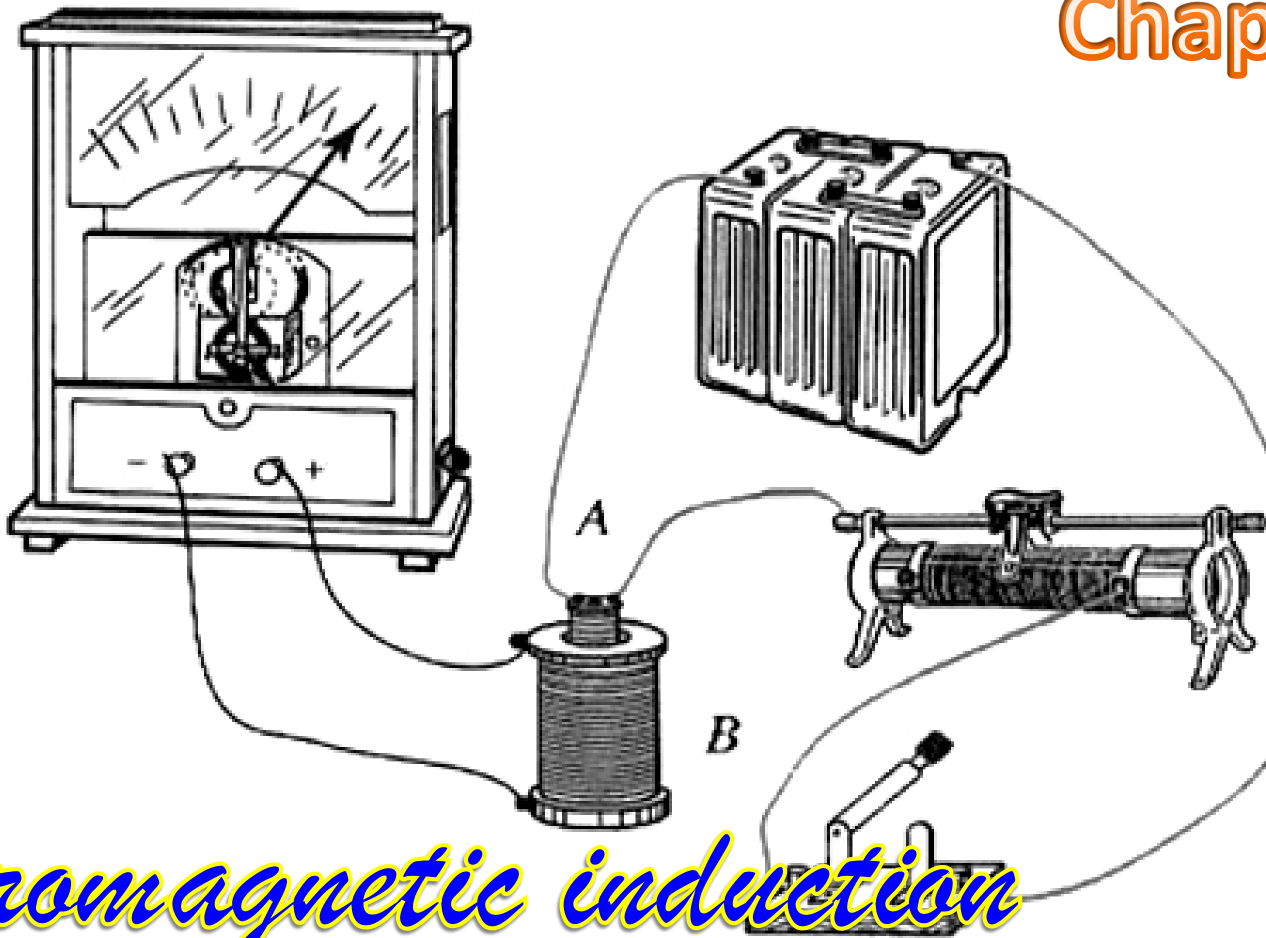
Chapter 8



electromagnetic induction

Basic law of electromagnetic field

primary coverage

1. Faraday's law of electromagnetic induction

2 dynamic electromotive force, induced electromotive force vortex field

3. Self-feeling and mutual feeling

4 The transient process of inductance and capacitance

5 The energy of the magnetic field

6 of Maxwell's Equations

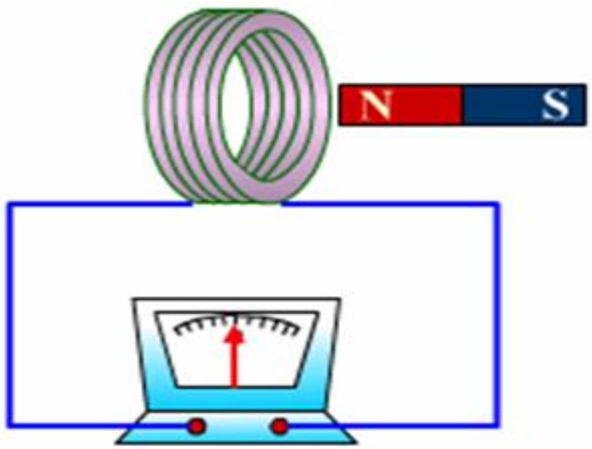
§ 8.1

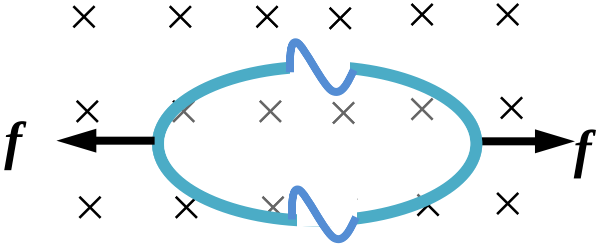
Faraday's law of electromagnetic

