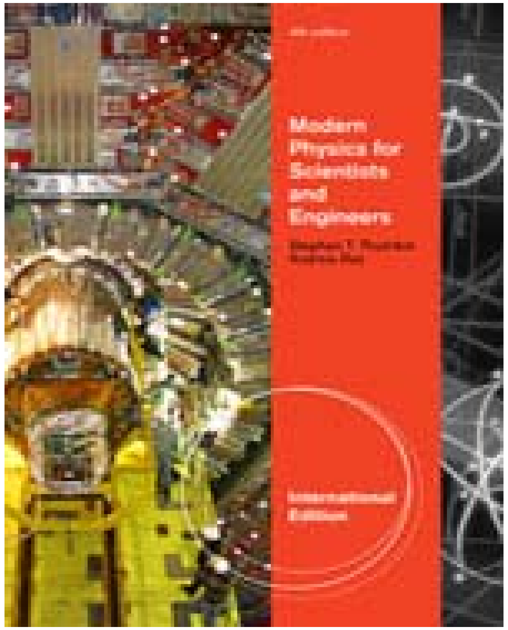
Modern Physics for Scientists and Engineers International Edition, 4th Edition

송석호 교수

자연과학관 445호
shsong@hanyang.ac.kr
http://optics.hanyang.ac.kr/~shsong



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The lecture notes used in this class are originally downloaded before modification from the website: http://physics.lakeheadu.ca/courses/P2331/P2331.php

1. THE BIRTH OF MODERN PHYSICS
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CHAPTER 1

The Birth of Modern Physics

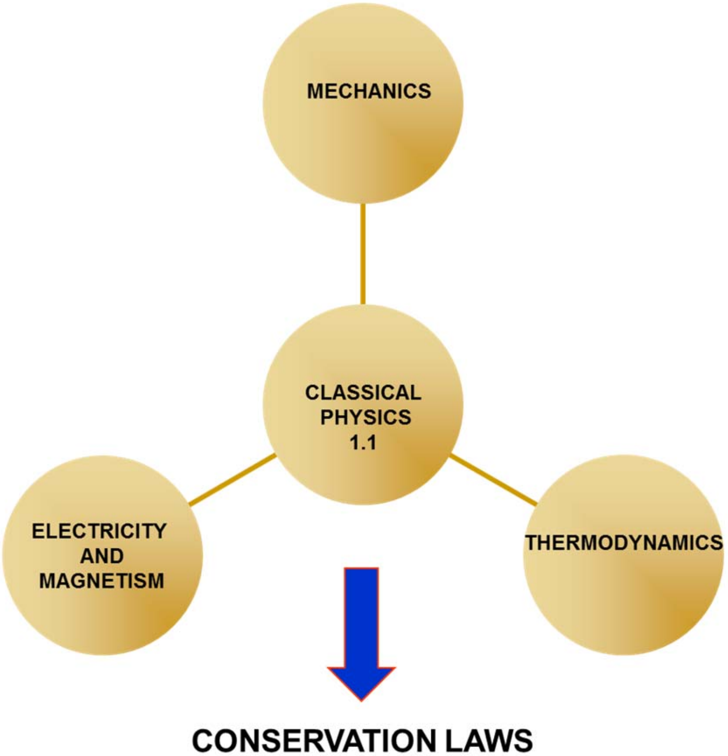
- "Modern Physics"
  - Physics based on discoveries made after 1895
- "Classical Physics"
  - Developments before 1895
    - Newton's Laws
    - Maxwell's Equations
    - Laws of Thermodynamics
  - Pervasive view late 19th century, physics "all wrapped up"

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

There is nothing new to be discovered in physics now. All that remains is more and more precise measurement. - Lord Kelvin, 1900.

1.1: Classical Physics of the 1890s

- Mechanics
- Electromagnetism
- Thermodynamics



Triumph of Classical Physics: Conservation Laws

- **Conservation of energy**
- **Conservation of linear momentum**
- **Conservation of angular momentum**
- **Conservation of charge**
- **Conservation of mass ??**

Mechanics

- Galileo (1564-1642)
  - Established experimental foundations and principle of inertia

- Isaac Newton (1642-1727)
  - provided insight into relationship between position, velocity, acceleration, and the forces underlying motion.
  - Insight encompassed in 3 laws of motion.

