Welcome to PHYS-222, Modern Physics for Engineers!

SYLLABUS – PHYSICS 222: Modern Physics
Fall 2022

Course Description: *Modern Physics* covers Relativity, Models of the Atom, an Introduction to Quantum Mechanics, Atomic Physics, Nuclear physics, and Modern Astrophysics.

Course Objectives: Conceptual student learning outcomes: (1) Understanding of the physical laws of the topics described above. (2) Learning about the historic context of the physical developments and their implications for science and technology today. (3) Learning to think critically/scientifically and developing the skills needed to attack complex problems.

Instructor Information:
Name: Prof. Hans Schuessler
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Office hours: All interactions outside the class will be electronic (i.e. through Zoom). Please email me with questions (I will try to answer speedily) or if you need to make an appointment.

TA Information:
Name: Carlos Rodriguez
E-mail: carlos.rodriguez@tamu.edu (please start the subject line with **PHYS222**)
Office hours: TBD. Office hours will be through Zoom unless otherwise noted.

Class times: MW 5:45pm - 7:00pm
Class Location: Mitchel Physics Building, MPHY 203
Class Website: http://sibor.physics.tamu.edu/teaching/phys222/ & Canvas

Web Pages of Interest:
The main website for this course will be located at the course website (SIBOR) . All lecture notes, exam results and course information will be located here. Homework will be done through WEBASSIGN assignments, with a link located on the course Canvas page. Grades, exams, and extra notes will be located on Canvas.

Course Grade:

Homework	15
Participation	10
Midterm Exams	$3\times15=45$
Final Exam	30
Total Points	100

Course Score	Final Letter Grade
$\geq 90\ \%$	A
$\geq 80\ \%$	B
$\geq 70\ \%$	C
$\geq 60\ \%$	D
$< 60\ \%$	F

A Message from the Texas A&M Senate:

"To help protect Aggieland and stop the spread of COVID-19, Texas A&M University urges students to be vaccinated and to wear masks in classrooms and all other academic facilities on campus, including labs. Doing so exemplifies the Aggie Core Values of respect, leadership, integrity, and selfless service by putting community concerns above individual preferences. COVID-19 vaccines and masking — regardless of vaccination status — have been shown to be safe and effective at reducing spread to others, infection, hospitalization, and death."

-Dale Rice

Speaker, TAMU Faculty Senate, 2021-2022

"To contribute in protecting students in attendance I am providing masks at the classroom entrances. In the spirit of Aggieland let us fight together and continue to show that Aggies are stronger than the pandemic and do not make other Aggies sick by not wearing masks."

- Hans Schuessler, Professor of Physics, Chair of Optical and Biomedical Physics

CHAPTER 1

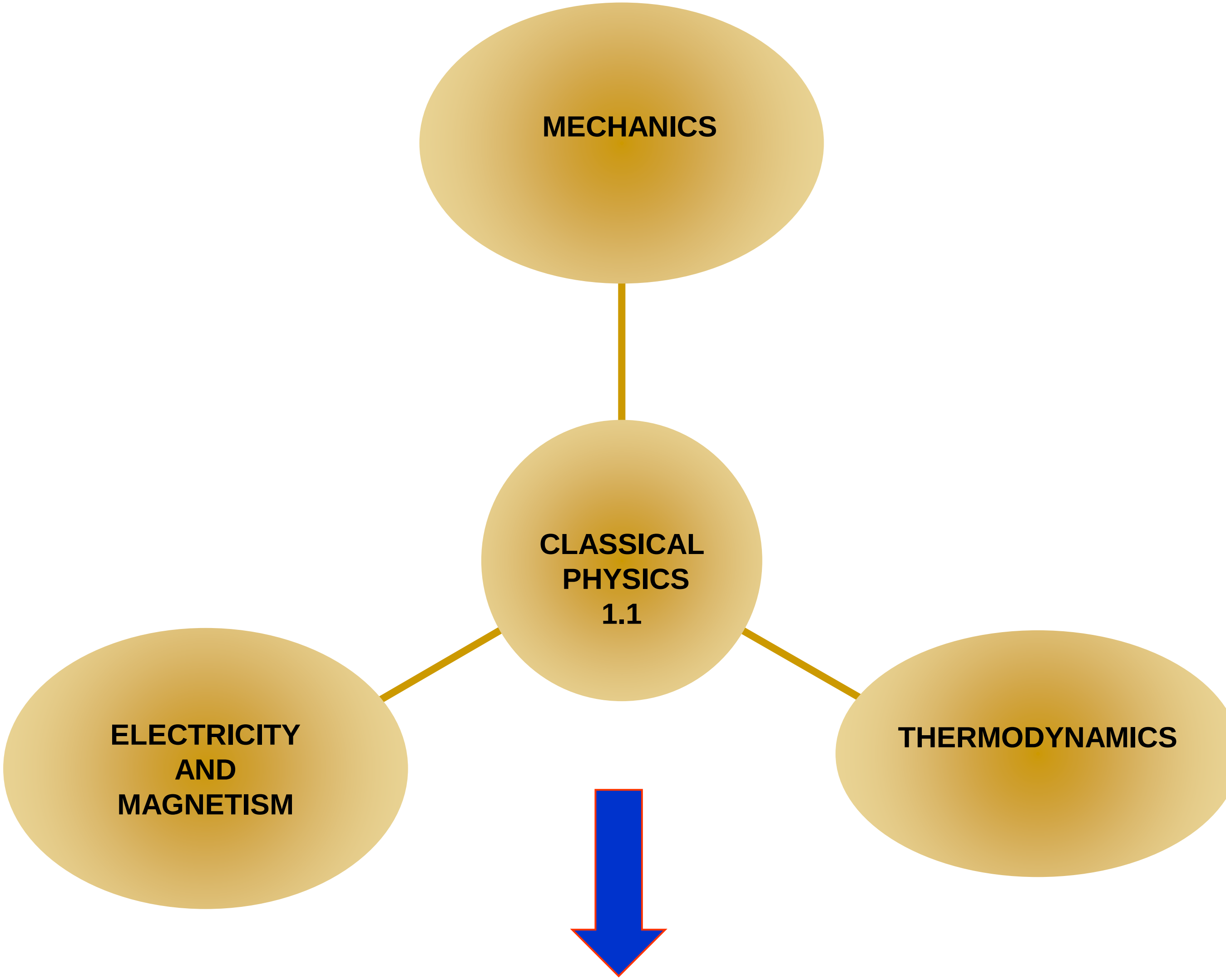
"The eternal mystery of the world is its comprehensibility.“
"Anyone who has never made a mistake has never tried anything new."

