CHAPTER 1

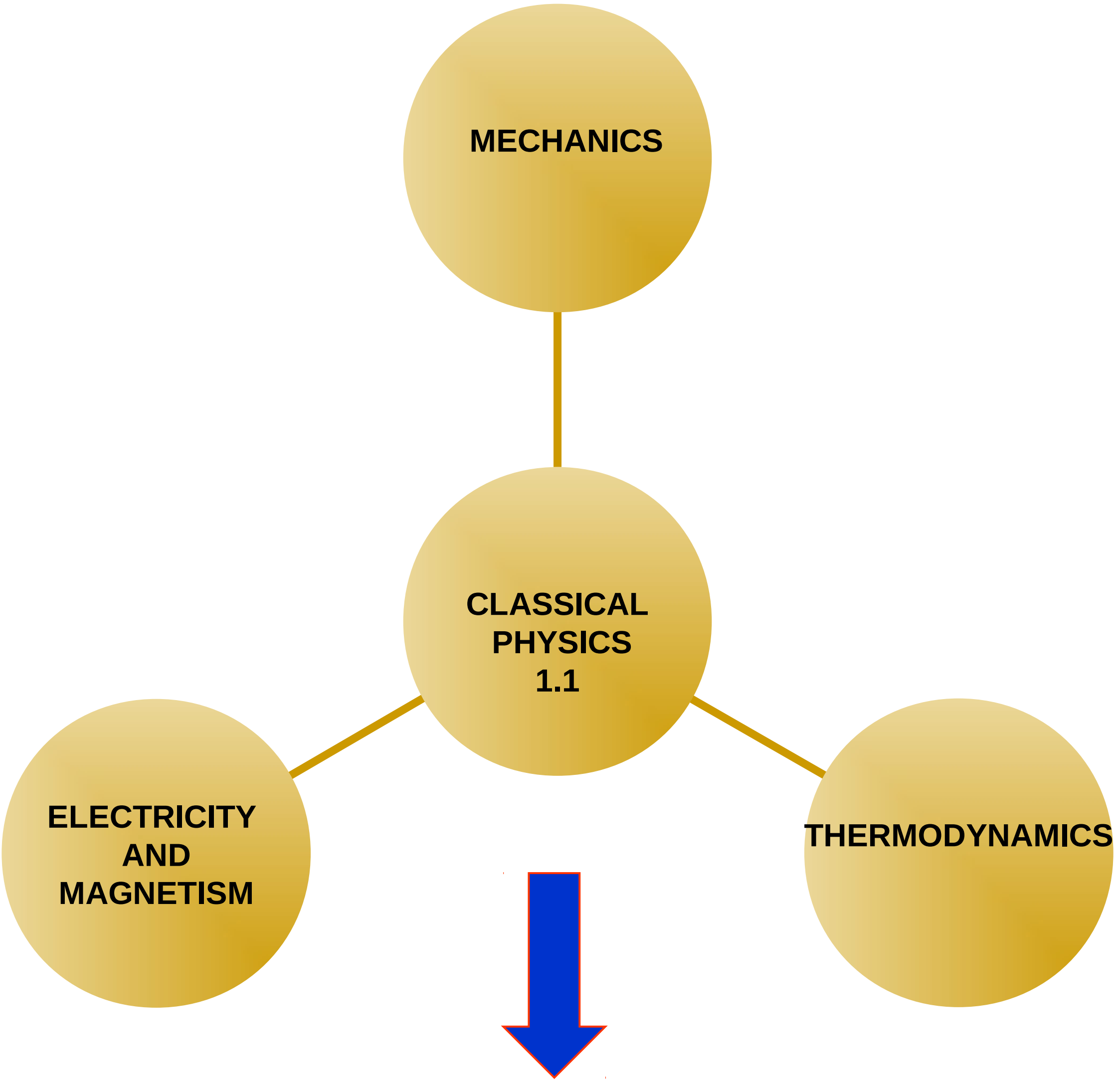
The Birth of Modern Physics

- 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 Outstanding Problems of 1895 and New Horizons

The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote…Our future discoveries must be looked for in the sixth place of decimals. - Albert A. Michelson, 1894

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

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 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.

