Chap 1

The birth of modern physics

- Overview of classical physics
- Optics
- Electromagnetism
- Kinetic theory of gases
- Atomic theory of matter
- Unresolved questions around 1890s

Before 1900: Classical physics

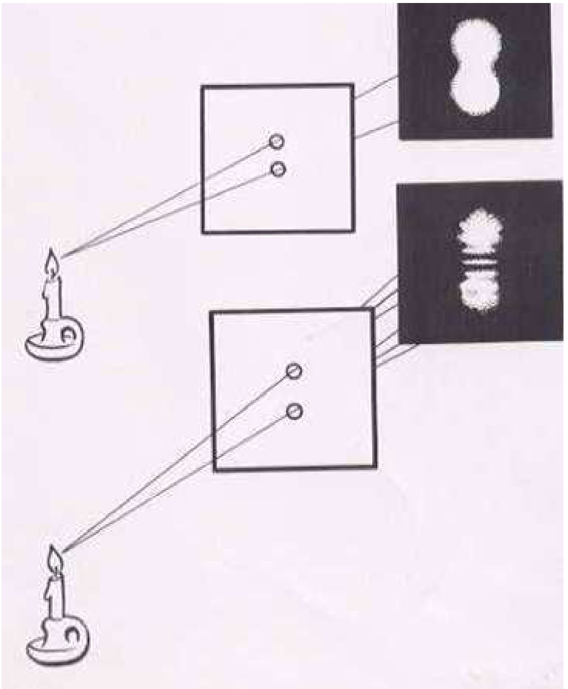
- Optics (since ancient Greek)
- Classical mechanics (Galileo, Newton, Lagrange, Hamilton …)

  including fluid mechanics, theory of elasticity …
- Thermodynamics (Joule, Carnot, Thomson, Clausius, Helmholtz …)
- Statistical Mechanics (Maxwell, Boltzmann, Gibbs …)
- Electrodynamics (Coulomb, Ampere, Faraday, Maxwell …)
- Also, the atomic theory of matter (Avogadro, Dalton …)

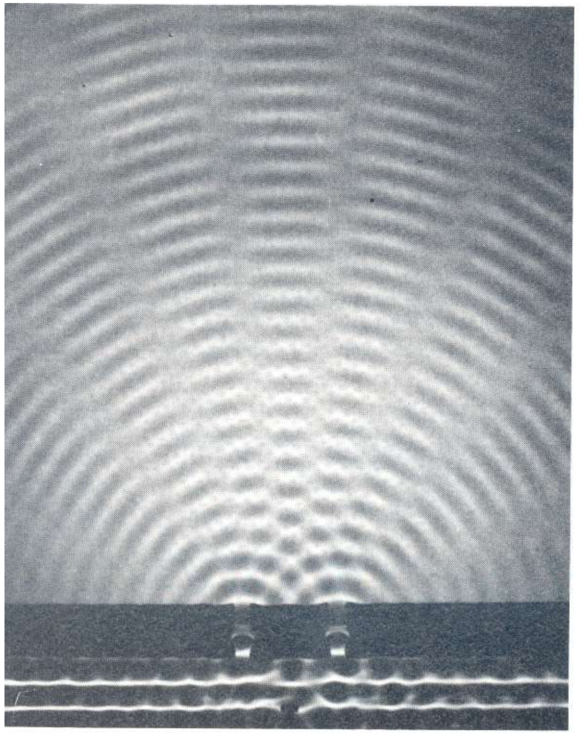
Below is a selected review.

Properties of light

Light as a wave (Young, 1800)



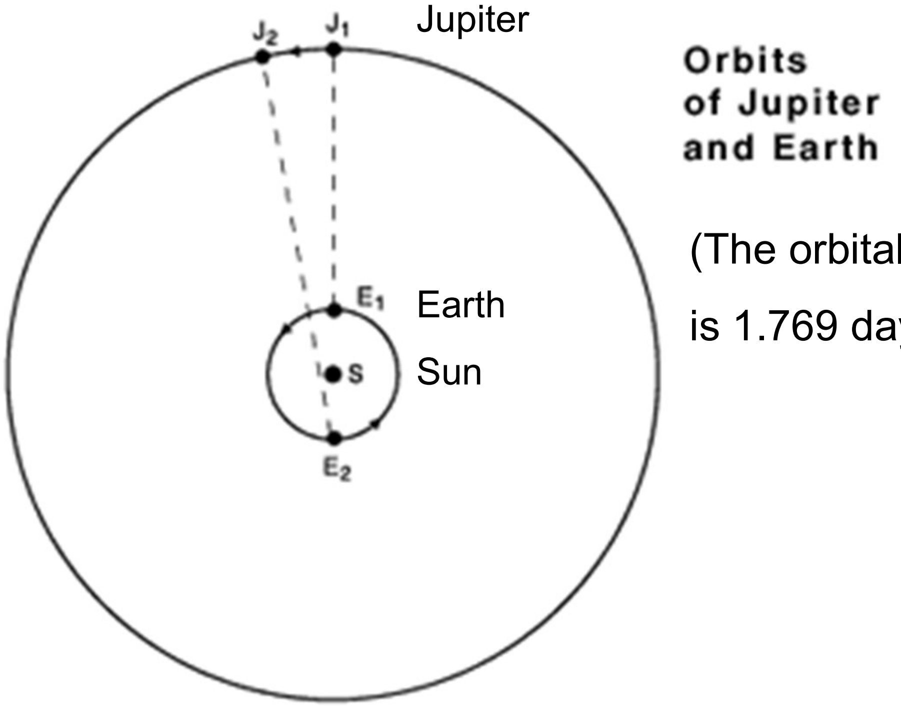
Analogy: water wave



- Determine the wavelength of light
  (from the interference pattern)
- The speed of light was known earlier
  (Roemer, 1676, by timing eclipses of Jupiter's moon Io)

optional

How did Roemer measured the speed of light?



