西南交通大學
Southwest Jiaotong University

Physics 2: **Electricity , Optics and Quanta**

Week 6 - Magnetic field and Electric current

2023.10

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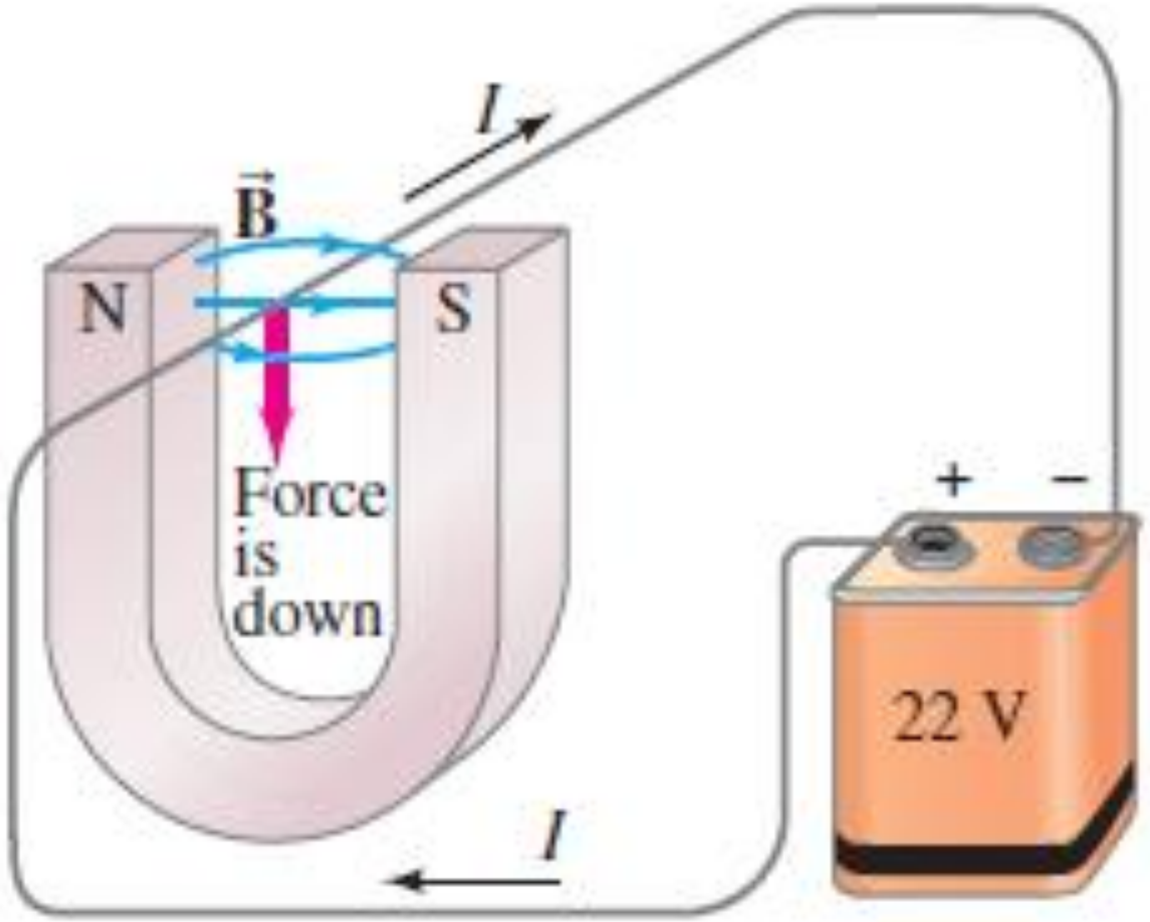
Structure

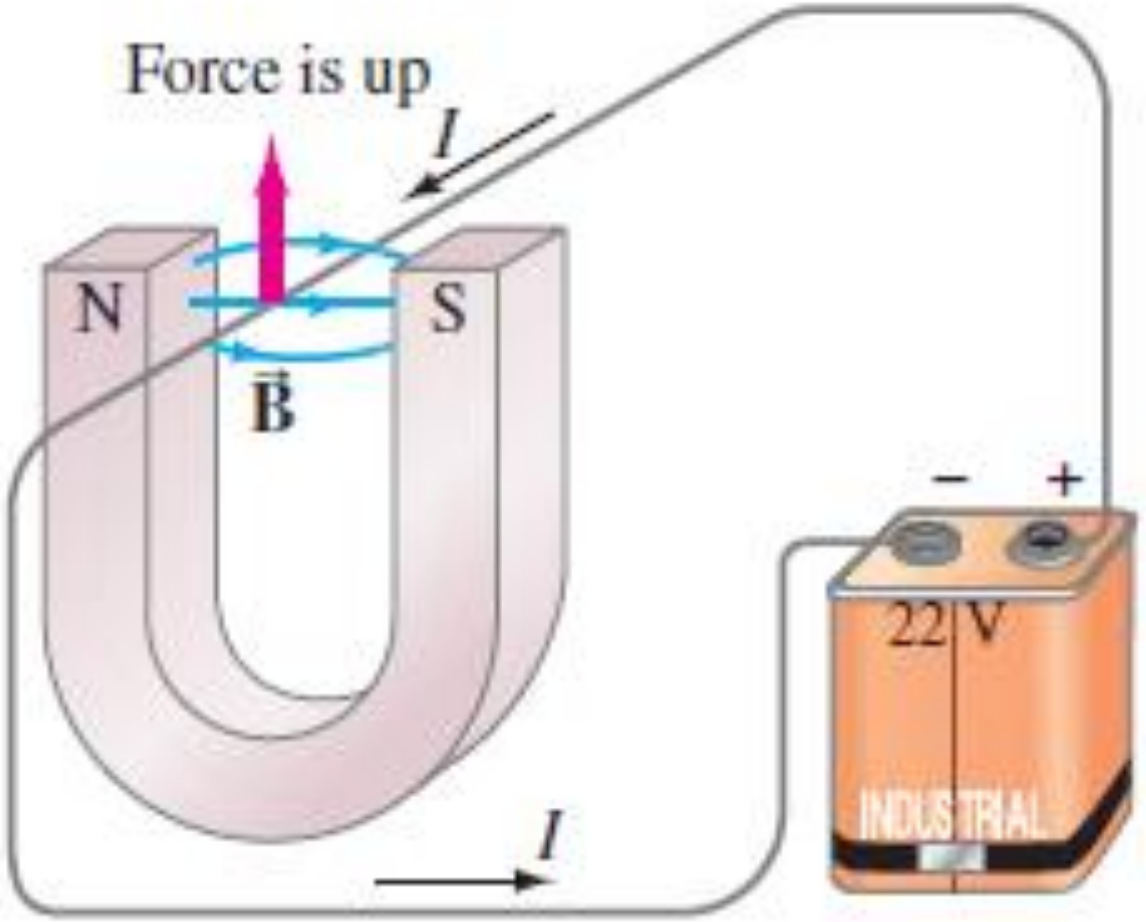
- Magnetic field
  - Field line
  - The effect of magnetic field on moving charges and current
    - Hall effect
    - Electric motors
  - Magnetic field generated by electric current
    - Magnetic circuit

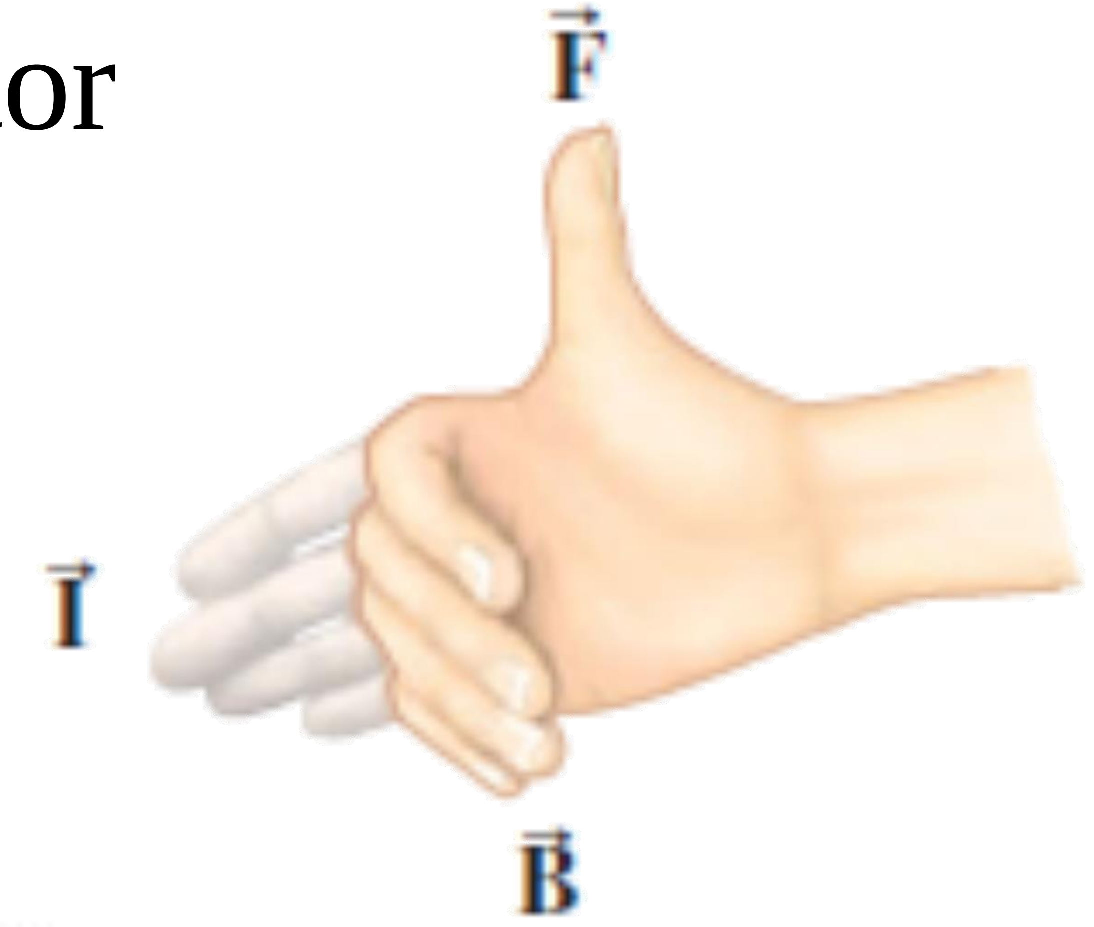
Videos

Electric car

Magnetic force on a current-carrying conductor







Magnetic force on a current-carrying conductor

Try to derive

unknown: Forces on the conductor

known:

- I, B, l
- $F = qvB$ for charges

The charges move with the "drift" velocity: $\boldsymbol{v_d}$

$\boldsymbol{N}$ = number of charges moving in the section of wire

$\boldsymbol{A}$ = cross section of the wire

$\boldsymbol{l}$ = length of the wire (diameter of the magnet)

$\boldsymbol{n}$ = density of charge carriers (1/m^3)

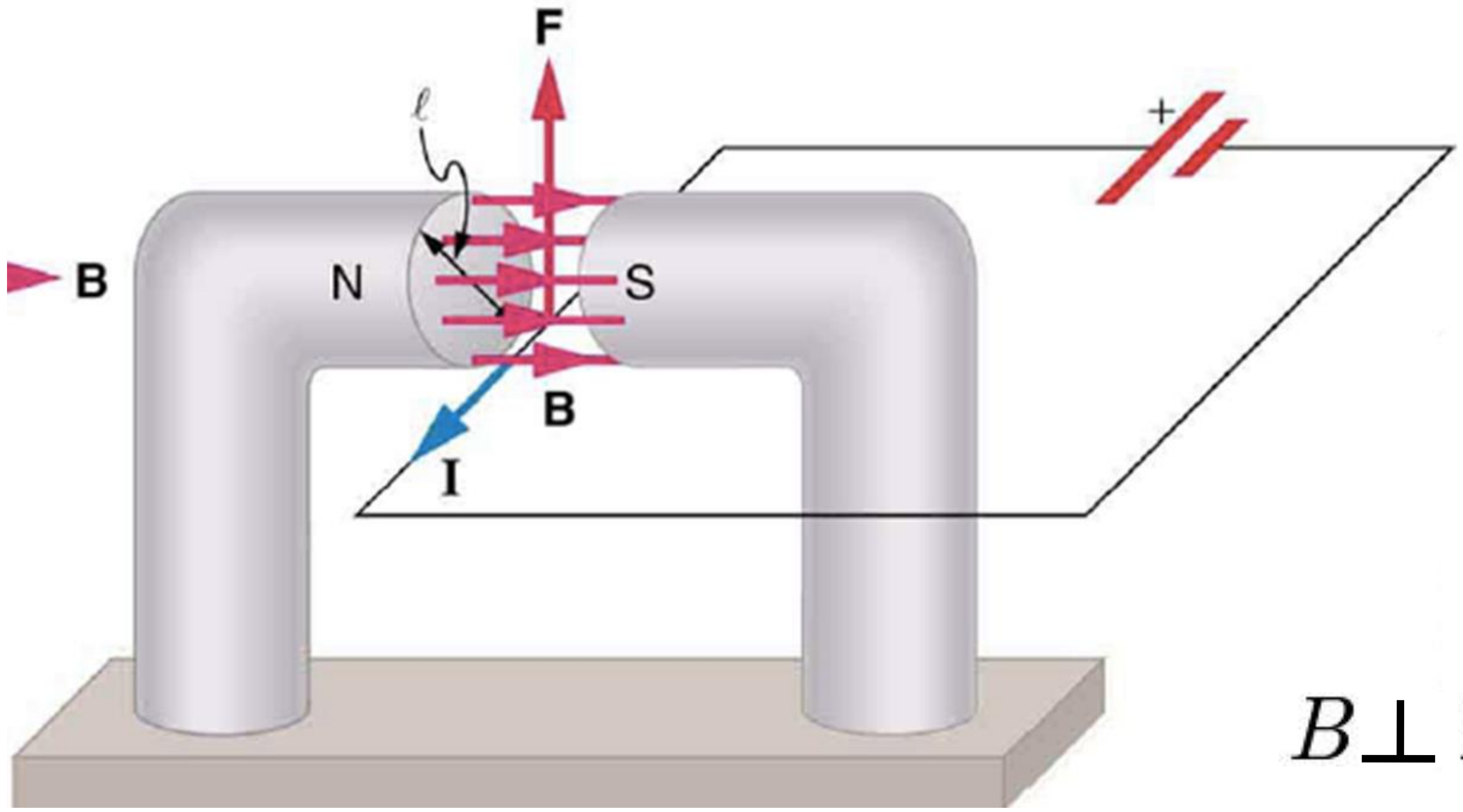
Magnetic force on a current-carrying conductor

Magnetic forces on moving charges

$$F = (q\, v_d B) N$$

$$N = nV = nA\, l \qquad V = A\, l$$

$$F = \underbrace{(nqAv_d)}_{\Delta Q/\Delta t} l\, B$$

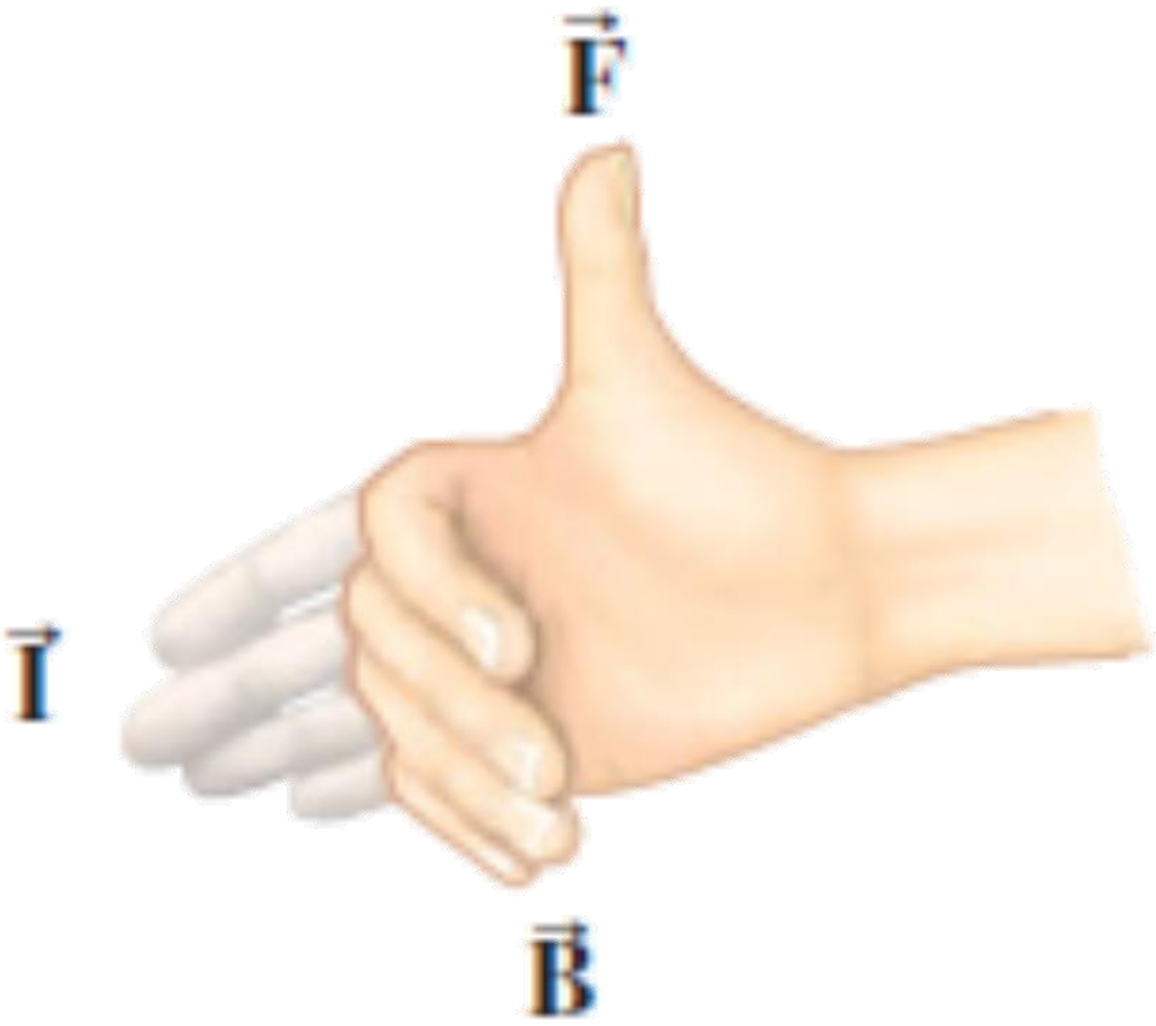


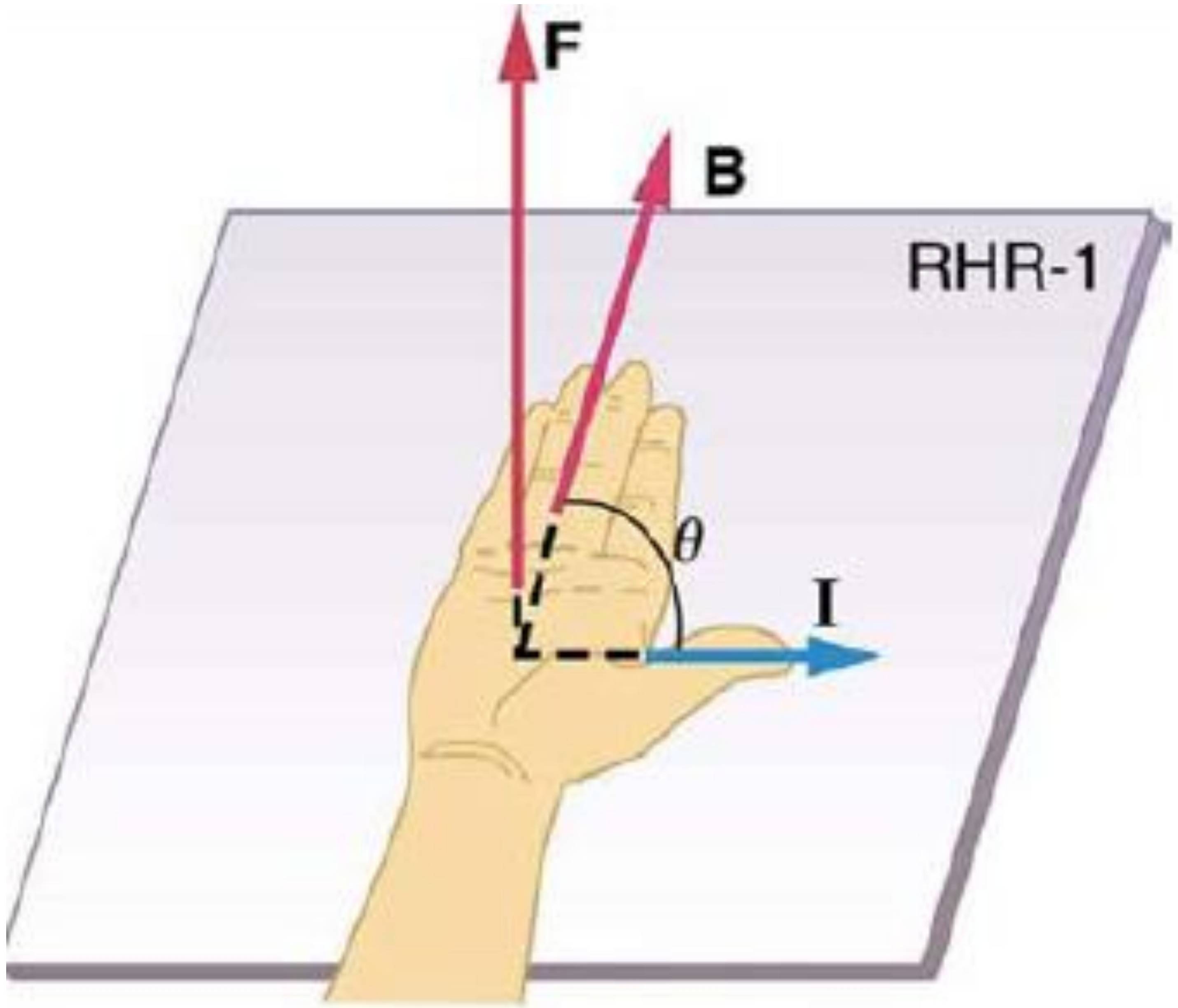
$B \perp I$

$$\Longrightarrow F = I\, l\, B \sin\theta$$

θ : angle between B and I

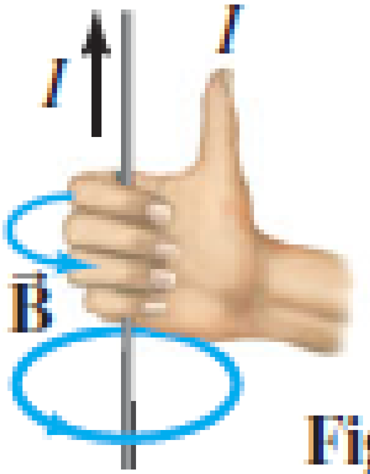
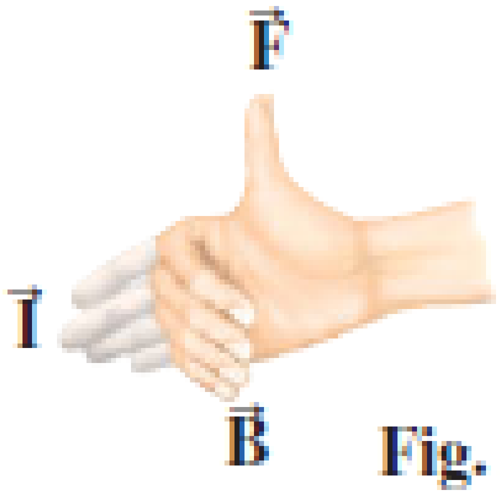
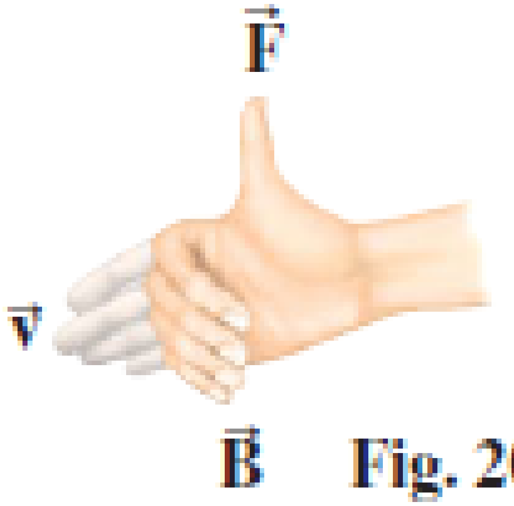
Right hand rule



