TOPIC 1

Physics (NPHY 32104)

Mechanics

Introduction to Modern Physics

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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

CHAPTER 1
The Birth of Modern Physics

- The discipline of physics has its roots in the work of Galileo and Newton and others in the scientific revolution of the 16^{th}sixteenth and 17^{th} centuries.

- The knowledge and practice of physics grew steadily for 200 to 300 years until another revolution in physics took place, which is the subject of this book.

- Physicists distinguish classical physics, which was mostly developed before 1895, from modern physics, which is based on discoveries made after 1895.
- The precise year is un important, but monumental changes occurred in physics around 1900.

There is nothing new to be discovered in physics now. All that remains is more and more precise measurement. ***William Thomson (Lord Kelvin), 1900***

1.1: Classical Physics of the 1890s

- Mechanics
- Electromagnetism
- Thermodynamics

- The ideas of classical physics are just as important and useful today as they were at the end of the nineteenth century.
  - For example, they allow us to build automobiles, telephones and produce electricity

1.1: Classical Physics of the 1890s

- Mechanics
- Electromagnetism
- Thermodynamics

- No idea about condensed matter, why do gold and iron have vastly different properties??
- Classical physics didn't clearly explain the structure of matter
- 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 (vector relation).
- **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 Galilee (1564 -1642)
  - Great experimentalist
  - Principle of inertia
  - The earth may well be moving, we don’t fall off because we are moving with it, **Galiee’s relativity of mechanical experiments**
  - **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)

- We owe to Newton our present understanding of motion.
- He understood clearly the relationships among position, velocity, displacement, and acceleration
- He was able to elucidate the 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)

Electromagnetism

Maxwell (1831-1879)

- Electricity and magnetism were separate subjects for hundreds of years.
- These were combined by James Clerk Maxwell in his four equations.
- Maxwell showed optics to be a special case of electromagnetism.
- Waves, which permeated mechanics and optics, were known to be an important component of nature.
-
- Many natural phenomena could be explained by wave motion using the laws of physics

Culminates in Maxwell's Equations

- Gauss's law (Φ_E): (electric field)
  - The electric field flux passing through any closed surface is proportional to the total charge within that surface

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

- Gauss's law (Φ_B): (magnetic field)
  - The total magnetic flux passing through any closed surface is zero

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

- Faraday's law:
  - Changing magnetic flux through a surface induces an EMF in any boundary path of that surface

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

- Ampère's law:
  - Electric currents and changes in electric fields are proportional to the magnetic fields circulating about the areas where they accumulate

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

Magnetism (electrodynamis) and electrostatics are really the same phenomenon

Maxwell's Equations

$$\nabla \cdot E = \frac{\rho}{\varepsilon_0}$$

Gauss's Law: The electric field's mapping is equal to the charge density divided by the permittivity of free space. The relationship between electric field and electric charge

$$\nabla \cdot B = 0$$

Gauss's Law for Magnetism: The net magnetic flux out of any closed surface is zero. There is no such thing as a magnetic monopole