(The orbital period of Io is 1.769 days)

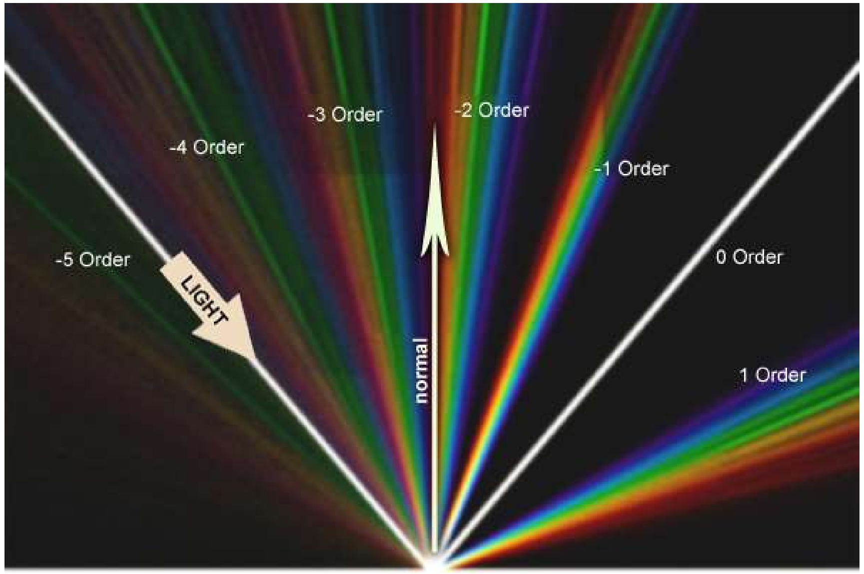
- 1676, Roemer measured the delay of the eclipse of Io between E_1 and E_2 (~ 22 mins, correct value is 16.7 mins).
- Knowing approximately the diameter of the Earth's orbit (~ 3×10^8 km). He made the first good estimate of the speed of light (~ 210000 km/s).

https://www.amnh.org/learn-teach/curriculum-collections/cosmic-horizons-book/ole-roemer-speed-of-light

Spectroscopy

Prism (Newton …)