8.1.1 Electromagnetic induction phenomenon

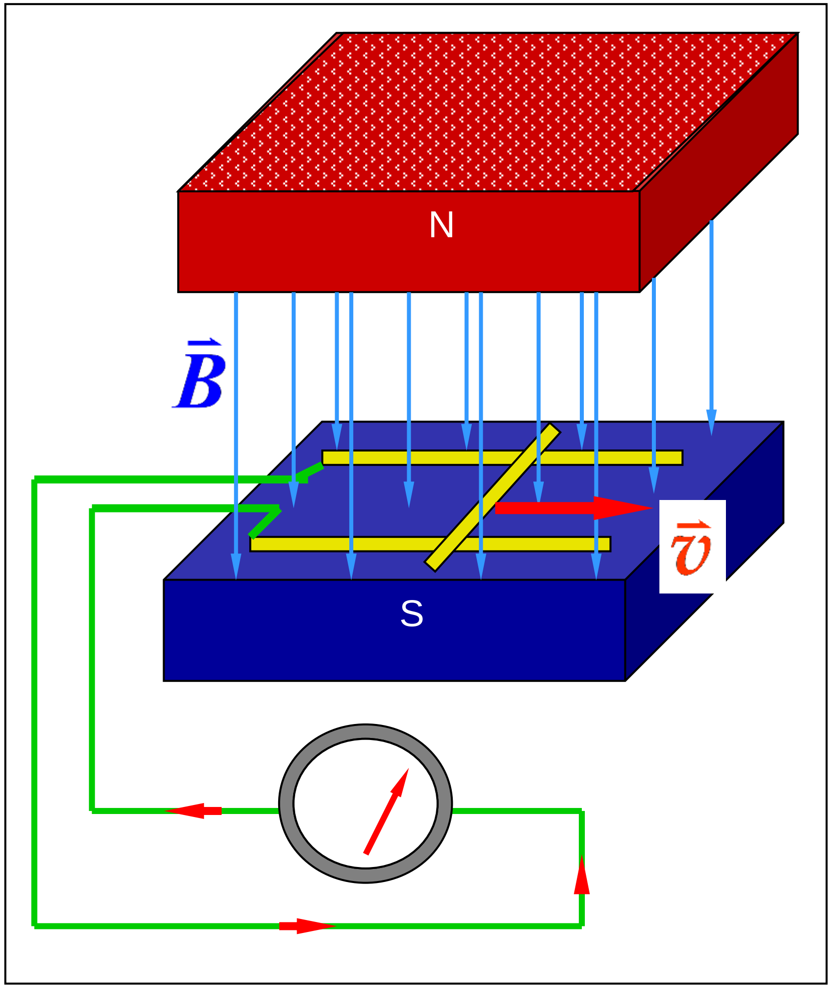
Faraday (Michael Faraday, 1791-1867)

A British physicist and chemist, one of the founders of the electromagnetic theory. He creatively proposed the idea of field, and first introduced the name magnetic field. In 1831, the phenomenon of electromagnetic induction was discovered, and then successively found the law of electrolysis, the diamagnetism and paramagnetism of matter, and the rotation of the polarization surface of light in the magnetic field.