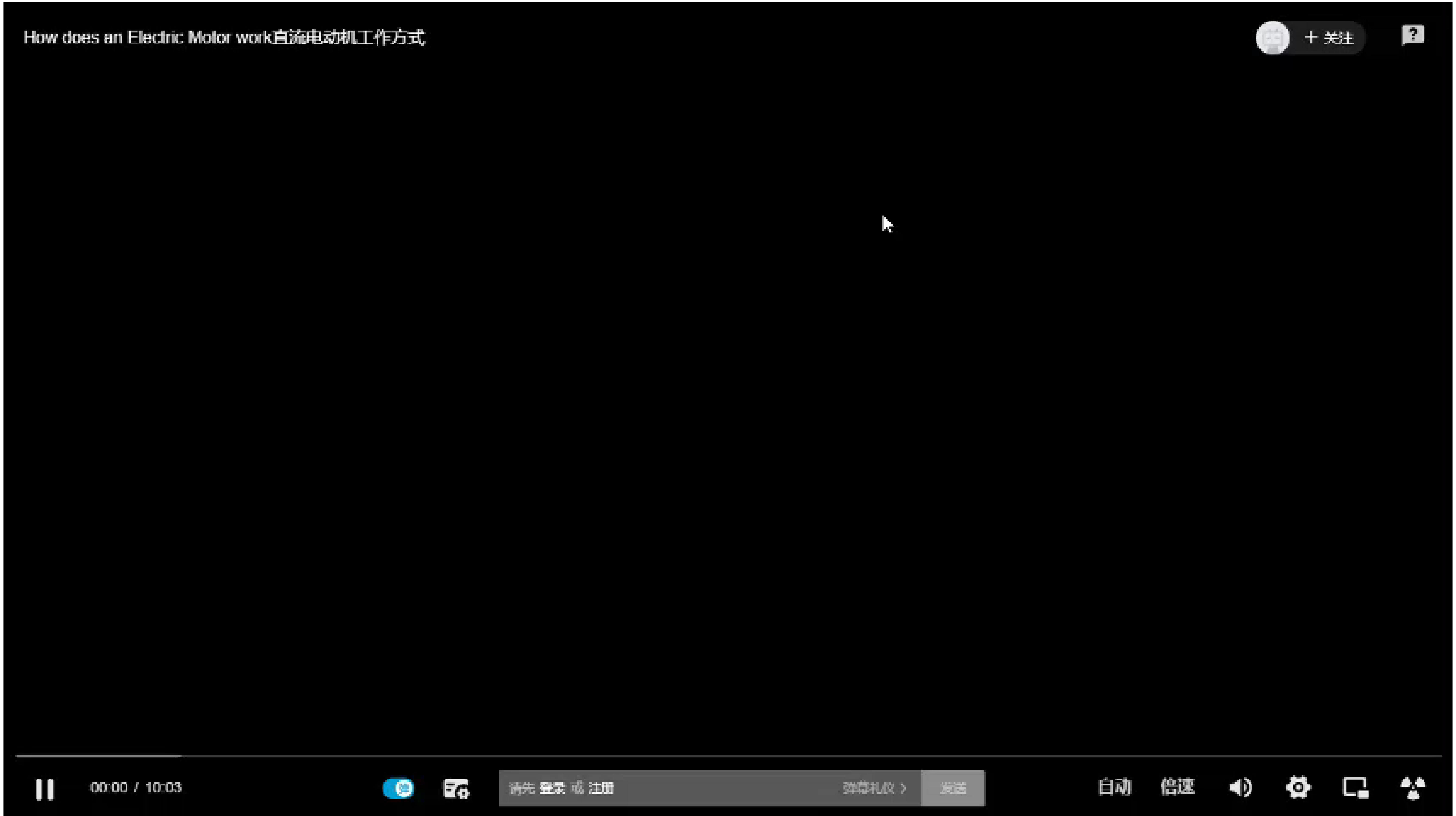


One of them is enough

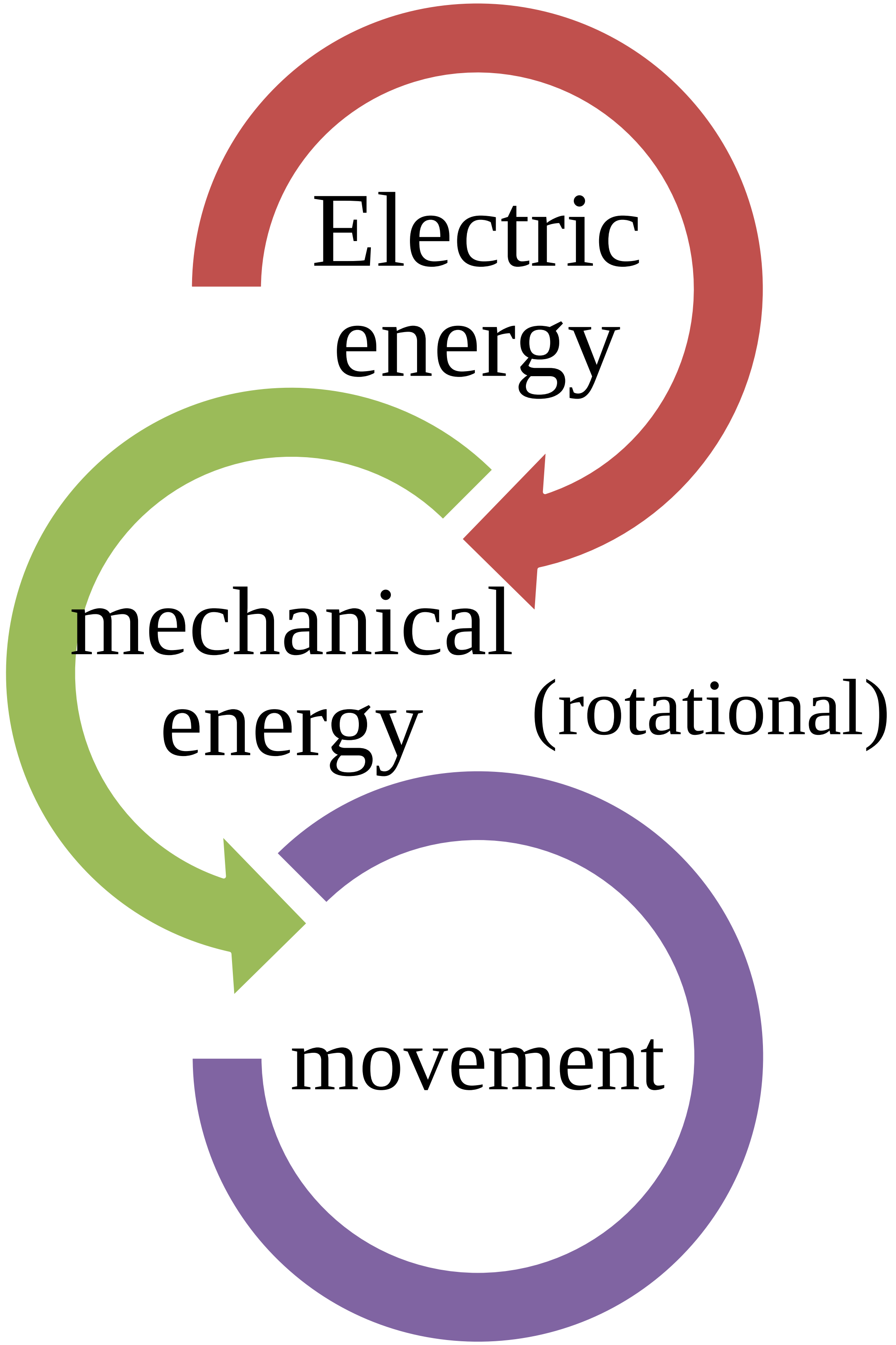
TABLE 20–1 Summary of Right-hand Rules (= RHR)

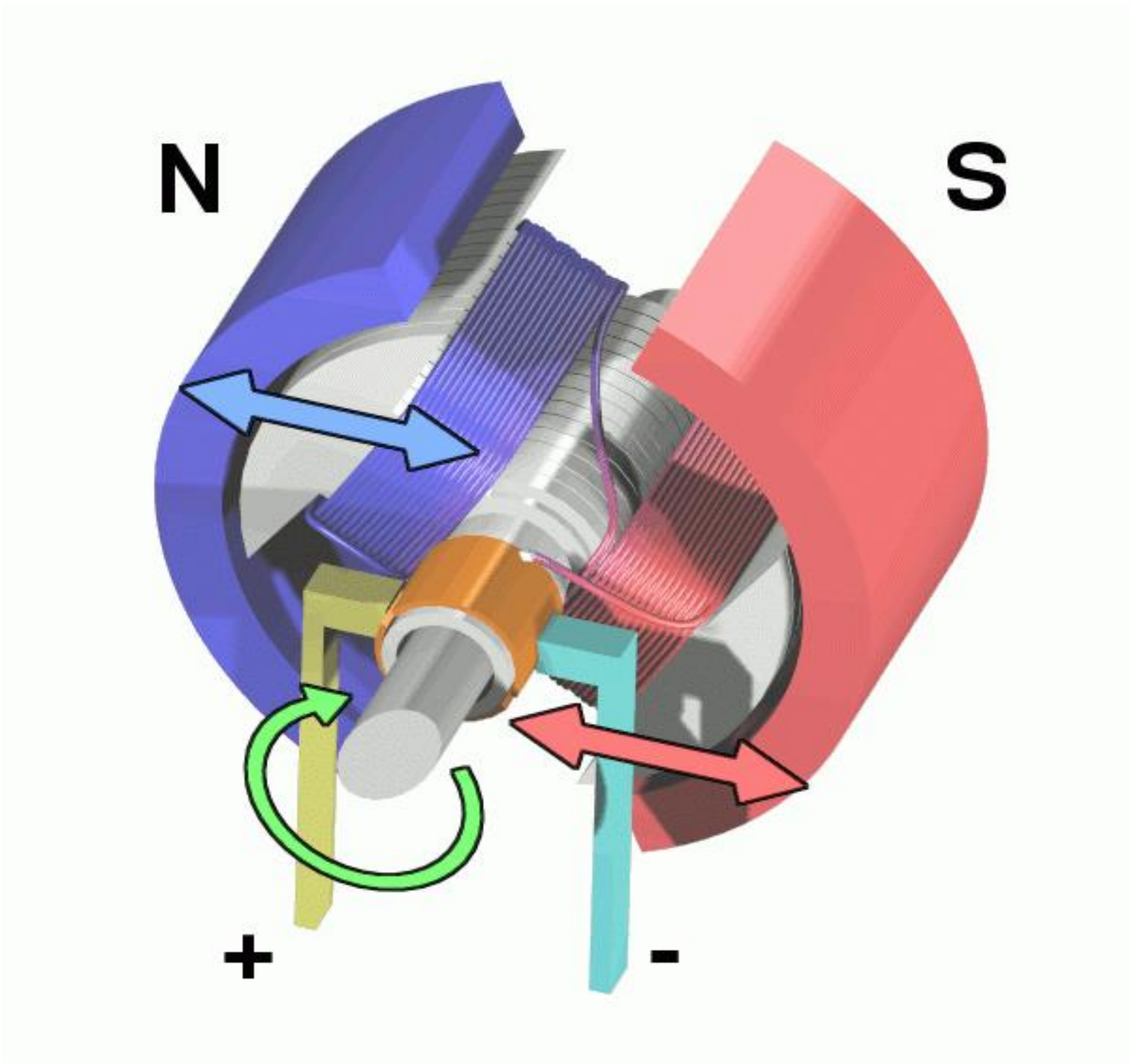
Physical Situation	Example	How to Orient Right Hand	Result
1. Magnetic field produced by current (RHR-1)	 Fig. 20–8d	Wrap fingers around wire with thumb pointing in direction of current I	Fingers curl in direction of $\vec{B}$
2. Force on electric current I due to magnetic field (RHR-2)	 Fig. 20–11c	Fingers first point straight along current I, then bend along magnetic field $\vec{B}$	Thumb points in direction of the force $\vec{F}$
3. Force on electric charge $+q$ due to magnetic field (RHR-3)	 Fig. 20–15	Fingers point along particle's velocity $\vec{v}$, then along $\vec{B}$	Thumb points in direction of the force $\vec{F}$

Electric motor



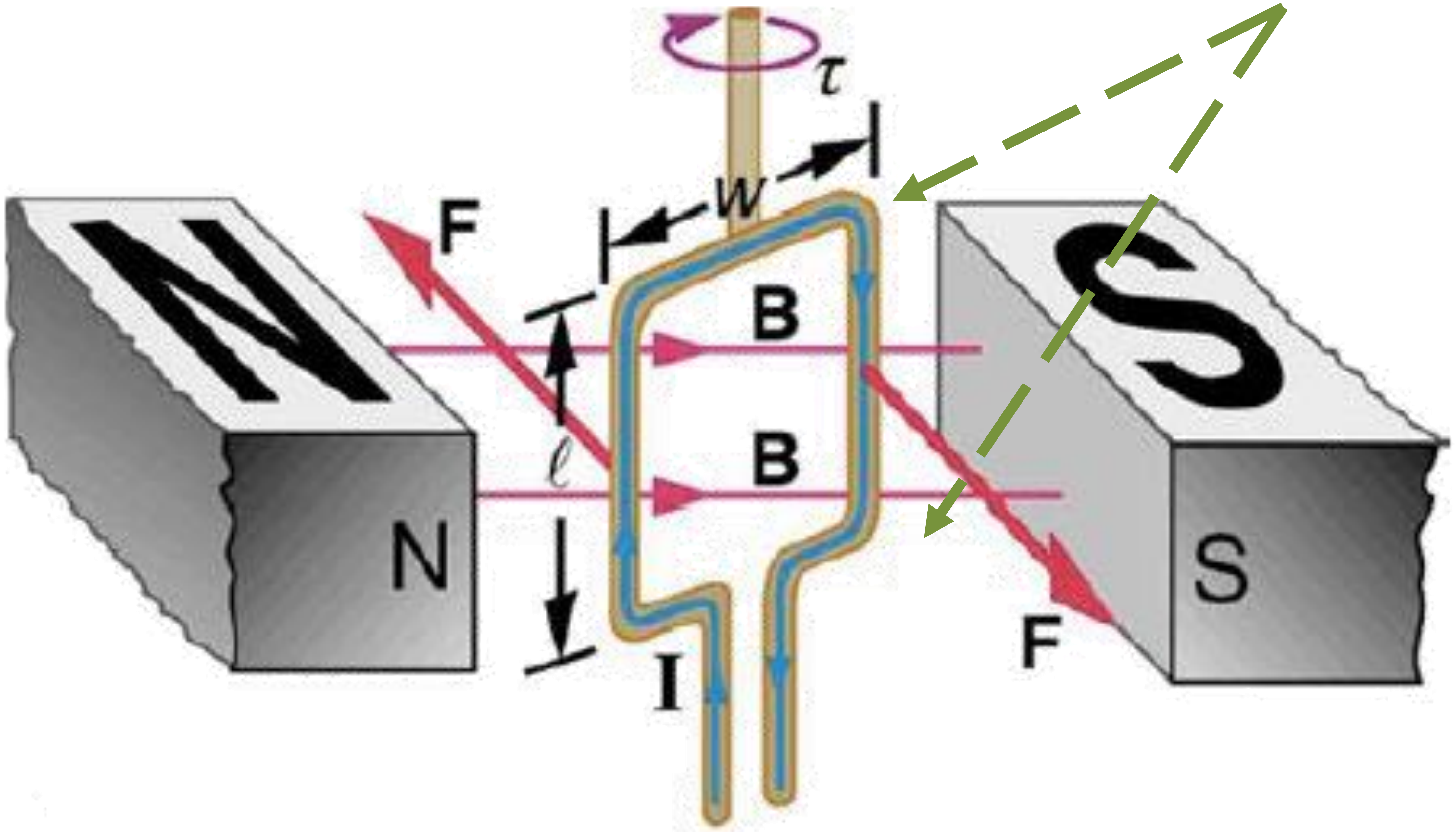
Electric motor





Electric motor

forces on these two parts
are vertical (**no torque**)



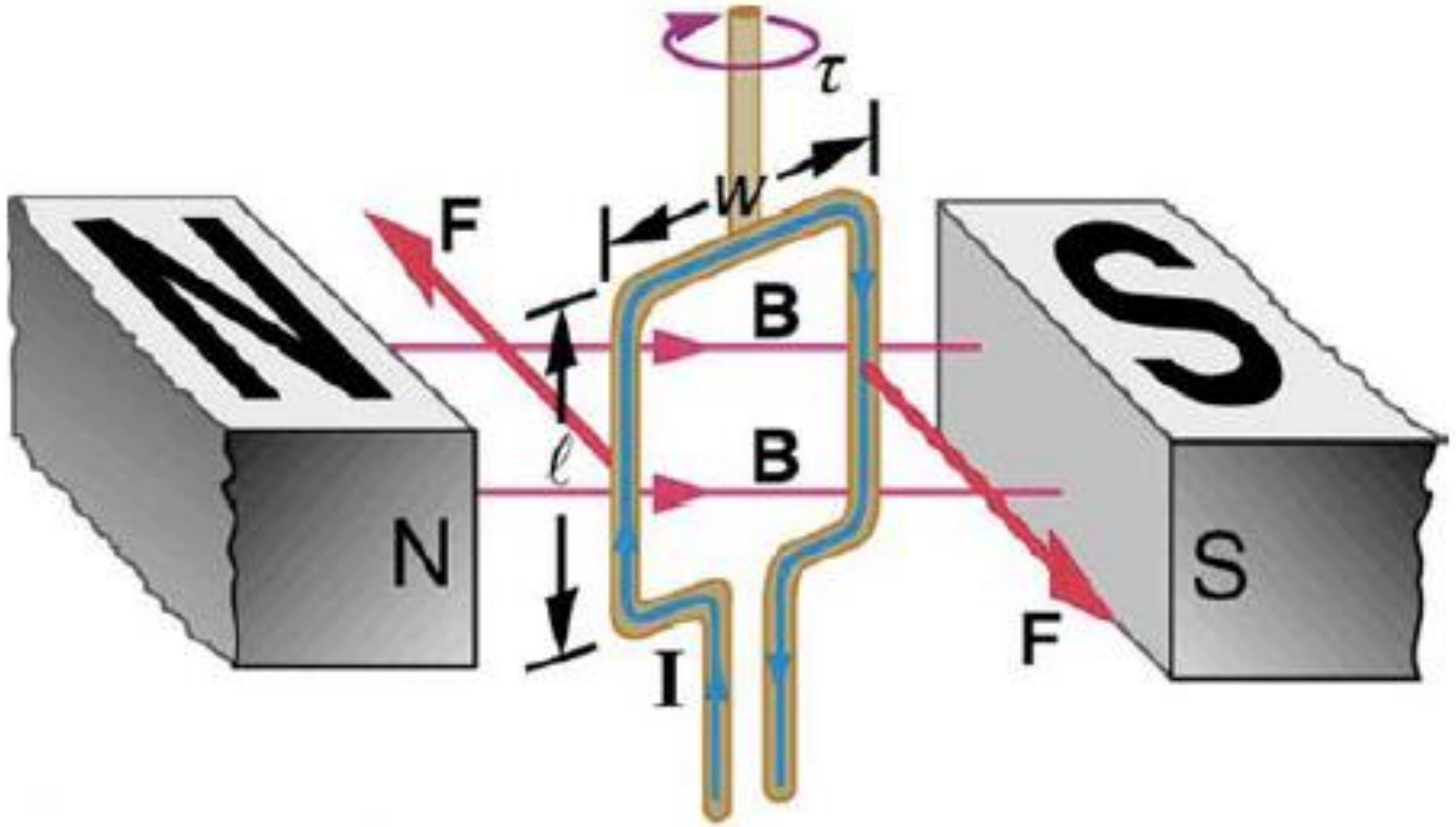
The magnetic force on the conductor creates ***torque***

Electric motor

torque: $\tau = rF\sin\theta$

r : distance from the pivot $\quad r = w/2$

θ : angle between F and r



- The torque on each vertical segment is the same

total torque: $\tau = \frac{w}{2}F\sin\theta + \frac{w}{2}F\sin\theta = wF\sin\theta$

