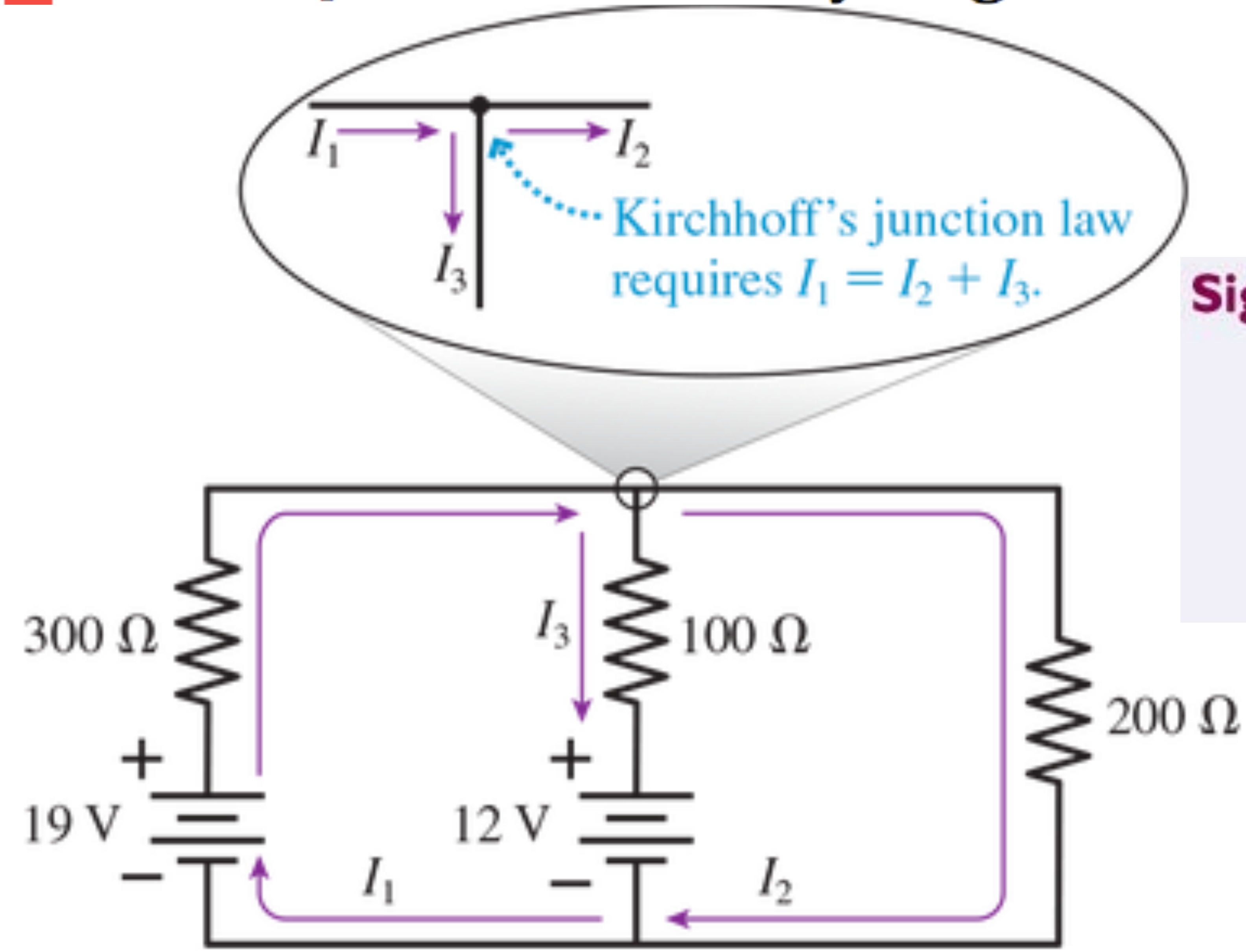
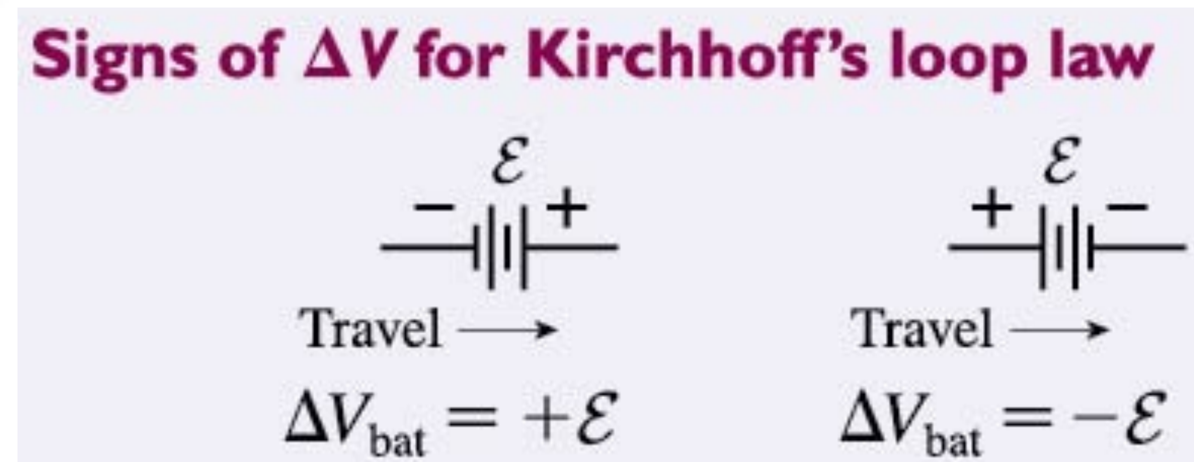
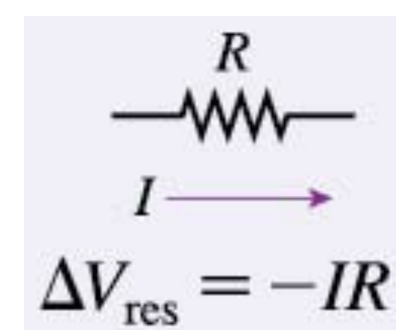
Summary: Analyzing two-loop circuits