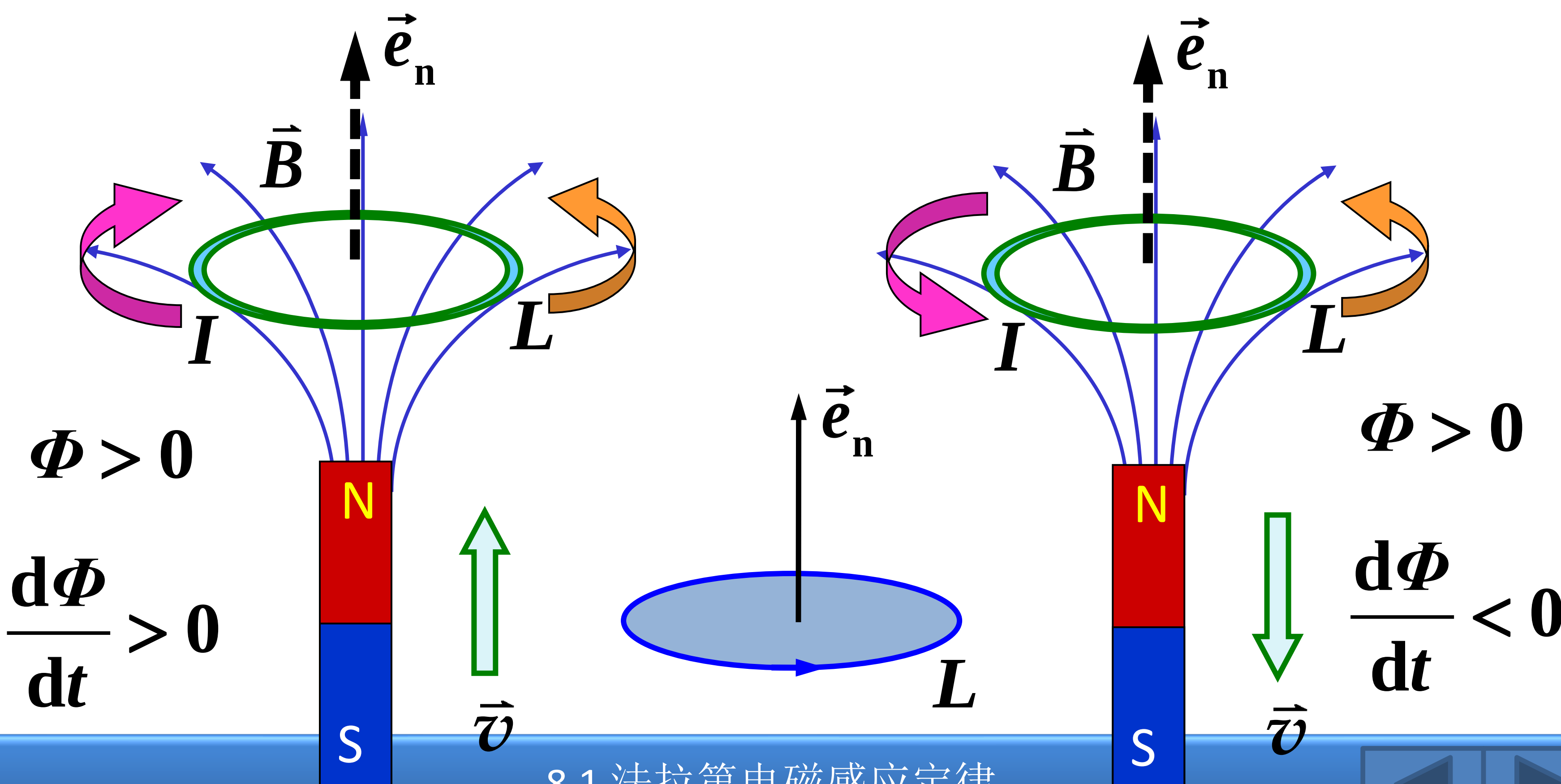
Area change of the closed coil



Summary: The magnetic flux through the coil changes to create an induced current in the coil.

8.1.2 Lenzi's law

The induced current in the closed wire circuit always makes the magnetic field it inspires itself resist against any cause of electromagnetic induction (against relative movement, magnetic field change, or coil deformation, etc.)



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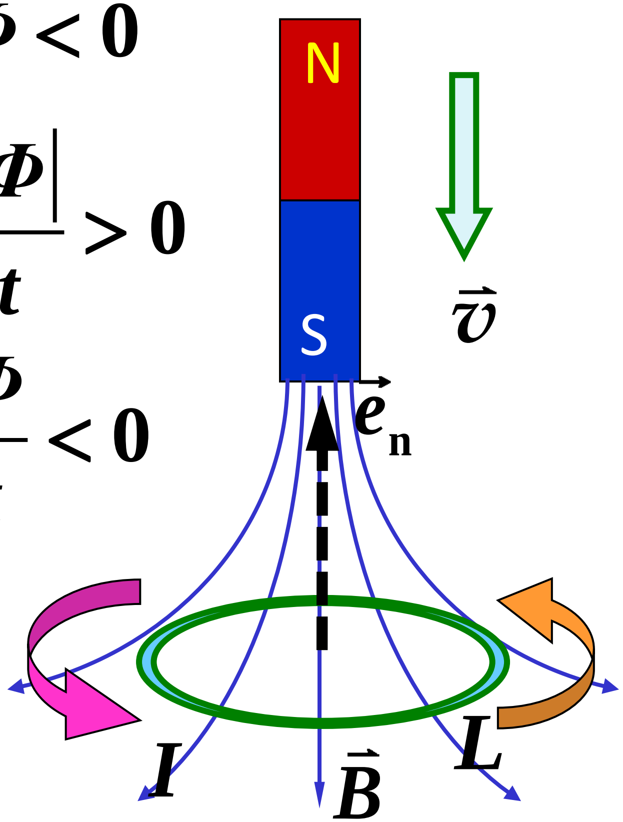
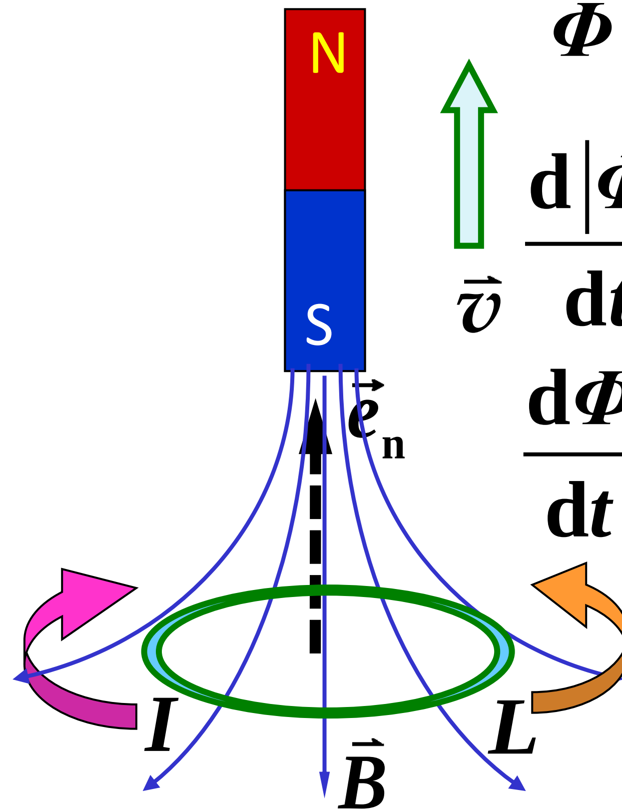
$$\Phi < 0$$