Newton’s Laws of Motion

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**: The acceleration of a body is proportional to the net force and inversely proportional to the mass.

$$\vec{a} = \frac{\vec{F}}{m} \rightarrow \vec{F} = m\vec{a}$$

A more general statement relates force (F) as responsible for the change in linear momentum (p):

$$\vec{F} = \frac{d\vec{p}}{dt} = \frac{d(m\vec{v})}{dt} = \frac{dm}{dt}\vec{v} + \frac{d\vec{v}}{dt}m$$

- **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

- Building on developments of others (Coulomb, Oersted, Young, Ampère, Faraday),
- Maxwell (1831-1879) summarized the behavior of electricity and magnetism in four equations:

$\oint \vec{E} \cdot d\vec{A} = \frac{q}{\varepsilon_0}$	Gauss's law (E field)
$\oint \vec{B} \cdot d\vec{A} = 0$	Gauss's law (B field)
$\oint \vec{E} \cdot d\vec{s} = -\frac{d\Phi_B}{dt}$	Faraday's law
$\oint \vec{B} \cdot d\vec{s} = \mu_0 \varepsilon_0 \frac{d\Phi_E}{dt} + \mu_0 I$	Ampère's law:

$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$ **Lorentz law (force)**

Thermodynamics

- deals with variables of temperature T, heat Q, work W, and internal energy U of systems.
  - developed in 19th century
- Primary results can be described in following laws
  - **The "zeroth" law:** Two systems in thermal equilibrium with a third system are in thermal equilibrium with each other.
  - **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

    $$\Delta U = Q + W$$

    (generalizes conservation of energy to include heat)
  - **Second law:** It is not possible to convert heat completely into work without some other change taking place.
  - **Third law:** It is not possible to achieve an absolute zero temperature

1.2: The Kinetic Theory of Gases

- Theory introduced fact that gases are composed of atoms and molecules in rapid motion bouncing off one another and off walls of container (widely accepted by 1895).
- Culminates in the **ideal gas equation** for *n* moles of a "simple" gas:

$$PV = nRT$$

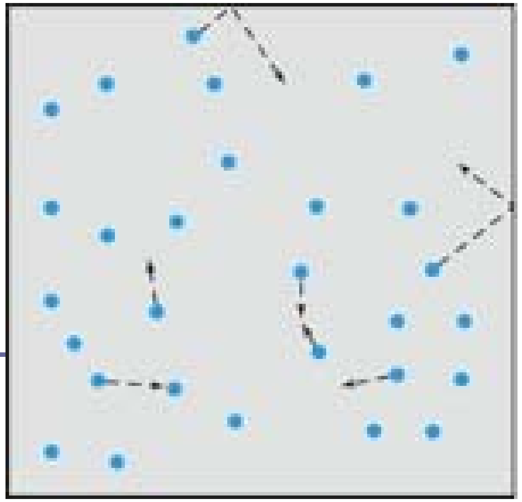
- Statistical interpretation of thermodynamics developed in later half of nineteenth century by Maxwell, Boltzmann, Gibbs.

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

i.e. Average kinetic energies of molecules is prop. to the temperature and internal energy of gas.

$\langle K \rangle$ = *average kinetic energy of molecules*

f = *degrees of freedom (3 translation)*



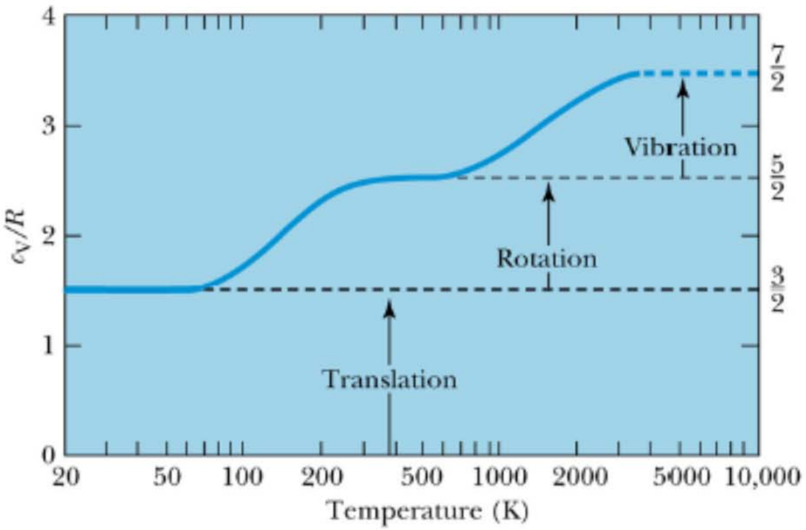
Other Developments

- **Equipartition Theorem**
  - each degree of freedom (f) of a molecule contributes an average energy $\frac{1}{2}k_B T$ to the internal energy.