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

We can make an electric field by changing a magnetic field

$$\nabla \times B = u_0 J + \mu_0 \varepsilon_0 \frac{\partial E}{\partial t}$$

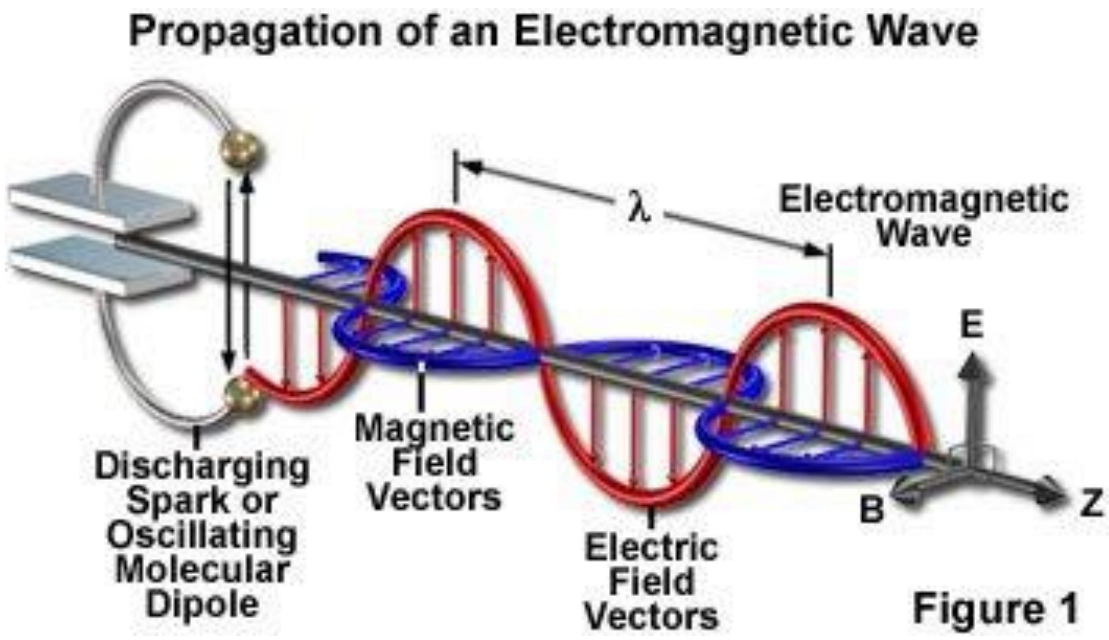
We can make a magnetic field with a changing electric field or with a current

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

Culminates in Maxwell's Equations

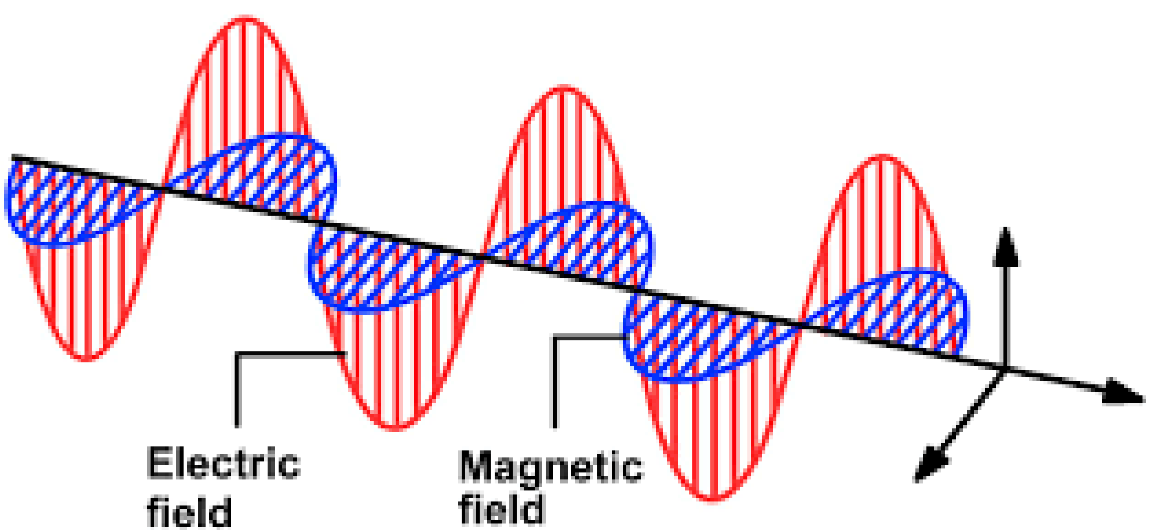
- Maxwell's equations indicate that charges and currents create fields, and in turn, these fields can create other fields, both electric and magnetic

Magnetism (electrodynamis) and electrostatics are really the same phenomenon



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

Wave in both space and time, λ [m] and T period [s] = 1/f



Thermodynamics

Contributions made by:

- Amedeo Avogadro (1776-1856)
- Daniel Bernoulli (1700-1782)
- Benjamin Thompson (1753-1814) (Count Rumford)
- Sadi Carnot (1796-1832)
- John Dalton (1766-1844)
- James Joule (1818-1889)
- Rudolf Clausius (1822-1888)
- William Thompson (1824-1907) (Lord Kelvin)

Crowning achievements

- **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
- defines temperature as a measure of internal energy
- Introduces idea of thermal equilibrium
- Generates limitations of the energy processes that cannot take place,
- Entropy maximation 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. **OR** Heat flows from a body of higher temperature to a body of lower temperature.