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

Electromagnetism

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

Thermodynamics

Contributions made by:

- Benjamin Thompson (1753-1814) (Count Rumford)
- Sadi Carnot (1796-1832)
- James Joule (1818-1889)
- Rudolf Clausius (1822-1888)
- William Thompson (1824-1907) (Lord Kelvin)

Primary Results

- Establishes the atomic theory of matter
- Introduces thermal equilibrium
- Establishes heat as energy
- Introduces the concept of internal energy
- Creates temperature as a measure of internal energy
- Generates limitations of the energy processes that 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 by 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)
- Charles (1746-1823)
- 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)
- Daniel Bernoulli (1700-1782)
- John Dalton (1766-1844)
- Ludwig Boltzmann (1844-1906)
- J. Willard Gibbs (1939-1903)
- James Clerk Maxwell (1831-1879)

Primary Results

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

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

(N_A = Avogadro's Number)

Primary Results

1. The molar **heat capacity** (c_V) is given by

$$c_v = \frac{du}{dt} = \frac{f}{2} R$$

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

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
  - Both required Newtonian mass
  - 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 promotes 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 promotes 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 non-medium
- Light was 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

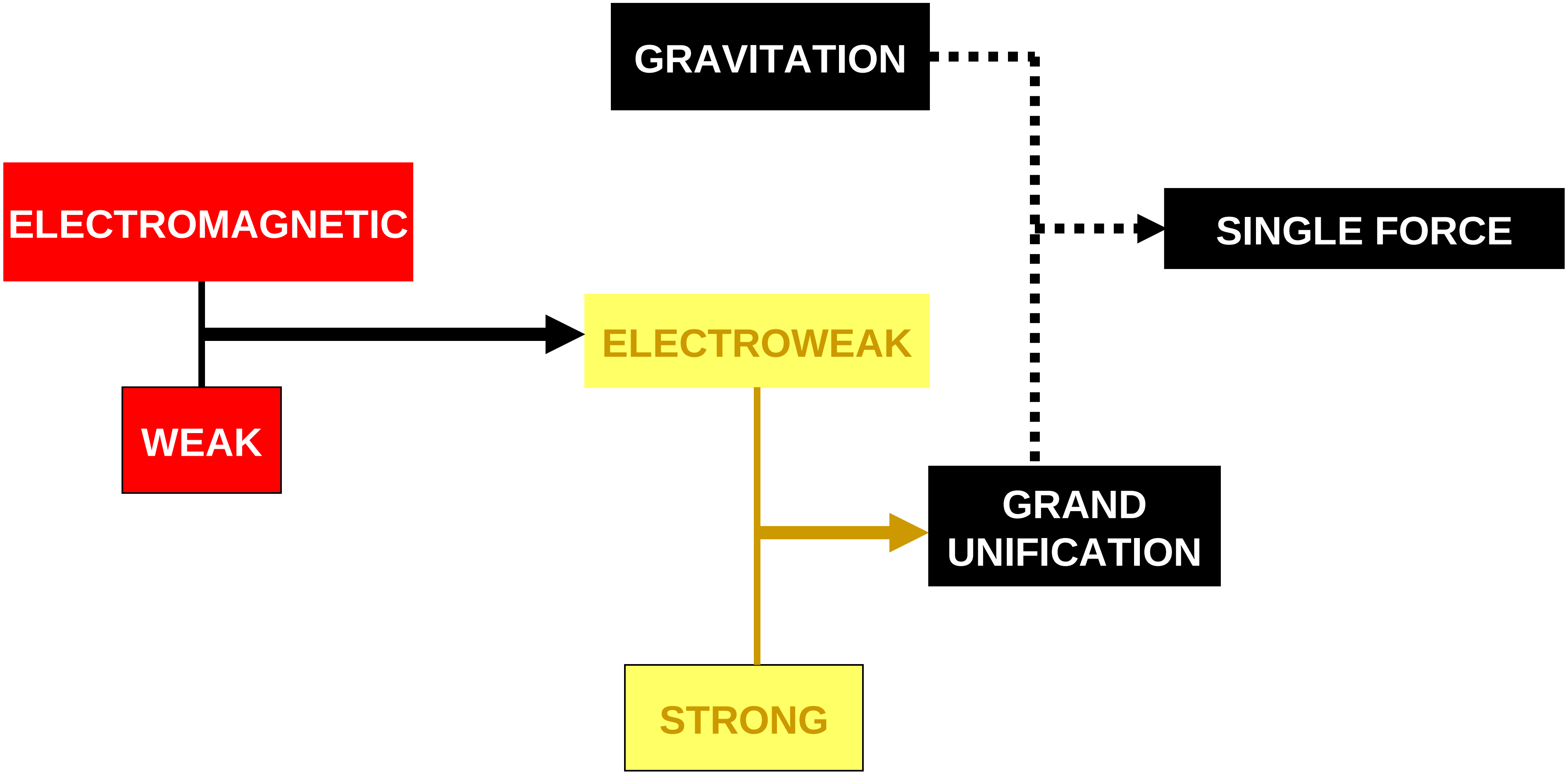
Unification

- Unification of inertial mass m_i and gravitational mass m_g
  - $m_i = m_g = m$
  - Where the same *m* responds to Newtonian force and also induces the gravitational force
- This is more appropriately referred to as the principle of equivalence in the theory of general relativity

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 Salem 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
- 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 the classical foundations
- To this end the introduction of the modern theory of relativity and quantum mechanics becomes the starting point of this most fascinating revision