    ($k_B \equiv$ Boltzmann's constant = R/N_A)

    - translation $f = 3$, rotation and vibration add more

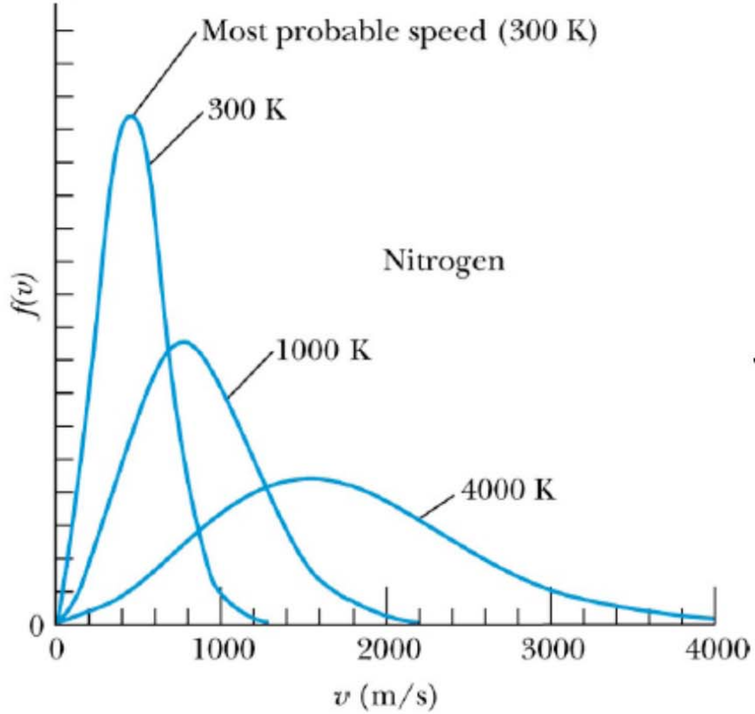
$$U = f \times \left(\frac{1}{2} nRT \right)$$



$$C_V \equiv \frac{\partial U}{\partial T} = \frac{f}{2} nR$$

Molar heat capacity for H_2 Gas

- Kinetic theory also provides insight into:
  - diffusion, speed of sound, mean free path and collision frequency
  - **Maxwell's Speed Distribution** (1850's)
    - Distribution of speeds as a function of speed and T.



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

Maxwell-Boltzmann Distribution

- Maxwell-Boltzmann dist. can be used to determine the root-mean-square (rms) speed of the molecules

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

$$\therefore U = nN_A \langle K \rangle = nN_A \frac{m\langle v^2 \rangle}{2}$$

$$= \frac{3}{2} nRT$$

1.3: Waves and Particles

- Many aspects of physics can be understood by treating the bodies as simple **particles** and collisions which transfer of momentum and kinetic energy.

- Conversely other natural phenomena can only be understood in terms of **waves** wherein energy is transfered by way of vibrations.

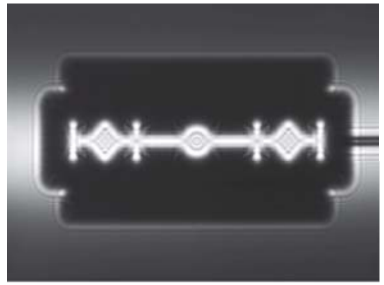
  - The distinctions are observationally quite clear; however, not so for the case of visible light

  - Thus by the 17th century begins the major disagreement concerning the nature of light

The Nature of Light

- Nature of light debated since time of Isaac Newton (1642-1742)
- Interference experiments by Young were thought to settle the debate in 1802 i.e. light a wave.
- In 1860 Maxwell proposed theoretically that light consisted of oscillating electric and magnetic fields.
- *Maxwells ideas verified by Hertz in 1887*

Conclusion: light propagates as a wave



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Light a wave?

- Apparent certainty lasted only 20 years
- Unresolved issues with EM waves lead to the two revolutionary theories of modern physics!

1. **Relativity**

2. **Quantum Mechanics**

1.4: Conservation Laws and Fundamental Forces

- Recall conservation laws are guiding principles in classical physics
- We will see that in Modern Physics refinement of these laws will be required
  - i.e. in relativity:
    - **conservation of mass**
    - **conservation of energy**

    } **conservation of mass-energy**.