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

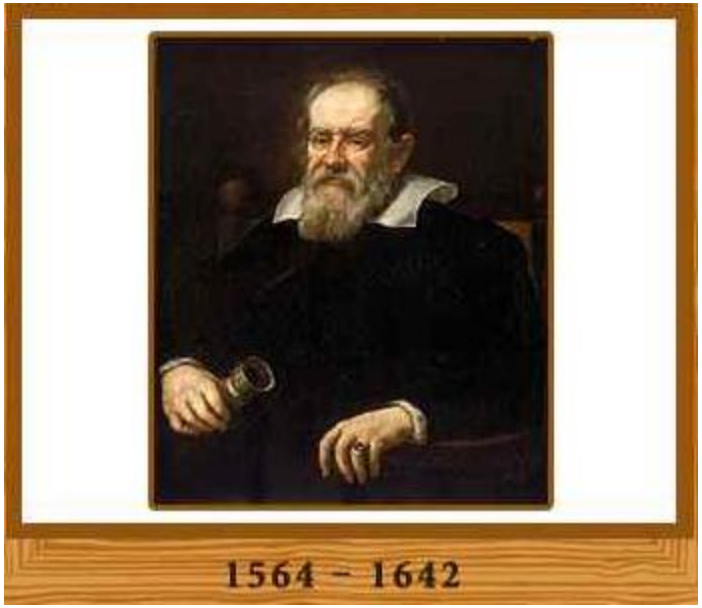


CONSERVATION LAWS

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:

$$v = dx / dt$$

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

$$v = v_0 + at$$

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

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

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

Motion with const acceleration

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

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

$$v_{av} = \frac{v_0 + v}{2} = \frac{v_0 + v_0 + at}{2} = v_0 + \frac{1}{2}at$$

$$v_{av} = \frac{x_2 - x_1}{t_2 - t_1} = \frac{x - x_0}{t - 0} \Rightarrow \boxed{x = x_0 + v_0 t + \frac{1}{2}at^2}$$

