CHAPTER 1
The Birth of Modern Physics

- 1.1 Classical Physics up to the early 1890s plus/minus a few years
- 1.2 The Kinetic Theory of Gases, no theory of condensed matter at all
- 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

- No idea about condensed matter, why do gold and iron have vastly different properties?? No rational way of designing materials for some specific purpose …

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.
- Chemistry uses the concept that masses are conserved in a chemical reaction – not quite true, just a very small effect, that could not be measured at the time

Mechanics

- Galileo Galilei (1564 -1642)
  - Great experimentalist
  - Principle of inertia
  - The earth may well be moving, we don’t fall off because we are moving with it
  - Conservation of mechanical energy
  - Established scientific method, interplay between theory and experiment, introduction of models to reduce complexity to a manageable level

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.

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

Universal law of gravitation $\vec{F}_g = -G\frac{m_1 m_2}{r^2}\hat{r}$ $\quad G_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa T_{\mu\nu} \quad \kappa = \frac{8\pi G}{c^4}$

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)

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

- Establishes heat as energy, can be converted to work, heat engine, motor in a car
- Introduces the concept of internal energy
- Creates temperature as a measure of internal energy
- Introduces thermal equilibrium
- Generates limitations of the energy processes that cannot take place, entropy principle

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)
- Jacques Alexandre César 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)

This is just a model, real gasses at higher densities do not really behave that way !!! Condensed matter behaves very differently,

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

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

only for idea gas, a model, dilute, only elastic collision between atoms or molecules and between the container walls and these entities

Mono-atomic gas, f = 3,

a dumbbell molecule rotating f = 5, a dumbbell molecule rotating and vibrating f = 7

Very different for solid state, Einstein to the rescue

Other Primary Results

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

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

So at a high enough temperature, there will be some molecules which move faster than the speed of light !!!

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 are observed: *waves*

Particles vs. Waves

- Two distinct phenomena describing physical interactions
  - Both require “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
  - Explains sharp shadows (they are not really sharp, but the effect is so small that it was overlooked at the time)
  - Explains 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
  - Explains reflection and refraction
  - Does not explain sharp shadows (that do not exist anyway)

The Wave Theory Advances…

- Contributions by Huygens, Young, Fresnel and **Maxwell**
- Double-slit interference patterns
- Refraction of light from air into a liquid, a spoon appears to be bend
- ***Light is an electromagnetic phenomenon***
- ***Establishes that light propagates as a wave***

- *Problem: all other waves need a medium to travel in, light also travels in a vacuum*

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)

Electromagnetic waves can have very different wavelengths and frequencies, but they all travel with the speed of light

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,**

- **introductory chemistry textbook often state that mass itself is conserved, but it really is another form of energy**