Also in the Modern Context…

- The three fundamental forces are introduced
  - **Gravitational**: $\vec{F}_g = -G\frac{m_1 m_2}{r^2}\hat{r}$
  - **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

Goal: Unification of All Forces into a Single Force

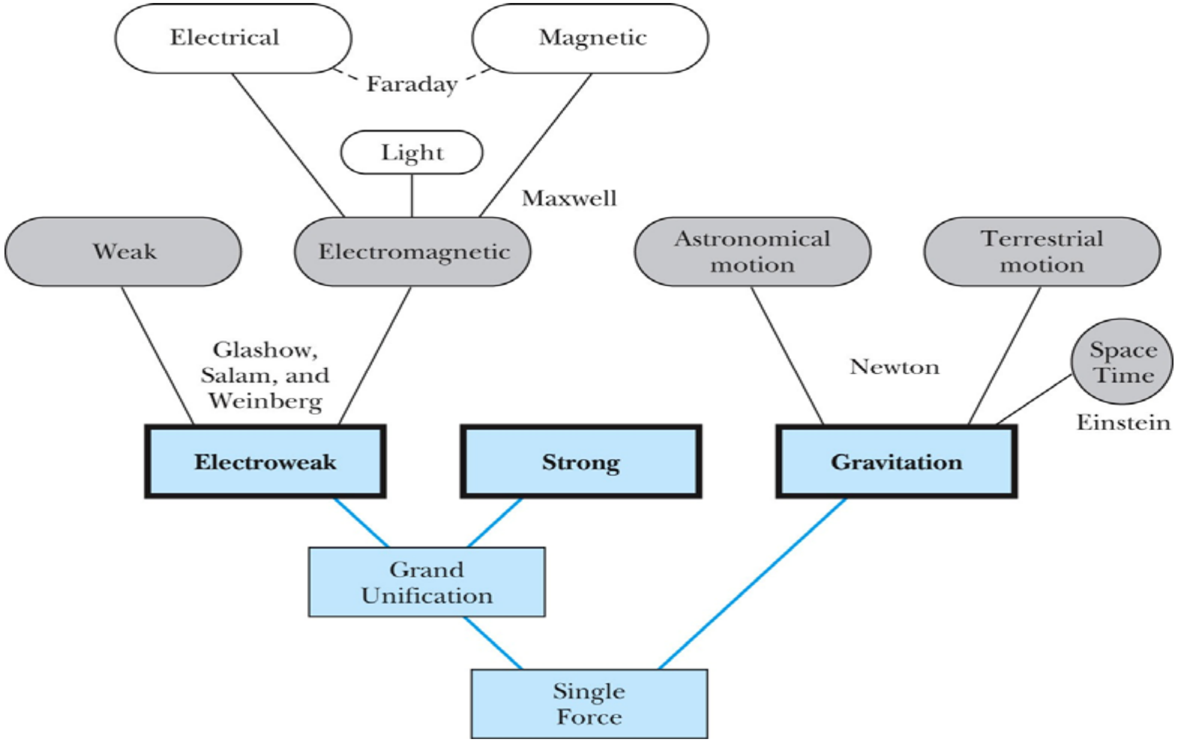


Table 1.1 Fundamental Forces

Interaction		Relative Strength*	Range
Strong		1	Short, $\sim 10^{-15}$ m
Electroweak	Electromagnetic	10^{-2}	Long, $1/r^2$
	Weak	10^{-9}	Short, $\sim 10^{-15}$ m
Gravitational		10^{-39}	Long, $1/r^2$

*These strengths are quoted for neutrons and/or protons in close proximity.

1.5: The Atomic Theory of Matter

- Initiated by Democritus and Leucippus (~450 B.C.)
  (first to us the Greek ***atomos***, meaning "indivisible")
- **Avogadro** proposes in 1811 that all gases at the same temperature, pressure, and volume contain the ***same number of molecules (atoms)***; 6.02×10^{23} atoms
- Robert **Brown** (1753 – 1858) observes in 1827 microscopic "random" motion of suspended grains of pollen in water -> ***Brownian motion***
- **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
- **Einstein** in the 20th century explains Brownian motion using atomic theory

Overwhelming Evidence for Existence of Atoms

- **Albert Einstein** (1879 – 1955), in one of his three famous papers published in 1905 (the others were about special relativity and photoelectric effect), uses molecules to explain Brownian motion and determines the approximate sizes and masses of atoms and molecules from experimental data.

- **Jean Perrin** (1870 – 1942) in 1908 experimentally verifies Einstein's predictions. His experiment was constituent with the Einstein's atomic theory and gave a quantitative determination of Avogadro's number.

