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In-depth study of AP Physics 2

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Introduction

This book/document is designed to foster students' interest in physics, not to help them improve their AP Physics 2 scores. While grades are important, I have always believed that to excel in physics, you need to be genuinely interested in it. Otherwise, you will likely underperform on the exam. This is because you will only memorize general knowledge, which anyone can memorize. But when unfamiliar questions appear on the exam, you will panic because you have not memorized the knowledge. However, those truly interested in physics will devote themselves to understanding the fundamentals of physics. They will reflect and ultimately understand. This way, no matter what questions they encounter on the exam, they can adapt flexibly because the underlying logic remains the same. Therefore, learning physics requires understanding, not just memorizing formulas; otherwise, you will not get a high score. This is why I chose to write a book on AP Physics 2 rather than AP Physics 1, because AP Physics 2 covers more topics and requires a higher level of comprehension. For example, when studying AP Physics 2, I, the author of this book, often spent an entire morning deriving formulas, asking AI questions, and consulting university physics textbooks for a single point, ultimately achieving a 5. However, when I looked at the textbooks available, I found they were simply focused on teaching you how to answer questions correctly and get a 5, rather than genuinely trying to instill an interest in physics. Consequently, many students are elated by a good test score, but real physics is far from that. You need to think like a physicist. This does not mean you need to be as skilled as physicists like Stephen Hawking or Albert Einstein, but rather you need to develop a strong physical intuition for approaching difficult problems. Therefore, it is crucial not to apply mathematical thinking to AP Physics II. While it might be useful for AP Physics I, it is fatal for AP Physics II. Physics is a natural science that studies the nature of natural phenomena, while mathematics is a formal science that focuses on logical correctness. Therefore, practicing exercises is not about practicing logic, but about developing a way of thinking—about the fundamentals of how things work. Therefore, this book will help you gain a deep and thorough understanding of the key concepts in AP Physics II, building a comprehensive knowledge base and enabling you to develop the ability to think independently. Most importantly, it will cultivate your interest in the subject. Finally, do not give up on physics just because you did not do well in it. Learning physics requires imagination—as I mentioned above, understanding why a phenomenon works the way it does. It is useless to be the top scorer, because physics exams test what those who came before you know. Real physics research allows you to predict and discover new phenomena and patterns. Therefore, all you need is passion and perseverance. Passion is the best teacher. Note: This book is not suitable for beginners and requires a certain foundation in physics.

I. Thermodynamics

Thermodynamics - Wikipedia

Recommend video： https://youtu.be/GOrWy_yNBvY?si=_-NcoIb6kuKdeYIv

1.1 thermal equilibrium and temperature

1. Specific heat capacity: Use the letter c to represent.

Definition: An inherent property of matter. Numerically, it is equal to the amount of heat absorbed or released by a unit mass of this substance when its temperature rises or falls by 1 K (or 1°C).

Pay attention: Specific heat capacity is a property of matter. The specific heat capacity of different substances is generally different and is also related to the state of the substance, such as ice and water.

Unit: J/(kg·K) The amount of heat required to raise the temperature of 1 kg of a substance by 1 K

The c of water is 4200 J/(kg·K)

Formula: $c = \frac{Q}{m\Delta T}$

The relationship between heat and specific heat capacity can be expressed using the formula: $Q = m \times c \times \Delta T$

Q represents the amount of heat absorbed or released by the system

Q>0∶ absorb heat $\Delta T > 0$

Q<0: release heat $\Delta T < 0$

As a result, Large specific heat capacity: I. Strong endothermic and exothermic effect

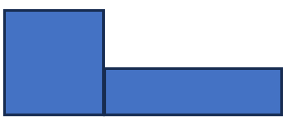
II. Temperature is not easy to change

For example: Sand has a small specific heat capacity and a large temperature difference between day and night.

2 thermal equilibrium formula: $c \cdot m1 \cdot (T1 - T3) = c \cdot m2 \cdot (T3 - T2)$

The two blue rectangles are in thermal equilibrium after contact, and their temperatures are equal. $Q\ absorb = Q\ release$

m1 m2



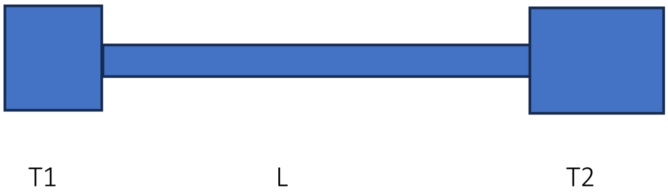
2.heaut current: $Q/t = k \cdot A \cdot (T1 - T2) \ /L$

Q/t is the heat current.

K: heat conductivity

A: Cross-sectional area

L: length of the pipe



Think of it as a connected pipe

3.the Zeroth law of thermodynamics： If two thermodynamic systems are in thermal equilibrium with a third system, the two systems must also be in thermal equilibrium with each other.

1.2 heat transfer

①heat conduction： Heat flows from a high temperature object to a low temperature object

②heat convection : fluid/ gas transfer heat

③heat radiation: by electromagnetic wave example: Sunlight

1.3 idea gas law:

①formula:$PV = nRT = NKT$

②P: pressure: P atmosphere = 1✖10^5 pa $P = \frac{F}{A} = \frac{nRT}{V}$

③Constants: N_A (Avogadro constant) = $6.02214076 \times 10^{23}\ mol^{-1}$ $N = N_A \times n$

R/N_A = K =1.38✕10^-23 J/K: Boltzmann constant

R: universal gas constant = 8.31 J/mol·k

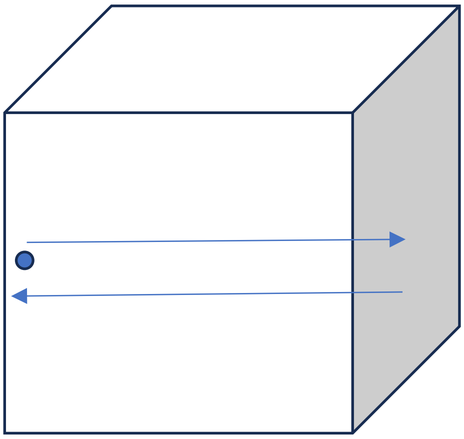
Derivation:

$$\rho = \frac{m}{V}$$

$$\therefore P = \frac{m}{MV}RT = \frac{\rho RT}{M}$$

$$\therefore \rho = \frac{PM}{RT}$$

④kinetic theory of gas:



Let us assume there is a particle in a square container. The particle moves to the right at a constant speed and then bounces back to its original position (the left side).

Vx (Horizontal direction speed (x-axis speed))

-Vx

Because velocity is a vector.

$$F = \frac{\Delta P}{\Delta t} = \frac{-mVx - mVx}{\Delta t} = -\frac{2mVx}{\Delta t}$$

Then, we also know that the side length of the cube is L

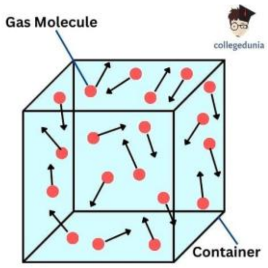
So, t=2L/Vx $\therefore F = \frac{mVx^2}{L}$

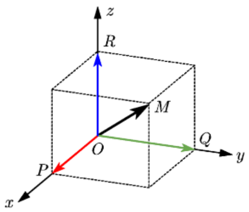
This is the case of just one particle, so suppose there are N particles:

$$F = \frac{NmVx^2}{L}$$

$$\therefore P = \frac{F}{A} = \frac{NmVx^2}{L^3} = \frac{Nmv^2}{3L^3} = \frac{1}{3}\rho v^2$$

Explain：





Since it is a cube container, so： $V^2 = Vx^2 + Vy^2 + Vz^2$ $Vx = Vy = Vz$

$$\therefore F = PA = \frac{nRT}{V} \cdot A = \frac{1}{3}\rho v^2 \cdot A = \frac{1}{3} \cdot \frac{PM}{RT} v^2 \cdot A$$

It is important to distinguish whether v is velocity or volume. It is not convenient to write it here!!

$$\therefore v^2 = \frac{3RT}{M}$$

$$v = \sqrt{\frac{3RT}{M}} = \sqrt{\frac{3KT}{m}}$$

This is the average velocity of a single particle

So: $k = \frac{1}{2}mv^2 = \frac{3}{2}$KT

This is the average kinetic energy of a single particle

As for the internal energy: It is the combination of the kinetic energy of N particles

Why: First, we need to understand what an ideal gas is:

Key assumptions of an ideal gas:

Molecular volume is negligible.

Gas molecules are considered point particles, their individual volumes extremely small compared to the overall volume of the gas.

There are no interactions between molecules.

Except for brief interactions during collisions, there are no attractive or repulsive forces.

Thus, internal energy is derived entirely from kinetic energy, excluding potential energy.

Molecules are in random thermal motion.

Movement in all directions is equally probable, with no preferred direction.

Intermolecular collisions are completely elastic.

Energy and momentum are conserved during collisions, with no energy loss.

And then: The reason we say internal energy is the sum of the kinetic energies of N particles is because in the ideal gas model, we make two important assumptions:

1, Ideal gas molecules are very small.

Molecules have no volume and no interactions (except for the momentary elastic effect during collisions).

This means there is no contribution from "potential energy."

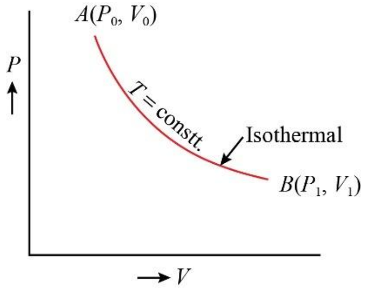
2, Molecules only move in random translational motion.

(For monatomic gases, there are no degrees of freedom such as rotation and vibration; for polyatomic gases, higher temperatures excite more degrees of freedom.)

So, energy comes entirely from the kinetic energy of the molecules.

internal energy: $U = N \cdot \frac{3}{2}KT = \frac{3}{2}nRT = \frac{3}{2}PV$

the work done by the system: $W = F \cdot L = PAL = PV$



(P–V Diagram)

In a PV diagram, if you want to know the work done by the system, look at the area enclosed by the function and the x-axis. If you want to know the internal energy, look at the difference between 3PV/2 at points A and B.

⑤ Thermal motion: Molecules are in constant, irregular motion, and they will only stop when they reach absolute zero： -273 degrees Celsius.

for example: Liquid diffusion, Brownian motion: This is evidence of molecular thermal motion. Particles suspended in a liquid or gas move randomly because molecules collide with the particles.

When molecules collide, kinetic energy is conserved and the total kinetic energy remains unchanged!!!!!!!!!!!!!!!!!!!!!!!!!

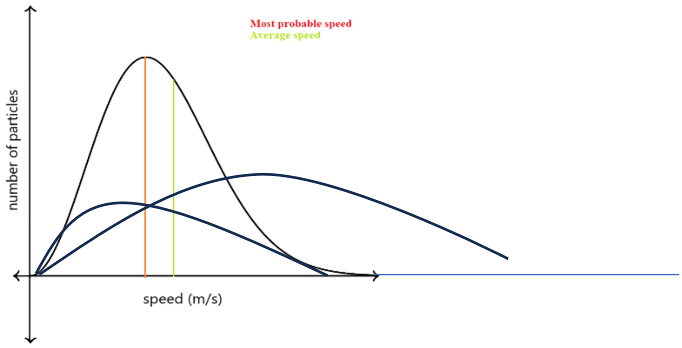
Question for reflection: Why do molecules move?

Because energy Distribution Since the Birth of the Universe

Since the Big Bang, the universe has been filled with energy. After matter formed, this energy naturally distributed itself among particles in the form of kinetic energy.

Collisions and interactions between particles occur constantly, so motion is a natural state.

⑥most probable speed



we can use

$$v = \sqrt{\frac{3KT}{m}}$$

so, the image to the right shows a higher temperature, or use particles with smaller mass.

Area: number of molecules, does not change!!

Right: T increases

1.4 thermodynamics first law

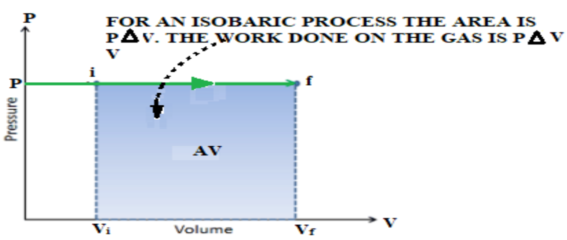
①$\Delta U = Q - W$ if: gas to environment : w>0 Q: Heat absorbed

② temperature increases, it is not necessarily because of heat absorption, it may also be because of work. Currently, Q=0, w<0, ΔU>0, temperature increases.

③ T is a symbol for measuring kinetic energy k and internal energy U

1.5 Thermodynamic process

①isobaric process



Ni Nf: Number of wall collisions per unit time

Because: $PV = nRT$

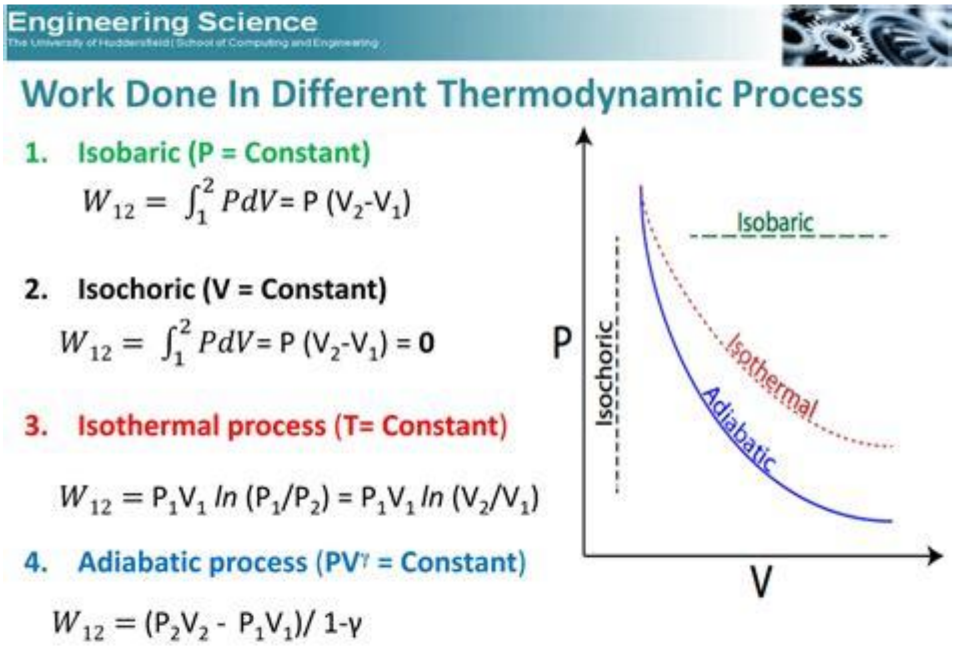
$$\therefore P = nRT/V$$

Because Pi=Pf　　*Vi<Vf*

SoTi<Tf

So Ni <Nf

② isothermal process ΔU=0 Q=W③ adiabatic process Q=0，ΔU=W



④isovolumetric ：No work

Question: Why is the image of the adiabatic process below the image of the isothermal process?

Because the isothermal process absorbs heat from the outside, the decrease is slow.

1.6　　2 cycles　　　　　　　　　　　positive cycle

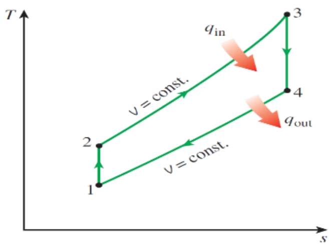
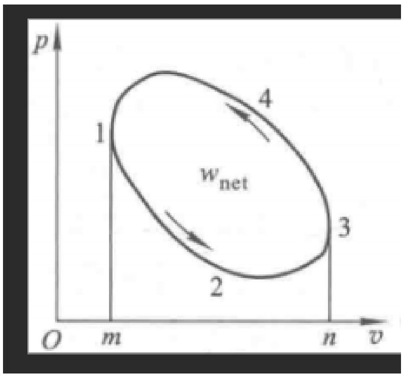


FIGURE 9–15
T-s diagram of the ideal Otto cycle.

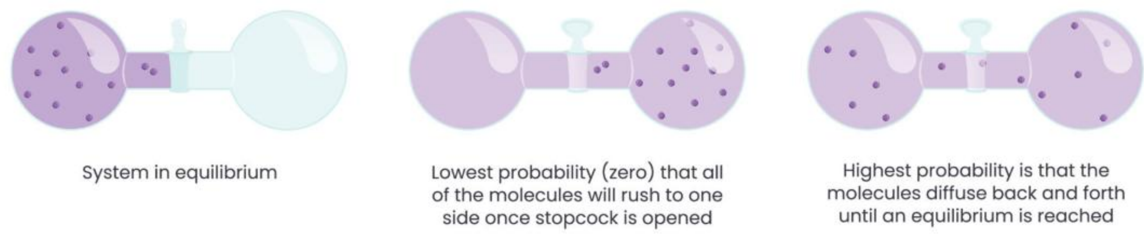
U does not change, ΔU=0, W>0, Q>0　so: absorb heat



negative cycle

U does not change, ΔU=0 W<0, Q<0   so: release heat

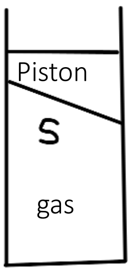
1.7 the second law of thermodynamics



The more disorder, the greater the entropy

All things develop towards disorder. So entropy will always increase and will never decrease!!!(In an isolated system)

Replenish:



$p = \frac{F}{A}$ A: Cross-sectional area of the piston

II. Magnetism

Recommend video： https://youtu.be/XoVW7CRR5JY?si=vckdIeHPnTIot9_S

2.1 materials

①Ferromagnetic material

For example： iron， nickel， cobalt

It has magnetic domain (Ferromagnetic materials produce small magnetized regions with different directions in the process of spontaneous magnetization to reduce static magnetostatic energy.). If there is an external magnetic field, the material will be permanently magnetized. Removing the external magnetic field does not work.

②paramagnetic material ： no magnetic domain

Once the external magnetic field is removed, there is no magnetism and no permanent magnetization

③all materials have the property of diamagnetism.

Permanent magnet

Current-carrying wires

Moving charge

Generate a magnetic field

2.2 magnetic field: It transmits the interaction between magnets

①where does it from?

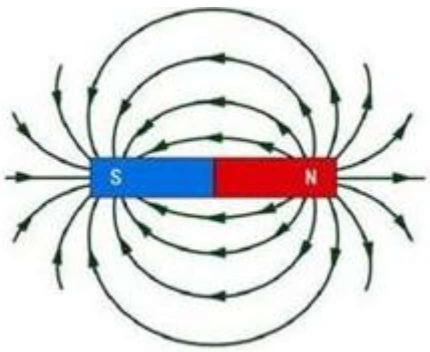
Electrons revolve around the nucleus→ Generates a circular current (with a spin direction)→ tiny magnetic field→magnetic field

②direction: North pole, and magnetic monopole does not exist!

③magnetic flux lines： i. External： N out S in

ii Internal： S→N

Forming a closed loop



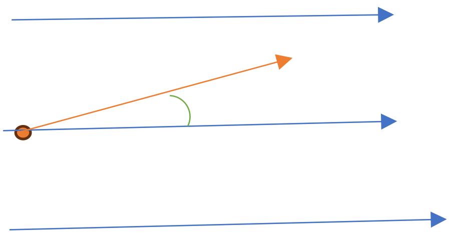
④Density represents the strength of the magnetic field

Question: What is the difference between electromagnetism and magnetism?

Electromagnetism: Produced by wire

Magnetism: Produced by magnets

2.3 The magnetic field force on a moving charge



①

Orange ball: Moving charge: q

Trajectory: Orange line

Angle with magnetic field lines: a

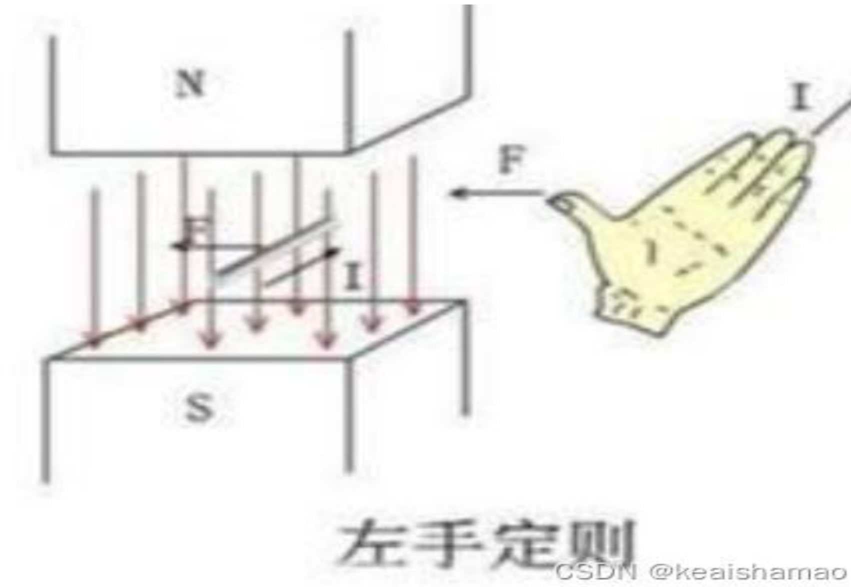
Magnetic field lines: Blue line

$$F = q \cdot B \cdot v \cdot \sin a$$

The direction of the electromagnetic force is always perpendicular to the magnetic field, but the electric force is parallel to the electric field!!!

So, only when electric charges cut through magnetic lines of force will they be affected by magnetic force.

② Left-hand rule: The magnetic field lines pass through the palm of your hand, the four fingers point in the direction of the current, and the direction of the thumb is the direction of the magnetic field force



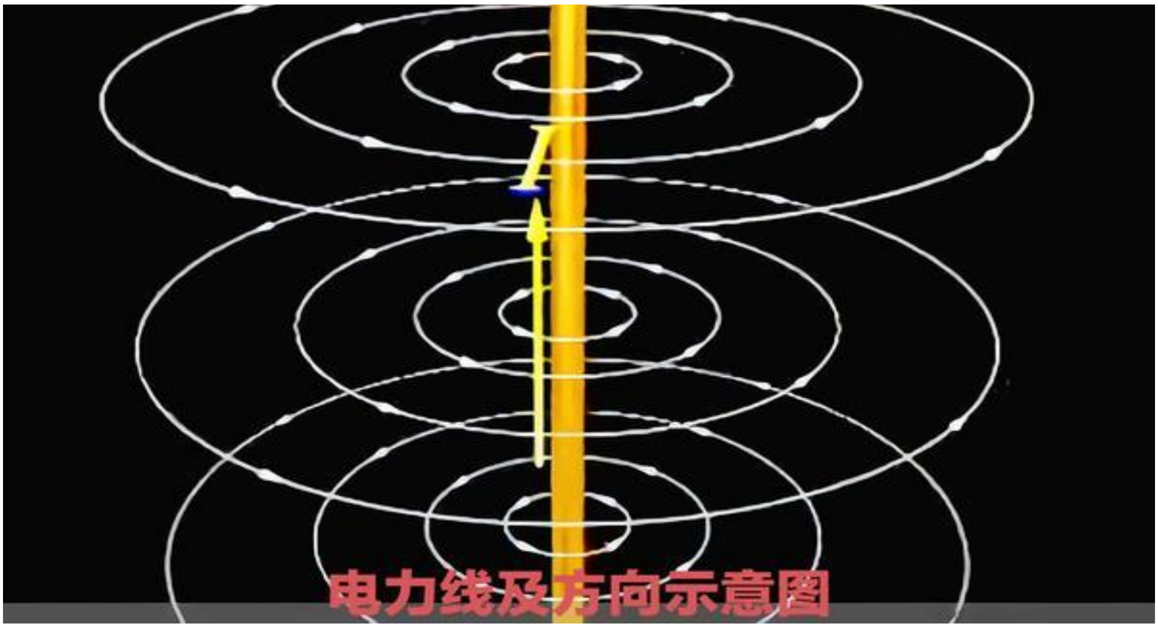
③intensity of magnetization : B

$$B = uI/2\Pi r$$

u=4Π✕10^7 magnetic permeability, which is related to element composition, distribution, temperature.

r: Distance between point and wire

I: The current in the wire that generates the magnetic field.



Unit: Tesla T

$$B = F/IL$$

$$F = BIL$$

$$\therefore 1T = 1\frac{N}{A \cdot m}$$

unit

④ How magnetic fields are generated?

We need to use special relativity.

In special relativity, magnetic field forces can actually be understood as the relativistic effects of electric fields in different reference frames. In other words, the magnetic field is not a fundamental interaction that "exists independently," but rather a manifestation of the electric field in a moving reference frame. Let me explain in detail:

1. Starting Point: Coulomb Interaction

In a stationary reference frame, if two parallel straight wires are charged and both charges are stationary, then only the Coulomb force (electric force) exists between them. In this case, no magnetic field exists.

2. Introducing Relativistic Velocity Transformations

Suppose that the charges on the wires are moving, for example, electrons flowing along the wires at velocity v, forming a current.

In the "stationary reference frame" of the electron, the electrons are stationary, but the positive ions are moving backward. Due to the length contraction effect, the distance between the positive ions appears smaller in the electron reference frame, resulting in a larger linear charge density.

Thus, in the electron reference frame, the wires are observed to have a net positive charge density, generating an electric field that pushes the electrons toward the other wire.

3. Returning to the Laboratory Reference Frame

In the "laboratory reference frame":

We see that the positive ions are essentially stationary, while the electrons are in motion.

The electrons repel each other, but at the same time, the effect they experience around the moving electrons in the other wire can be described by a new "field": this field is what we call the magnetic field.

Under special relativity, the "electric field effect" on the electrons is transformed into a magnetic field force, which is the origin of the Lorentz force$F = q(E + vB)$.

4. Unified Description of the Electromagnetic Field

Under the framework of special relativity, the electric field and the magnetic field are different manifestations of the same object: they together constitute the electromagnetic field tensor. In one inertial frame, you might only see the electric field; however, in another inertial frame in relative motion, this portion of the electric field may be "mixed" into an electric field + a magnetic field.

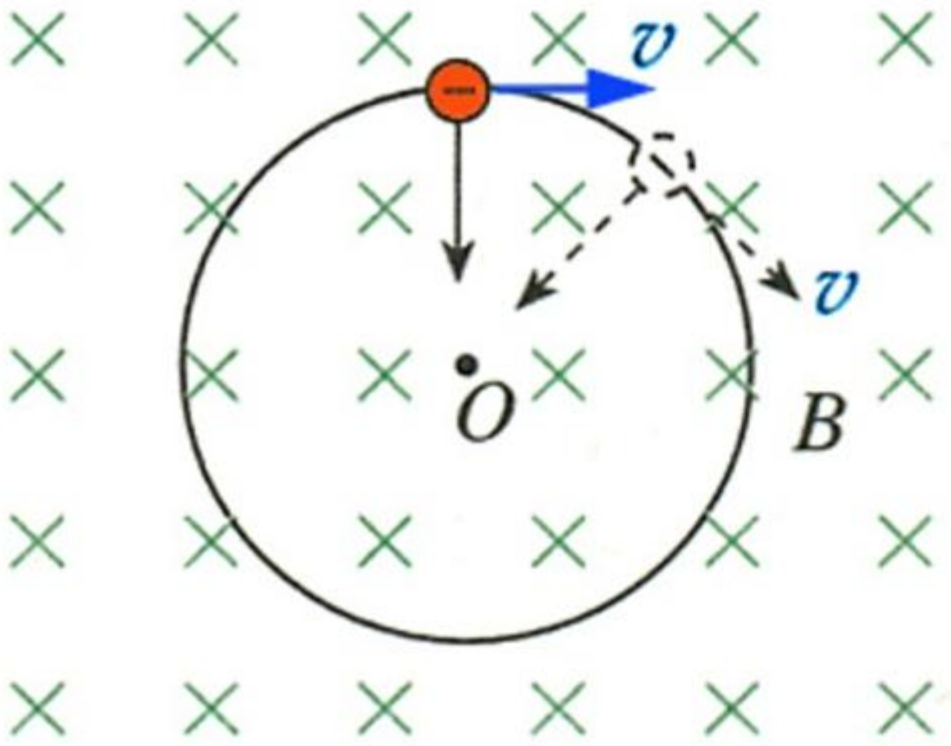
Thus, the magnetic field is the relativistic projection of the electric field in different reference frames.

Shouldn't F=qvB be the Lorentz force? What does F=q(E+vB) mean?

$F = q \cdot v \cdot B$ is a special case where the electric field is zero and the velocity is perpendicular to the magnetic field.

$F = q(E + vB)$ is the complete Lorentz force formula.

⑤circular motion



i $$F = m\frac{v^2}{r}$$

$$m\frac{v^2}{r} = qvB$$

$$r = \frac{mv^2}{qvB} = \frac{mv}{qB}$$

$$v = \frac{qBr}{m}$$

period: T $$T = \frac{2\Pi r}{v} = \frac{2\Pi m}{qB}$$

kinetic energy $k = \frac{1}{2}mv^2 = \frac{q^2B^2r^2}{2m}$

ii. specific charge=$\frac{q}{m} = \frac{v}{Br} = \frac{\sqrt{\frac{2qU}{m}}}{Br}$

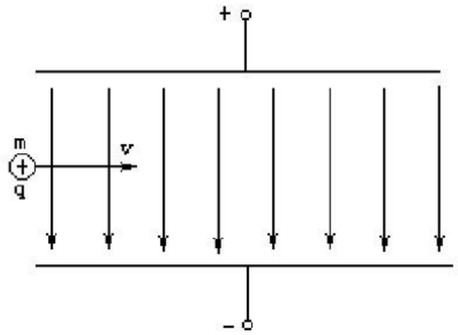
U: Potential difference, which will be discussed later

So: $\frac{q}{m} = \frac{2U}{B^2r^2}$

Because particles moving in a magnetic field must have an accelerating voltage

So $v = \sqrt{\frac{2qU}{m}}$ (velocity)

⑥velocity selector:$qEd = qU = \frac{1}{2}mv^2$ $qvB = qE$ $v = \frac{E}{B}$

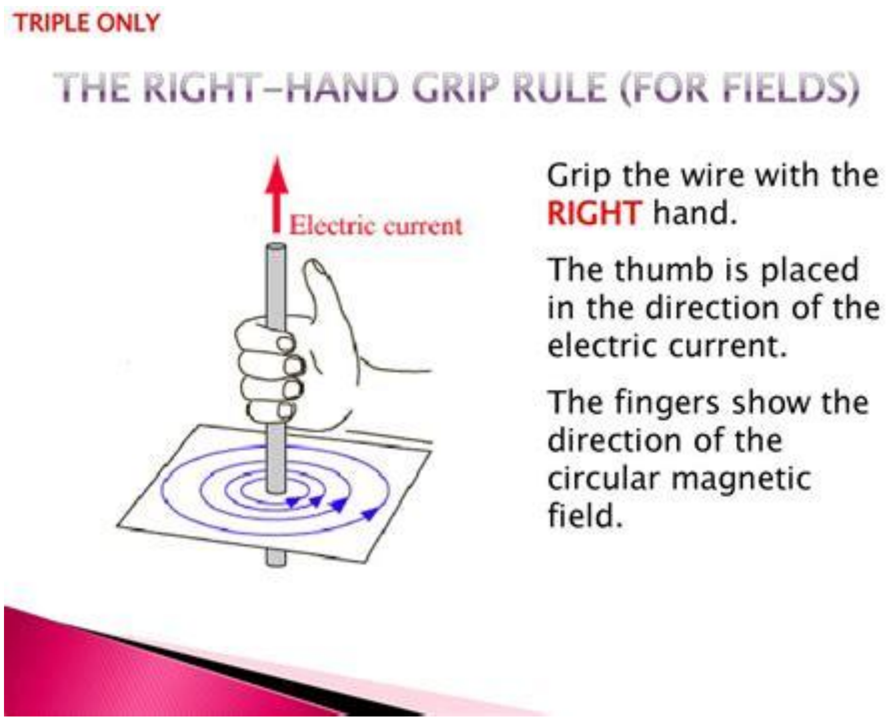


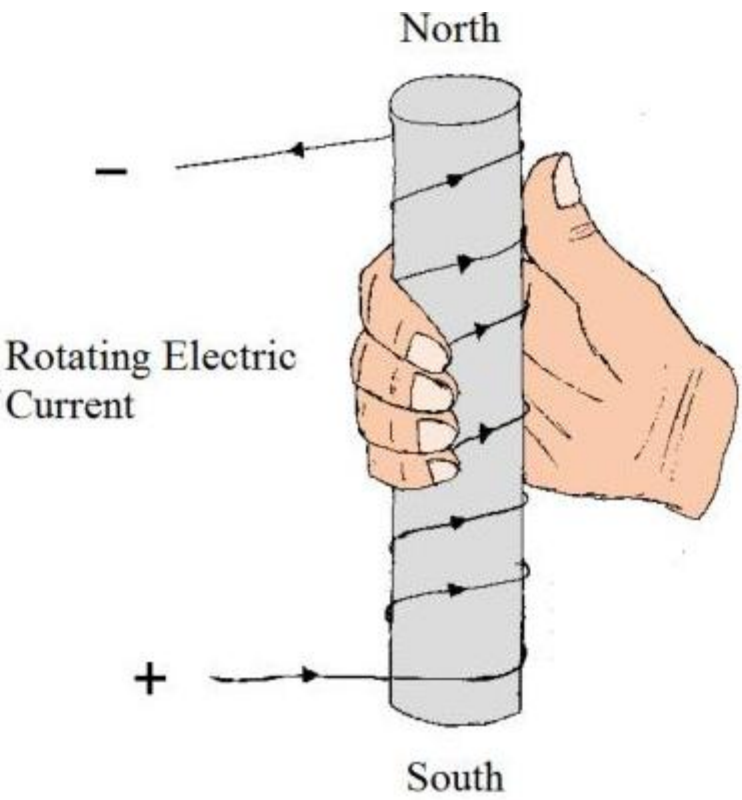
If: v>E/B deflect upward qvB>qE

If: v<E/B deflect downward qvB<qE

2.4 electromagnetic induction

① Right-hand rule

i. 



ii.

