterns
- Refraction of light from a vacuum to a medium
- Light is an electromagnetic phenomenon
- *Establishes that light propagates as a wave*

The Electromagnetic Spectrum

- Visible light covers only a small range of the total electromagnetic spectrum
- All electromagnetic waves travel in a vacuum with a speed *c* given by:

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

(where μ_0 and ε_0 are the respective permeability and permittivity of "free" space)

1.4: Conservation Laws and Fundamental Forces

- Recall the fundamental conservation laws:
  - Conservation of energy
  - Conservation of linear momentum
  - Conservation of angular momentum
  - Conservation of electric charge

- Later we will establish the **conservation of mass** as part of the **conservation of energy**

Modern Results

- In addition to the classical conservation laws, two modern results will include:
  - The conservation of baryons and leptons
  - The fundamental invariance principles for time reversal, distance, and parity

Also in the Modern Context…

- The three fundamental forces are introduced
  - **Gravitational**: $\vec{F}_g = -G\frac{m_1 m_2}{r^2}\hat{r}$
  - **Electroweak**
    - **Weak**: Responsible for nuclear beta decay and effective only over distances of ~10^{-15} m
    - **Electromagnetic**: $\vec{F}_C = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}\hat{r}$ (Coulomb force)
  - **Strong**: Responsible for “holding” the nucleus together and effective less than ~10^{-15} m