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

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

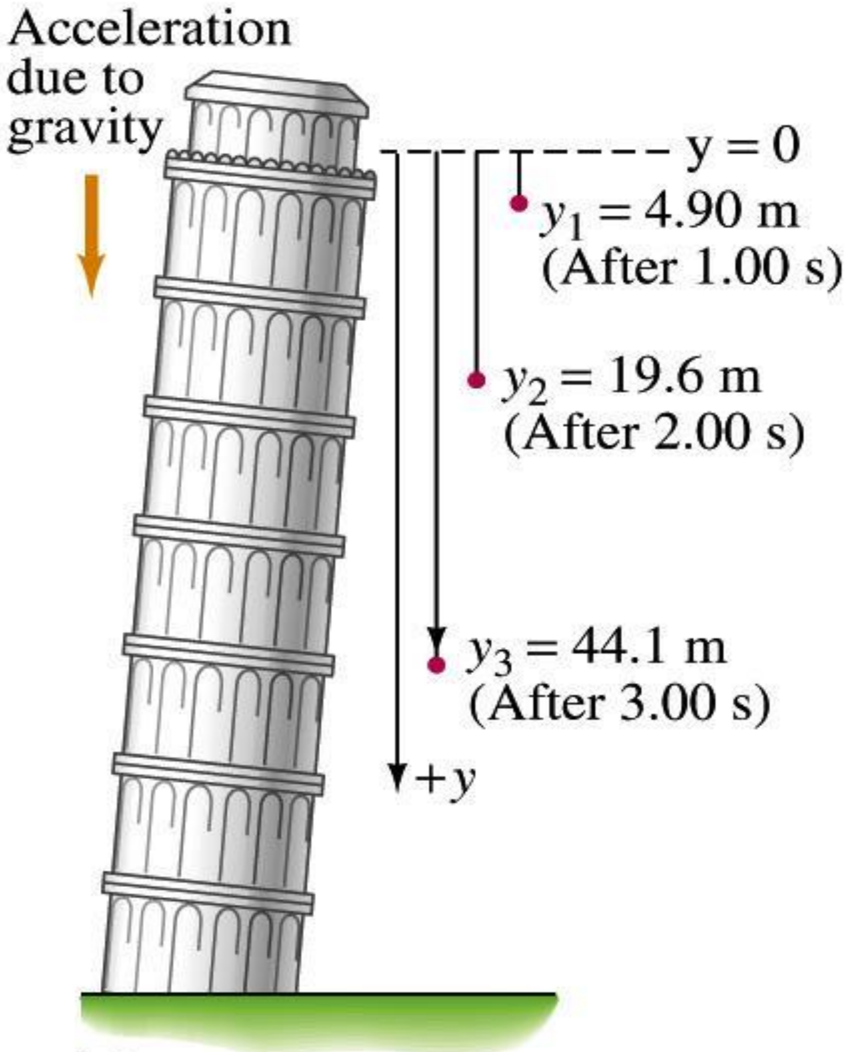
$$= \cancel{2v_0 v} - 2v_0^2 + v^2 + v_0^2 - \cancel{2vv_0}$$

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

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

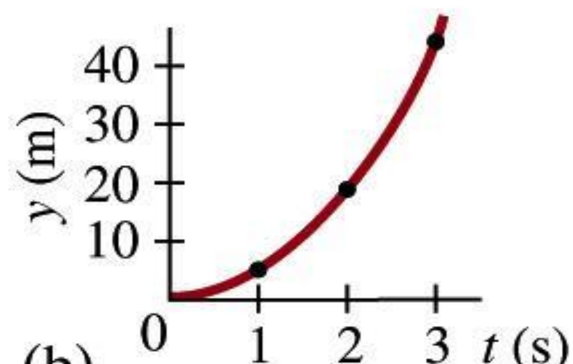
$$\boxed{x - x_0 = \left(\frac{v_0 + v}{2}\right)t}$$