- **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 is 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)

R = 8.3144598 J mol^{-1} K^{-1} $N_A = 6.02214076 \times 10^{23}$ mol^{-1}

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 !!!

k: Bolzmann's constant: 1.380649 × 10^{-23} m^2 kg s^{-2} K^{-1} (Nm K^{-1} or Ws K-1 or J K^{-1})

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
  - 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 transversal wave***

Problem: all other waves need a medium to travel in, but light also travels in what appears to be 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**

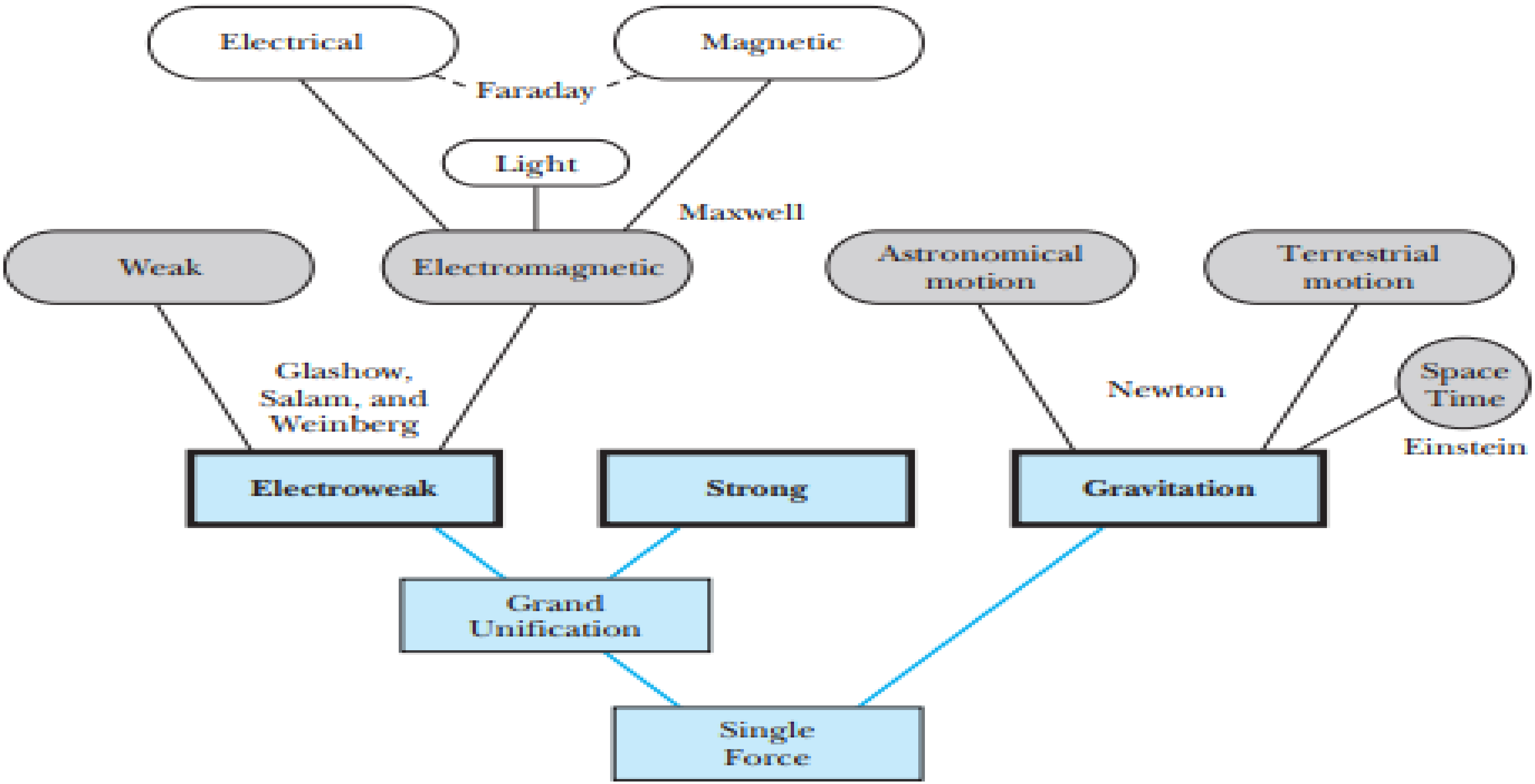
Also in the Modern Context…

- The three fundamental “forces” are introduced
  - **Gravitational**: $\vec{F}_g = -G\dfrac{m_1 m_2}{r^2}\hat{r}$ 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**: $\vec{F}_C = \dfrac{1}{4\pi\varepsilon_0}\dfrac{q_1 q_2}{r^2}\hat{r}$ (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



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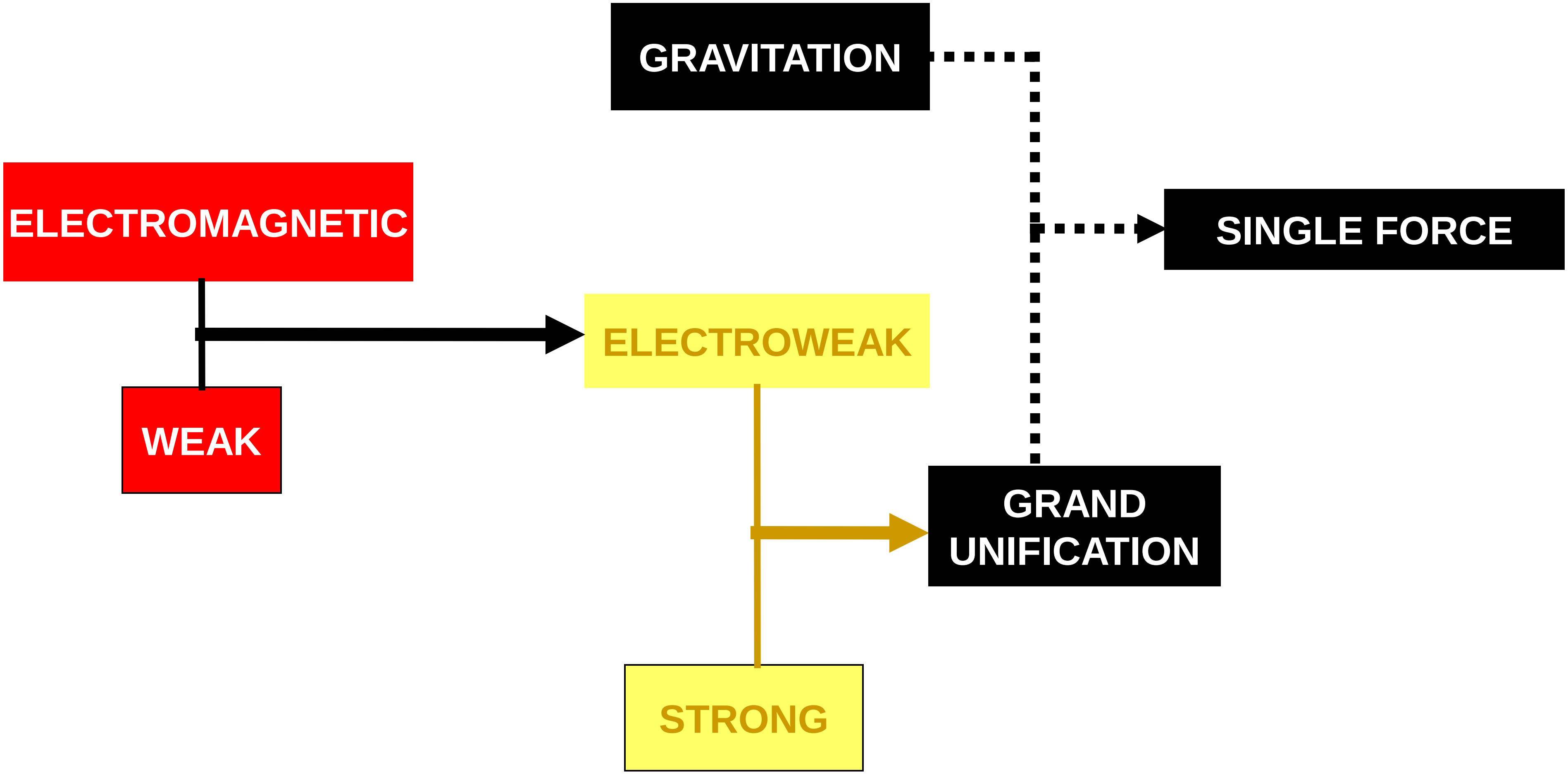