$$\frac{\mathrm{d}|\Phi|}{\mathrm{d}t} > 0$$

$$\frac{\mathrm{d}\Phi}{\mathrm{d}t} < 0$$





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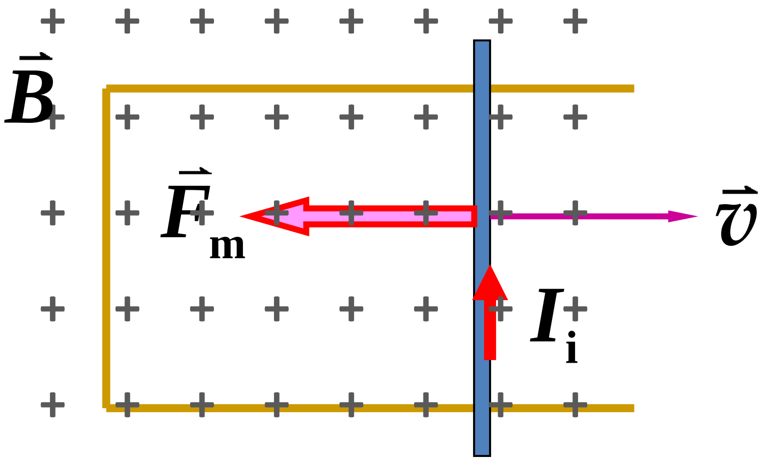
Lenzi's law is a manifestation of the law of conservation of energy



mechanical ener | Joule heat

To maintain the slide bar movement, a force must be added, the process of converting the external force into joule heat.

8.1.3 Faraday's law of electromagnetic induction

When the magnetic flux through the area enclosed by the closed loop changes, the induced electromotive force is generated in the loop, and the induced electromotive force is proportional to the negative value of the time flux of the magnetic flux.

$$\mathsf{E} = -\frac{\mathrm{d}\Phi}{\mathrm{d}t}$$

among:
$$\Phi = \int_S \boldsymbol{B} \cdot \mathrm{d}\boldsymbol{S} = \int_S B \cos\theta \mathrm{d}S$$

♦ If the N turn coil
$$\psi = \Phi_1 + \Phi_2 + \cdots + \Phi_N$$

$$\mathsf{E} = -\frac{\mathrm{d}\psi}{\mathrm{d}t}$$
like $\psi = N\Phi$ Is $\mathsf{E} = -N\frac{\mathrm{d}\Phi}{\mathrm{d}t}$

♦ In the circuit, the induced current

$$i = \frac{\mathrm{E}}{R} = -\frac{1}{R}\frac{\mathrm{d}\Phi}{\mathrm{d}t}$$

♦ Induced charge in the circuit

$$i = \frac{\mathrm{d}q}{\mathrm{d}t} \Rightarrow q = \int i\mathrm{d}t$$

$$q = \int_{t_1}^{t_2} i\mathrm{d}t = -\frac{1}{R}\int_{\Phi_1}^{\Phi_2}\mathrm{d}\Phi = \frac{1}{R}(\Phi_1 - \Phi_2)$$

It shows that the amount of inductive charge through the wire cross section during a period of time is proportional to the change of the magnetic flux surrounded by the wire loop during this period, and does not have the speed of the magnetic flux change.

§ 8.2

Dynamic electromotive force, induced

8.2.1, with a dynamic electromotive force

1. motional electromotive force

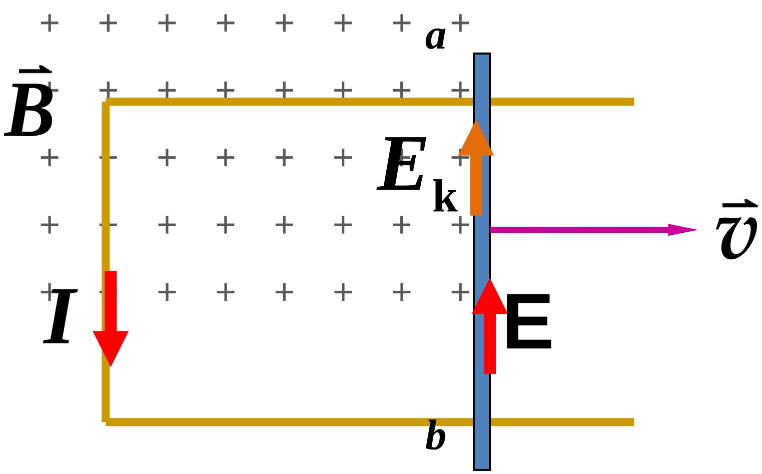
The Lorentz force： the non-static electric field source of the dynamic electromotive force

Non-electrostatic field strength

$$\vec{F} = -e\vec{v} \times \vec{B}$$

$$\vec{E}_k = \frac{\vec{F}}{-e} = \vec{v} \times \vec{B}$$

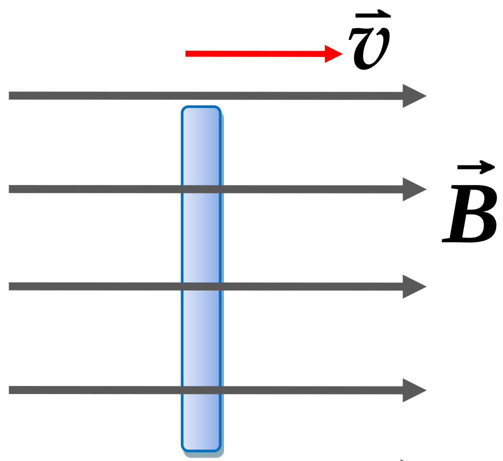
$$\mathcal{E}_i = \oint \vec{E}_k \cdot d\vec{l} = \oint (\vec{v} \times \vec{B}) \cdot d\vec{l}$$