Four fingers: current direction Thumb: magnetic field direction

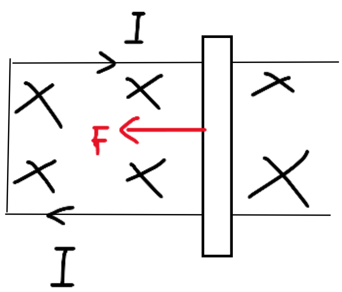
② Motional electromotive force: The induced electromotive force(emf) generated by the conductor cutting the magnetic flux lines.

Emf is just like the Voltage.

When there is a change in magnetic flux, an induced emf is produced in the coil.

$$\varepsilon = vBL$$

The external force makes the stick move to the left, as shown in the figure, and generates current. This is because the stick cuts the magnetic flux lines and generates induced electromotive force.



Emf $\longrightarrow$ current(I)

Closed circle

What is the difference between induced electromotive force and inductive electromotive force?

For moving devices: induced electromotive force: Caused by the movement of a conductor in a magnetic field

$$\varepsilon = vBL$$

For stationary devices: inductive electromotive force: Caused by changes in B

$\varepsilon = \frac{d\phi}{dt}$

As a result, if only B changes, there is also current.

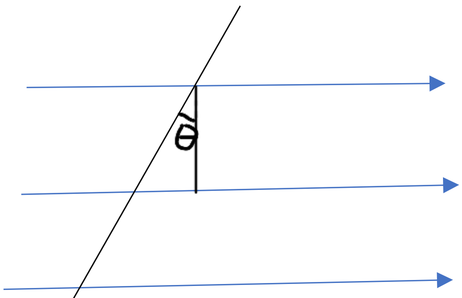
If only the ring moves upward, there will be no current, because the two currents generated are in opposite directions and cancel each other out.

$$\phi changes \rightarrow \varepsilon \rightarrow I$$

If:

③ Faraday's law of electromagnetic induction

i.magnetic flux $\phi = B \cdot A$ unit: wb A: Cross-sectional area through which magnetic flux passes



$$\phi = BA \cdot \cos\theta$$

$$\varepsilon = \frac{d\phi}{dt} = \frac{BdA}{dt} = \frac{BLdx}{dt} = vBL$$

$$\varepsilon = \lim_{\Delta t \to 0} \frac{\Delta \phi}{\Delta t} = \phi'$$

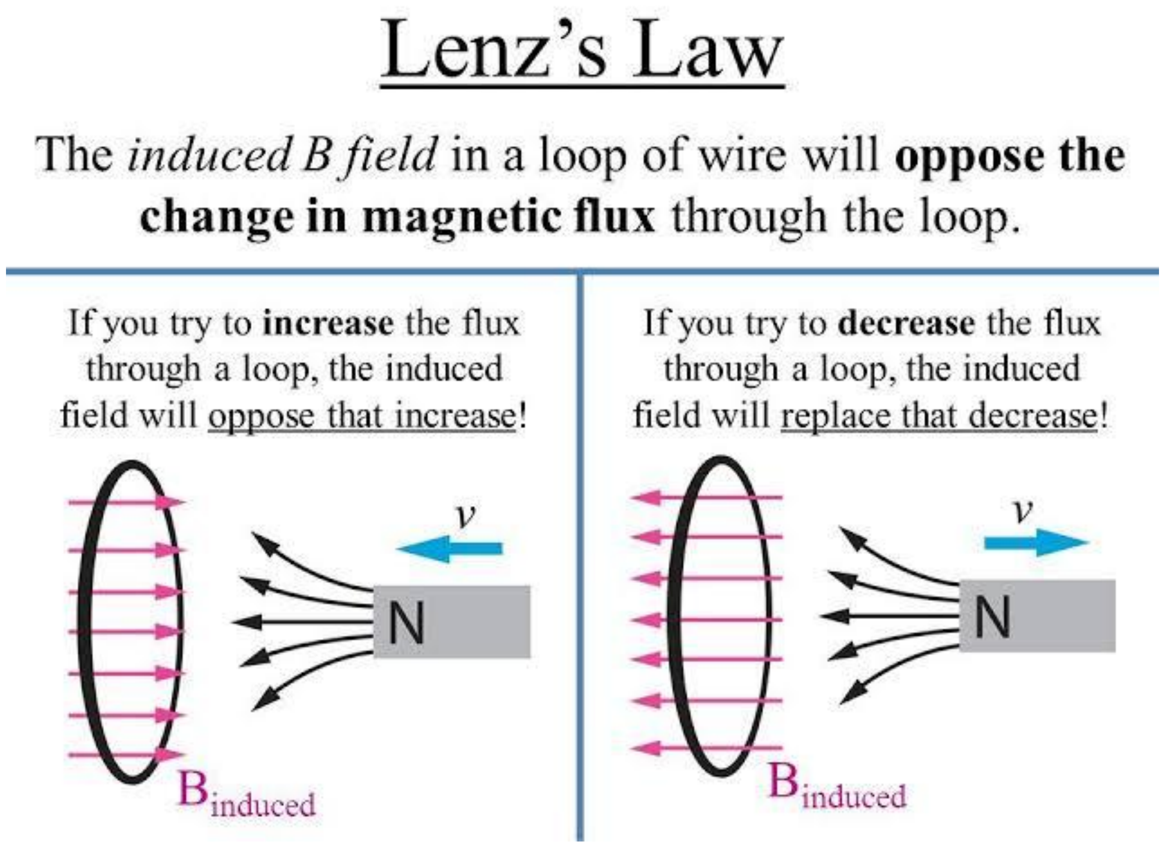
When calculating magnetic flux, do not multiply by the number of turns. When calculating induced electromotive force, do multiply by the number of turns.

ii. Lenz's law

The direction of the magnetic field generated by the induced current needs to hinder the change of the magnetic flux that causes the induced current.

$\phi changes \to I(nature: emf) \to B$

hinder

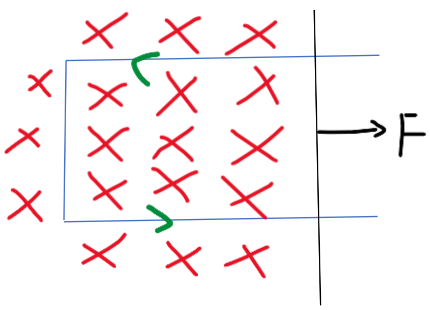


$\phi increases \rightarrow The\ metal\ ring\ has\ a\ tendency\ to\ expand$

$\phi decreases \rightarrow\ \ The\ metal\ ring\ has\ a\ tendency\ to\ shrink$

That is because:$\phi = B \cdot A$

④ Right-hand rule 3



Magnetic lines of force pass through the palm of your hand: your thumb points in the direction of motion (conductor, external force), and your four fingers point in the direction of the induced current.

Replenish: In electromagnetic induction: $Q = n \cdot \frac{\Delta\Phi}{R}$

III. Electricity

3.1 charge and the law of conservation

$e=1.6\times10^{-19}$ c $m_e=9.11\times10^{-31}$kg(electron) $m_p=1.66\times10^{-27}$kg(proton)

In an isolated system, the total amount of charge remains constant. Like charges repel each other, and unlike charges attract each other.

Glass rod rubbed with silk: Positive charge   Fur-rubbed rubber stick: negative charge

the law of conservation: Electric charge can neither be created nor destroyed, it can only be transferred from one object to another. During the transfer process, the total amount of electric charge remains unchanged.

3.2 charging method

3.2.1 charging by friction

Cause: When different materials come into contact and separate, surface electrons (or ions) are transferred or redistributed.

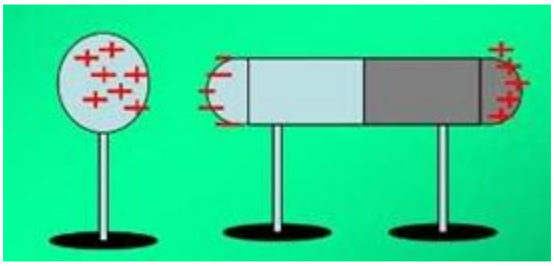
Essence: Triboelectric charging is essentially a charge imbalance caused by the redistribution of charge between objects.

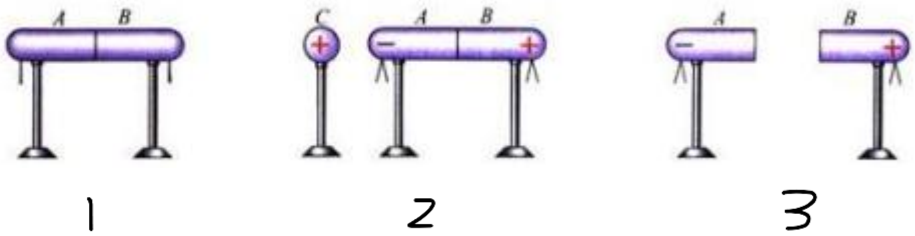
Electroneutrality: Equal number of positive and negative charges

3.2.2 electrostatic induction

1.definition: When a charged body approaches another conductor without contact, the force of the charges causes the free charges inside the conductor to be redistributed, resulting in the accumulation of opposite charges on the side close to the charged body and the accumulation of the same charges on the side away from the charged body.

2. Induction electrification





Note: Separate AB first, then remove C to get Figure 3!!! Otherwise, AB is neutral and has no charge.

3.nanture: The free charges in a conductor are transferred from one part of the conductor to another part under the action of a charged body.

Note: Regardless of the electrification method, the law of conservation of charge is followed.

3.3Coulonb's law

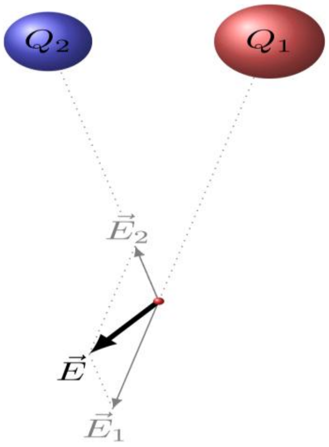
3.3.1

①.definition: The interaction force between two stationary charges in a vacuum.

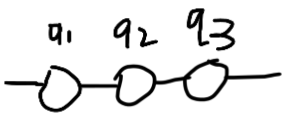
② expression:$F = k\frac{Q \cdot q}{r^2}$ k=9✖10^9 $N \cdot m^2/c^2$

r: Distance between sphere centers

3.3.2 Superposition of Coulomb forces



The **superposition of Coulomb forces** means that the net electric force on a charge is the vector sum of the individual Coulomb forces exerted on it by all other charges independently.

Replenish: 

$$\sqrt{q1 \cdot q2} + \sqrt{q2 \cdot q3} = \sqrt{q1 \cdot q3}$$

Why positive and negative electrons attract each other, and What is the nature of electric field force?

[Macroscopic, Intuitive Level]

↓

Coulomb's Law: $F = k \cdot q1 \cdot q2 / r^2$

→ Opposite charges have a negative product → mutual attraction

→ Like charges have a positive product → mutual repulsion

↓

[Energy and Field Level]

Electric charge = source or sink of electric field lines

→ Positive charge emits electric field lines, negative charge absorbs them

→ When positive and negative charges are close, the electric field lines become shorter and straighter, reducing electric field energy

→ Nature tends towards minimum energy → attraction occurs

↓

[Electromagnetic Field Theory Level]

Electric force is not a "mysterious pull" at a distance

→ A charge alters the electromagnetic field distribution in surrounding space

→ Another charge interacts with this local field → experiences a force

→ Therefore, "electric field" is merely a field that describes the interaction

↓

[Quantum Electrodynamics (QED) Level]

Electromagnetic interaction is determined by U(1) gauge symmetry

→ To maintain symmetry, a gauge field (electromagnetic field) must be introduced

→ Quantum of the field = photon

→ Interaction between charges = exchange of virtual photons

- Opposite charges → virtual photon exchange lowers system energy → results in attraction

- Like charges → system energy increases → results in repulsion

↓

[Most Fundamental Summary]

The essence of electric force = interaction between charges through the exchange of virtual photons

Attraction between positive and negative charges = a necessary consequence of electromagnetic interaction tending towards minimum system energy

3.4 electric field and electric field strength

①electric field: It is a special substance that transmits the interaction between charges.

Field has energy and is also a form of material existence.

②electric field strength:

Meaning: The magnitude of the force per unit charge

$$E = \frac{F}{q} = \frac{kQ}{r^2}$$

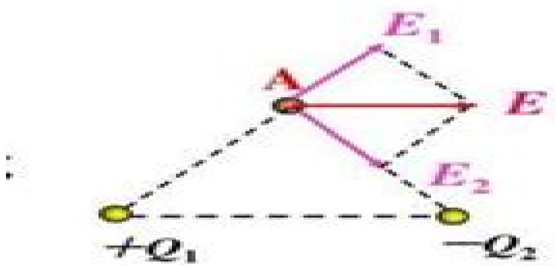
Unit:N/C it is a vector

Difference: $E = \frac{F}{q} \rightarrow$ any electric field

$E = \frac{kQ}{r^2} \rightarrow Vacuum\ and\ Q\ is\ a\ point\ charge$

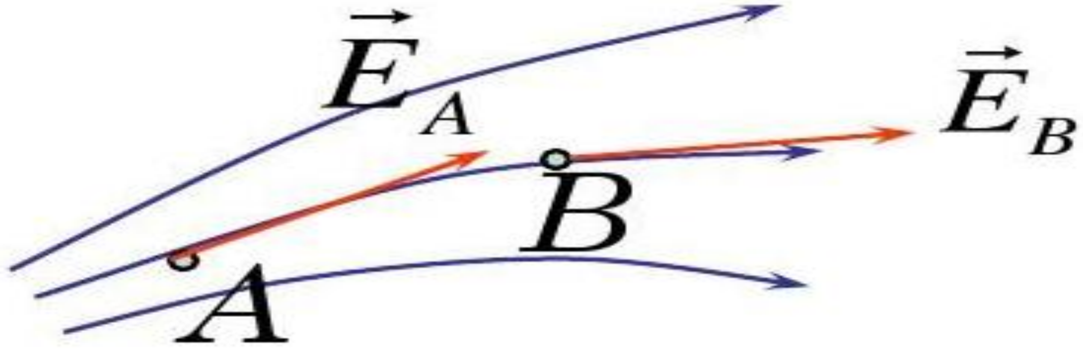
The direction of the electric field strength at a point in the electric field is the same as the direction of the force on the positive charge at that point, and opposite to the direction of the electrostatic force on the negative charge at that point!!!!!!!!!!!!!

③ Electric field superposition: Parallelogram Law

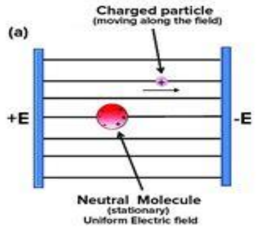


④ Electric field lines:1. The tangent direction indicates the direction of the electric field strength at that point. Does not actually exist, not closed

2. Its density represents the strength of the electric field.



⑤ Uniform electric field: same magnitude and direction (at every point)



3.5 Energy in electrostatic fields

3.5.1. Electric potential energy and electric potential

① Characteristics of electrostatic work

i. The work done by electrostatic force is related to the starting position of the charge, not the path the charge takes.

② Electric potential energy

i. Zero point: infinity

ii.relationship(work):$W_{AB}=E_A-E_B$ $W=-\Delta E$ $F\cdot\Delta r\cdot\cos\theta=-\Delta E$(Uniform electric field)

The amount of positive work done by electrostatic force on the charge is the amount of potential energy reduction.

Electric potential energy is a scalar quantity, the positive and negative values indicate the magnitude, not the direction.

iii. To know the electric potential energy at a certain point, first set a point with zero electric potential energy, and then add the work.

$0 + F \cdot \Delta r \cdot \cos\theta$

$V = 0 + Ed \quad E = V \cdot q$ Uniform electric field

iv. $F \cdot \cos\theta = -\frac{\Delta E}{\Delta r}$

so, along the direction of the electric field force, the electric potential energy decreases fastest.

v.role: Describes the ability of charges in an electric field to do work, which can be converted into kinetic energy or used to overcome the electric field force to do work.

vi.$E = \frac{KQq}{r}$ $\quad E = qV$ V: electric potential

The amount of charge and the electric potential together determine the magnitude of the electric potential energy

③ electric potential: i. The electric potential energy of a unit charge at that point.

The electric potential is a property of the electric field itself and has nothing to do with the presence or size of a test charge.

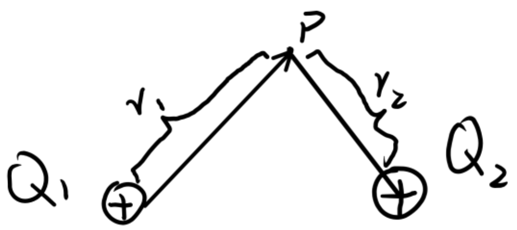
The magnitude of the electric potential indicates the amount of potential energy stored in the electric field and describes the intensity of the energy distribution in the electric field. Its magnitude indicates the potential of the electric field to do work on the charge.

ii.formula:$V = E/q$ unit: volt $V = \frac{KQ}{r}$

iii. Along the electric field lines, the electric potential gradually decreases.

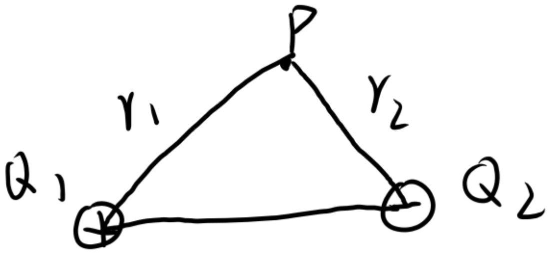
iv. scalar

v. Look at the electric field itself and the zero potential point, which has nothing to do with potential energy and q.



$$V_P = \frac{kQ_1}{r_1} + \frac{kQ_2}{r_2}$$

$$\frac{kQ_2}{r_2}$$



$$V_P = \frac{kQ_1}{r_1} - \frac{kQ_2}{r_2}$$

Notice: $E = \frac{kQq}{r}$ $, which\ is\ equal\ to\ E = \frac{kQq}{r^2} \cdot r$ is coincidence, and you can't calculate like this.

④potential difference $U_{ab}=V_a-V_b$

$$W_{AB} = U_{AB} \cdot q = (V_A - V_B) \cdot q = E_A - E_B$$

⑤equipotential surface:

A surface composed of points with the same electric potential.

Characteristic: 1. Electric field lines are perpendicular to equipotential surfaces.

2. Electric field lines point from higher equipotential surfaces to lower equipotential surfaces.

3. The denser the electric field lines, the denser the equipotential surfaces.

Why:

$$\because \quad E \cdot \cos\theta = -\frac{\Delta V}{\Delta r}$$

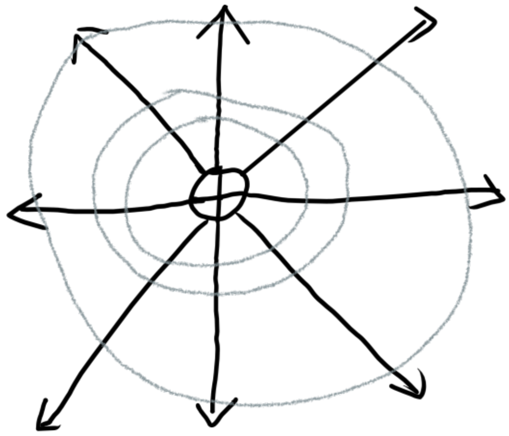
E ↓ electric field

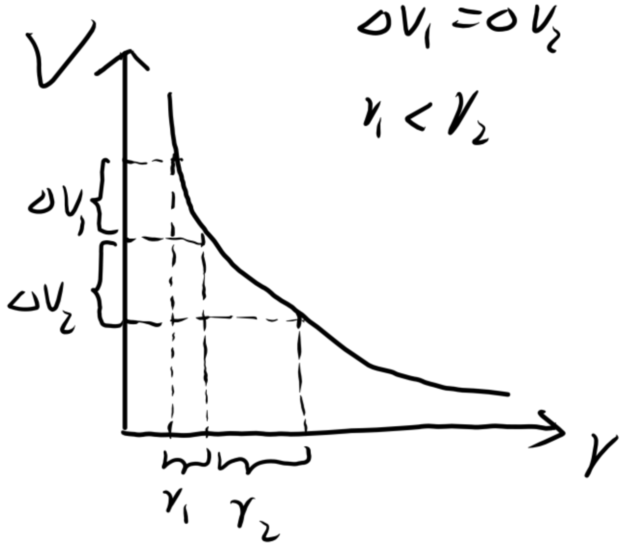
This is also the formula for calculating the average electric field

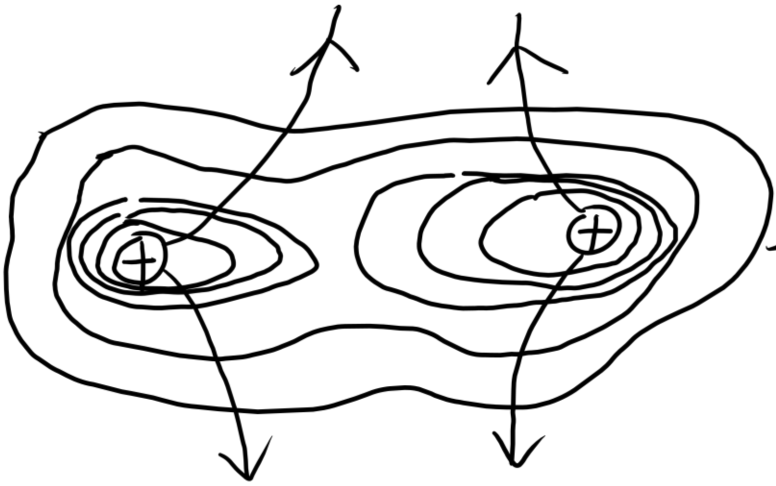
4. Moving charges on equipotential surfaces does not require electrostatic force to do work.

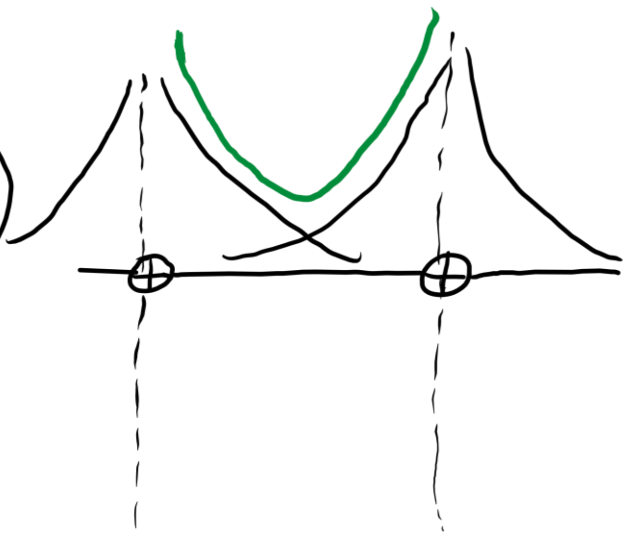
$\Delta V_1 = \Delta V_2$

$r_1 < r_2$

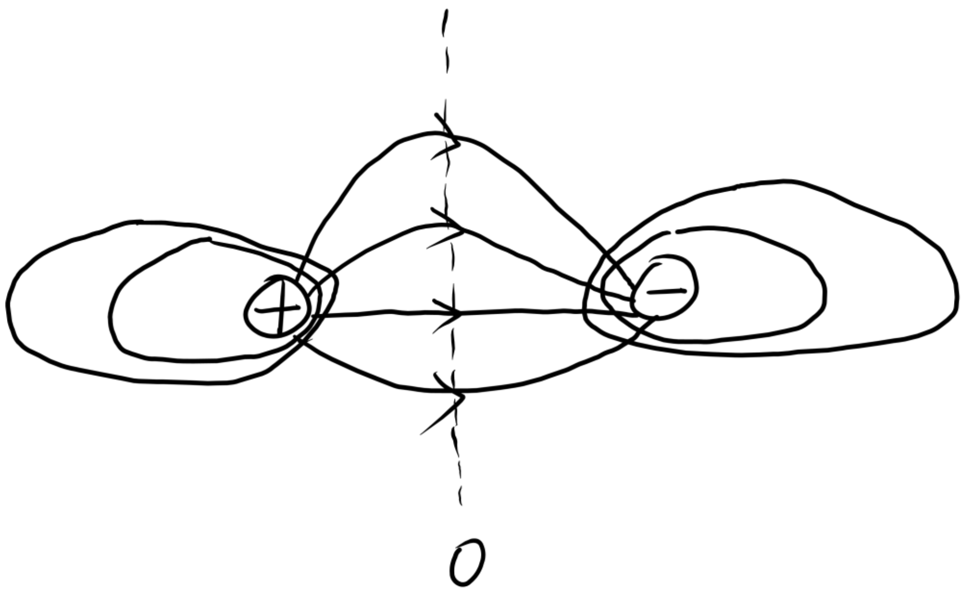








function



3.5.2 Electrostatic force does work

①

$$\Delta V = \frac{w}{q} = \frac{E_{p_1}}{q} - \frac{E_{p_2}}{q}$$

$$w = \int dw = \int_R^\infty \frac{kQq}{r^2}\,dr = kQq\int_R^\infty r^{-2}\,dr = 0 - \left(-\frac{kQq}{R}\right) = \frac{kQq}{R}$$

Equal to the electric potential energy at a certain point

②Electric field force does work

$$\begin{cases} \oplus: & \oplus \longrightarrow \ominus & : E_p \downarrow \\ \ominus: & \ominus \longrightarrow \oplus & : E_p \downarrow \end{cases} \Bigg\} \text{posi} \to 0 \to \text{negative}$$

$\downarrow$ moving charge

$\downarrow$ path

3.5.3 work and energy

$$F \begin{cases} \text{conservative force} \\ \\ \text{non-conservative force} \end{cases}$$

$$W_c = -\Delta E_p \text{ (potential energy)}$$

$$W_{net} = \Delta E_k \text{ (kinetic energy)}$$

$$W_{nc} = \Delta E_k + \Delta E_p = W_{net} + \Delta E_p$$
$$= W_c + W_{nc} + \Delta E_p$$
$$= W_{nc}$$

$\therefore$ W_{nc} = Mechanical energy change

Note: The direction of work done by the electric field force is not necessarily the direction of the electric field, but the direction of movement in the natural state.

eg,

$\ominus$ is moving to the left

$E_p \downarrow$

When only conservative forces do work, the change in mechanical energy is zero! The work done by a non-conservative force is equal to the change in mechanical energy!

3.6 the relationship between ΔV and E $\longrightarrow$ electric field

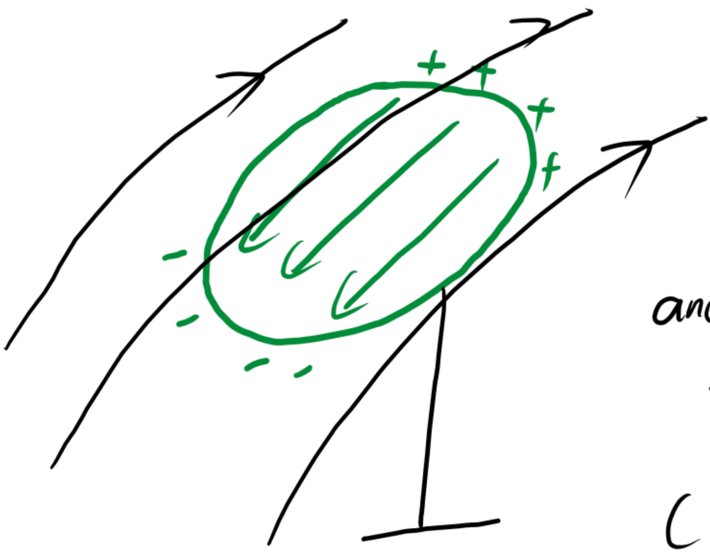
$$U = \Delta V = \frac{Eqd}{q} = Ed$$

$W = qU = qEd$ $\qquad E = \frac{U_{AB}}{d}$

Only applicable to uniform electric fields

If used for non-uniform electric field: the calculated value is the average electric field!

Replenish:



$E_{in} = E_{out}$

and E_{in} cannot be greator than E_{out}

(electric field)

In a non-uniform electric field, the electric field force is not constant, so the work cannot be directly calculated by multiplying the force by the displacement.

But: $W = q \cdot \Delta V$

3.7 The movement of charged particles in an electric field.

$$E = \frac{U}{d} \qquad F = q \cdot E = \frac{qU}{d} \qquad \therefore a = \frac{qU}{md}$$

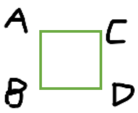
$$v^2 = 2ad = 2 \cdot \frac{qU}{md} \cdot d = \frac{2qU}{m}$$

$$\therefore v = \sqrt{\frac{2qU}{m}}$$

way 2: $qU = \frac{1}{2} m v^2$

$$v = \sqrt{\frac{2qU}{m}}$$

Replenish: In a uniform electric field:



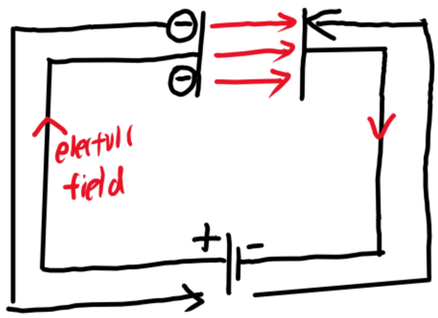
V_A – V_B = V_C- V_D

3.8 capacitor’s capacitance

Capacitor: store energy, does not store charge

①the amount of charge in an capacitor is the amount of charge on one plate.

$$E = \frac{V}{d}$$



$$E_p = \frac{kQq}{r}$$

$$E = \frac{kQ}{r^2}$$

When the electric field generated by the power supply is as large as the electric field generated by the capacitor, charging is completed!!!

This is the conversion of the potential energy of the power supply into the potential energy of the plate.

Note: The same charge does not mean the same electric field, because it is also related to the distance between the plates.

②formula:

Definition $C = \frac{Q}{V}$

$Q \rightarrow$ the amount of charge on one plate

$V \rightarrow$ the potential difference between 2 plates

Deterministic $C = \frac{Q}{V} = \frac{\varepsilon_0 A}{d} = \frac{A}{4\pi k d} = \frac{KA}{4\pi k d}$

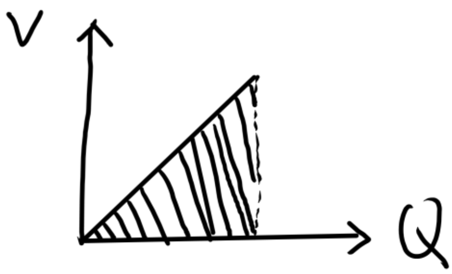
$\frac{A}{4\pi k d} \rightarrow$ nothing between the plates

$\frac{KA}{4\pi k d} \rightarrow$ in the presence of dielectric

Interpretation: V: Electric potential energy per unit charge

So: C: The amount of charge fixed per unit of energy.

