Electromagnetics

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Outline

- Chapter 1: Understanding of Electromagnetics
- Chapter 2: Tools Needed for Electromagnetics
- Chapter 3: Electrostatics
- Chapter 4: Magnetostatics

Contents

1-1 Necessity of Electromagnetism

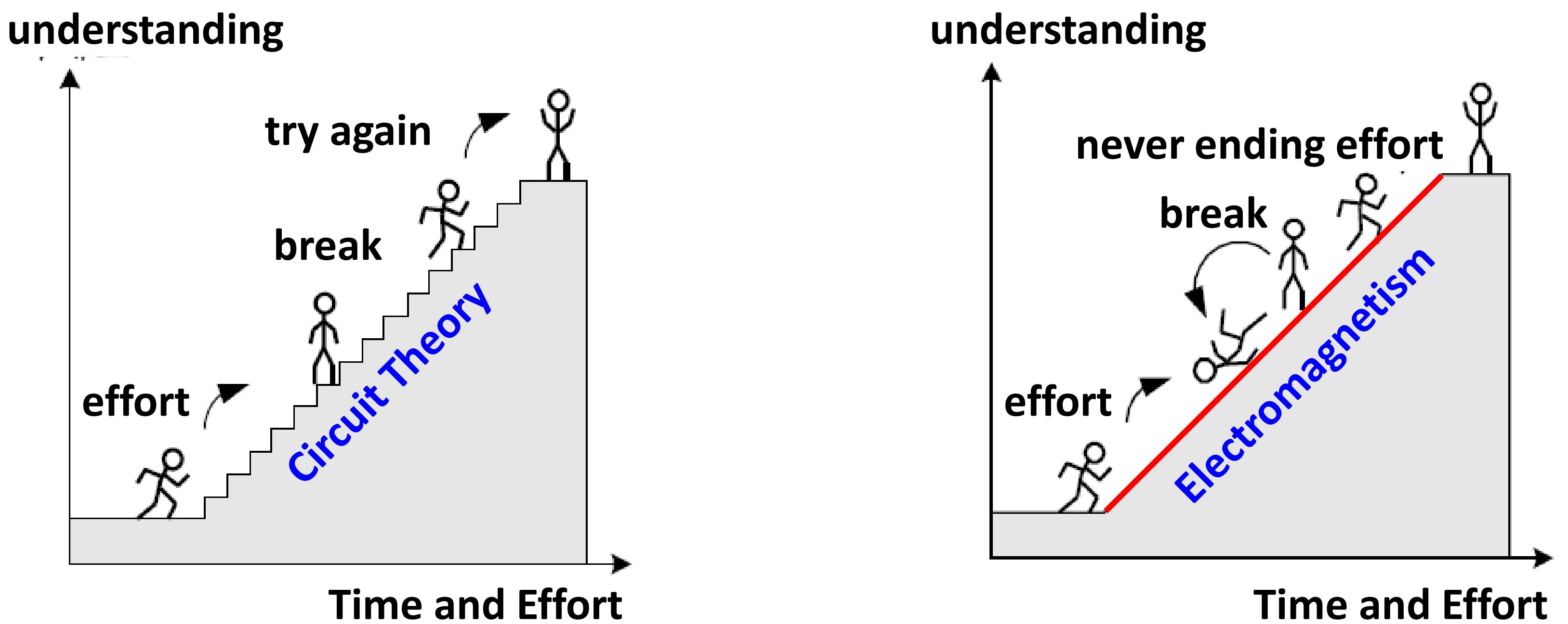
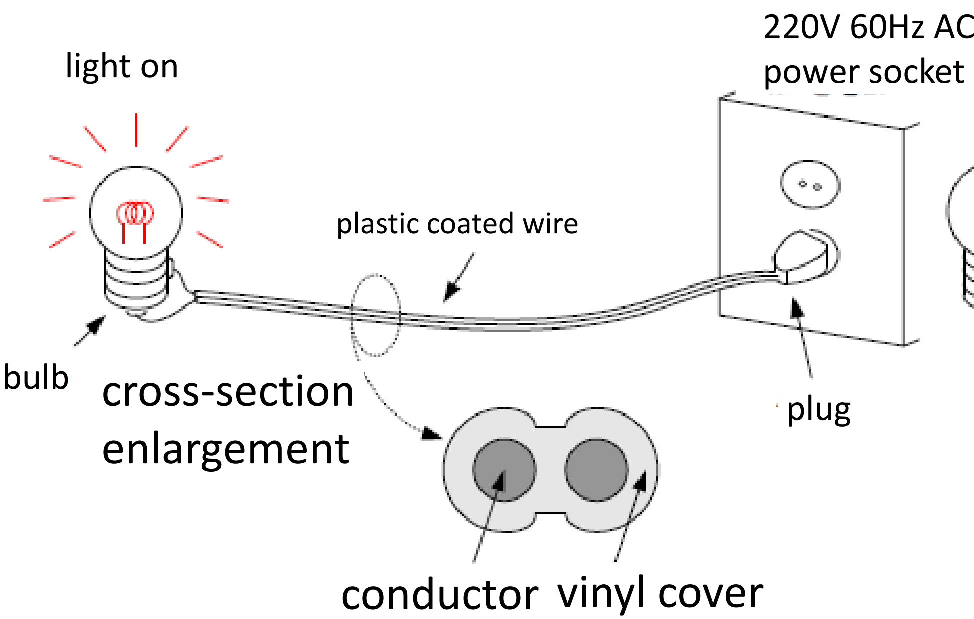


Fig. 1.1 Comparison between circuit theory and electromagnetics

Simple example



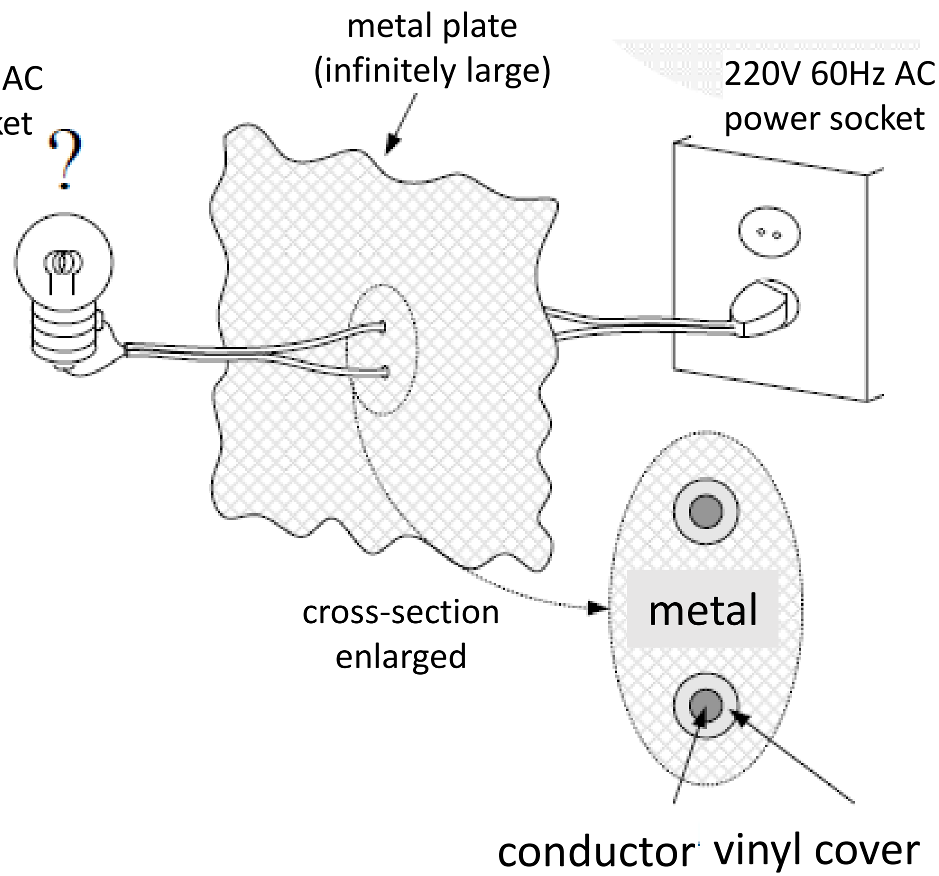
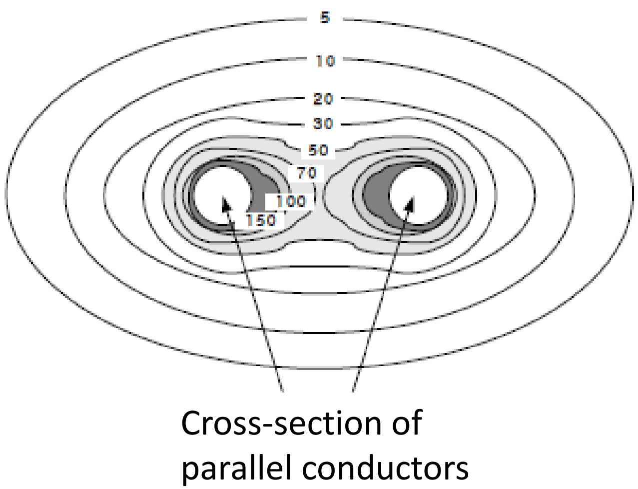


Fig. 1.2 Lighting of light bulbs using AC power supplied to the home

Fig. 1.3 Possibility of power transfer when two conductors are separated from each other and pass through a metal plate

Simple example

- **The reality of power transmission through two conductors ⇒ Electromagnetism is required**
  - Most of the power is transferred to the air outside the two conductors
  - Electromagnetic wave = electric field (unit: V/m) + magnetic field (unit: A/m)
  - Quantity multiplied by electric field and magnetic field =
    Power density per unit area (V/m × A/m = VA/m^2 = W/ m^2)
  - Role of two conductors: Inducing power in the direction in which the two conductors travel by just concentrating the power distribution between the two conductors



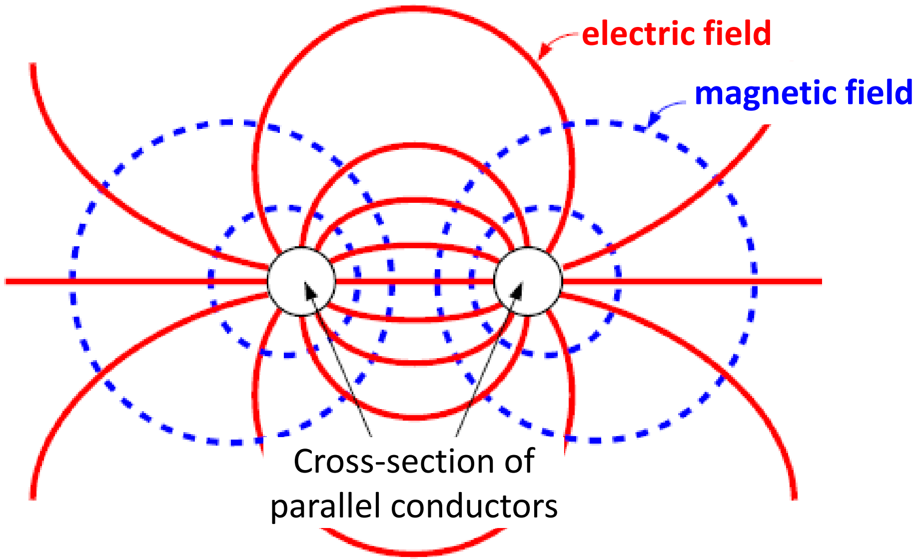


Fig. 1.4 Cross-sectional distribution of electromagnetic physical quantity propagating through two conductors

Specific example

- EMI (electromagnetic interference)
- EMS (electromagnetic susceptibility)
- EMC (electromagnetic compatibility)

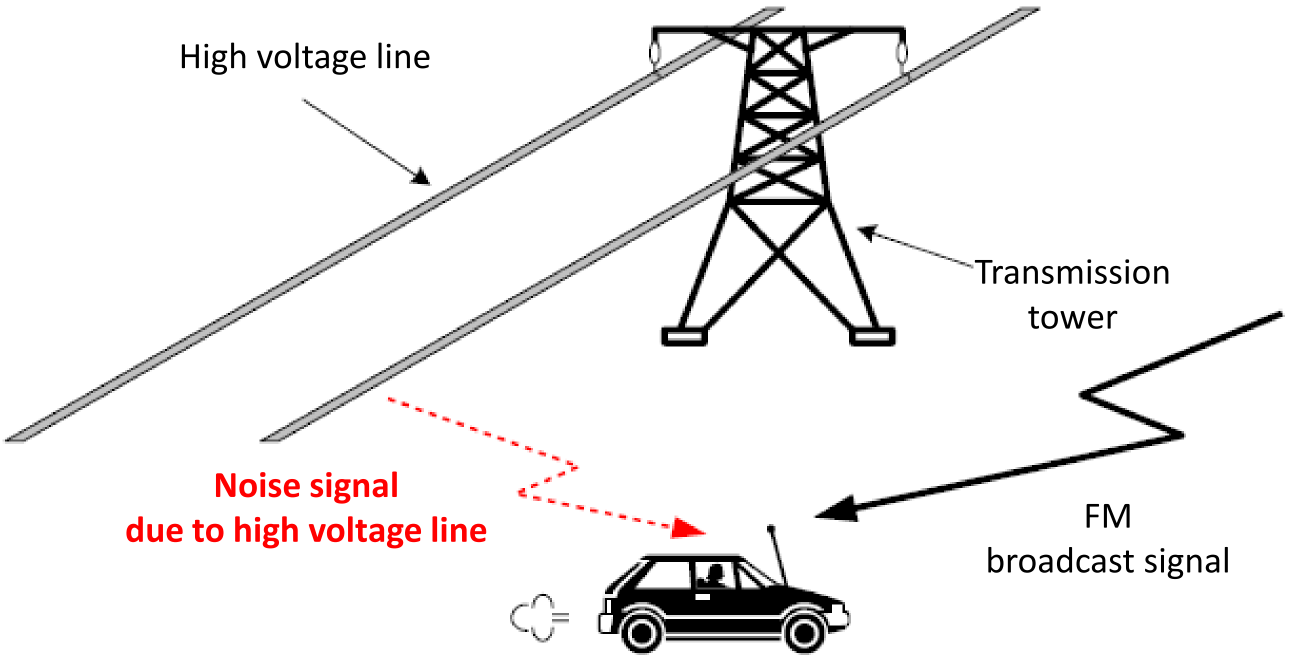


Fig. 1.5 Electromagnetic disturbances around power lines

1-1 Necessity of Electromagnetism

✓ **Electromagnetics**

- A study that provides the basic principles of generation, transmission, reception, processing, conversion, and storage of electromagnetic energy or signals

- Applied to all fields of electrical and electronic engineering such as electronic circuits, electric devices, power generation/transmission/distribution, control, communication, semiconductor, computer, etc.

Ex) **Circuit theory**: A theory approximated from electromagnetics only in limited cases where the time changes of voltage and current **are very small**

Ex) **Optical theory**: A theory approximated from electromagnetics only in limited cases where the time change of voltage and current **is very large**

1-2 Etymology of Electromagnetism

✓ **Western: electromagnetics = electro + magnet + ics**

- electro ⇒ Derived from the Greek word for amber, electrum
- magnet ⇒ Originated from Magnesia, a region where many magnets were produced in ancient times.
- ics ⇒ ending for study

→ **electromagnetics**: the study of the phenomenon that amber attracts feathers or straw and a magnet attracts a piece of iron

✓ **East: 電磁氣學**

- 電 (electric) ⇒ 'lightning', 'electricity', 'flashing'
- 磁 (magnet) ⇒ 'magnet', 'porcelain'
- 氣 (air) ⇒ 'energy', 'weather or climate', 'hide', 'strength', 'air', 'vigorous'
- 學 (study) ⇒ 'learning', 'study',

→ **電磁氣學 :** the study of energy related to lightning and magnets--> The study of the transformation of force and energy acting on lightning strikes or fern pulls iron

East vs West

✓ **Oriental spirit**

- The basic material foundations that shape natural existence
- A continuous substance with intrinsic energy, such as gas or air
- When it thickens, it is a tangible thing ← → When it disperses, it is an intangible energy
- Movement principle (=理): the intrinsic power or vitality of the qi (氣) itself

✓ Western laws of physics

- Law of Conservation of Mass → Law of Conservation of Energy → $E=mc^2$
- Law of increasing entropy
- Law of Minimum Time
- Uncertainty
- Force: gravity, electromagnetic force (electric force + magnetic force), nuclear force (strong + weak force), etc.