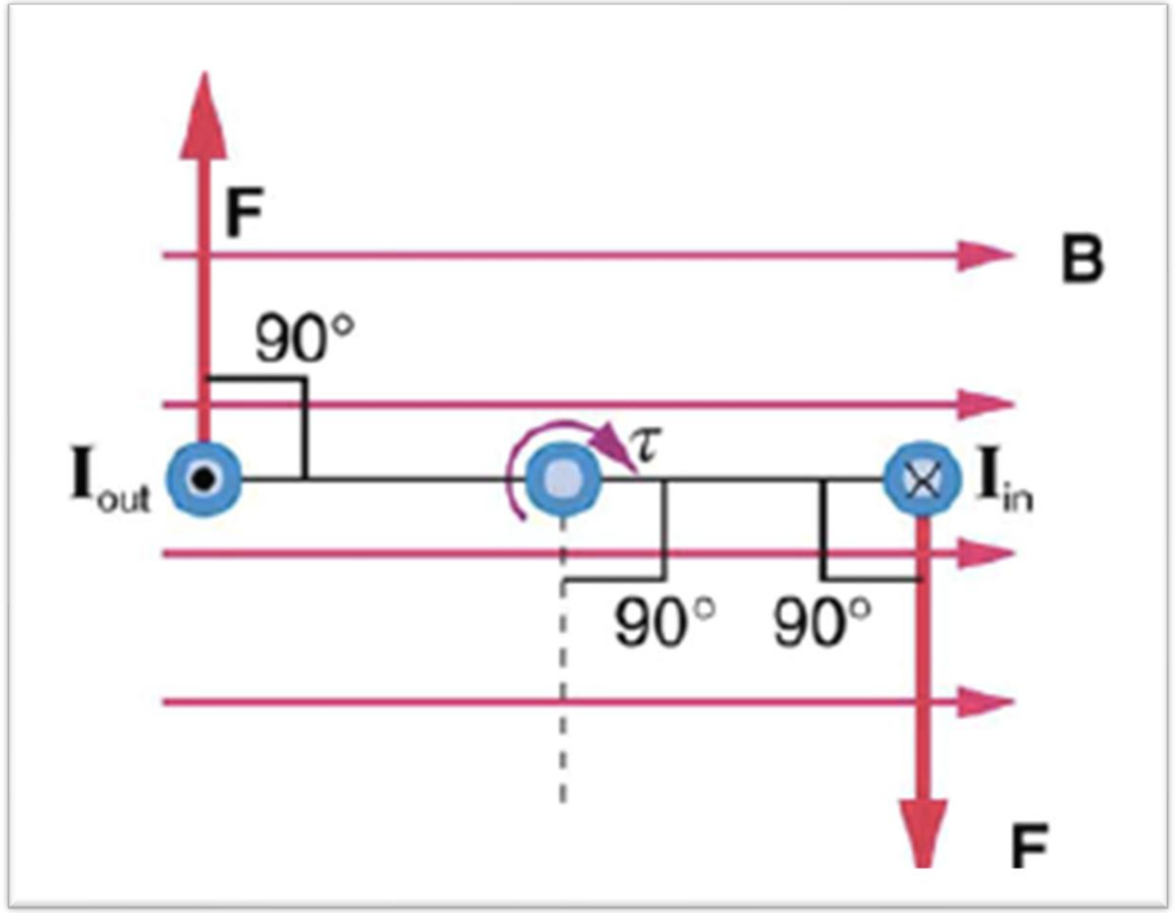
Electric motor

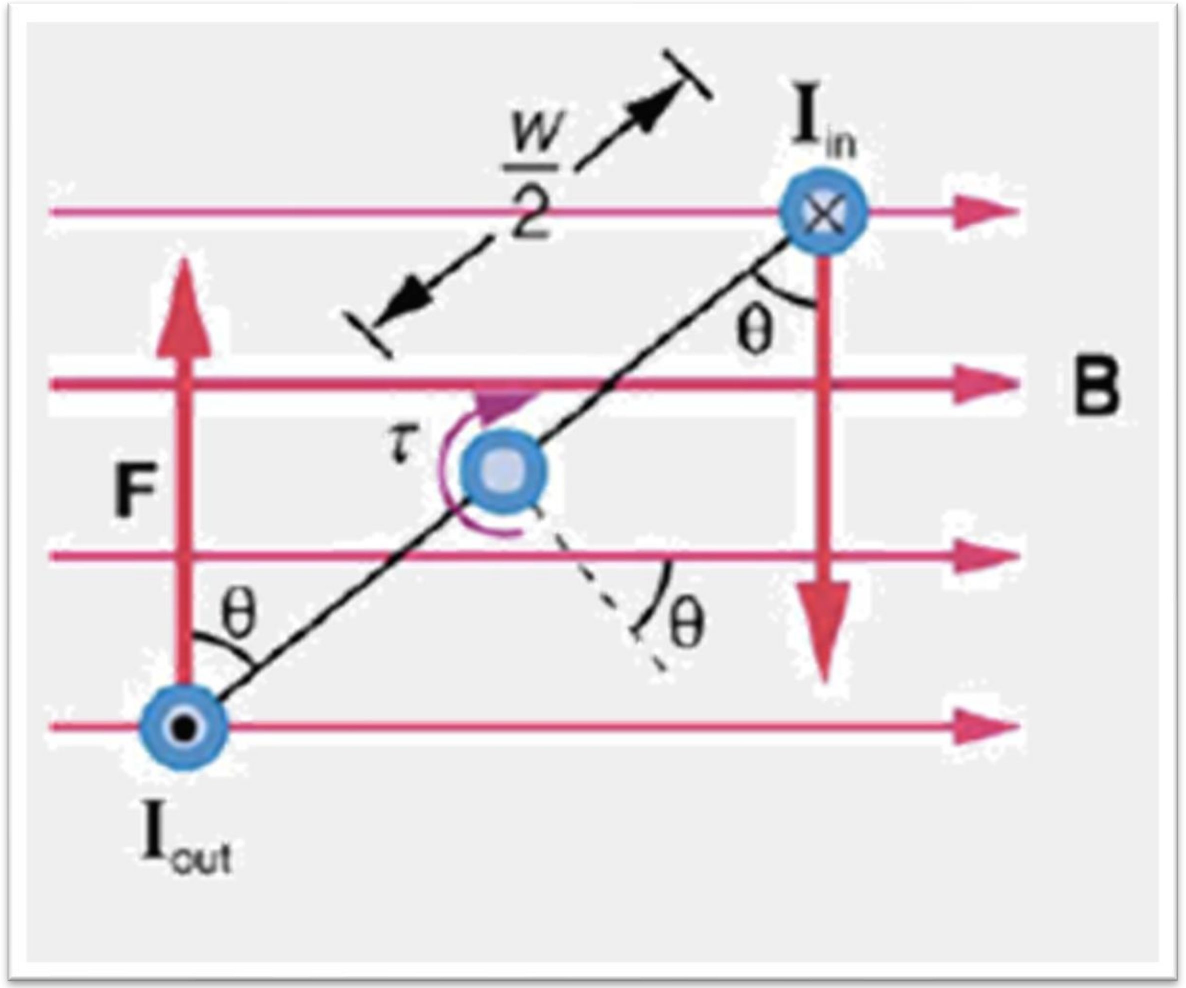
$$\tau_{\max} = w\,I\,l\,B$$

$$\tau = wF\sin\theta$$

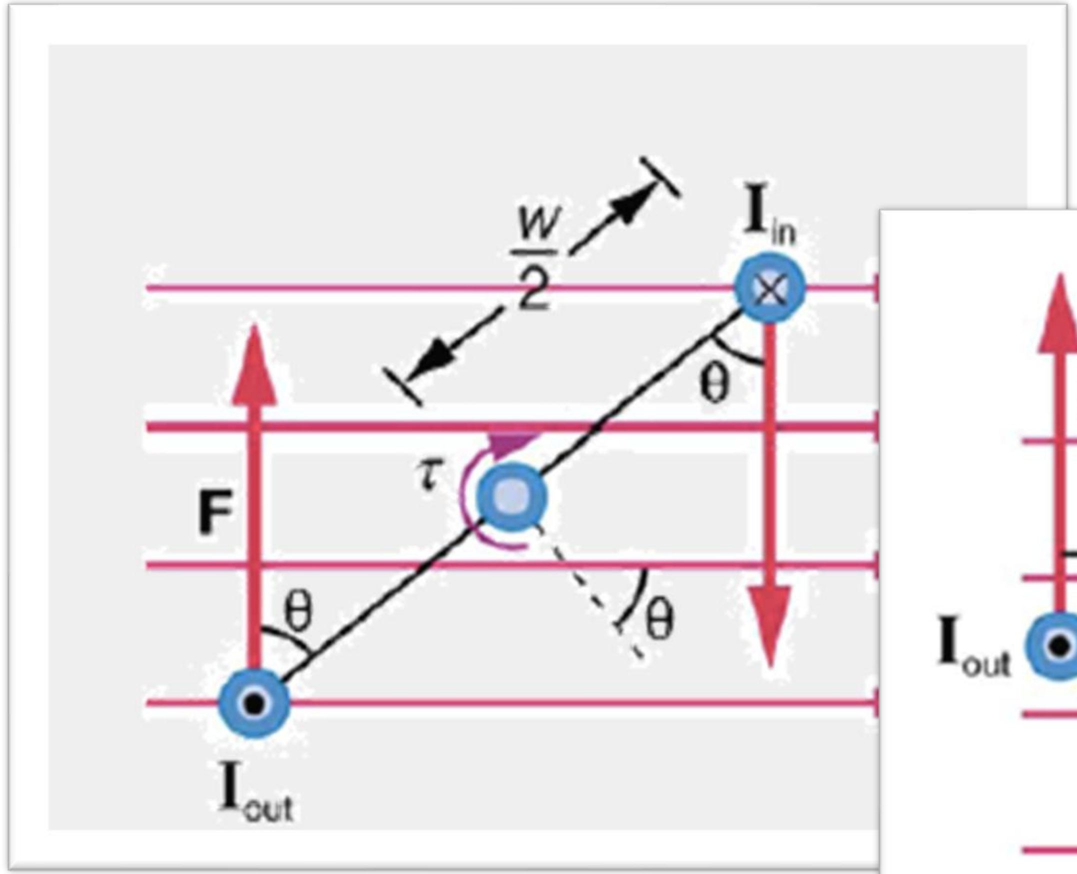
$$F = I\,l\,B$$

$$\Longrightarrow \tau = w\,I\,l\,B\sin\theta$$

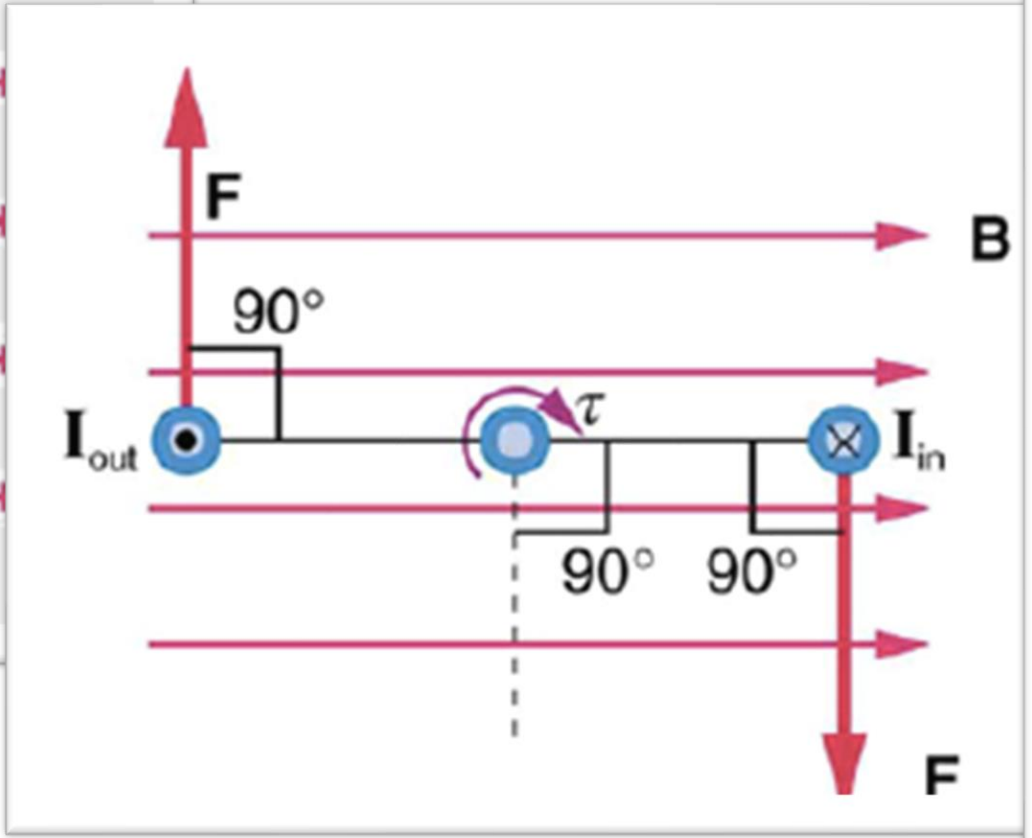




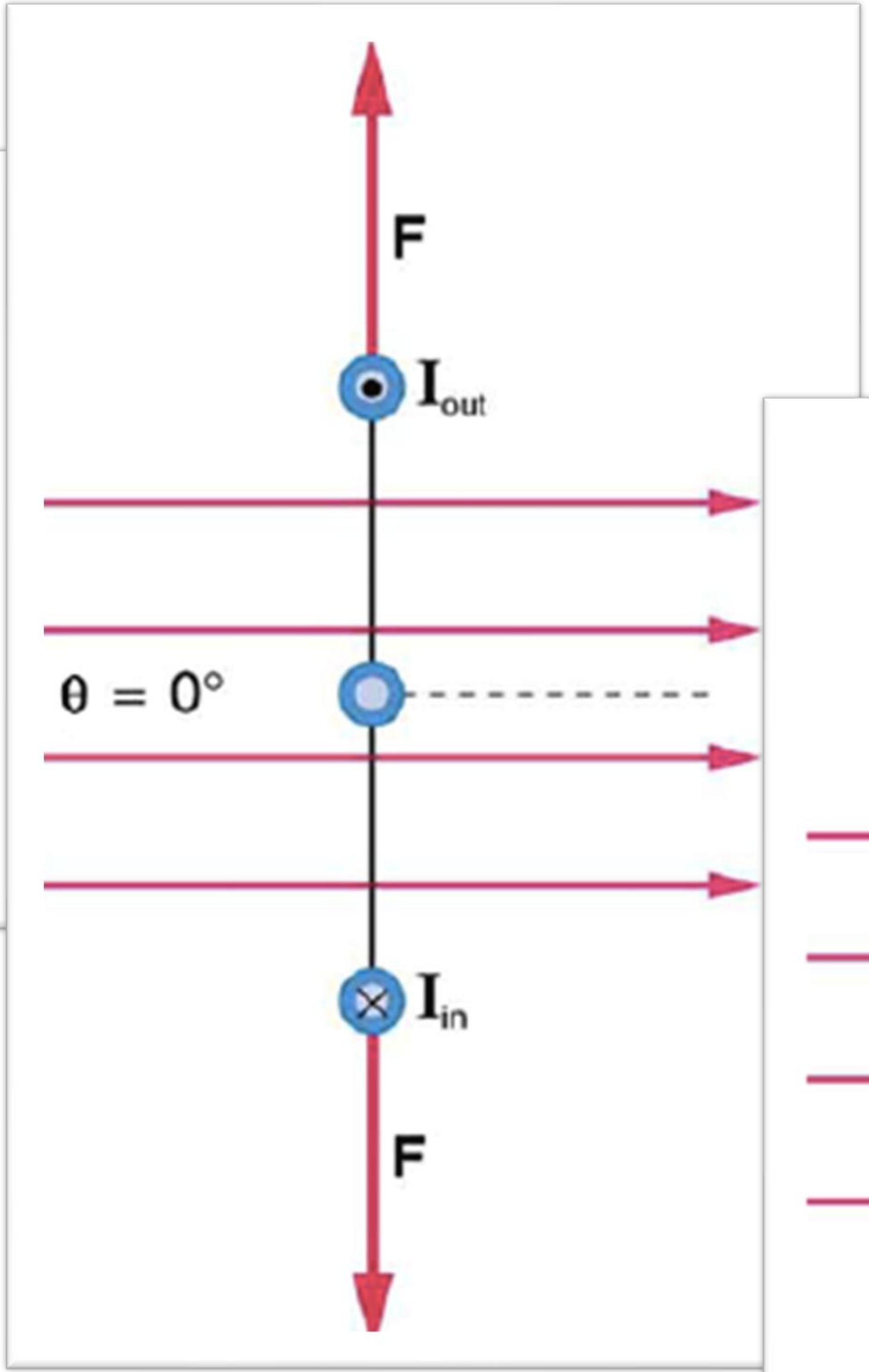
Electric motor



$$\tau = w\,I\,l\,B\sin\theta$$



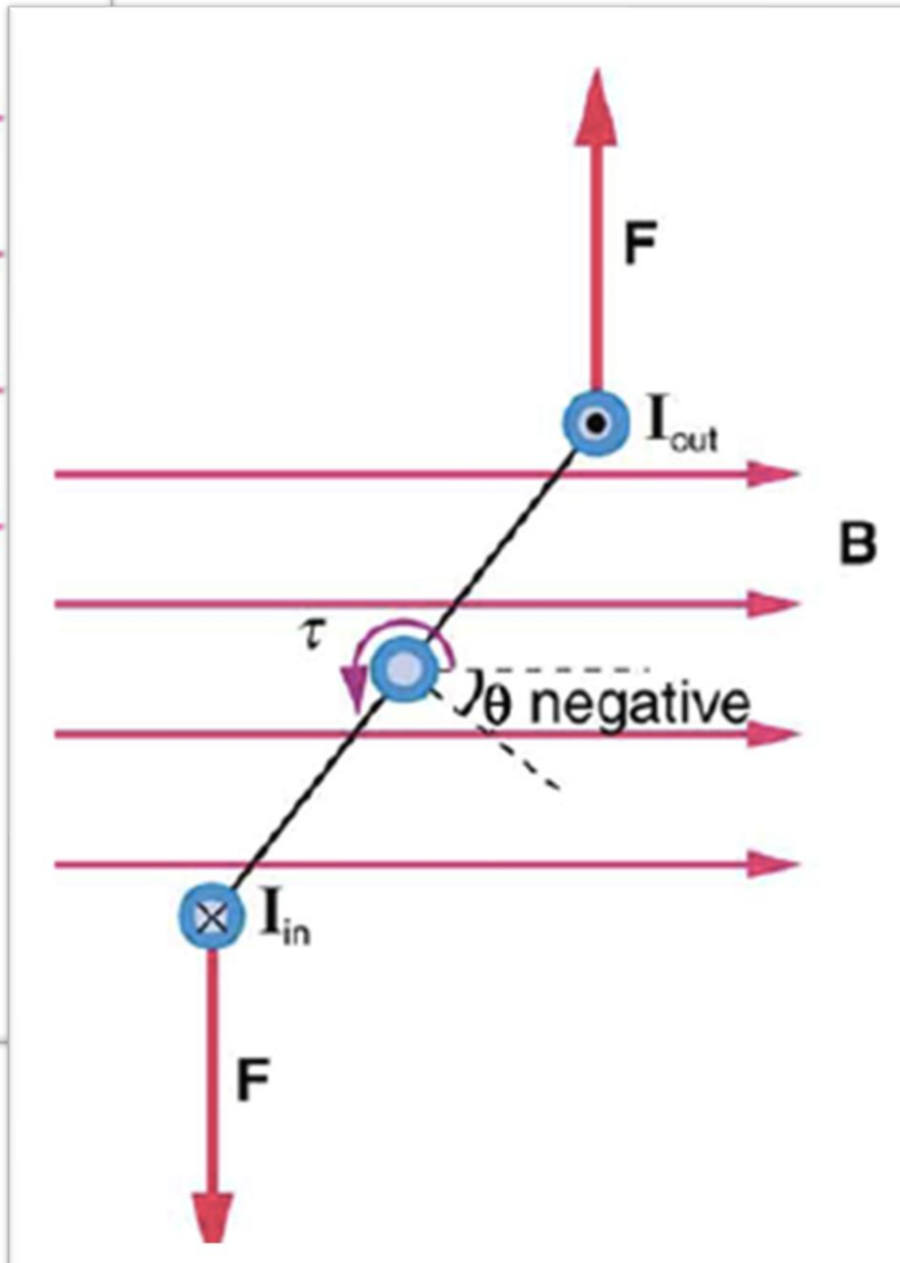
$$\tau_{\max} = w\,I\,l\,B$$

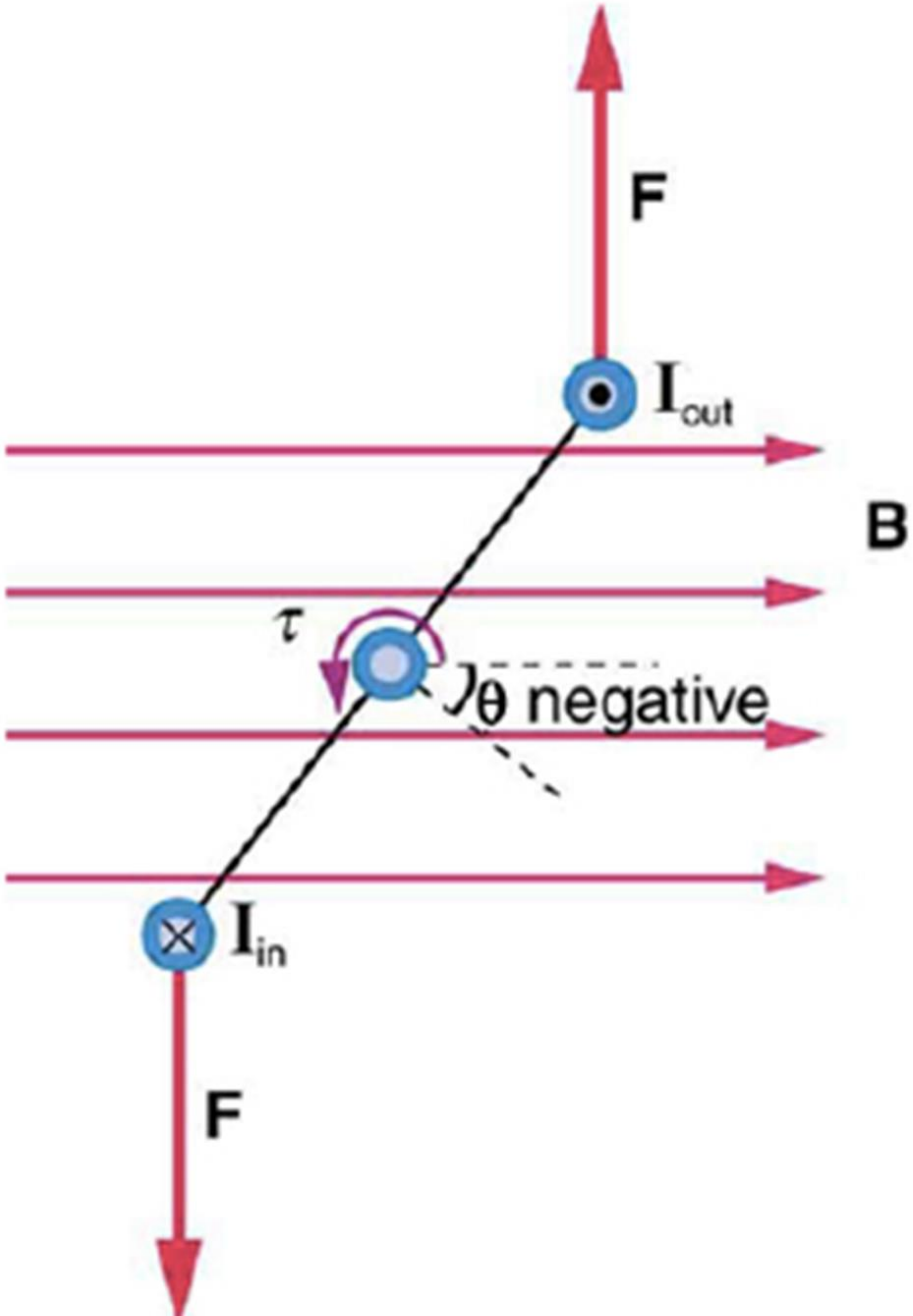


$$\theta = 0 \Longrightarrow \tau = 0$$

motor will stop?

torque is negative



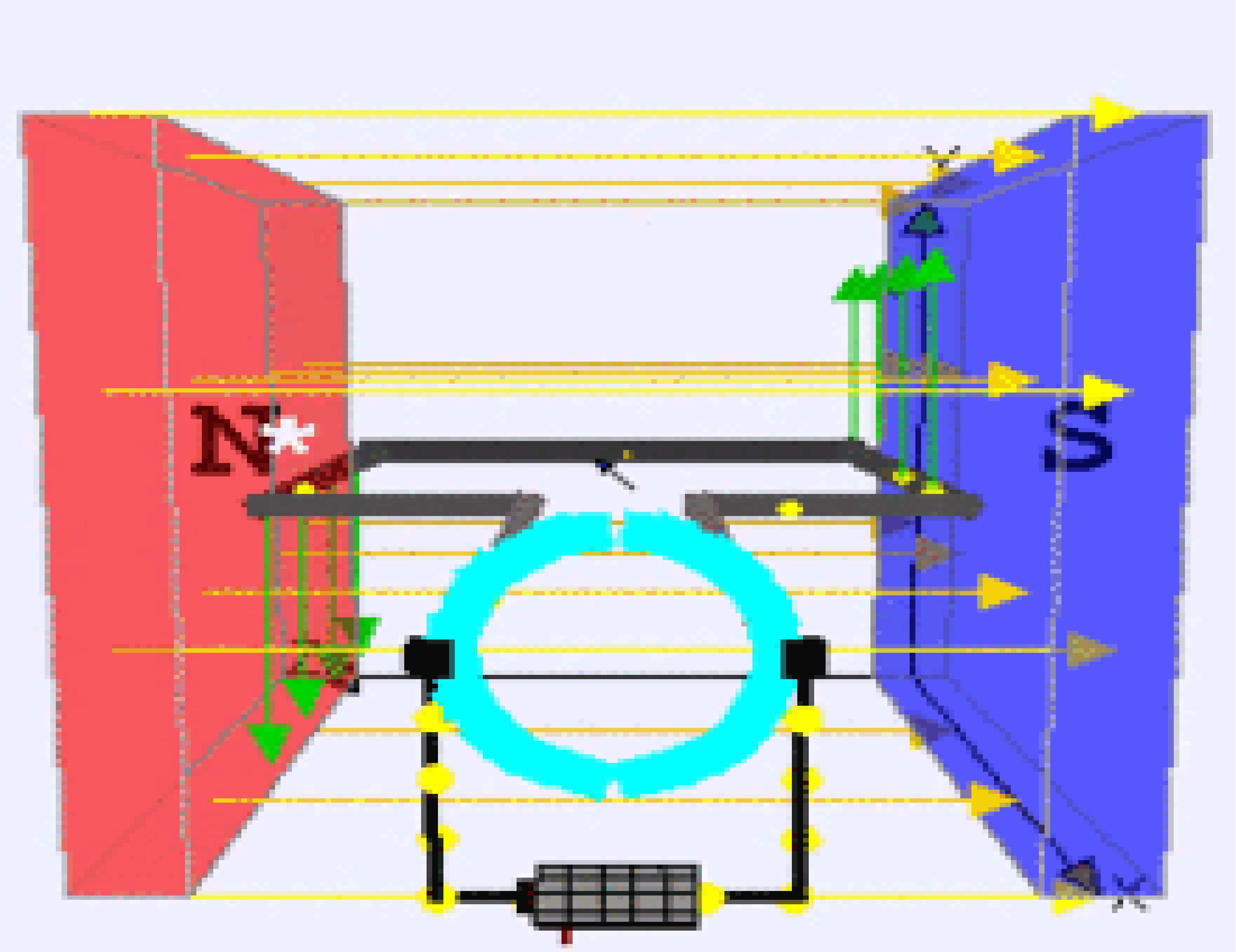


How to keep the motor going?

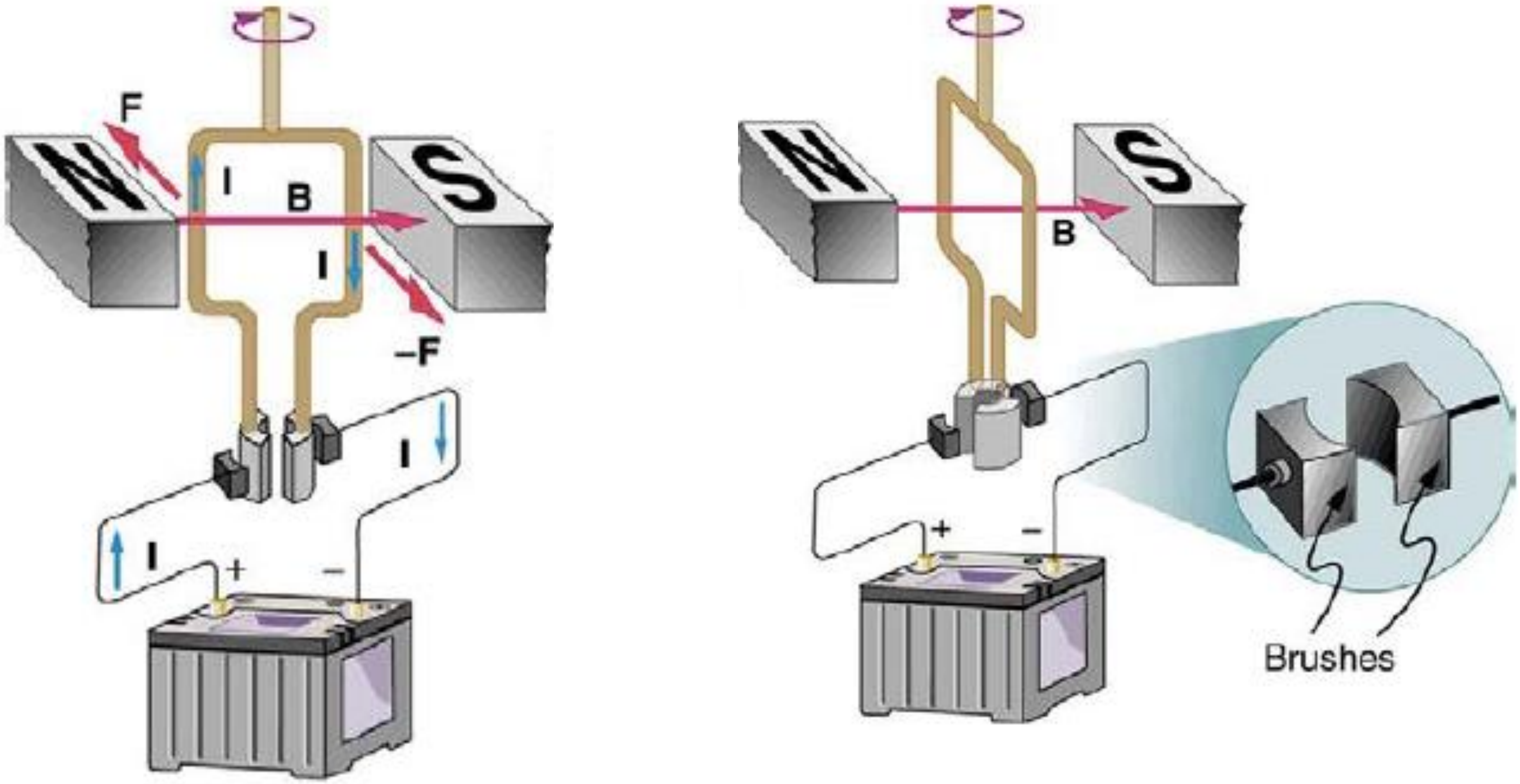
- by having the torque always in the same direction

Ways to keep the motor going?

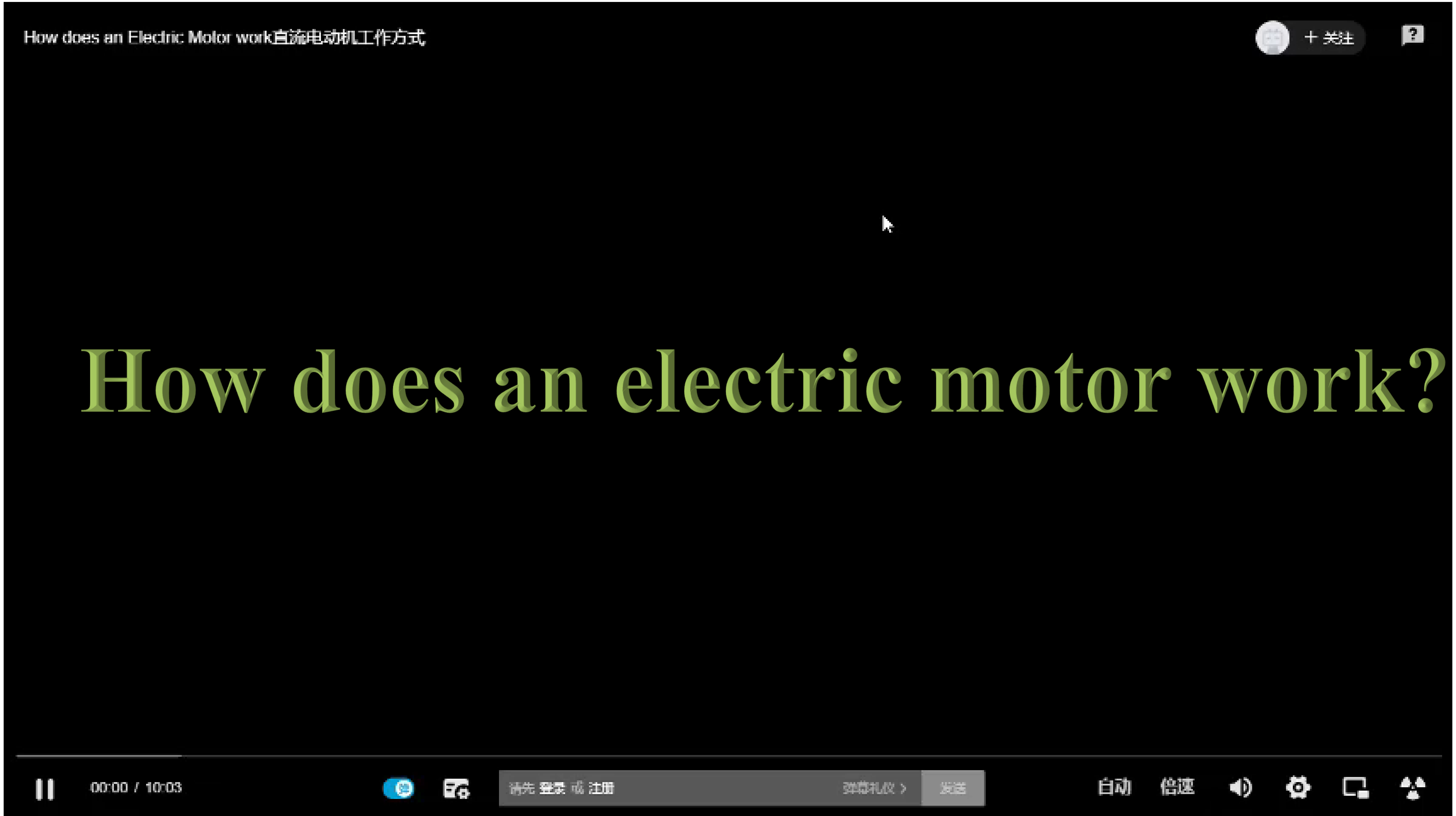
- Change the direction of :
  1. magnetic poles
  2. current


N
S

The direction of the current is reversed whenever the loop goes through $\theta = 0$



Video


How does an Electric Motor work直流电动机工作方式
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How does an electric motor work?
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请先 登录 或 注册
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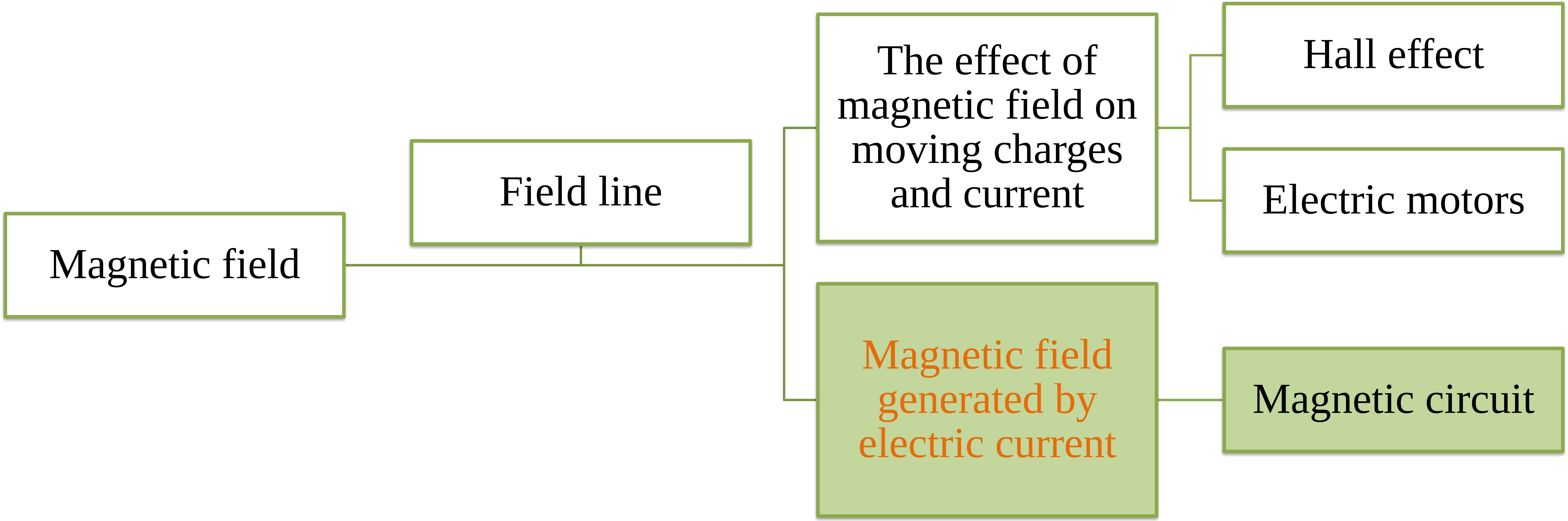
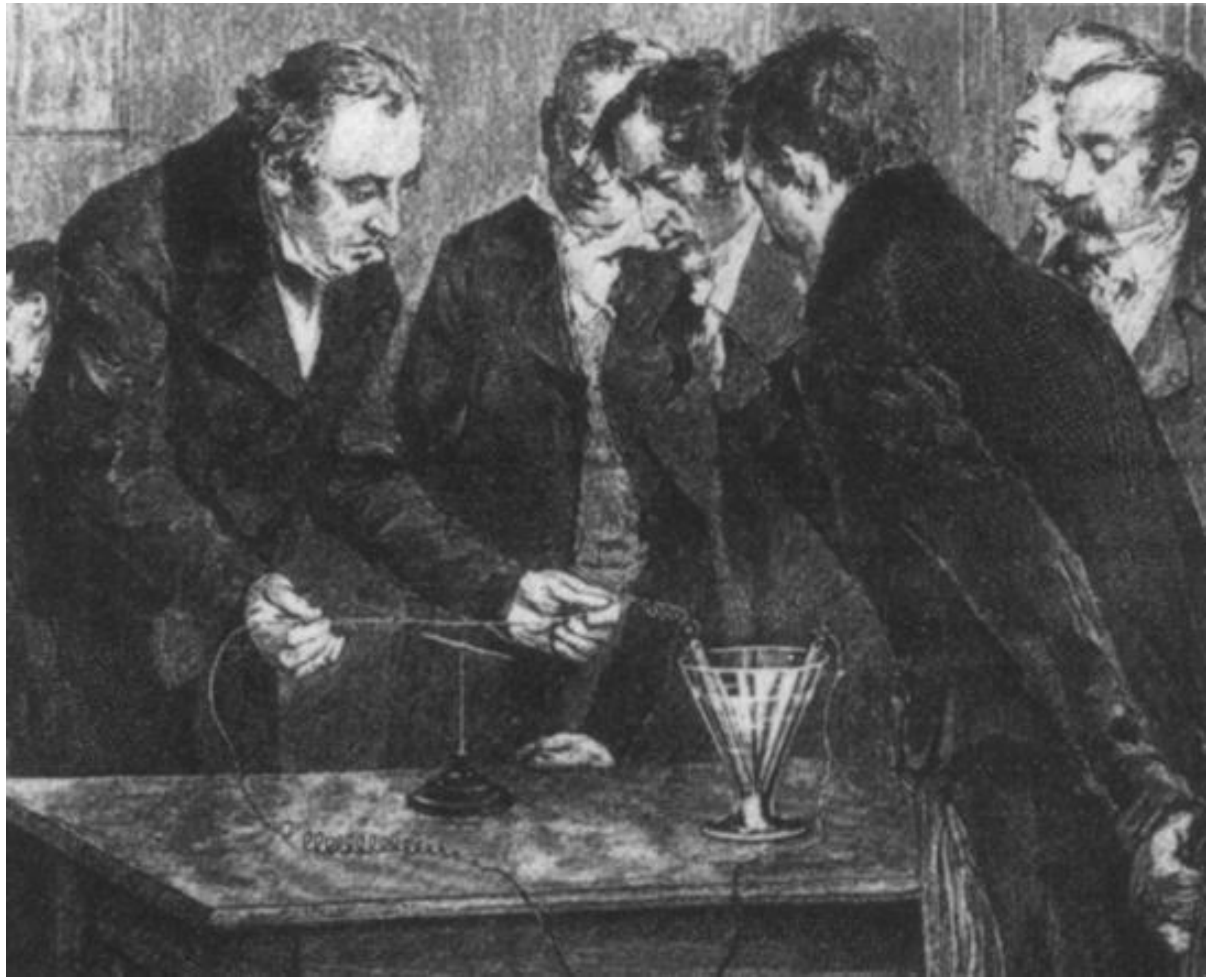
Structure