1802, Wollaston found dark lines in solar spectrum

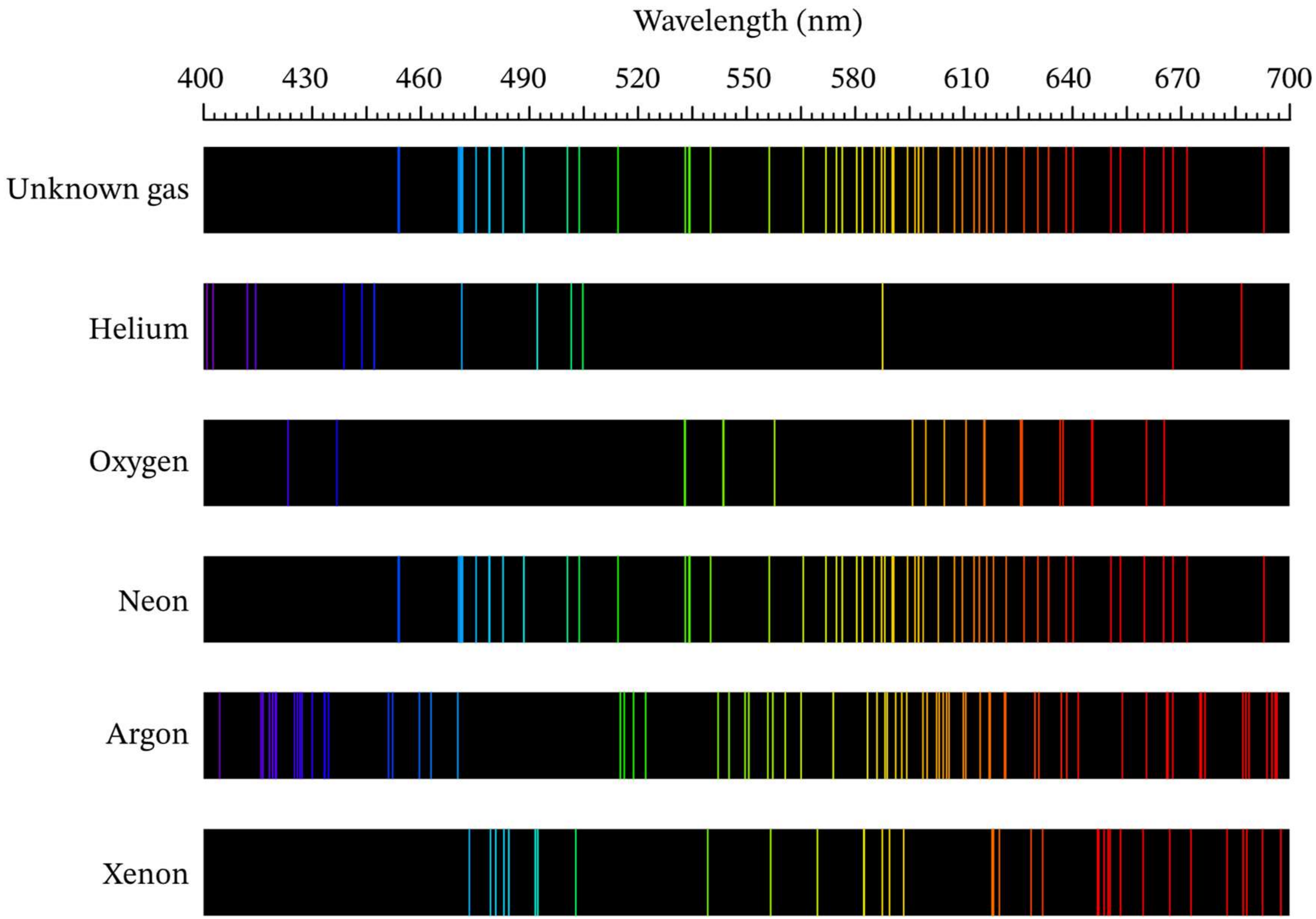


1814, Fraunhofer replace a prism with a diffraction grating

➡ Kirchhoff, Bunsen et al, 1859 forward
systematic study of the spectra of chemical elements
e.g., Kirchhoff used this method to discover cesium and rubidium

https://www.ossila.com/pages/history-of-spectroscopy

Different spectral lines from different elements ~ fingerprints



The first strong hint that light is an electromagnetic wave

(1856, Weber and Kohlrausch, before Maxwell's theory)

電磁常數與光速

庫侖定律中的比例係數（即庫侖常數）為 $\frac{1}{4\pi\varepsilon_0} = 8.987\times 10^9$ (N · m²/C²)。必歐－沙伐定律的比例係數為 $\frac{\mu_0}{4\pi} = 10^{-7}$ (T · m/A)。如果這兩個比例係數相除，可得

$$\frac{1}{\varepsilon_0\mu_0} = 8.987\times 10^{16}\ (\mathrm{N\cdot m\cdot A/T\cdot C^2})$$

由於 1 (T) = 1 (N/A · m)，代入上式的單位中，得 $\mathrm{N\cdot m\cdot A/T\cdot C^2 = m^2/s^2}$，因此

$$\frac{1}{\varepsilon_0\mu_0} = 8.987\times 10^{16}\ (\mathrm{m^2/s^2}) \text{ 或 } \boxed{\frac{1}{\sqrt{\varepsilon_0\mu_0}} = 2.9978\times 10^{8}\ (\mathrm{m/s})}$$

等號右邊的數值，恰好就是光在真空中行進的速度 c ！

1873, Maxwell's equations (17 variables in 17 eqs)