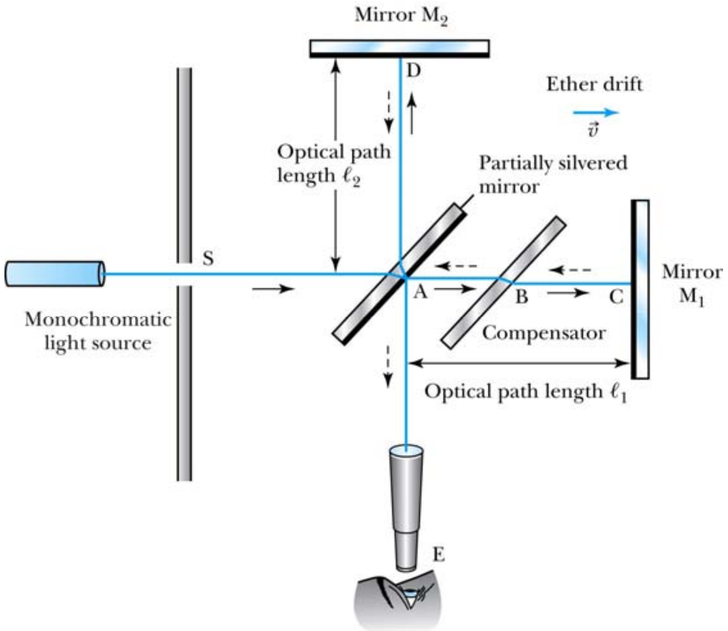
- Since 1908 the atomic theory of matter has been accepted.

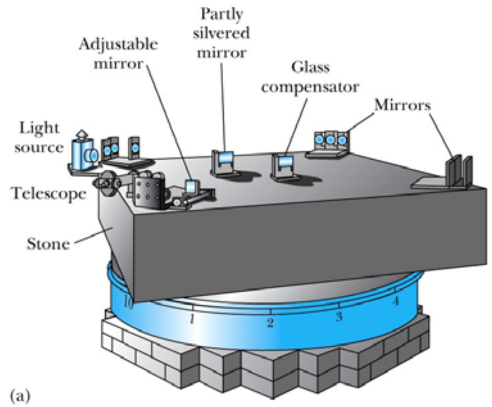
1.6: Unresolved Questions of 1895 and New Horizons

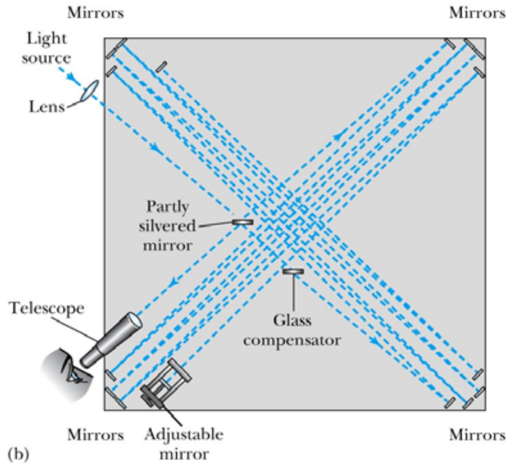
- In famous speech in 1900 Lord Kelvin referred to ***"two clouds on the horizon"***
  - *Electromagnetic Ether* ⟶ *Relativity*
  - *The failure of classical physics to explain blackbody radiation.* ⟶ *Quantum Mechanics*

Electromagnetic Ether

- Ether: Medium for Electromagnetic waves.
- Up to 1895 experimental attempts to detect the Ether were unsuccessful.



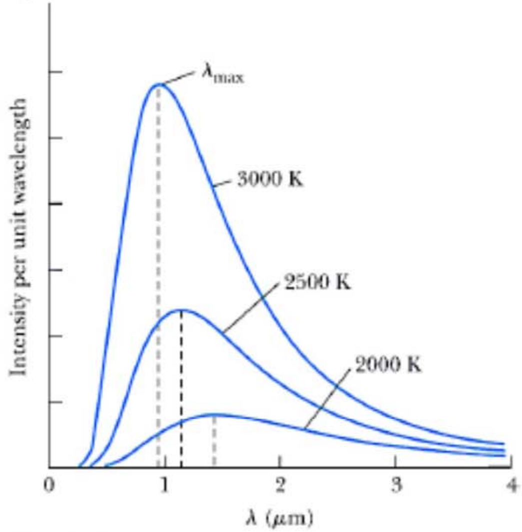




Michelson and Morley experiment

Blackbody Radiation

- Despite successes of Kinetic theory the wavelength dependent emission of EM radiation from objects at non–zero T could not be explained.



- Classical Theory predicts infinite emission at low wavelength (ultraviolet catastrophe).

- Solution by Planck was fundamental development.

Additional Discoveries Contribute to the Complications during 1895-1897

- 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.