East vs West

✓ **Electromagnetic (EM) phenomena: all phenomena in electrical and electronic engineering**

- Individual principles for each EM phenomenon are dealt with in the relevant field
- Examples
    - Static shock felt when holding an iron handle in winter
    - Electric power produced by the power plant is supplied to the home through wires to drive various home appliances, etc.
    - Chat with friends via cordless phone
    - Seeing an object with the light that enters the eye

✓ **Key topics covered in this subject:**

- The principle of operation common to various phenomena caused by EM waves

= **"Principles" that dominate electromagnetism**

= Maxwell Equations

- Examples
    - A current of 60 Hz that supplies a home will pass through metal and not through air
    - Light travels well into the air, and metal does not pass through at all
    - Nevertheless, both current and light at 60 Hz satisfy the same Maxwell equation

1-3 Source of electricity: electric charge

➤ Electric charge : Source of electricity. The amount of electricity an object has

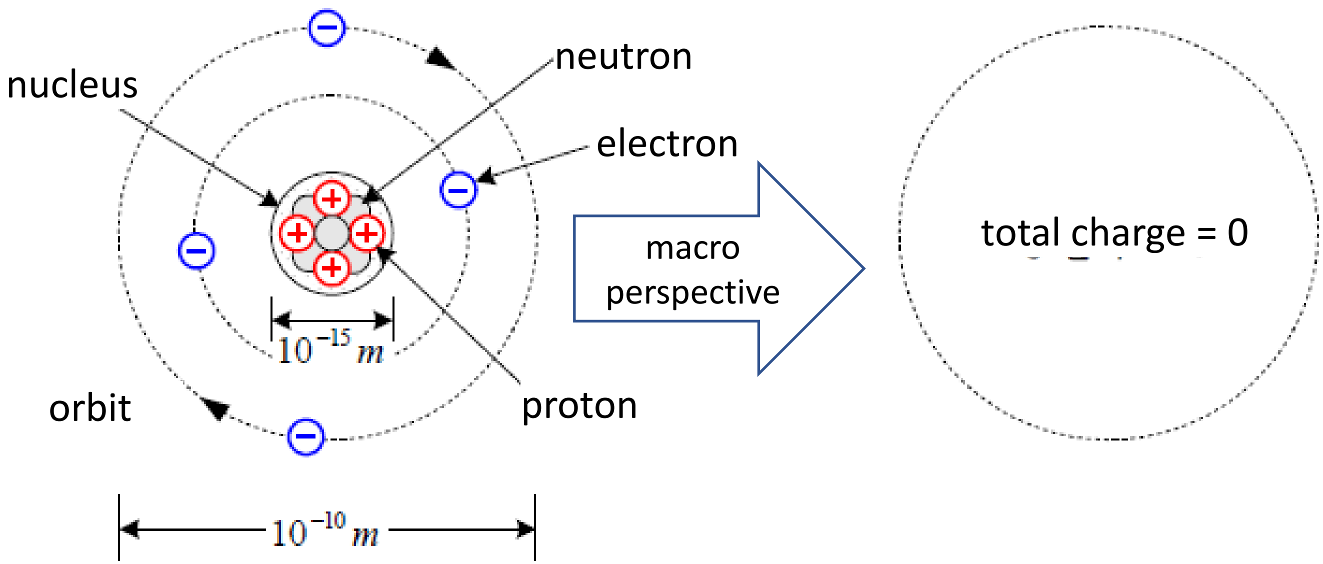


Fig. 1.7 Bohr's Atomic Model

<Axiom 1> There are two types of electric charges: **positive and negative charges**.

<Axiom 2> Since an atom is the smallest structural unit of all materials, the charge of all materials exists only as **an integer multiple** of the charge of one electron.

1-3 Source of electricity: electric charge

- electrification: when energy is applied to an atom in the form of friction or light from the outside, the outermost electrons are out of orbit.
  - the escaped electrons called free electrons have negative charge
  - Atoms from which electrons have been released are positively charged

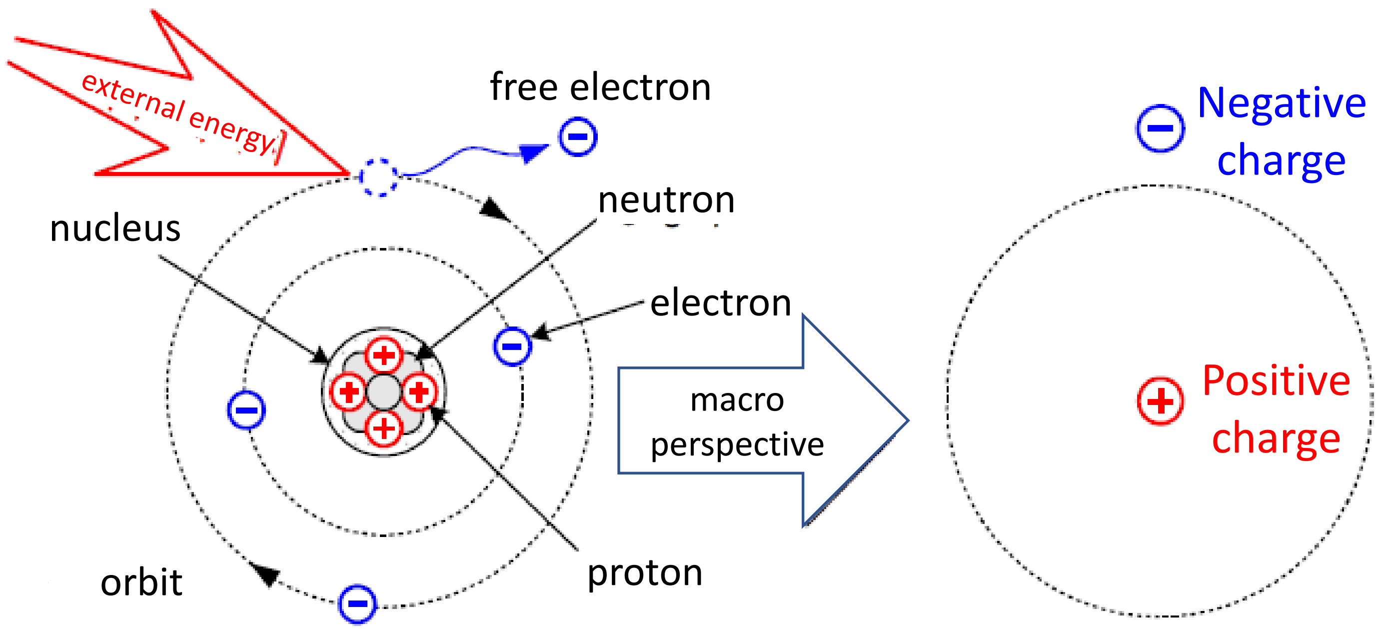
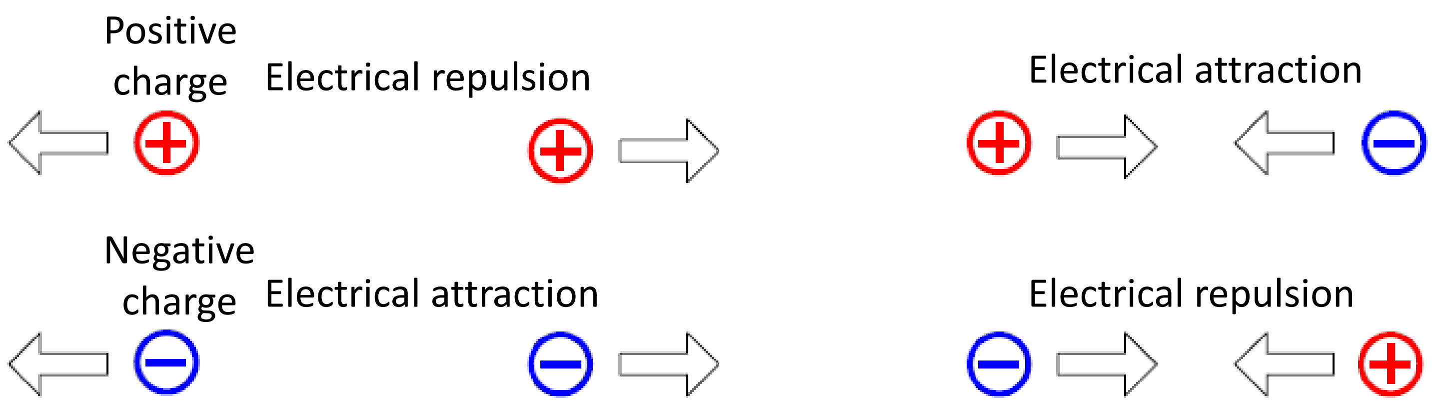


Fig. 1.8 electrification by free electrons leaving electron orbits in the atomic model

1-4 Electricity and electricity

<Axiom 3> Electrical forces occurring between two charges falling by a certain distance

- -Inversely proportional to the ranges of the distance between the two charges
- -Prop proportion to the product of the two charges
- -If the polarity of the two charges is the same, it acts as a manpower if the polarity of the two charges is different.



(a) In the case of the same polarity
: electrical repulsion

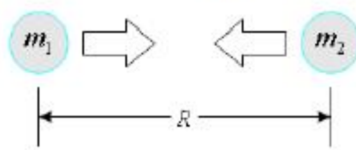
(b) In the case of the opposite polarity
: electrical attraction

Fig. 1.9 Electricity between two charge

1-4 Electricity and electricity

- Similarities and differences between gravity and electrical power
  - Size (similar to gravity): action at a distance
  - Direction (difference from gravity): active as a manpower or chuck power depending on the polarity of the two charges

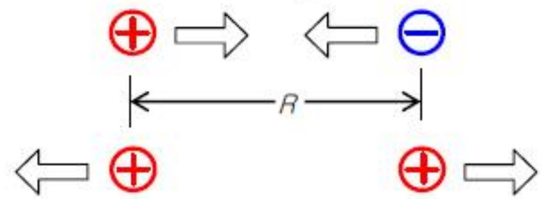
$$F = G\frac{m_1 m_2}{R^2}$$



<Gravity between two mass>

<Isaac Newton(1642-1727)>

$$F = k\frac{q_1 q_2}{R^2}$$

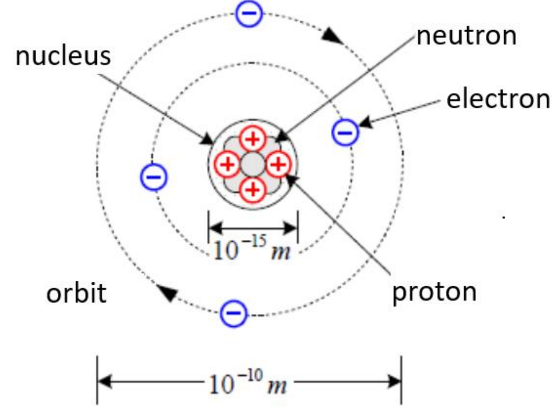


<Electricity between two charges>

<C.-A. de Coulomb(1736-1806)>

1-4 Electricity and electricity

- Nuclear force vs Electric force :
  - Nuclear force (narrow area)
  - Electric force (wide area)



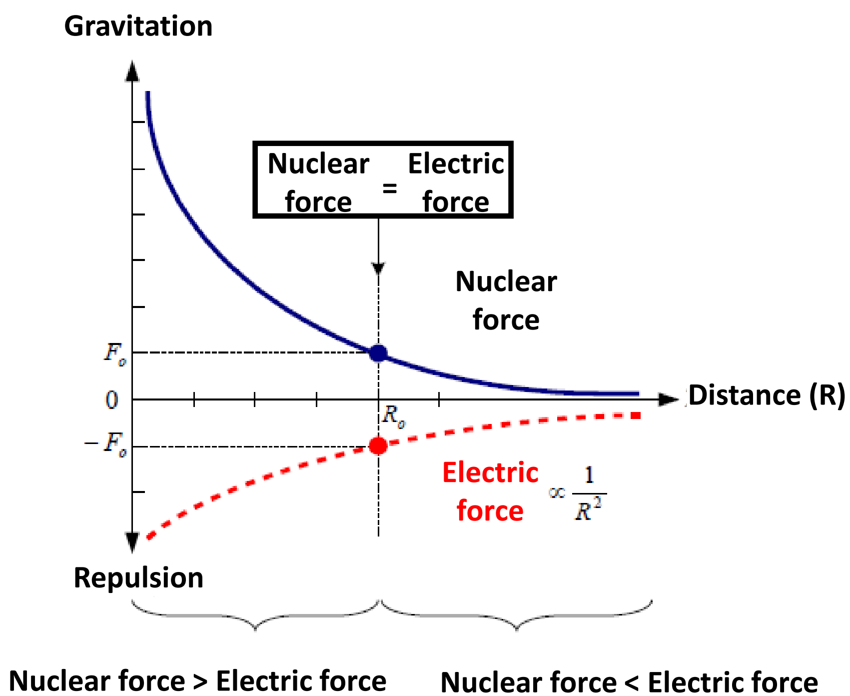


Fig. 1-11 Electricity and nuclear force in the atomic model

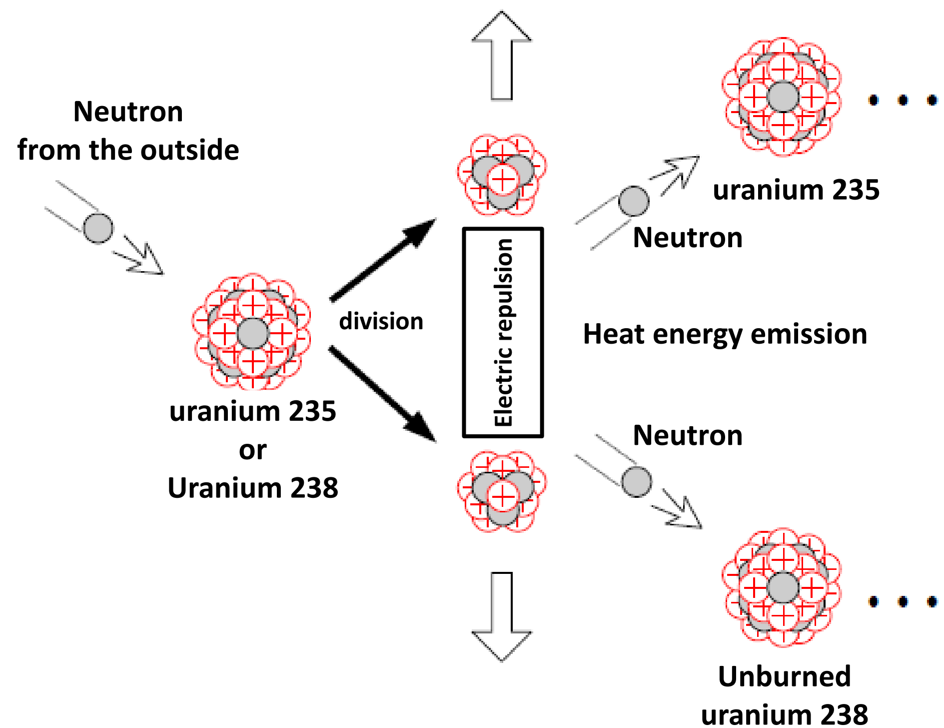
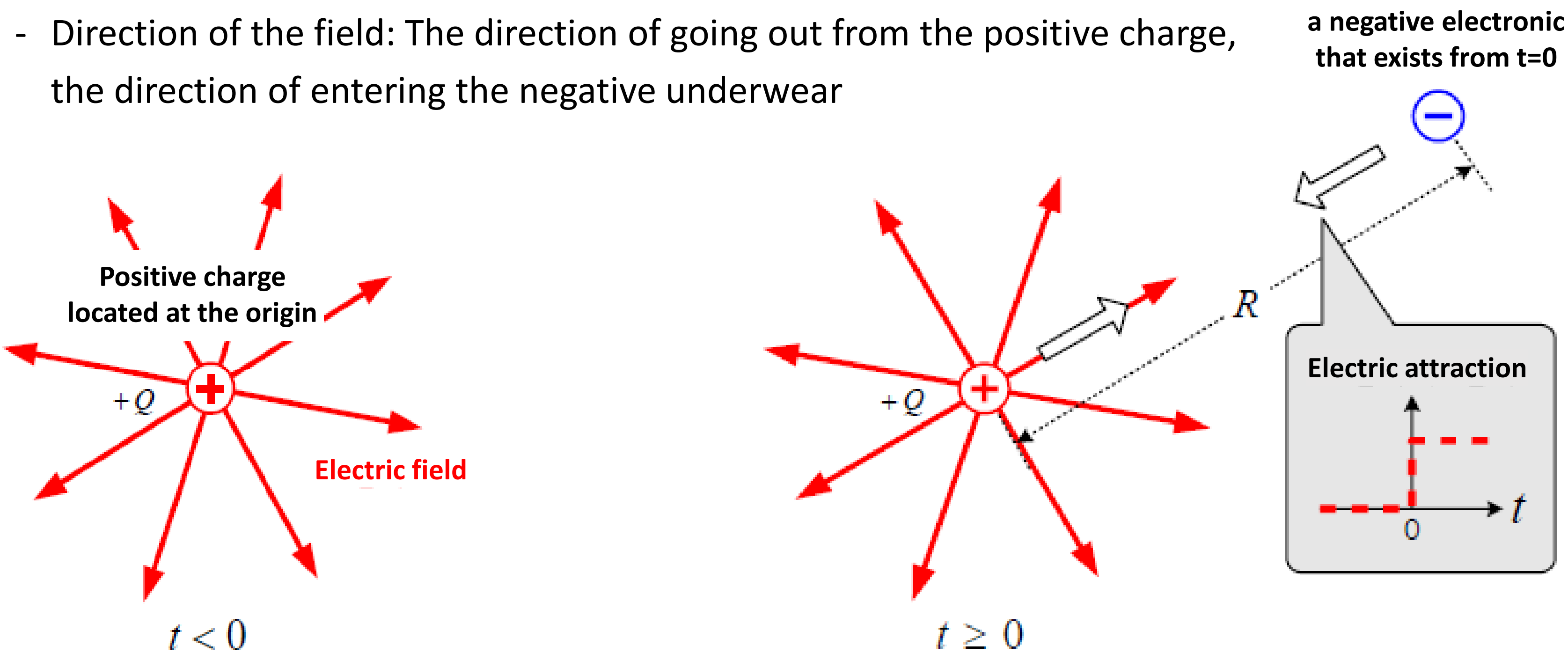


Fig. 1-12 Division of atomic nucleus by neutrons

1-4 Electricity and electricity

- **Electric Field**: A potential ability to immediately generate electrical force if only the unit charge is added
  - Size of the field: inversely proportional to the size of the charge
  - Direction of the field: The direction of going out from the positive charge, the direction of entering the negative underwear