1.5: The Atomic Theory of Matter

- 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, physical foundations of future **law of definite proportions**
- John 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/contents (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

Further Complications

Three fundamental problems:

- **Electromagnetic Medium**
  - The waves that were well known and understood by physicists all had media in which the waves propagated.
  - Water waves traveled in water, and sound waves traveled in any material.
  - It was natural for nineteenth century physicists to assume that electromagnetic waves also traveled in a medium, and this medium was called the ether.
  - Several experiments, the most notable of which were done by Michelson, had sought to detect the ether without success.

Further Complications

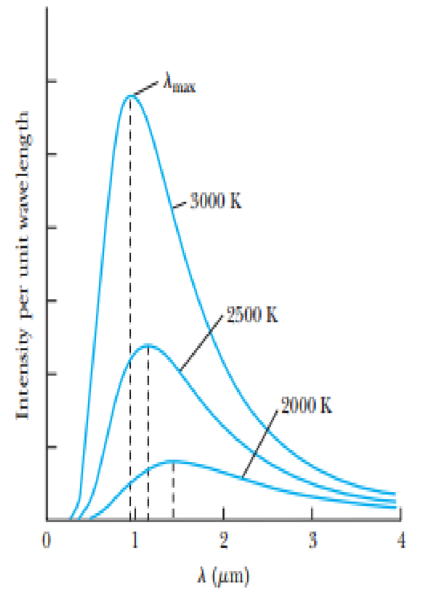
Three fundamental problems:

- **Electrodynamics**
  - The other difficulty with Maxwell's electromagnetic theory had to do with the electric and magnetic fields as seen and felt by moving bodies.
  - What appears as an electric field in one reference system may appear as a magnetic field in another system moving with respect to the first.
  - Although the relationship between electric and magnetic fields seemed to be understood by using Maxwell's equations, the equations do not keep the same form under a Galilean transformation.

Further Complications

Three fundamental problems:

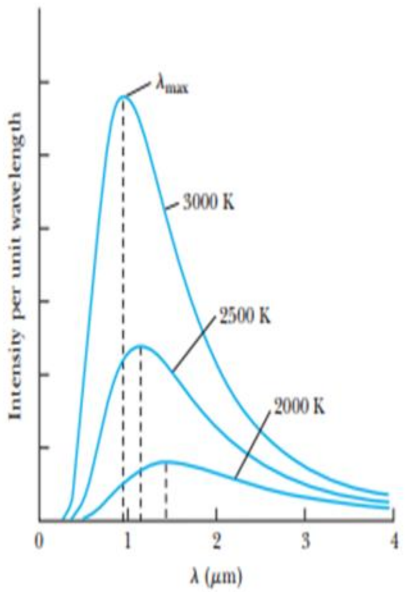
- **Blackbody Radiation**
  - One of the interesting experiments in thermodynamics concerns an object, called a blackbody,
  - A blackbody is an object that absorbs the entire spectrum of electromagnetic radiation incident on it.
  - An enclosure with a small hole serves as a blackbody, because all the radiation entering the hole is absorbed.
  - A blackbody also emits radiation, and the emission spectrum shows the electromagnetic power emitted per unit area.
  - The radiation emitted covers all frequencies, each with its own intensity.