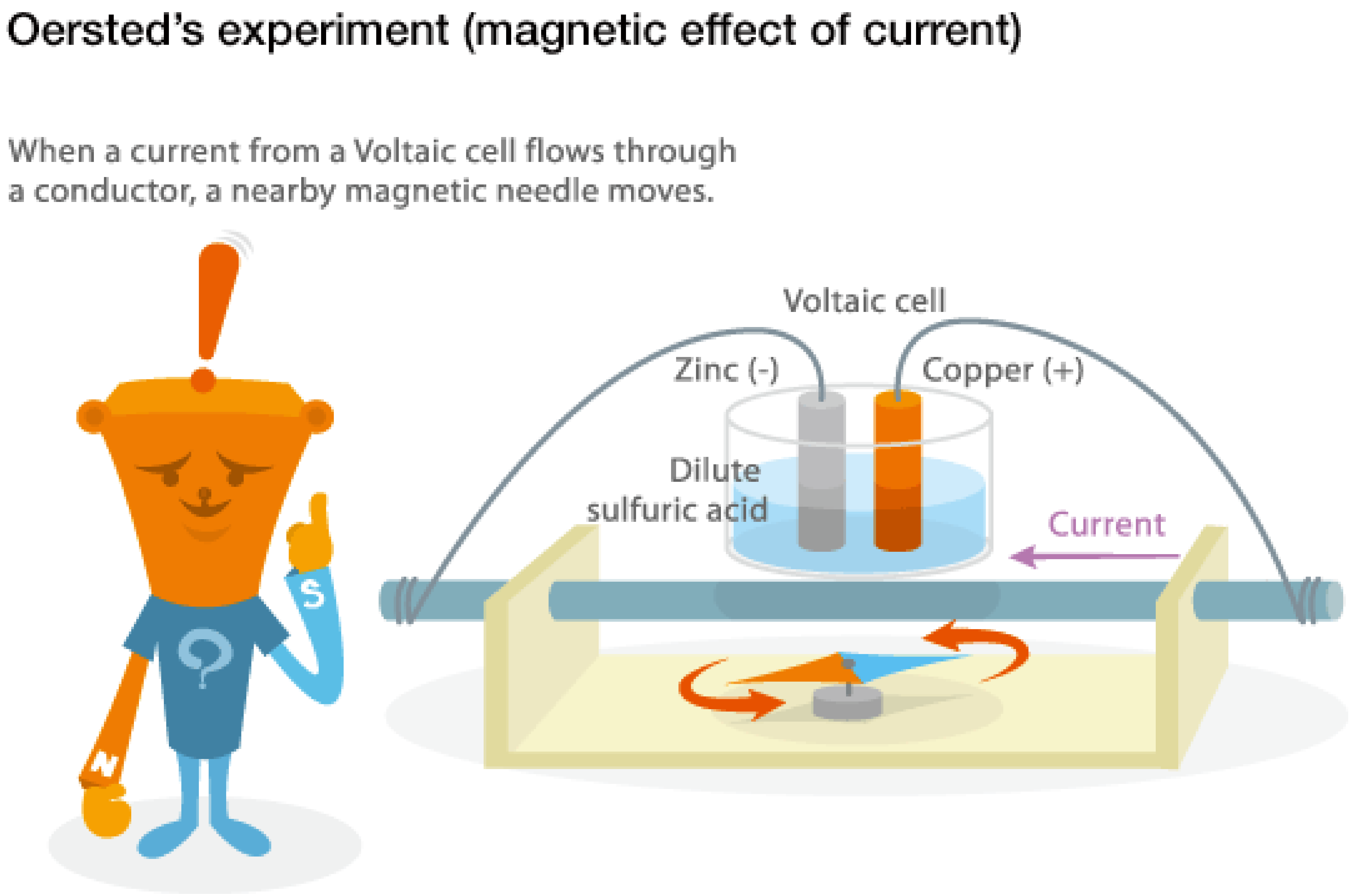

Magnetic field
Field line
The effect of magnetic field on moving charges and current
Hall effect
Electric motors
Magnetic field generated by electric current
Magnetic circuit

An electric current induces a magnetic field

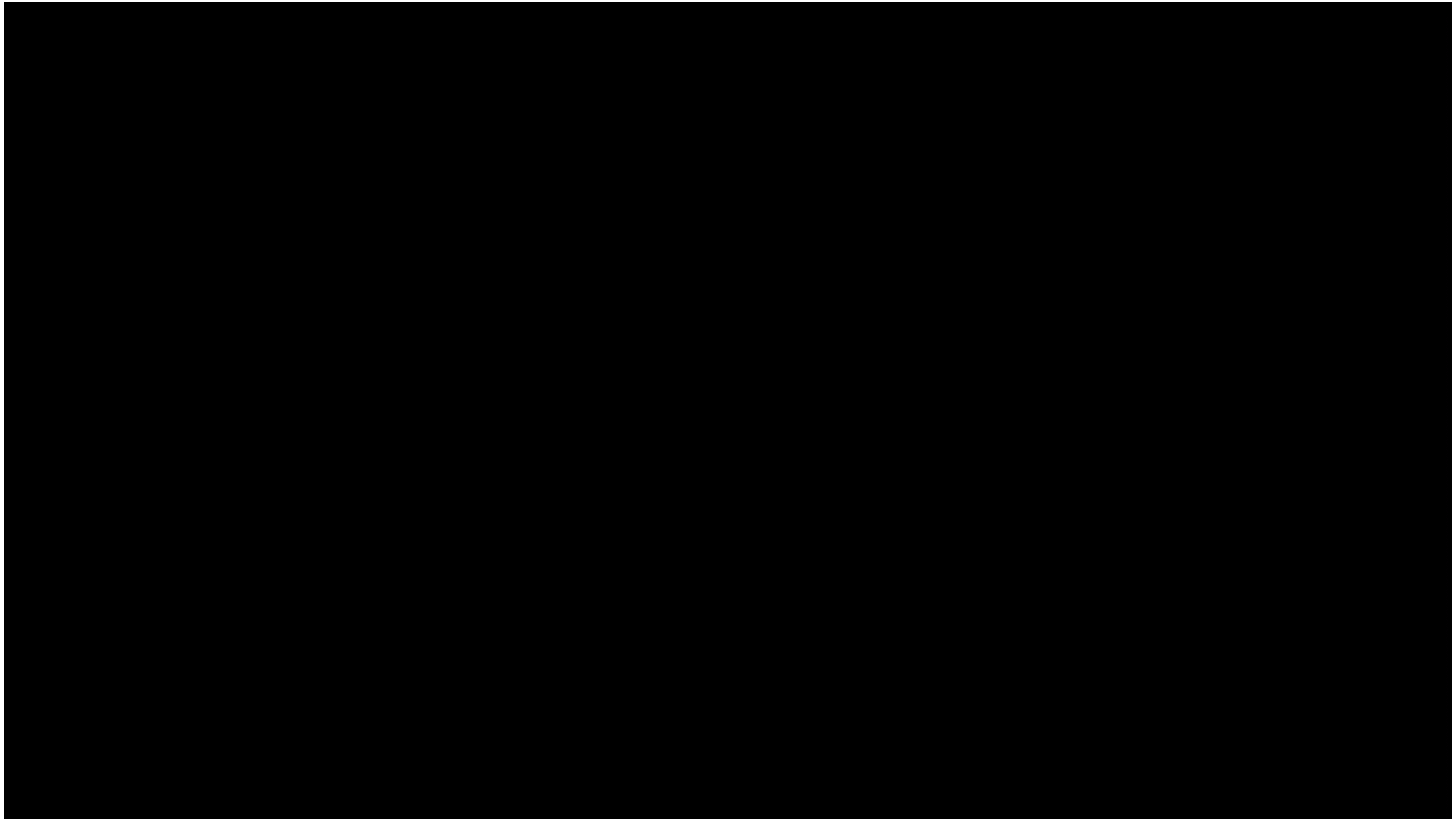


Hans Christian Ørsted (1820)

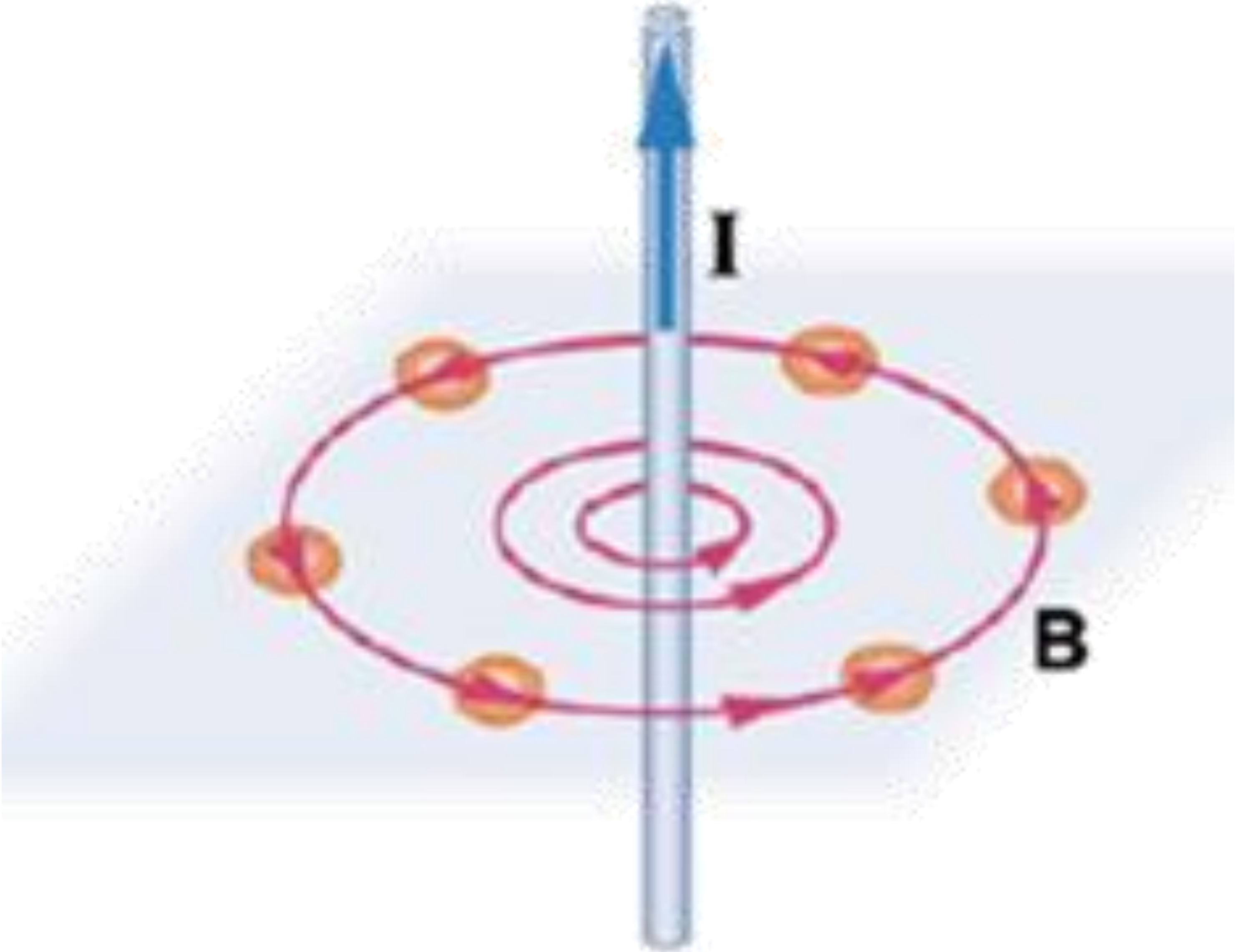
An electric current induces a magnetic field

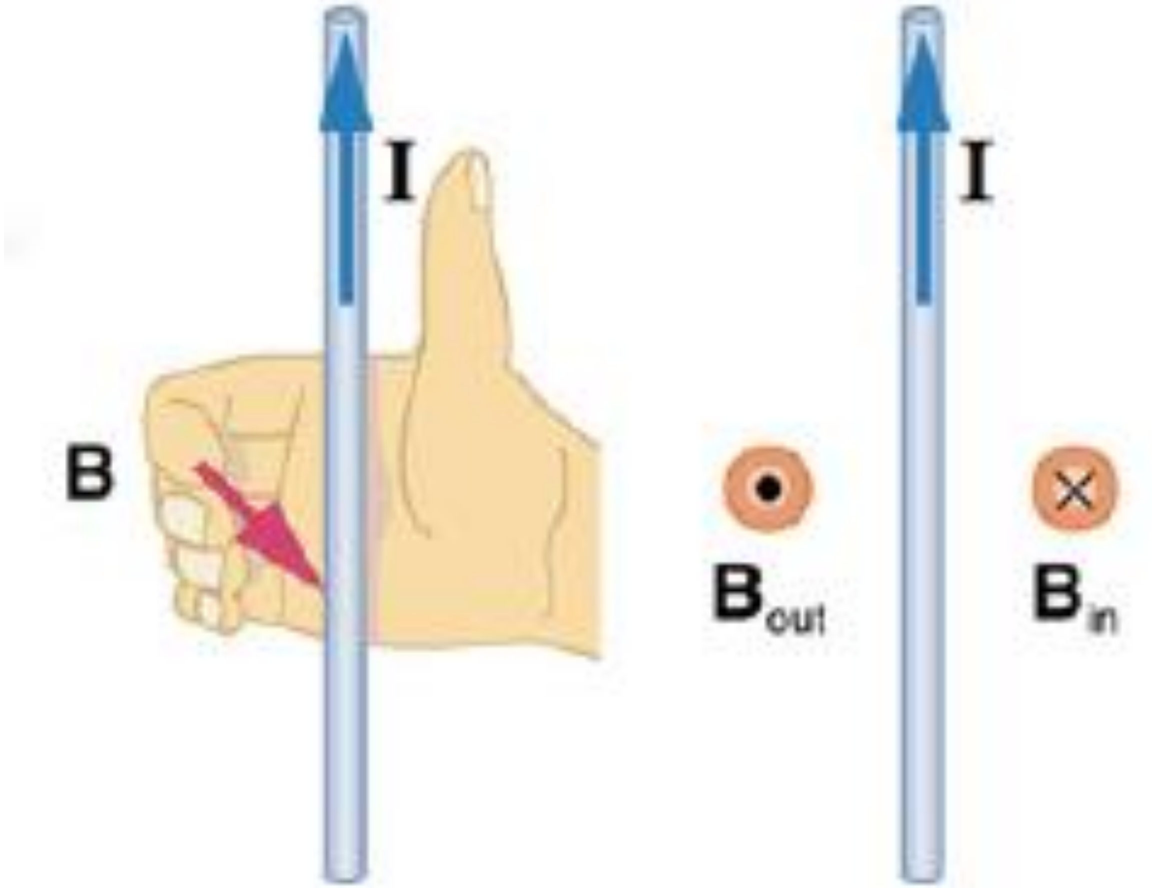


Oersted Experiment



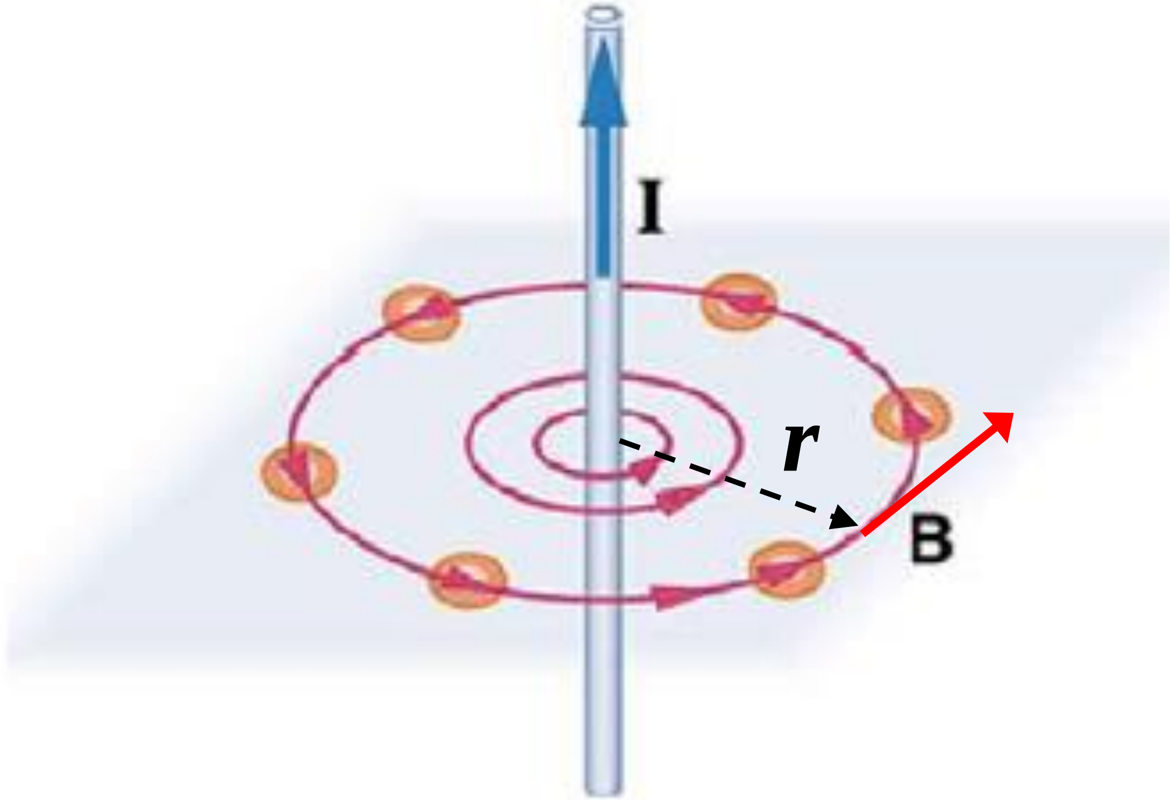
Right hand rule





Ampere's law: Magnetic field produced by a current

long, **straight** wire



$$B = \frac{\mu_0 I}{2\pi r}$$

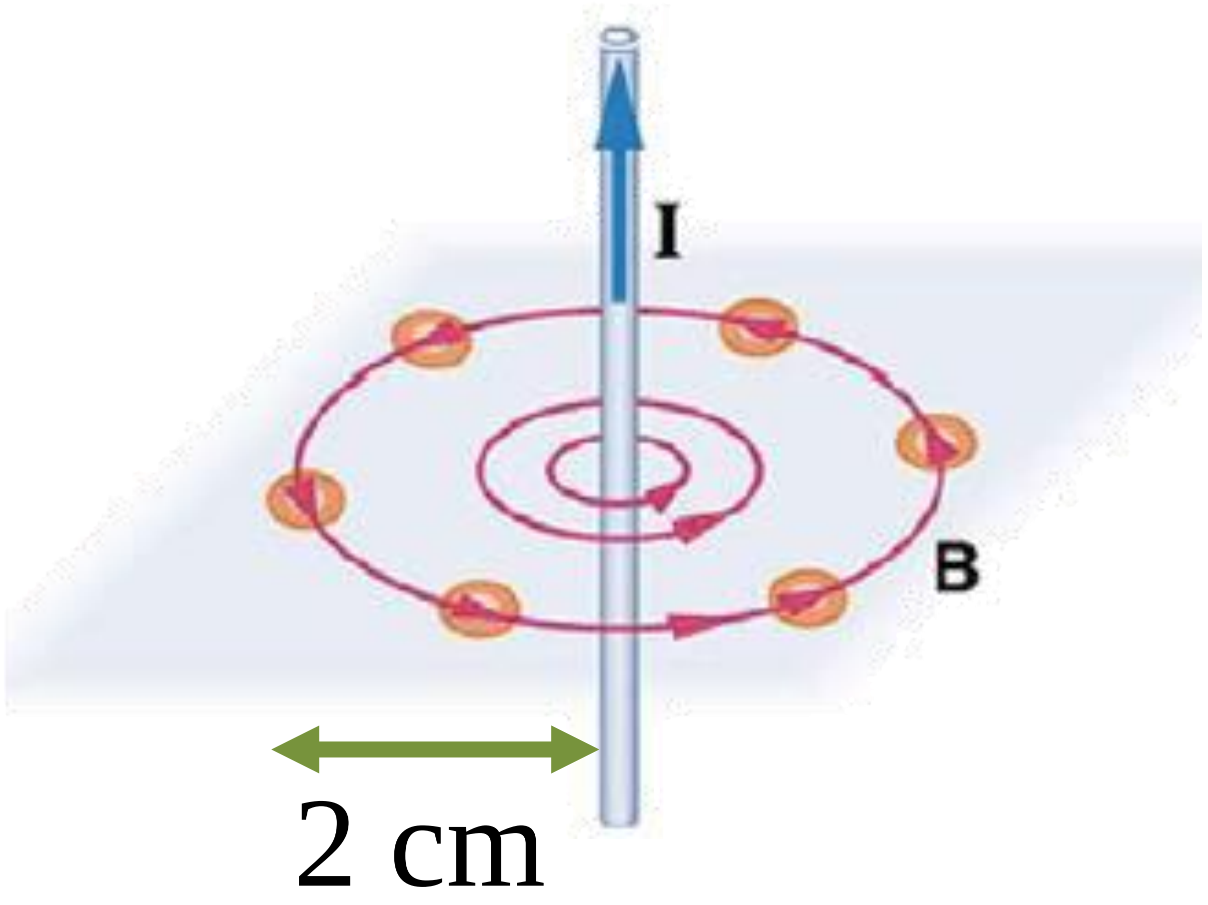
$\mu_0 = 4\pi \times 10^{-7}$ T m/A

(N/A^2)

permeability of free space

Example

How much current is needed to produce a magnetic field equal to that of the Earth, at 2 cm from a long wire ?



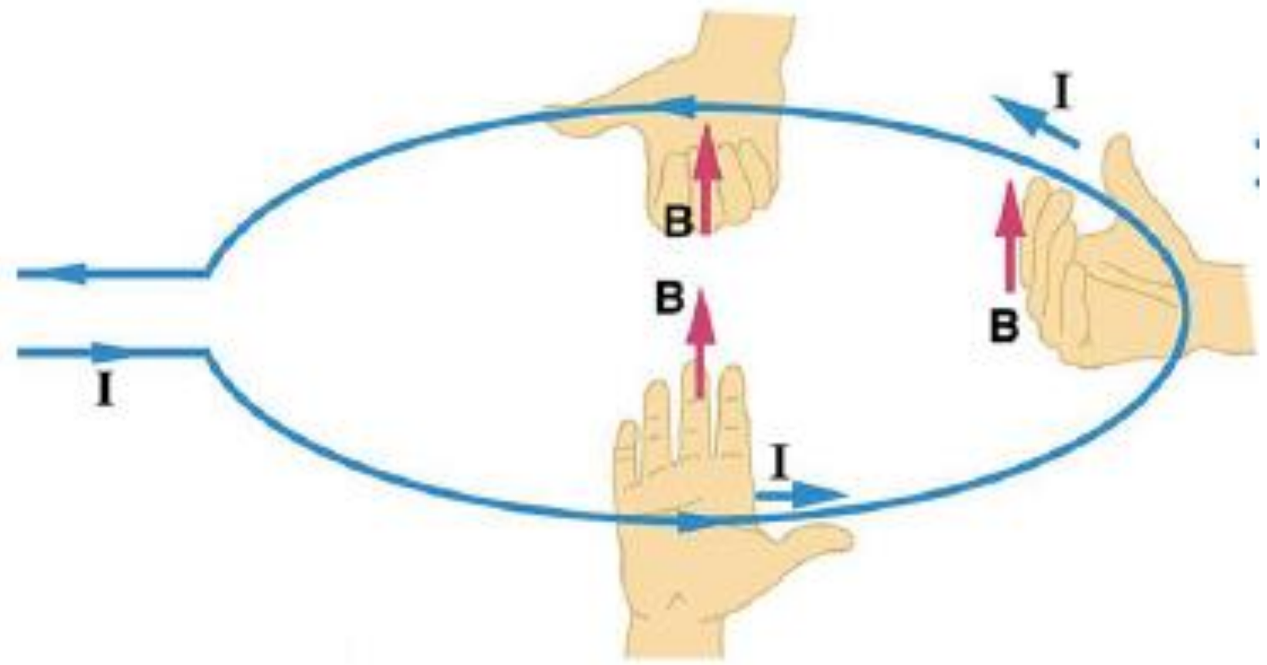
$$B = \frac{\mu_0 I}{2\pi r}$$

$B = 5 \times 10^{-5}$ T

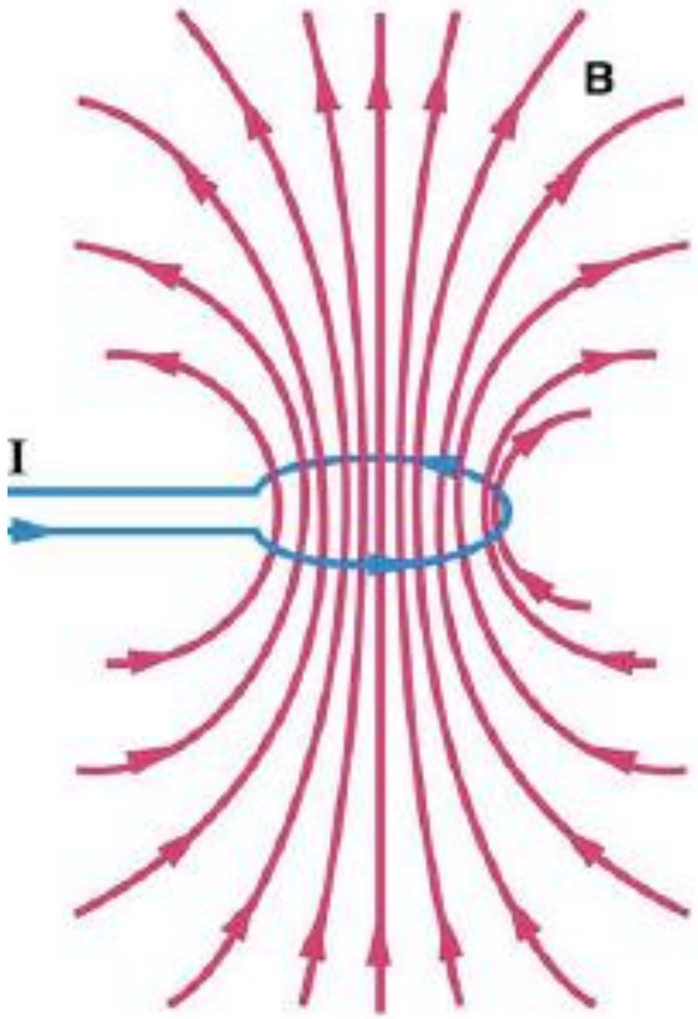
$r = 2 \times 10^{-2}$ m

$$I = \frac{2\pi r B}{\mu_0} \qquad = \frac{2\pi \times 2 \times 10^{-2}\,\text{m} \times 5 \times 10^{-5}\,\text{T}}{4\pi \times 10^{-7}} = 5\,A$$