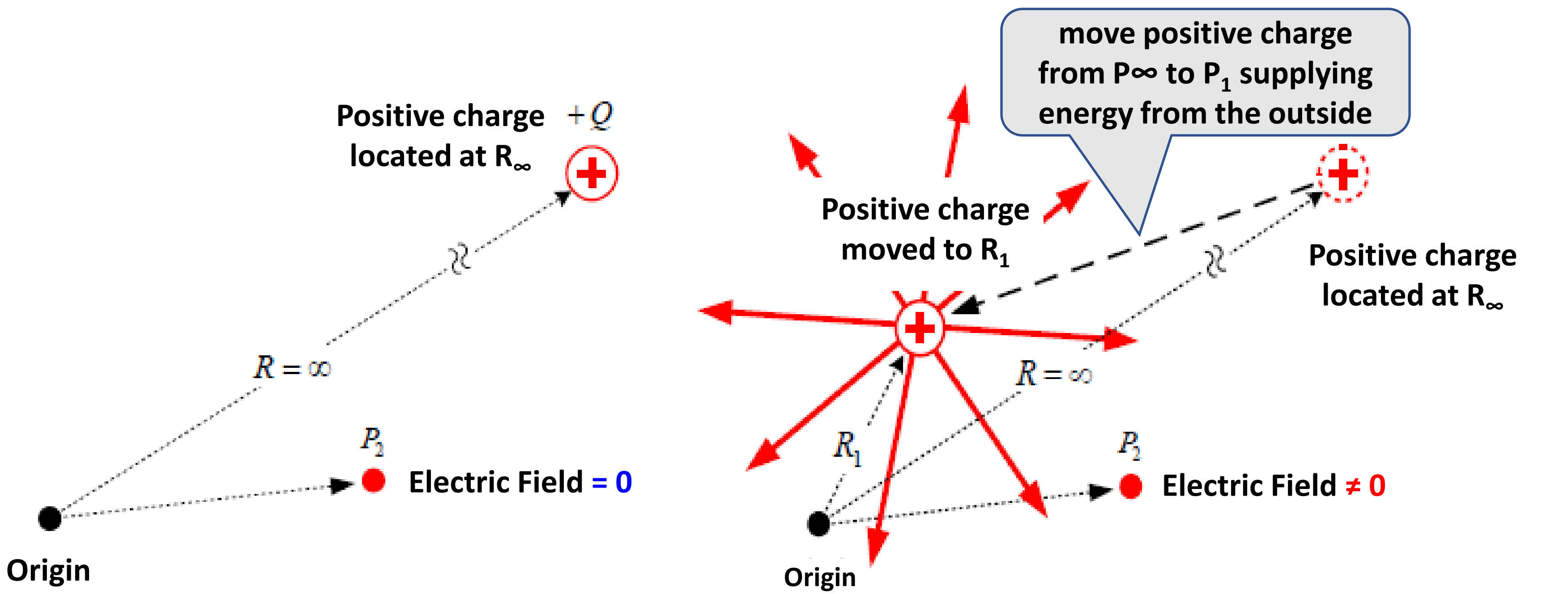
(a) Charge Q present at time t < 0
(electrical power = 0)

(b) Add a unit charge in the distance R point at t = 0
(t> 0 to electricity ≠ 0)

Fig. 1.13 Response time of the electrical force applied to a charge

1-4 Electricity and electricity

- Field distribution in space: electrical energy is distributed in the relevant space
  (The same amount of the energy consumed when locating a charge that creates this field)



(a) When the charge is in an infinitely distant point p_∞ (b) When moved along the dotted from p_∞ to a point P_1

Energy supplied from outside =
Electrical energy stored in space influenced by the charge

Fig. 1.14 Field distribution in space

1-4 Electricity and electricity

- Definition of Electric Field

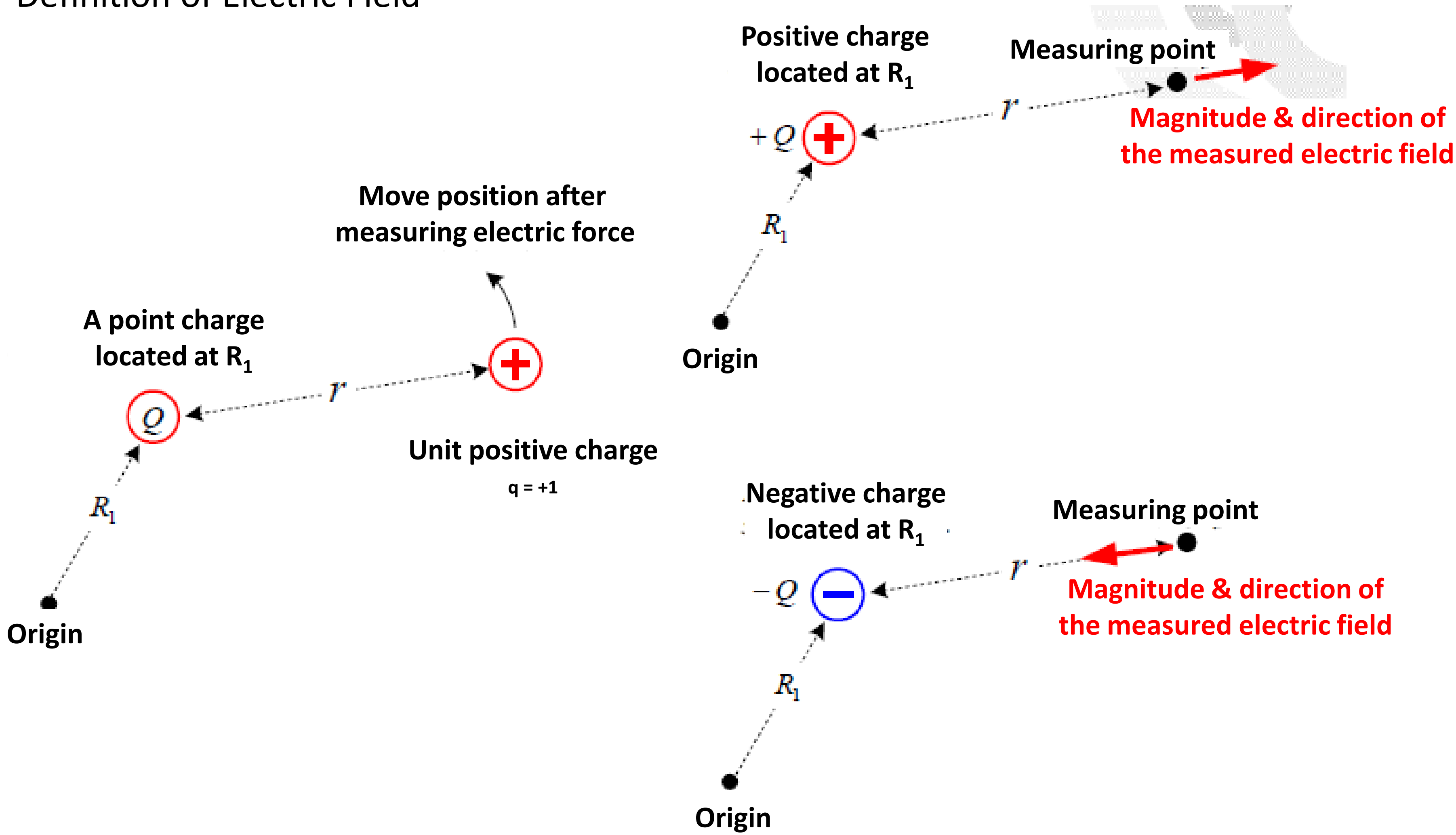
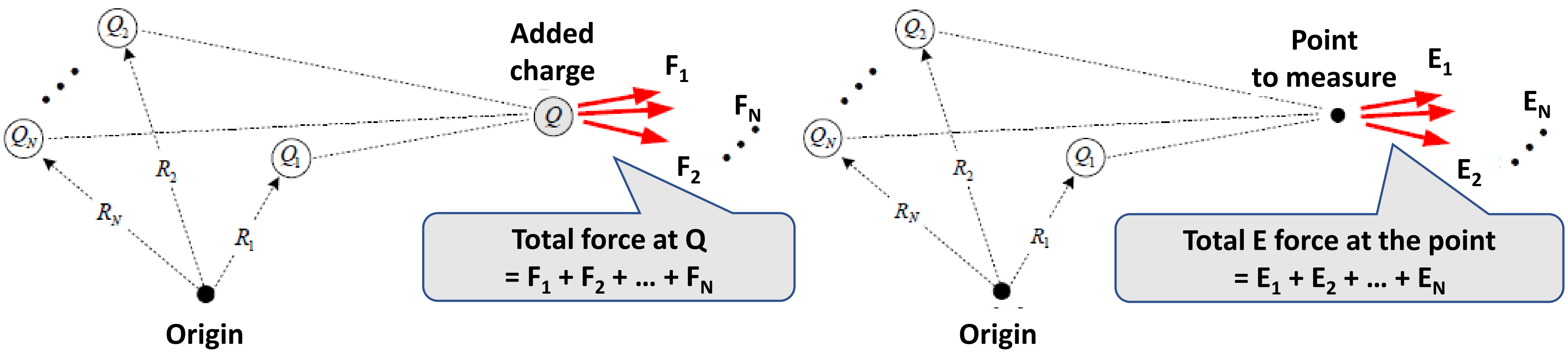


Fig. 1.15 Direction of electric field

1-4 Electricity and electricity

- Superposition of Electric Field



(a) Supposition of force **(b) Supposition of electric field**

Fig. 1.16 Principle of Superposition

1-4 Magnet and Electron Spin

➢ Superposition of Electric Field

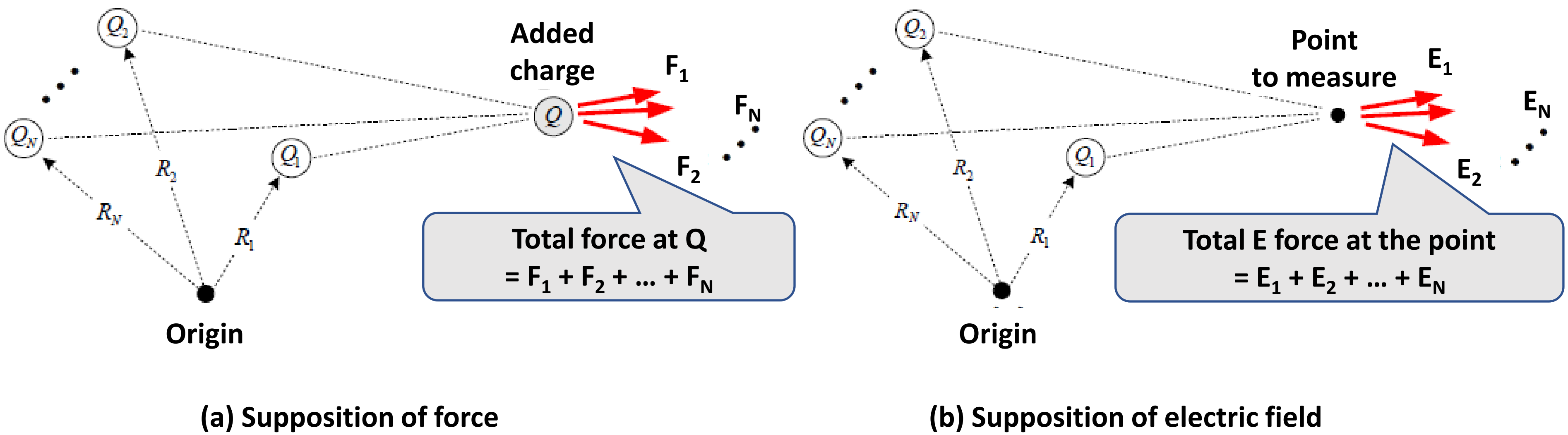


Fig. 1.16 Principle of Superposition

1-5 Magnet and Electron Spin

<Axiom 4> In a magnet, the N and S poles always exist together
<Axiom 5> Repulsive force between the same poles, Attractive force acts among different poles

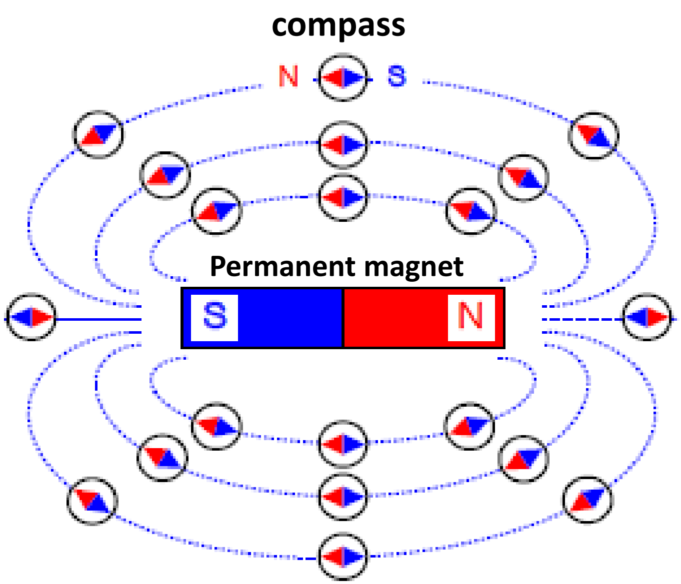


Fig. 1.17 Magnetic field due to a magnet

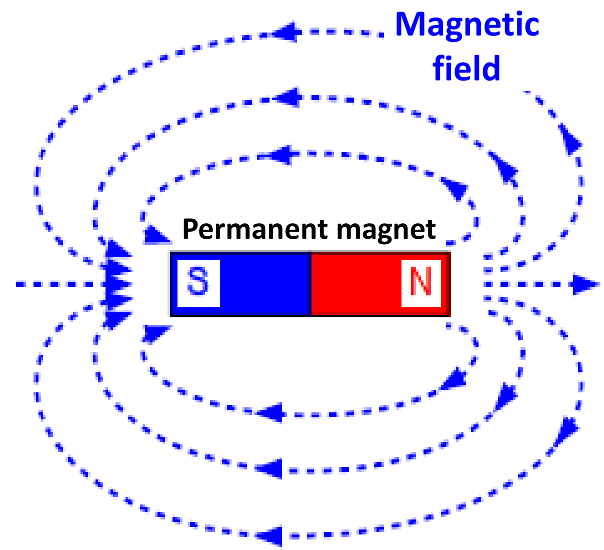


Fig. 1.18 Direction of the magnetic field

- Direction of magnetic field: **exits from the N pole** of the magnet and **enters the S pole**
- Conditions to have the properties of a magnet
  - Presence of incomplete orbits with only (+) spin
  - (+) spindles in an atom are aligned in the same direction
  - All (+) spins in adjacent atoms are aligned in the same direction

1-5 Magnet and Electron Spin

✓ Characteristics of magnets

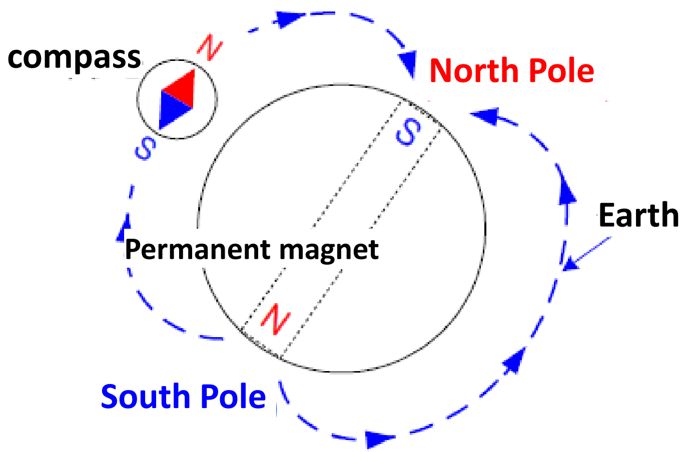


Fig. 1. 19 Distribution of Earth's Magnetism

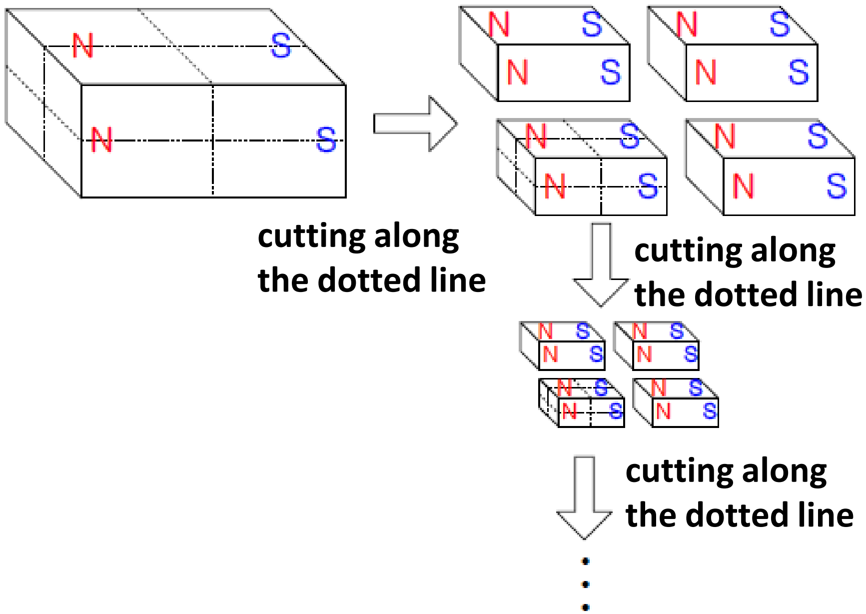


Fig. 1. 20 Even if a magnet is divided into small pieces, each piece becomes a mini-magnet

1-5 Magnet and Electron Spin

✓ Electron Orbitals

Table 1.2 Orbital diagram of electrons in an atom

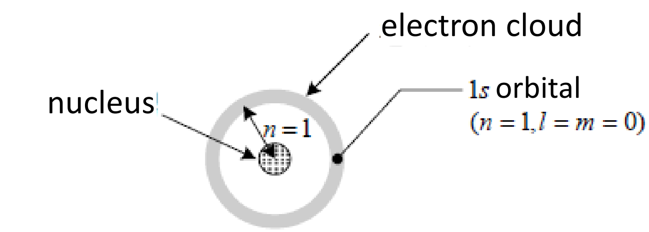
n	l				m						
	0	1	2	3	−3	−2	−1	0	1	2	3
1	1s							*			
2	2s							*			
		2p					*	*	*		
3	3s							*			
		3p					*	*	*		
			3d			*	*	*	*	*	
4	4s							*			
		4p					*	*	*		
			4d			*	*	*	*	*	
				4f	*	*	*	*	*	*	*