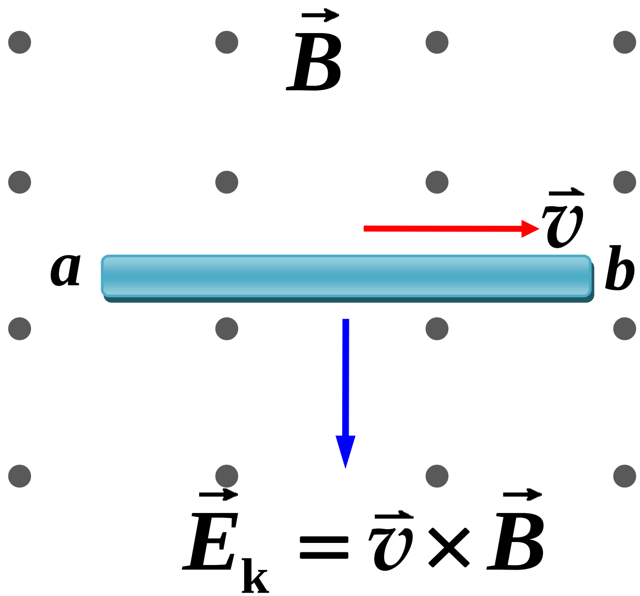


Nonelectrostatic field strength exists only in the moving conductor ab segment

$$\mathcal{E}_i = \int_a^b \vec{E}_k \cdot d\vec{l} = \int_a^b (\vec{v} \times \vec{B}) \cdot d\vec{l}$$

Discussion 1





Note: A dynamic electromotive force is generated only when the wire cuts transversely.

◆ In any steady and constant magnetic field, any shape of the wire due to motion or deformation

The speed of any first line of dl is v,

$$\mathrm{d}\mathscr{E} = (\vec{v} \times \vec{B}) \cdot \mathrm{d}\vec{l}$$

The kinetic electromotive force generated in the whole conductor or loop L is

$$\boxed{\begin{aligned} \mathscr{E} &= \int_L (\vec{v} \times \vec{B}) \cdot \mathrm{d}\vec{l} \\ \mathscr{E} &= \oint_L (\vec{v} \times \vec{B}) \cdot \mathrm{d}\vec{l} \end{aligned}}$$

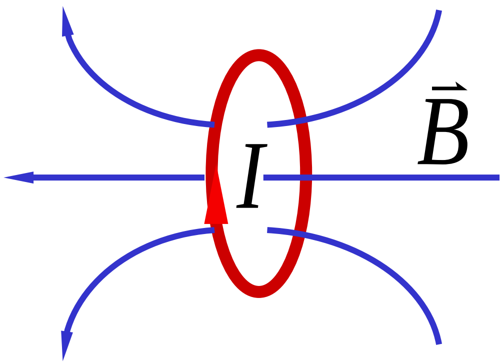
§ 8.3

Self-feeling and mutual feeling

8.3.1 Self-sensing phenomenon and self-sensing coefficient

Magnetic flux passing through the closed current loop $\Phi = LI$

1. Self-perception definition 1 $L = \Phi / I$



If the coil has N turns

Number of magnetic flux turns $\psi = N\Phi$

self-inductance $L = \psi / I$

pay attention to

Without ferromagnet, self-sensing is only related to coil shape, magnetic medium and N.

2. Self-inductive electromotive force

$$\mathcal{E}_L = -\frac{\mathrm{d}\Phi}{\mathrm{d}t} = -(L\frac{\mathrm{d}I}{\mathrm{d}t} + I\frac{\mathrm{d}L}{\mathrm{d}t})$$

equal $\frac{\mathrm{d}L}{\mathrm{d}t} = 0$ time, $\mathcal{E}_L = -L\frac{\mathrm{d}I}{\mathrm{d}t}$

Self-sensing definition 2 $L = -\mathcal{E}_L \Big/ \frac{\mathrm{d}I}{\mathrm{d}t}$ (Condition L is unchanged)

Unit: 1 Henry (H) = 1 Webber / Ampere (1 Wb / A)

$$1\mathrm{mH} = 10^{-3}\,\mathrm{H},\quad 1\,\mu\mathrm{H} = 10^{-6}\,\mathrm{H}$$

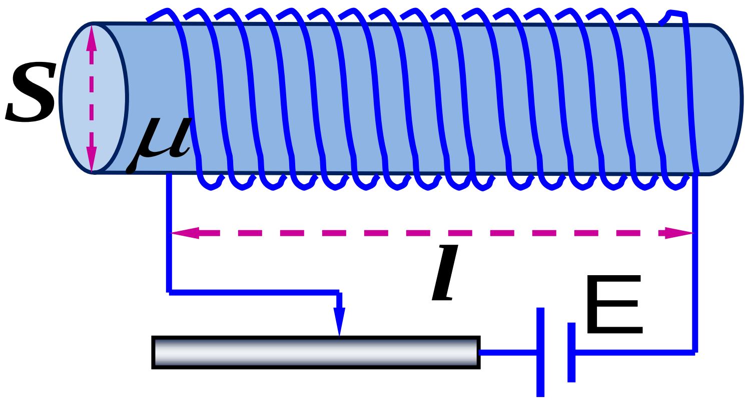
3. The calculation method of self-perception

Example 1 The long straight-wound solenoid shown in the figure,

known, l, S, N, μ

Seek its own feeling L .(Ignore the edge effect)