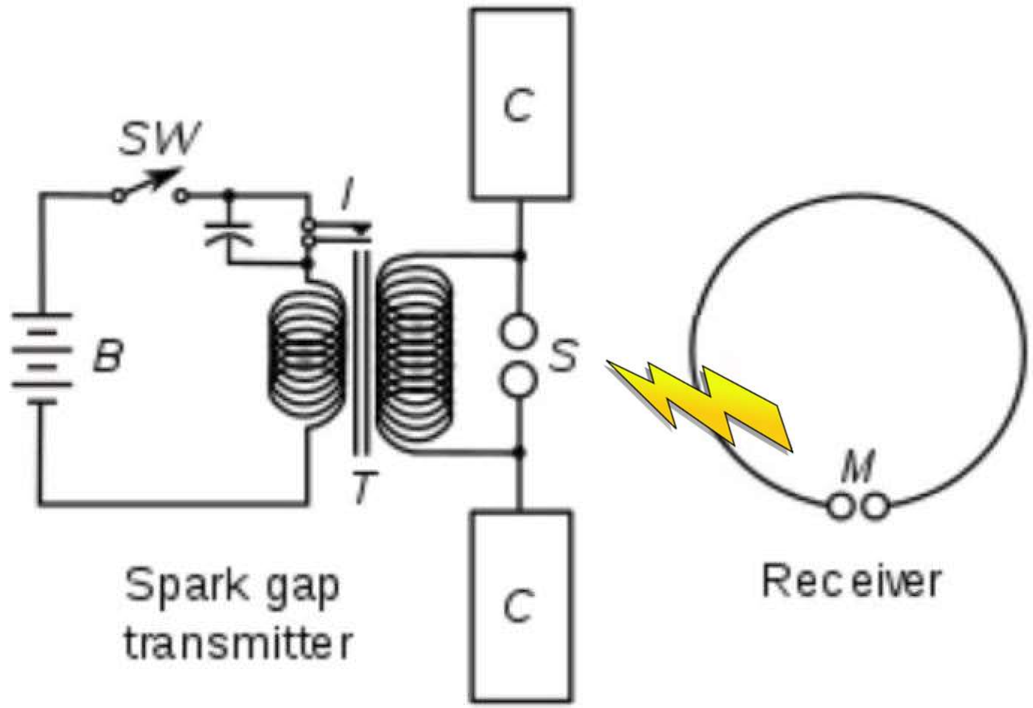
1879, Maxwell died at the age of 48

$e+\frac{df}{dx}+\frac{dg}{dy}+\frac{dh}{dz}=0$	(1)	Gauss' Law	$\nabla\cdot\vec{E}=\frac{\rho}{\varepsilon_0}$
$\mu\alpha=\frac{dH}{dy}-\frac{dG}{dz}$ $\mu\beta=\frac{dF}{dz}-\frac{dH}{dx}$ $\mu\gamma=\frac{dG}{dx}-\frac{dF}{dy}$	(2)	Equivalent to Gauss' Law for magnetism	$\vec{B}=\nabla\times\vec{A}$
$P=\mu\left(\gamma\frac{dy}{dt}-\beta\frac{dz}{dt}\right)-\frac{dF}{dt}-\frac{d\Psi}{dx}$ $Q=\mu\left(\alpha\frac{dz}{dt}-\gamma\frac{dx}{dt}\right)-\frac{dG}{dt}-\frac{d\Psi}{dy}$ $R=\mu\left(\beta\frac{dx}{dt}-\alpha\frac{dy}{dt}\right)-\frac{dH}{dt}-\frac{d\Psi}{dz}$	(3)	Faraday's Law (with the Lorentz Force and Poisson's Law)	$\vec{E}=\vec{v}\times\vec{B}-\dot{\vec{A}}-\nabla\psi$
$\frac{d\gamma}{dy}-\frac{d\beta}{dz}=4\pi p'$ $\quad p'=p+\frac{df}{dt}$ $\frac{d\alpha}{dz}-\frac{d\gamma}{dx}=4\pi q'$ $\quad q'=q+\frac{dg}{dt}$ $\frac{d\beta}{dx}-\frac{d\alpha}{dy}=4\pi r'$ $\quad r'=r+\frac{dh}{dt}$	(4)	Ampère-Maxwell Law	$\nabla\times\vec{B}=\mu_0\vec{J}+\frac{1}{c^2}\frac{\partial\vec{E}}{\partial t}$
$P=-\xi p \quad Q=-\xi q \quad R=-\xi r$		Ohm's Law	$\vec{E}=\rho\vec{J}$
$P=kf \quad Q=kg \quad R=kh$		The electric elasticity equation (**E** = **D**/ε)	$\vec{E}=\frac{\vec{D}}{\varepsilon_0}$
$\frac{de}{dt}+\frac{dp}{dx}+\frac{dq}{dy}+\frac{dr}{dz}=0$		Continuity of charge	$\frac{\partial\rho}{\partial t}+\nabla\cdot\vec{J}=0$

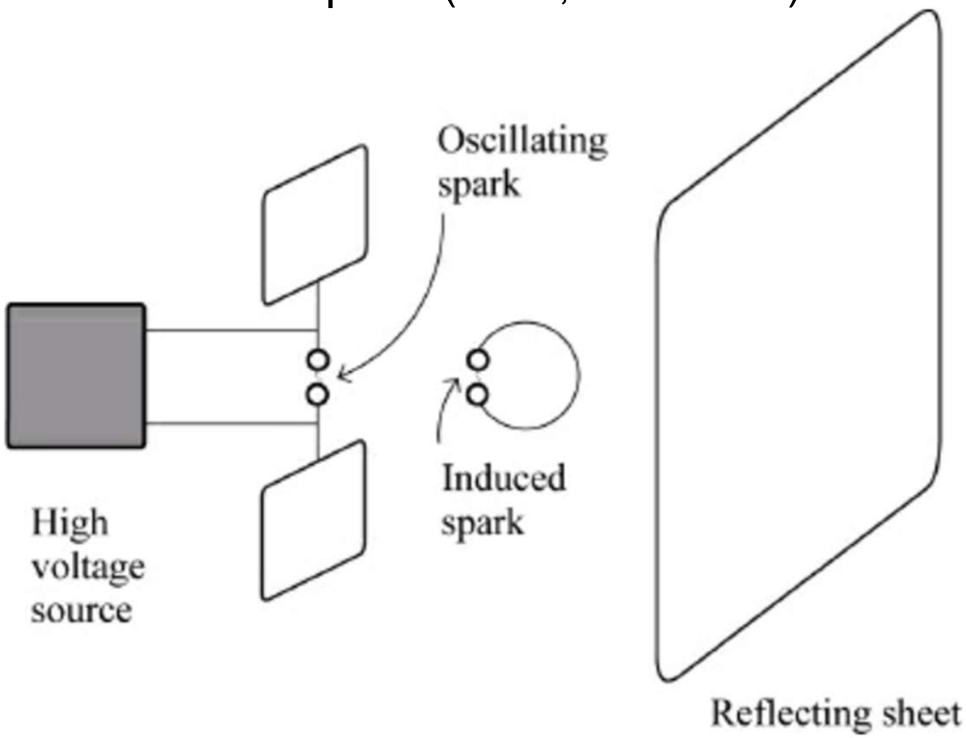
https://ddcolrs.wordpress.com/2018/01/17/maxwells-equations-from-20-to-4/

Generation and detection of electromagnetic wave

1886, Hertz noticed oscillatory discharge of Leyden jar through a wire loop induces sparks across a gap at a nearby loop

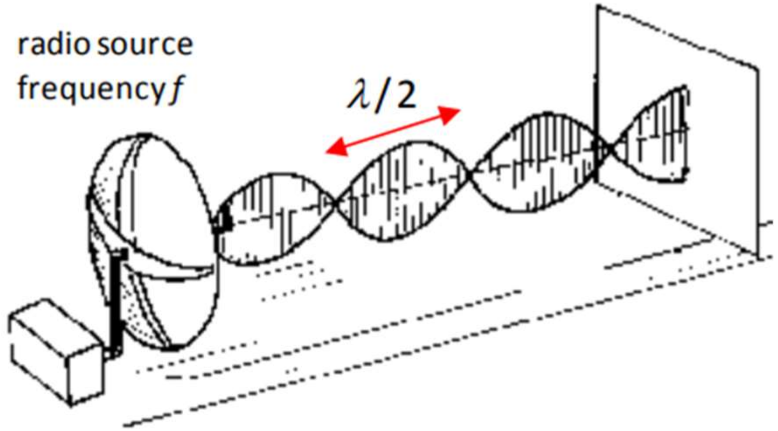


Electromagnetic wave in free space (Hertz, 1887-1888)