Electric potential energy: $E_p = \frac{1}{2} Q V = \frac{1}{2} C V^2 = \frac{1}{2} \frac{Q^2}{C}$



Why one-half?

Because Q and V are changing (both during charging and discharging).

Why V is changing? But in the circuit there are only wires, switches, power supplies, and capacitors, so how is the power supply voltage distributed? Why isn't the capacitor voltage equal to the power supply voltage?

1. Two Phases of Circuit State

We must take time into account and divide the circuit's operation into two phases:

Transient Process: Within a very short period of time after the switch is closed, the voltage and current in the circuit fluctuate dramatically and have not yet stabilized.

Steady-State Process: After a long period of time after the switch is closed, the voltage and current in the circuit stabilize and no longer fluctuate.

The main point of confusion lies in the transient process.

2. Transient Process: How is the voltage distributed?

At the instant the switch is closed ($t=0+$), there is no charge on the capacitor ($Q=0$). According to the formula $V_c = Q / C$, the capacitor voltage $V_c = 0$.

Now, let's look at the voltage distribution throughout the circuit. According to Kirchhoff's voltage law, the sum of the voltage rises in any closed circuit must equal the sum of the voltage drops.

In this simple circuit:

There is only one source of voltage rise: the power source V_{source}.

There are two sources of voltage drop: the voltage V_c across the capacitor and the resistance of the wire itself (although very small).

The circuit equation can be written as:

$V_{source} = V_c + V_{wire}$

Where V_{wire} is the voltage drop across the tiny resistance of the wire when current flows through it.

At the moment the switch closes:

$V_c = 0$

Substituting this into the equation: $V_{source} = 0 + V_{wire}$

This means that almost all of the source voltage is distributed to the wire! This huge voltage difference, V_{wire}, generates an extremely strong electric field, driving a large instantaneous current in the circuit.

This massive current acts like a torrent, rapidly "pumping" charge from the source to the capacitor plates.

3. The Dynamic Process from "Unequal" to "Equal"

Charging Begins: The massive current means that charge is accumulating on the capacitor at an extremely rapid rate.

Vc Begins to Rise: According to $V_c = Q / C$, the charge Q increases, and the capacitor voltage, V_c, gradually rises from 0.

Voltage Redistribution: Since V_c increases, according to the circuit equation V_source = V_c + V_wire, the voltage V_wire distributed across the wire resistance must decrease (since V_source is fixed).

Current Decrease: V_wire decreases (V_wire = I * R_wire), which means that the current I also decreases. Charge accumulation slows.

Forward Cycle: Current decreases → Charge accumulation slows → V_c rises slower → V_wire becomes smaller → Current decreases... and so on.

4. Final State: Equality

This process continues until:

The capacitor voltage V_c approaches the source voltage V_source.

At this point, the voltage drop V_wire across the wire approaches zero.

The voltage difference driving charge movement disappears, and the current decreases to zero.

Charge movement ceases, and both V_c and Q reach stable values.

At this point, the circuit equation becomes:

V_source = V_c + 0

Eventually, the capacitor voltage equals the source voltage. The circuit enters steady state.

Core Concept and Metaphor

The voltage difference is the driving force: Charges don't move on their own. It's the difference between the capacitor voltage and the source voltage that provides the "push" (electric force) that moves the charge. The greater this push, the greater the current and the faster the charging.

This "push" dissipates: the charging process itself reduces this "push" (because Vc is increasing). When the push reaches zero (Vc = V_source), the process stops.

Perfect Metaphor: A Race

The source voltage is like the finish line.

The capacitor voltage is like the runner.

Closing the switch is the starting signal.

At the start, the runner (Vc = 0) is farthest from the finish line (V_source), the gap is the largest, so he runs as hard as he can (high current).

As he gets closer to the finish line, the gap narrows, and his speed slows down (lower current).

When he crosses the finish line, the gap is zero, and he stops (current = 0). At this point, his position (Vc) equals the position of the finish line (V_source).

Summary:

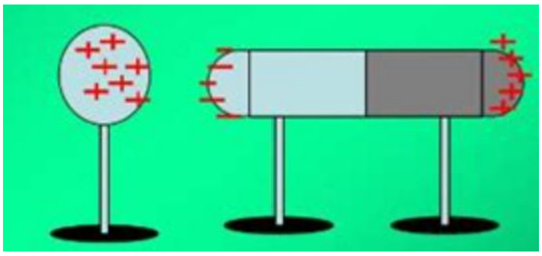
At the final stage of stability, the capacitor voltage is indeed equal to the source voltage. However, before reaching this stable state, a "charging" process is required. During this process, because the charge movement takes time, the capacitor voltage gradually increases from zero, temporarily not equaling the source voltage. This "not equal" voltage difference is the fundamental reason for driving current and completing the charging process.

$$\varepsilon = 8.85 \times 10^{-12}$$

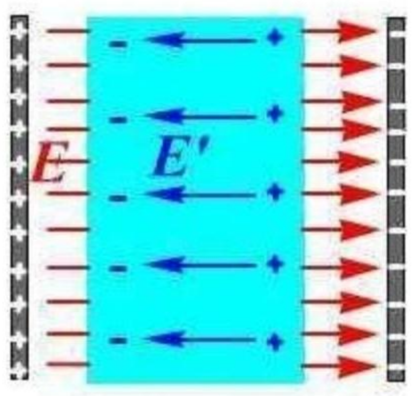
(The dielectric constant of a vacuum, when there is nothing in between)

③polarization

Conductor: Induction charging



Non-conductors: Insulators can also be polarized



Dielectric polarization

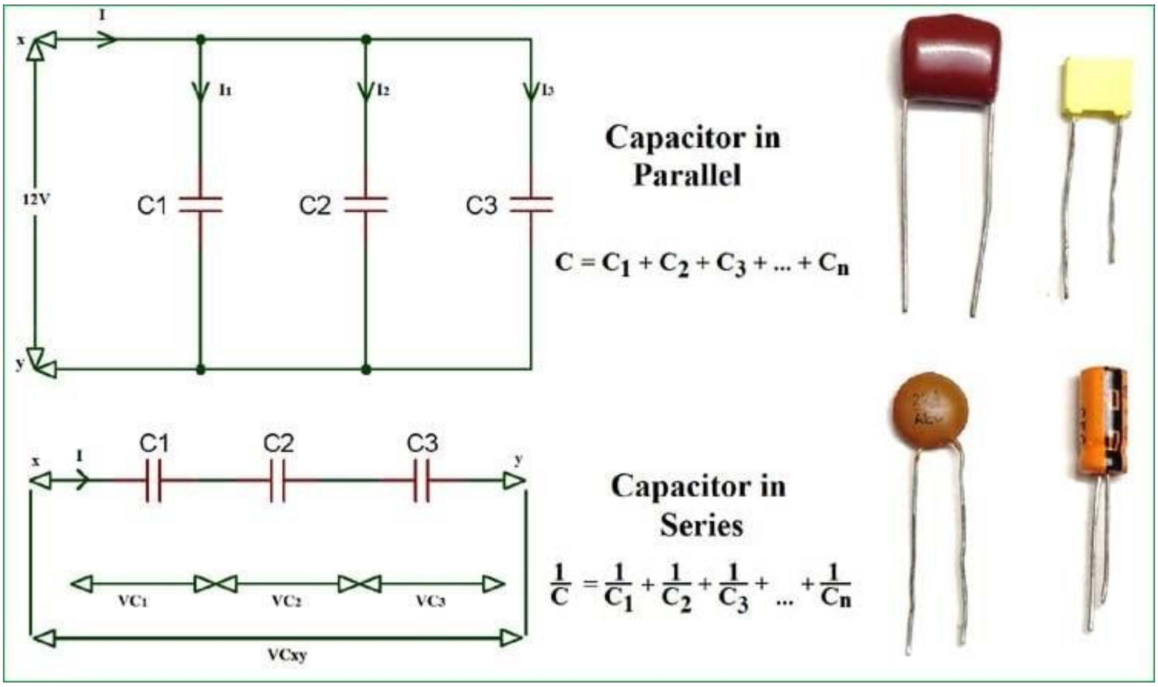
The internal electric field is smaller than the external electric field

$E=E_{out}-E_{in}=\frac{E_{out}}{K}$ *Dielectric constant of dielectric*

$V'= E\times d=\frac{E_{out}}{K}\times d=\frac{V}{K}$

$C'=\frac{Q}{V'}=\frac{KQ}{E_{out}}\cdot\frac{1}{d}=K\cdot\frac{Q}{V}=KC=\frac{KA}{4\Pi kd}$

④combined capacitance of several capacitors connected in series and paralleled.



Series： Q=Q1=Q2=Q3   V=V1+V2+V3

Q/c = Q1/C1 + Q2/C2 + Q3/C3

So, 1/C = 1/C1 + 1/C2 + 1/C3

Parallel: Q=Q1+Q2+Q3

V1=V2=V3=V

So: C=C1+C2+C3

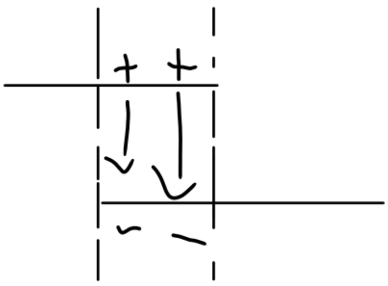
But why Q=Q1+Q2+Q3?

Because $I=I_1+I_2+I_3$

$It=I_1 \times t+I_2 \times t+I_3 \times t$

Q=Q1+Q2+Q3

⑤dynamic analysis



Between the two plates: uniform electric field has dielectric: $E = \frac{V}{d} = \frac{Q}{Cd} = \frac{Q}{\frac{KA}{4\Pi kd} \cdot d} = \frac{Q}{\frac{KA}{4\Pi k}} = \frac{4\Pi kQ}{KA}$

no dielectric: $E = \frac{V}{d} = \frac{Q}{Cd} = \frac{Q}{\frac{A}{4\Pi kd} \cdot d} = \frac{Q}{\frac{A}{4\Pi k}} = \frac{4\Pi kQ}{A}$

$So: d \uparrow:$

$$\begin{cases} Q \rightarrow \\ V \uparrow \\ Ep \uparrow \\ E \rightarrow \\ C \downarrow \end{cases}$$

Electric field

Add a dielectric:

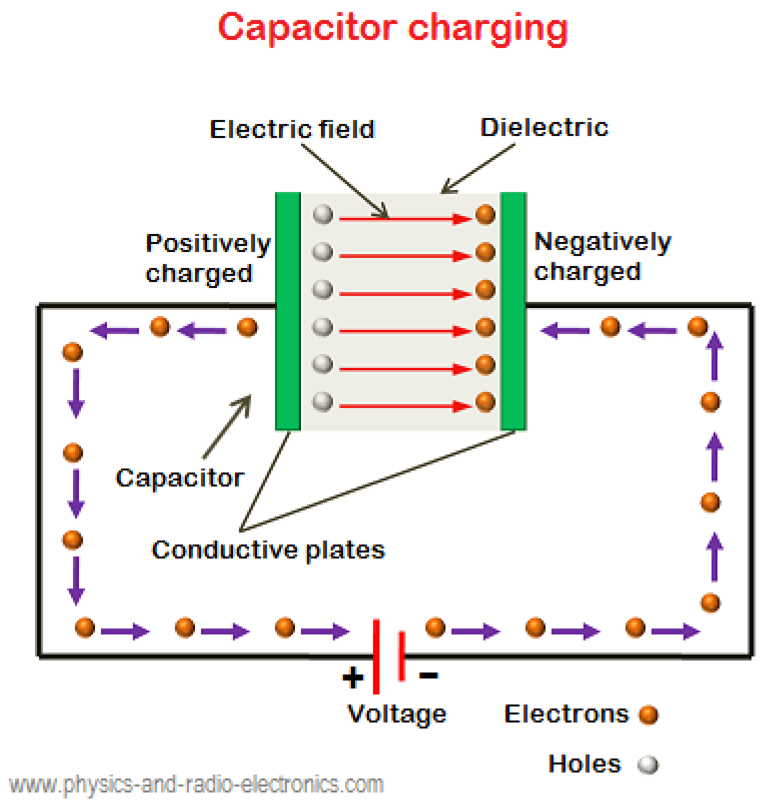
$$\begin{array}{l} Q \rightarrow \\ V \downarrow \\ Ep \downarrow \\ E \downarrow \\ C \uparrow \end{array}$$

$A\downarrow:$

$$\begin{cases} Q \rightarrow \\ V \uparrow \\ Ep \uparrow \\ E \uparrow \\ C \uparrow \end{cases}$$

As long as the power supply remains unchanged, Q remains unchanged.

A capacitor when fully charged is a resistor: $V = \varepsilon\text{-}Ir = \varepsilon$ because I=0

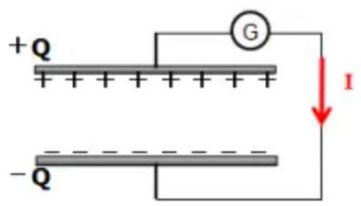


The charge itself does not actually pass through the plates

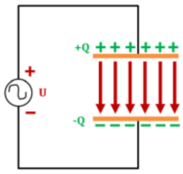
What is the function of a capacitor's dielectric?

Increasing the capacitance can store more electrical energy. Because of the polarization of the dielectric, opposite charges attract each other.

Capacitor discharge: When the capacitor discharges, the voltage of the component decreases as the voltage of the capacitor decreases.



Deep Thinking:



$$Ep = \frac{1}{2}QV$$

BUT: $\frac{1}{2}QV \neq V\_out \cdot q$

Capacitor potential energy (stored) The electric potential energy provided by the

power supply

q: the amount of charge provided by the power supply

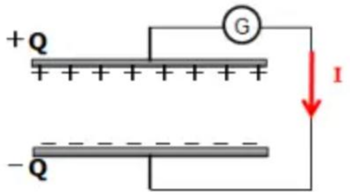
$$V\_out \cdot q = V\_capacitor \cdot q + Energy\ consumed\ by\ the\ wire$$

Potential energy absorbed by the capacitor

$V\_capacitor \cdot q$ and $\frac{1}{2}QV$ what is the difference?

To exemplify: Jack earned \$100 a day ($V\_capacitor \cdot q$), but his bank account was \$100 million ($\frac{1}{2}QV$).

Discharge:



talk about it later

$$q_{remain} = Q \cdot e^{-\frac{t}{RC}}$$

q: output charge

$$Q = V_{max\,(capacity)} \cdot C$$

if $q = e$: that means only one electron is released.

$$\frac{q_{remain}}{C} = \frac{Q}{C} \cdot e^{-\frac{t}{RC}}$$

$$V_{remain} = V \cdot e^{-\frac{t}{RC}}$$

$$V_{remain} \cdot q = V \cdot q \cdot e^{-\frac{t}{RC}}$$

$$E_{remain} = E \cdot e^{-\frac{t}{RC}}$$

The potential energy consumed by the remaining capacitor voltage

IV. Circuits

4.1 current

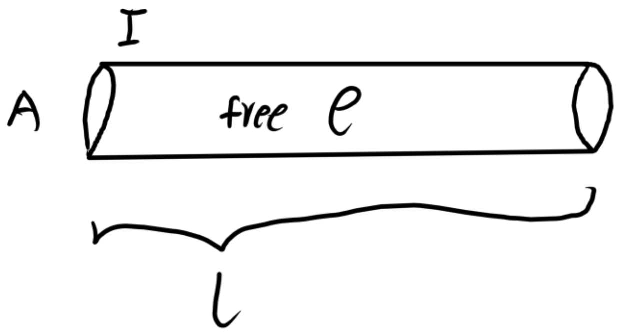
Definition: Qualitative: current is the flow of charge.

Quantitative: $I = \frac{Q}{t}$ current is defined as the amount of charge passing a point per unit time.

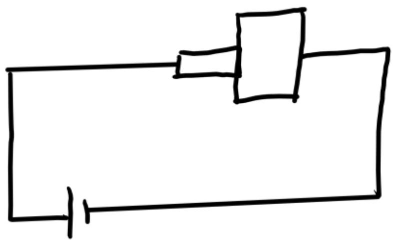
To exemplify: I=5mA t=10s Q=5✕10^-3 A ✕10s = 5✕10^-2

number n=Q/e

4.1.2 microscopic expression



$$I = \frac{Q}{t} = \frac{n \cdot A \cdot l \cdot e}{t} = n \cdot A \cdot e \cdot V$$



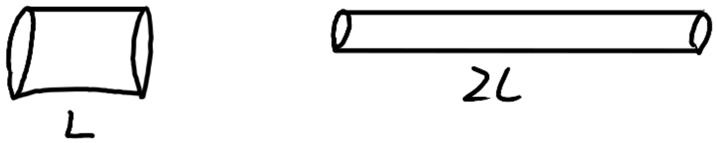
I is the same, so according to I=nAeV, thinner resistor has faster electron.

Note: When the current increases, it is the speed of the electrons that changes, because the number of electrons n is constant!!!!!

4.2 resistance

$R = V/I$

$R = \rho \frac{l}{A}$ $\rho: resistivity$

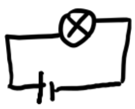


V is the same

$$R = \rho \frac{L}{A} = \rho \frac{L}{\frac{V}{L}} = \rho \frac{L^2}{V} \to \text{volume}$$

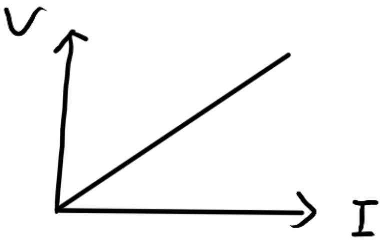
4.2.2 I V character

Charge carrier: Freely moving particles with electric charge are the main carriers of electric current. Metals: Carriers are free electrons.

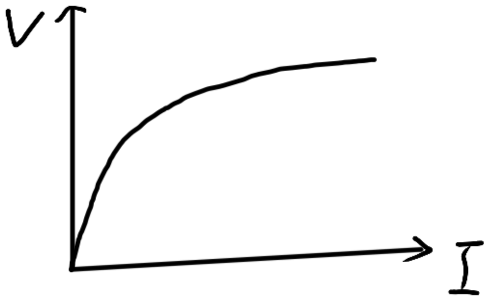


The nature of electron movement: the power supply generates an electric field in the circuit.

①ohmic/ metallic resistor $R = \frac{V}{I}$ R is constant



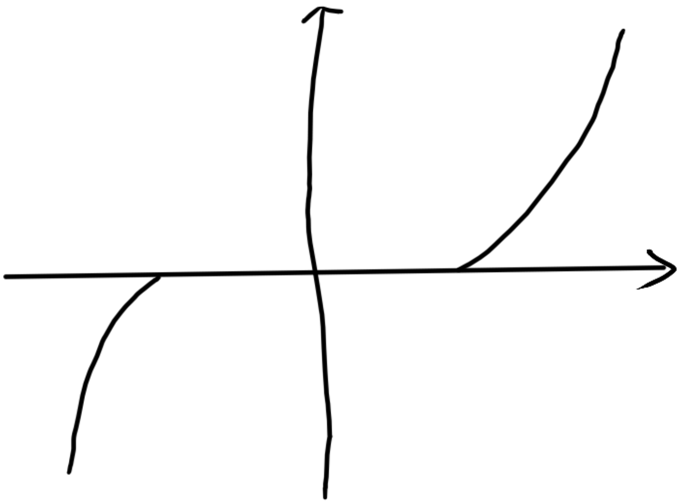
②thermistor



R is decreasing

③filament lamp : R is increasing

④ diode :Electricity can only flow in one direction, otherwise there will be no current.



4.3 The difference between voltage and electromotive force

$$V_1 - V_2 = \frac{E_1}{q} - \frac{E_2}{q} = \frac{E_1 - E_2}{q} = \frac{\Delta E}{q}$$

ΔE: the energy transferred from electrical to other form of energy.

or work done by electric force

For example, Light bulb Convert electrical energy into light energy.

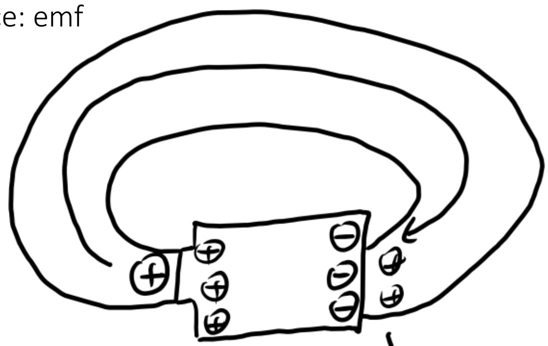
Voltage: Ability to convert electrical potential energy

$$\Delta E = UIt = UQ$$

Supplement: If you want to calculate the electric potential/potential energy in a circuit, first determine the zero potential energy surface. The circuit is a uniform electric field.

$$E = 0 + V \cdot q$$

Electromotive force: emf

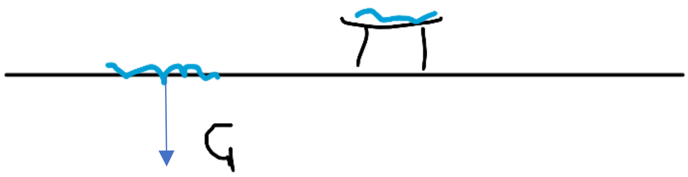


positive charges cannot accumulate here ∵ they will attract the negative charges

So， When positive charge moves from the negative electrode to the positive electrode, the electric field force does negative work and the electric potential energy increases.

However, the force that makes the charge move from the negative electrode to the positive electrode does not exist, and the positive charge moves from the negative electrode to the positive electrode through the redox reaction.

For example:



Because of the influence of gravity, water cannot move from the ground to the table, so a chemical reaction (evaporation, liquefaction) is required to allow water to move to the table.

$$emf = \frac{energy\ transformed\ from\ other\ form\ to\ electrical}{q}$$

Note: This is just a single charge and is not usable in a circuit because there are too many charges in the circuit.

In external circuit, electric potential energy drops along the current.

In internal circuit, electric potential energy increases from negative electrode to positive electrode.

$$W = UIt$$

$$p = \frac{W}{t} = UI = I^2R = \frac{V^2}{R}$$

$$W = p \cdot t \longrightarrow$$ Electrical work, which represents the conversion of electrical energy into other energy.

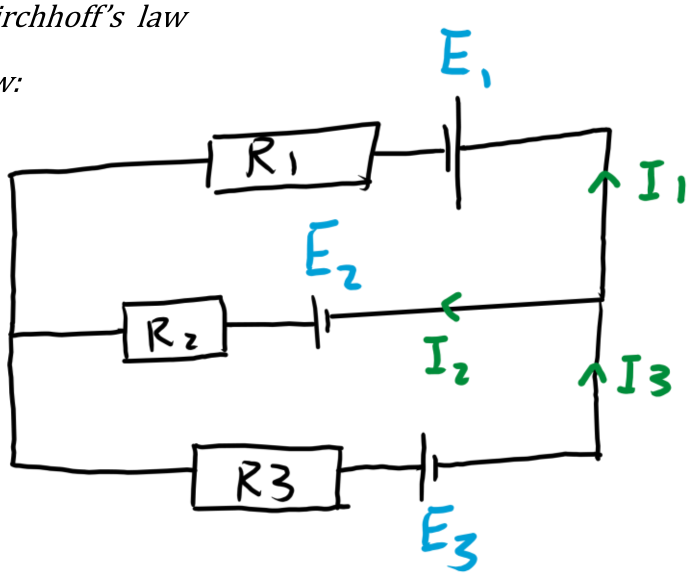
$V = IR$: Only pure resistance circuit will work.

Non-pure resistance circuit: $VIt > I^2Rt$

To exemplify: electric fan: $VIt = I^2Rt + kinetic\ energy$

4.4 Kirchhoff's law

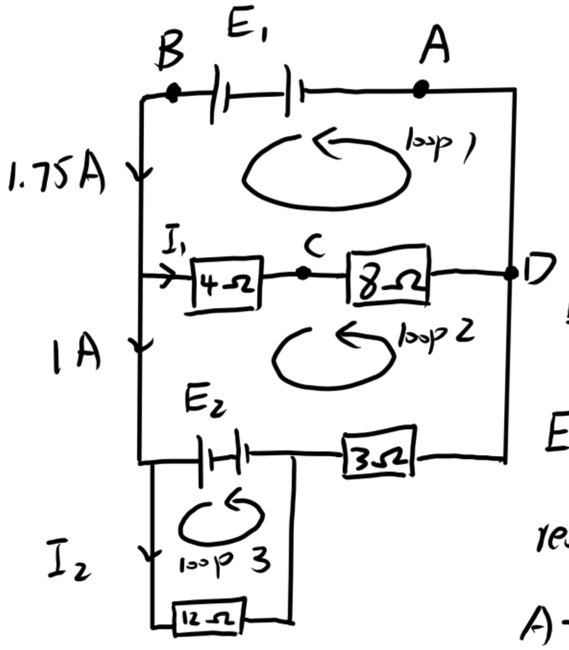
1st law:



The sum of the current entering any point is equal to the sum of the current leaving the same point.

2nd law: the change of potential around any closed circuit is zero.

$I_1 = 1.75A - 1A = 0.75A$



After one circuit, the potential difference at point A is zero.

$E_1 - 0.75 \times 4 - 0.75 \times 8 = 0$

E_1 : other energy $\rightarrow E_p$ $\quad E_p \uparrow$

resistor: $E_p \rightarrow$ other energy $\quad E_p \downarrow$

$A \rightarrow B \rightarrow C \rightarrow D \rightarrow A$

loop 2: $+0.75 \times 4 - E_2 - 1 \times 3 + 8 \times 0.75 = 0$

$E_2 = 6V$

loop 3: $-12 \times I_2 + 6 = 0$

$I_2 = 0.5A$

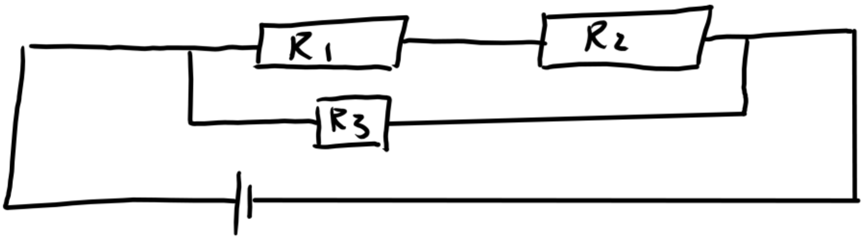
When passing through a power source or component, if the voltage increases, take the positive. If the voltage decreases, take the negative.

The direction is opposite to the current direction: if it is positive, the voltage increases. The direction of the current is the same as the winding direction, if it is negative, the voltage decreases. (Voltage across the resistor)

The symbol of the power supply voltage:

Negative electrode → positive : Voltage increases, take the positive, +V (+E)

Positive electrode → negative : Voltage decreases, take the negative ,-V (-E)

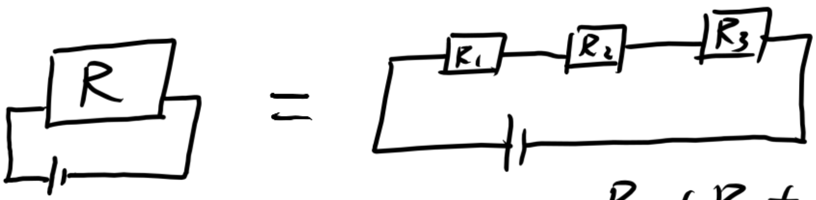


① $E_1 - I_1 R_1 - I_1 R_2 = 0$

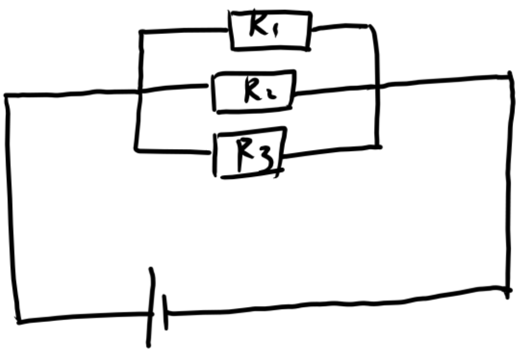
② $E_1 - I_2 R_3 = 0$

③ $-I_1 R_1 - I_1 R_2 + I_2 R_3 = 0$

4.5 combined resistance



$$R = R_1 + R_2 + R_3$$



$$\frac{E}{R} = \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}$$

$$\because E = V_1 = V_2 = V_3$$

$$\therefore \frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

Therefore, the more parallel connections, the smaller the total resistance.

4.6 Ohm's Law of closed circuit

$$V = \varepsilon - Ir$$

$$q \cdot \varepsilon = q \cdot V + I^2 r t$$

$I \cdot r$: lost Volt

r : internal resistance of power supply

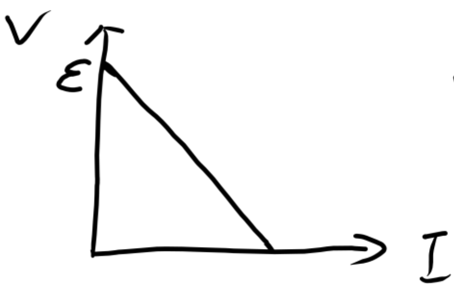
V : terminal potential difference

$$\because V = \varepsilon - Ir$$

$$IR = \varepsilon - Ir$$

$$I = \frac{\varepsilon}{R+r}$$

Closed circuit, and non-pure resistance circuit is not available



$$V = -r \cdot I + \varepsilon$$

slope : $-r$

y-intercept : ε

This is also the method of measuring the internal resistance of the power supply.

By changing the external resistance, the voltage and current can be changed.

4.6 power $P = UI$

1. $P_{total} = \varepsilon I = \frac{\varepsilon Q}{t} = \frac{\varepsilon^2}{R+r}$

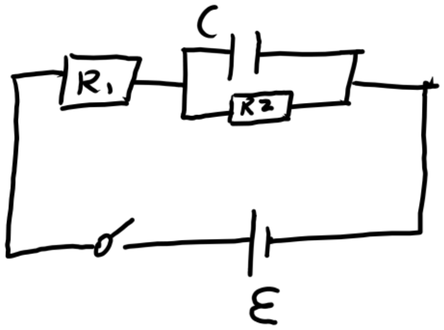
2. $P_{external} = UI = \frac{UQ}{t} = \frac{\varepsilon^2}{(R+r)^2} \cdot R$

3. $P_{internal} = I^2 r = \frac{\varepsilon^2}{(R+r)^2} \cdot r$

$$P_{total} = P_{external} + P_{internal}$$

Note: The brightness of the bulb is related to the power, not the current.

4.7 RC circuit (resistance and capacitor)

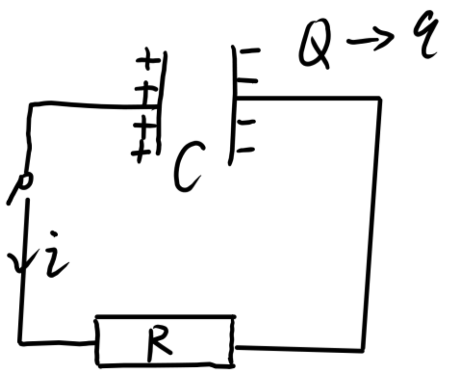


$$V_C = \frac{\varepsilon}{R_1+R_2} \cdot R_2$$

①immediately after the switch is closed, the capacitor can be treated as a conductive wire.

②After the switch is closed for a long time, the capacitor can be treated as an open circuit.

③Time constant: the time taken for the original amount of charge to $\frac{1}{e}$ of its original value.