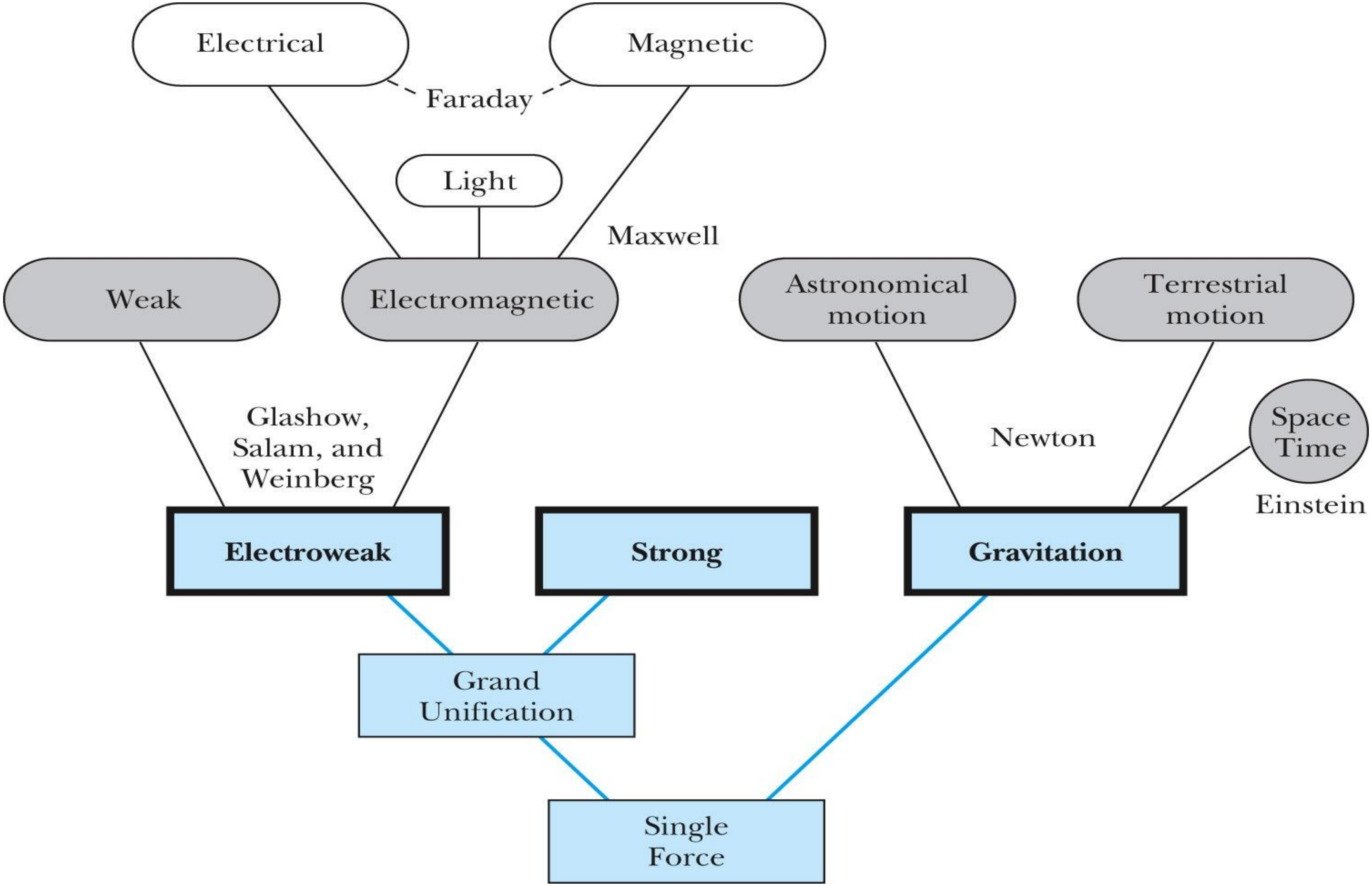
Unification

- Neutrons and protons are composed of *quarks*, which have the *color* force acting between them
- Grand Unified Theory (GUT) attempts to unify electroweak and strong forces
    - String theory is one of these
    - They have yet to be verified experimentally

Unification of Forces

- Maxwell unified the electric and magnetic forces as fundamentally the same force; now referred to as the **electromagnetic force**
- In the 1970's Glashow, Weinberg, and Salam proposed the equivalence of the electromagnetic and the weak forces (at high energy); now referred to as the **electroweak interaction**

Goal: Unification of All Forces into a Single Force



1.5: The Atomic Theory of Matter

- Initiated by Democritus and Leucippus (~450 B.C.) (first to us the Greek *atomos*, meaning “indivisible”*)*
- In addition to fundamental contributions by Boyle, Charles, and Gay-Lussac, Proust (1754 – 1826) proposes the **law of definite proportions**
- Dalton advances the **atomic theory of matter** to explain the law of definite proportions
- Avogadro proposes that all gases at the same temperature, pressure, and volume contain the ***same number of molecules (atoms)***; viz. 6.02×10^{23} atoms per mole
- Cannizzaro (1826 – 1910) makes the distinction between atoms and molecules advancing the ideas of Avogadro.

Further Advances in Atomic Theory

- Maxwell derives the speed distribution of atoms in a gas
- Robert Brown (1753 – 1858) observes microscopic “random” motion of suspended grains of pollen in water
- Einstein in the 20th century explains this random motion using atomic theory

Opposition to the Theory

- Ernst Mach (1838 – 1916) opposes the theory on the basis of logical positivism, i.e., atoms being *"unseen" place into question their reality*
- Wilhelm Ostwald (1853 – 1932) supports this premise but on experimental results of radioactivity, discrete spectral lines, and the formation of molecular structures

Overwhelming Evidence for Existence of Atoms

- Max Planck (1858 – 1947) advances the concept to explain blackbody radiation by use of submicroscopic “quanta”
- Boltzmann requires existence of atoms for his advances in statistical mechanics
- Albert Einstein (1879 – 1955) uses molecules to explain Brownian motion and determines the approximate value of their size and mass
- Jean Perrin (1870 – 1942) experimentally verifies Einstein’s predictions

1.6: Unresolved Questions of 1895 and New Horizons

- The atomic theory controversy raises fundamental questions
  - It was not universally accepted
  - The constitutes (if any) of atoms became a significant question
  - The structure of matter remained unknown with certainty

Further Complications

Three fundamental problems:

- The question of the existence of an electromagnetic medium
- The problem of observed differences in the electric and magnetic field between stationary and moving reference systems
- The failure of classical physics to explain blackbody radiation

Additional Discoveries Contribute to the Complications

- Discovery of x-rays
- Discovery of radioactivity
- Discovery of the electron
- Discovery of the Zeeman effect

The Beginnings of Modern Physics

- These new discoveries and the many resulting complications required a revision of the fundamental physical assumptions that culminated in the huge successes of physics

- To this end, the introduction of the modern theory of relativity and quantum mechanics becomes the starting point of this most fascinating revision.

- Four forces video