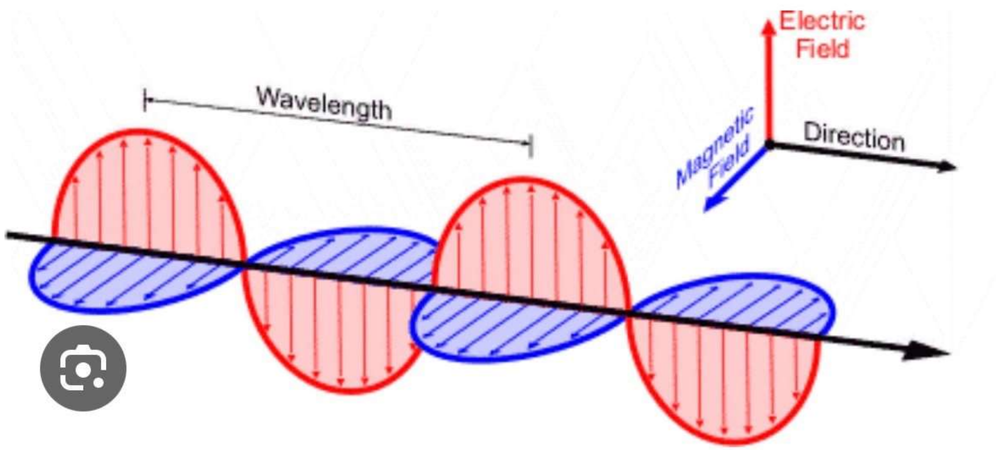
- Hertz generated EM wave ~ 50 MHz
- He studied the properties of reflection, refraction, velocity, diffraction, interference, polarization… and confirmed that EM wave ~ light.

➡ The strongest support to Maxwell's theory.



Summary: Light as electromagnetic (EM) wave

- 1864 Maxwell's equations
- 1887 Hertz generated and detected EM wave
- 1895 Röntgen discovered X-ray
- 1899 Planck studied the physics of thermal radiation
- 1901 Wireless communication across the Atlantic ocean
- …



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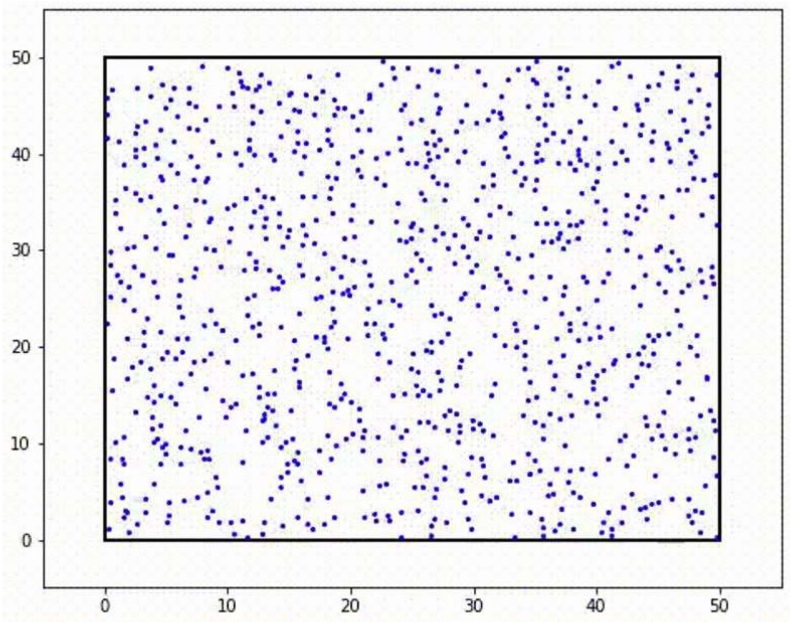
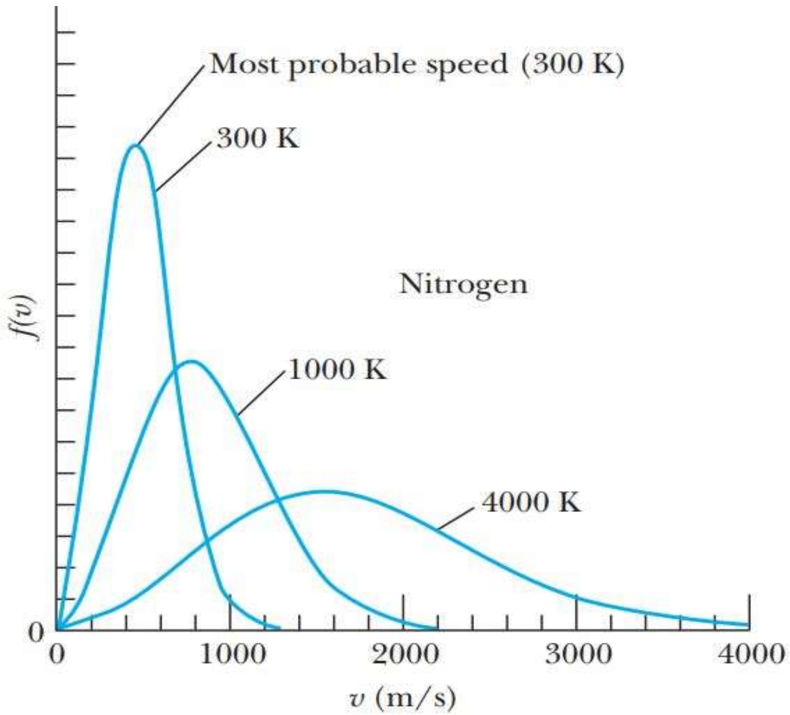
Kinetic theory of gases