Testing Kinetics for $a = 9.80 m/s^2$



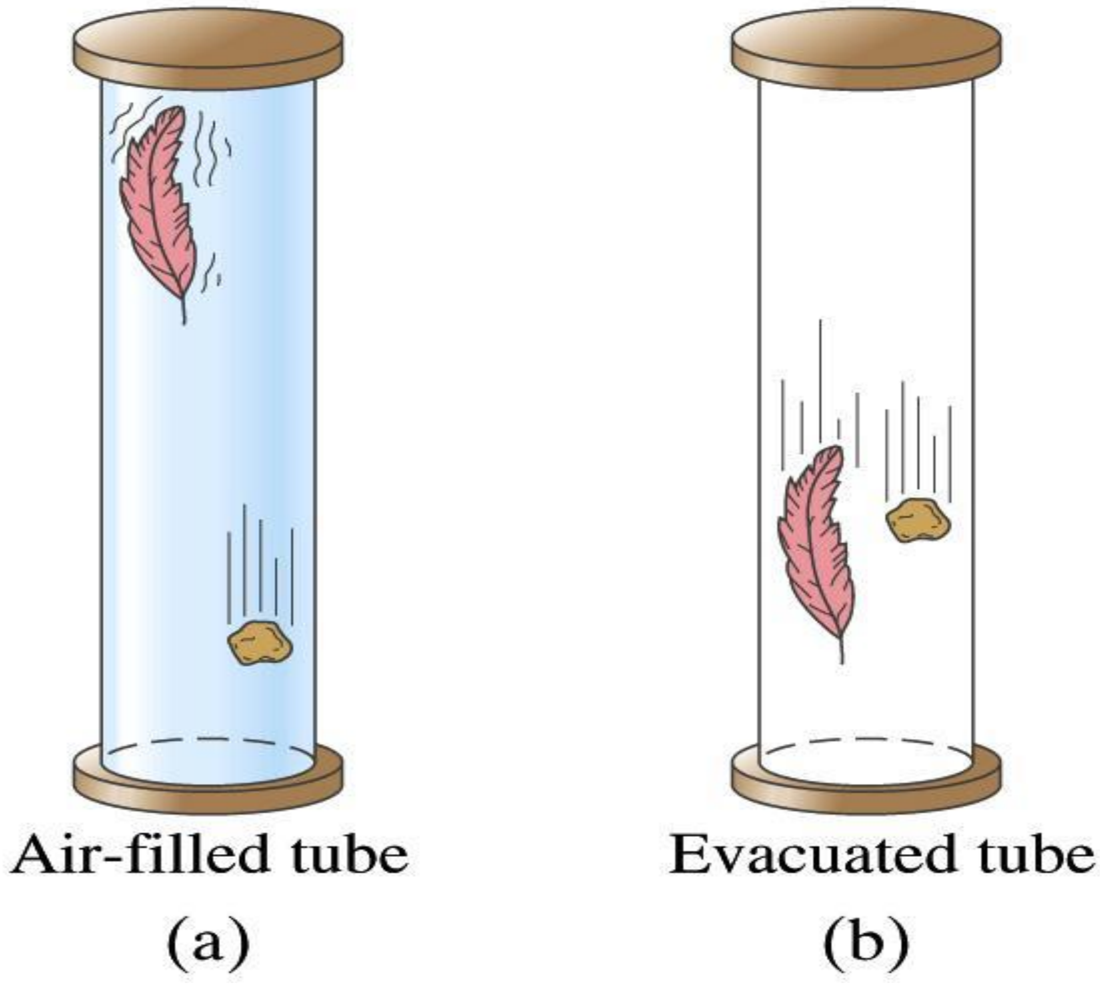
(a)

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

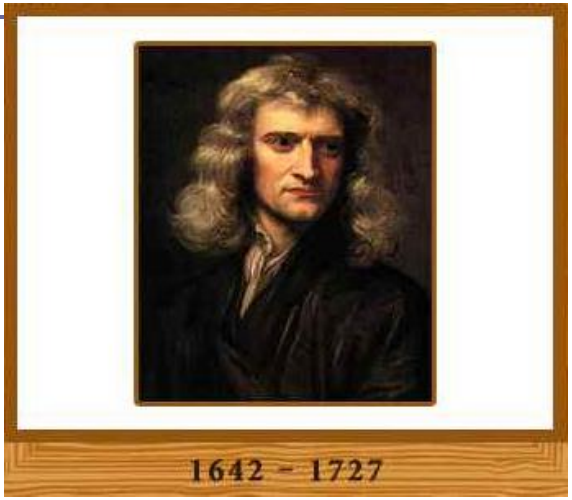


(b)

All objects fall with the same constant acceleration!!



Isaac Newton (1642-1727)



Three laws describing the relationship between mass and acceleration.

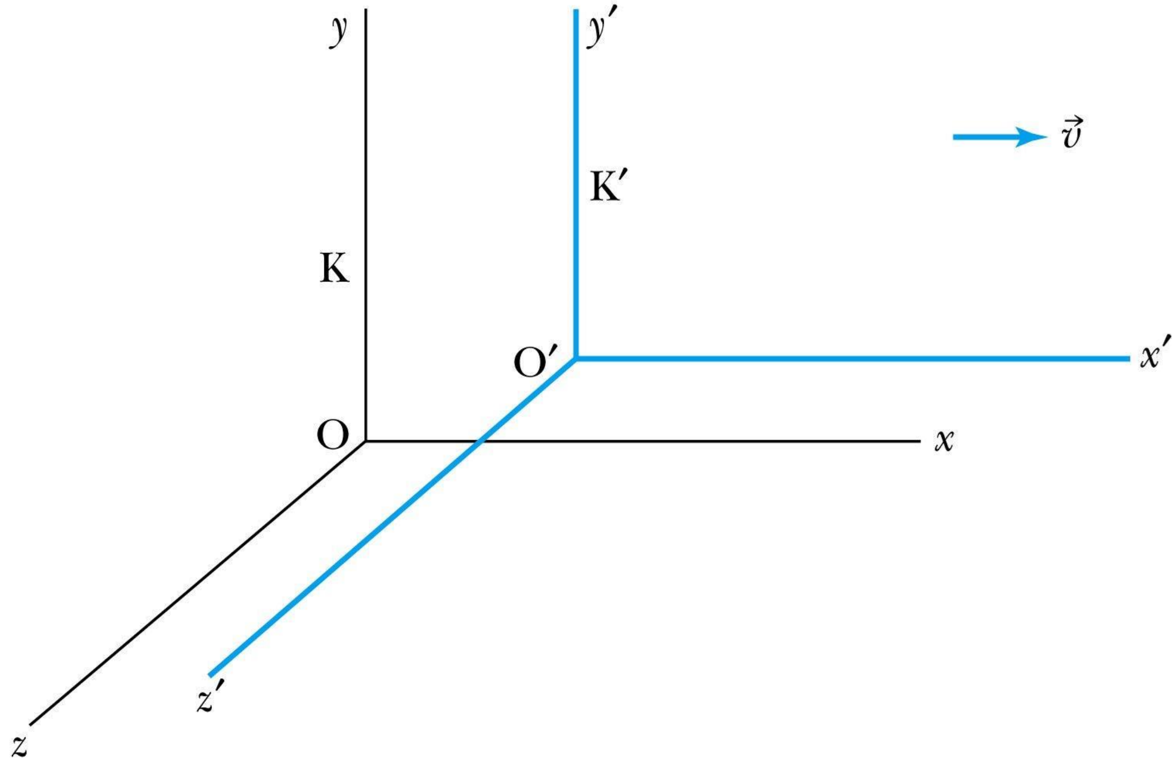
- **Newton's first law** (*law of inertia*): An object in motion with a constant velocity will continue in motion unless acted upon by some net external force.
- **Newton's second law**: Introduces force (F) as responsible for the change in linear momentum (p):