Magnetic field from a circular current loop

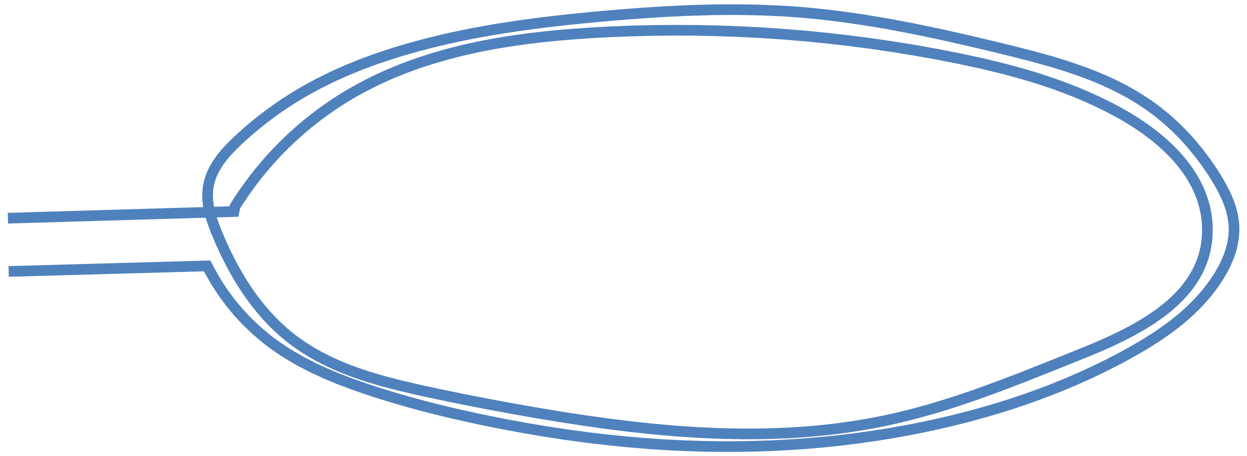


all elements of wire produce a field



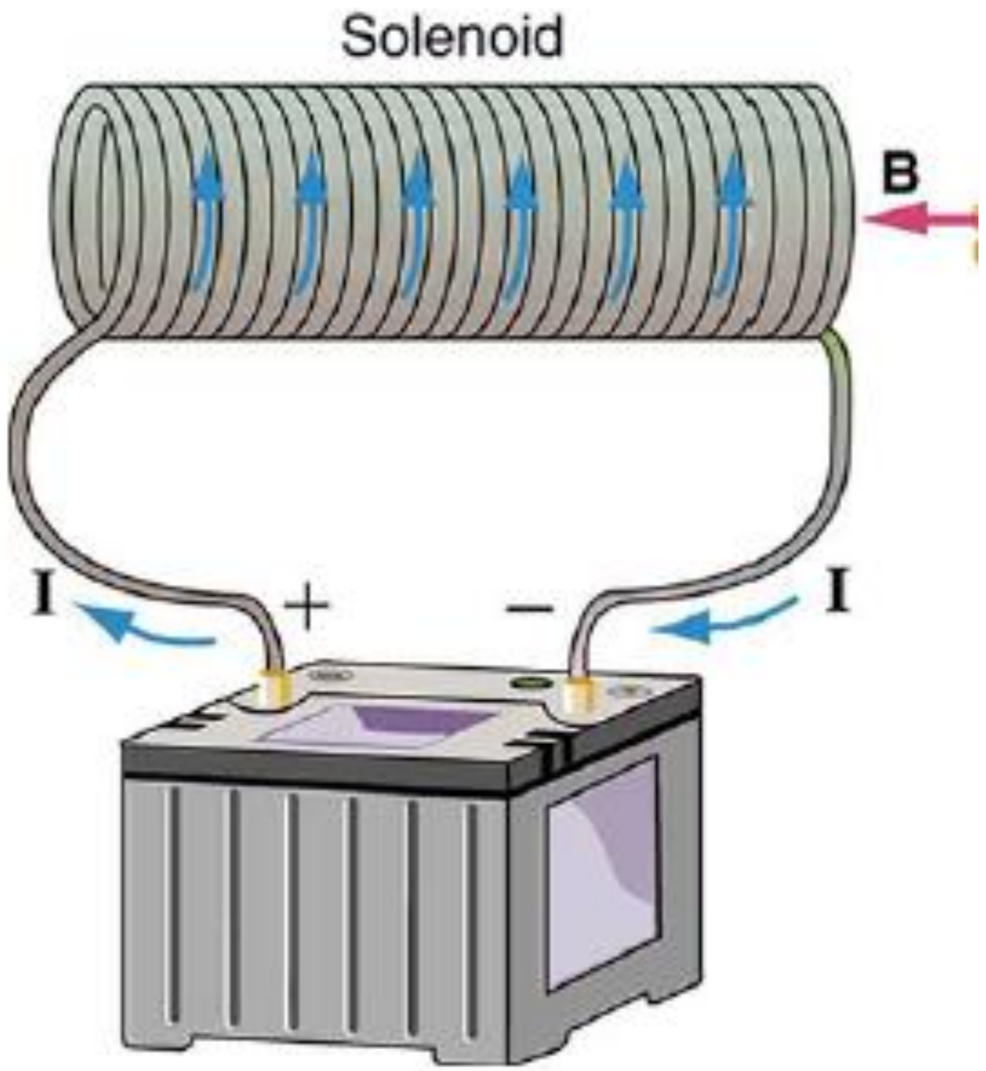
at the center:

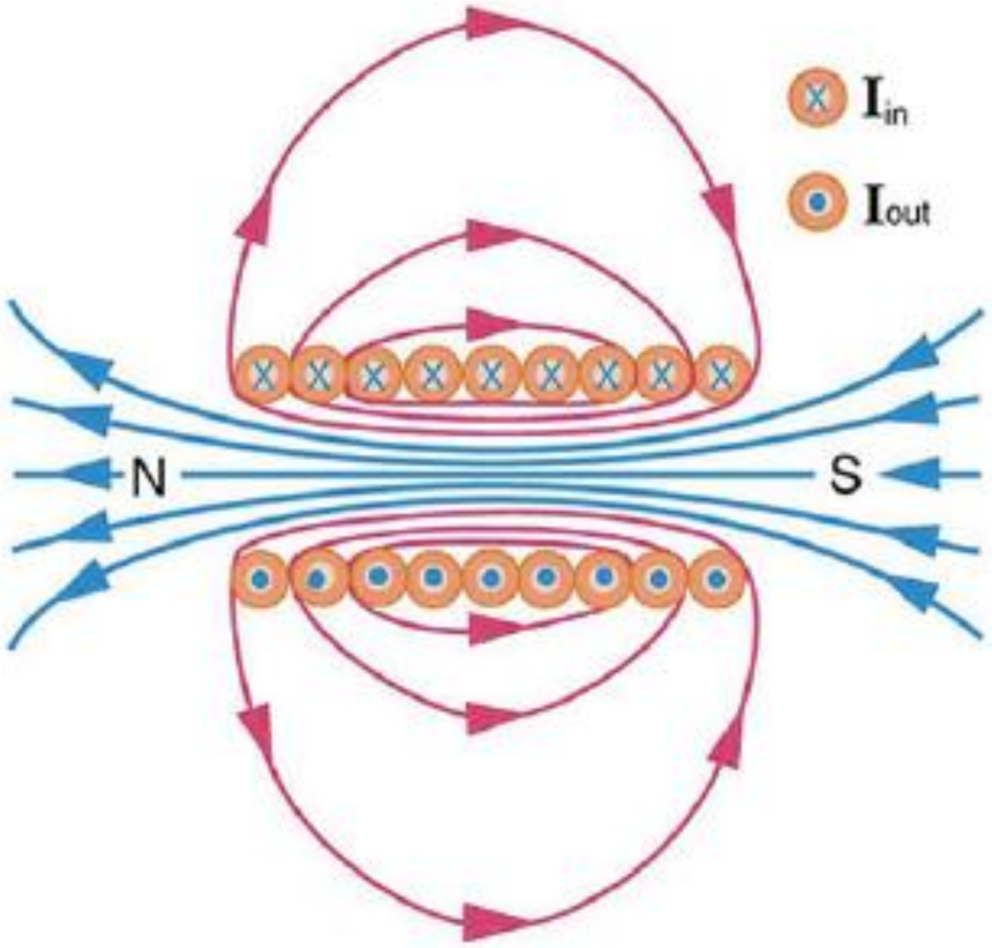
$$\boxed{B = \frac{\mu_0 I}{2R}}$$



for N loops: $B = N\frac{\mu_0 I}{2R}$

Solenoid - many loops of wire along one axis





n is the *number* of turns per unit of length

The magnetic field is almost constant (uniform) inside:

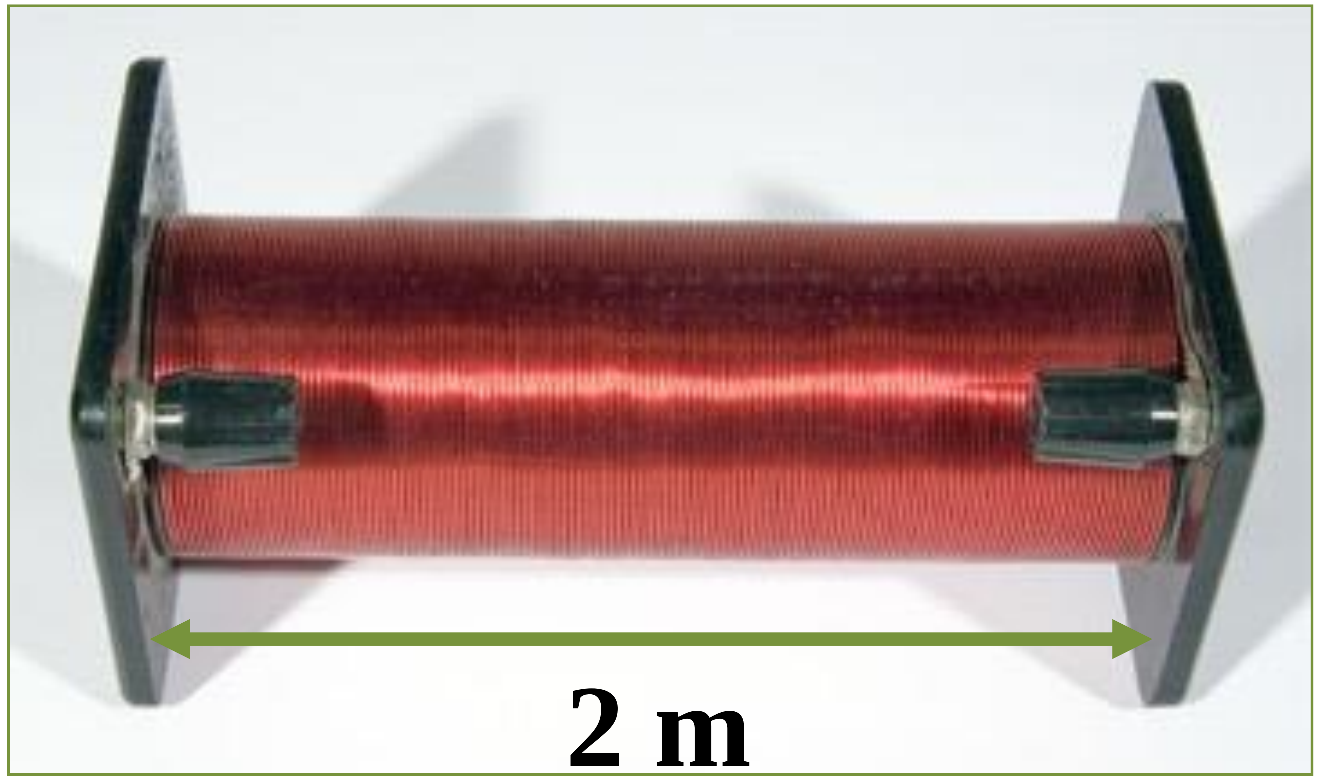
$$\boxed{B = \mu_0 n I}$$

Solenoid

2000 loops $\rightarrow$ 1000 loops/m

- current =1600 A

very large current!



What is the field B inside ?

$$B = \mu_0 \, n \, I = 4\pi \times 10^{-7} \times 1000 \,\text{loops/m} \times 1600 \, A = 2.01 \,\text{T}$$

Magnetic force

1. An electric current produces a magnetic field

$$B = \frac{\mu_0 I}{2\pi r}$$

2. A moving charge in a magnetic field will be subject to a magnetic force

$$F = qvB$$

3. An electric current is made of moving charges

$$F = IlB$$

→ A wire carrying electric current will exert a force on another wire carrying electric current!

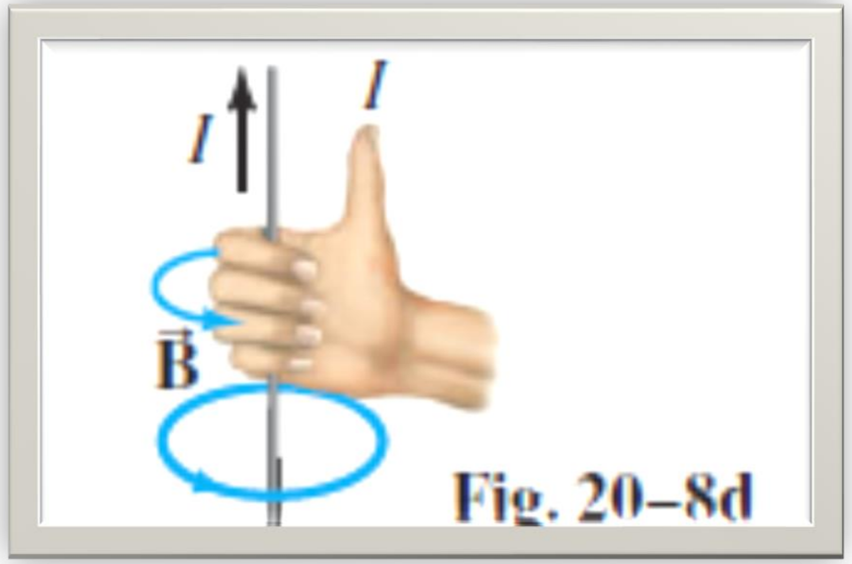


Fig. 20–8d

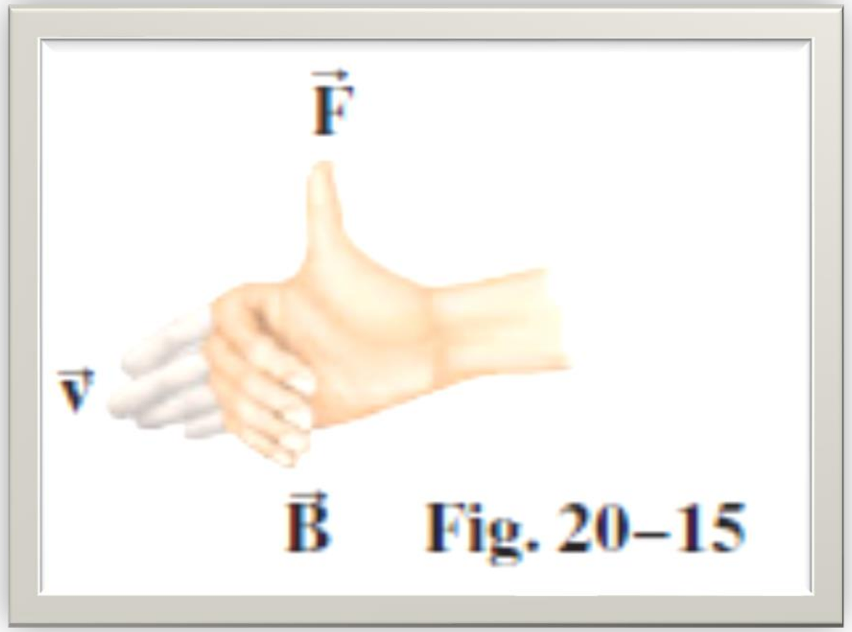


Fig. 20–15

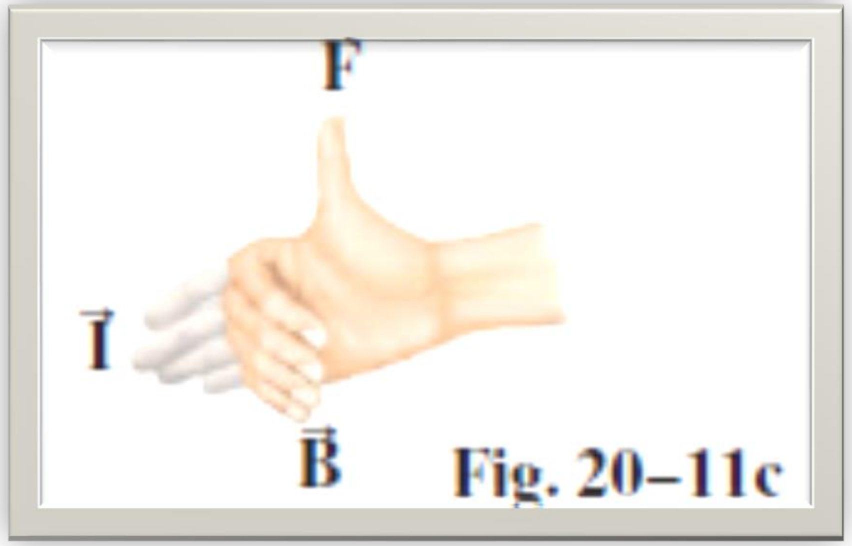
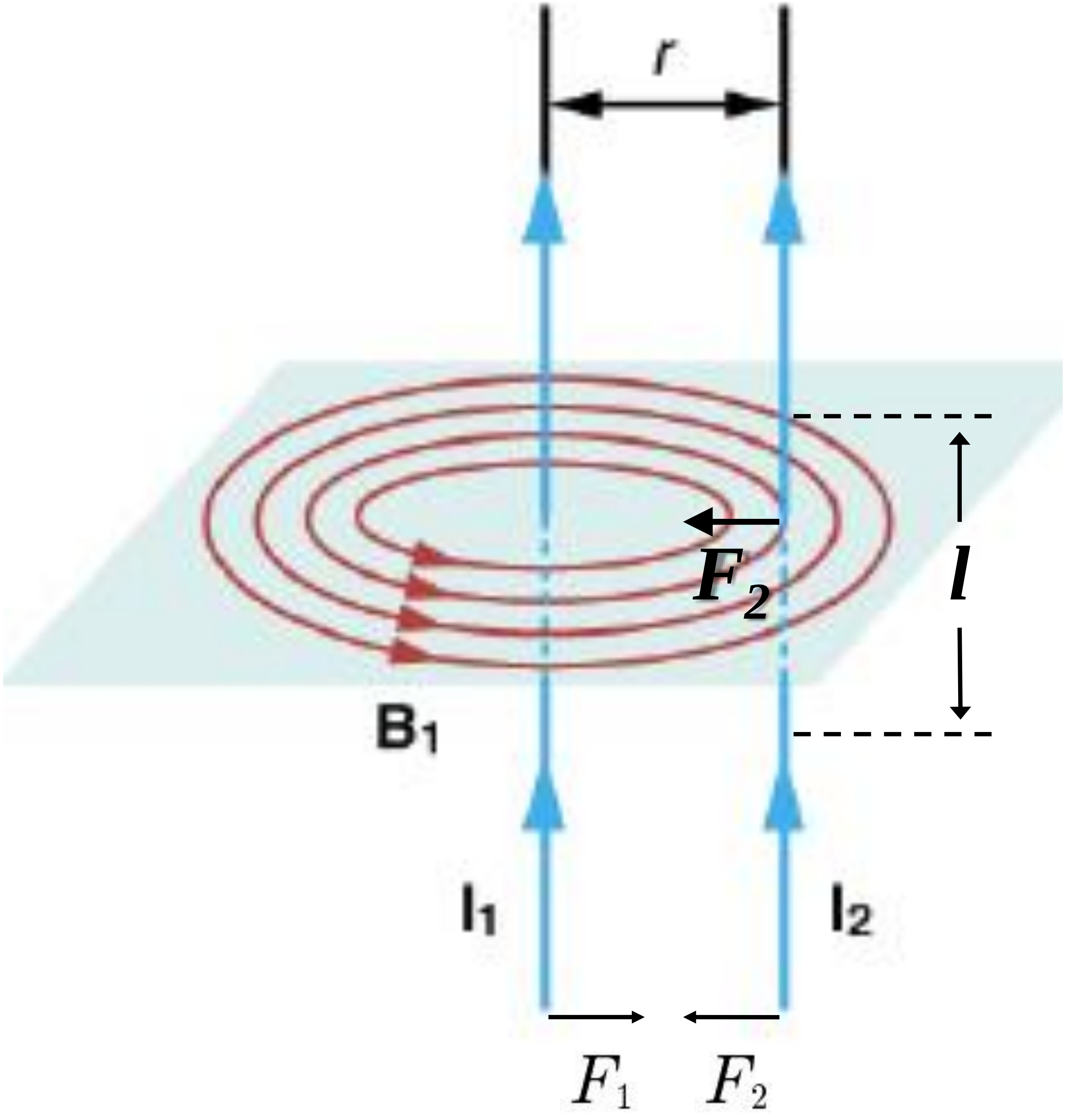
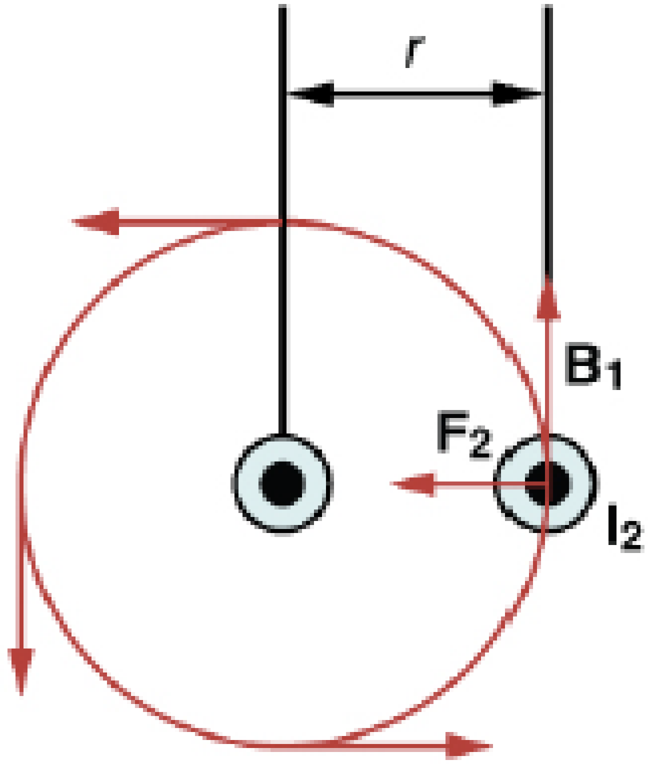


Fig. 20–11c

Magnetic force on Wire 2 from a parallel wire (Wire 1)

$$B_1 = \frac{\mu_0 I_1}{2\pi r}.$$



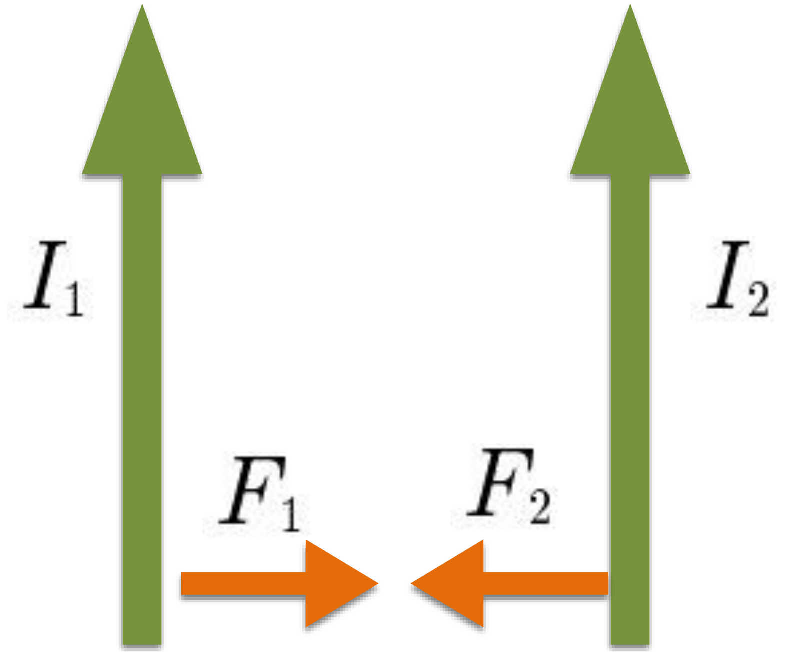


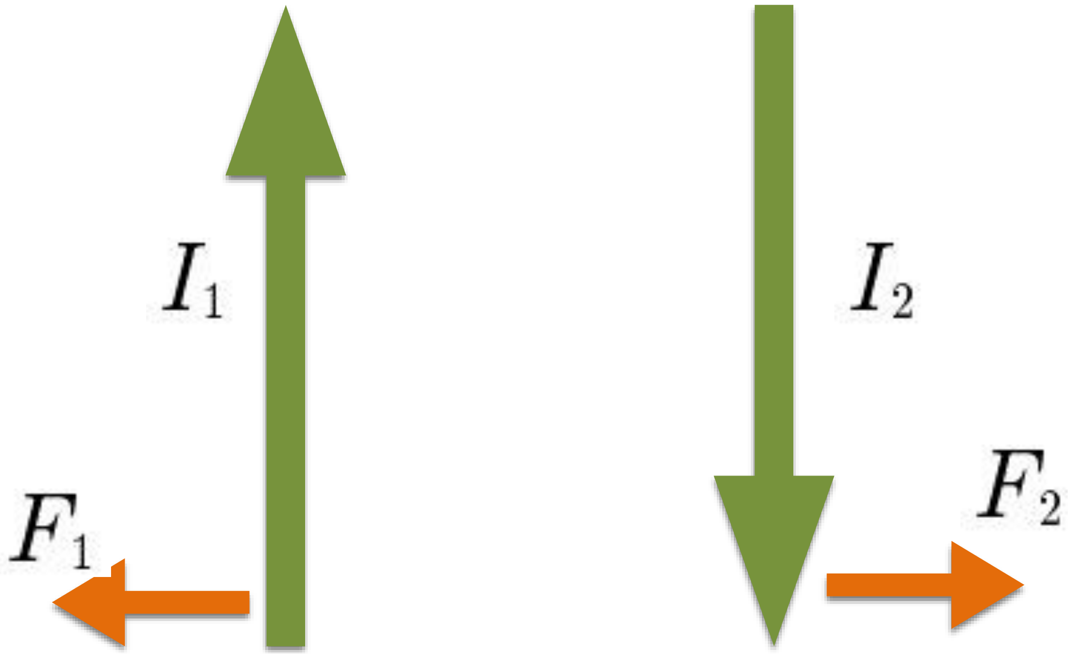
length l : $F_2 = I\,l\,B_1 \sin\theta$ $\quad \sin\theta = 1$