Table 1.3 Orbital diagram of electrons in an atom Priority of the orbital in which electrons up to atomic number 30 enter

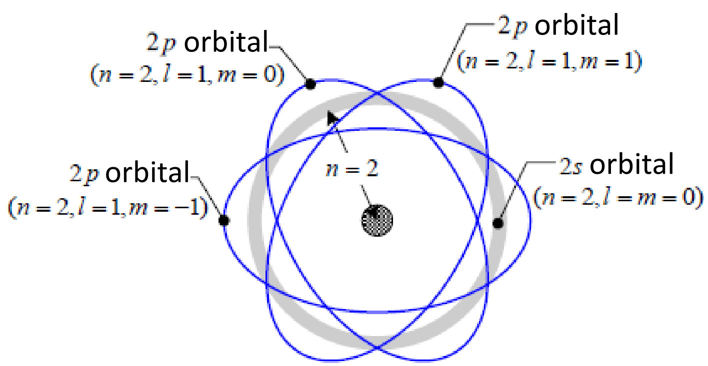
Orbit 1s	1, 2				
Orbit 2s	3, 4				
Orbit 2p	5, 8	6, 9	7, 10		
Orbit 3s	11, 12				
Orbit 3p	13, 16	14, 17	15, 18		
Orbit 3d	21, 26	22, 27	23, 28	24, 29	25, 30
Orbit 4s	19, 20				

1-5 Magnet and Electron Spin

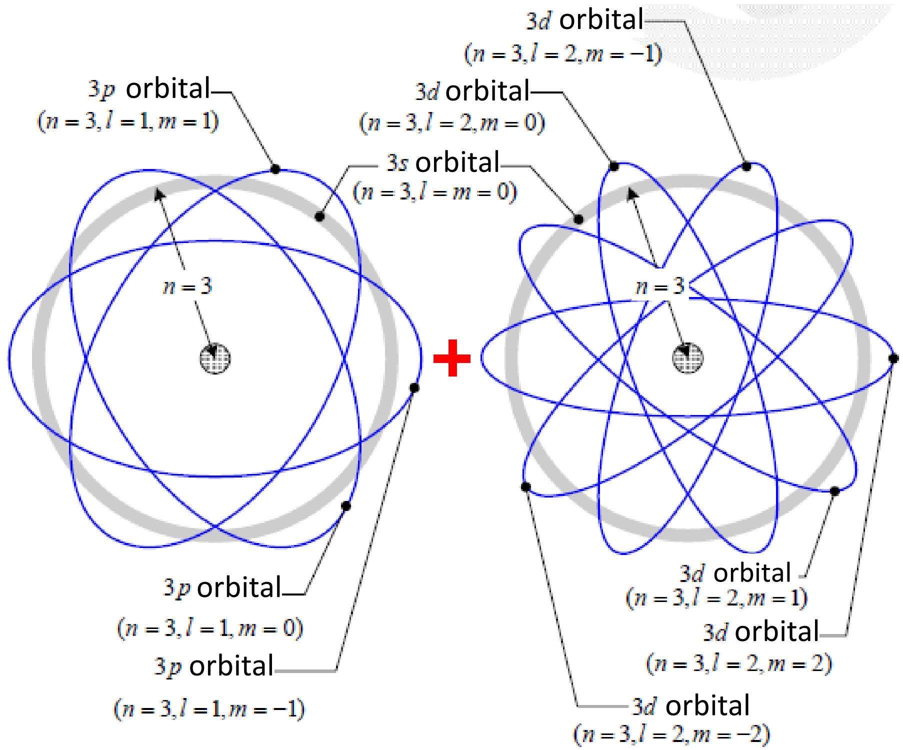
✓ Electron Orbitals



(a) when n = 1



(b) when n = 2



(c) when n = 3

Fig. 1. 20 Electron orbits in an atom

1-5 Magnet and Electron Spin

✓ Electron arrangement of an iron atom

Table 1.4 Orbital diagram of 26 electrons in an iron atom

n	l				m						
	0	1	2	3	−3	−2	−1	0	1	2	3
1	1s							↑ ↓			
2	2s							↑ ↓			
		2p					↑ ↓	↑ ↓	↑ ↓		
3	3s							↑ ↓			
		3p					↑ ↓	↑ ↓	↑ ↓		
			3d			↑	↑	↑ ↓	↑	↑	
4	4s							↑ ↓			
		4p									
			4d								
				4f							

* In the table, ↑ means (+) electron spin or spin up, and means (-) electron spin or spin down.

1-6 Current and Magnetic Field

<Axiom 6> When a DC current flows, the magnetic field is distributed around it according to the right-hand screw rule.

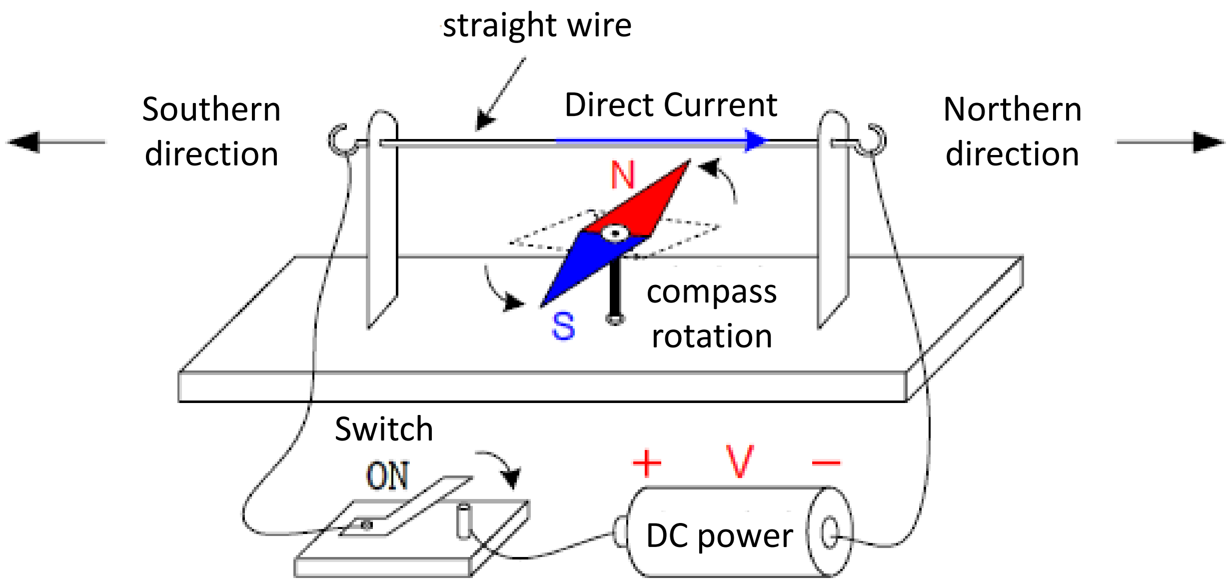
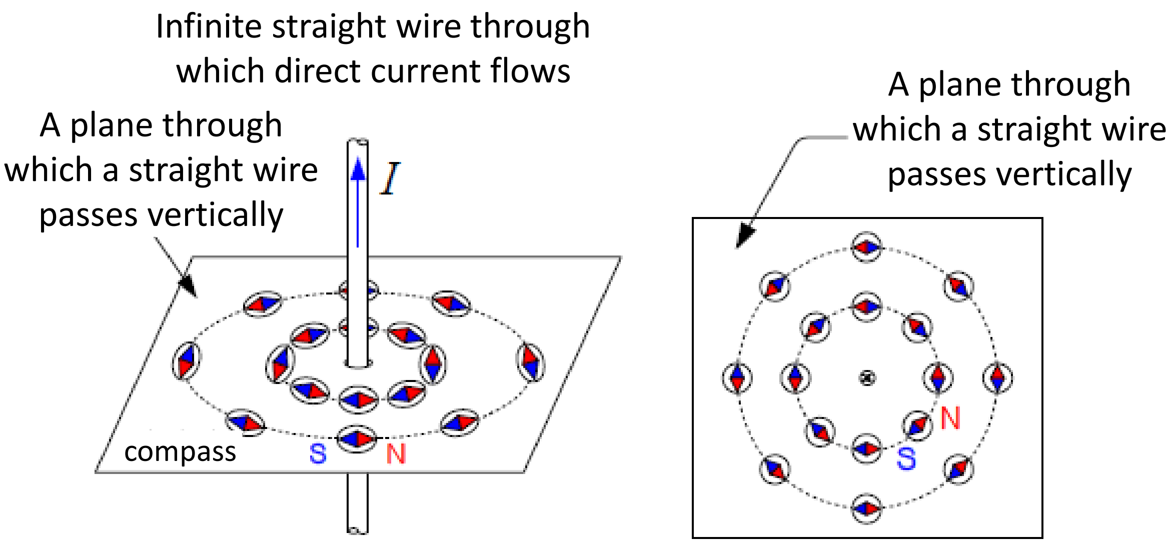


Fig. 1. 22 Oersted's experiment in 1820

1-6 Current and Magnetic Field

✓ Ampere's Law



(a) side view

(b) cross section

Fig 1-23 Compass arrangement near direct current flowing along an infinitely long straight

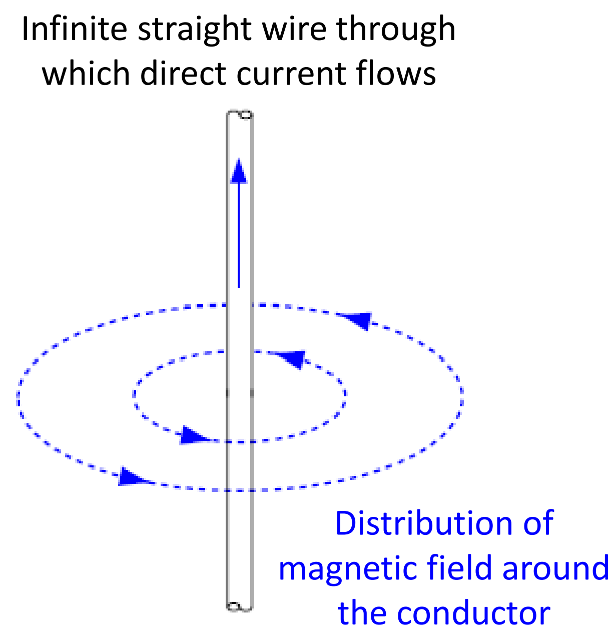
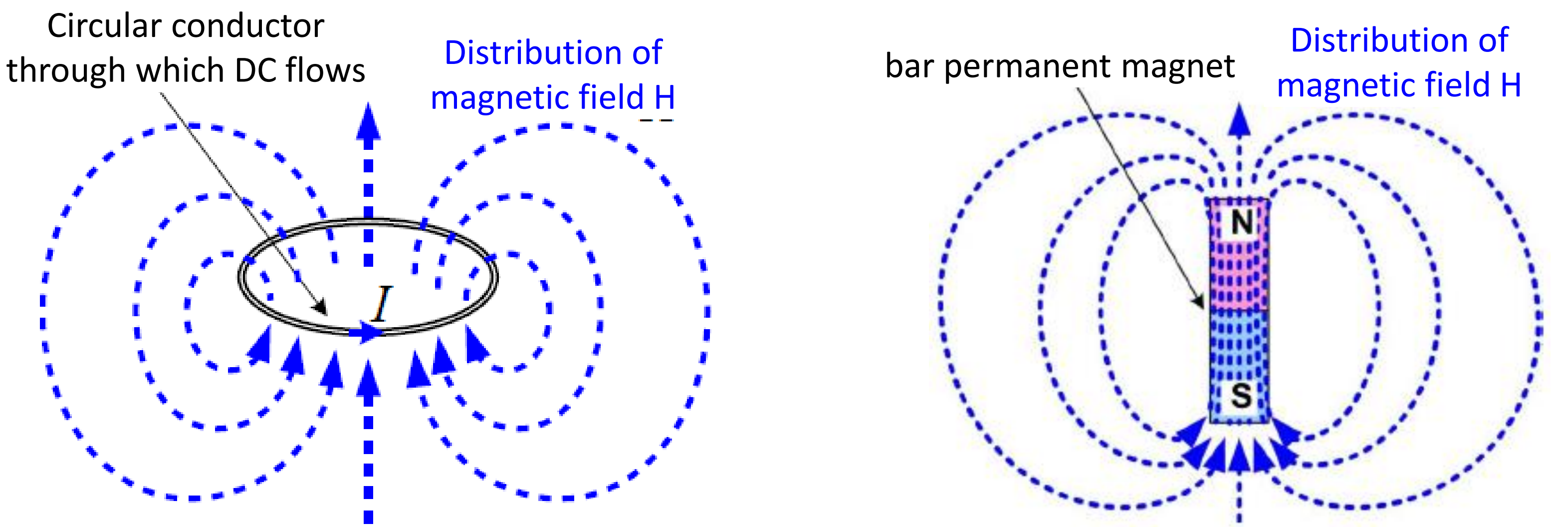


Fig. 1.24 Ampere's right-hand screw rule

1-6 Current and Magnetic Field

✓ Equivalent between current flowing in a circular conductor and a bar magnet



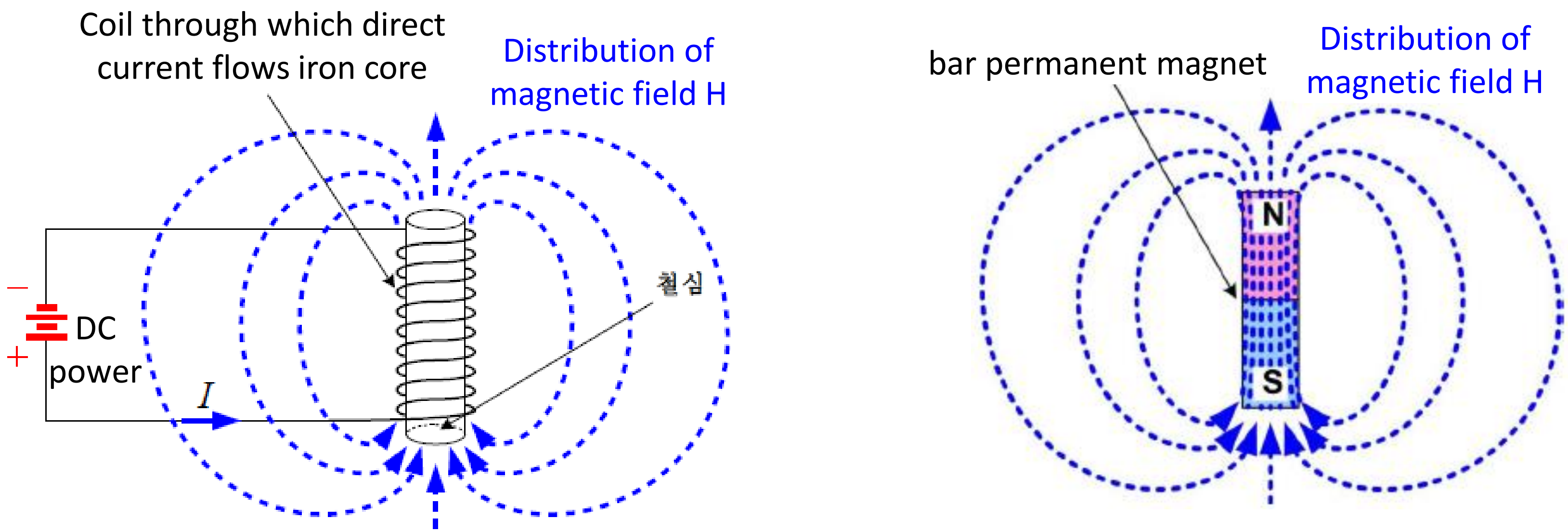
(a) Magnetic field due to DC current flowing along the circular conductor

(b) Magnetic field by permanent bar magnet

Fig. 1.25 Equivalence of DC Current and Permanent Magnet

1-6 Current and Magnetic Field

✓ Equivalent between current flowing in a circular conductor and a bar magnet



(a) An electromagnet made of a coil through which direct current flows;