C: fully charged

$$Q \rightarrow \frac{Q}{e} = q$$

$$\frac{q}{C} - i \cdot R = 0 \qquad i = \frac{-dq}{dt} \left(\because dq \text{ is negative} \right)$$

$$\frac{q}{C} + \frac{dq}{dt} R = 0$$

$$q = -\frac{dq}{dt} RC$$

$$-\frac{1}{RC} dt = \frac{1}{q} dq$$

$$\frac{t}{RC} = -\ln q + C$$

$$-\frac{t}{RC} + C = \ln q$$

$$q = e^{-\frac{t}{RC} + C}$$

$$q = C \cdot e^{-\frac{t}{RC}}$$

when $t = 0$, $q = Q$

$$C = Q$$

$$\therefore \frac{q}{Q} = e^{-\frac{t}{RC}}$$

$$\frac{1}{e} = e^{-\frac{t}{RC}}$$

$$\frac{t}{RC} = 1$$

$$t = RC \quad \star$$

the time from $Q \rightarrow \frac{Q}{e}$

Therefore, if the resistance becomes smaller, the time becomes smaller and the discharge is faster.

Charge: The time required for the capacitor to charge from 0 to $\frac{e-1}{e} \cdot Q$

$$Q = Q_0 \left(1 - e^{-\frac{t}{RC}}\right) = \mathcal{E} \cdot C \cdot \left(1 - e^{-\frac{t}{RC}}\right)$$

Q_0: fully charged

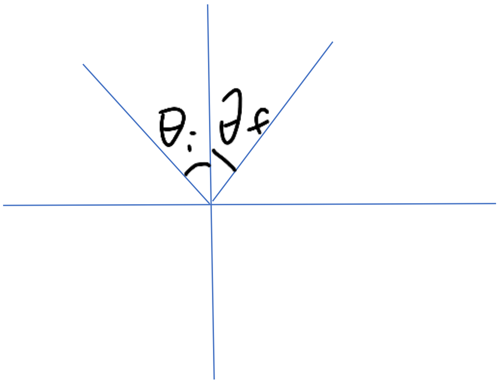
$$Q = Q_0 - Q_0 \cdot e^{-\frac{t}{RC}}$$

when $t = RC$ $\quad Q = Q_0 - \frac{Q_0}{e} = \frac{e-1}{e} \cdot Q_0$

V. Geometric optics

5.1.the law of reflection

The incident and reflected rays and the normal all lies in the same plane, which is called the plane of incidence. $\theta i = \theta f$



5.2. reflection of light

5.2.1. index of refraction.

①definition: It describes the change in speed of light and its deflection when it propagates in a medium.

②formula: $n = \frac{c}{v}$ (Applicable to everything)

C: Speed of light in a vacuum: 3✕10^8 m/s

V: Speed of light in a medium.

n does not have the unit. Transparent objects have a refractive index.

The index of refraction depends not only on the substance but also on the wavelength of the light.

③$\lambda \downarrow$ $f \rightarrow$

$v \downarrow$ $n \uparrow$

The smaller the wavelength, the easier it is for light to be deflected and the greater the refractive index.

When light propagates through different media, the speed of light decreases, but f remains unchanged.λ $decreases$ Because frequency is determined by light source.

$\lambda 2 = \frac{n1}{n2} \lambda 1$ $n2 > n1$ $n_{air} = 1$

Derivation: $v = \lambda \cdot f$

$$\because n = \frac{c}{v}$$

$$\therefore v = \frac{c}{n}$$

$$\frac{v1}{v2} = \frac{\frac{c}{n1}}{\frac{c}{n2}} = \frac{n2}{n1}$$

$$V2 = \frac{n1}{n2} V1$$

$$\because\ f\ is\ constant$$

$$\therefore\ \lambda 2 = \frac{n1}{n2} \lambda 1$$

5.2.2 Snell's law

$$\frac{\sin \theta 1}{\sin \theta 2} = \frac{n2}{n1}$$

Sending light from a vacuum into a medium：

$$\frac{\sin in}{\sin out} = n$$

n：The refractive index of the medium $n = \frac{\sin air}{\sin material}$

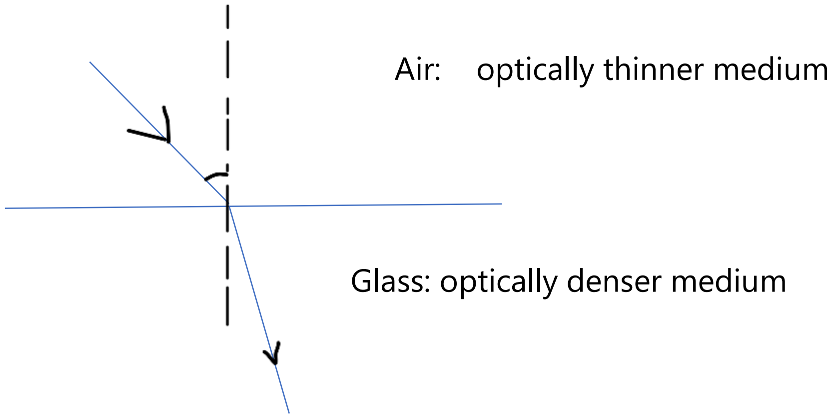
The refractive index of light in a vacuum is 1.

5.2.3 medium

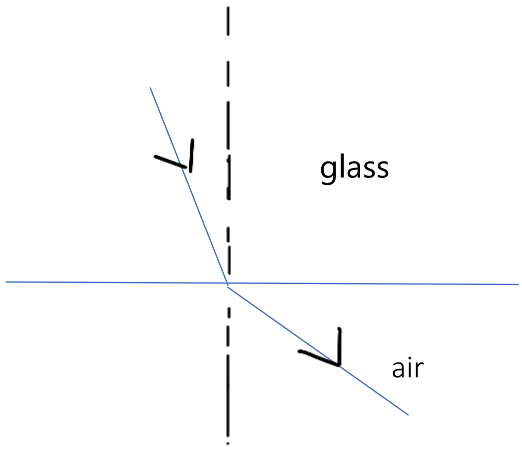
①optically denser medium: n is greater

② optically thinner medium: n is smaller.

For example:



Thinner → denser: Smaller refraction angle



denser → thinner : greater refraction angle

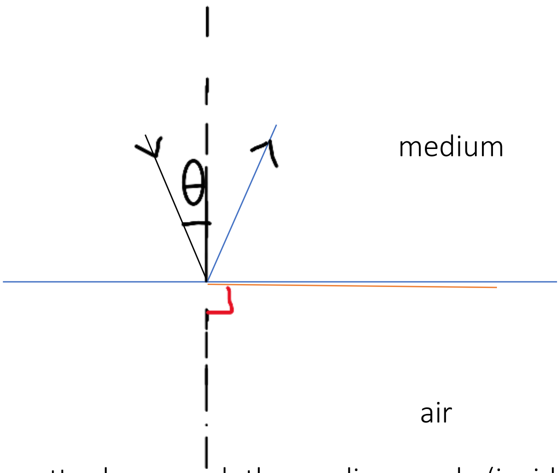
5.2.4 total internal reflection

① Light travels from a denser medium to a less dense medium. When the medium is small, there is both refraction and reflection.

As the air angle increases, the medium angle also increases.

$$n = \frac{\sin air\ \uparrow}{\sin medium\ \uparrow} \qquad n \rightarrow$$

When the air angle increases to 90 degrees, it reaches the critical point, the refracted light disappears completely, and only the reflected light remains. Total internal reflection.

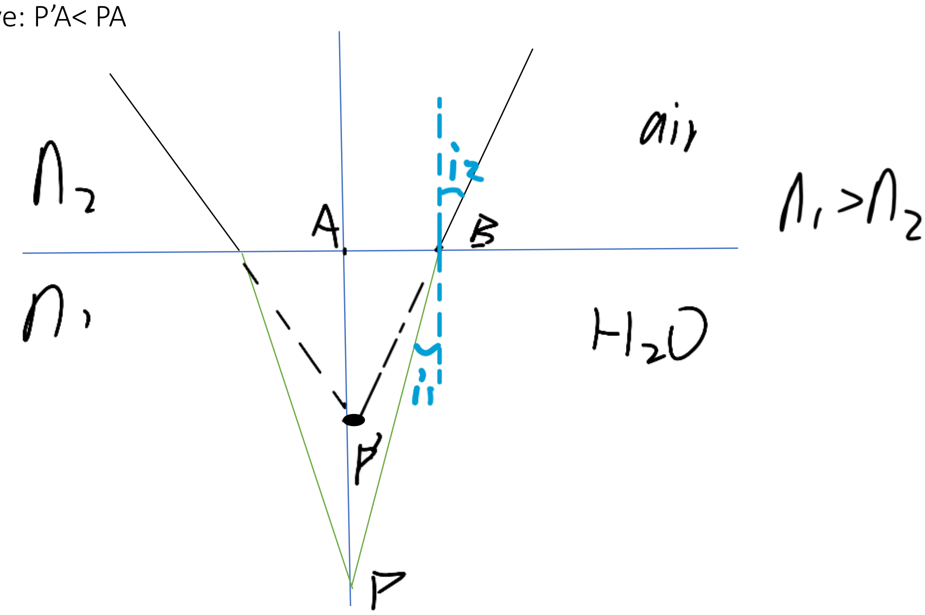


At this point, no matter how much the medium angle (incident angle) is increased, no refracted light can be seen, only reflected light can be seen.

$$n = \frac{\sin air}{sin\ medium} = \frac{1}{sin\ medium} = \frac{1}{\sin\theta}$$

Total internal reflection can occur between any two transparent media.

Extra: prove: P'A< PA



Since the angle is not large, we can assume that:

$$sin\ i1 = tan\ i1 \qquad sin\ i2\ = \ tan\ i2$$

By Smell's law:

$$n1\ \cdot sin\ i1\ = n2\ \cdot sin\ i2$$

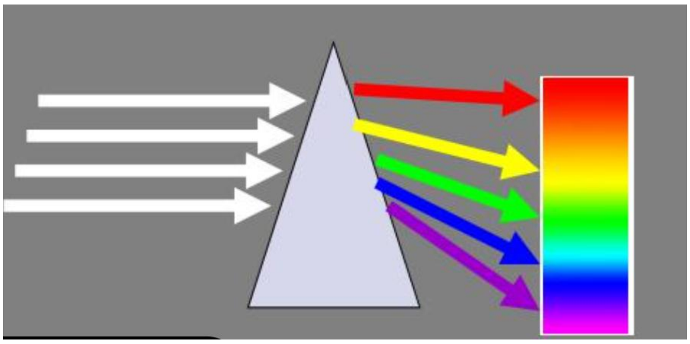
$$sin\ i1 = tan\ i1 = \frac{AB}{PA}$$

$$sin\ i2 = tan\ i2 = \frac{AB}{P'A}$$

$$\frac{n1}{n2} = \frac{\sin i2}{\sin i1} = \frac{PA}{P'A} \longrightarrow P'A = \frac{n2}{n1}PA$$

Since n1>n2 So: P’A< PA

5.2.5 dispersion of light

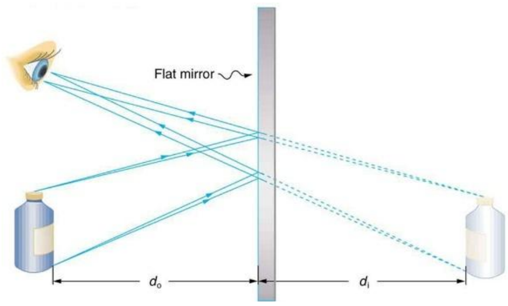


from red to violet: $\lambda \downarrow \quad f \uparrow$

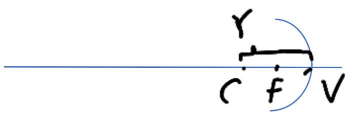
But: $f \downarrow \quad Stronger\ resistance\ to\ particles\ in\ the\ medium$

$$\therefore n \uparrow \quad More\ and\ more\ deflections$$

5.3 image formation by mirrors



5.4 object-image formula



5.4.1 spherical mirror (mirror!!!!)

1.types of spherical mirror

I Converging/concave mirror

II diverging/convex mirror

2.main concepts

C is the center of curvature of the surface

V is the vertex of the mirror

CV is called the optic axis

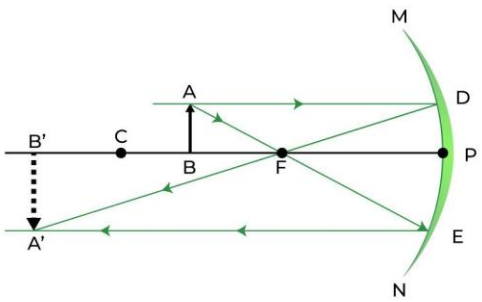
3. sign rule (Suitable for both lenses and mirrors)

S: Object distance S’: image distance r: Mirror radius

$$\frac{1}{S}+\frac{1}{S'}=\frac{2}{r}=\frac{1}{f}$$

f (focal length) =r/2

let $S=\infty \frac{1}{S\prime}=\frac{2}{r}$ $S'=\frac{r}{2}=f$



If S=r

$$\frac{1}{r}+\frac{1}{S'}=\frac{2}{r} \qquad S'=r$$

S’ (image distance): positive: Real image, image and object on the same side

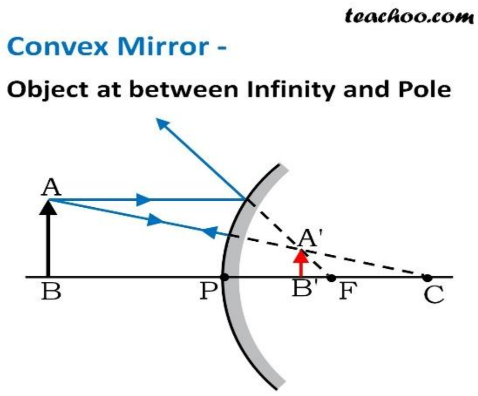
Negative: Virtual image, image and object on different sides

r: convex mirror: r<0 The side that reflects light is convex

Concave mirror: the side that reflects light is concave, r>0

The real image must be inverted.

4. image formation of an extended object



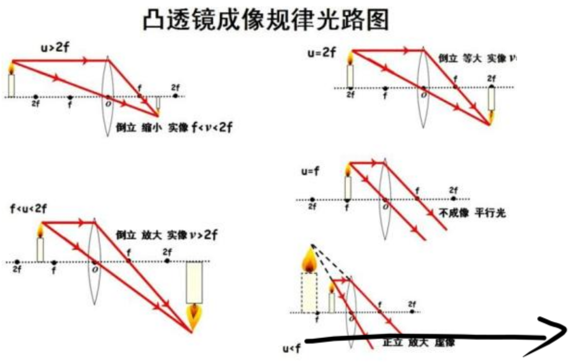
Lateral magnification:

$$m = \frac{A\prime B\prime}{AB} = \frac{PB\prime}{PB}$$

What about the area ratio?

$$\frac{A'}{A} = \frac{{y'}^2}{y^2} = \frac{X'^2}{X^2}$$

5.4.2 using object-image formula for lens



As you get closer to the focus, the magnification increases. When X=2f, y'=y, X'=X.

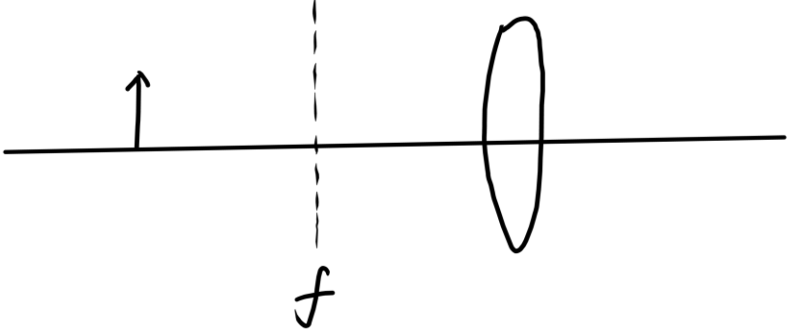


image : small → big → small

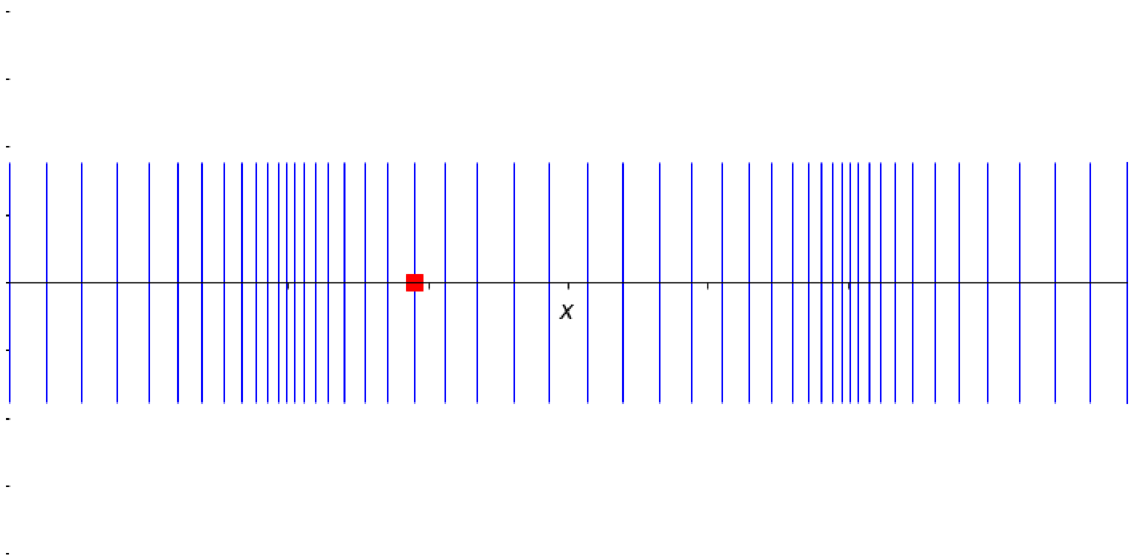
VI. Waves

A wave is a way of transmitting energy, not matter.

6.1 Types of waves

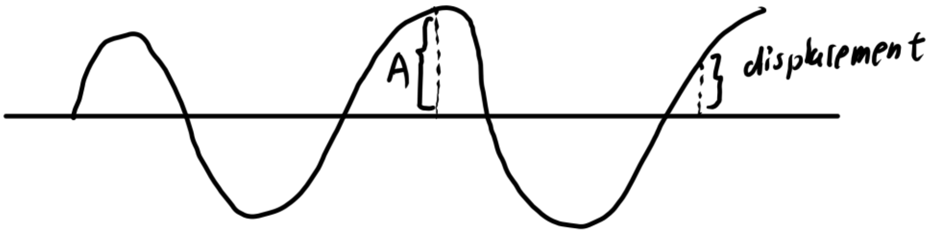
① Transverse wave

②longitudinal wave

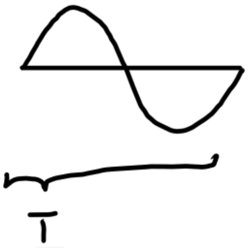


6.2 Quantities to describe wave

①displacement: The distance from the particle to the horizontal axis. Below the horizontal axis: the displacement is negative.



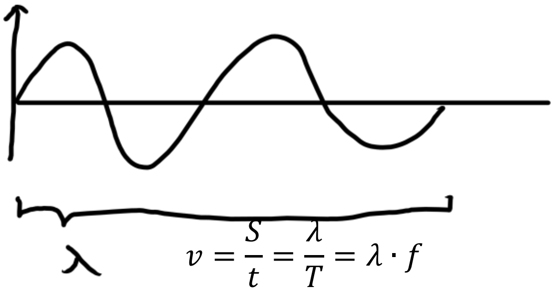
②amplitude(A): the greatest displacement. A cyclic particle moves with four amplitudes.



③period (T): The time required to complete a cycle.

④frequency(f): $f = \frac{1}{T}$ *Represents how many waves pass in one second.* Unit: S^{-1}

⑤wavelength(λ)



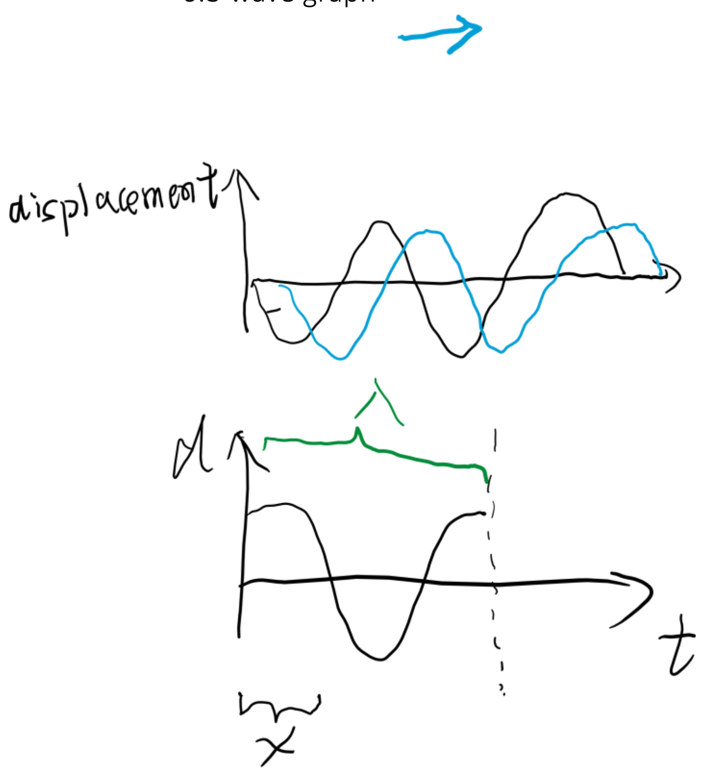
$$v = \frac{S}{t} = \frac{\lambda}{T} = \lambda \cdot f$$

$$v = \sqrt{\frac{T}{\mu}}$$

T: tension μ: *linear density* $\mu = \frac{m}{l}$ m: the mass of rope l:the length of rope

$$f = \frac{1}{\lambda}\sqrt{\frac{T}{\mu}}$$

6.3 wave graph



$$\frac{x}{\lambda} = \frac{\theta}{2\pi} \qquad \theta = 2\pi \cdot \frac{x}{\lambda}$$

$$y = A \cdot \cos(2\pi \cdot \frac{x}{\lambda})$$

$$d = A \cdot \cos(\omega t) = A \cdot \cos(2\pi f) = A \cdot \cos(2\pi \frac{t}{T})$$

$$\omega = \frac{2\pi}{T}$$

$$\therefore \frac{x}{\lambda} = \frac{t}{T}$$

Extra:

6.4 sound wave (longitudinal wave)

6.4.1 doppler effect: For a wave source moving toward an observer, the observed frequency is greater than the rest frequency.

For a wave source moving away from an observer, the observed frequency is less than the rest frequency.

Because there is relative motion between the wave source and the observer, the observer perceives a change in frequency.

When the wave source and the observer move closer to each other, the received frequency increases (the pitch rises). When the wave source and the observer move further apart, the received frequency decreases.

As long as there is relative motion, the Doppler effect will occur!!!!!

1. When the wave source and observer are stationary relative to each other, the frequency of the wave remains unchanged.
2. Relative motion between the wave source and the observer: ①. When the wave source moves towards the observer: the wavefront is compressed, the wavelength decreases, and the frequency increases. ② When the wave source moves away from the observer: the wavefront stretches, the wavelength increases, and the frequency decreases.

   Note: The speed of sound is relative to the ground; it does not change.

   Question: Shouldn't the speed of a sound wave be the speed of the source plus the speed of sound?

1. The speed of sound is determined by the medium.

2. The Doppler effect changes the wavelength, and consequently the frequency, but not the speed of sound.

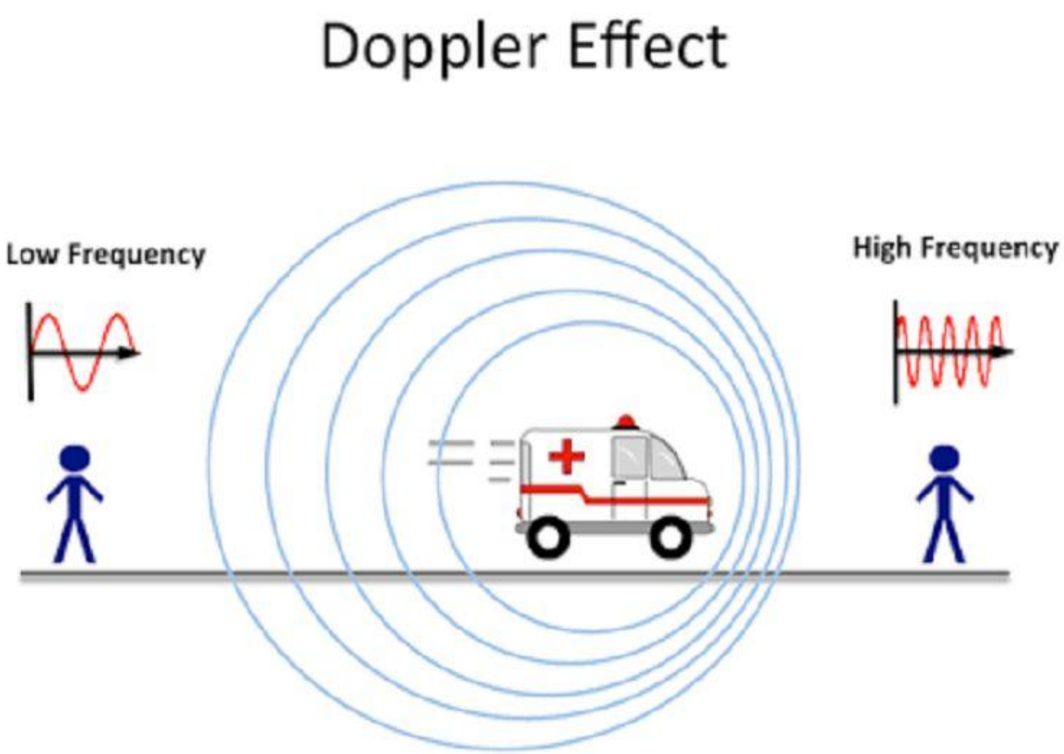
When the sound source is moving: the wavelength of the sound changes.

When the receiver is moving: the relative speed changes.

If the observer is stationary: V = V_sound

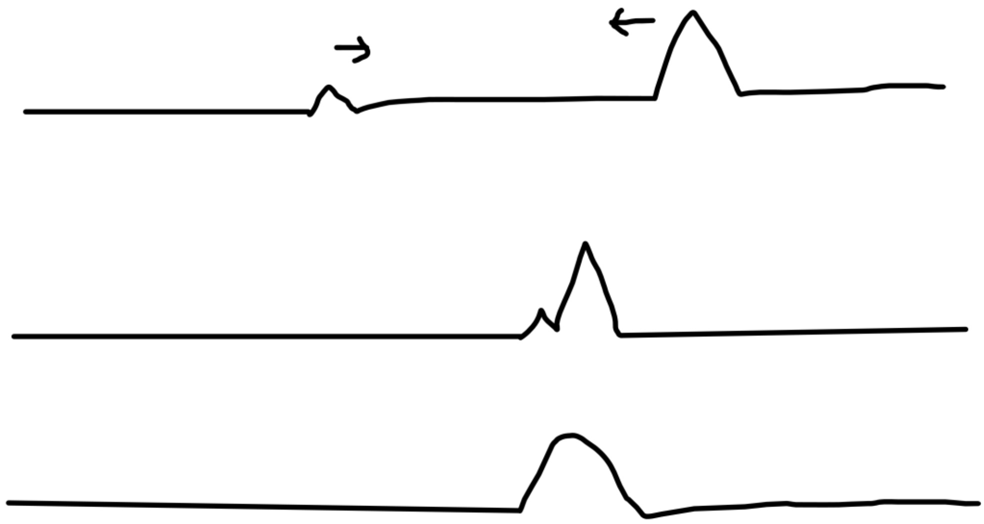
If both the sound source and the observer move to the right at the same speed, there will be no Doppler effect.

$$f = \frac{V \quad (observer\ to\ wave)}{\lambda \quad (sound)}$$



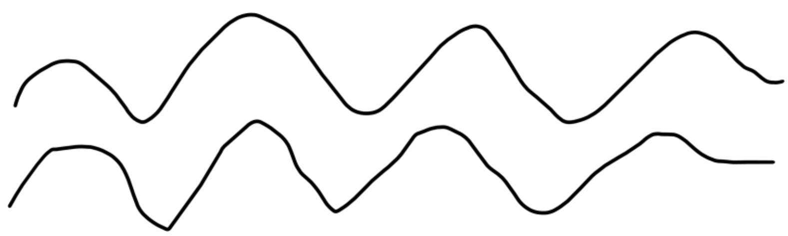
6.5 superposition of waves

Total displacement: the sum of the two displacements.

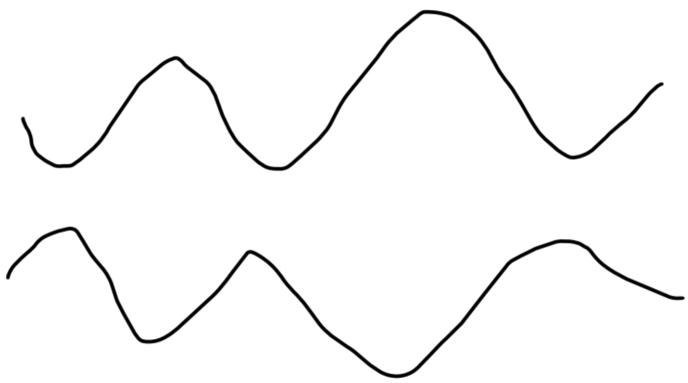


When two waves meet, each wave will retain its original characteristics, such as frequency, wavelength, amplitude, wave speed, and direction of vibration.

6.6 interfere of waves



If two waves meet in phase, the amplitude is $A1 + A2$



If two waves meet antiphase, the amplitude is A1-A2

When two waves meet at a point, whether they are in phase or out of phase depends on two factors: the initial phase difference and the path difference.

$$A \uparrow, The\ vibration\ at\ that\ point\ is\ amplified.$$

$$A \downarrow, The\ vibration\ at\ that\ point\ has\ decreased.$$

The areas of enhancement and weakening remain fixed. The enhancement area will always enhance, and the weakening area will always weaken.

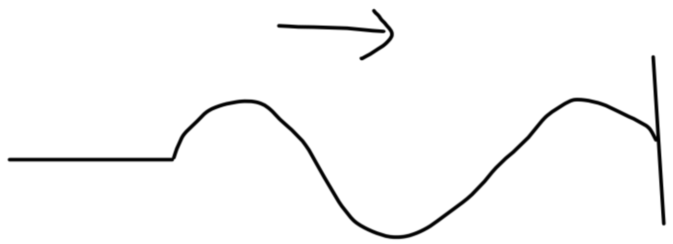
Conditions for interference: identical frequency, constant phase difference, and parallel direction of vibration→ $coherent\ wave$

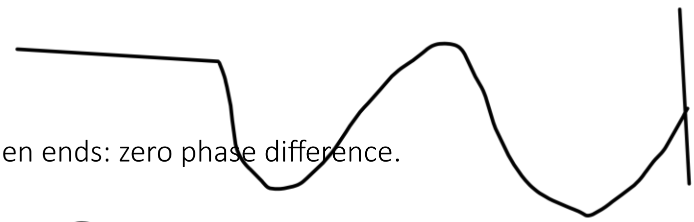
Replenish: Rope waves travel from a thick rope to a thin rope: $V \uparrow \quad \lambda \uparrow$
$f\ does\ not\ change$

sound waves travel from a thick rope to a thin rope: $V \downarrow \quad \lambda \downarrow \quad f\ does\ not\ change$

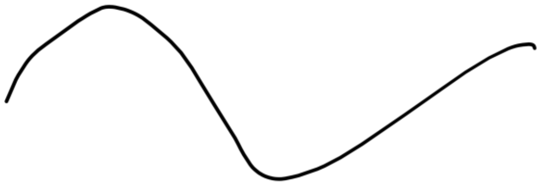
Rope waves travel from a thin rope to a thick rope:$V \downarrow \quad \lambda \downarrow \quad f\ does\ not\ change$

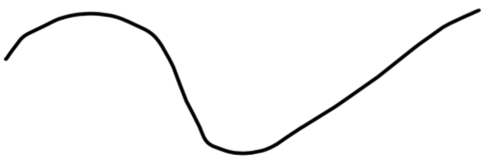
One end of the rope is open, while the other end is closed: Phase difference:$\frac{1}{2}\lambda$



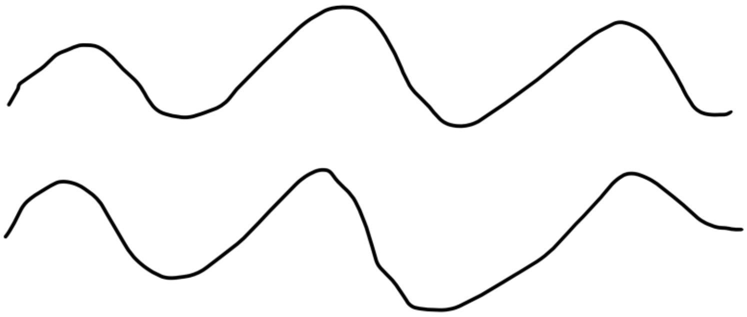


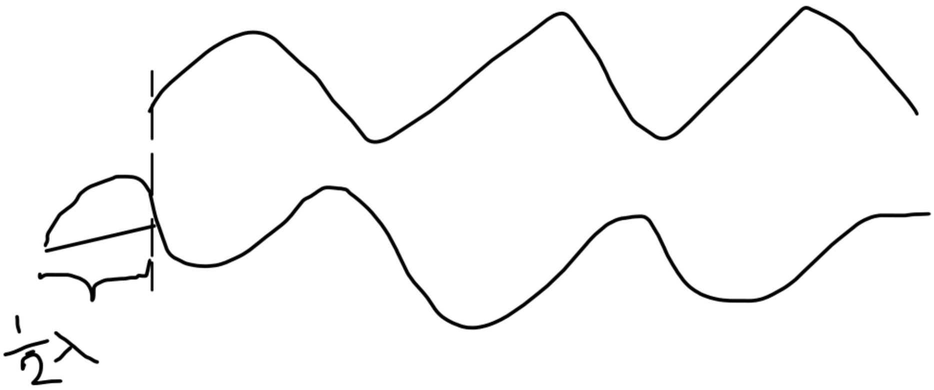
Open ends: zero phase difference.