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

- **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’

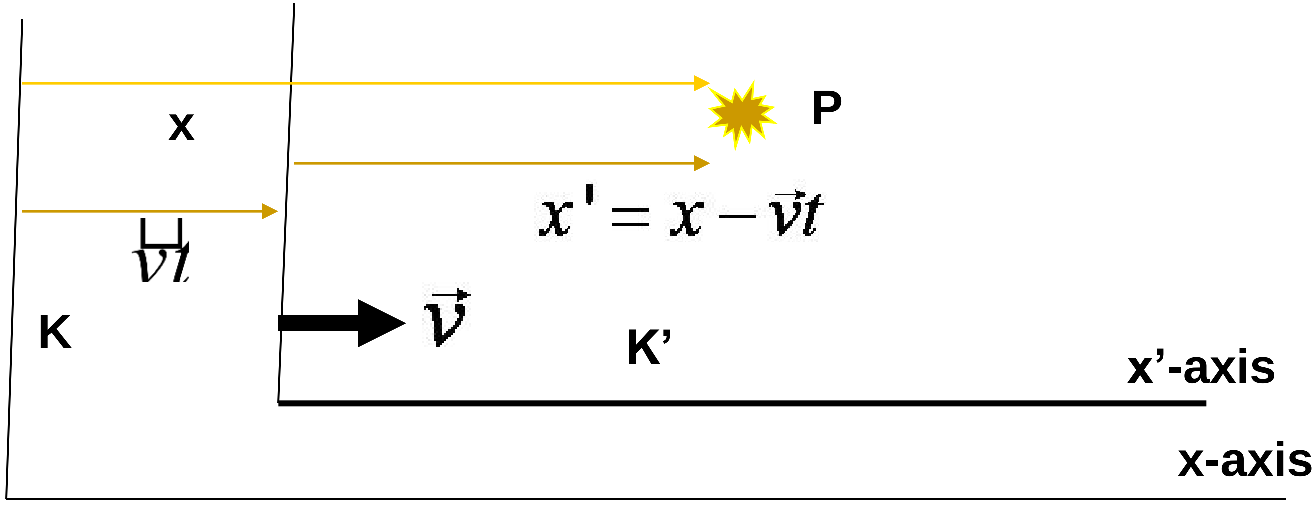


- K is at rest and K’ is moving with constant velocity
- Axes are parallel
- K and K’ are said to be *INERTIAL COORDINATE SYSTEMS*