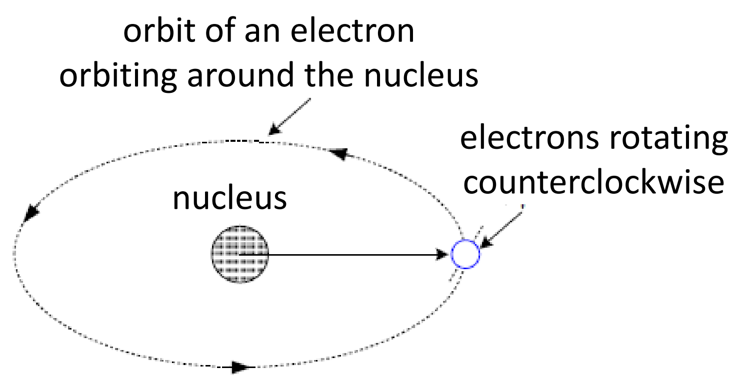
(b) bar permanent magnet

Fig. 1-26 Equivalence of coil and magnet through which DC current flows

1-6 Current and Magnetic Field

✓ **Source of magnetic field :**

Electron spin = DC current flowing along a circular loop = Permanent bar magnet



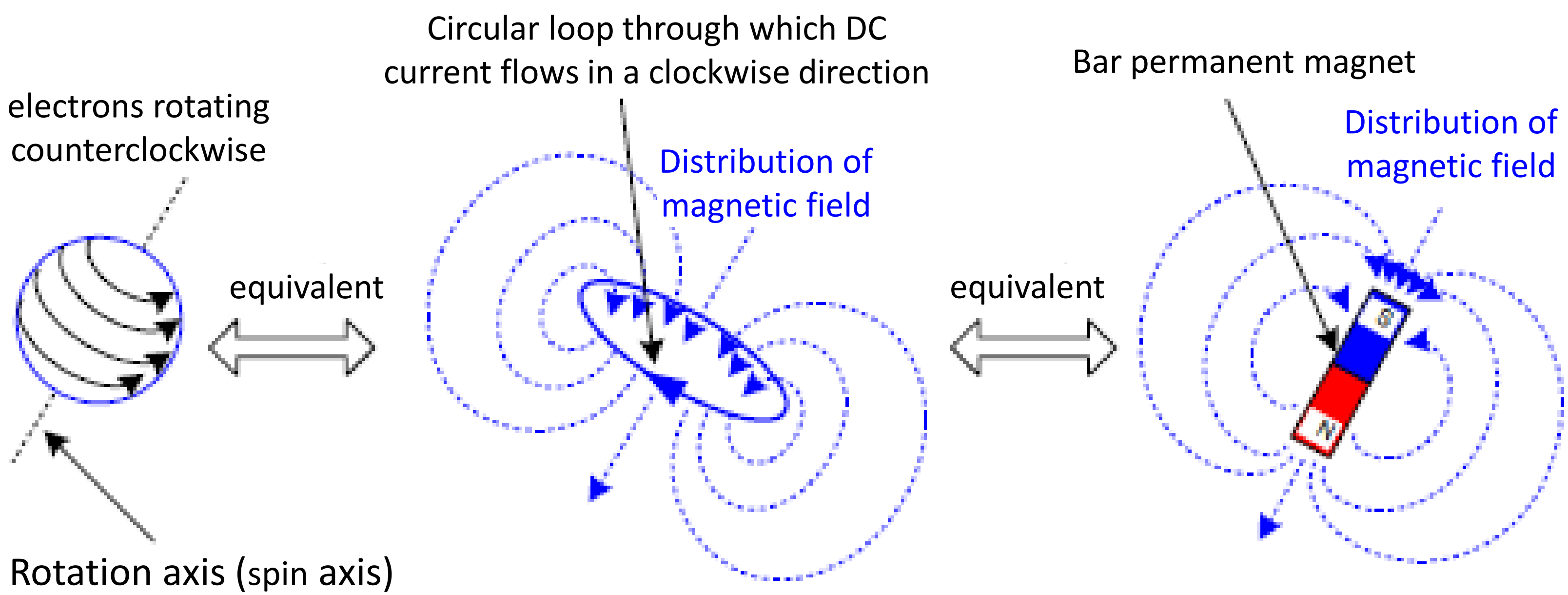


Fig. 1-27 Equivalent of Electron Spin and Magnet

1-6 Current and Magnetic Field

✓ **Strength of magnetic field** : the faster rotation, the stronger the magnetic field

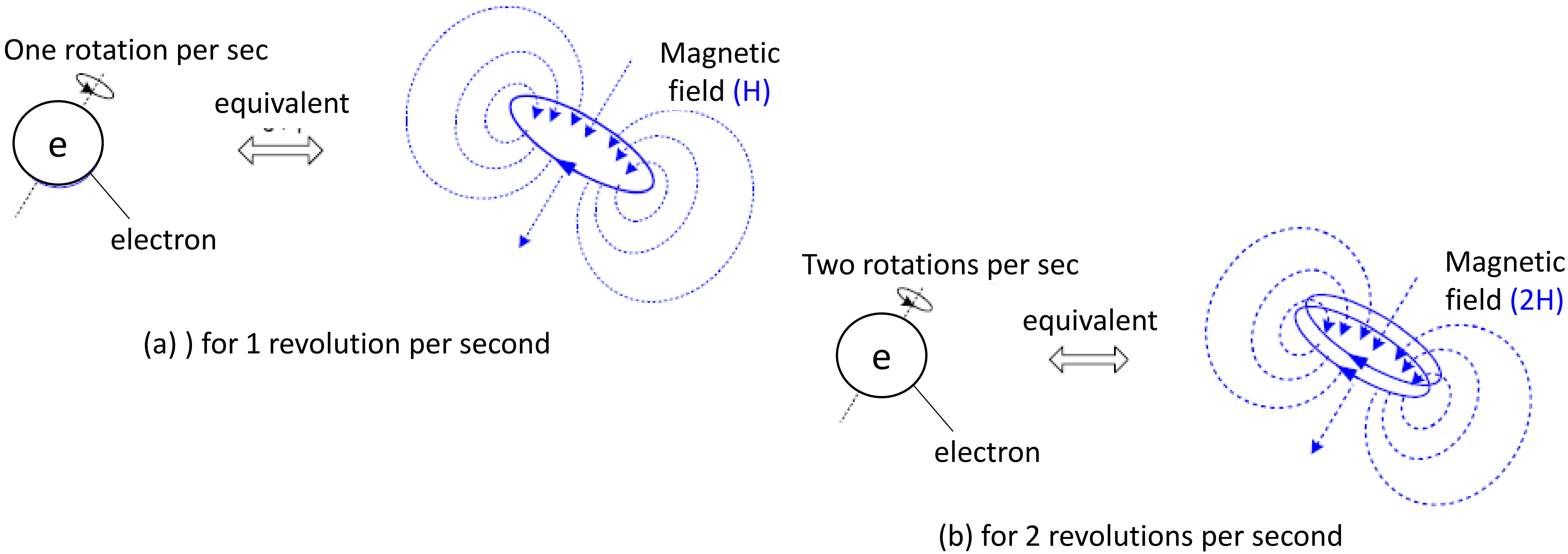


Fig. 1-28 Rotational speed of electron spin and strength of magnetic field

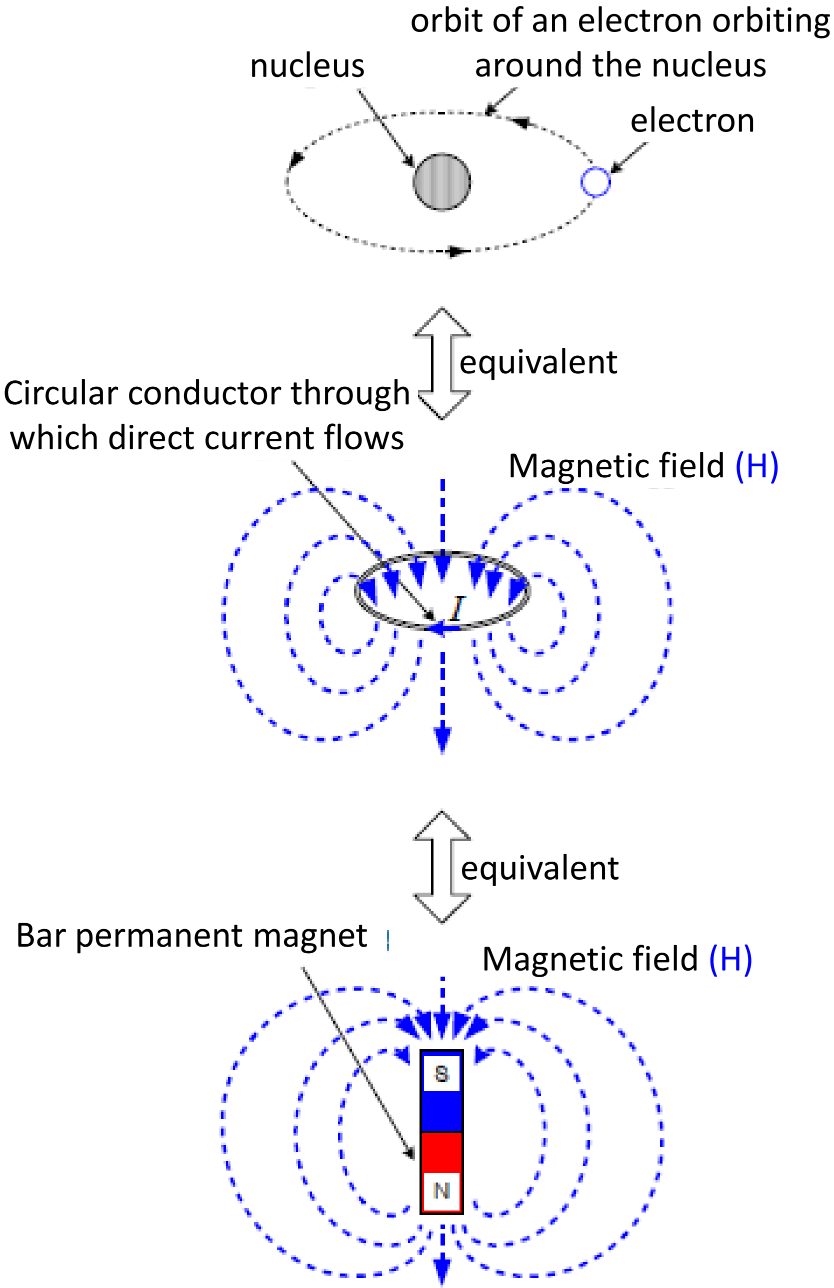


Fig. 1-29 Equivalence of electrons and magnets orbiting around the nucleus of an atom

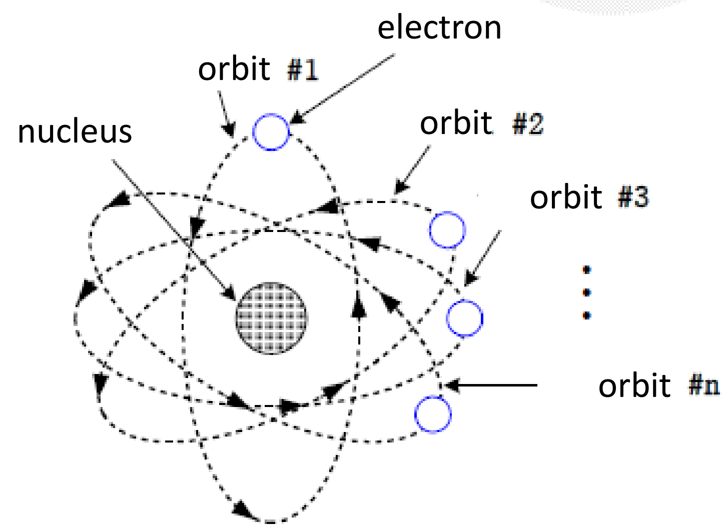


Fig. 1-30 Orbits of electrons orbiting around the nucleus of an atom

1-6 Current and Magnetic Field

✓ Electromagnet

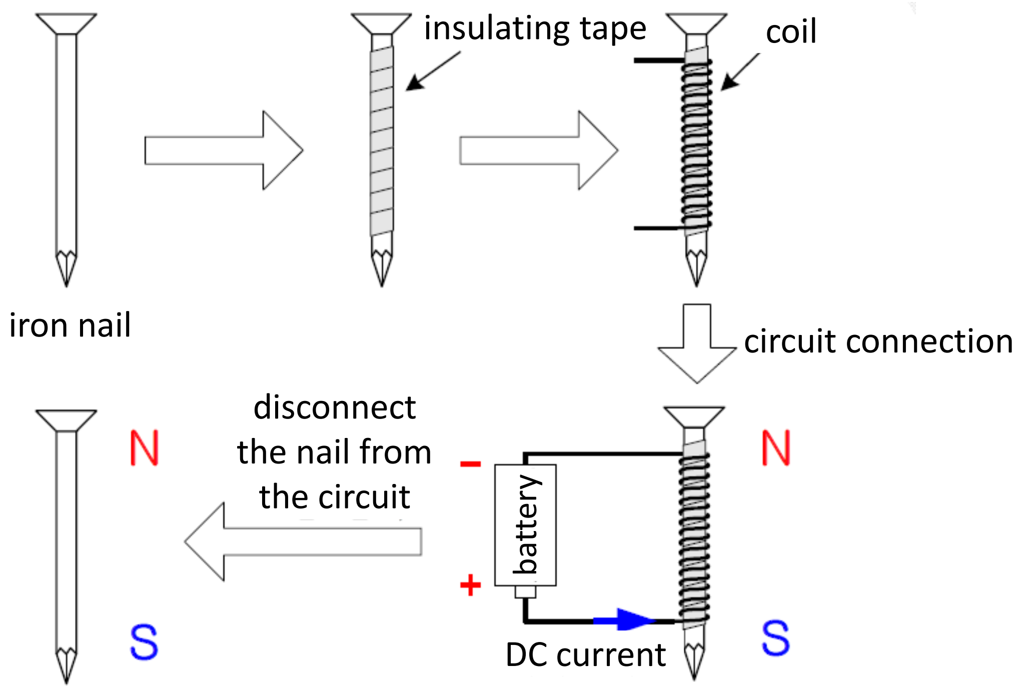
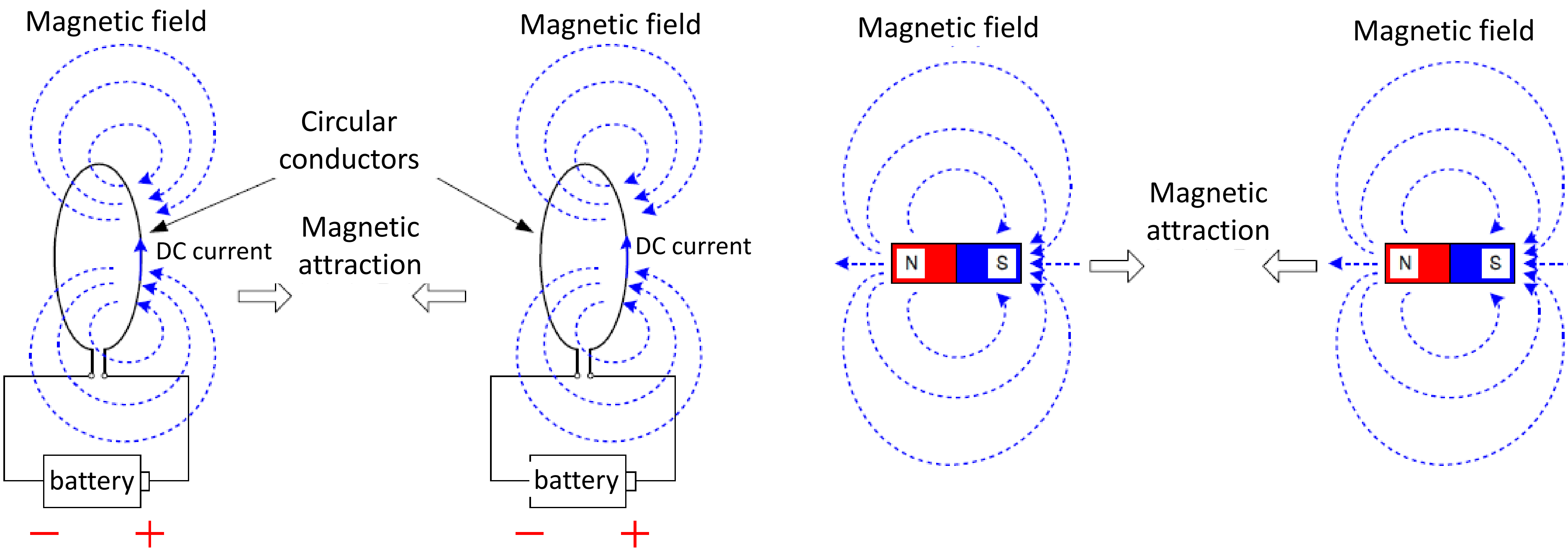


Fig. 1-31 The process of making a nail into a magnet

1-6 Current and Magnetic Field

<Axiom 7> Between two parallel conductors,
when current flows in the same direction, they attract each other, and
when current flows in opposite directions, magnetic force repels each other



(a) Magnetic force between two circular conductors through which direct current flows

(b) Magnetic force between two adjacent magnets

Fig. 1-32 Current and Magnetic Force

1-7 Independence: electric field vs magnetic field

<Axiom 8> The law of conservation of energy is always established in the natural world

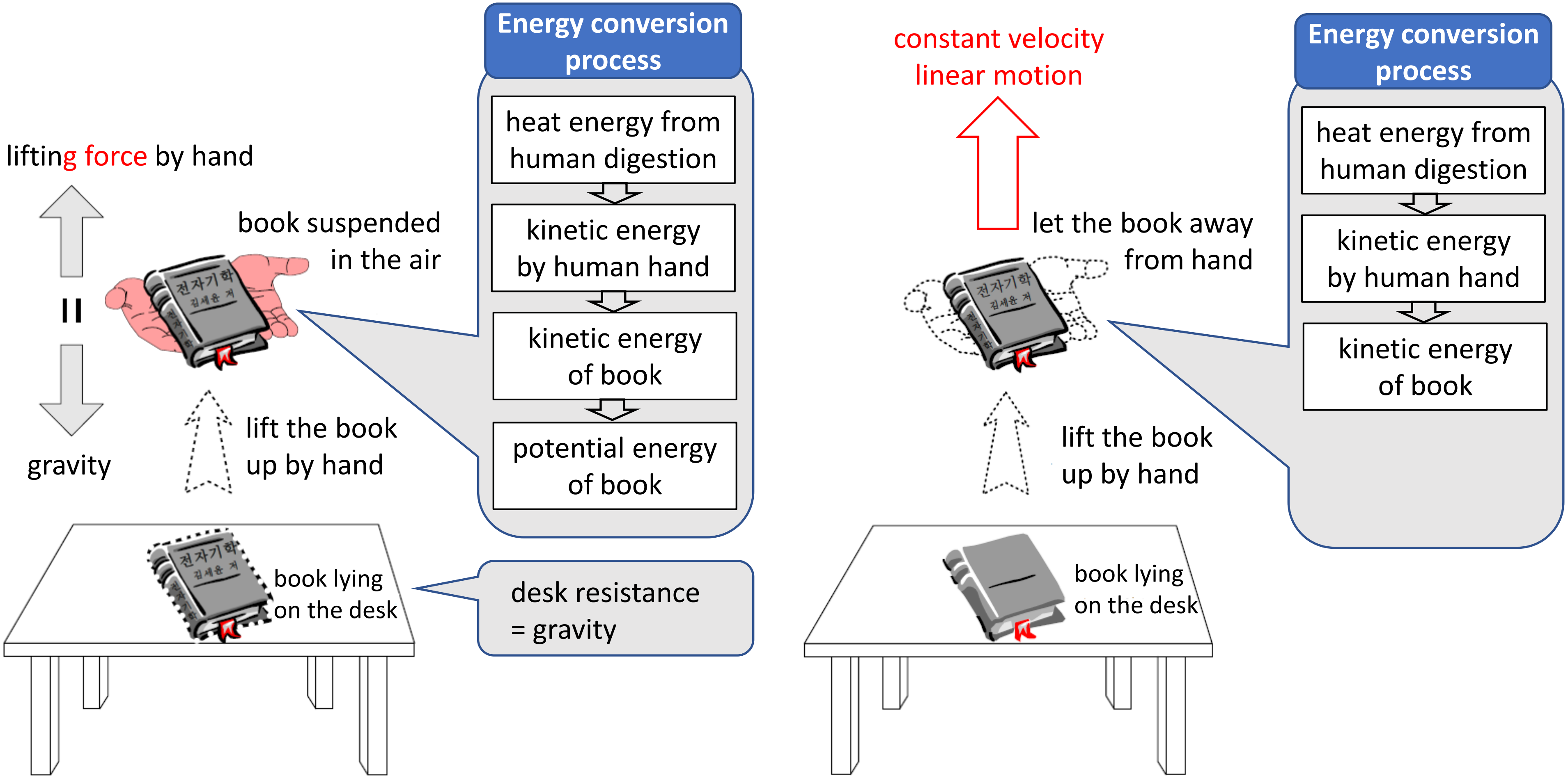
Table 1-32 1-5 Basic Differences Between Electricity and Magnetism