Maxwell's speed distribution

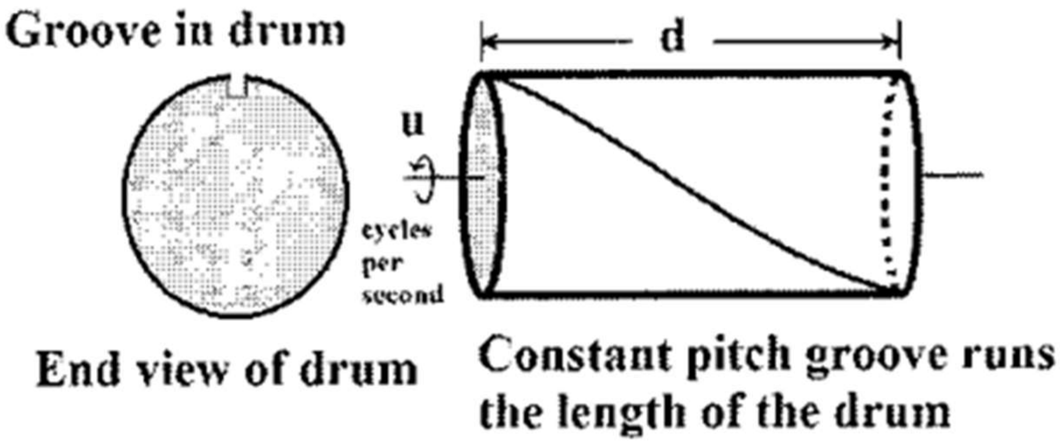
of ideal gas (1860)



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

more in Chap 9

Experimental test (Stern 1921)



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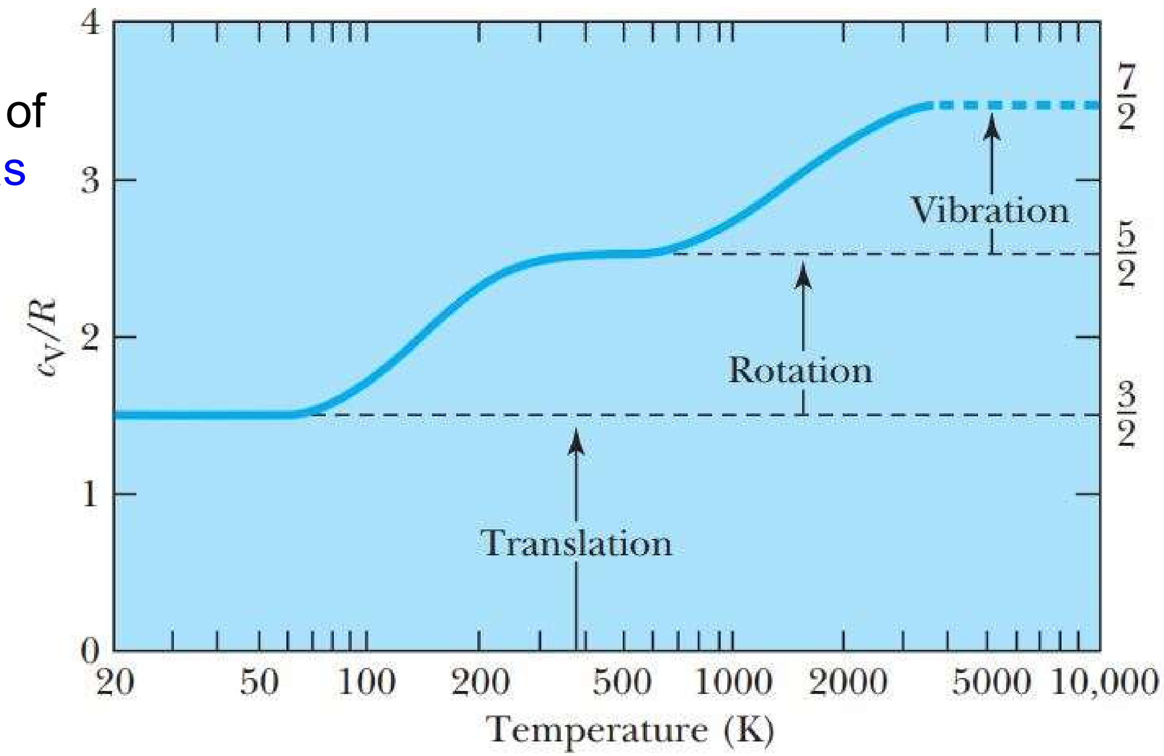
Equipartition theorem (Maxwell, Boltzmann) 能量均分定理

For a system in *thermal equilibrium*, the energy is shared equally among all *energetically accessible* degrees of freedom (DOF).

e.g., internal energy of ideal gas: $U = nN_A\langle K\rangle = \frac{3}{2}nRT$

Specific heat of a diatomic gas

$$U = \frac{f}{2}nRT$$



2 vibrational DOF

2 rotational DOF

more in Chap 9

The atomic theory of matter

How do we know the world is made of atoms

Ref: Foundation of Modern Physics, by S. Weinberg

- Properties of gas
  (from mid 17th century)
- Chemistry
  (from late 18th century)
- Electrolysis
  (from early 19th century)

} → atoms

Properties of gas

- Boyle (1662) + Charles (1780s) + Gay Lussac (1802)

T, P, V fixed respectively

➡ $$PV = kNT$$

In principle, k can depend on the type of gas.

- However, there is Avogadro's hypothesis (1812):

Equal volumes of all gases, at the same temperature and pressure, have the same number of molecules.