force per unit length

$$\frac{F_2}{l} = -\frac{F_1}{l} = \frac{\mu_0 I_1 I_2}{2\pi r}$$

Magnetic force between two wires





currents in the same direction

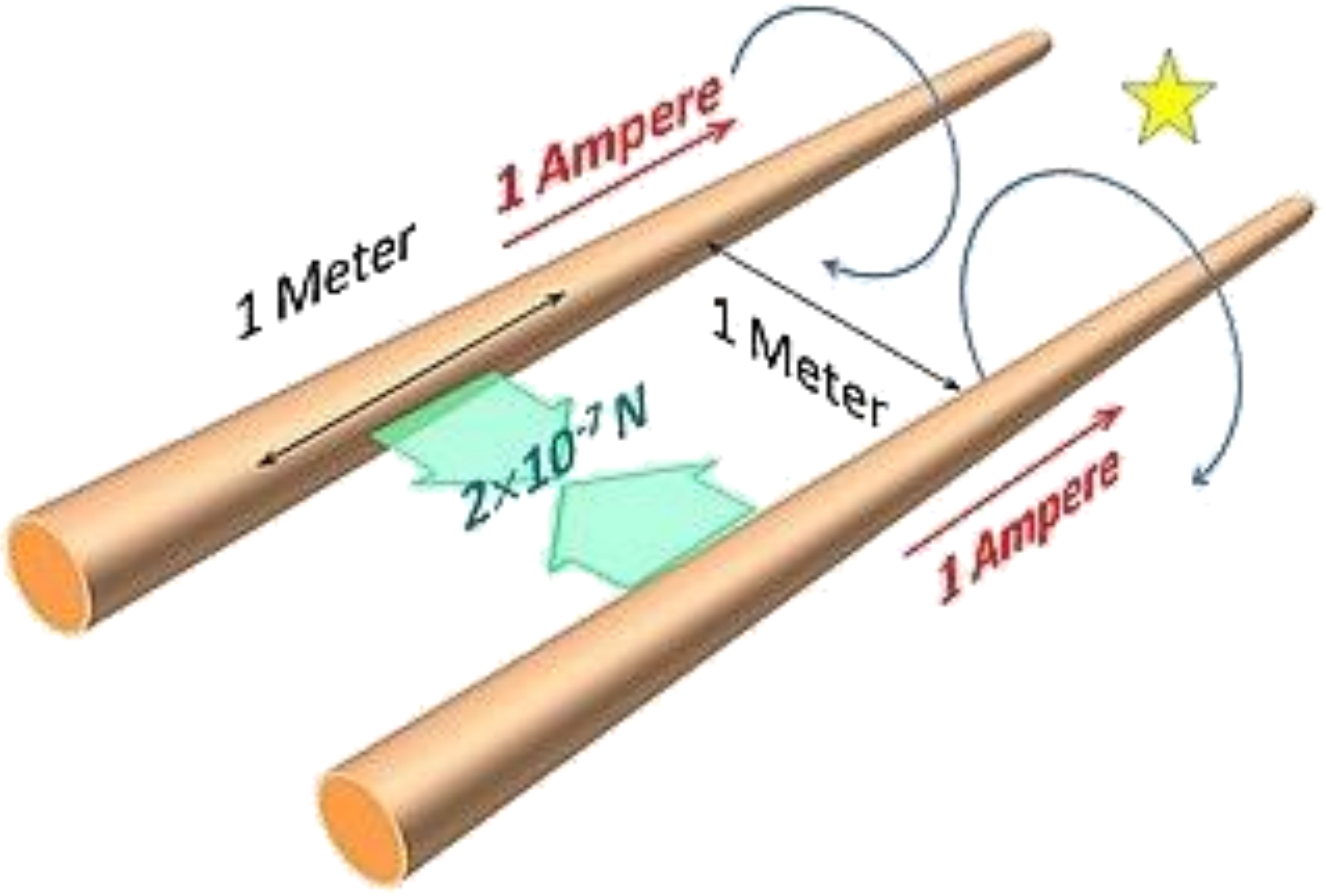
→ attractive force

currents in opposite directions

→ repulsive force

Official definition of the Ampere

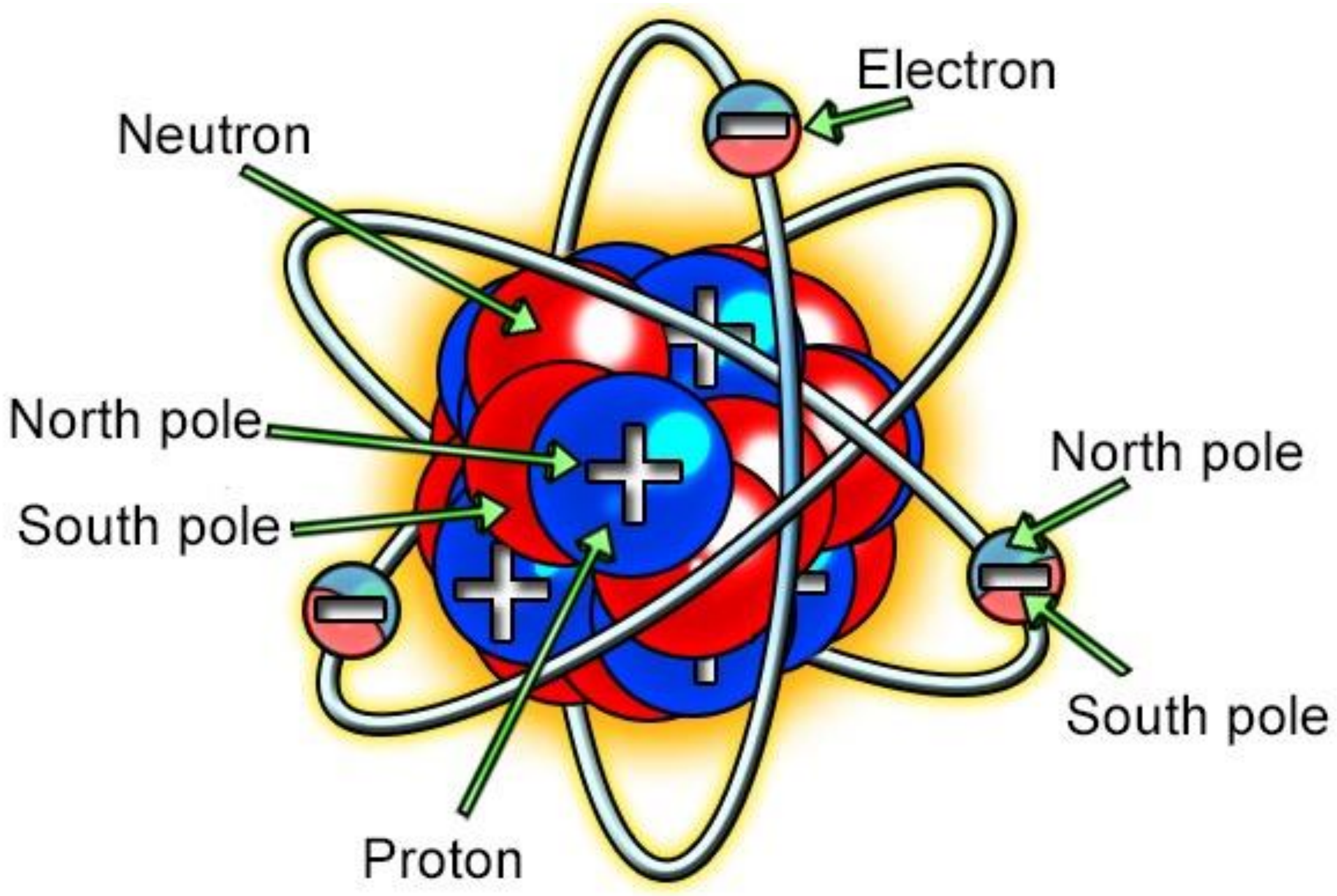
The *ampere* is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per meter of length.

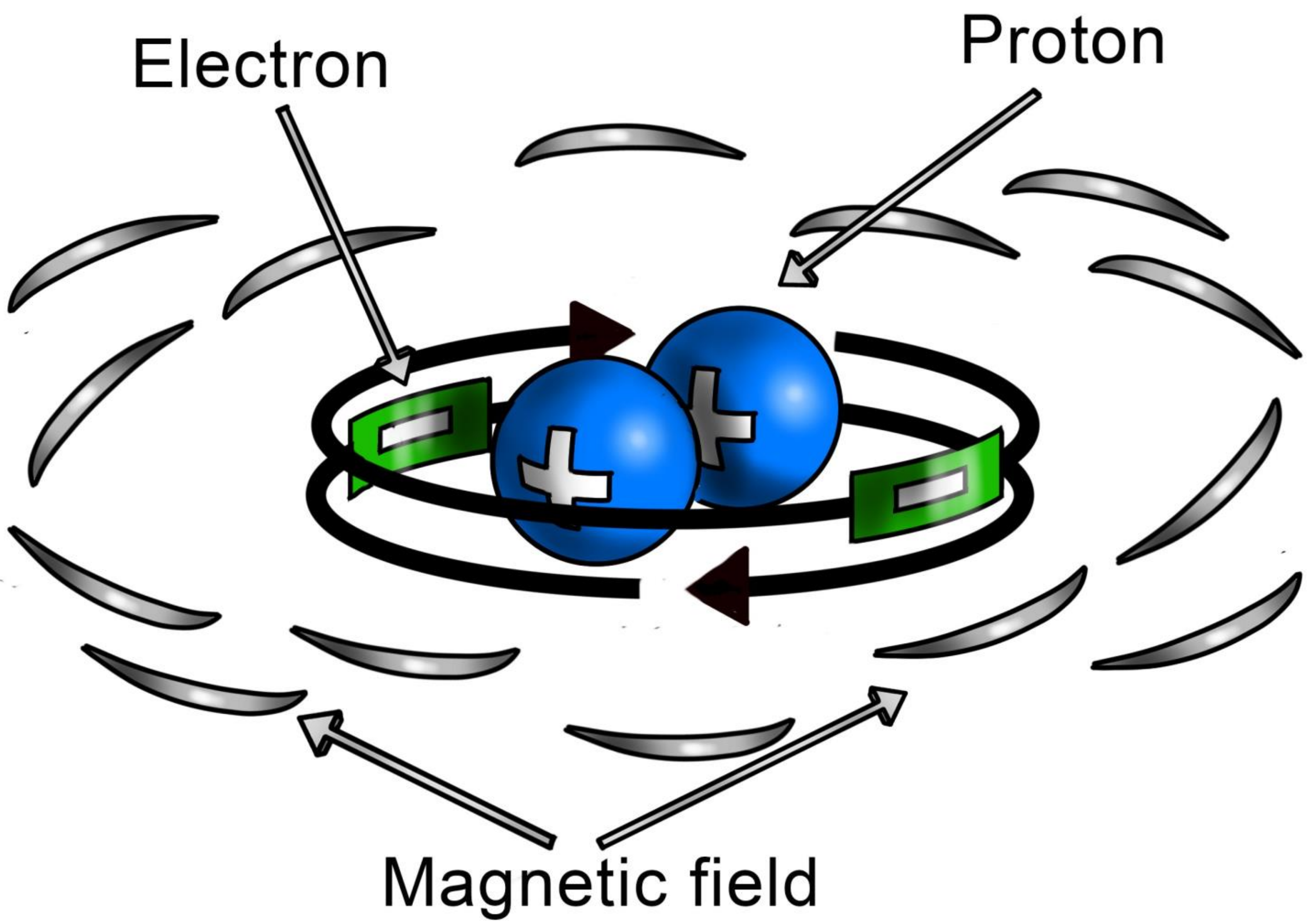


Where does magnetism come from?

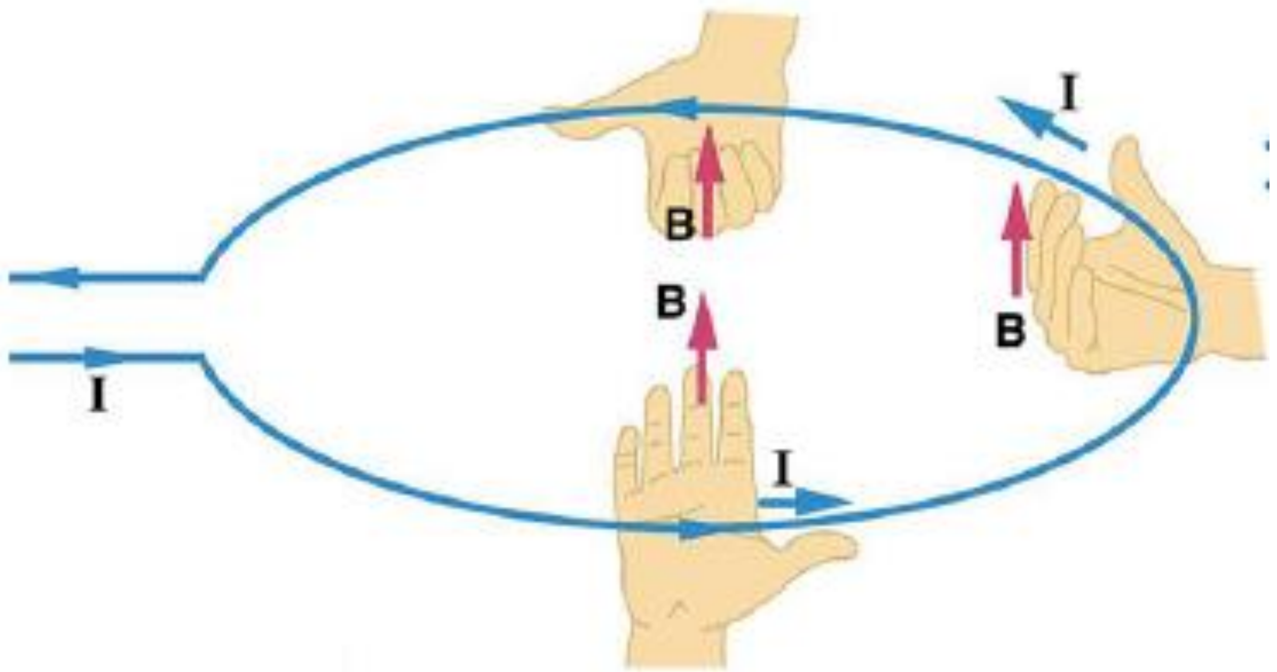
Comes from electric current → *From moving charges*

Moving electrons in atoms

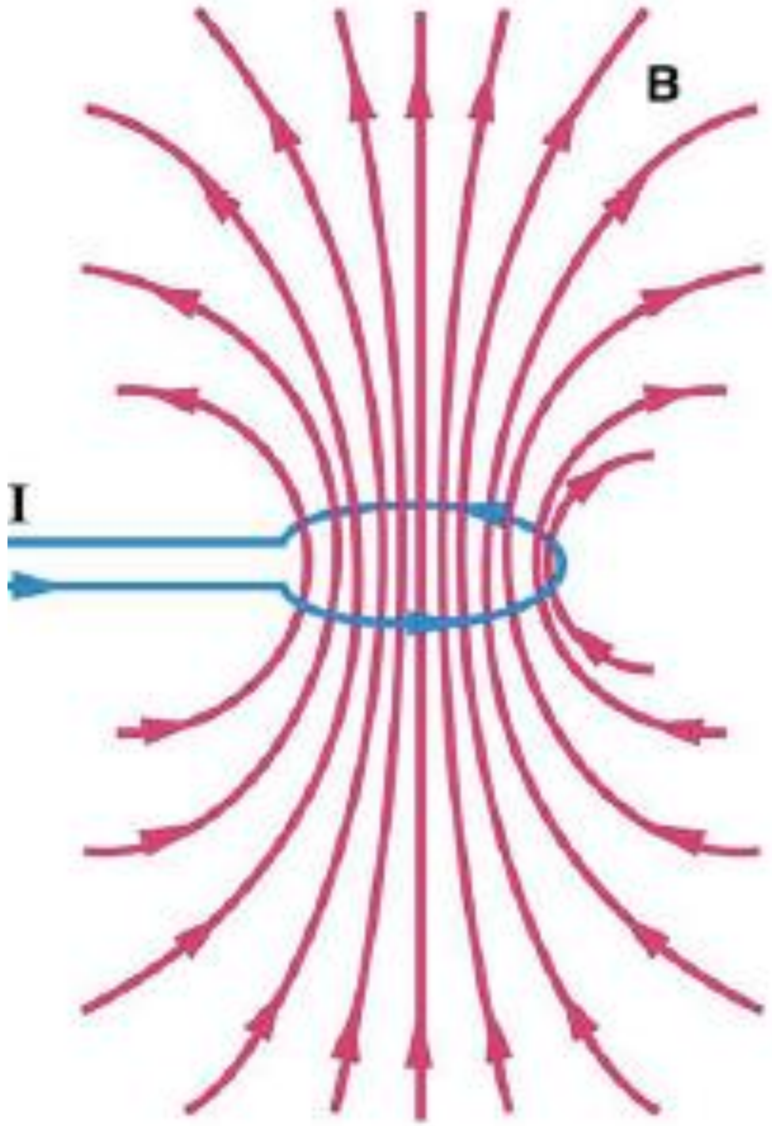


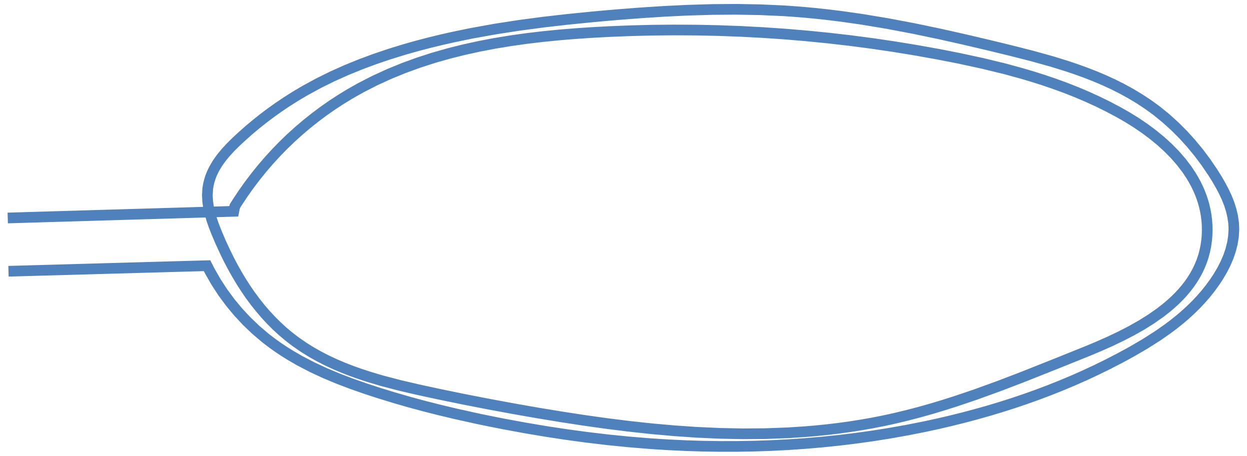


Magnetic field from a circular current loop



all elements of wire produce a field





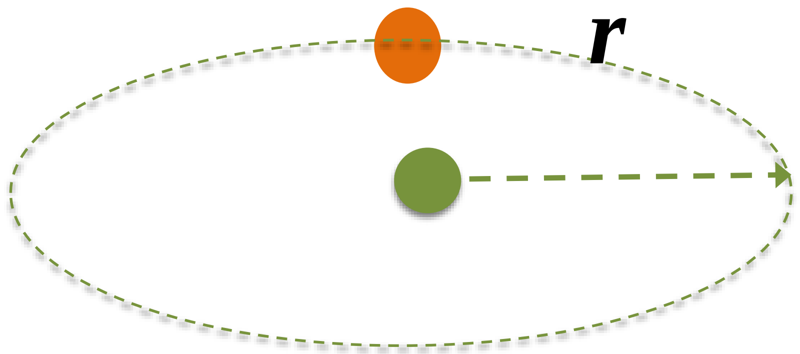
for N loops: $B = N\frac{\mu_0 I}{2R}$

at the center:

$$\boxed{B = \frac{\mu_0 I}{2R}}$$

Magnetic Field of a moving charge

moving charge = electric current



circular motion = current loop

$$I = \frac{Q}{t} \quad \Rightarrow \quad I = \frac{q}{T}$$

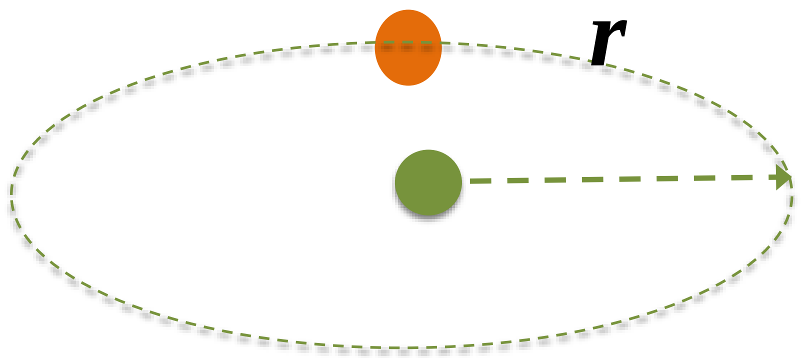
charge on the particle

period of the circular motion

at the center: $B = \dfrac{\mu_0 I}{2R}$ $\qquad B = \dfrac{\mu_0 q}{2rT}$

What is the magnetic field at the nucleus due to the moving electron in a hydrogen atom at its ground state?

Magnetic Field of a moving charge



The magnetic field at a hydrogen nucleus due to the moving electron

$$B = \frac{\mu_0 q}{2rT}$$

electric force on electron $\quad F_e = \dfrac{e^2}{4\pi\varepsilon_0 r^2}$

centripetal force needed by electron $\quad F_c = \dfrac{mv^2}{r}$

$$v^2 = \frac{e^2}{4\pi\varepsilon_0 mr}$$

The period $\quad T = \dfrac{2\pi r}{v} = \dfrac{2\pi r\sqrt{4\pi\varepsilon_0 mr}}{e}$

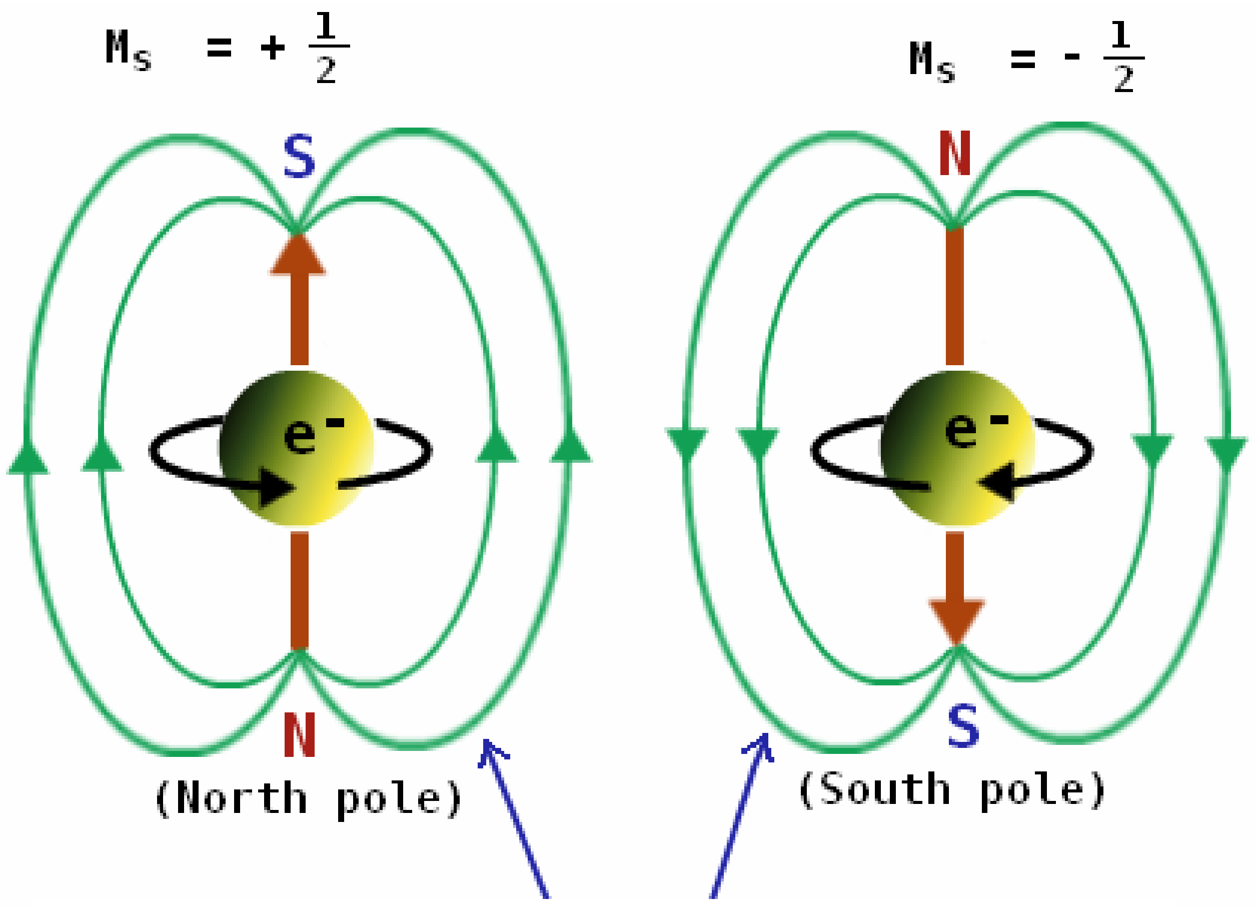
$$B = \frac{\mu_0 e^2}{8\pi^{\frac{3}{2}} r^{\frac{5}{2}} \sqrt{\varepsilon_0 m}}$$

Using *Bohr radius r_0 = 0.53 Å* for hydrogen *ground state*

$$\boxed{B = 12.5\ T}$$

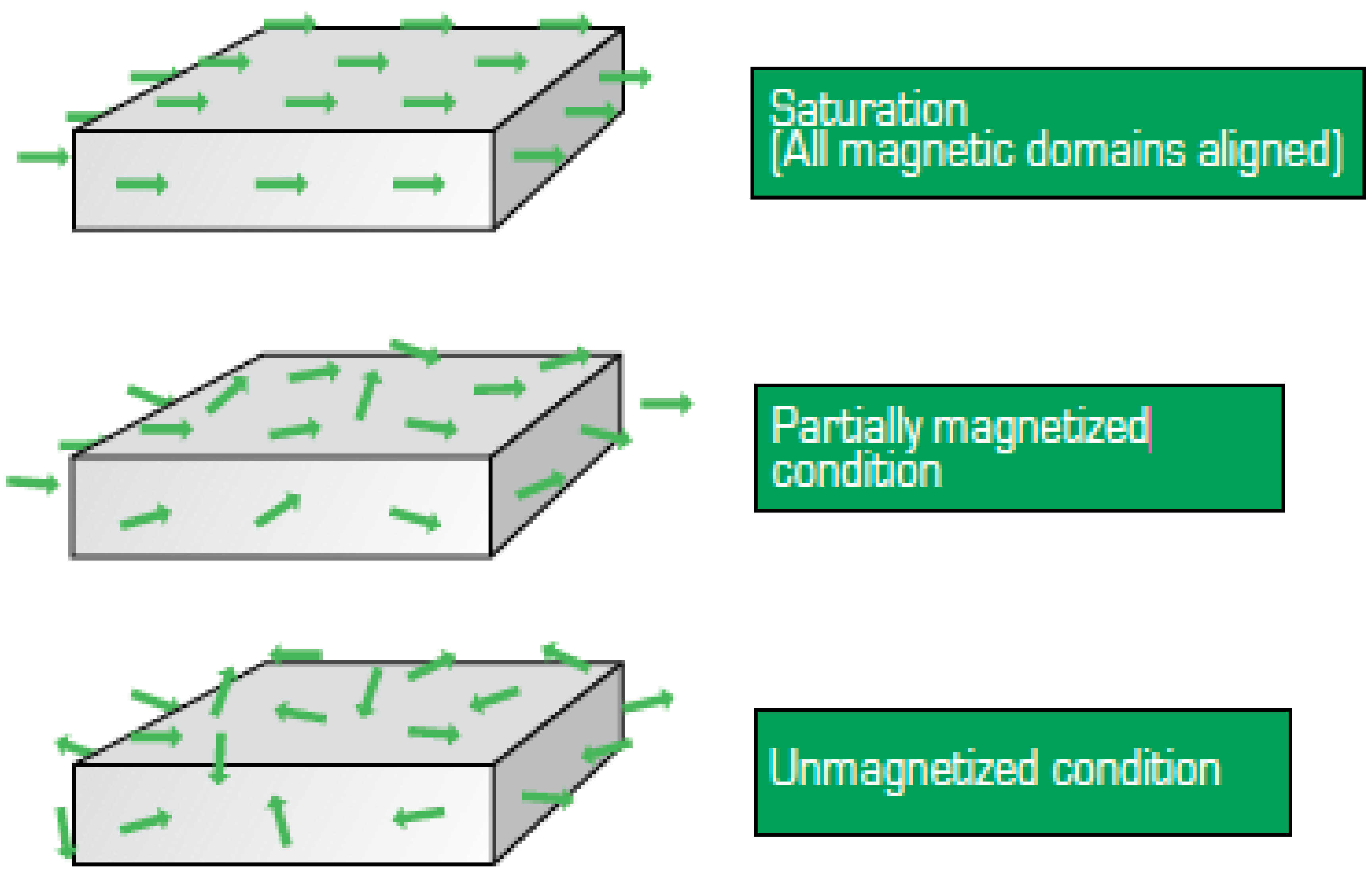
Magnetic Field of a moving charge

- electrons "spin" on themselves
- This is like a current, that creates a magnetic field