	Electric	Magnetic
source	charge	current
polarity	+ / -	N / S
force	E force	M force
field	Electric field	Magnetic field
field direction	Positive charge → negative charge	S --> N (magnet inside magnet) N → S (outside the magnet)

- When there is no change in electromagnetic state
- - When the electric charge is stopped
- - current (by constant motion of electric charge) => DC current

1-7 Independence: electric field vs magnetic field

✓ **The law of conservation of energy**



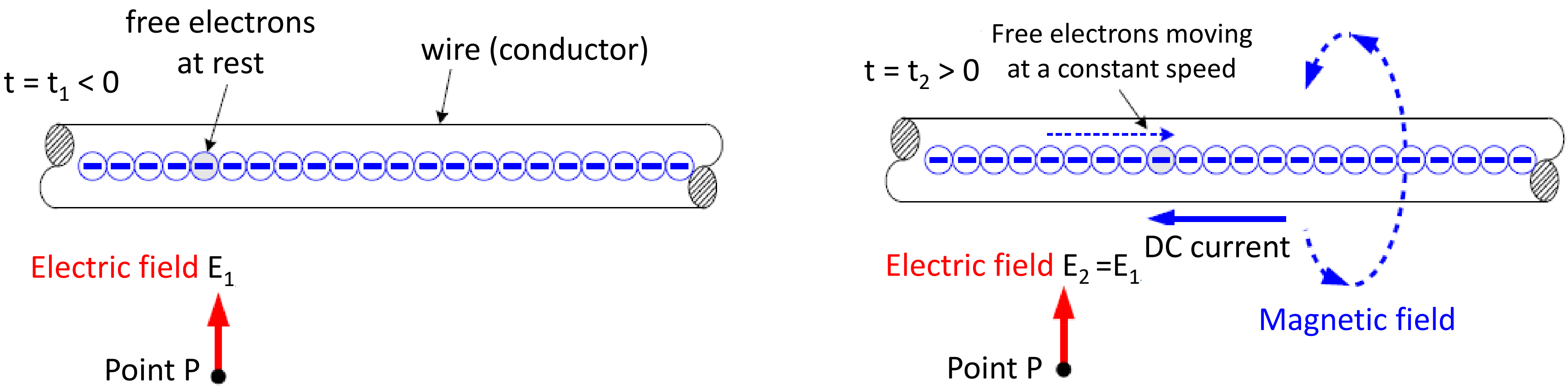
(a) In the presence of gravity (b) in the absence of gravity

Fig. 1-33 Motion of an object

1-7 Independence: electric field vs magnetic field

- From the point of view of electric charge, current = movement of electric charge
- (magnetic phenomena caused by electric current cannot be interpreted only by electric field: that is, introduction of magnetic field is required)
  ==> electric field and magnetic field are separate physical quantities:
  electric and magnetic forces are also different forces

- only electric field is distributed around when electrons stand still
- when electrons move: DC current flows = distribution of electric and magnetic fields around



(a) When a uniform negative charge distribution stands still

(b) when a uniform negative charge distribution moves at a constant speed

Fig. 1.34 Electric field and magnetic field distributed around by DC current

1-7 Independence: electric field vs magnetic field

✓ **Electrical circuit Perspective**

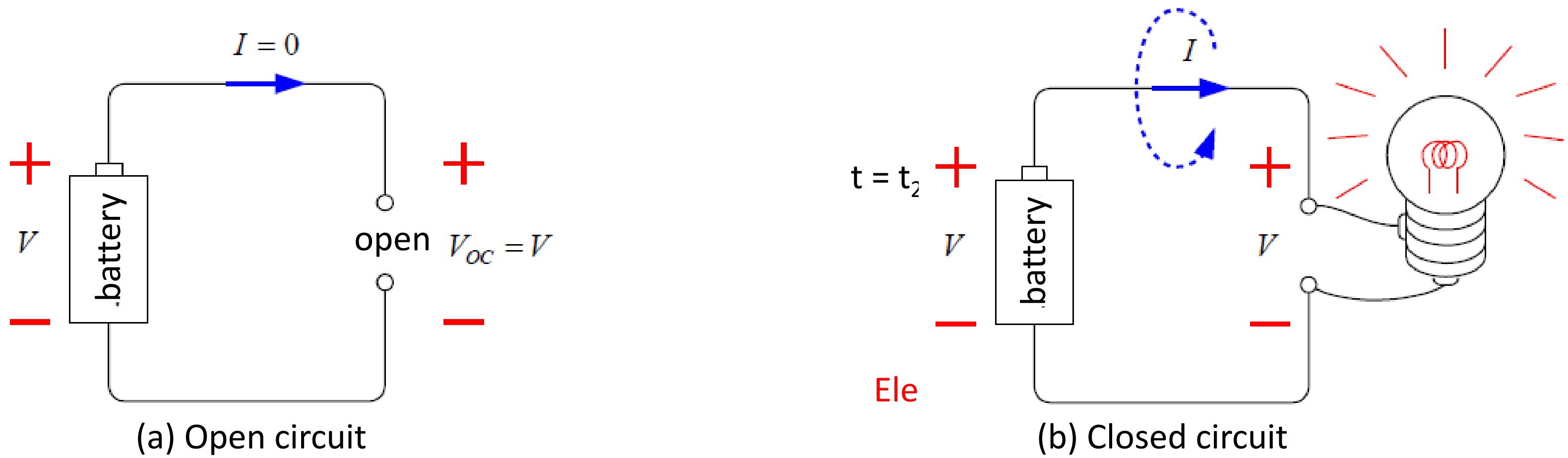
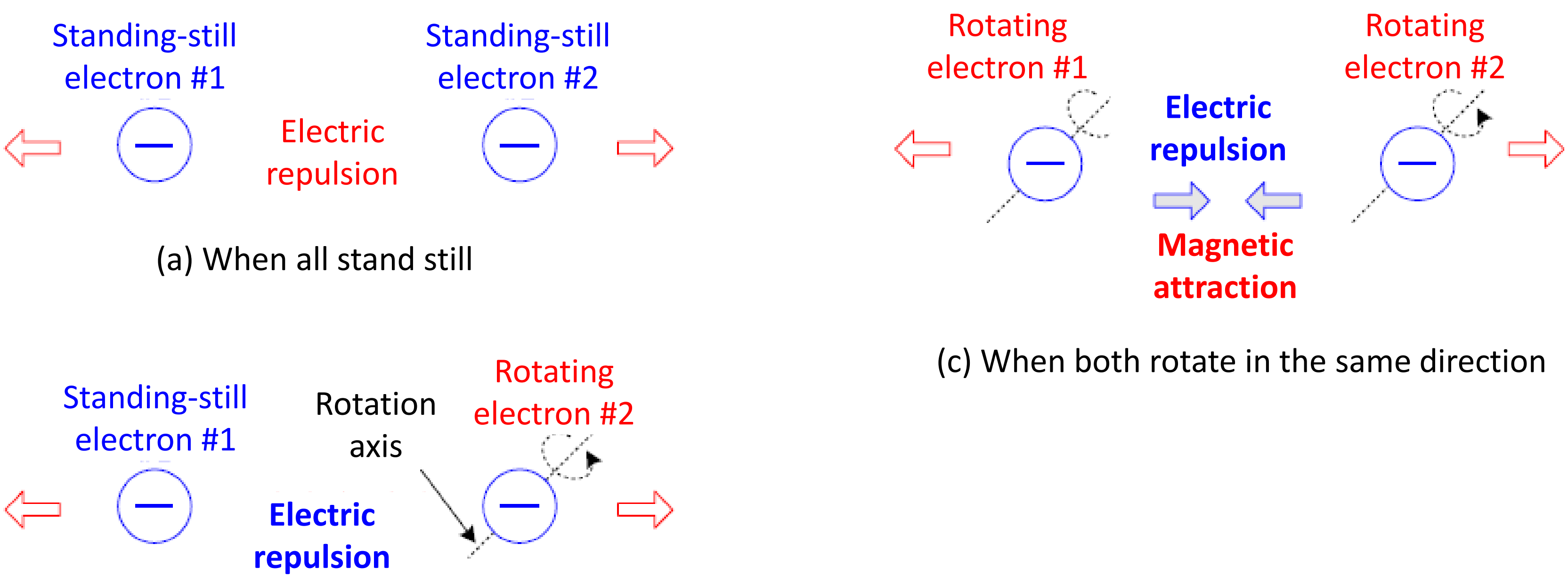


Fig. 1.35 Voltage and current in electrical circuits

1-7 Independence: electric field vs magnetic field

✓ Electric Force vs Magnetic Force



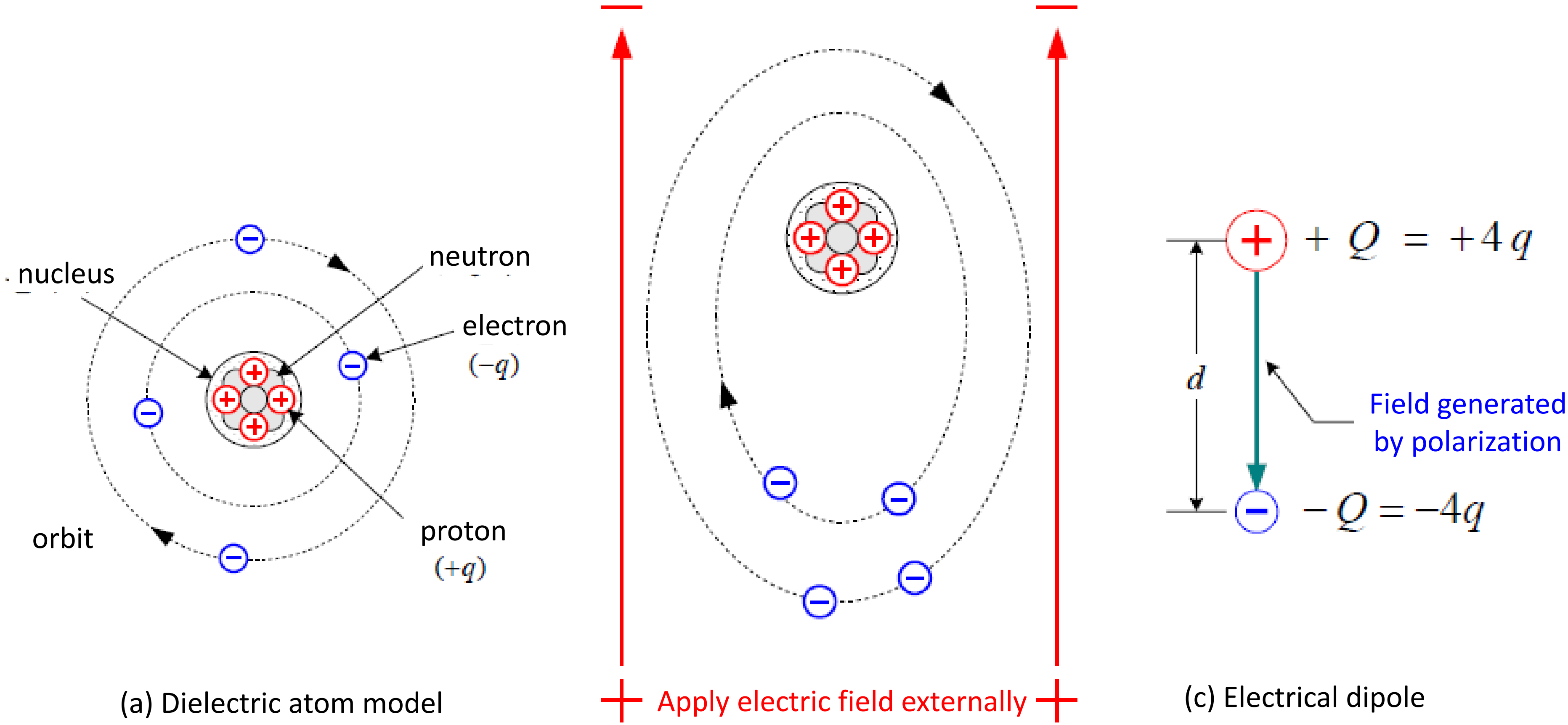
(a) When all stand still

(b) When one electron stands still while the other rotates

(c) When both rotate in the same direction

Fig. 1.34 The electrical and magnetic forces acting between the two electrons

1-8 Media variables: permittivity, conductivity, permeability
(dielectric constant)



(a) Dielectric atom model when the electric field = 0

(b) Dielectric atom model when the electric field ≠ 0

(c) Electrical dipole

Fig. 1.37 Reaction of the dielectric to the electric field

1-8 Media variables: permittivity, conductivity, permeability

✓ **Permittivity : Ɛ**

- Represented by the Greek letter **Ɛ** and read as epsilon

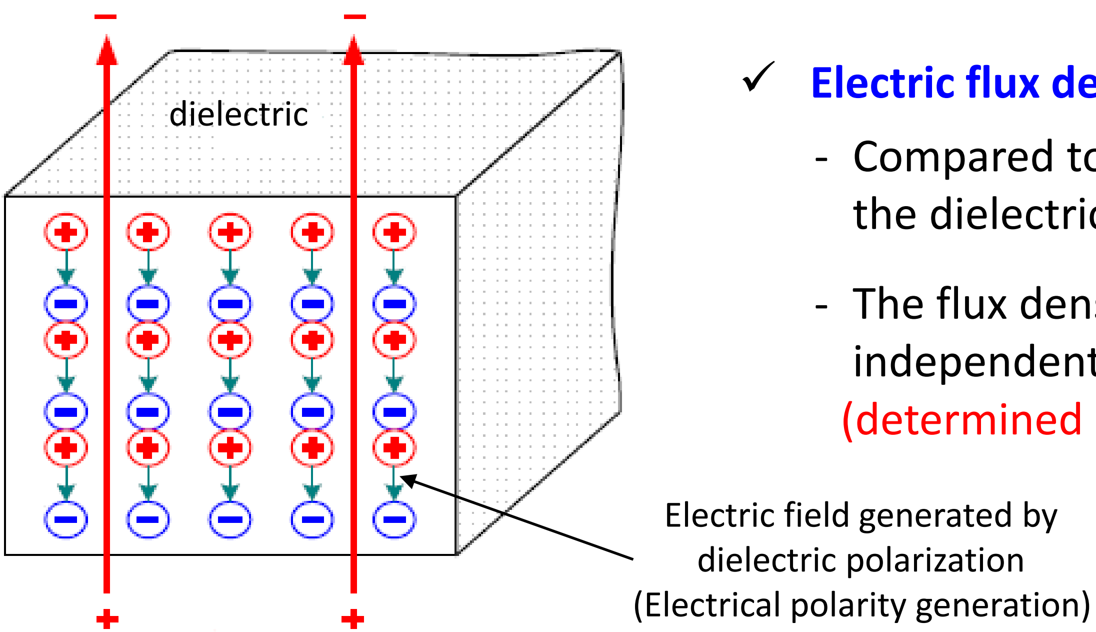


Fig. 1.38 Total field in the dielectric system

✓ **Electric flux density: D = Ɛ E**

- Compared to free space, the electric field in the dielectric field decreases in size
- The flux density D in the medium is independent of the medium (determined only by the charge distribution)

Total field inside the dielectric field
= Applied field - Field generated by polarization

1-8 Media variables: permittivity, conductivity, permeability

✓ **conductivity : σ**

- Represented by the Greek letter **σ** and read as sigma

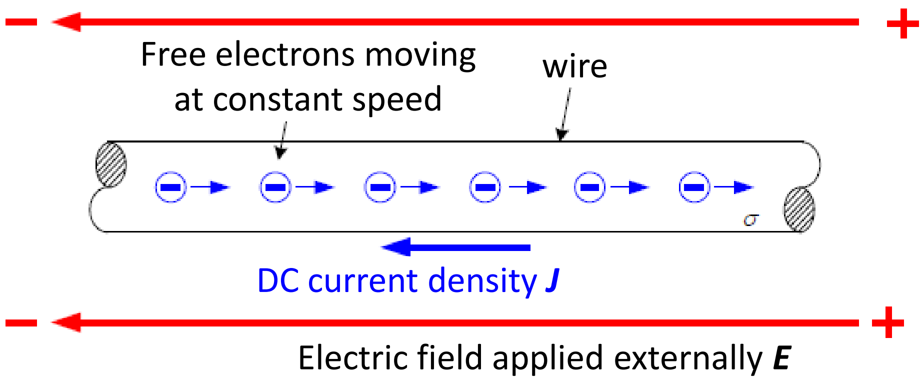


Fig. 1.39 The movement of free electrons in a conductor when an electric field is applied to the conductor from the outside.