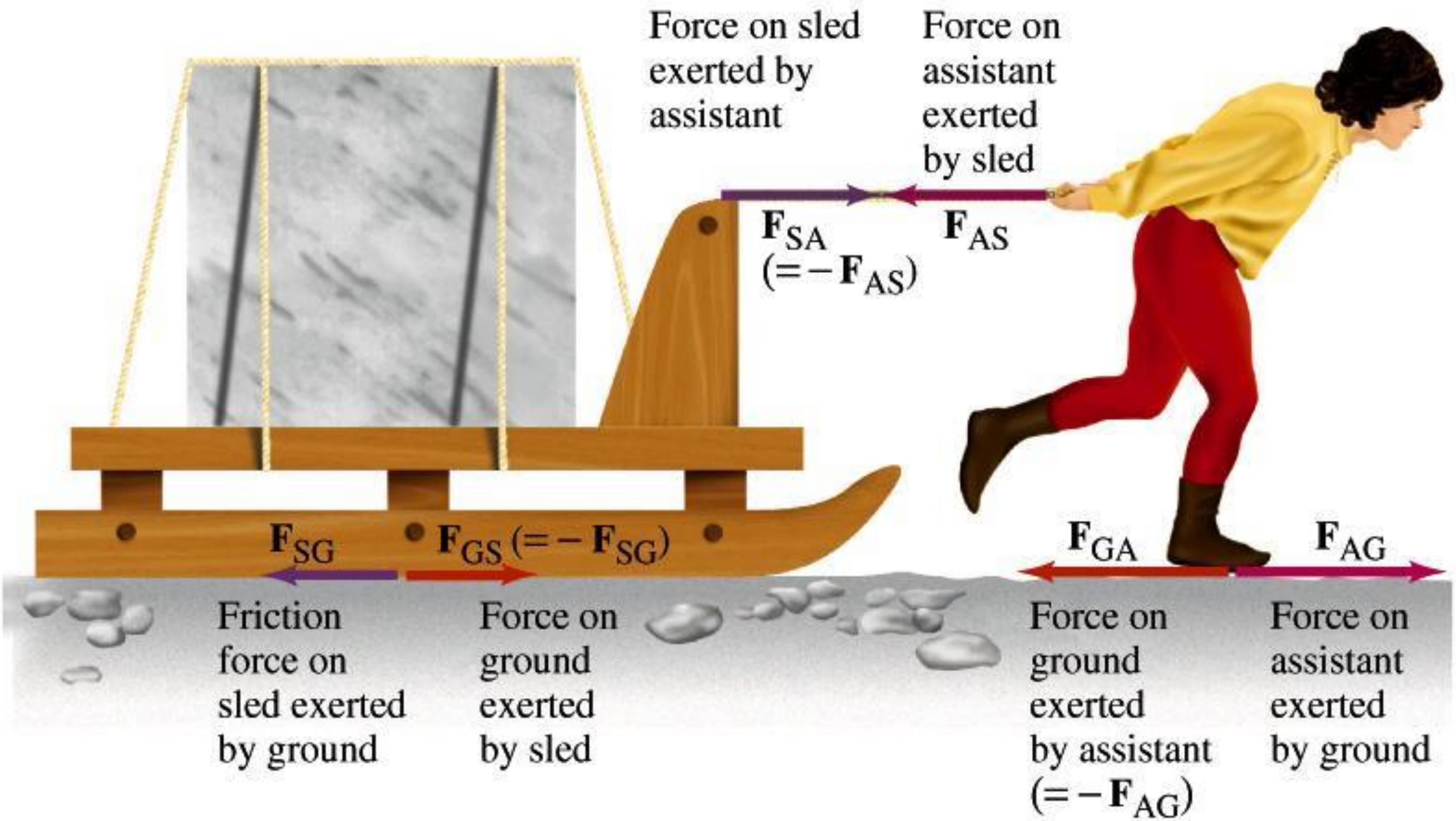
The Galilean Transformation

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

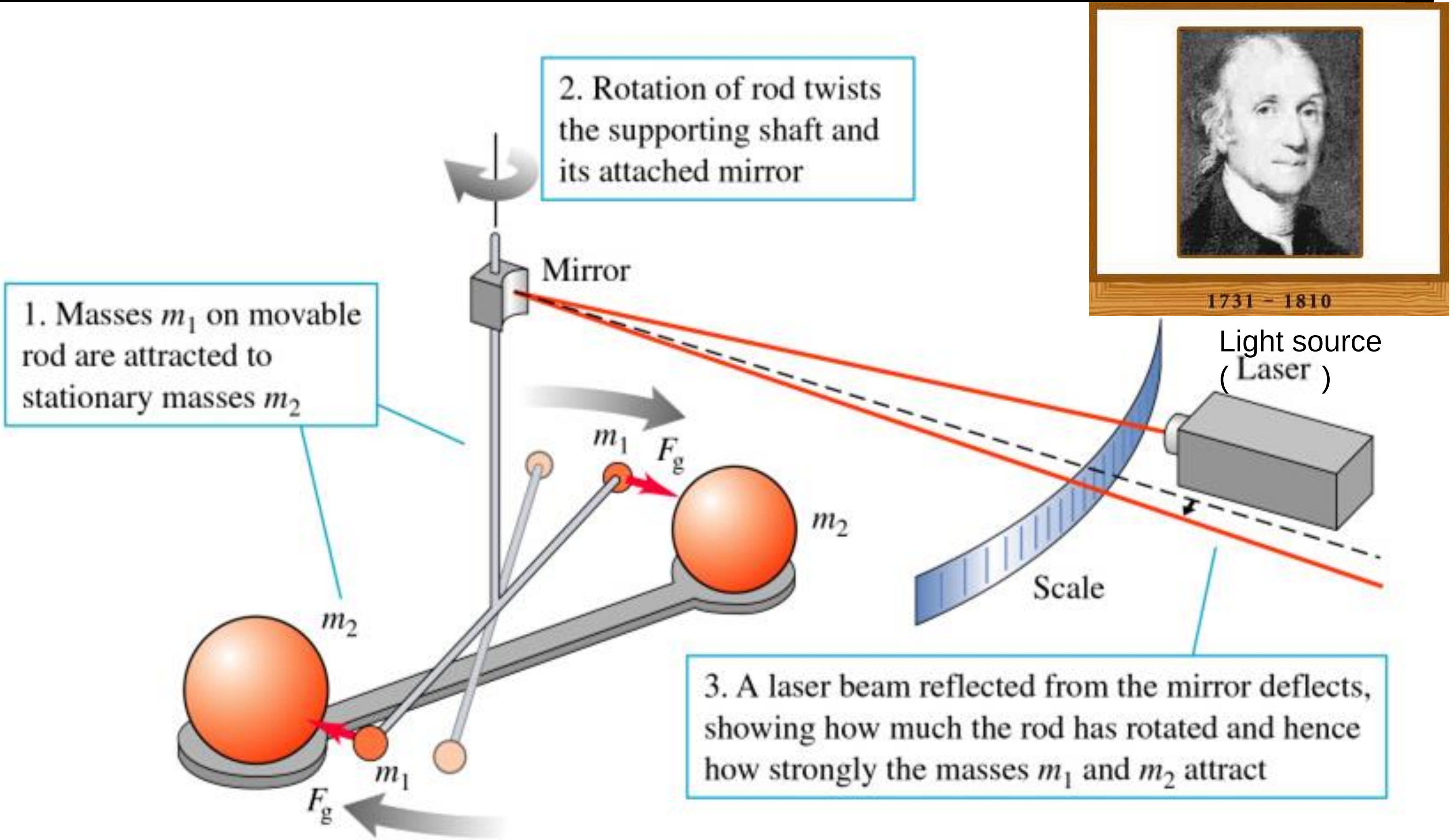
$$F_g = \frac{Gm_1 m_2}{r^2}$$

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

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



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??

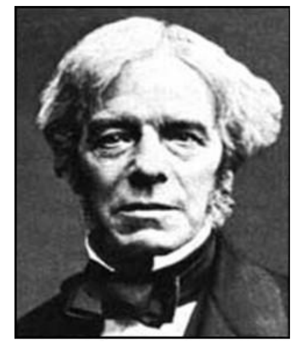
Electromagnetism: 18th-19th centuries

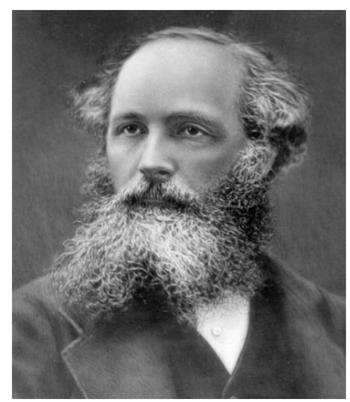