*Actually a **relativistic effect**, not really spinning*

Magnetization



molecular "magnets" align under external magnetic filed

Magnetic materials

$$\boxed{\mu = \mu_0 \mu_r}$$

Ferromagnetic materials	• Producing **strong** magnetic field after magnetization • May make permanent magnets
Paramagnetic materials	• Weakly responds to external magnetic field • Inducing a weak field in the **same** direction
Diamagnetic materials	• Induce an opposing magnetic field (weak)

Magnetic materials

$$\boxed{\mu = \mu_0 \mu_r}$$

Ferromagnetic materials

- $\mu_r \gg 1$
- Cobalt, Iron, Nickel, Gadolinium, Dysprosium, ***Some compounds containing above elements***

Paramagnetic materials

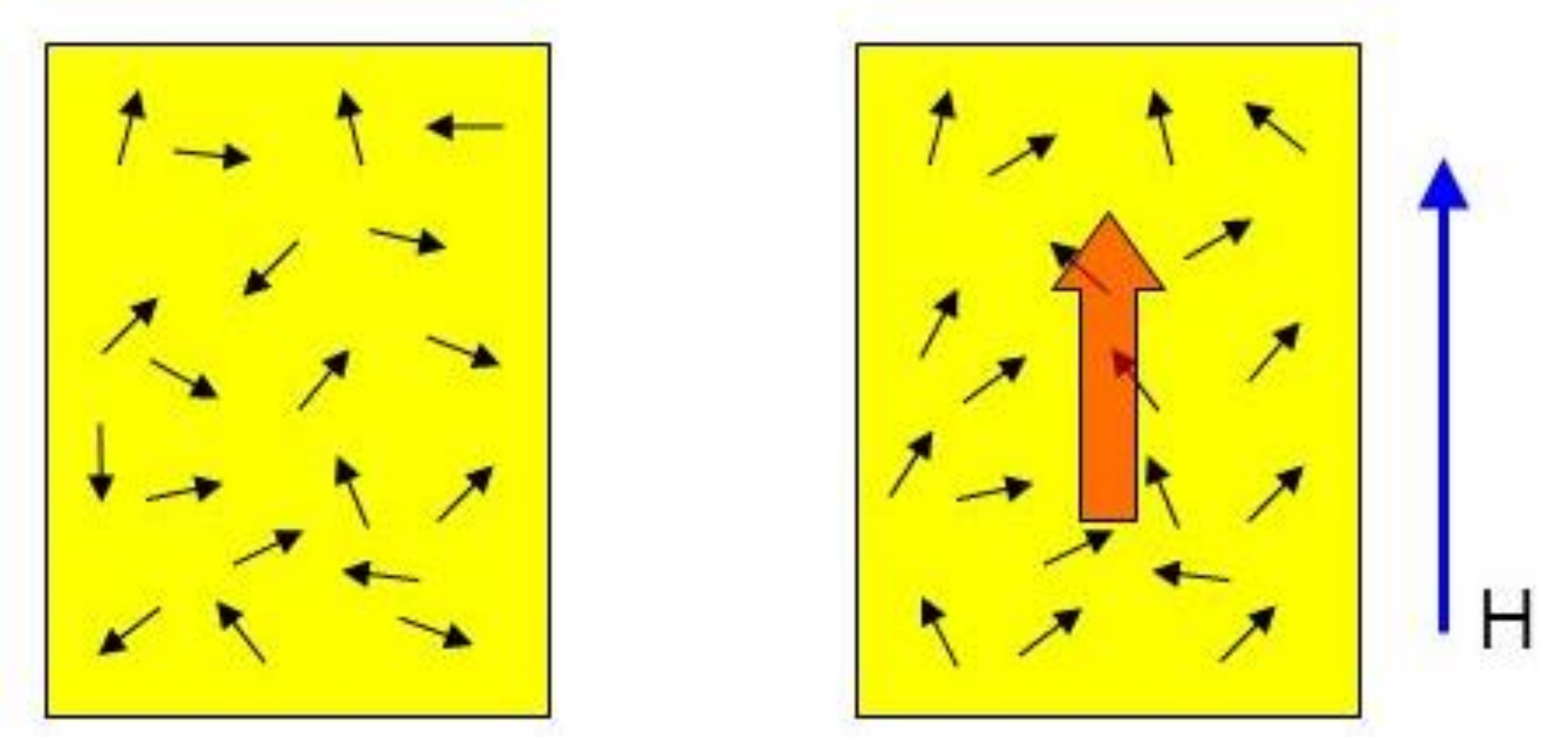
- μ_r slightly greater than 1
- Aluminum, Oxygen, Titanium, FeO

Diamagnetic materials

- μ_r slightly smaller than 1
- ***most materials*** … Graphite, Gold, Silver, Water,

Paramagnetism

The partial alignment of permanent atomic magnetic moments by a magnetic field

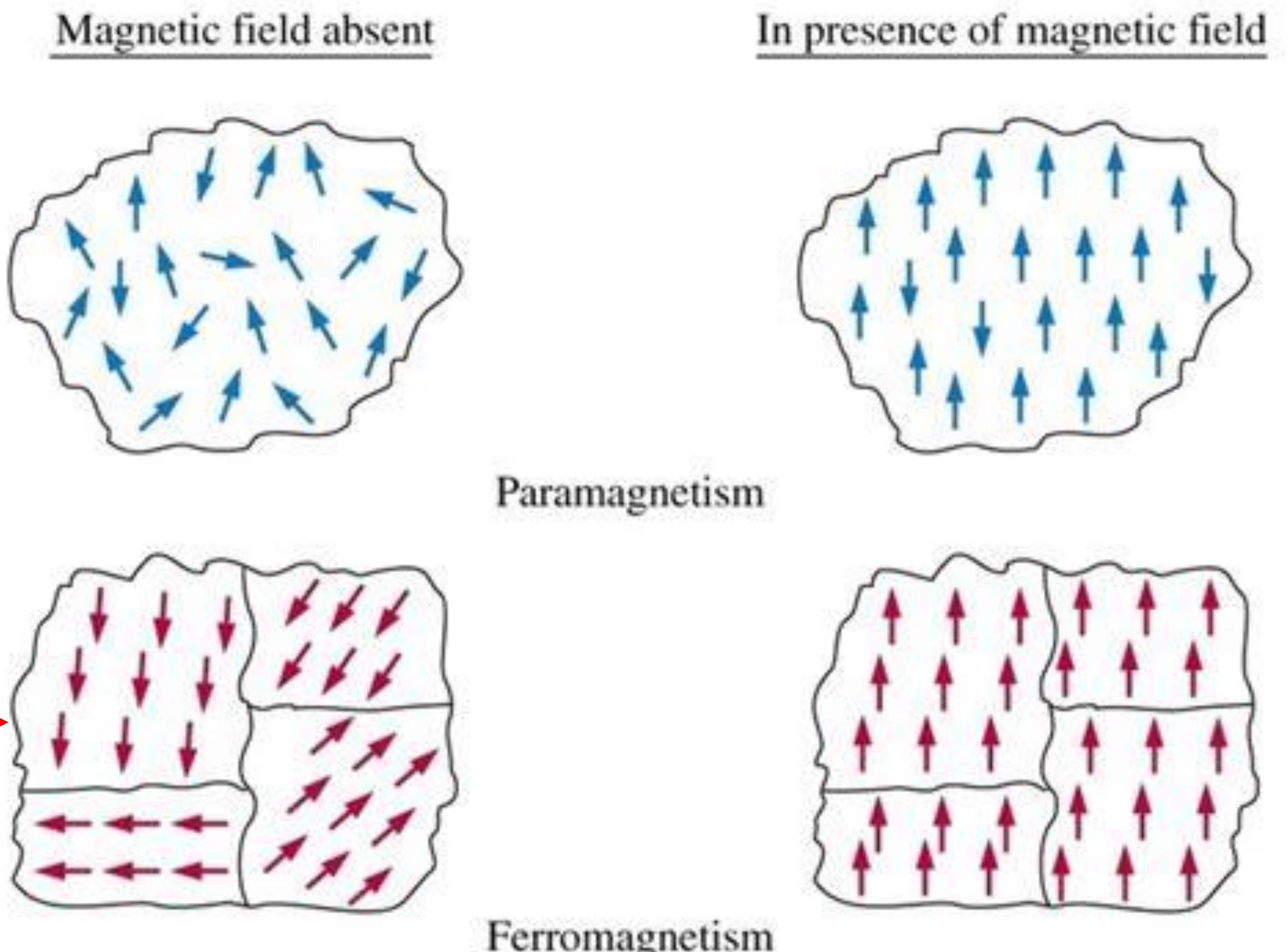


Alignment resisted by thermal motion

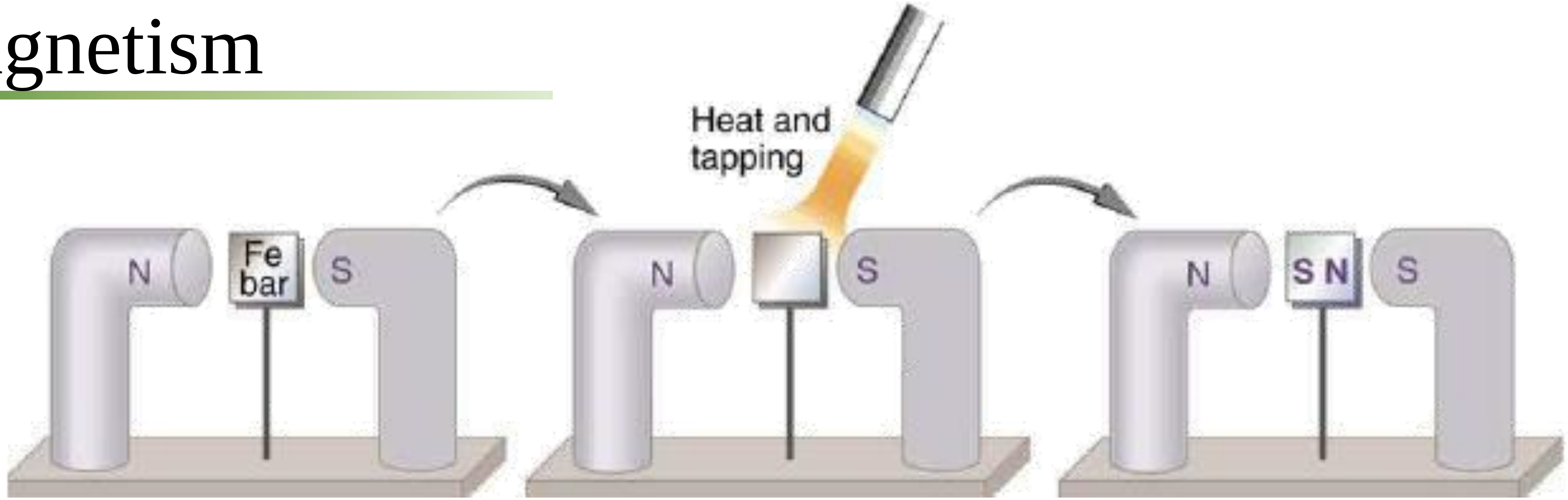
Partial magnetization

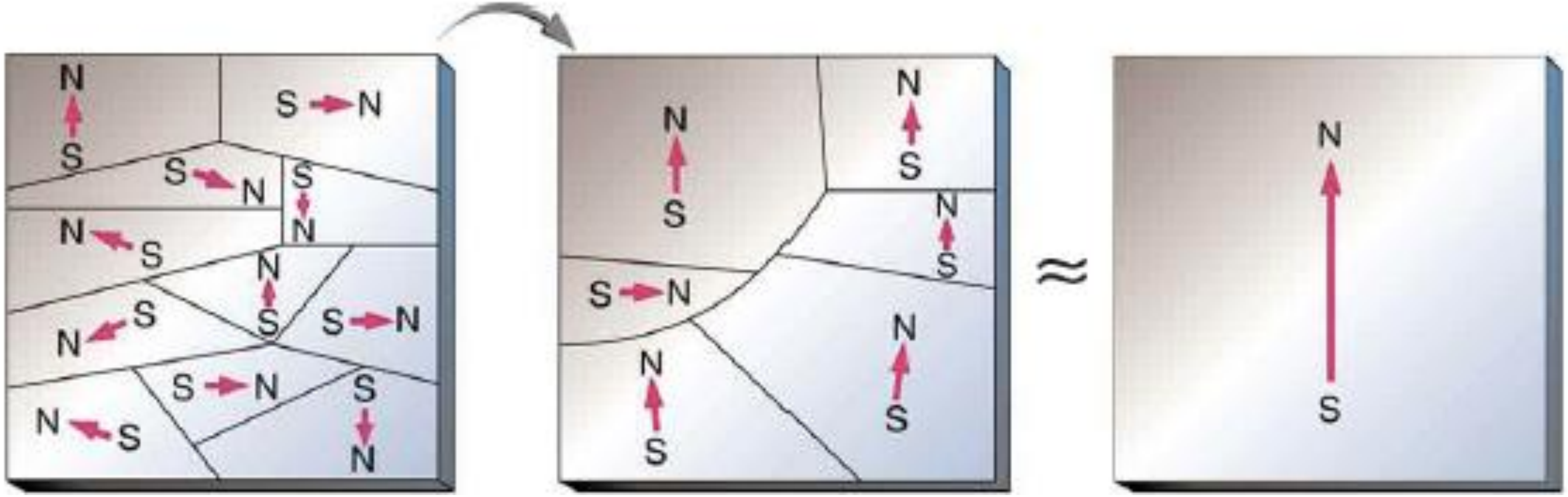
Difference between paramagnetism and ferromagnetism

Strong interactions between molecular "magnets"



Ferromagnetism





Ferromagnetism

Ferromagnetic material	Relative permeability (μ_r)
Iron (99.95% pure Fe annealed in H)	200000
Cobalt-iron (high permeability strip material)	18000
Iron (99.8% pure)	5000
Electrical steel (silicon steel)	4000
Martensitic stainless steel (annealed)	750 – 950
Carbon steel	100
Nickel	100 – 600
Martensitic stainless steel (hardened)	40 – 95
Austenitic stainless steel	1.003 – 7

$$\mu_r = \frac{\mu}{\mu_0}$$

$$\mathbf{H} \equiv \frac{\mathbf{B}}{\mu_0} - \mathbf{M}$$

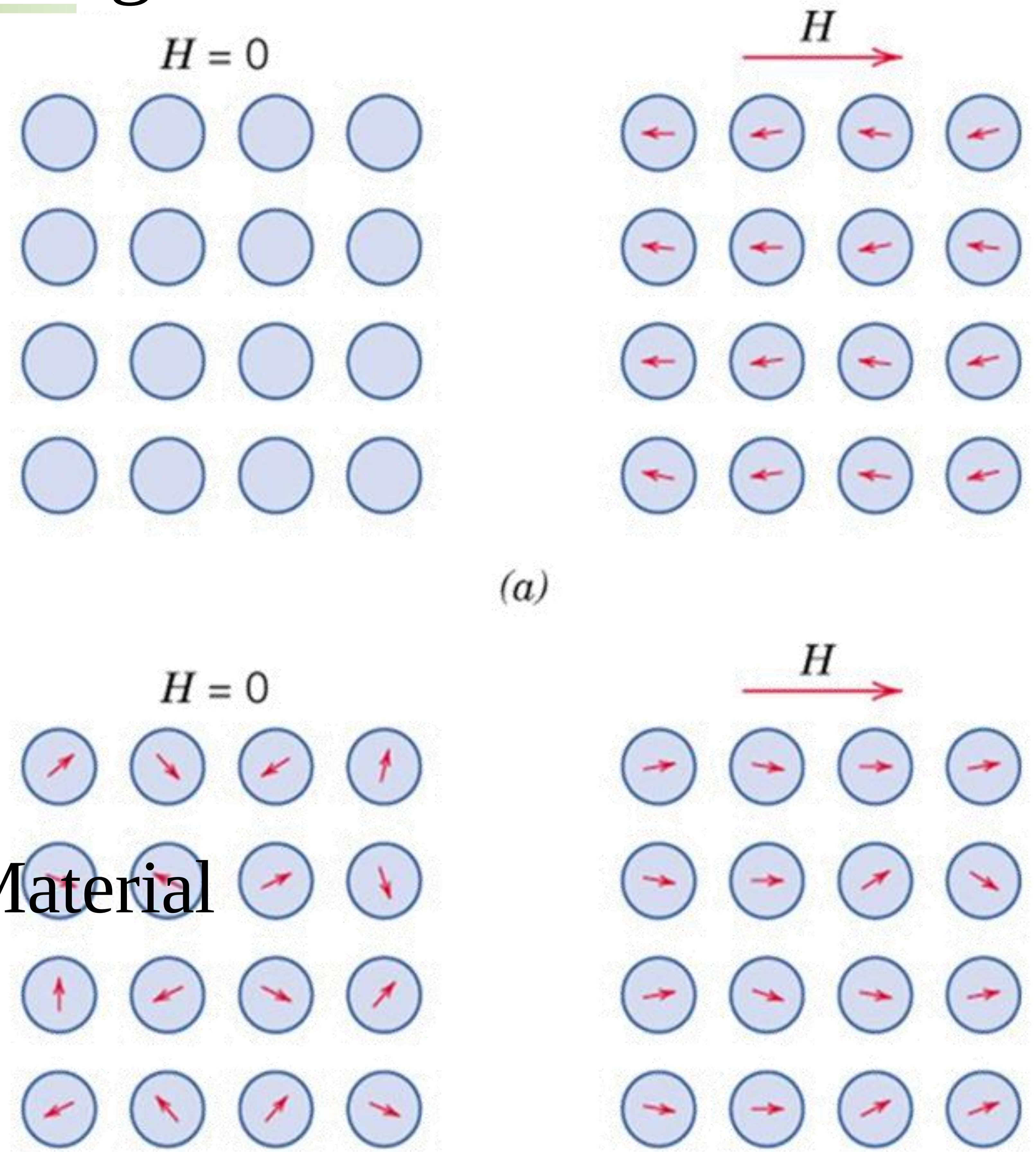
$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$$

$$\mathbf{B} = \mu\mathbf{H}$$

Diamagnetic and Paramagnetic material

Diamagnetic Material

In presence of a field, dipoles are induced and aligned opposite to the field direction



A universal quantum effect!

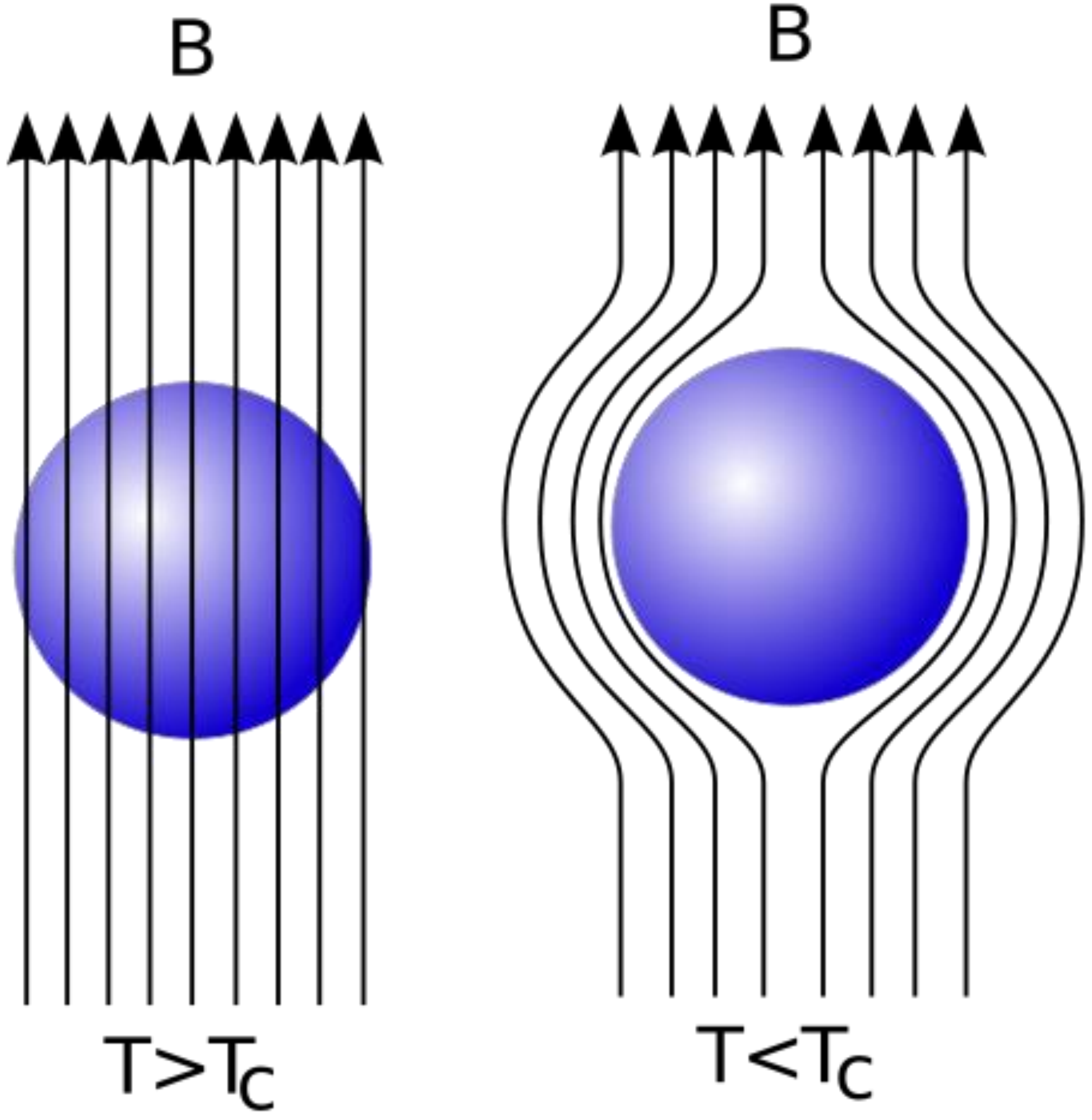
Paramagnetic Material

Superconductor – perfect diamagnetism

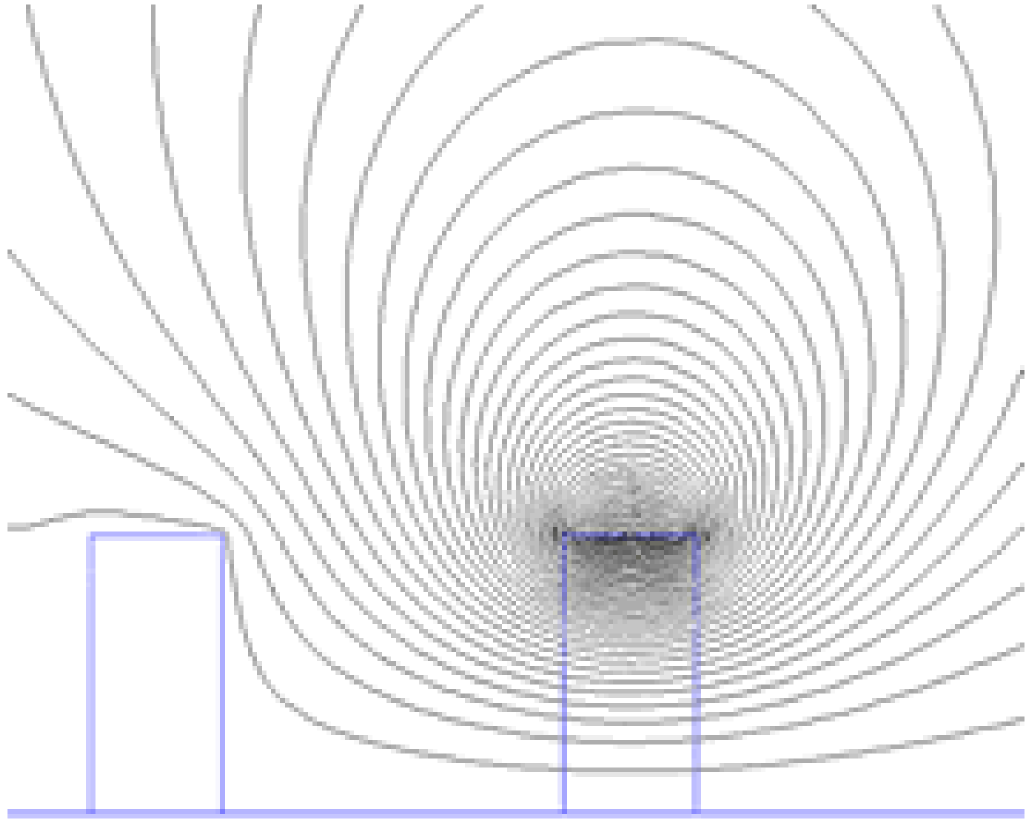
$\mu_r = 0$

Meissner effect

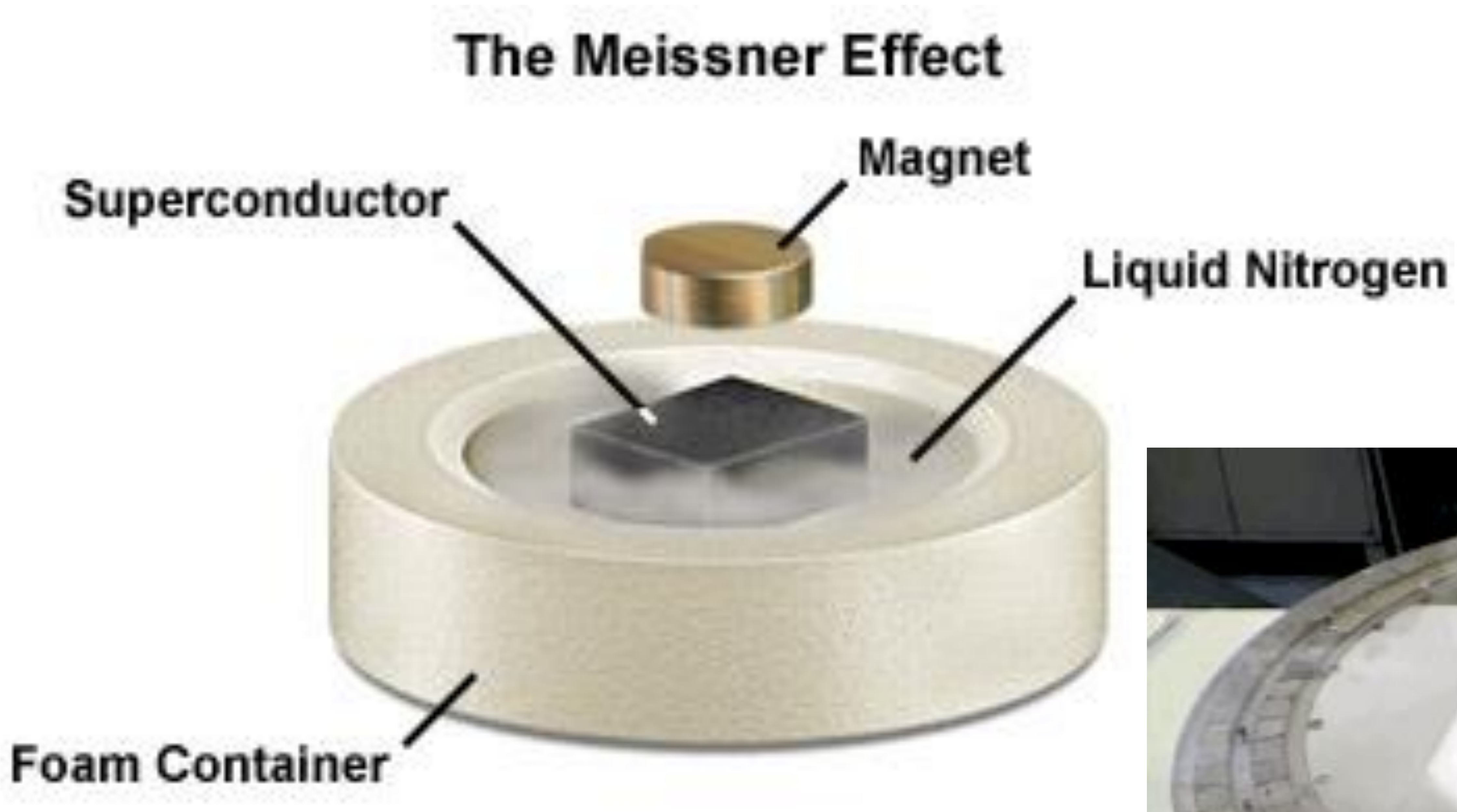
All magnetic field will be **expelled** from a superconductor during its ***transition to the superconducting state***