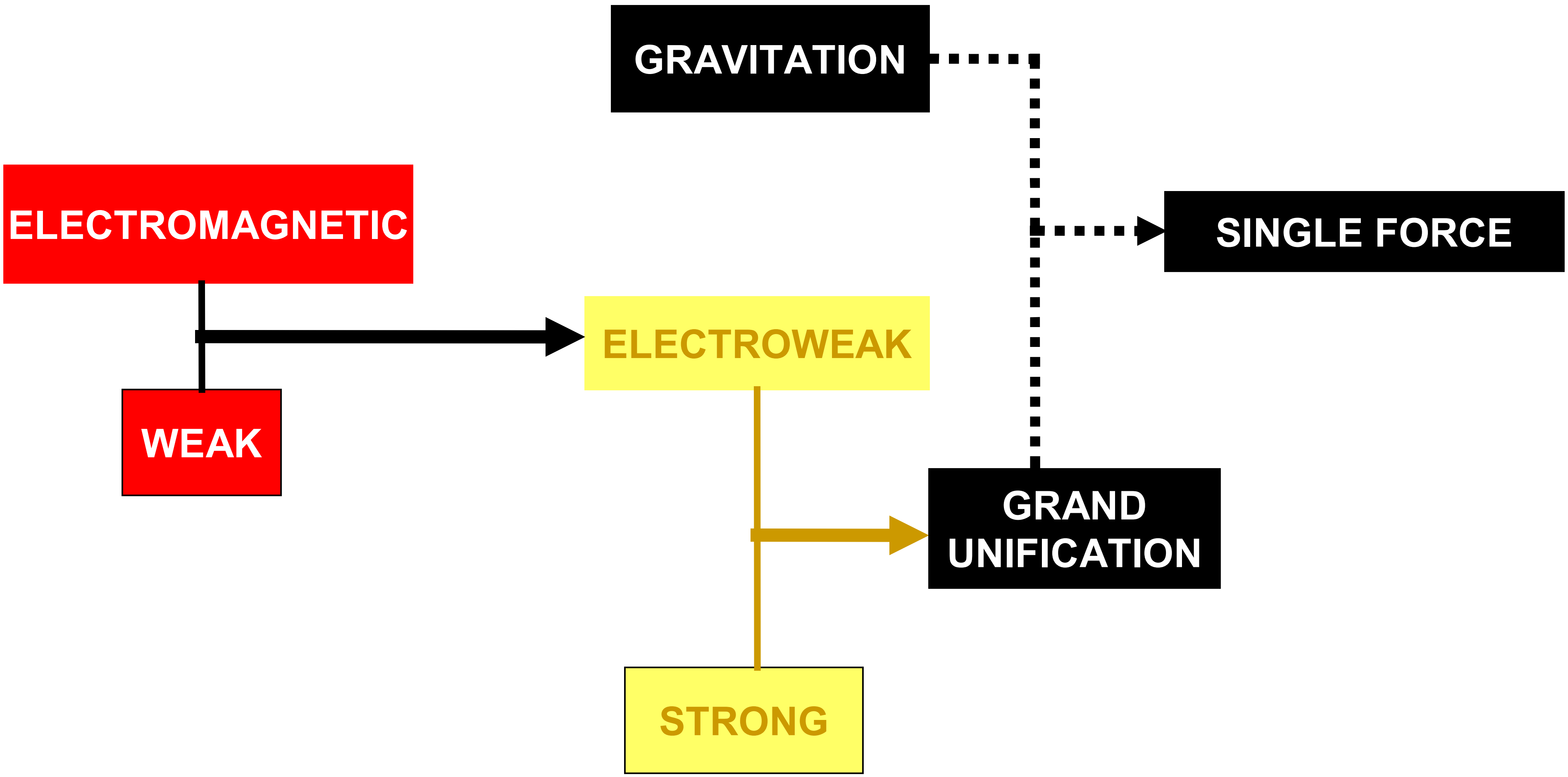
Also in the Modern Context…

- The three fundamental "forces" are introduced
  - **Gravitational**: $\vec{F}_g = -G\frac{m_1 m_2}{r^2}\hat{r}$ mass is purely understood, according Einstein's general relativity there is only curved space time
  - **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 of Forces

- Einstein unified the electric and magnetic forces as fundamentally the same force; now referred to as the **electromagnetic force, special relativity was needed for that**
- 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 model atoms in an ideal gas (again a model, so only valid for the model conditions)
- Robert Brown (1753 – 1858) observes microscopic “random” motion of suspended grains of pollen in water
- Einstein in 1905 explains this random motion using atomic theory, and determines that sucrose (common sugar) molecules are about one nm in size (atoms are an order of magnitude smaller), **start of quantitative nanoscience**
- 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

  - Revolutionary idea, properties of matter should be due to their structure (rather than their very nature)

Further Complications

Three fundamental problems:

- The necessity of the existence of an “electromagnetic medium” for light waves to travel in
- 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 – modern physics starts from the necessity of energy in bound systems to be quantized in order for Max Planck’s theory to fit experimental data over a very large range of wavelengths

Additional discoveries that complicate classical physics interpretations

- Discovery of x-rays, 1895
- Discovery of radioactivity, 1896
- Discovery of the electron, 1897
- Discovery of the Zeeman effect, 1897

- And modern physics takes off in October 1900, first ignored, Max Planck deeply unhappy of the implication of his black-body radiation formula then Einstein in 1905 delivers the major theoretical breakthroughs

The Beginnings of Modern Physics

- These new discoveries and the many resulting inconsistencies required a revision of the fundamental physical assumptions that let to classical physics in the first place, which is just fine if large things move at low velocities

- The very small and the very fast are very different:
- *"In a fundamental sense, all extant physical theories are false. Each is a good representation of nature only over a limited range of the independent variables."*

Concepts of Modern Physics, Unraveling Old and New Mysteries by George Duffey, 2010,