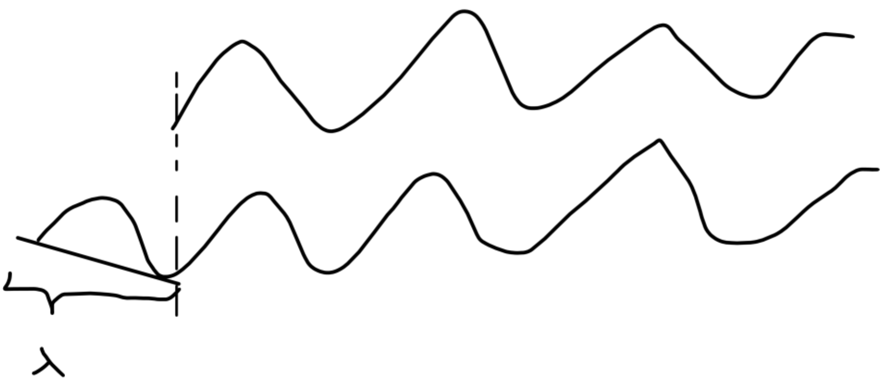




① The waves in the 2 strings vibrate in phase.







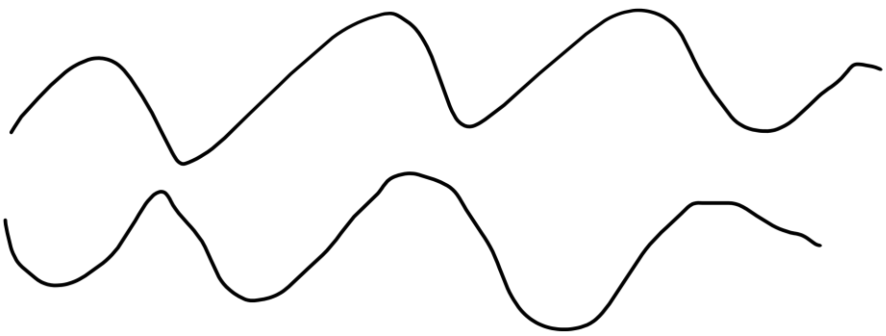
Initial phase difference = 0

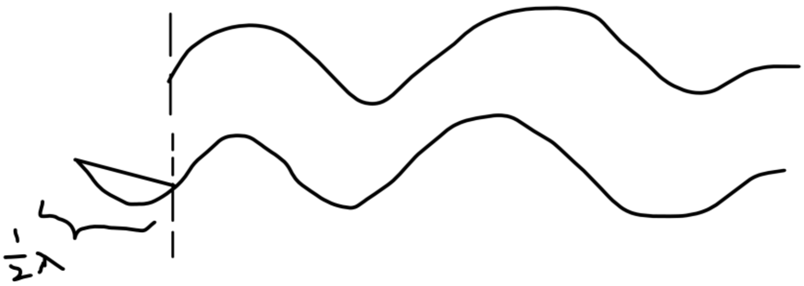
Path difference = n· λ → meet in phase

Path difference = $(n-\frac{1}{2}) \cdot \lambda$ → A=0, meet antiphase

② When the wave source and the vibration are out of sync： meet antiphase weaken

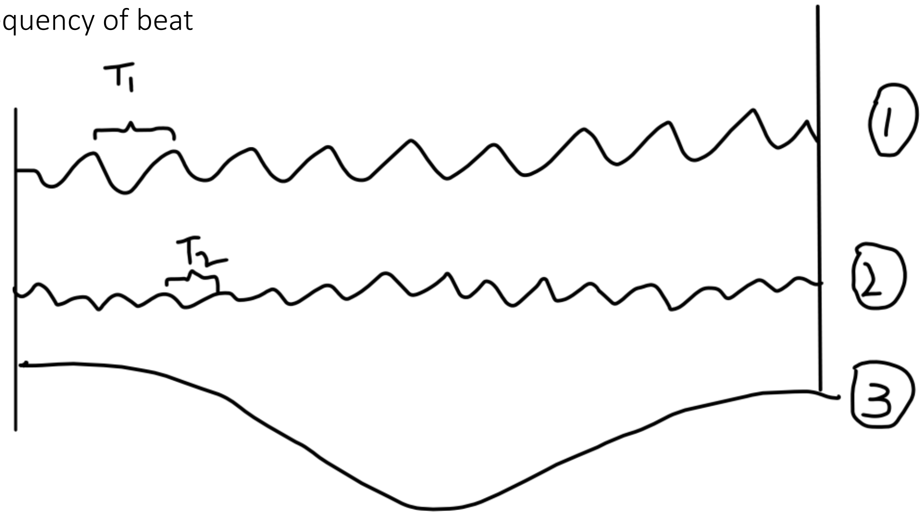
$(n-\frac{1}{2})\ \lambda$: meet in phase： strengthen





Coherent waves means that the waves have a constant phase difference.

6.7 frequency of beat



2 is one cycle longer than 1.

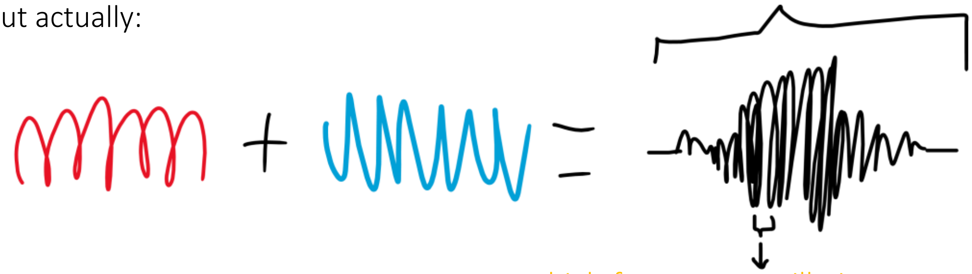
(Determined by f1—f2)

①+②=③

The period of the beat frequency

envelope

But actually:



high-frequency oscillation

Determined by $\frac{f1+f2}{2}$ (average frequency)

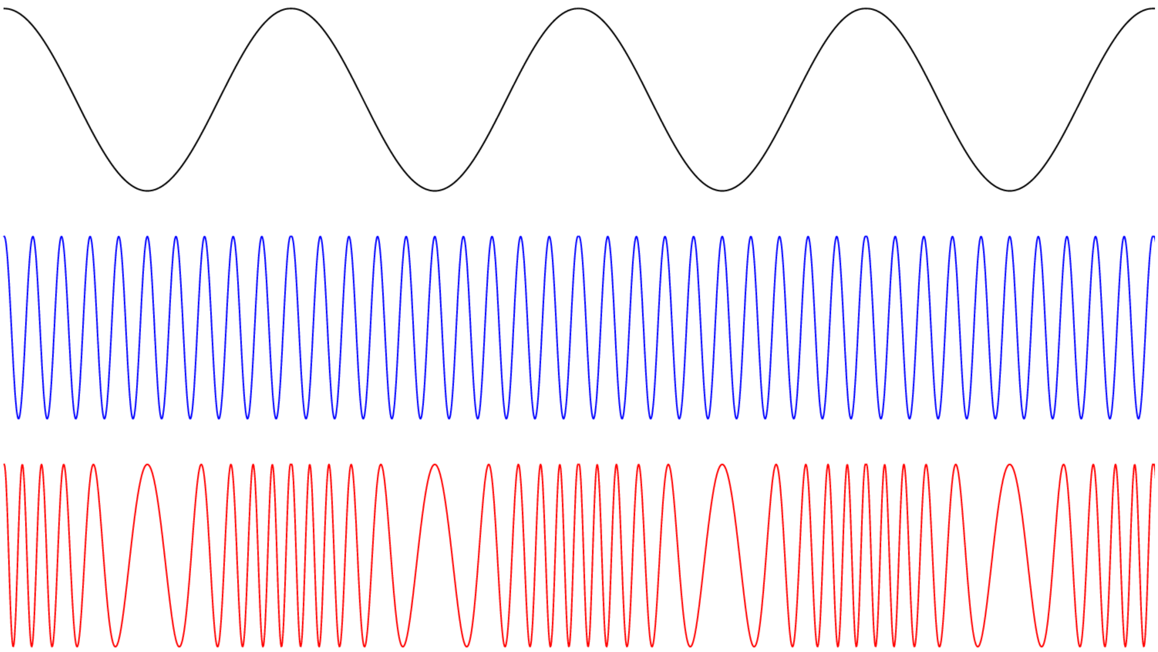
Derivation:

$$T1 = \frac{1}{f1} \qquad T2 = \frac{1}{f2}$$

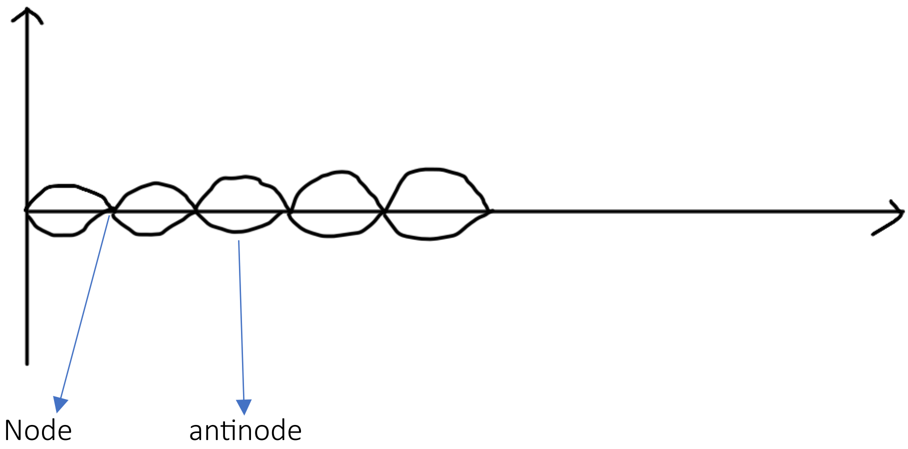
$$\frac{T}{T2} - \frac{T}{T1} = 1$$

$$T \cdot f2 - T \cdot f1 = 1$$

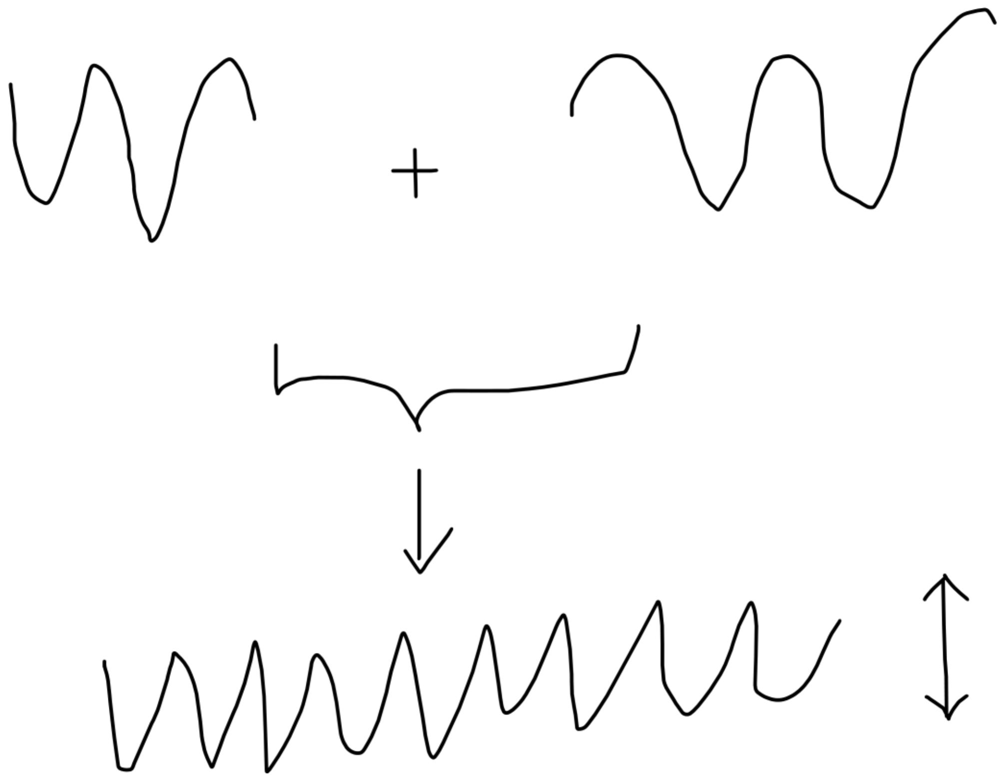
$$f2 - f1 = f$$

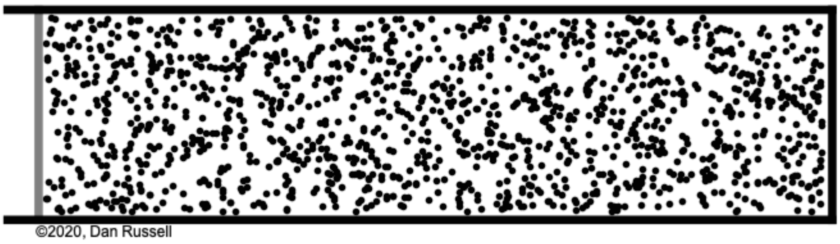


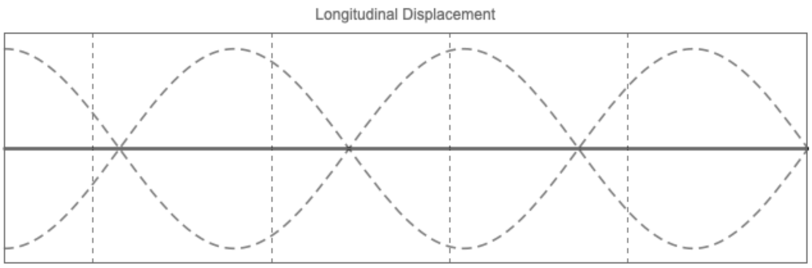
6.8 standing waves

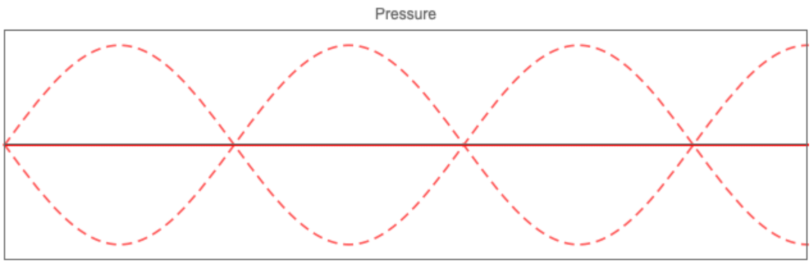


(stationary)









Formation conditions: The two waves have the same frequency (f) and velocity (v) and λ.

Opposite direction. But The amplitudes can be different.

Number of standing waves:

Closed at both ends: $\frac{n\lambda}{2} = l$

One end is open, and the other end is closed: $l = \frac{(2n-1)\lambda}{4}$

Open at both ends : $l = \frac{n\lambda}{2}$

n: The number of times a standing wave is formed

6.8.2 ①guitar and standing waves

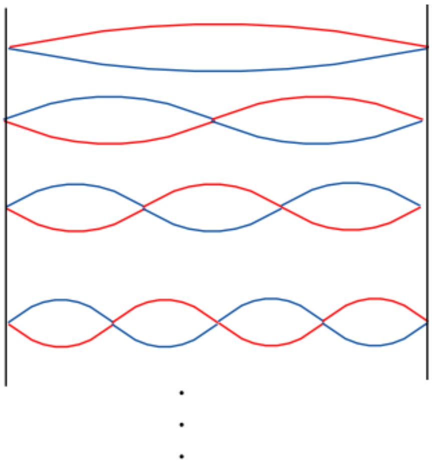
Fundamental
1st Harmonic

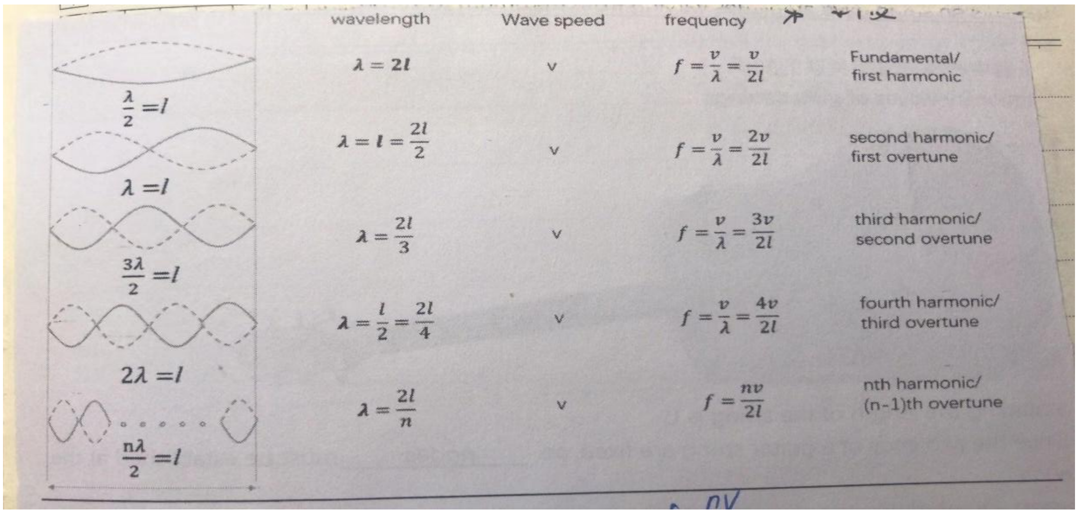
First Overtone
2nd Harmonic

Second Overtone
3rd Harmonic

Third Overtone
4th Harmonic

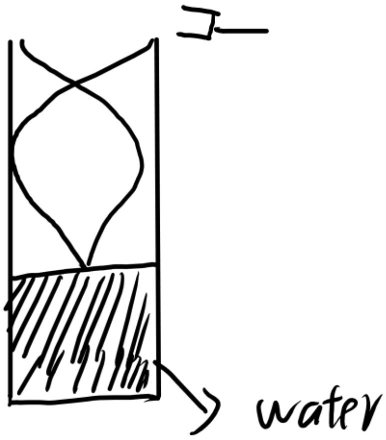
And so on...





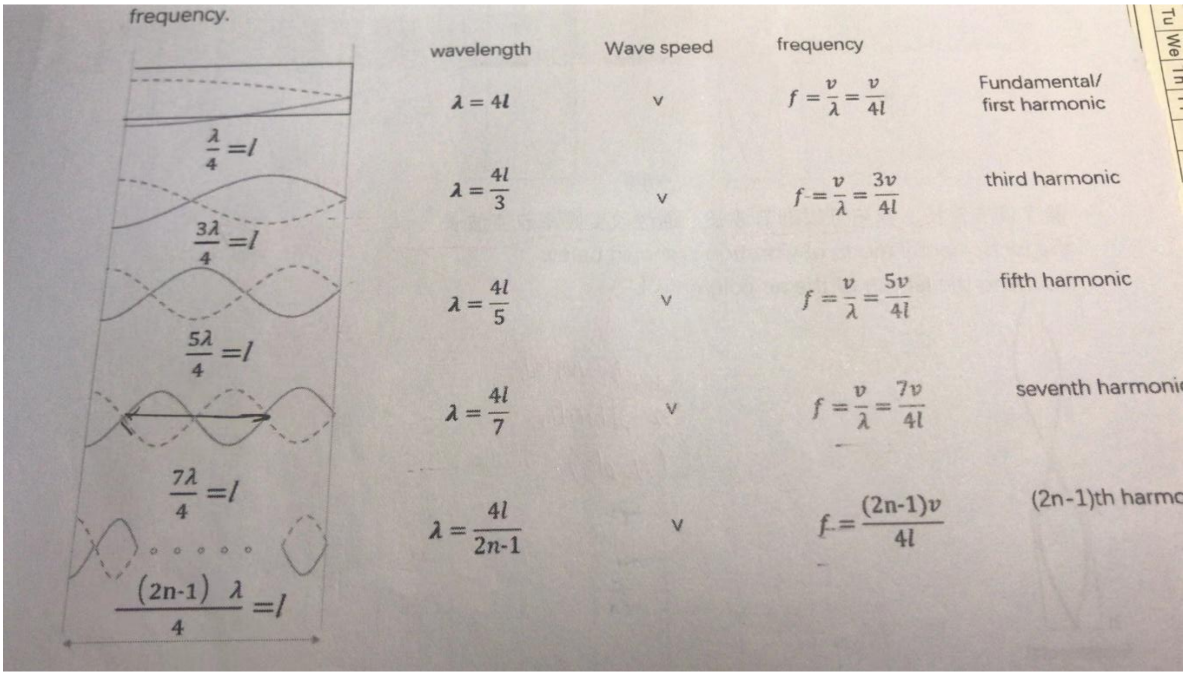
	wavelength	Wave speed	frequency	
$\frac{\lambda}{2} = l$	$\lambda = 2l$	v	$f = \frac{v}{\lambda} = \frac{v}{2l}$	Fundamental/ first harmonic
$\lambda = l$	$\lambda = l = \frac{2l}{2}$	v	$f = \frac{v}{\lambda} = \frac{2v}{2l}$	second harmonic/ first overtune
$\frac{3\lambda}{2} = l$	$\lambda = \frac{2l}{3}$	v	$f = \frac{v}{\lambda} = \frac{3v}{2l}$	third harmonic/ second overtune
$2\lambda = l$	$\lambda = \frac{l}{2} = \frac{2l}{4}$	v	$f = \frac{v}{\lambda} = \frac{4v}{2l}$	fourth harmonic/ third overtune
$\frac{n\lambda}{2} = l$	$\lambda = \frac{2l}{n}$	v	$f = \frac{nv}{2l}$	nth harmonic/ (n-1)th overtune

②tuning fork



How to change the wavelength?

Adjust the length of the tube, or change the tuning fork.

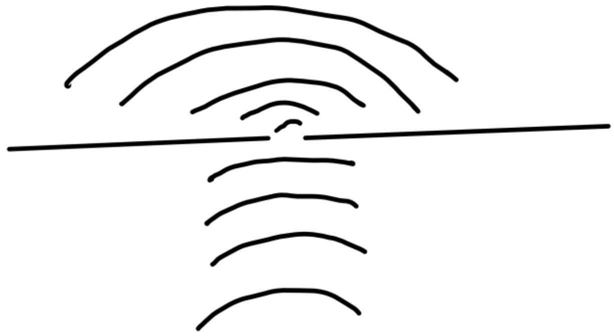


frequency.

	wavelength	Wave speed	frequency	
$\frac{\lambda}{4}=l$	$\lambda = 4l$	v	$f=\frac{v}{\lambda}=\frac{v}{4l}$	Fundamental/ first harmonic
$\frac{3\lambda}{4}=l$	$\lambda=\frac{4l}{3}$	v	$f=\frac{v}{\lambda}=\frac{3v}{4l}$	third harmonic
$\frac{5\lambda}{4}=l$	$\lambda=\frac{4l}{5}$	v	$f=\frac{v}{\lambda}=\frac{5v}{4l}$	fifth harmonic
$\frac{7\lambda}{4}=l$	$\lambda=\frac{4l}{7}$	v	$f=\frac{v}{\lambda}=\frac{7v}{4l}$	seventh harmoni
$\frac{(2n-1)\lambda}{4}=l$	$\lambda=\frac{4l}{2n-1}$	v	$f=\frac{(2n-1)v}{4l}$	(2n-1)th harmo

VII. Physics Optics

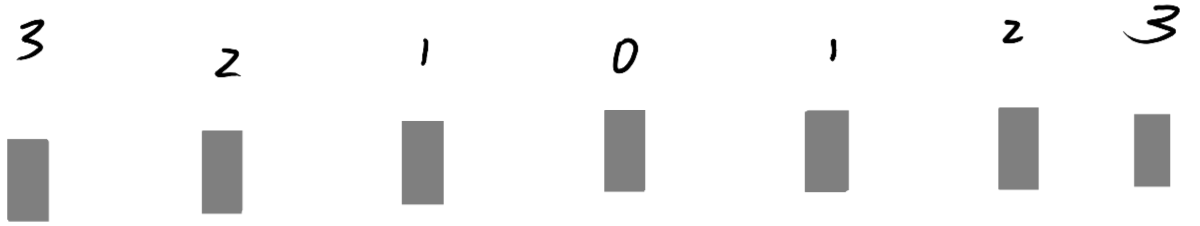
7.1. single-silt diffraction of light

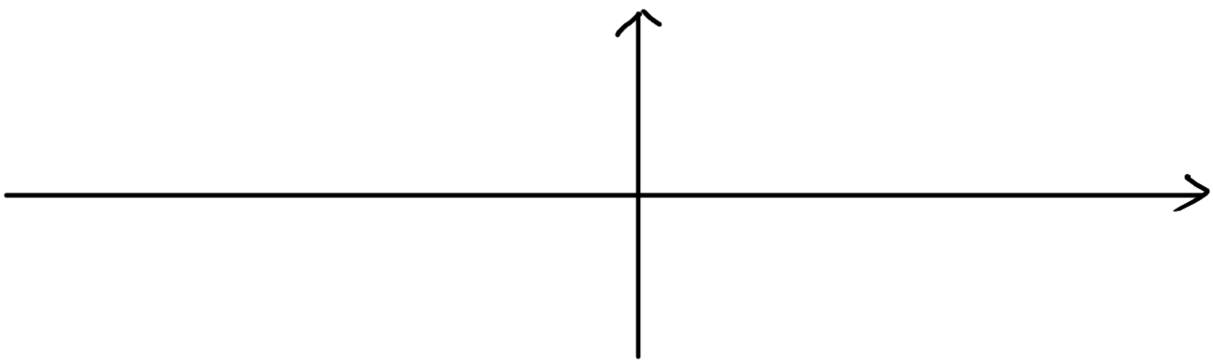


$$gap \downarrow \qquad The\ greater\ the\ diffraction.$$

$$gap \uparrow \qquad The\ less\ the\ diffraction.$$

Note: The width of the slit does not affect the wavelength of the waves passing through the narrow opening.





Formula for the nth dark fringe: $b \cdot sin\theta = n \cdot \lambda$ *(θ is variable)*

θ is the angle between the line connecting the center of the slit to a point on the screen (the location of a bright or dark fringe) and the central axis.

1. Physical Meaning of the Formula

When a beam of parallel light passes through a narrow single slit, a pattern of alternating bright and dark fringes is formed on a screen (or the focal plane of a lens) located at a distance. This formula tells us the conditions under which certain points on the screen become dark (minimum intensity) due to destructive interference of light, thus forming dark fringes.

2. Meaning of Symbols in the Formula

b: Width of the single slit. This is a key parameter for diffraction; the slit must be narrow enough, typically on the same order of magnitude as the wavelength of light.

θ: Diffraction angle. This is the angle between the line connecting the center of the slit to a dark fringe on the screen and the central axis.

n: Order of the dark fringe. This is a non-zero integer (n = ±1, ±2, ±3, ...). It indicates the order of the dark fringe.

n = ±1 corresponds to the first-order dark fringes on either side of the central bright fringe.

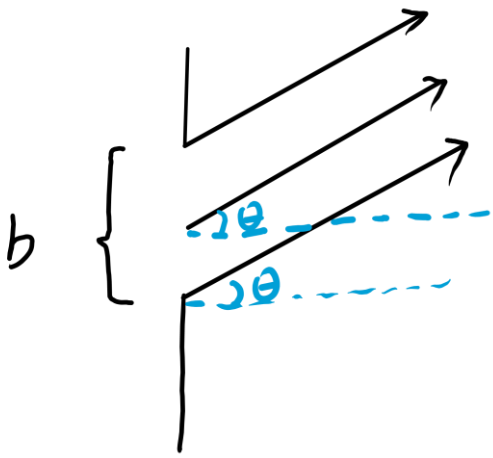
n = ±2 corresponds to the second-order dark fringes, and so on.

Note: n cannot be 0. When n = 0, ϑ = 0, which corresponds to the center of the central bright fringe, where the light intensity is maximum.

λ: Wavelength of the incident light. Different colors of light have different wavelengths, so the diffraction pattern will also be different.

Single-slit diffraction of light: Formula for dark fringes

$$b \cdot sin\theta = n \cdot \lambda$$



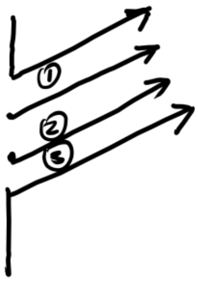
$$\frac{b}{2} \cdot sin\theta = \frac{1}{2}\lambda$$

*Why is it expressed as (b/2) * sin(ϑ) instead of $b \cdot sin\theta$?*

This is because $b \cdot sin\theta$ can only make the two points at the edge cancel each other out, while other points between the two lines cannot be paired and canceled out.

Why isn't it $\frac{b}{3} \cdot sin\theta$?

Because



Items 1 and 2 cancel each other out, but item 3 cannot be canceled out.

Physical Meaning of Dark Fringes (Cancelled Waves)

In the interference of light, the essence of dark fringes is "destructive interference" — when two coherent light beams reach a certain point, the optical path difference is exactly "an odd multiple of half a wavelength", causing the vibrations to cancel each other out (wave crests and wave troughs overlap), and the brightness becomes 0.

For the formula $\frac{b}{2} \cdot \sin\theta = \frac{1}{2}\lambda$, we can derive the optical path difference:

The distance between the wave sources of the two light beams is b. When the light rays propagate at an angle θ , the optical path difference of the two light beams is $b\sin\theta$ (derived from geometric relations: from the double slits to the observation point, the path difference of the two light beams is determined by b and θ).

The condition for "destructive interference (dark fringes)" is that the optical path difference is an odd multiple of half a wavelength, that is, $b\sin\theta = (2k+1)\frac{\lambda}{2}$ ($k = 0, \pm1, \pm2, \ldots$, where k is the order of the dark fringe).

When $k = 0$, the optical path difference $b\sin\theta = \frac{\lambda}{2}$. Dividing both sides by 2 gives the formula you provided: $\frac{b}{2} \cdot \sin\theta = \frac{1}{2}\lambda$. This corresponds to the condition for the **first - order dark fringe** (the dark fringe closest to the central bright fringe) — at this time, the optical path difference of the two light beams is $\frac{\lambda}{2}$, which cancels out exactly, forming a dark fringe.

To summarize briefly: This formula describes the condition for "destructive interference (dark fringes)" in interference, that is, when the optical path difference of two coherent light beams satisfies a certain relationship, the vibrations cancel out and dark fringes appear.