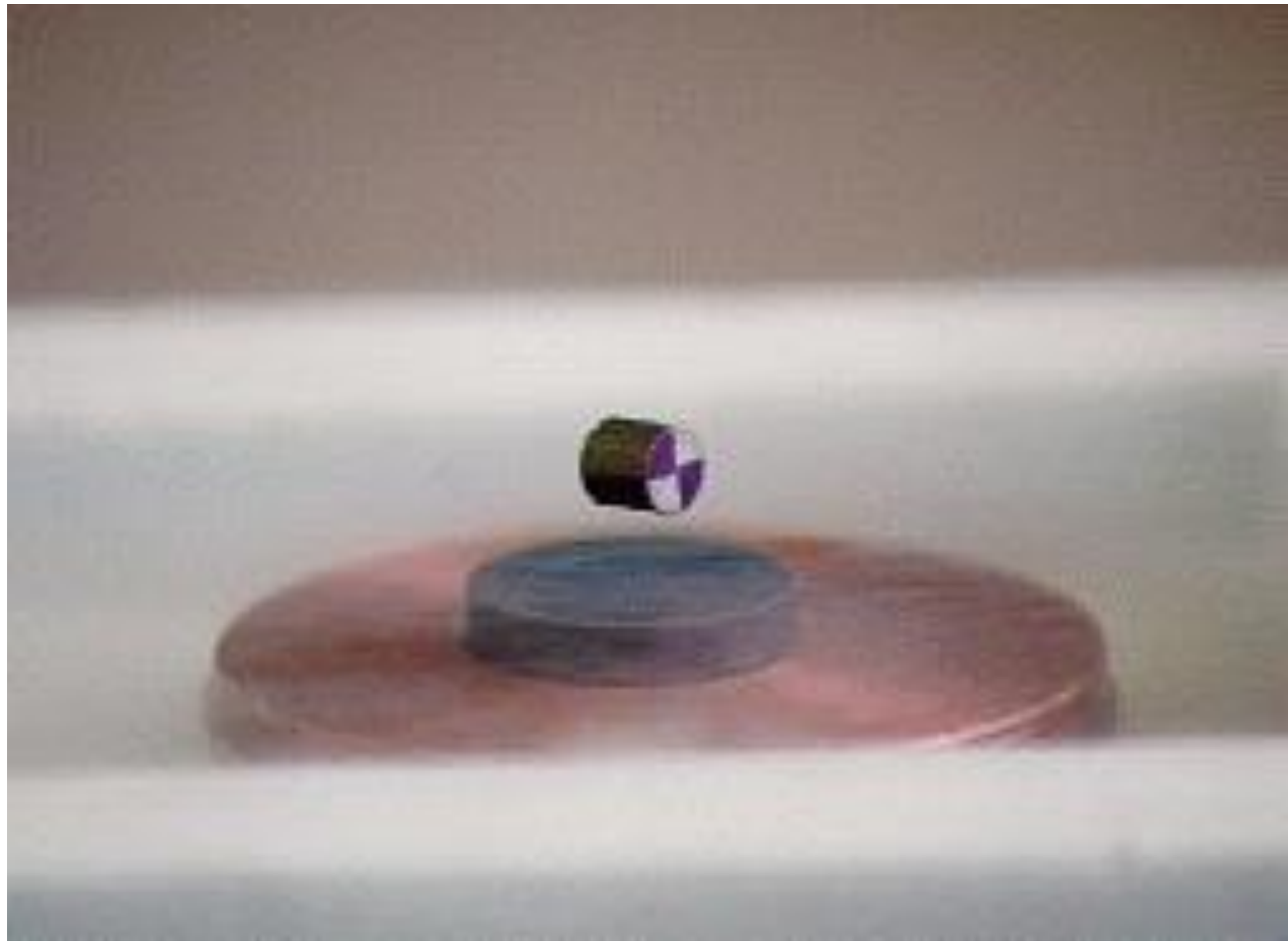


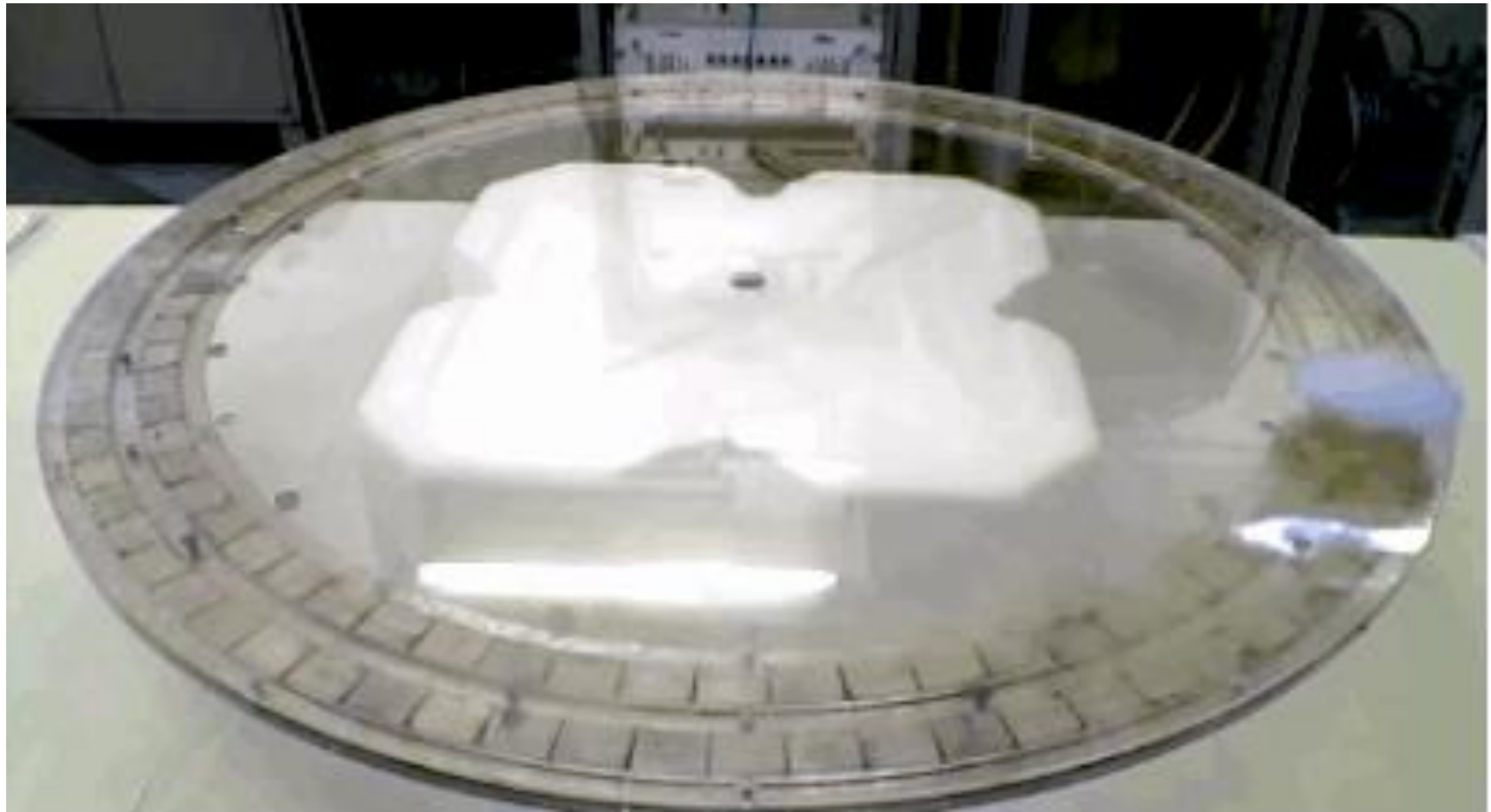
Repulsive force



Superconducting magnetic levitation



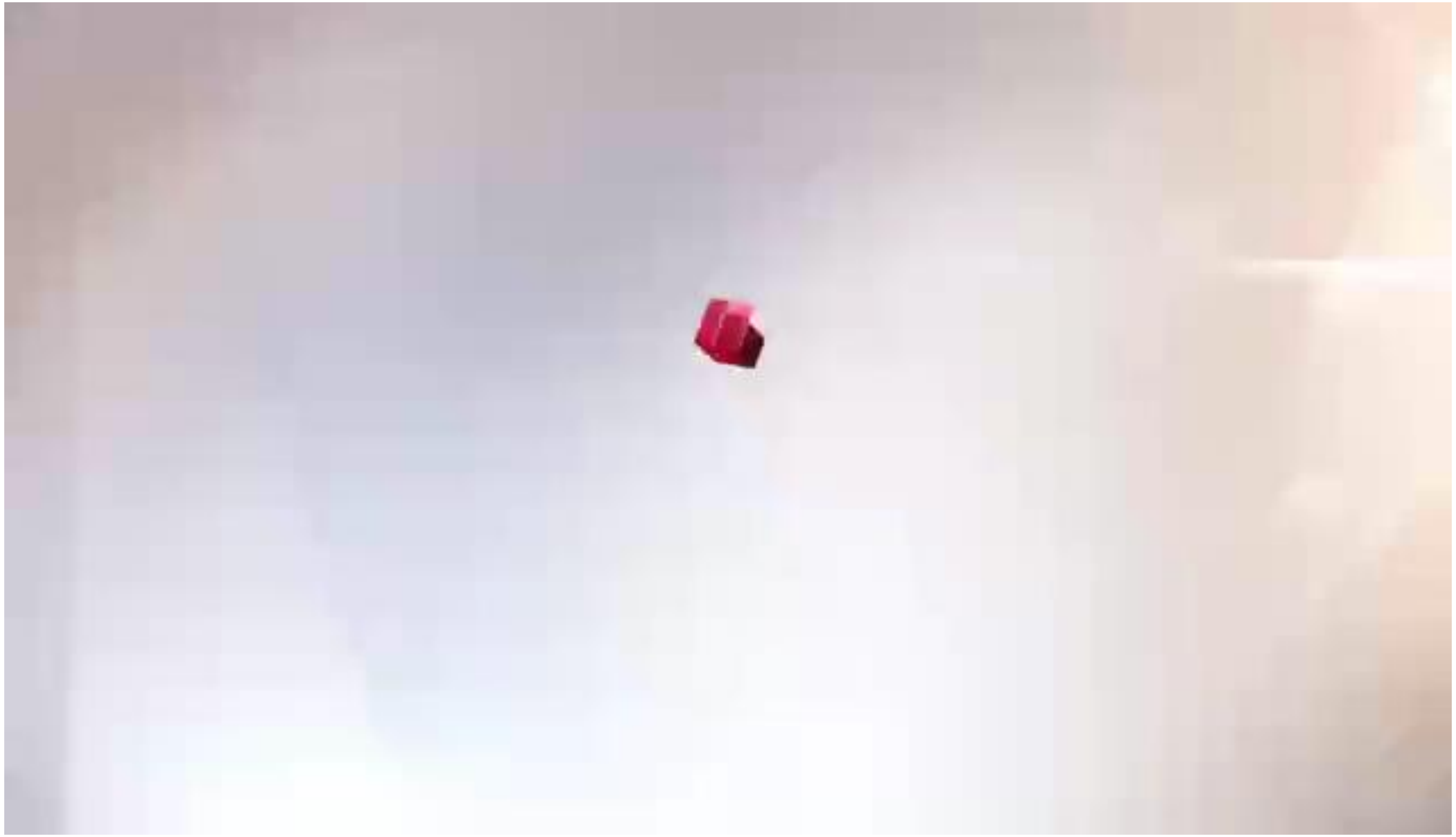




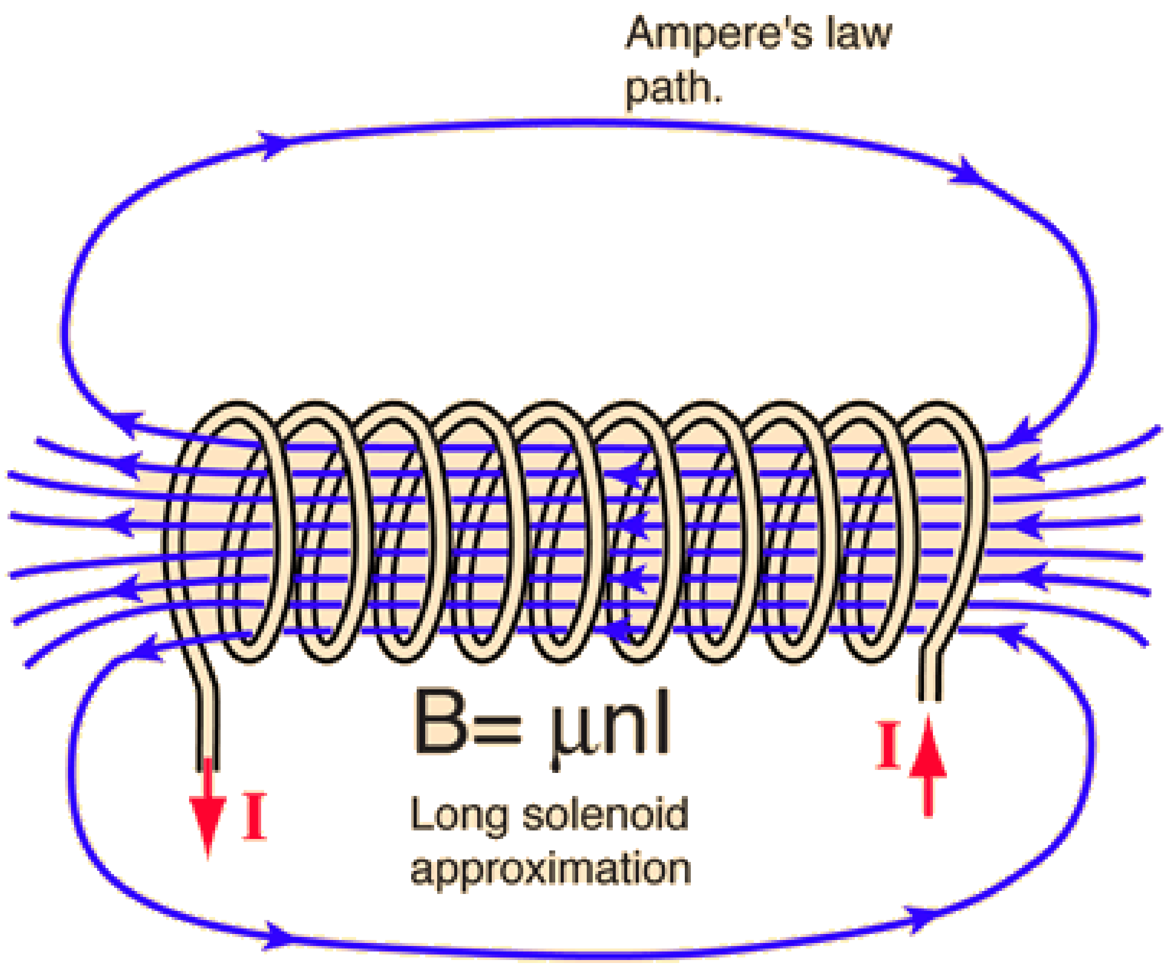
A SUPER CHUTE

THIS RING IS THE racetrack on which the future of ground transportation might be riding. Deng Zigang, a professor at Southwest Jiaotong University, in Chengdu, China, stands in the center of a prototype designed to test the latest turn in maglev (magnetic levitation) train technology. Right now, the best maglev trains reach speeds exceeding 400 kilometers (250 miles) per hour. Yeah, that's fast, but researchers like Deng are confident that the train cars, which are suspended

IN SWJTU

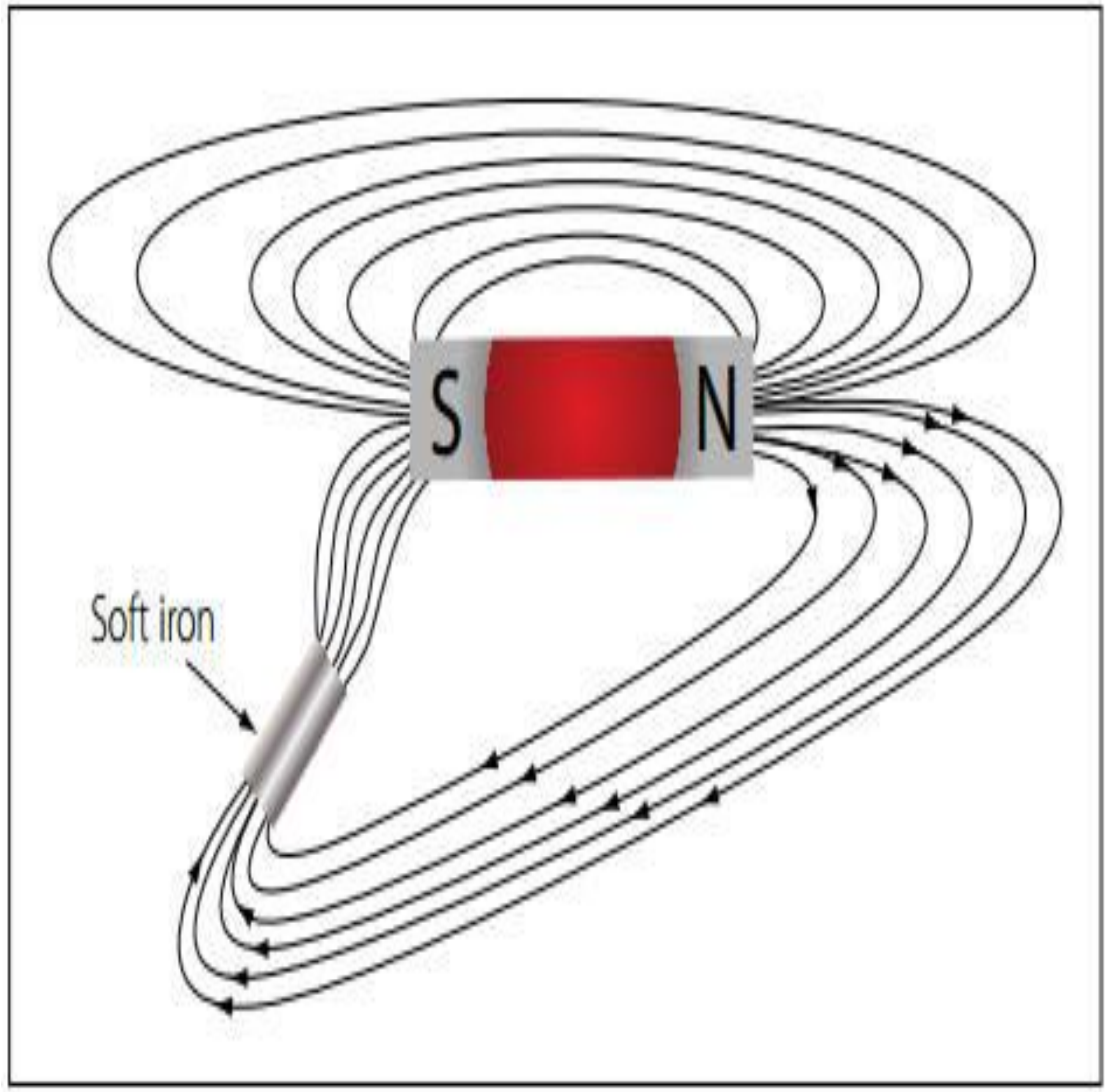


Solenoid with a ferromagnetic core



$$\boxed{B = \mu n I}$$

$$\mu = \mu_0 \mu_r$$

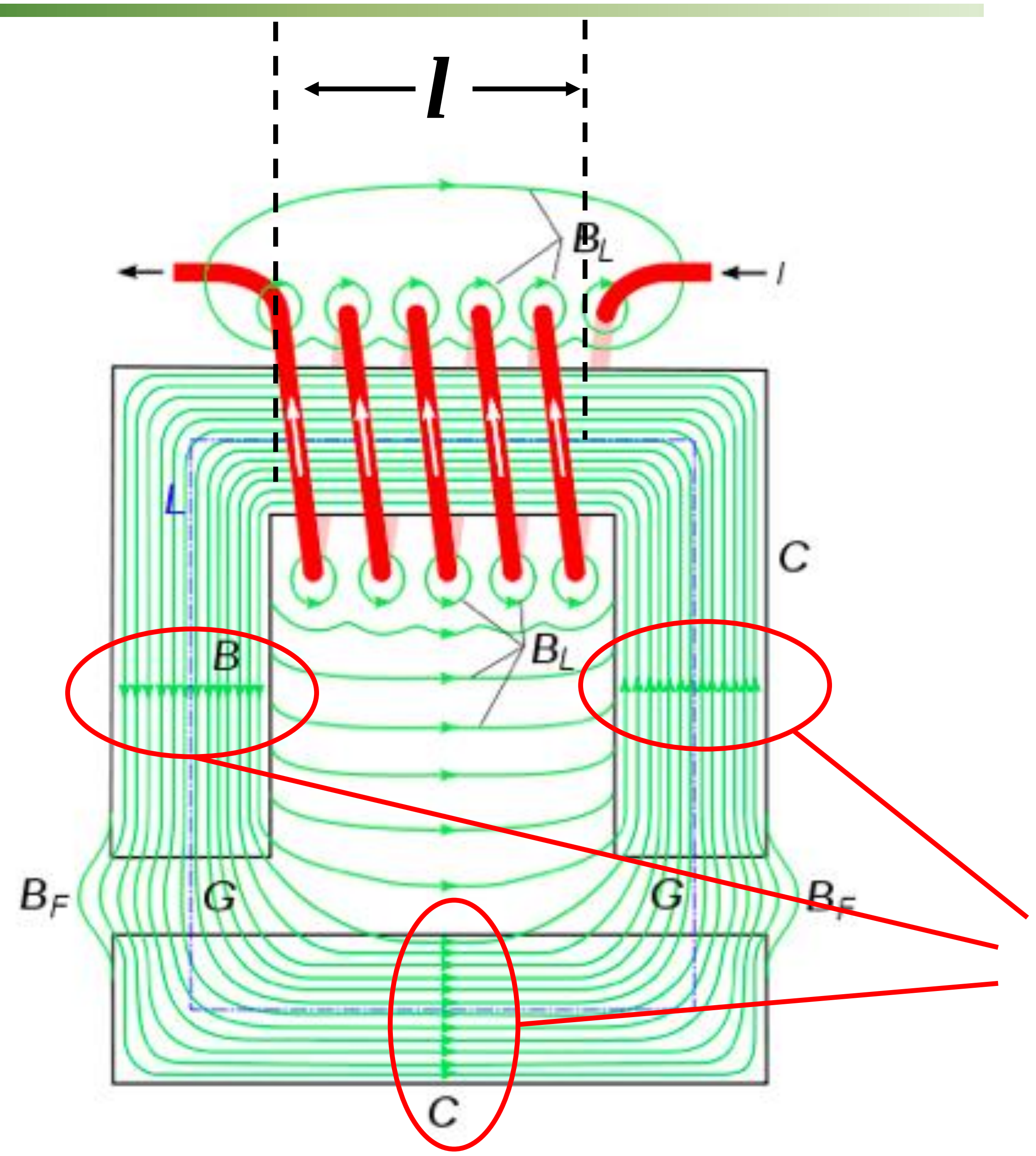


The Magnetic Fields concentrated into a nearly uniform field in the center of a long solenoid. The field outside is weak and divergent

n - the number of turns per unit of length

"**soft**" ferromagnetic materials have very large $\boldsymbol{\mu_r}$ value

Magnetic circuit



$$B = \mu n I$$

$$\frac{\Phi}{A} = \mu \frac{NI}{l}$$

Almost all the magnetic filed lines are contained in the soft ferromagnetic materials (having very large $\boldsymbol{\mu_r}$ value)

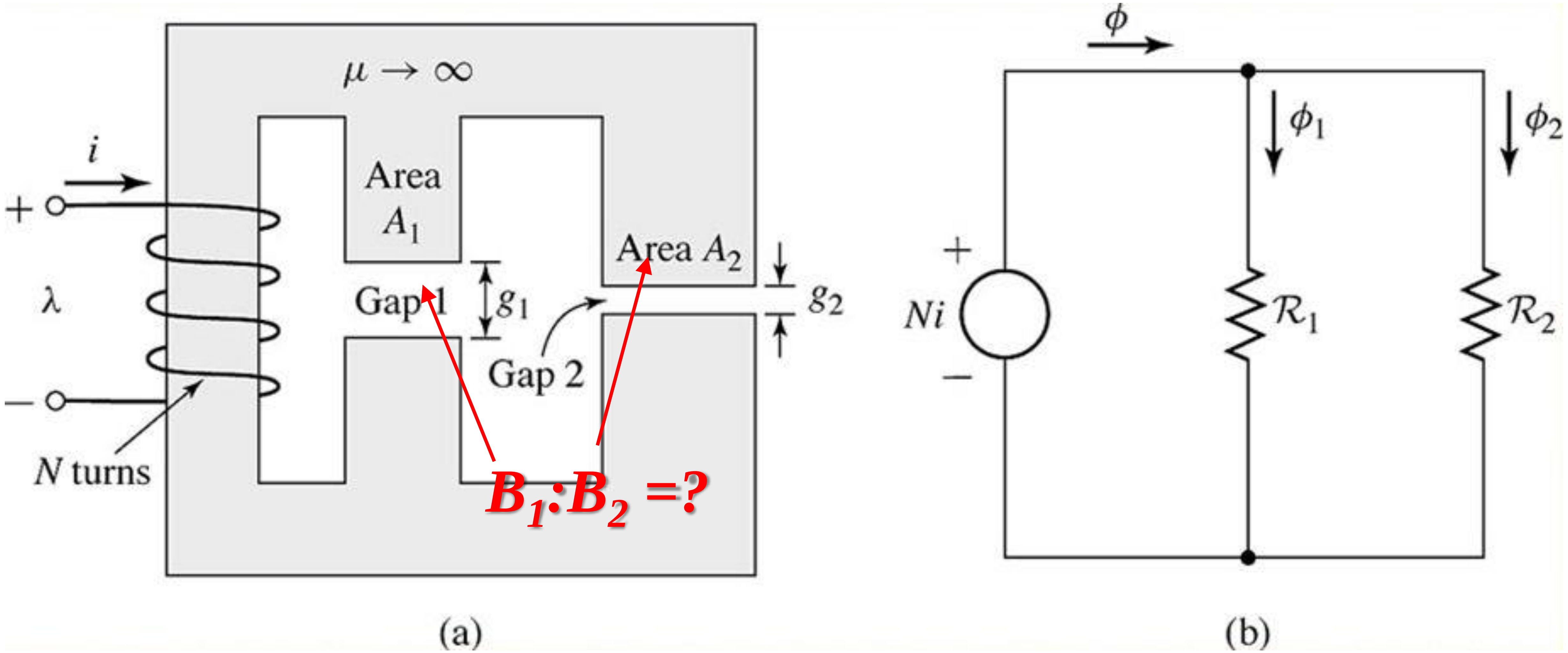
Same *magnetic flux* $\boldsymbol{\Phi}$

$$\boxed{\Phi = \mu \frac{A}{l} NI}$$

Same ***current*** in an *electric circuit*

$$\boxed{I = \sigma \frac{A}{l} \ \varepsilon}$$

Magnetic circuit *vs.* Electric circuit



reluctance $$R_m = \frac{l}{\mu A}$$

$$\frac{\Phi_1}{\Phi_2} = \frac{R_2}{R_1} = \frac{A_1 g_2}{A_2 g_1}$$

$$\frac{B_1}{B_2} = \frac{g_2}{g_1}$$

Magnetic circuit *vs.* Electric circuit

Magnetic				Electric		
Name	Symbol	Units		Name	Symbol	Units
Magnetomotive force (MMF)	$\mathcal{F} = \int \mathbf{H} \cdot d\mathbf{l}$	ampere-turn		Electromotive force (EMF)	$\mathcal{E} = \int \mathbf{E} \cdot d\mathbf{l}$	volt
Magnetic field	H	ampere/meter		Electric field	E	Volt/meter
Magnetic flux	Φ	weber		Electric current	I	ampere
Reluctance	R_m	1/henry		Electrical resistance	R	ohm
Permeance	$P = \frac{1}{R_m}$	henry		Electric conductance	$G = 1/R$	siemens
Magnetic flux density	B	tesla		Current density	J	ampere/meter^2
Permeability	μ	henry/meter		Electrical conductivity	σ	siemens/meter