Solution: set the current I → to obtain H according to the ampere loop theorem → B → Φ → L



$$n = N/l$$

$$B = \mu H = \mu n I$$

$$\psi = N\Phi = NBS$$

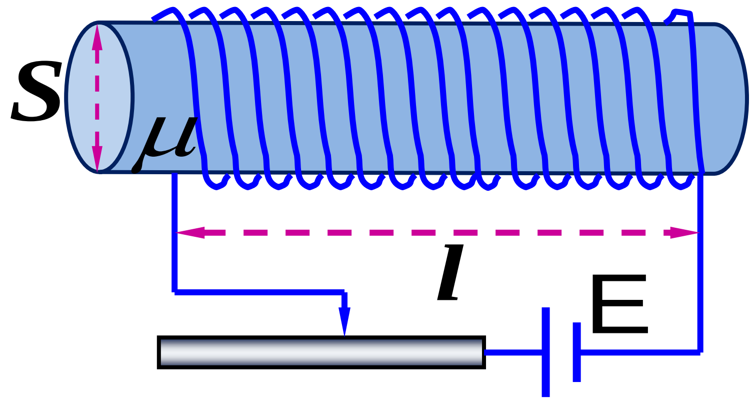
$$= N\mu \frac{N}{l} IS$$

$$\psi = N\mu \frac{N}{l} IS$$

$$L = \frac{\psi}{I} = \mu \frac{N^2}{l} S$$

$$n = N/l \qquad V = lS$$

$$\therefore L = \mu n^2 V$$



In general, the following formula can be used to measure the self-perception

$$\mathrm{E}_L = -L \frac{\mathrm{d}I}{\mathrm{d}t}$$

4. The application of self-sensing steady flow, LC resonant circuit, filter circuit, induction ring, etc.

Example 2 has two coaxial cylindrical conductors with a radius of R_1 and R_2, and the currents passing through them are both I , but the current direction is opposite. The two cylinders are filled with uniform magnetic μ medium of self-sensing L.

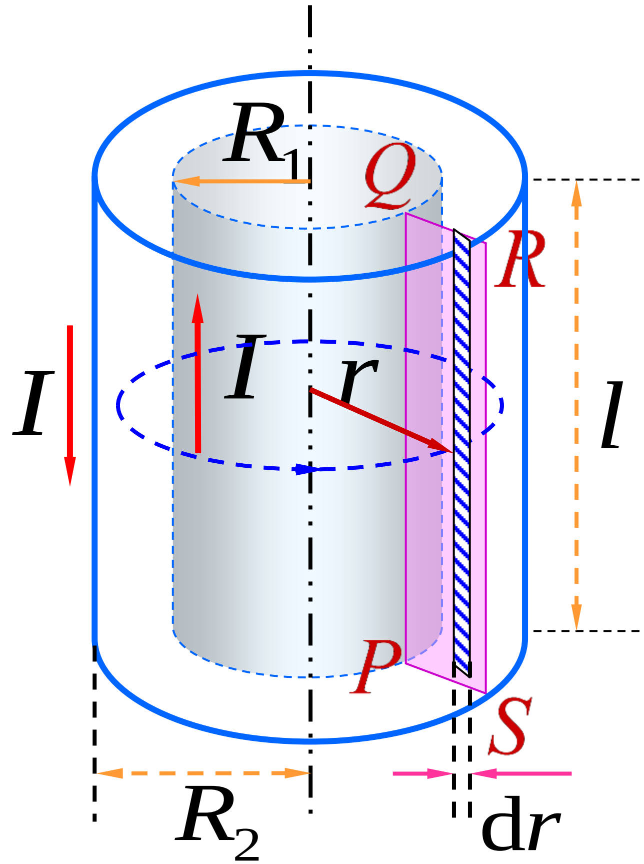
Solution: between the two cylinders

$$B = \frac{\mu I}{2\pi r}$$

Take a long l face PQRS between two cylinders and divide it into many small faces.

Is $$\mathrm{d}\Phi = \vec{B} \cdot \mathrm{d}\vec{S} = Bl\mathrm{d}r$$

$$\Phi = \int \mathrm{d}\Phi = \int_{R_1}^{R_2} \frac{\mu I}{2\pi r} l \mathrm{d}r$$



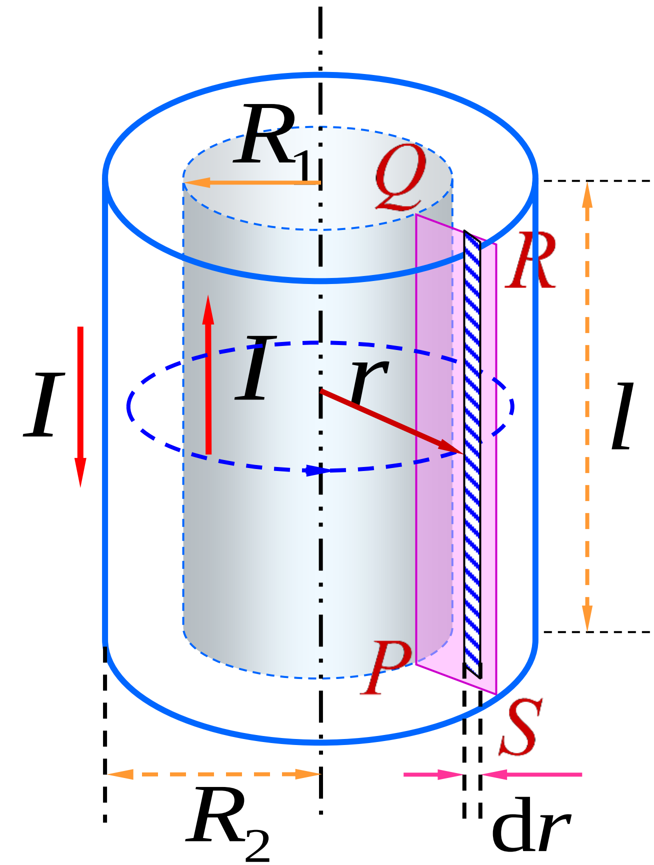
$$\Phi = \int \mathrm{d}\Phi = \int_{R1}^{R2} \frac{\mu I}{2\pi r} l \mathrm{d}r$$