$\frac{b}{2} \cdot \sin\theta = \frac{\lambda}{2}$ $\qquad b \cdot \sin\theta = \lambda$

$\frac{b}{4} \cdot \sin\theta = \frac{\lambda}{2}$ $\qquad b \cdot \sin\theta = 2 \cdot \lambda$

$\frac{b}{6} \cdot \sin\theta = \frac{\lambda}{2}$ $\qquad b \cdot \sin\theta = 3\lambda$

$$b \cdot \sin\theta_1 = 1 \cdot \lambda$$

$$\theta_1 = \frac{\lambda}{b}$$ (approximation)

$\because \quad b \cdot \sin\theta = n \cdot \lambda$

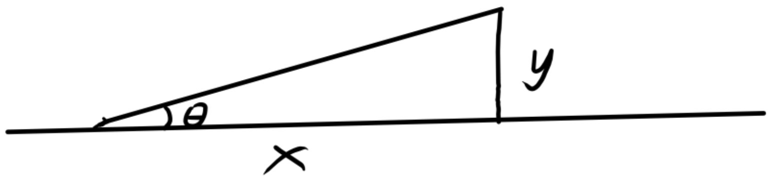
let $\theta = 90^\circ$

$$b = n \cdot \lambda$$

$$n = \frac{b}{\lambda}$$

$\Downarrow$

The highest number of dark fringe orders



$\sin\theta = \theta = \tan\theta$ (approximation)

$$b \cdot \sin\theta = n \cdot \lambda$$

$$b \cdot \theta = n \cdot \lambda$$

$$b \cdot \frac{y}{x} = n \cdot \lambda$$

D: distance $= x$

$$b \cdot \frac{y}{D} = n \cdot \lambda$$

$$y = \frac{D\lambda}{b}$$

The distance between the first dark fringe and the central bright fringe.

$$d = \frac{2D\lambda}{b}$$

↓

The distance between two symmetrical dark bands. It is also the width of the central bright band.

$$b \cdot \frac{y_n}{D} = n\lambda$$

$$y_n = \frac{Dn\lambda}{b}$$

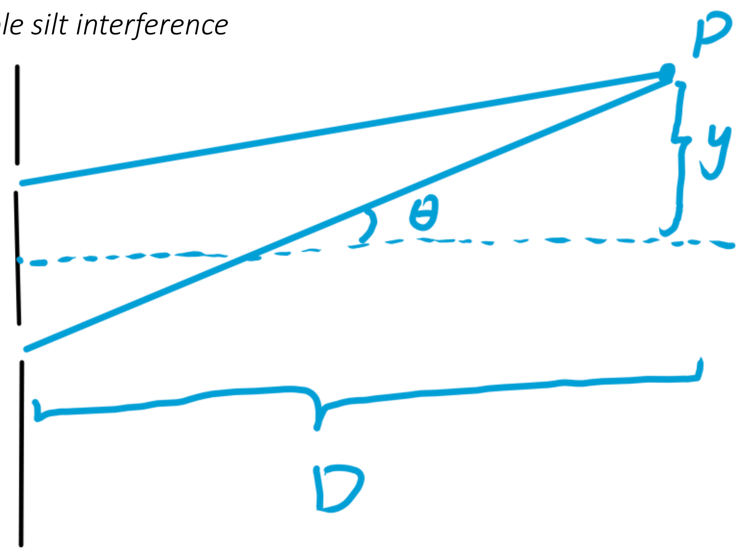
$$\therefore y_{n+1} - y_n = \frac{D\lambda}{b}$$

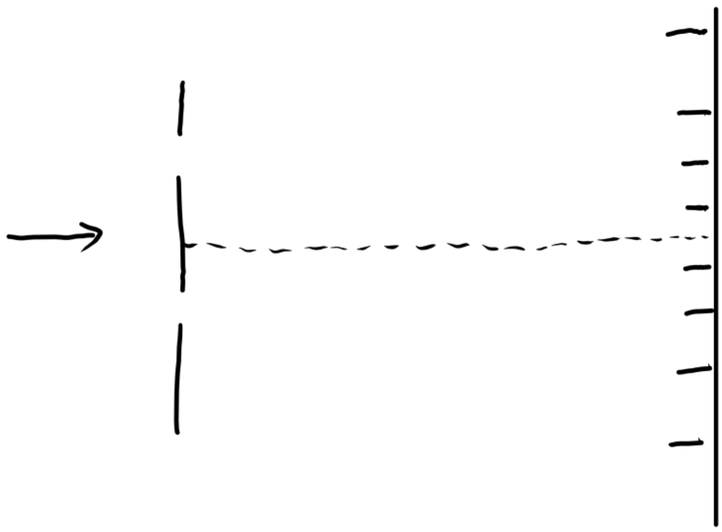
he width of the bright stripes.

The distance between two adjacent dark fringes is the same as the distance between the first dark fringe and the central bright fringe.

Light's λ ↑ Distance between adjacent dark fringes↑

7.2 Double silt interference

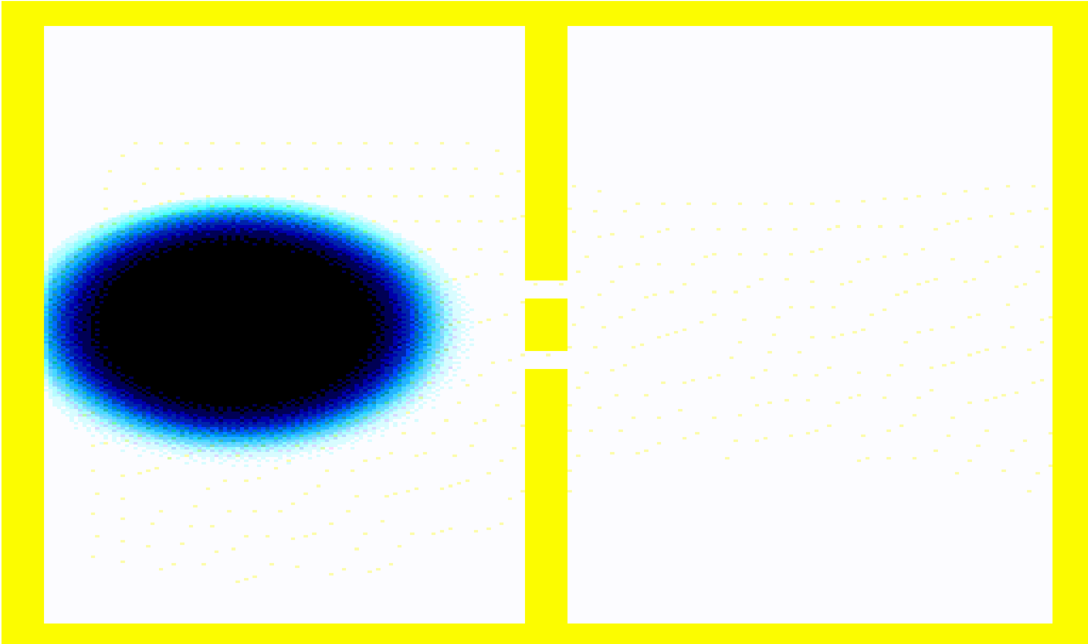




θ: The angle between the line connecting the center of the double slits to a point on the screen and the central axis.

Single-slit diffraction: $\begin{cases} b \cdot \sin\theta = n \cdot \lambda & \text{dark stripes} \\ b \cdot \sin\theta = (n + \frac{1}{2})\lambda & \text{bright stripes} \end{cases}$

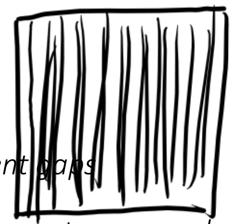
double-slit diffraction: $\begin{cases} a \cdot \sin\theta = n\lambda & \text{bright} \\ a \cdot \sin\theta = (n - \frac{1}{2})\lambda & \text{dark} \end{cases}$



7.3 diffraction grating

1mm in thickness, yet with 500 gaps: grating

$$d = \frac{1}{500}\,mm$$



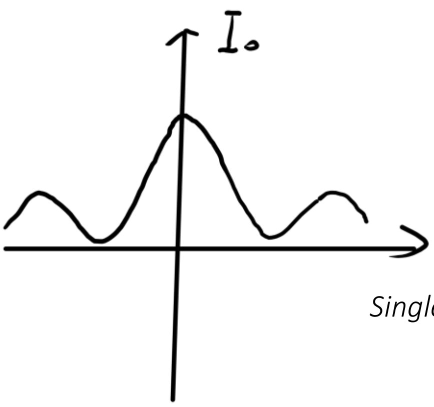
d: The distance between two adjacent gaps

A diffraction grating is an optical element composed of a large number of parallel slits with equal width and spacing.

The more slits there are in the diffraction grating, the narrower the bright fringes will be.

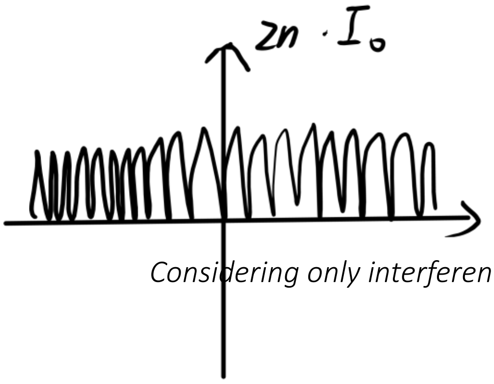
$$\therefore \Delta\theta \approx \frac{\lambda}{N \cdot d}$$

N: the number of slits



Single-slit diffraction

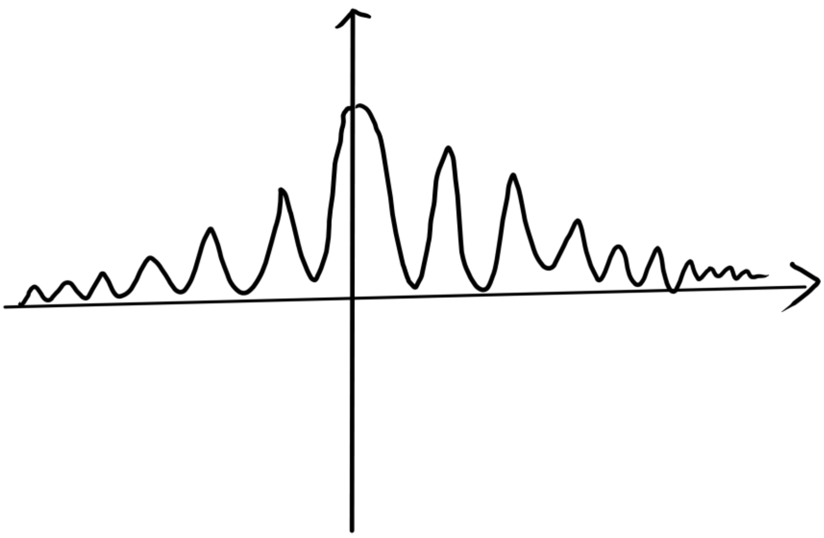
Why is the light intensity different on both sides? Because interference occurred.



Multiple slit interference

Considering only interference, the brightness should be uniform.

grating diffraction is the combined effect of single-slit diffraction and double-slit interference.



①

$$N \cdot d \cdot \sin\theta = n \cdot \lambda$$

The position of the n-th order dark fringe in a diffraction grating

N: the number of slits

d: The spacing between adjacent slits

$$\sin\theta \approx \theta \approx \frac{n \cdot \lambda}{N \cdot d}$$

why it is not $d \cdot \sin\theta = (n-\frac{1}{2})\lambda$?

This only applies to two slits; in the case of a diffraction grating, there are too many slits, and the diffraction pattern results from the combined effect of all the slits.

② $d \cdot \sin\theta = n \cdot \lambda$

Describe the location of the bright stripes. The more slits there are in the diffraction grating, the brighter the diffraction pattern. Because *in a diffraction grating, the intensity of bright fringes is proportional to the square of the number of slits, so more slits make the diffraction pattern brighter.*

$$d \cdot \sin\theta = n \cdot \lambda$$

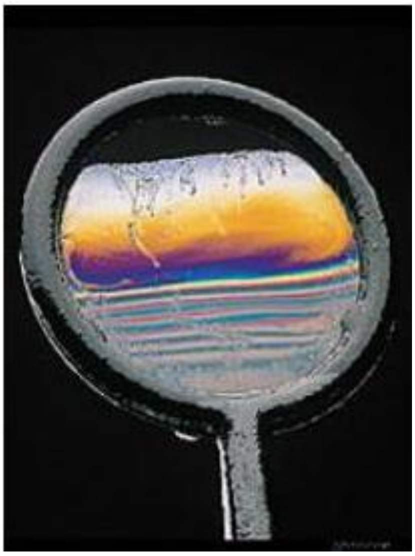
$$\sin\theta = \frac{n\lambda}{d}$$

$$\frac{n\lambda}{d} < 1$$

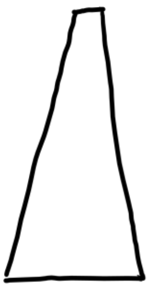
$$\frac{\lambda}{d} < \frac{1}{n}$$

$$n < \frac{d}{\lambda}$$

7.4 the film interference

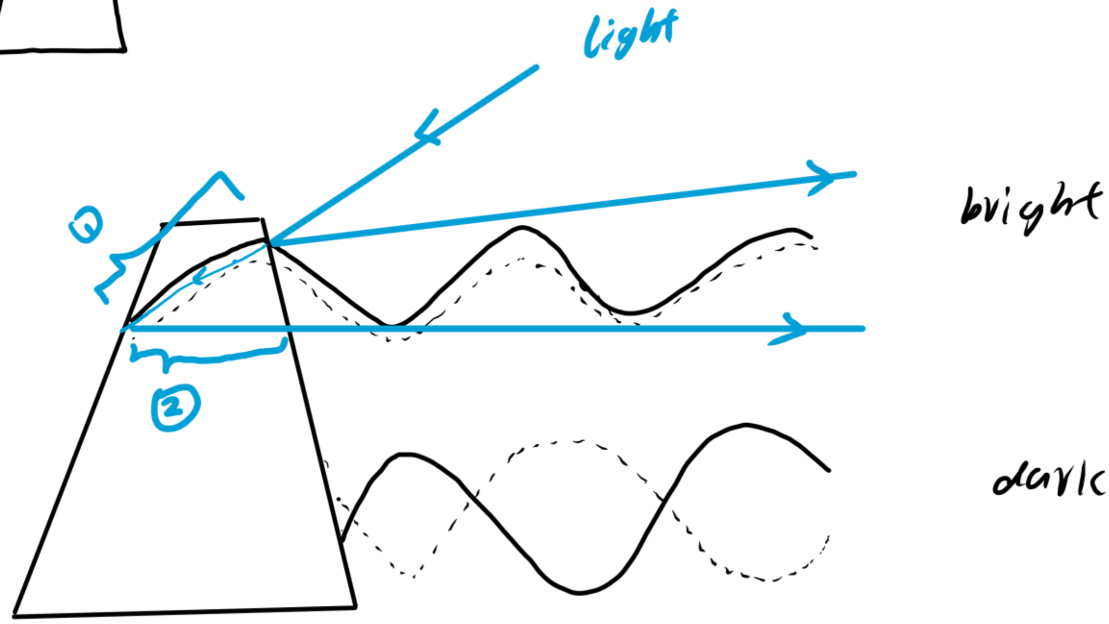


Because of the gravity:



soap solution film

Narrow at the top, wide at the bottom

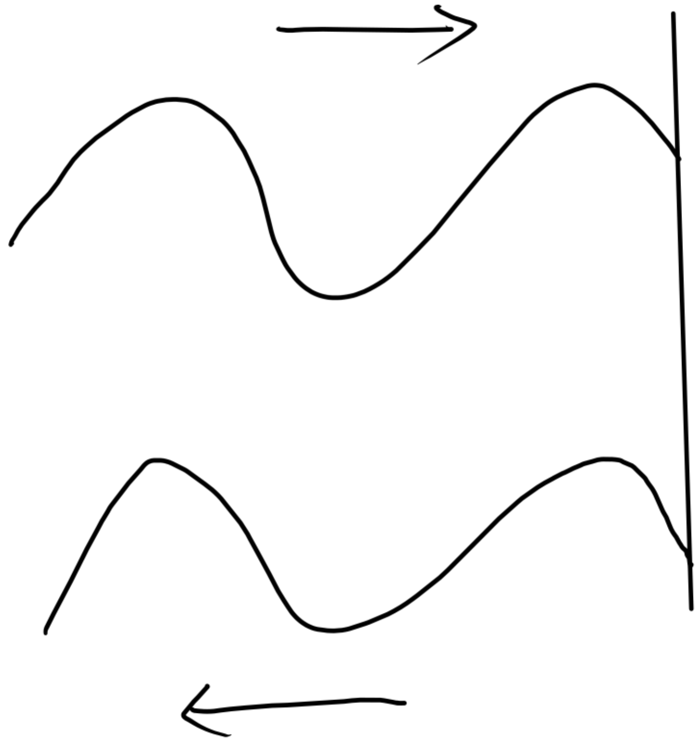


① + ② = $\frac{\lambda}{2}$

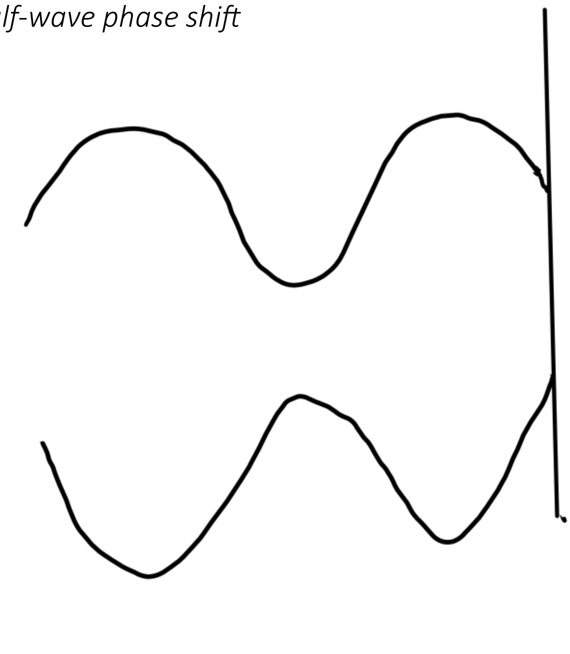
This occurred due to the half-cycle phase shift

7.4.2 half-wave phase shift

When light travels from a less dense medium to a denser medium, it experiences a half-wave phase shift.

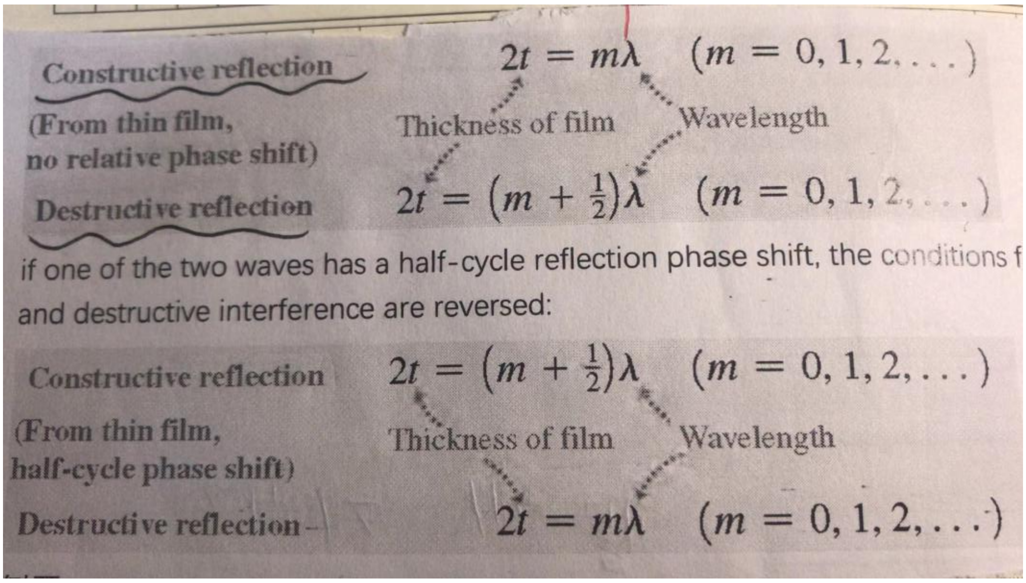


no half-wave phase shift



Has half-wave phase shift.

Reflection causes a half-wavelength phase shift, while refraction does not!!!



Constructive reflection	$2t = m\lambda$	$(m = 0, 1, 2, \ldots)$
(From thin film, no relative phase shift)	Thickness of film	Wavelength
Destructive reflection	$2t = \left(m + \frac{1}{2}\right)\lambda$	$(m = 0, 1, 2, \ldots)$

if one of the two waves has a half-cycle reflection phase shift, the conditions f
and destructive interference are reversed:

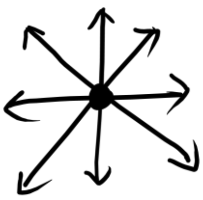
Constructive reflection	$2t = \left(m + \frac{1}{2}\right)\lambda$	$(m = 0, 1, 2, \ldots)$
(From thin film, half-cycle phase shift)	Thickness of film	Wavelength
Destructive reflection	$2t = m\lambda$	$(m = 0, 1, 2, \ldots)$

$$\lambda: Wavelength\ in\ a\ medium$$

2t: The path difference of wavelengths

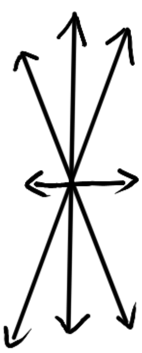
7.5 polarization of light

Light:  *a kind of wave*

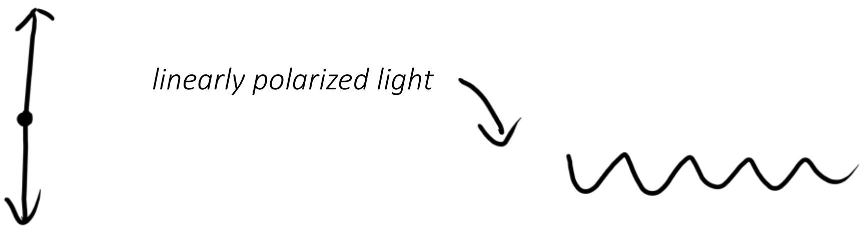


Unpolarized light/ nature light: The light shines in all directions.

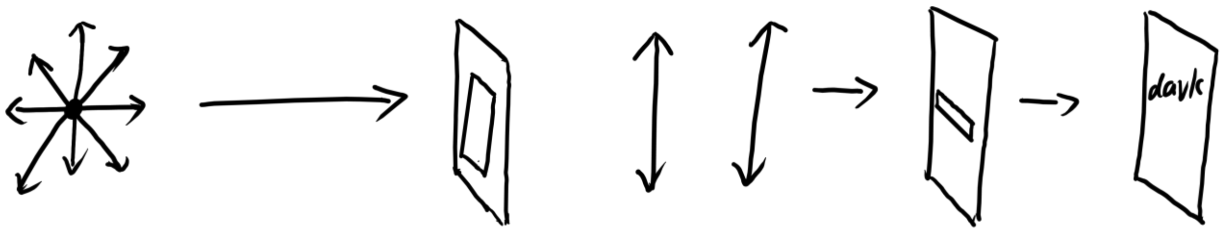
For example, sunlight



partially polarized light

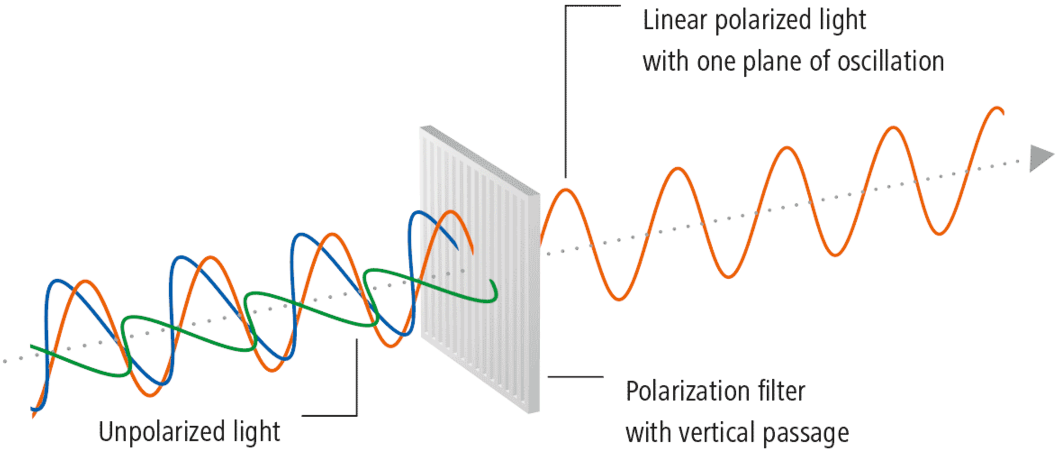


Only transverse waves exhibit polarization; longitudinal waves can pass through narrow slits regardless of orientation.



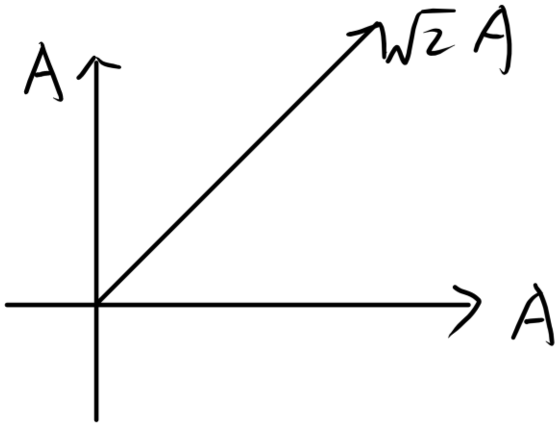
if the board is here

it is bright.



$$I \propto A^2$$

light intensity *amplitude*



$\rightarrow$

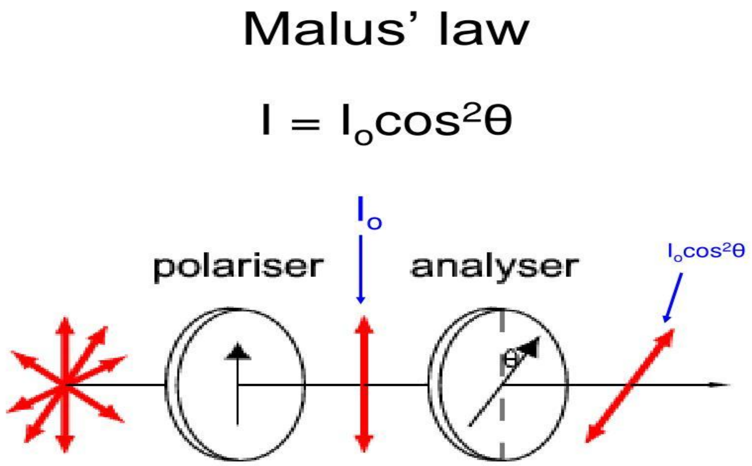
$I \propto A^2$

$\downarrow$

$I \propto 2A^2$

Therefore, when natural light passes through a polarizer, its intensity is reduced to half of its original value.

Malus's law:



VIII. Quantum physics

8.1 black body radiation

Definition of a Blackbody

A blackbody, also known as an ideal black body, is an idealized physical model defined as follows:

An object that, at any temperature, can completely absorb all incident electromagnetic radiation (regardless of wavelength, angle of incidence, or polarization) without any reflection or transmission.

This definition includes three key points:

Complete absorption: The absorptivity is equal to 1 (i.e., 100%) for all wavelengths of electromagnetic radiation.

No reflection or transmission: This means its reflectivity and transmissivity are both zero.

Idealized model: In reality, no material can absorb 100% of all wavelengths of radiation, but we can create devices that closely approximate a blackbody.

It absorbs electromagnetic waves while simultaneously emitting them. The temperature remains constant. The amount absorbed equals the amount emitted.

A black body does not reflect electromagnetic waves, but it does emit electromagnetic radiation.

Key Characteristics of Blackbody Radiation

1. Universality

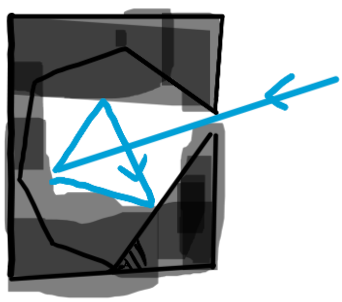
The energy distribution of blackbody radiation depends solely on the absolute temperature (T) of the blackbody, and is independent of the material, shape, size, and composition of the blackbody. This means that whether you use a piece of iron, a ceramic sphere, or a cavity made of any other material, as long as they are at the *same temperature and are ideal blackbodies, their emitted radiation spectra will be identical.*

2. Continuous Spectrum

The spectrum of blackbody radiation is continuous, encompassing all wavelengths of electromagnetic radiation (from radio waves to gamma rays). However, the energy distribution across different wavelengths is highly uneven.

3. Peak Wavelength

The radiation energy spectrum of a blackbody is not flat; rather, it has a peak intensity at a specific wavelength, which is called the peak wavelength.



Blue line：electromagnetic waves. A small hole is made in the wall of the cavity; electromagnetic waves can enter through the hole, but cannot escape from the cavity. Such a body is called a perfect black body.

Q: The difference between radiation and reflection

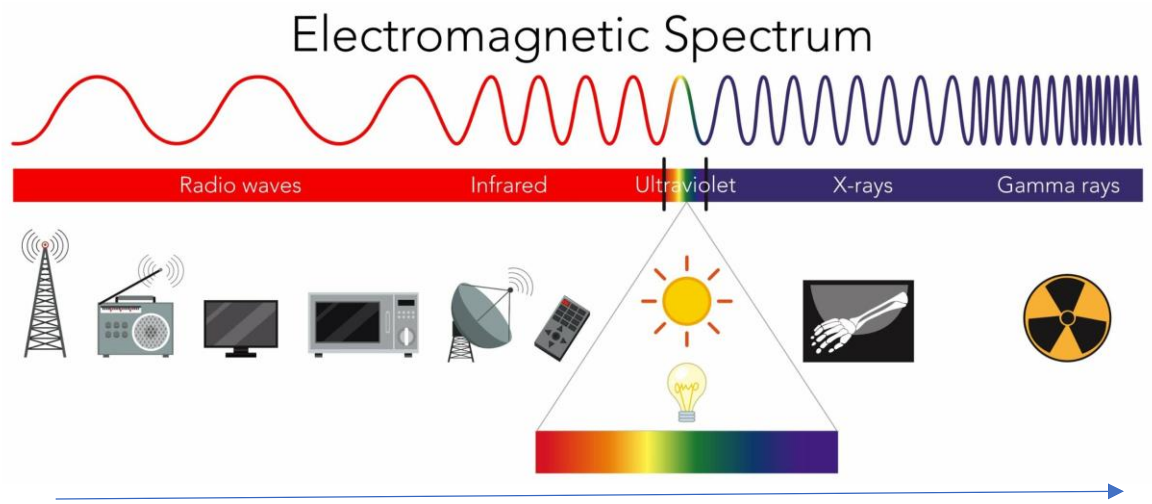
Radiation: This refers to an object emitting its own light and heat. Examples include the sun, a light bulb, a campfire, and even your own body, which radiates heat (infrared radiation).

Reflection: This refers to an object bouncing light back. Examples include a mirror, the moon, and the surface of water; these objects don't emit their own light, but only reflect sunlight.

In short:

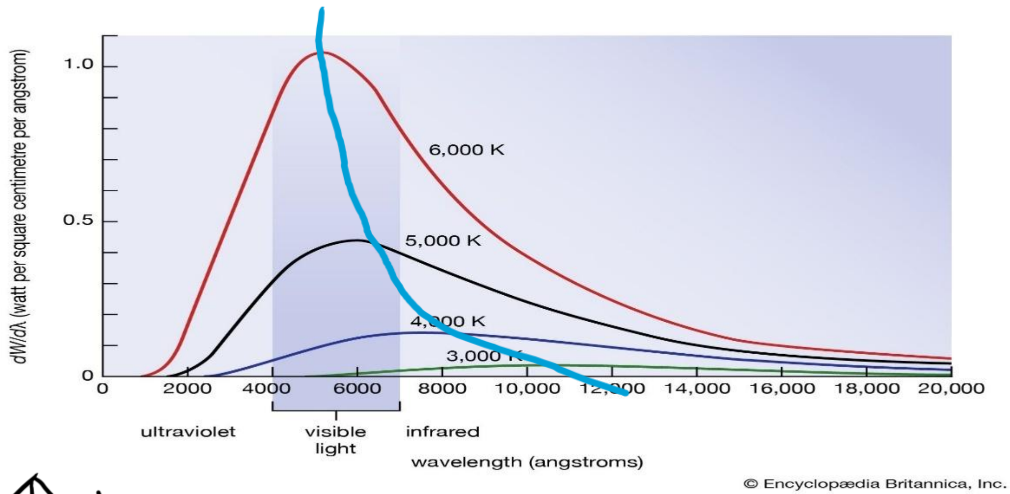
Radiation is "emitting light/heat," while reflection is "bouncing light off."