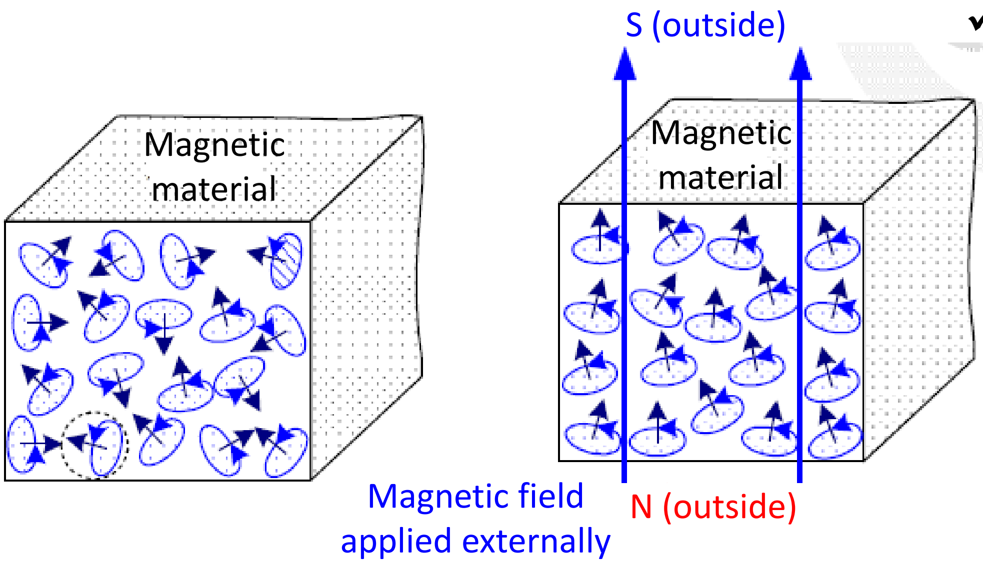
✓ **conduction current density : J = s E**

- Free electrons in a conductor increase the speed of movement in proportion to the electric field
- A medium that is well electrified when the conductivity is high
- In the absence of a medium, i.e. in a vacuum, of course, the conductivity is 0

1-8 Media variables: permittivity, conductivity, permeability

✓ **permeability : μ**

- Represented by the Greek letter **μ** and read as mu



(a) No magnetic field applied from the outside

(b) Magnetic field applied from the outside

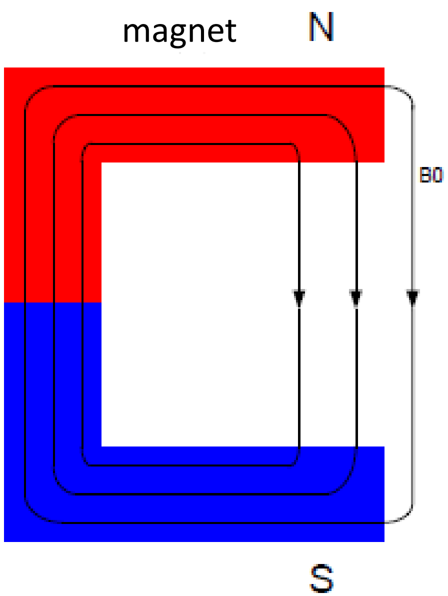
Fig. 1.40 Magnetic substance's Response to the Magnetic Field

✓ **Magnetic flux density: B = μH**

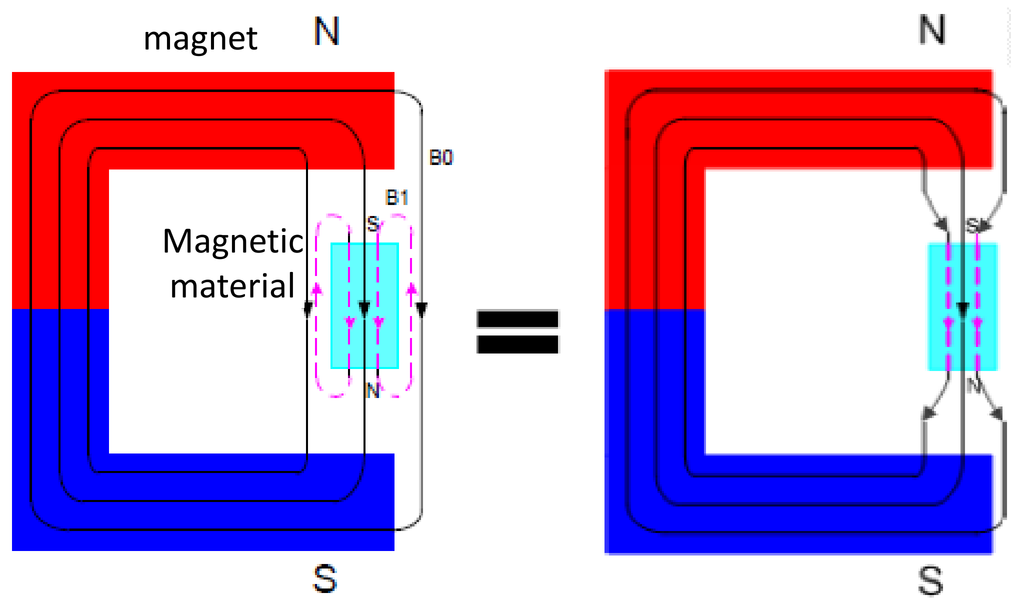
- The magnetic field is independent of the medium, but is determined by the current distribution
- Increased magnetic flux density within the magnetic material

1-8 Media variables: permittivity, conductivity, permeability

✓ **Magnetic flux density distribution inside and around the magnetic substance**

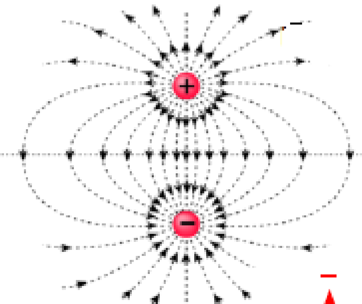


(a) When there is no magnetic material around a magnet



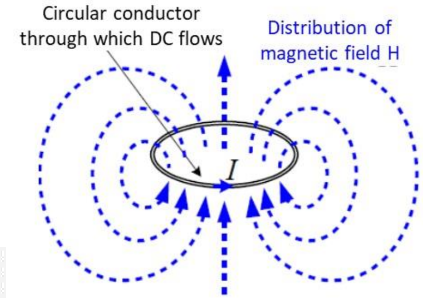
(b) If there is a magnetic material around a magnet

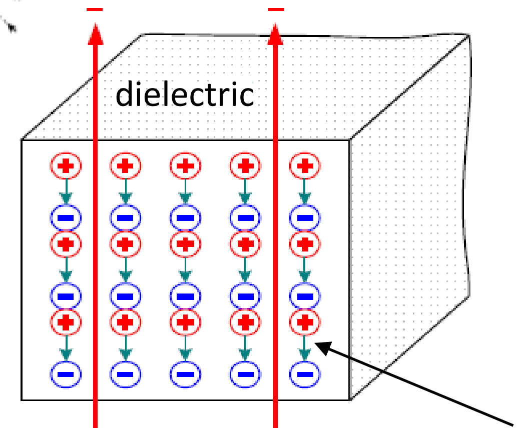
<The reaction of the magnetic body to the magnetic flux density>

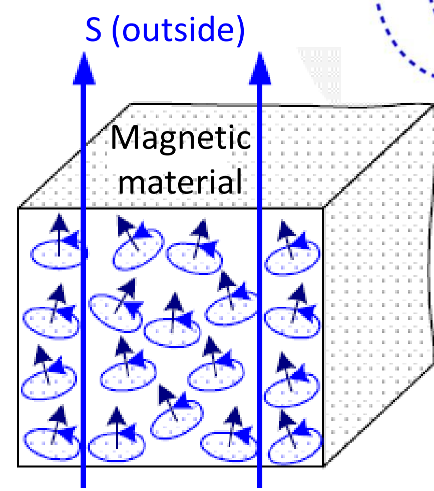


Electric dipole vs Magnetic dipole

Electric flux density vs Magnetic flux density







Total field inside the dielectric field
= Applied field - Field generated by polarization

✓ **Electric flux density: D = εE**

- Compared to free space, the electric field in the dielectric decreases in size
- The flux density D in the medium is independent of the medium (determined only by the charge distribution)

✓ **Magnetic flux density: B = μH**

- The magnetic field is independent of the medium, but is determined by the current distribution
- Increased magnetic flux density within the magnetic material

1-9 Electromagnetic (EM) wave

✓ **Time-varying electromagnetics**

- when the field and magnetic field change over time

✓ <Characteristics of EM Waves>

1. All electromagnetic waves move at a speed of 3×10^8 m/s in the air
2. All electromagnetic waves consist of **a time-varying electric field** and **a time-varying magnetic field** that are orthogonal to each other, and the propagation direction is perpendicular to both the electric and the magnetic fields.

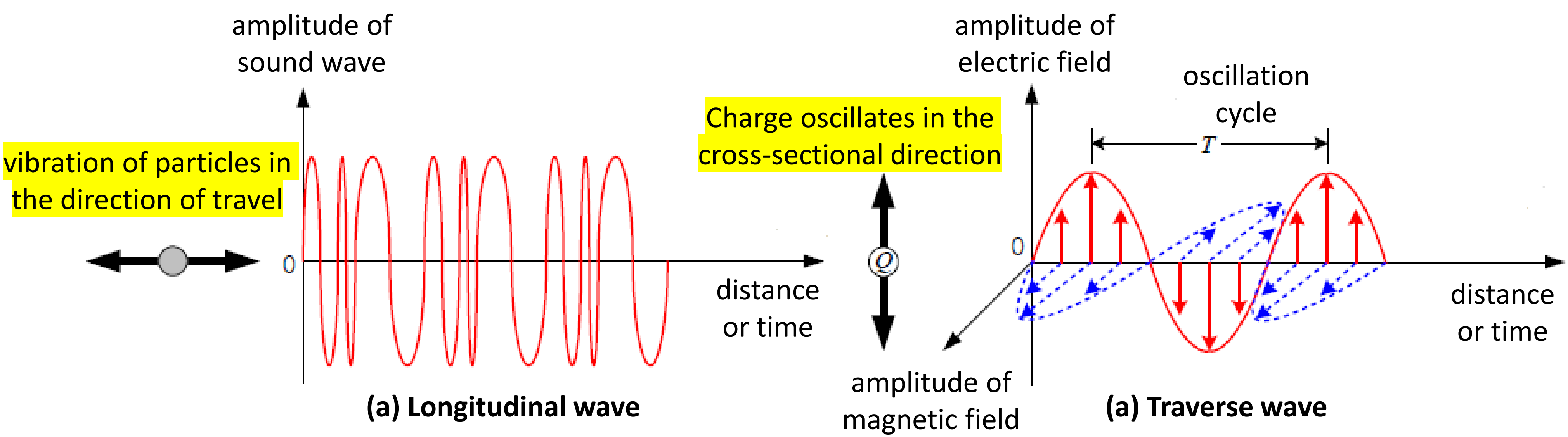


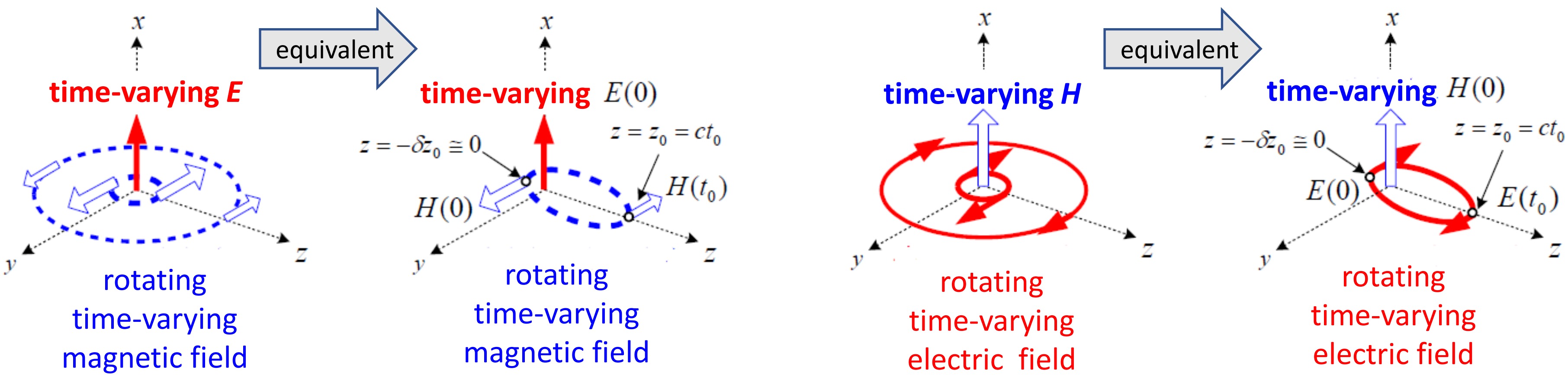
Fig. 1.42 Type of waves

1-9 Electromagnetic (EM) wave

✓ <Characteristics of EM Waves>

3. Time change in electric field at a point
   = magnetic field component rotating around that point (right-handed screw rule)

   Time change in magnetic field at a point
   = electric field component rotating around that point (left-handed screw rule)



(a) time-varying magnetic field caused by time-varying electric field

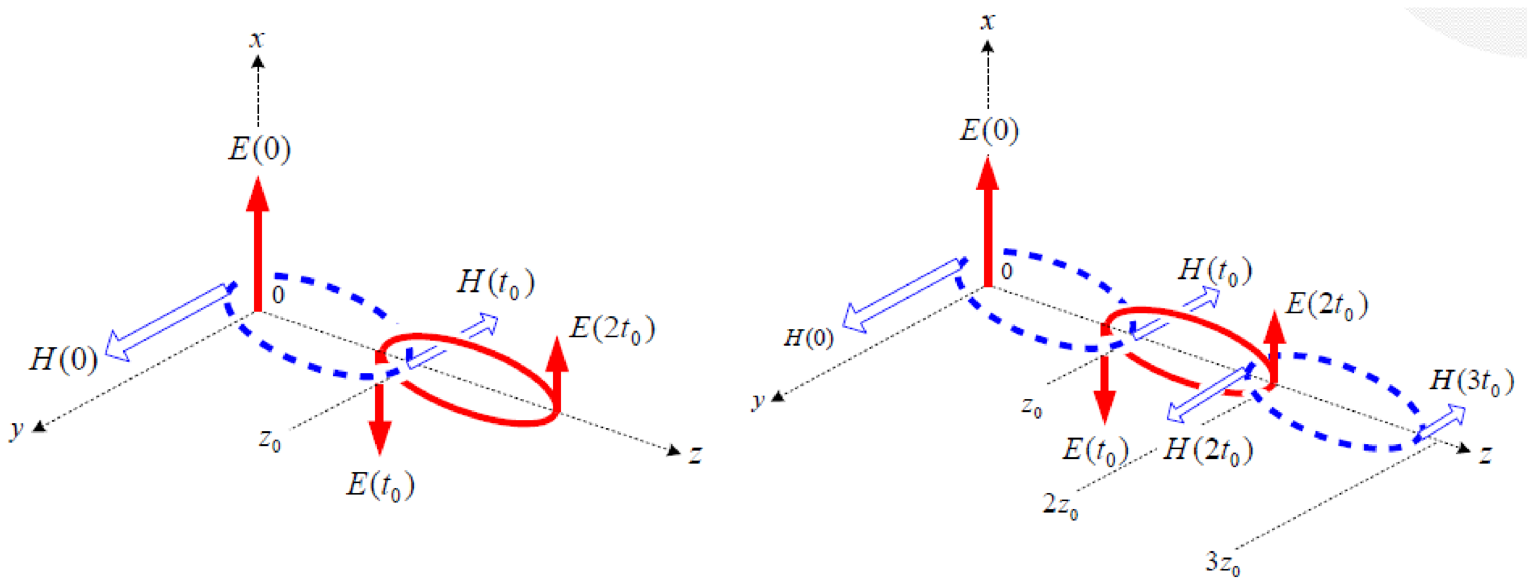
(b) time-varying electric field caused by time-varying magnetic field

Fig. 1.43 Interaction between electric field and magnetic field

1-9 Electromagnetic (EM) wave

✓ Spatial propagation of electromagnetic waves:

- Repeatedly applying <Characteristics 3 of electromagnetic waves> sequentially



(a)) Propagation in the +z-axis direction until time t = $2t_0$

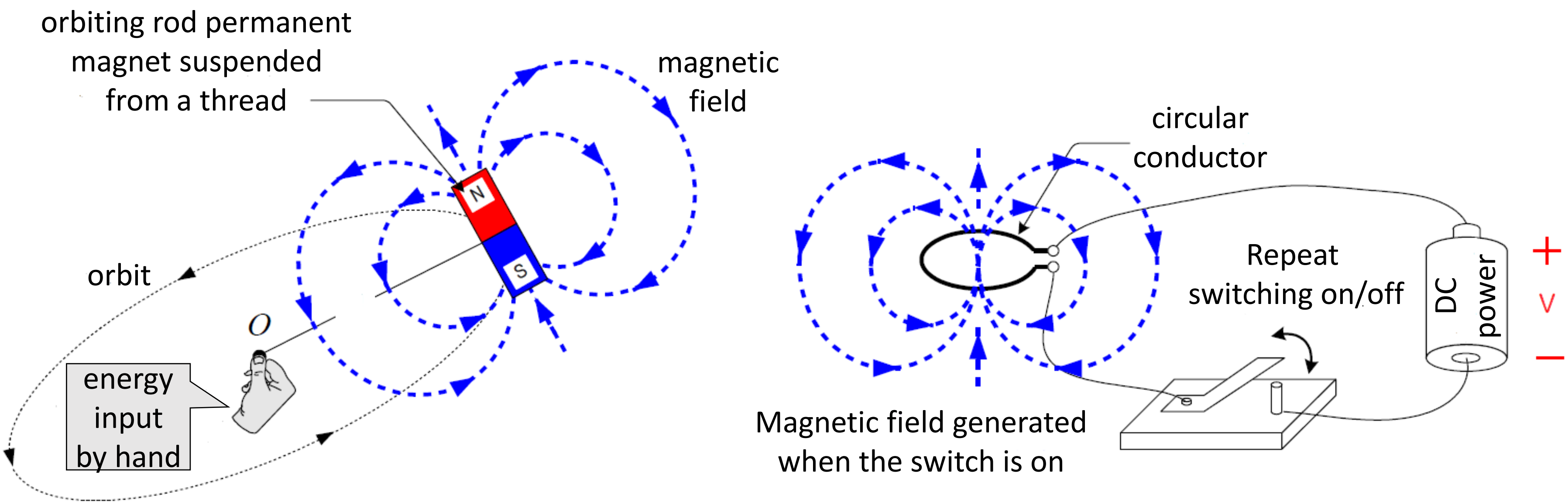
(b) Propagation in the +z-axis direction until time t=$3t_0$

Fig. 1.44 Propagation of electromagnetic waves by time-varying electric field in the +x direction at the origin at time t = 0

1-9 Electromagnetic (EM) wave

✓ **energy source of electromagnetic waves**:

- The energy consumed to move or change electric charges or current with time



(a) When rotating a magnet by hanging it on a thread

(b) In case of repeating the on/off of the switch between the battery and the conductor

Fig. 1.46 Simple electromagnetic wave generation method

1-9 Electromagnetic (EM) wave

✓ **Electrostatic Fields and Electromagnetic Waves**

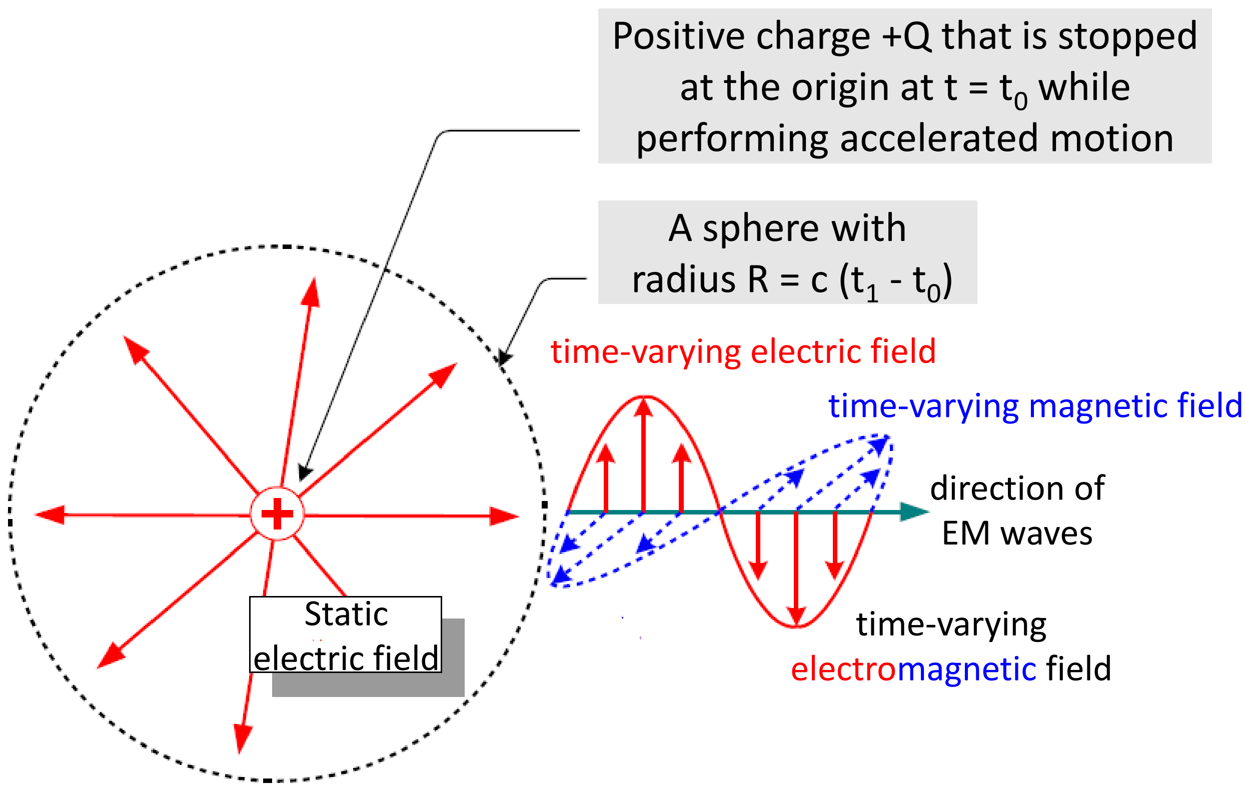
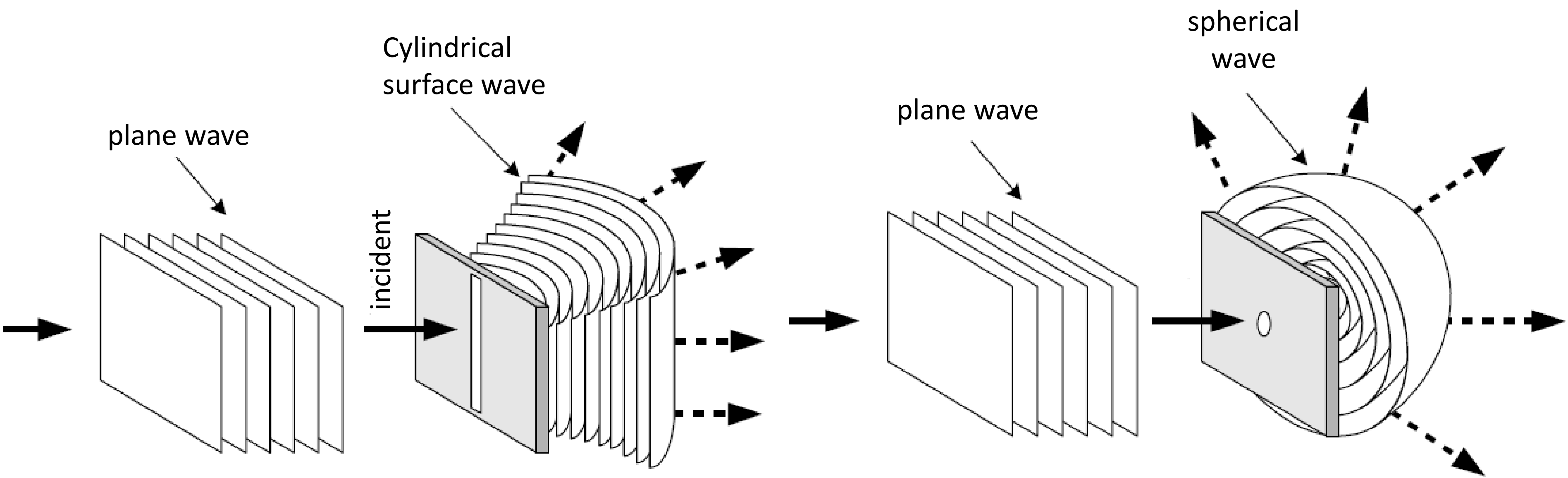


Fig. 1-47 Distribution boundary of EM waves and electrostatic field after moving charge stops

1-10 Scope and Applications of EM Waves

✓ Classification of electromagnetic waves 1 :
- Classified **according to the spatial distribution of waves with the same phase**



(a) When a plane wave passes between a long and narrow gap, it is converted into a cylindrical surface wave.

(b) When a plane wave passes through a small hole, it is converted into a spherical wave

Fig. 1-47 Planar, cylindrical and spherical waves

1-10 Scope and Applications of EM Waves

✓ Classification of electromagnetic waves 1, < simplest plane wave > :

- A sinusoidal wave moving in the +x direction at a speed c according to time t

$$s(x,t) = \cos(\omega t - kx) = \cos(2\pi f t - kx) = \cos\left(\frac{2\pi}{T}t - \frac{2\pi}{\lambda}x\right) = \cos\left[k\left(\frac{\omega}{k}t - x\right)\right] = \cos[k(ct - x)]$$

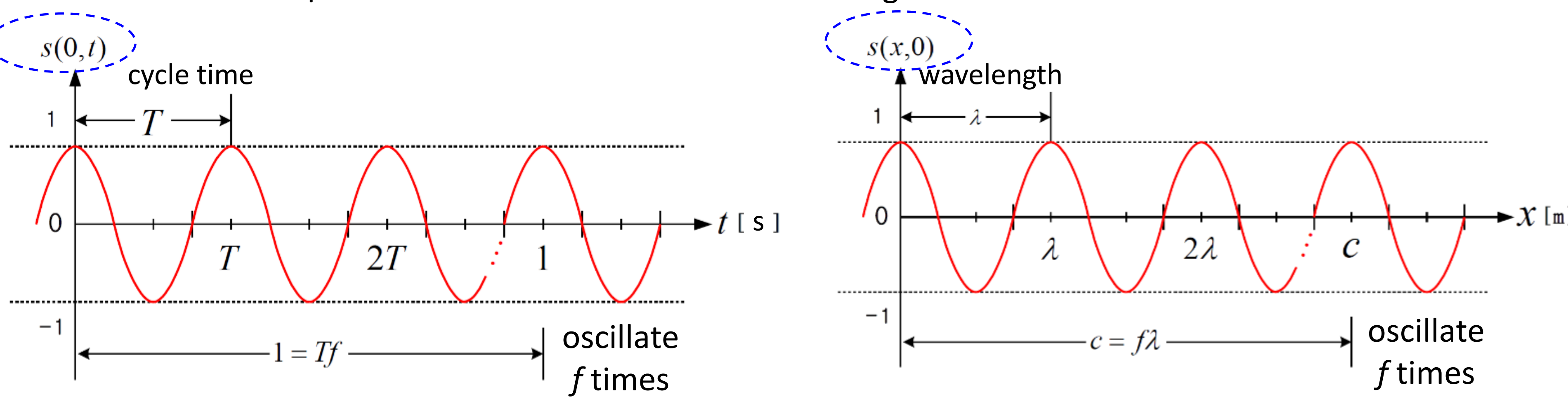
ω : angular frequency or angular velocity

f : frequency

k : wavenumber

T : period

λ : wavelength



(a) Period and Frequency

(b) Wavelength and Frequency

Fig. 1-49 A sine wave moving in the +x direction with velocity c

1-10 Scope and Applications of EM Waves

- ✓ Classification of electromagnetic waves 2 :
  - classified according to frequency *f* indicating the degree of change over time
  - The magnitude of the component with frequency f in the time function v(t) = spectrum *V*(*f*)

Fourier Transform

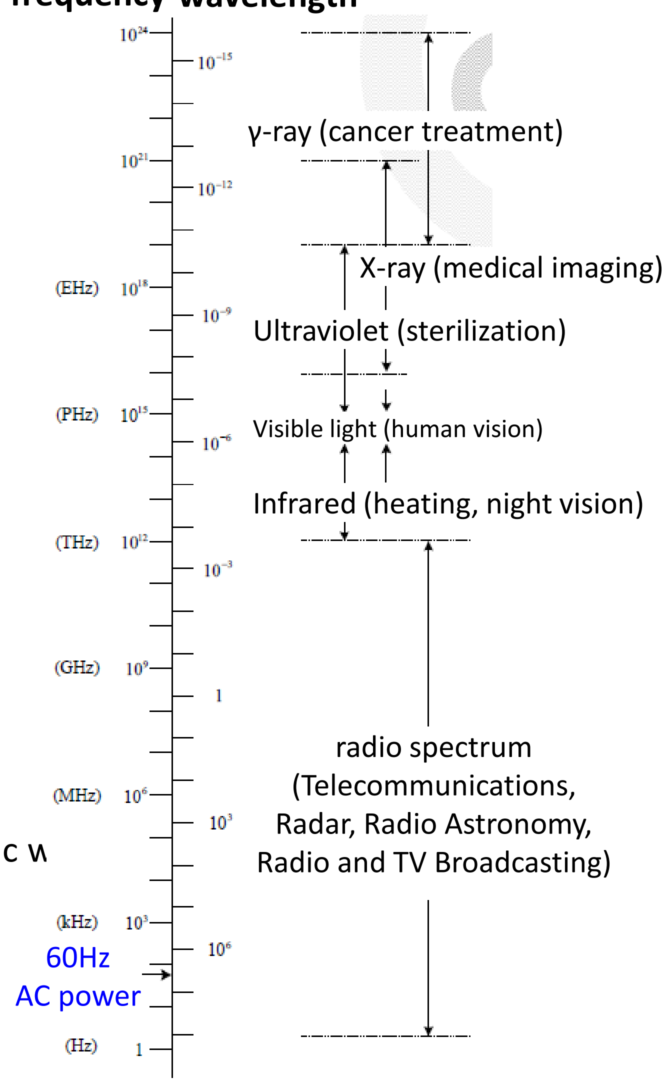
$$V(f) = \int_{-\infty}^{+\infty} v(t) e^{-j2\pi f t} dt$$

$\Updownarrow$

Inverse Fourier Transform

$$v(t) = \int_{-\infty}^{\infty} V(f) e^{j2\pi f t} df$$

Fig. 1-51 Classification of electromagnetic w
according to frequency in air



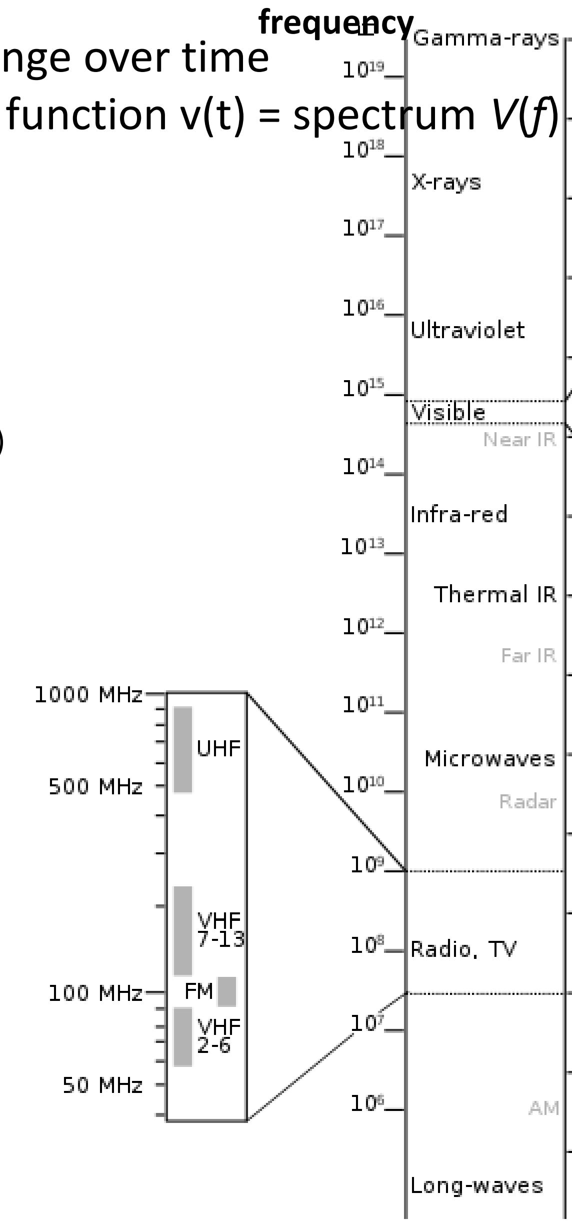


Table 1-6 Classification of frequency bands commonly used in radio

Band name	주Frequency (Hz)	wavelength (m)	applications
EHF	$3\times10^{10}-3\times10^{11}$	$10^{-2}-10^{-3}$	Radar, mm wave communication, remote sensing
SHF	$3\times10^{9}-3\times10^{10}$	$10^{-1}-10^{-2}$	Radar, satellite communication
UHF	$3\times10^{8}-3\times10^{9}$	$10^{0}-10^{-1}$	Radar, TV, Microwave, PCS
VHF	$3\times10^{7}-3\times10^{8}$	$10^{1}-10^{0}$	TV, FM broadcasting, air traffic control
HF	$3\times10^{6}-3\times10^{7}$	$10^{2}-10^{1}$	shortwave broadcast
MF	$3\times10^{5}-3\times10^{6}$	$10^{3}-10^{2}$	AM broadcast
LF	$3\times10^{4}-3\times10^{5}$	$10^{4}-10^{3}$	Radar Beacons
VLF	$3\times10^{3}-3\times10^{4}$	$10^{5}-10^{4}$	Placemark
ULF	$3\times10^{2}-3\times10^{3}$	$10^{6}-10^{5}$	Ionospheric measurements, power lines, submarine communications
SLF	$3\times10^{1}-3\times10^{2}$	$10^{7}-10^{6}$	Buried metal measurement
EFF	$3\times10^{0}-3\times10^{1}$	$10^{8}-10^{7}$	geomagnetic measurement

* name above, E: Extremely, S: Super, U: Ultra, V: Very, H: High, M: Medium, L: Low, and F: Frequency.