➡ So k is the same for different gases

The volume of 1 mole of an ideal gas at STP is 22.41 ℓ.

This is probably the most remembered and least useful number in chemistry (google).

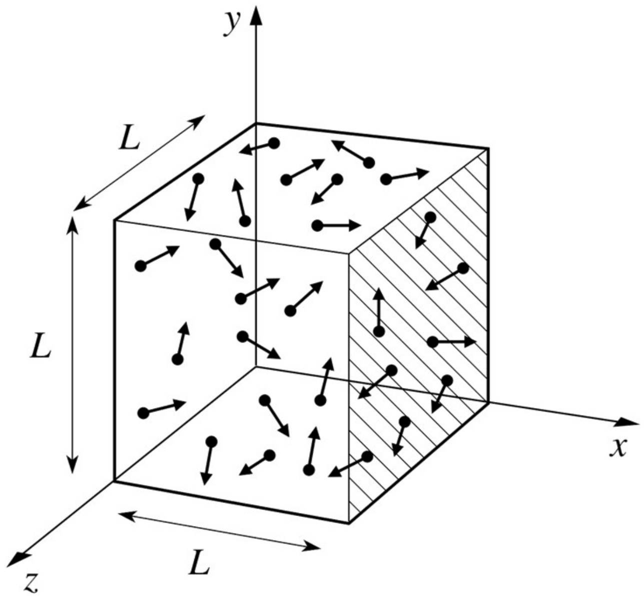
- Old definition of mole: The number of atoms in 12 g of ^{12}C.

It was not until 1860 that Avogadro's number—the number of molecules in one mole—was "measured".

Pressure comes from particles hitting the wall

- This is first proposed by D. Bernoulli (1738, ignored for 100 years) , then re-discovered by Herapath (1820).
- The modern derivation is given by Clausius (1857, *The nature of the motion we call heat*)

$$P = \frac{1}{3} nm\langle v^2 \rangle$$



Compare with *PV=kNT*

$$\Rightarrow \quad \frac{1}{2} m\langle v^2 \rangle = \frac{3}{2} kT$$

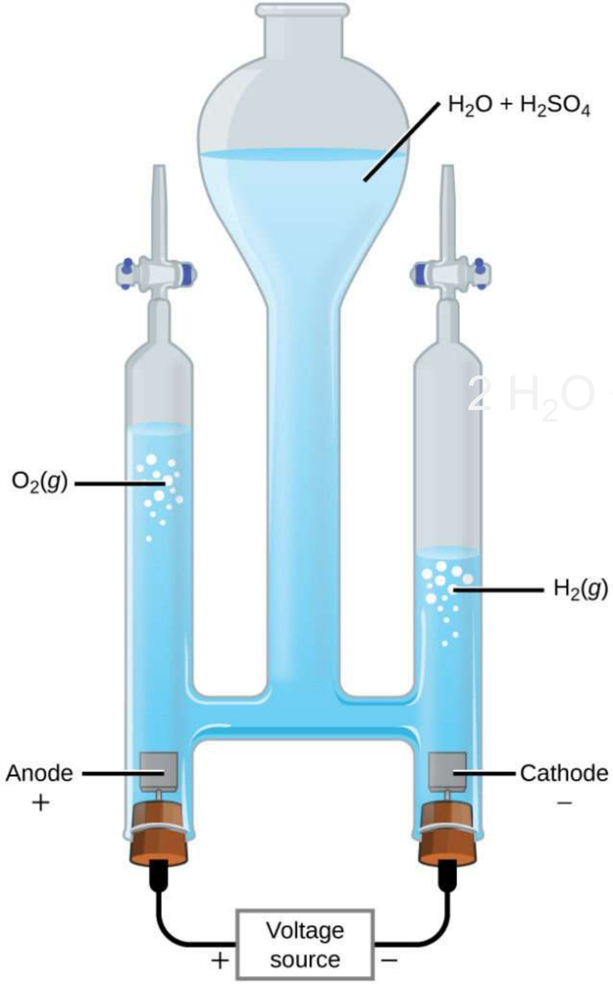
(this is what you learned in high school)

optional

Electrolysis (from 1800)　　電解

(Note that Volta just invented battery a few years ago)

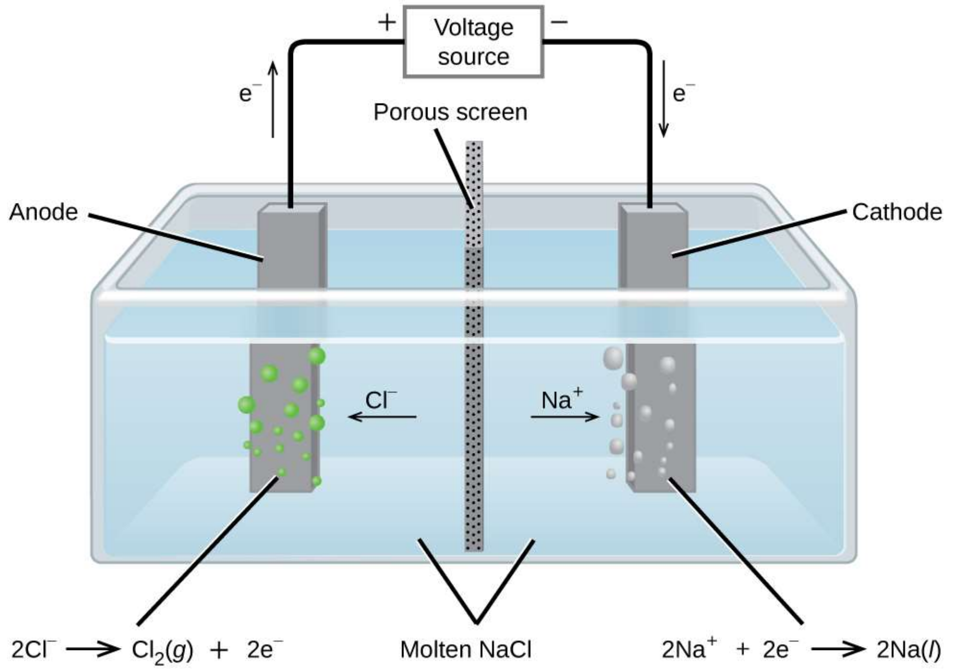
- Nicholson and Carlisle decomposed water into hydrogen and oxygen (1800).