Further Complications

Three fundamental problems:

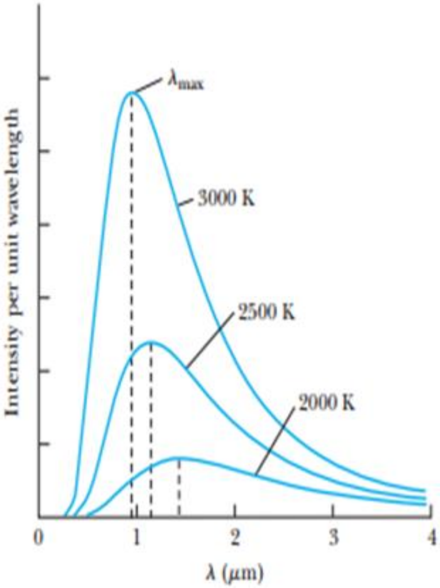
- **Blackbody Radiation**
  - Precise measurements were carried out to determine the spectrum of blackbody radiation, such as that shown in Figure 1.8.
  - Blackbody radiation was a fundamental issue, because the emission spectrum is independent of the body itself—it is characteristic of all blackbodies.
  - It was possible to understand the spectrum both at the low-frequency end and at the high-frequency end, but no single theory could account for the entire spectrum.



Further Complications

Three fundamental problems:

- **Blackbody Radiation**
  - When the most modern theory of the day **(the equipartition of energy applied to standing waves in a cavity)** was applied to the problem, the result led to an infinite emissivity (or energy density) for high frequencies.
  - The failure of the theory was known as the "ultraviolet catastrophe."
  - The solution of the problem by Max Planck in 1900 would shake the very foundations of physics.



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 led 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,

The Concepts of Space and Time in classical and Modern Physics

- **The Concept of Time**
- In high-energy collisions between two protons, many new particles can be produced, one of which is a pi meson (also known as a pion).

- When the pions are produced at rest in the laboratory, they are observed to have an average lifetime (the time between the production of the pion and its decay into other particles) of 26.0 ns (nanoseconds, or $10^{-9}s$).

- On the other hand, pions in motion are observed to have a very different lifetime.
- In one particular experiment, pions moving at a speed of $2.737 \times 10^8\ m/s$ (91.3% of the speed of light) showed a

The Concept of Time

- Let us imagine this experiment as viewed by two different observers

  - Observer #1, at rest in the laboratory, sees the pion moving relative to the laboratory at a speed of 91.3% of the speed of light and measures its lifetime to be 63.7 ns.

  - Observer #2 is moving relative to the laboratory at exactly the same velocity as the pion, so according to observer #2 the pion is at rest and has a lifetime of 26.0 ns.

The Concept of Time

- The two observers measure different values for the time interval between the same two events—the formation of the pion and its decay.
- According to Newton, time is the same for all observers. Newton’s laws are based on this assumption.
- The pion experiment clearly shows that time is not the same for all observers.
- Which indicates the need for a new theory that relates time intervals measured by different observers who are in motion with respect to each other

The Concepts of Space and Time in classical and Modern Physics

The Concept of Space

- The pion experiment also leads to a failure of the classical ideas about space.
  - Suppose observer #1 erects two markers in the laboratory, one where the pion is created and another where it decays.
  - The distance D_1 between the two markers is equal to the speed of the pion multiplied by the time interval from its creation to its decay:
    - $D_1 = (2.737 \times 10^8\, m/s)\,(63.7 \times 10^{-9} s) = 17.4m$
  - To observer #2, traveling at the same velocity as the pion, the laboratory appears to be rushing by at a speed of $2.737 \times 10^8\, m/s$
  - The time between passing the first and second markers, showing the creation and decay of the pion in the laboratory, is 26.0 ns.

The Concepts of Space and Time in classical and Modern Physics

The Concept of Space

- According to observer #2, the distance between the markers is $D_2 = (2.737 \times 10^8\, m/s)(2.6\ \times 10^{-9}\, s) = 7.11m.$

- Once again, we have two observers in relative motion measuring different values for the same interval, in this case the distance between the two markers in the laboratory.

- The physical theories of Galileo and Newton are based on the assumption that space is the same for all observers, and so length measurements should not depend on relative motion.

- The pion experiment again shows that this cornerstone of classical physics is not consistent with modern experimental data.