Contributions made by:

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

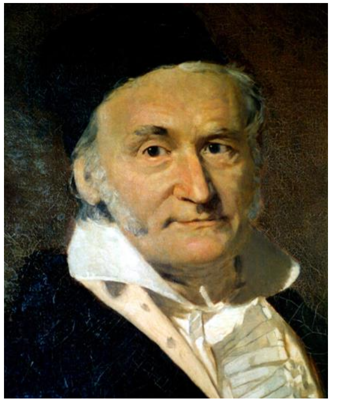









Culminates in Maxwell's Equations



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

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

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

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

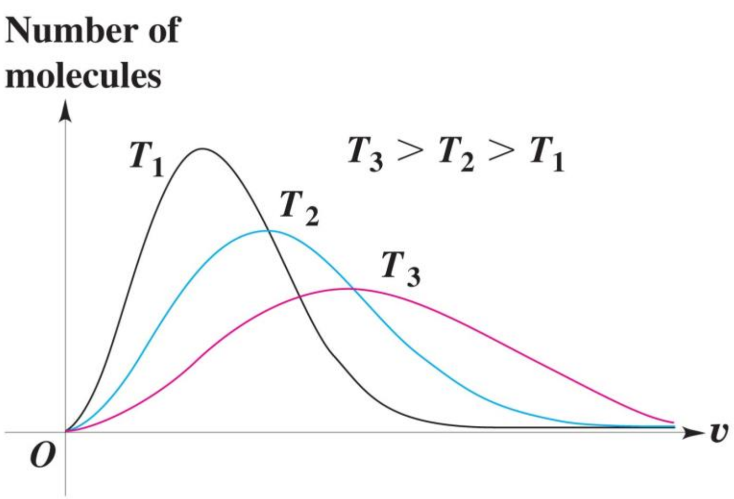
$$\boxed{v_{rms} = \sqrt{v_{av}^2} = \sqrt{\frac{3kT}{m}} = \sqrt{\frac{3RT}{M}}}$$