approach $\Phi = \dfrac{\mu I l}{2\pi} \ln \dfrac{R_2}{R_1}$

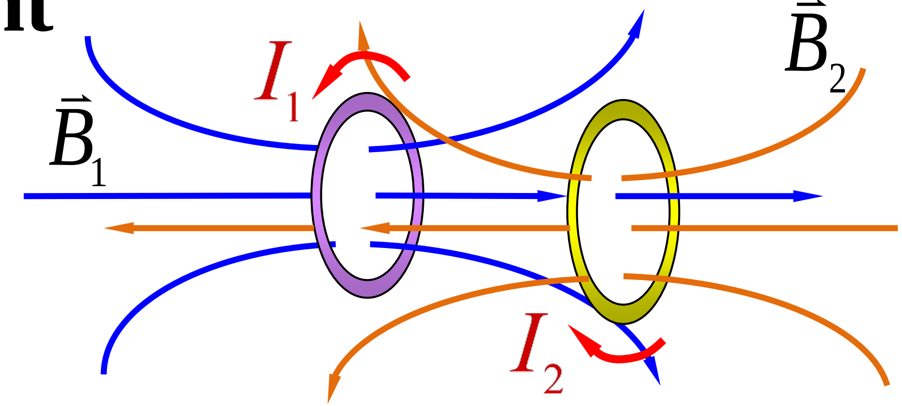
Can be defined by self-perception

$$L = \frac{\Phi}{I} = \frac{\mu l}{2\pi} \ln \frac{R_2}{R_1}$$

Self-sensing per unit length is $\dfrac{\mu}{2\pi} \ln \dfrac{R_2}{R_1}$



8.3.2 Mutual perception phenomenon and mutual sensing coefficient



Magnetic flux generated by I_1 in the I_2 current loop

$$\boldsymbol{\Phi_{21} = M_{21} I_1}$$

Magnetic flux generated by I_2 in the I_1 current loop

$$\boldsymbol{\Phi_{12} = M_{12} I_2}$$

1. Mutual sensitivity coefficient definition 1

$$\boldsymbol{M_{12} = M_{21} = M = \frac{\Phi_{21}}{I_1} = \frac{\Phi_{12}}{I_2}}$$

(Theoretically proven)

pay attention to

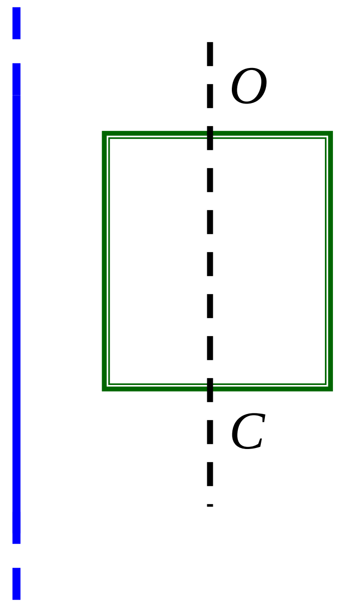
Mutual sensation is only related to the two coil shapes, size, turns, relative position, and surrounding magnetic media (constant without ferromagnet)

2. Mutual inductive electromotive force

$$\mathcal{E}_{12} = -M\frac{\mathrm{d}I_2}{\mathrm{d}t} \qquad \mathcal{E}_{21} = -M\frac{\mathrm{d}I_1}{\mathrm{d}t}$$

Mutual sensitivity coefficient definition 2

$$M = -\frac{\mathcal{E}_{21}}{\mathrm{d}I_1/\mathrm{d}t} = -\frac{\mathcal{E}_{12}}{\mathrm{d}I_2/\mathrm{d}t}$$



Q: Does the feelings of the following situations changed?

1) Movement of parallel straight wire of the wire frame;

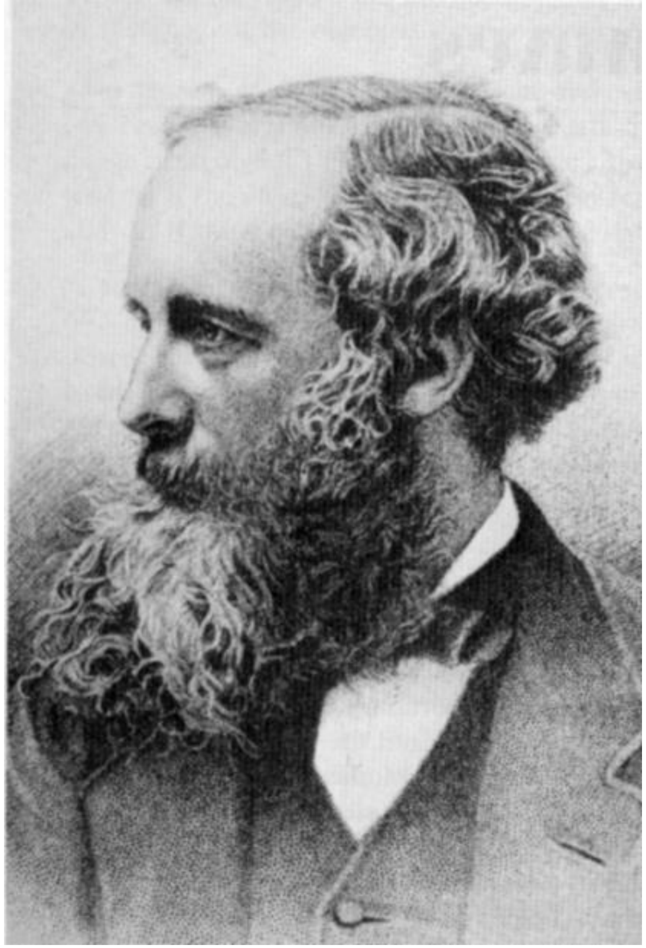
2) The wire frame moves perpendicular to the straight wire;