$$2\,H_2O + 2\,e^- \rightarrow H_2 + 2\,OH^-$$

optional

Davy decomposed salt into Na and Cl (1807)



- Later, aluminum, potassium, sodium, barium, calcium, copper and magnesium … etc were discovered by Davy using electrolysis (1807,1808)
- It takes 96500 C (called Faraday constant) to convert one mole of M^+ to neutral atoms. So if we know the charge of the electron, then we know N_A.

optional

How do we know that water is H_2O

1. Law of combining weights (Dalton, 1808) 氣體化合量定律

- When gases react together to form other gases, the ratio between the weights of the reactant gases and the products can be expressed in simple integers.

For example,

1 grams of hydrogen + 8 gram of oxygen → 9 grams of water

- Dalton thought that the formula of water is HO, instead of H_2O. To get the correct one, we need the following law:

optional

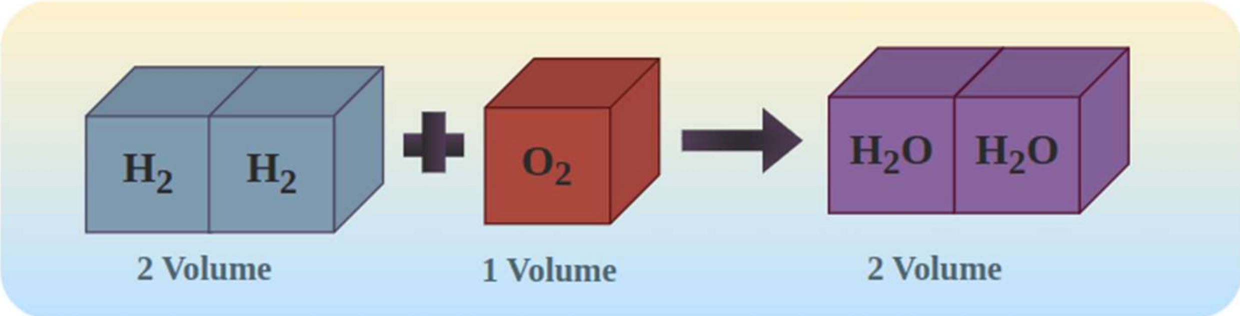
2. Law of combining volumes (Gay Lussac, 1809) 氣體化合體積定律

- When gases react together to form other gases, the ratio between the volumes of the reactant gases and the products can be expressed in simple integers.

For example,

2 liters of hydrogen gas + 1 liter of oxygen gas

→ 2 liters of gaseous water vapor



- With the law of combining volumes and Avogadro's hypothesis, we have $2H_2 + O_2 \rightarrow 2H_2O$. ← Avogadro's "diatomic" hypothesis (ridiculed by Dalton)

  Q: Why not $2H + O \rightarrow H_2O$?

Dalton's atomic theory (1808)

- **All matter consists of tiny particles called atoms.**
- **Atoms are indestructible and unchangeable.** Dalton based this hypothesis on the law of conservation of mass as stated by Lavoisier and others around 1785.
- **Elements are characterized by the weight of their atoms.** Dalton suggested that all atoms of the same element have identical weights. Atoms of different elements, such as oxygen and mercury, are different from each other.
- **In chemical reactions, atoms combine in small, whole-number ratios.** Experiments indicated that chemical reactions proceed according to atom to atom ratios which were precise and well-defined.
- **When elements react, their atoms may combine in more than one whole-number ratio.** Dalton used this assumption to explain why the ratios of two elements in various compounds, such as oxygen and nitrogen in nitrogen oxides, differed by multiples of each other (NO, NO_2).

What scientists knew before 1900 - a partial summary
(not necessarily accepted by everyone at that time)

- Thermal current is energy flow (not from caloric fluid)
- Light is electromagnetic wave
- Thermal radiation (infrared) is also EM wave
- Matter is composed of atoms from various chemical elements, which form a periodic table.
- Electric current is composed of electrons, and there are probably electrons in atoms.

From macroscopic world to microscopic world.

⇒ Discreteness of *matter* and *energy*.

Some unresolved puzzles in the 1890s

- Properties of the **medium of light** (ether) → Special relativity
- How to explain the **spectral distribution of thermal radiation**? (like the way we describe the speed distribution of an ideal gas) → Quantum theory

Both involves the nature of light!

Also, new stuffs kept popping up, such as the discovery of

- **Cathode ray** (1879)
- **photoelectric effect** (1887)
- **x-ray** (1895)
- **radioactivity** (1896)
- **Zeeman effect** (1896)
- **electrons** (1897) … etc.

Progress of physics: evolution leads to revolution

Foundation of **Modern physics**

Theory of Relativity

- Special theory (Einstein, 1905)
- General theory (Einstein, 1915)

Quantum Mechanics (Planck 1900, Heisenberg/Schrodinger 1925)

Relativistic quantum mechanics (Dirac, 1928)