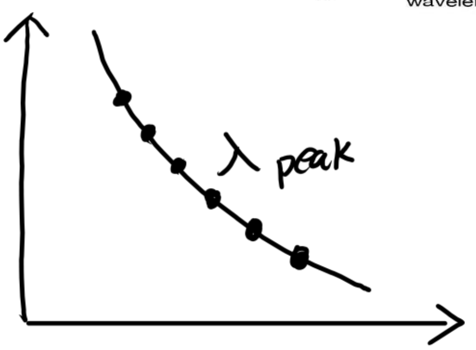
Electromagnetic wave spectrum:



Wavelength decreases from long to short, while frequency increases from low to high.

2.Experiments on blackbody radiation





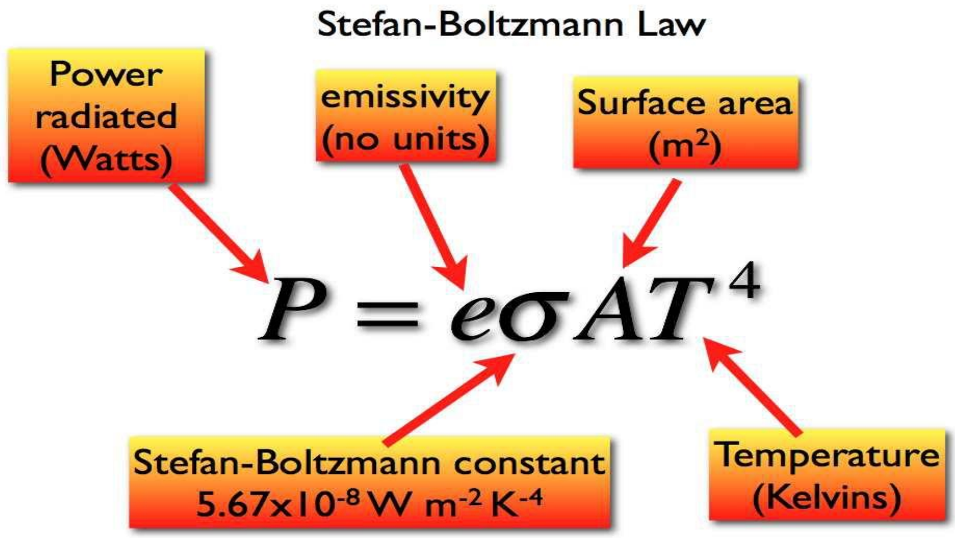
The higher the temperature, the more high-energy photons are emitted. At the same time, the wavelength of the emitted electromagnetic radiation becomes shorter.

Wein's law: $\lambda_{peak} \cdot T = b$ → Wein Constant

↓

temperature

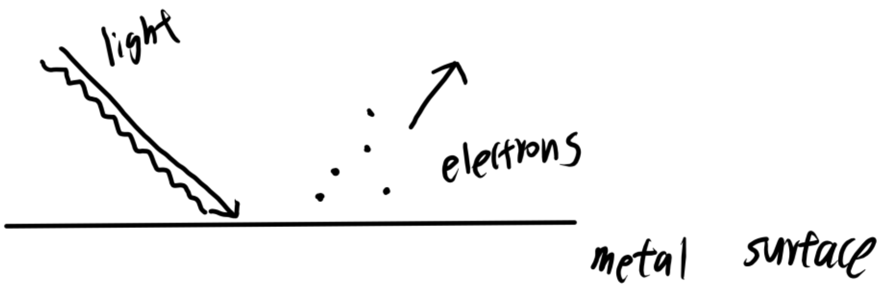
Stephan-Boltzmann law:



$$P \propto A \cdot T^4$$

8.2 photoelectric effect (Here: light is a particle)

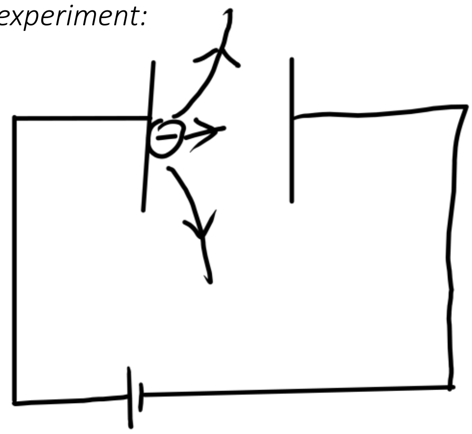
1

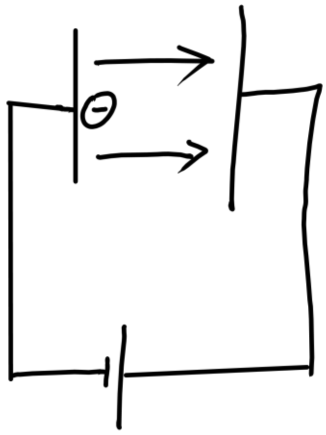


The emitted electrons are called photoelectrons

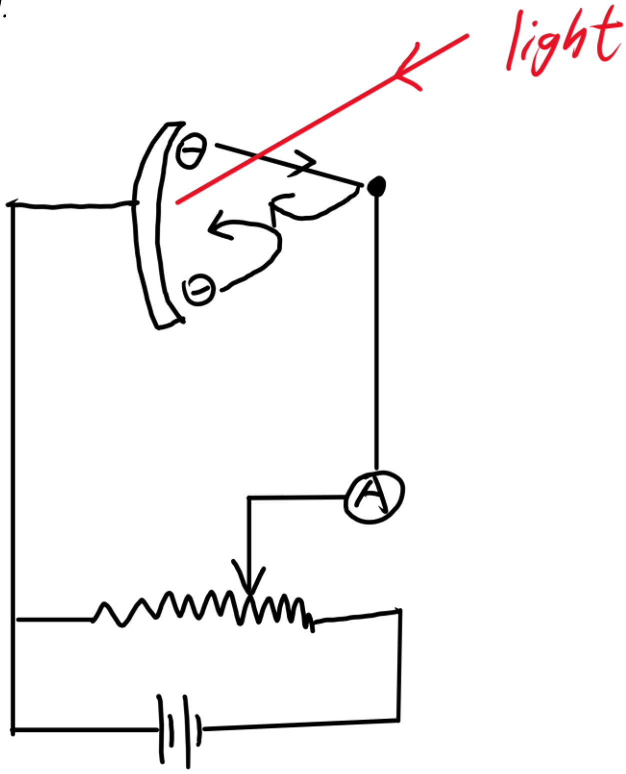
②the minimum energy required to cause emission of electrons from the surface is called work function.

③experiment:





The direction of the power supply depends on whether electrons are attracted or repelled.

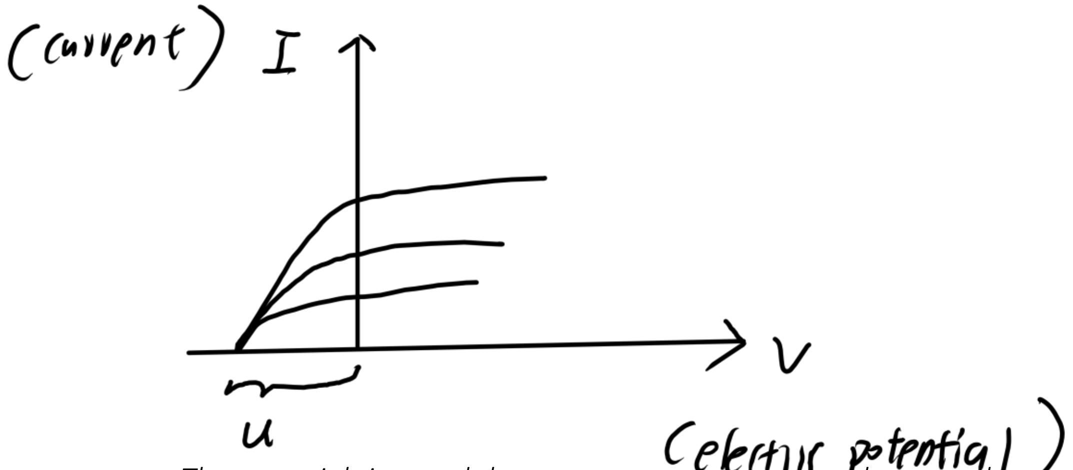


Relationship between light intensity and current:
Increasing light intensity increases current: more photons per unit time are incident, more electrons are excited per unit time, and thus the current increases.

$$I = \frac{Q}{t}$$

For example：Water flow: the amount of water flowing per unit time, not the water speed (the speed of electrons)

Kinetic energy can be converted into potential energy. Electron kinetic energy is converted into potential energy.



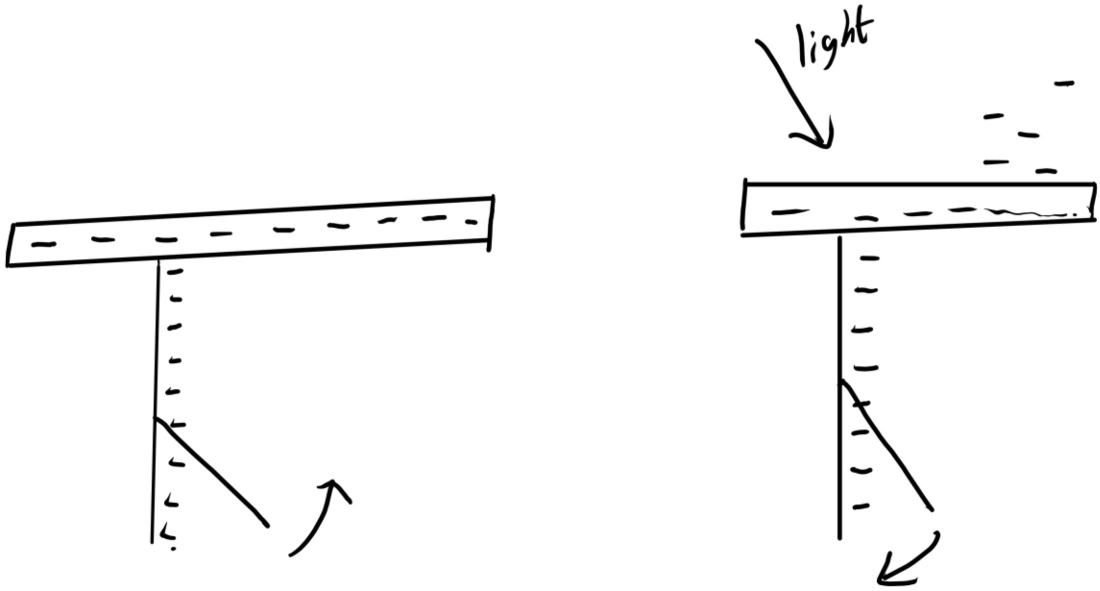
The potential rises and the current remains constant, because the number of electrons reaching the plate per unit time reaches its maximum, increasing the potential further will not allow more electrons to come out.

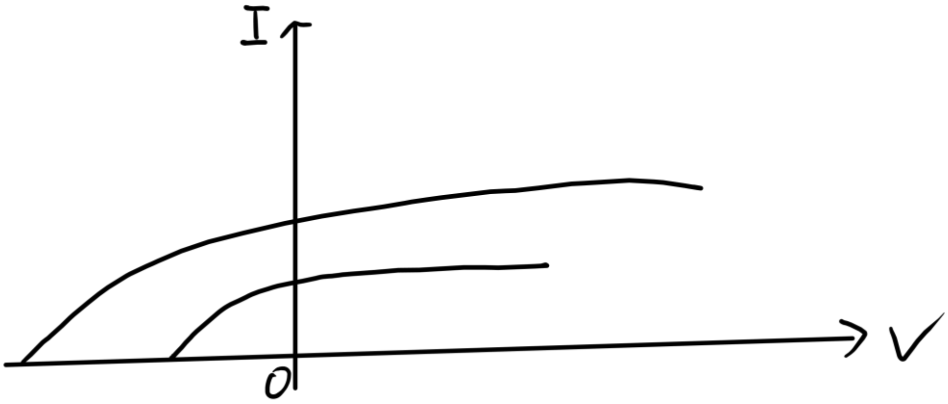
Look at the function graph above. The light intensity is different, but the cutoff voltage remains unchanged. This is because each electron only absorbs a fixed amount of light energy.

$E_k = e \cdot V = \frac{1}{2}mv^2$ → velocity

↓
electric potential

$$V = \frac{E_k}{e}$$





The initial kinetic energy of electrons increases, and the amount of charge passing through per unit time increases, so the current increases.

As the frequency of light increases, the electron's kinetic energy increases, and the cutoff voltage increases.

From red light to violet light: wavelengths become smaller, $c = f \cdot \lambda$
Frequency increases

$$E_{photon} = h \cdot f$$

$$E_k = h \cdot f - W$$

$$E_k \uparrow$$

intensity of light $= \frac{\text{Power}}{\text{area}}$

$= n \cdot hf$

$\frac{W/t}{A} = n \cdot hf$

$W = n \cdot hf \cdot A \cdot t$

The number of photons passing through per unit area and time

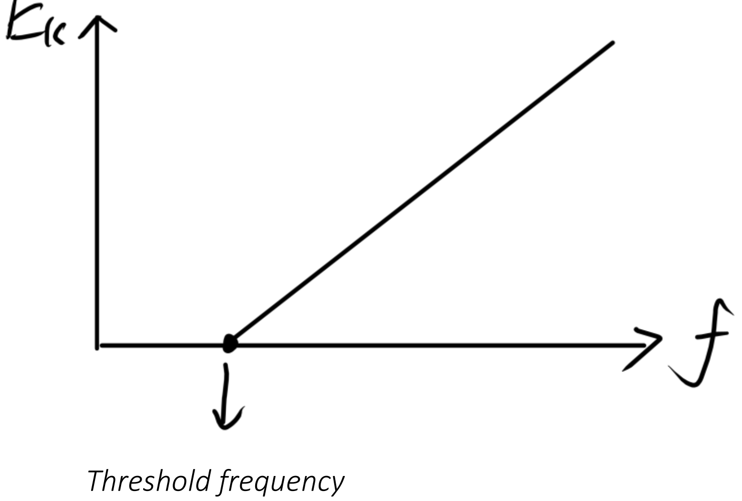
Note: $E = hf$ is not only applicable to photons

④$E = hf = h\frac{c}{\lambda}$ ***Photon energy***

⑤*the maximam energy of electron:* E_k

$$E_k = hf - W_0 \quad \text{(work function)}$$

$$= h\frac{c}{\lambda} - W_0$$



slope: h

$hf = W$

$f = \frac{W}{h}$

Threshold frequency

$E_k = eV$

$eV = hf - W$

$V = \frac{hf}{e} - \frac{W}{e} = \frac{\frac{1}{2}mv^2}{e}$ (cut-off voltage)

$E_k = \frac{hc}{\lambda} - W$

$\frac{hc}{\lambda} = E_k + W$ $\qquad \frac{1}{\lambda} = \frac{E_k}{hc} + \frac{W}{hc}$

Plank constant: $h = 6.626 \times 10^{-34}\ J \cdot S$

$= 4.14 \times 10^{-15}\ eV \cdot S$

$h \cdot c = 1.99 \times 10^{-25}\ J \cdot m$

$= 1.24 \times 10^{3}\ eV \cdot nm$

$eV = 1.6 \times 10^{-19} J$

The energy gained by an electron when it passes through a voltage of one volt

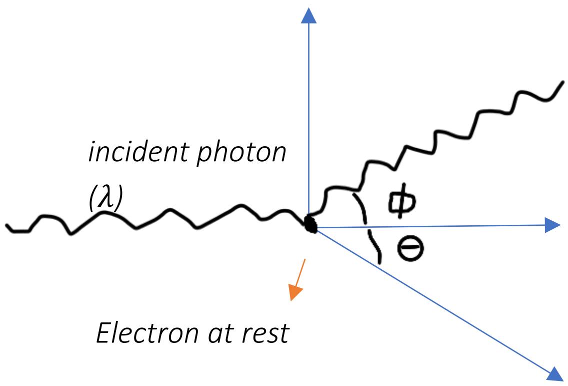
8.3 Wave-particle duality

①The energy of a particle with zero rest mass (such as a photon):

$$E = pc \qquad p = \frac{E}{c} = \frac{hf}{c} = \frac{h}{\lambda}$$

Momentum of a photon

②Compton effect



$$\lambda' = \lambda + \frac{h}{mc}(1 - \cos\phi)$$

$$only\ photon\ has\ compton\ effect$$

In atoms: photons will disappear when they hit electrons, but under this condition, the two particles are independent, so they are not considered to have disappeared.

$$\boldsymbol{\Delta\lambda = \frac{h}{mc}\ \ (1 - \cos\phi\ )}$$

③De Broglie wave length

$\boldsymbol{\lambda = \frac{h}{p}}$ *The wavelength formula of any particle*

$$\boldsymbol{\lambda = \frac{h}{p} = \frac{h}{\frac{E}{c}} = \frac{hc}{E} = \frac{hc}{hf} = \frac{c}{f} = \lambda}$$

$$\boldsymbol{K = \frac{1}{2}mv^2\ \ \ p = mv\ \ \ p = \sqrt{2mk}}$$

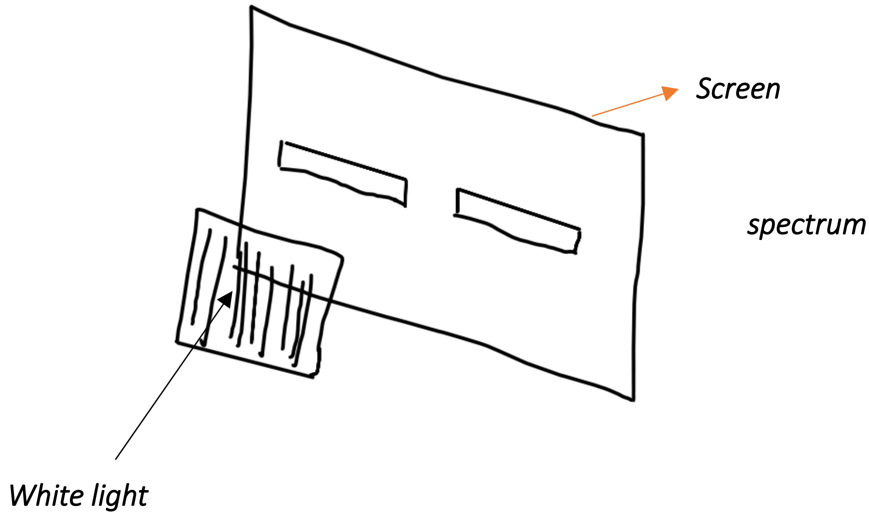
$$\boldsymbol{\lambda = \frac{h}{p} = \frac{h}{\sqrt{2mk}} = \frac{h}{mv}}$$

Supplement: Different colors of light are different wavelengths of photons. It depends on the energy of the photons.

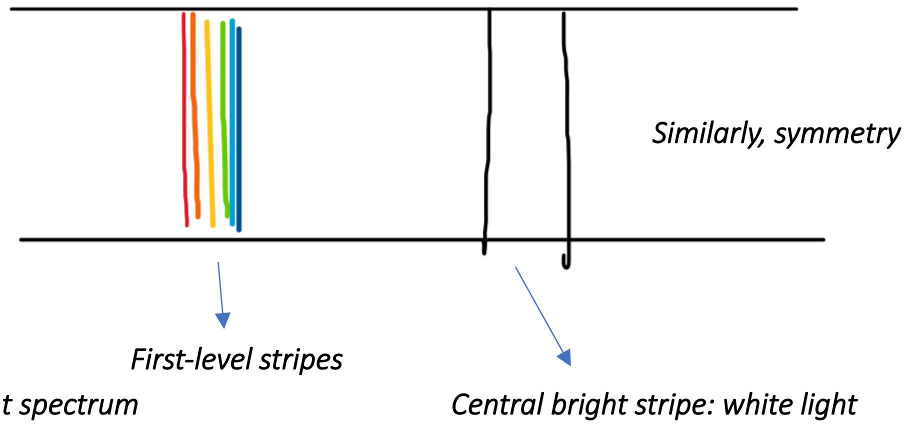
8.4 The Bohr model of the atom

8.4.1 the dispersion of light

Use a diffraction grating



Attention: white light does not have wavelength



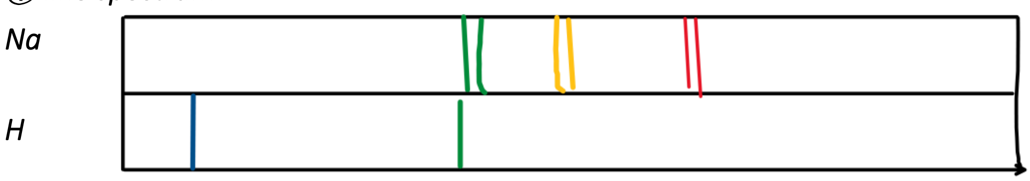
$$\boldsymbol{d \sin \theta = n\lambda}$$

When n is fixed： $\boldsymbol{\lambda\ increases\quad sin\theta\ increases}$

From red light to purple light： $\boldsymbol{\lambda\ decreases\quad sin\theta\ decreases}$

8.4.2 Bohr model： explanation of line spectra

① line spectrum



Line spectrum: Divided into emission spectrum and absorption spectrum
emission spectrum: Atoms release energy to produce. It is a bright line.
absorption spectrum: Dark areas formed when light is absorbed by a substance

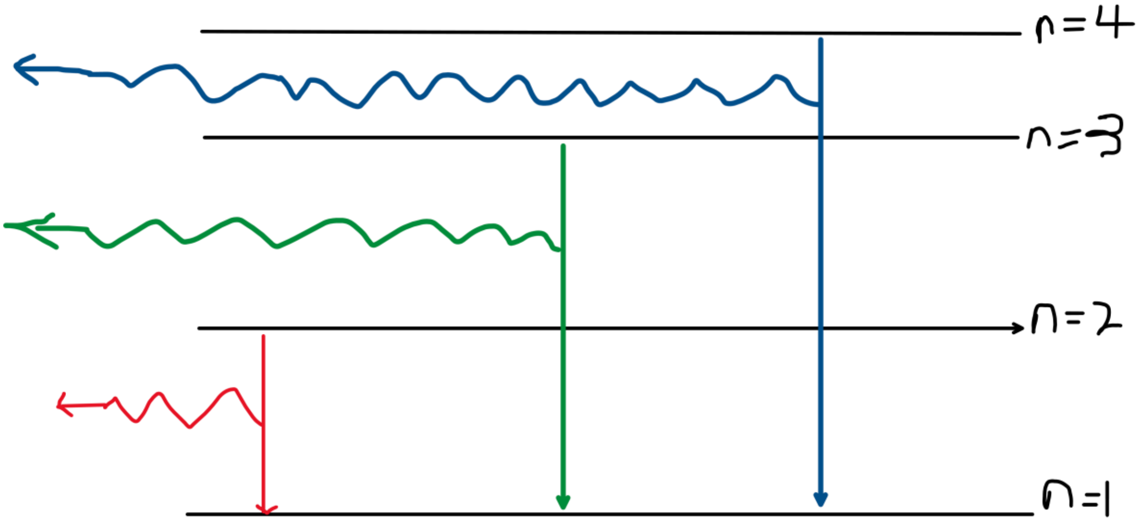
The electrons of each element can only jump between specific fixed energy levels.

Why does the spectrum of Na have two lines, while the spectrum of hydrogen has only one line?

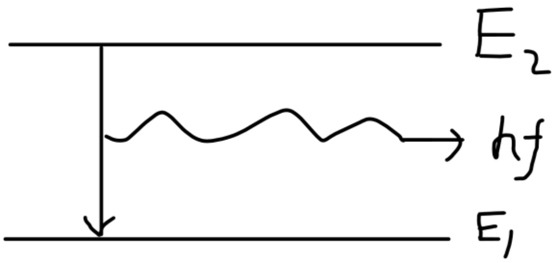
The sodium (Na) spectrum has two lines because, when excited, its electrons can jump from the ground state to different higher energy levels (such as the 3p and 4s orbitals). Returning to the ground state, they release light of specific wavelengths, forming multiple spectral lines (such as the sodium D doublet). The hydrogen (H) spectrum has only one distinct line (such as the Hα line) because its electronic structure is simpler, with only one electron. The transition from the ground state (1s) to the first excited state (2p) and back again produces a single spectral line.

How was the spectrum of that element derived?
The spectrum of an element is determined by heating or ionizing a sample, causing electrons in its atoms to transition from their ground state to a higher energy level. The electrons then release light of specific wavelengths as they return to the ground state. This light is then decomposed into distinct colors or spectral lines by a spectrometer, forming a unique spectrum. Each element's spectrum is unique due to its electronic structure, acting like a "fingerprint" and can be used to identify the element.

Based on the energy level transition of electrons, only light of specific wavelengths is emitted or absorbed to form discrete spectral lines



②



E: The energy level of the electron, which includes the kinetic energy of the electron and the potential energy of the nucleus

$$hf = E2 - E1$$

The energy released by the electron energy level transition is equal to the energy of the photon

E2>E1: Photons are emitted   E2<E1: Photons are absorbed

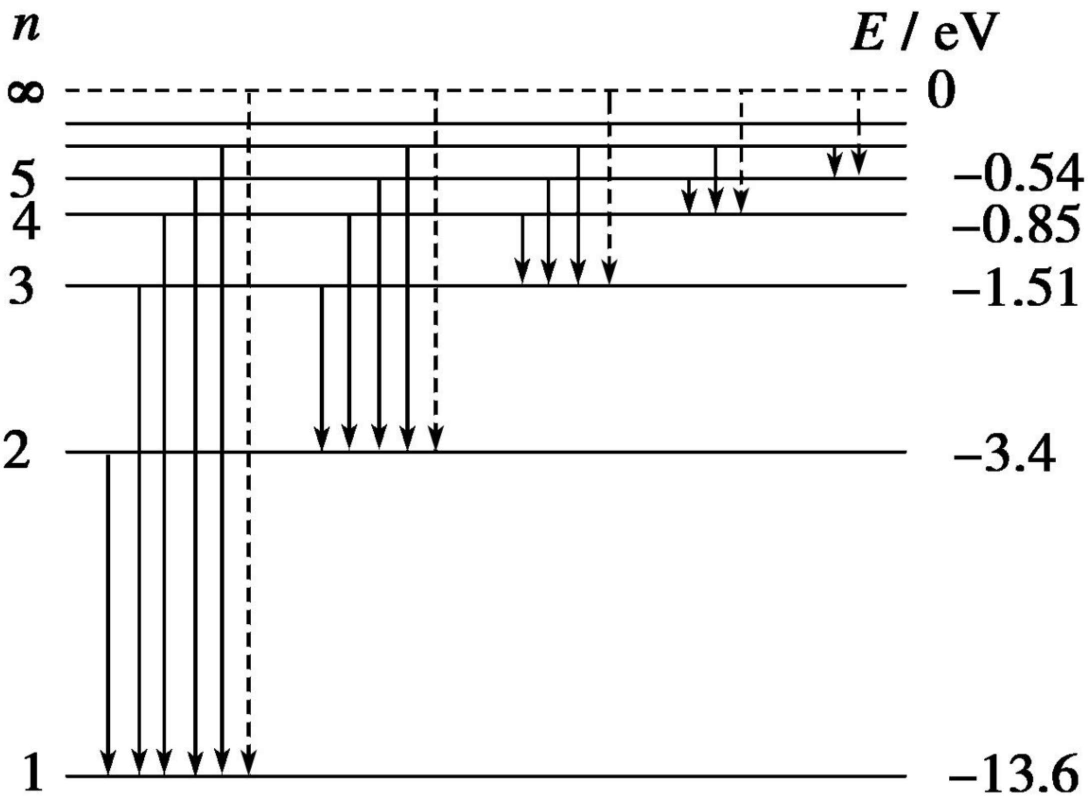
The wavelength of this photon:

Note: One electron transition releases only one photon

$$\lambda = \frac{c}{f} = \frac{c}{\frac{E}{h}} = \frac{hc}{E2 - E1}$$

The energy of photon   *the energy of electron*

Note: Free electrons (conducting electrons in metals) have no energy levels, so the formula does not apply to bound electrons.



n=1: ground state (the lowest energy level)
The higher states are called excited states.
n=2: first excited states

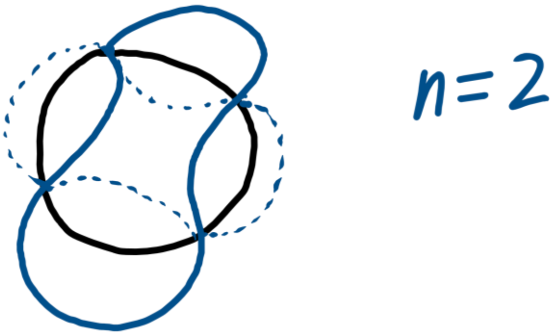
If an electron moves from a lower energy level to a higher energy level: 1. High temperature 2. High pressure 3. Light

For example: -15ev to -7ev 10ev photons are not enough, they must be 8ev

If an electron moves from a higher energy level to a lower energy level (happened naturally): Releases energy in the form of photons
Luminescence

8.4.3 de Broglie's hypothesis applied to atoms
According to de Broglie, a particle of mass m with a speed v would have a wavelength $\boldsymbol{\lambda = \frac{h}{mv}}$

Each electron orbit in an atom, is actually a standing wave.



$$2\pi r_n = n \cdot \lambda$$

$$2\pi r_n = n \cdot \frac{h}{mv}$$

$$mvr_n = \frac{nh}{2\pi}$$

The higher the energy level of the electron, the smaller the speed and the larger the wavelength of the electron.

IX. Nuclear physics

9.1 nucleus= $\underbrace{\text{proton + neutrons}}_{\text{Nucleons}}$

Atomic number(Z): the number of protons

The number of neutrons: N

The total number of nucleons: Z+N=mass number= A

The number of protons in the nucleus of an atom defines the element.

$^{A}_{Z}X$ → Element symbol

9.2 the nuclear force: the strong force and weak force

Protons are positively charged and would therefore experience a repulsive Coulomb force from each other. Why don't these nuclei explode?

What holds neutrons? → Which have no electric charge.

The strong nuclear force: bind neutrons and protons together.

Up: $+\frac{2}{3}e$ $\quad$ $\mathbf{down}: -\frac{1}{3}e$ $\quad$ e: Positive elementary charge

Proton: 1e: 2 up 1 down

Neutron: up down down zero e

9.3 nuclear reaction: radioactive decay

The mass is how many U the nucleons are.

(1) α radiation

α radiation is a beam of α particles.

Handwritten: α particle = alpha particle; up/down arrow: ORE

A particle is the nucleus of helium; it consists of two protons and two neutrons, its mass number 4, mass 4u, its charge is +2e. It is deflected in electric field and magnetic field.

$1u = 1.66 \times 10^{-27}$ kg → mass unit

When the nucleus of an atom emits an α particle, it is said to undergo α-decay.

The nucleus loses two protons and two neutrons, so both the proton number and neutron number decrease by 2, and the nucleon number decreases by 4.
α particle = He nucleus
Example reaction:
$^{234}_{92}U \rightarrow {}^{230}_{90}Th + {}^{4}_{2}He + energy$

---

(2) β-radiation and electron capture
β radiation is a beam of β particles.
There are two types of β particles: β minus particle (β^- particle) and β plus particle (β^+ particle).
$\beta^- \rightarrow$ electron, $\beta^+ \rightarrow$ positron
A β^- particle is an electron with negative charge of -e.
A β^+ particle is a positron with positive charge of +e.
positron = anti-electron
A particle (positron) is the antimatter of electron. When a positron collides with an electron, they annihilate each other. Their mass is converted into electromagnetic energy in the form of two gamma photons.
Both β^- and β^+ particles can be deflected by electric field and magnetic field.
When the nucleus of an atom emits a β particle, it is said to undergo β-decay.