3) The wire frame rotates around the OC axis;

4) Current change in the straight wire.

§ 8.6

Maxwell equations



Maxwell (1831-1879), a British physicist. The founder of the classical electromagnetic theory, one of the founders of the gas motion theory. He proposed the concept of spinning field and displacement current, established the classical electromagnetic theory, and predicted the existence of electromagnetic waves propagating at the speed of light. In gas motion theory, he also proposed the statistical law of gas molecule distribution by rate.

In 1865, Maxwell put forward the complete theory of electromagnetic field based on the summary of previous work. His main contribution was to put forward the two hypotheses of "vortex electric field" and "displacement current", thus predicting the existence of electromagnetic waves and calculating the speed of electromagnetic waves (i. e., the speed of light).

$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} \quad \text{(in vacuum)}$$

Hertz experiments in 1888 confirmed his prediction, and Maxwell's theory laid the foundation of classical dynamics and opened up broad prospects for the development of radio technology and modern electronic communication technology.

Integral form of the Maxwell electromagnetic field equation

♦ The electrostatic-field Gaussian theorem

$$\oint_S \vec{D}\cdot \mathrm{d}\vec{s} = \int_V \rho \mathrm{d}V = \sum q_{\mathrm{int}}$$

♦ Electrostatic field circulation theorem

$$\oint_L \vec{E}\cdot \mathrm{d}\vec{l} = 0$$

♦ Gaussian theorem

$$\oint_S \vec{B}\cdot \mathrm{d}\vec{S} = 0$$

♦ Ampere circuital theorem

$$\oint_L \vec{H}\cdot \mathrm{d}\vec{l} = \sum I_{\mathrm{c}} + \int_S \frac{\partial \vec{D}}{\partial t}\cdot \mathrm{d}\vec{S}$$

♦ equation of state

$$\vec{D} = \varepsilon_0 \varepsilon_{\mathrm{r}} \vec{E} \qquad \vec{H} = \frac{\vec{B}}{\mu_0 \mu_{\mathrm{r}}} \qquad \vec{j} = \gamma \vec{E}$$

8.2.2, properties of induced electric field

Non-electrostatic field-induced electric field generating the induced electromotive force

Maxwell assumes that a changing magnetic field stimulates an electric field in its surrounding space, called an induced electric field. $\vec{E}_{\mathrm{k}}$

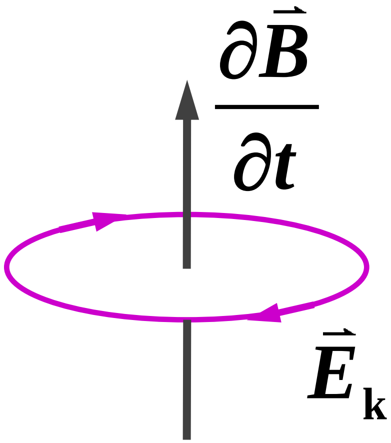
The induced electromotive force in the closed loop

$$\mathsf{E}_{\mathrm{i}} = \oint_L \vec{E}_{\mathrm{k}} \cdot \mathrm{d}\vec{l} = -\frac{\mathrm{d}\Phi}{\mathrm{d}t}$$

$$\Phi = \int_S \vec{B} \cdot \mathrm{d}\vec{S} \qquad \oint_L \vec{E}_{\mathrm{k}} \cdot \mathrm{d}\vec{l} = -\frac{\mathrm{d}}{\mathrm{d}t}\int_S \vec{B} \cdot \mathrm{d}\vec{S}$$

$$\mathsf{E}_{\mathrm{i}} = \oint_L \vec{E}_{\mathrm{k}} \cdot \mathrm{d}\vec{l} = -\int_S \frac{\partial \vec{B}}{\partial t} \cdot \mathrm{d}\vec{S}$$

Contrison between the induced and electrostatic fields



♦ $\vec{E}$ and $\vec{E}_{\mathrm{k}}$ both have potent effects on the charge.

♦ The electrostatic field is the conservative field $\oint_L \vec{E} \cdot \mathrm{d}\vec{l} = 0$

♦ The inductive electric field is a non-conservative field $\oint_L \vec{E}_{\mathrm{k}} \cdot \mathrm{d}\vec{l} = -\frac{\mathrm{d}\Phi}{\mathrm{d}t} \neq 0$

♦ The static electric field is generated by the charge;

The induced electric field is generated by a changing magnetic field.

rotational field $\oint_S \vec{E}_{\mathrm{k}} \cdot \mathrm{d}\vec{S} = 0$