Consider O_2 as an ideal gas at $27°C$. Find K_{av} and K_{tr}
$27°C = 300K$ per molecule per mole

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

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

$[J/mol \cdot K]$



1.3: Waves and Particles

Two ways in which energy is transported:

1) Point mass interaction: transfers of momentum and kinetic energy: *particles*

1) 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

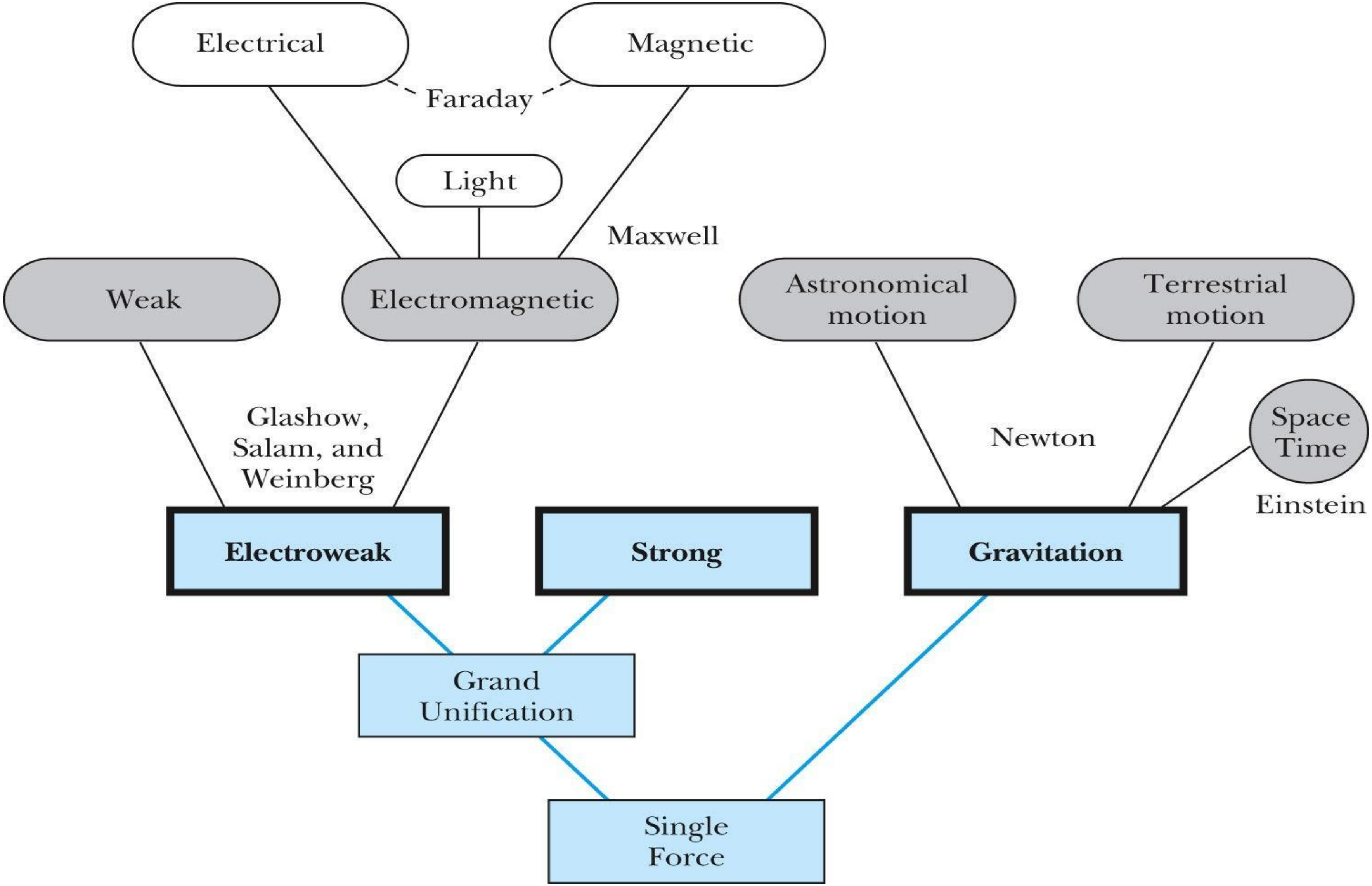
Unification

- 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 20^{th} 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