Nature of β^- radiation:
a neutron → proton + electron + antineutrino
In β^- decay, a neutron in the nucleus turns into a proton, a negative electron, and an electron-antineutrino.
Example reaction:
$^{214}_{82}Pb \rightarrow {}^{214}_{83}Bi + e^- + \overline{v}_e + energy$
The proton number of daughter nuclide is one more than parent nuclide; the nucleon number has no change.
n → neutron

- *p → proton*
- *$e^- \rightarrow$ electron*
- *$\overline{v}_e \rightarrow$ antineutrino*
- *"emit" → particle emission*
- *"energy" → released energy*

A free neutron cannot exist; it decays into a proton!!!

$${}^1_0\mathrm{n} \rightarrow {}^1_1\,\mathrm{p} + {}^0_{-1}\,\mathrm{e} + {}^0_0\,\bar{\nu} + \mathrm{energy}$$

Nature of β^+ decay:

A proton → a neutron + a positron + a neutrino

$${}^1_1\mathrm{p} \rightarrow {}^1_0\,\mathrm{n} + {}^0_1\,\mathrm{e} + {}^0_0\,\nu + \mathrm{energy}$$

Free protons can exist!!!

e^- and $\bar{\nu}$ go together; e^+ and ν go together

→ Conservation of lepton number

The lepton number is the count of positrons, neutrinos, and antineutrinos.

Each type of lepton has its own lepton number (L).

Electrons (e^-) and neutrinos (ν): lepton number $L = +1$

Positrons (e^+) and antineutrinos ($\bar{\nu}$): lepton number $L = -1$

for example: β– decay:
neutron → proton + electron + antineutrino
0 0 +1 -1

Sum of lepton numbers: 0 → 0
The number of leptons before the reaction is the same as that after the reaction.

Electron Capture
another way in which a nucleus can increase its neutron-to-proton ratio is capture an orbiting electron

p+ + e– → n + v
proton electron neutron neutrino

why happen: too many protons in the nucleus, β+ decay lacks energy, so electron capture occurs to reduce protons.

(3) γ radiationγ radiation is the process where a nucleus releases γ photons (high-energy electromagnetic radiation) when transitioning from a high-energy excited state to a low-energy state. It does not change the number of protons and neutrons, but releases energy.

α, β decay → excited state → γ radiation → ground state (more stable)

Corresponding to: X-ray
Nuclear transition: γ ray

Supplement: Particle decay occurs because the current state is unstable, tending to transition to a state with lower energy and more stability.

9.4 mass defect and binding energy
At a nuclear level, we measure the masses of nuclei and nucleons in atomic mass units(u). One atomic mass unit (1 u) is defined as being equal to one-twelfth of the mass of a carbon-12 atom. 1 u is equal to 1.6605 $\times 10^{-27}$ kg
Using this scale of measurement, to five decimal places, we have
isolated Proton mass m_p = 1.00728u
isolated Neutron mass m_n = 1.00867u
electron mass m_e = 0.000549u
Because all atoms and nuclei are made up of protons, neutrons and electrons, we should be able to use these figures to calculate the mass of any atom or nucleus.
For example. The mass of a helium-4 nucleus, consisting of two protons and two neutrons, should be
(2×1.00728u) + (2×1.00867u) = 4.0319 u
However, the true mass of a helium nucleus is 4.00151 u
The difference between the expected mass and the actual mass of a nucleus is called the mass defect of the nucleus.
In this case of the helium -4 nucleus, the mass defect is 4.0319u - 4.00151u=0.03039 u
Example:
Calculate the mass defect for a carbon-14 (^{14}C) nucleus. The measured mass is 14.00324u.
The nucleus contain 6 proton and 8 neutrons
total mass = (6×1.00728u) + (8×1.00867u) =14.11304 u

The actual mass of the nucleus is less than the mass of the protons and neutrons in their free state. This is because the binding energy is released.

Unit Conversions and Energy Calculation

- **Energy Unit Conversion**: $1\text{MeV} = 10^6\text{eV}$
- **Energy Released by ^4_2He Nucleus**: 28.4MeV (convert to joules: $28.4 \times 10^6 \times 1.602 \times 10^{-19}\text{J} \approx 4.55 \times 10^{-12}\text{J}$)
- **Length Unit Conversions**: $1\text{m} = 10\text{dm} = 100\text{cm} = 1 \times 10^3\text{mm} = 1 \times 10^6\mu\text{m} = 1 \times 10^9\text{nm}$

9.4.2 mass energy equivalence (mass-energy equivalence)

E=mc2

↓

mass loss *C: speed of light* *E: equivalent energy*

m= (sum of the rest masses of nucleons) - (actual mass of the nucleus)

E: total energy of an object: rest energy + kinetic energy + other energies
→ can also represent binding energy

1u=931 MeV

eg. mass defect 0.1098u bind energy =0.1098×931 MeV

9.4.3 binding energy

When protons and neutrons are joined together to form a nucleus, there is a mass defect, which is transformed into energy, this energy is called binding energy.

If we want to separate all nucleons, since there is strong force, energy is required, this energy is equal to the energy released when these nucleons join together.

The energy of the nucleus is not its own, but the energy it releases: fusion/fission energy. Nuclear binding is the energy released by the nucleus (binding energy). But fission requires absorbing energy, these two energies are the same.

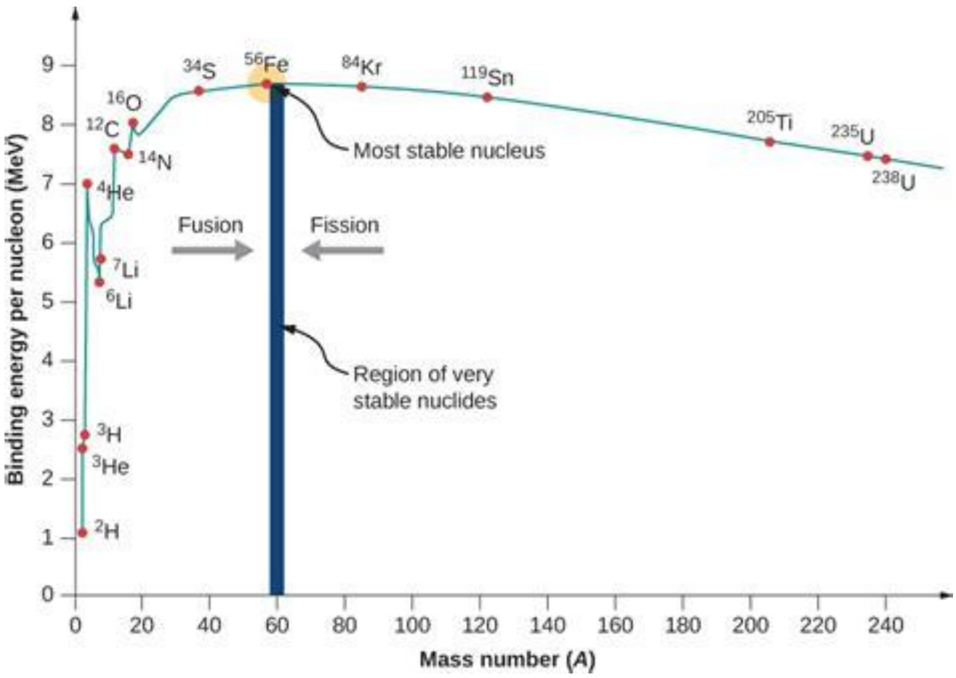
Release E1 first, then E2, and the binding energy increases.

So binding energy can be defined as the energy equivalent of the mass defect of a nucleus. It is the energy required to separate all the nucleons of a nucleus. The energy is from the external environment. From ∞ to aggregation: nuclear energy is released (strong interaction, release).
Nucleon absorb energy.

9.4.4 Stability of nuclei
Binding energy per nucleon is defined as the total energy needed to completely separate all the nucleons in a nucleus divided by the number of nucleons in the nucleus. （This is an indicator of stability： Binding energy of a single nucleon）

200 Mev *50 Mev*

Why is it that the greater the binding energy of a single nucleon, the more stable it is?
Because the greater the binding energy of a single nucleon, the tighter the nucleons in the nucleus are bound, and the higher the energy required to overcome the force of the nucleons, the more stable the nucleus is.



So nuclear fusion becomes stronger

Through energy loss, the energy gradually increases.

9.5 Nuclear fusion & nuclear fission

9.5.1 Nuclear fusion

Light atomic nuclei combine to form heavy atomic nuclei - hydrogen bomb principle

$$ {}_1^2H + {}_1^3H \rightarrow {}_2^4He + {}_0^1n + \text{energy} $$

↓

Which means + stable (rather than binding energy, mass defect, this is not dissociation energy)

Nuclear separation → (fission fragments)

9.5.2 Nuclear fission

$$ {}_{92}^{235}U + {}_0^1n \rightarrow {}_{92}^{236}U^* \rightarrow {}_{56}^{141}Ba + {}_{36}^{92}Kr + 3{}_0^1n + \text{energy} $$

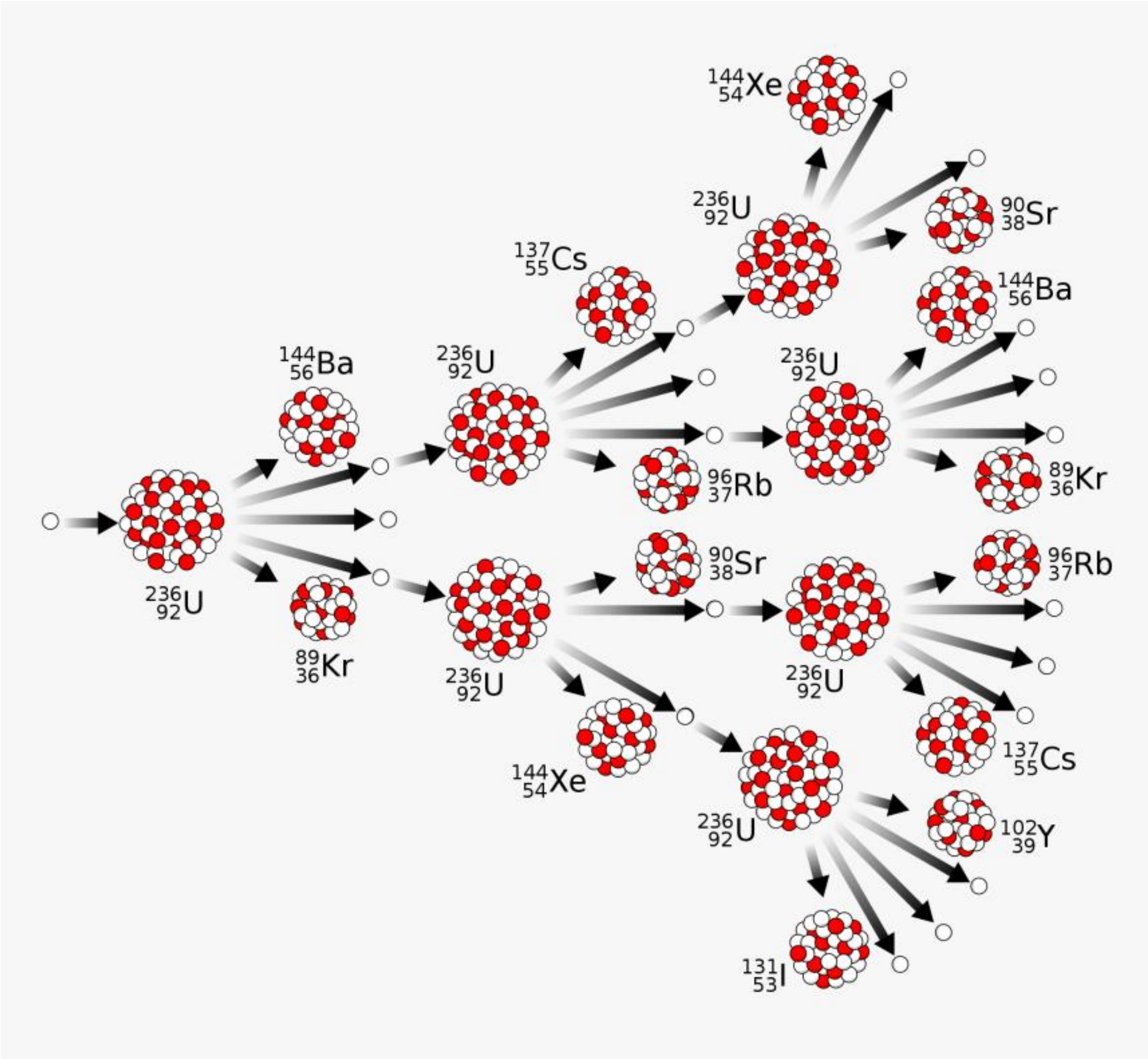
(Uranium-235) (Neutron) (Excited Uranium-236) (Barium-141) (Krypton-92)

Inducing nuclear fission requires neutron bombardment!

It is also the atomic bomb principle: heavy atomic nuclei → lighter atomic nuclei, releasing energy

Released in the form of fragment kinetic energy and neutron kinetic energy.

①uncontrolled nuclear fission

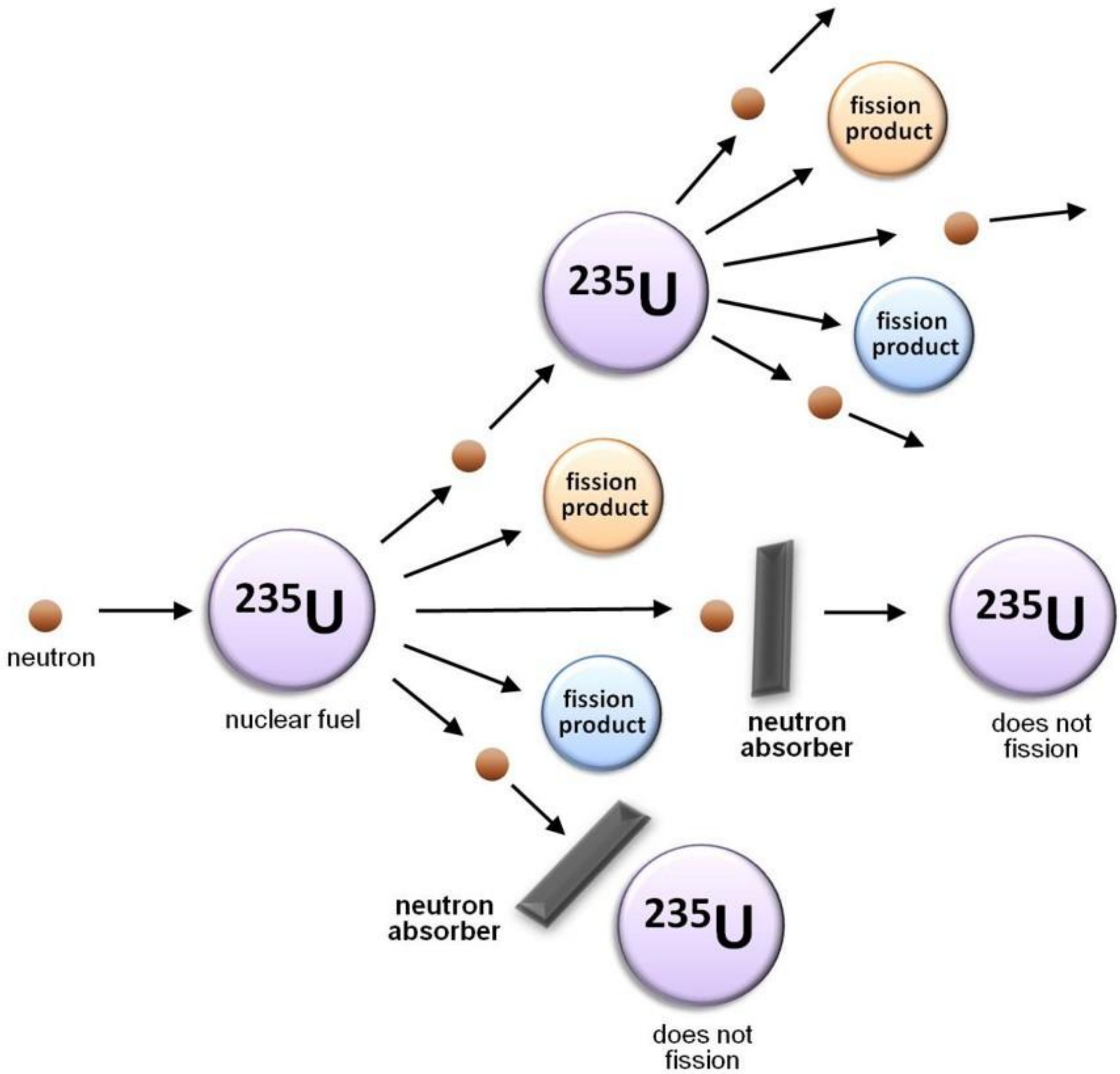


White ball: Neutron

This is the principle of the atomic bomb

② controlled

This is how nuclear power plants generate electricity



9.6 Nuclear disintegration energy (解离能, here referring to nuclear disintegration energy, but note that "解离能" in Chinese can sometimes refer to dissociation energy in a chemical context; here it's nuclear)

- *Binding energy: the energy released when nucleons combine to form a nucleus (or the energy required to disassemble a nucleus into its constituent nucleons) ①*
- *Disintegration energy: in nuclear reactions, the energy required to break chemical (nuclear, but note: in this context, it's more about nuclear reactions, not chemical bonds; there might be a translation nuance) bonds ②*
  E① > E②
- *①: strong force*
- *②: electromagnetic interaction*
  Symbol: atomic nucleus
  Q: energy
  A + B → C + D + Q

$$Q = [(m_A + m_B) - (m_C + m_D)]c^2$$
$$= (\Delta m)c^2$$

9.7 A mathematical treatment of radioactive decay

1. *Activity and decay constant*

The number of decays ΔN that occur in Δt is proportional to the total number of N of radioactive nuclei present, and is then proportional to Δt:

$$\frac{\Delta \boldsymbol{N}}{\Delta \boldsymbol{t}} = -\boldsymbol{\lambda} \cdot \boldsymbol{N}$$

↓

(Number of decays per unit time) (decay constant) (Number of undecayed atomic nuclei before decay)

$\Delta N \propto N \cdot \Delta t$

ΔN: final - initial: negative value

$\frac{\Delta N}{\Delta t}$: the activity of the sample

Unit: Bq

1 Bq=1 decay/second

The decay constants λ are different for different substances.

$$\frac{\Delta \boldsymbol{N}}{\Delta \boldsymbol{t}} = -\boldsymbol{\lambda} \cdot \boldsymbol{N}$$

$$\boldsymbol{\lambda} = -\frac{\frac{\Delta \boldsymbol{N}}{\boldsymbol{N}}}{\Delta \boldsymbol{t}}$$

$$\frac{\Delta \boldsymbol{N}}{\boldsymbol{N}}: \boldsymbol{The\ probability\ of\ a\ single\ atom\ decaying}$$

② exponential decay

③half life

$$\frac{dN}{dt} = -\lambda N$$

$$\frac{dN}{N} = -\lambda dt$$

$$\int \frac{dN}{N} = \int -\lambda dt$$

$$\ln N = -\lambda t + C$$

$$\ln N_0 = C \quad (t = 0, N = N_0)$$

$$\ln N = -\lambda t + \ln N_0$$

$$\ln\left(\frac{N}{N_0}\right) = -\lambda t$$

$$\frac{N}{N_0} = e^{-\lambda t}$$

$$N(t) = N_0 e^{-\lambda t}$$

As a result: *A: Radioactive decay activity*

$$A(t) = -\frac{dN}{dt}$$

$$N(t) = N_0 e^{-\lambda t}$$

$$\frac{dN}{dt} = -\lambda N_0 e^{-\lambda t}$$

$$A(t) = \lambda N_0 e^{-\lambda t}$$

$$A_0 = \lambda N_0 \quad (t = 0)$$

$$A(t) = A_0 e^{-\lambda t}$$

③half life

$$N(T_{1/2}) = \frac{N_0}{2}$$

$$\frac{N_0}{2} = N_0 e^{-\lambda T_{1/2}}$$

$$\frac{1}{2} = e^{-\lambda T_{1/2}}$$

$$\ln\left(\frac{1}{2}\right) = -\lambda T_{1/2}$$

$$-\ln 2 = -\lambda T_{1/2}$$

$$\ln 2 = \lambda T_{1/2}$$

$$T_{1/2} = \frac{\ln 2}{\lambda}$$

End of AP Physics 2 content

Popular Science

Ten Dark Clouds in Physics：

On April 27, 1900, the renowned British physicist Lord Kelvin delivered a speech at the Royal Institution titled "Nineteenth-Century Clouds Over the Dynamical Theory of Heat and Light." In it, he declared that the edifice of physics was essentially complete, with only two "small clouds" remaining to be resolved:

The "null result" of the Michelson-Morley experiment (the ether drift problem)

The "ultraviolet catastrophe" of blackbody radiation

However, it was precisely to resolve these two clouds that catalyzed a profound revolution in physics:

The first cloud gave rise to Einstein's special theory of relativity.

The second cloud gave rise to Planck's quantum theory, opening the door to quantum mechanics.

Thus, the term "clouds in physics" has become synonymous with major problems that cannot be explained by current theories but could potentially trigger the next scientific revolution.

Today, the edifice of physics is far more magnificent than it was in 1900, but it also presents more numerous and more profound "clouds." The following list is not an official ranking, but rather a collection of the ten most vexing problems recognized by the academic community, each pushing the boundaries of our understanding of the universe.

Ten Dark Clouds in Modern Physics (Detailed Version)

1. Dark Matter

What is the problem? Astronomers have discovered through gravitational effects (such as galaxy rotation curves, gravitational lensing, and the large-scale structure of the *universe) that the mass of visible matter in the universe (stars, planets, gas, etc.) is far insufficient to generate sufficient gravity to maintain the observed motion of celestial bodies. This requires the existence of a vast amount of matter that is invisible to us and does not interact with light (interacting only through gravity). This is "dark matter." Its total amount is approximately five times that of ordinary matter.*

Why is it a "dark cloud"? We do not know what kind of particle dark matter is. It does not belong to any known particle in the Standard Model of particle physics. Despite numerous candidates (such as WIMPs and axions), decades of direct and indirect detection experiments have yet to provide conclusive evidence. Its essence is a core mystery of particle physics and cosmology.

2. Dark Energy

What is the problem? In 1998, two independent research teams, observing Type Ia supernovae, discovered that the expansion of the universe is not only continuing but accelerating. This suggests that some unknown form of energy is counteracting gravity, pushing the universe apart. This mysterious force, pervading all space and causing the universe's accelerated expansion, is called "dark energy." It accounts for approximately 68% of the universe's total mass-energy.

Why is it a "dark cloud"? We know almost nothing about the nature of dark energy. The simplest explanation is Einstein's "cosmological constant" (vacuum energy), but the value of vacuum energy calculated by quantum field theory differs from the observed value by a factor of 10^120, making it the worst theoretical prediction in the history of physics. The nature of dark energy may have implications for the ultimate fate of the universe.

3. Quantum Gravity

What's the problem? The two pillars of modern physics—general relativity (which describes gravity and the macroscopic universe) and quantum mechanics (which describes the microscopic world of particles)—are fundamentally incompatible in their mathematical frameworks and physical concepts. Under extreme conditions (such as black hole singularities and the origin of the Big Bang), both fail.

Why is it a "dark cloud"? We need a unified theory that quantizes gravity, a "quantum theory of gravity." Candidate theories include string theory and loop quantum gravity, but to date, no experimental data has been able to verify or disprove any of them. Finding this ultimate theory is the crown jewel of physics.

4. Cosmic Inflation

What's the problem? The standard Big Bang theory cannot explain why the universe is so flat and uniform, nor why it has the same temperature over large distances (the horizon problem). Inflation theory solves this problem by proposing that the universe experienced an exponentially rapid expansion within a very short time after its birth (10^-36 to 10^-32 seconds).

Why the "dark cloud"? Inflation theory is very successful, but it is still a "theory." We don't know the specific nature of the "inflaton" field that drives inflation, how it began, and how it ended. Although observations of the cosmic microwave background radiation (such as data from the Planck satellite) strongly support inflation, we need more direct evidence, such as primordial gravitational waves.

5. Foundations of Quantum Mechanics

What is the problem? Quantum mechanics has been incredibly successful in applications, but the physical interpretation underlying its mathematical form remains a subject of intense debate. Wave function collapse, the measurement problem, Schrödinger's cat, the EPR paradox, and other issues all point to a core question: Is the probabilistic nature of the quantum world inherent, or is it simply a matter of ignorance?

Why is it a "dark cloud"? This raises questions about the ontology of reality. Mainstream interpretations include the Copenhagen interpretation, the many-worlds interpretation, and pilot wave theory, but they make different philosophical and even physical predictions. While experiments (such as Bell's inequality test) have ruled out local hidden variable theories, they do not reveal which interpretation is correct. Understanding this point could revolutionize our understanding of "reality."

6. The Magnetic Monopole Problem

What is the problem? Maxwell's equations are mathematically highly symmetrical, describing both electric and magnetic fields. However, in nature, we have electric charges (positive and negative electrons), but we have never observed isolated "magnetic charges" (i.e., magnetic monopoles). Some grand unified theories (GUTs) predict that magnetic monopoles should have been produced in large numbers in the early universe.

Why a "dark cloud"? Why can't we find any? This either suggests that the GUTs are wrong, or that some mechanism (such as cosmic inflation) is needed to dilute the density of magnetic monopoles, making them extremely rare. Their absence is a key constraint on particle physics theory.

7. Black Hole Information Paradox

What's the problem? According to Hawking radiation, black holes evaporate and eventually disappear. But quantum mechanics emphasizes the conservation of information (the initial information of a system is never lost). So, where does the information of an object swallowed by a black hole go after the black hole evaporates? Hawking initially believed that information is indeed lost, but this violates the basic principles of quantum mechanics.

Why a "dark cloud"? This paradox sharply reveals the direct conflict between general relativity and quantum mechanics in the realm of black holes. Recent research, such as the "firewall paradox" and the holographic principle, has attempted to resolve it, but consensus remains elusive. Resolving it could provide key clues to our understanding of the nature of spacetime and information.

8. Baryon Asymmetry in the Universe

What's the problem? According to particle physics theory, the Big Bang should have produced equal amounts of matter and antimatter. When the two met, they annihilated into photons. But if that were the case, the universe should be filled with only light, with no stars, planets, or us. Yet, observations show that the universe is composed almost entirely of matter.

Why a "dark cloud"? We need a physical process (satisfying the "Sakharov condition") that slightly favored the production of more matter in the very early universe. While CP violation in the Standard Model could provide some mechanism, its effect is far from sufficient to explain the observed asymmetry. New physics (such as neutrino oscillation) may be the answer.

9. Neutrino Mass

What's the problem? The Standard Model of particle physics originally predicted that neutrinos were massless (like photons). However, neutrino oscillation experiments (which won Nobel Prizes) have clearly shown that neutrinos have a tiny, non-zero mass.

Why a "dark cloud"? The fact that neutrinos have mass is the first solid experimental evidence that the Standard Model needs to be extended. We still don't know their absolute mass or why it's so small (millions of times lighter than an electron). Understanding neutrinos may lead to deeper new physics.

10. Axions and the Strong CP Problem

What's the problem? Quantum chromodynamics (QCD) theory allows for a CP violation effect that would cause neutrons to possess an electric dipole moment. However, experimental measurements have found that the neutron's electric dipole moment is negligibly small (<10^−26 e·cm). This huge asymmetry between theoretical predictions and experimental observations is known as the "strong CP problem."

Why the "dark cloud"? The most elegant solution is to introduce a new particle called the axion. Interestingly, this hypothetical, extremely light, and weakly interacting particle happens to be an excellent candidate for dark matter. Therefore, searching for axions kills two birds with one stone: solving a fine-tuning problem in particle physics and unveiling the mystery of dark matter.

Summary

These ten dark clouds are not independent; they intertwine and point to a larger, deeper unified theory. For example:

Solving quantum gravity (cloud 3) may help us understand the black hole information paradox (cloud 7).

The discovery of axions (cloud 10) may explain both dark matter (cloud 1) and the strong CP problem.

The mass of neutrinos (cloud 9) may be related to the mechanism that produces cosmic matter asymmetries (cloud 8).

The seven Millennium Problems are among the most challenging problems in mathematics. Proposed by the Clay Mathematics Institute in 2000, each of them offers a $1 million prize for its solution.

Of these seven problems, one has a profound and direct connection to physics, while another has applications in certain areas of physics.

1. Yang–Mills Existence and Mass Gap - Directly Related to Physics

This is the most central and direct physics problem of the seven. Essentially, it requires a rigorous mathematical proof that the core theory describing the world of particle physics—Yang–Mills theory—is valid.

Problem Background:

Yang–Mills theory is a mathematical framework proposed by physicists Chen-Ning Yang and Robert Mills in the 1950s. This theory describes the interactions between elementary particles (strong, weak, and electromagnetic forces) through "gauge fields." It is the cornerstone of the Standard Model of particle physics. Quantum electrodynamics (QED) and quantum chromodynamics (QCD) are both specific implementations of the Yang-Mills theory.

Two parts of the puzzle:

Existence: Prove that for any compact simple gauge group (such as SU(3), the group describing the strong force), the quantum Yang-Mills theory in four-dimensional Minkowski space exists (i.e., has a strict mathematical definition, such as satisfying the criteria of "axiomatic quantum field theory"). Currently, physicists rely on techniques such as perturbation expansions when using this theory, but its "existence" in a non-perturbative, strictly mathematical sense has not yet been proven.

Mass Gap: Prove that in the above theory, there is a non-zero energy difference between the lowest energy excited state (i.e., the state after vacuum) and the vacuum. This energy difference is called the "mass gap."

Why is the "mass gap" so important to physics?

The physical correspondence of this "mass gap" is: Why do some particles have mass?

Specifically, the strong force (described by the SU(3) group) is a short-range force. In the strong force, the particles that transmit the strong force are gluons. Experiments show that composite particles like protons and neutrons possess significant mass.

However, the gauge bosons (such as gluons) in Yang-Mills theory were originally mathematically predicted to be massless particles, just like photons. If this were true, the strong force would be a long-range force like the electromagnetic force, which contradicts observations (the strong force is a short-range force).

Physicists believe that due to the theory's inherent complexity and "confinement" nature (quarks and gluons cannot be observed individually), these massless gluons combine to form massive particles (such as protons), spontaneously creating a mass gap.

The challenge is to rigorously prove mathematically that, although the theoretical equations appear to allow for massless solutions, the actual quantum state does indeed have an energy gap, explaining the observed mass.

In short, this puzzle asks: "Prove mathematically and rigorously that the core components of the Standard Model of particle physics, which we physicists use successfully every day, are logically consistent and valid."

2. Navier–Stokes Existence and Smoothness - Important Applications in Physics

This is a mathematical problem originating from classical physics, primarily in the field of fluid mechanics.

Problem Background:

The Navier–Stokes equations are a set of partial differential equations that describe the motion of fluids (such as liquids and gases). They are one of the most fundamental laws of physics, from aerodynamics (aircraft design) to meteorology (weather forecasting) to oceanography.

Problem:

In three dimensions, prove whether, given a smooth initial velocity field, solutions to the Navier–Stokes equations always exist (without generating singularities in finite time).

If a solution exists, is it always smooth (without infinite kinetic energy density)?

Why is it a problem? While we numerically solve these equations every day in engineering and science (and often successfully), mathematically, we don't even know whether these solutions will always exist and be well-behaved. Mathematicians wonder whether, in principle, these equations are destined to produce uncontrollable turbulence or singularities at some point, rendering the model invalid. Or, can we always trust that the solutions are smooth?

Relevance to Physics:

The puzzle itself is about mathematical existence and smoothness, but the equations it studies—the Navier-Stokes equations—are fundamental equations of physics. Solving this puzzle would significantly advance our understanding of turbulence, one of the *most intractable problems in classical physics. It wouldn't revolutionize particle physics like the Yang-Mills problem did, but it would revolutionize our understanding of the mathematical foundations of fluid motion, impacting all areas of physics and engineering that rely on fluid calculations.*

Ready to be a physicist