Example 28.10 Analyzing a two-loop circuit







$$I_3 = I_1 - I_2$$

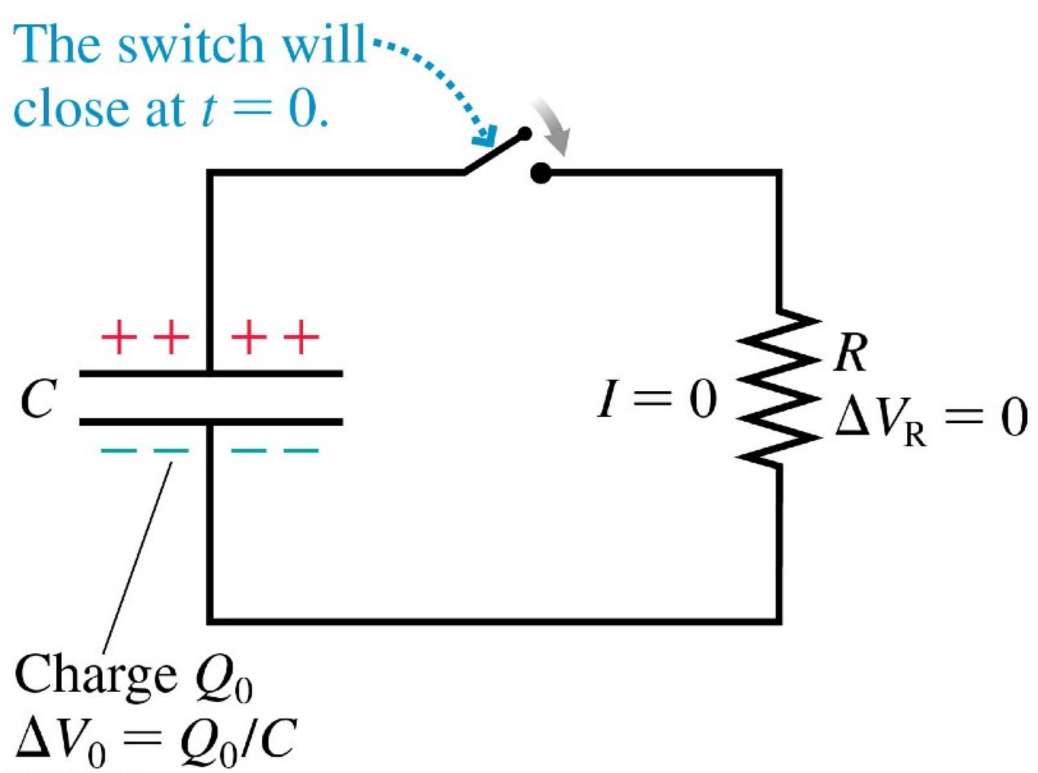
$$\sum(\Delta V)_i = 19\text{ V} - (300\,\Omega)\,I_1 - (100\,\Omega)\,I_3 - 12\text{ V} = 0$$

$$\sum(\Delta V)_i = 12\text{ V} + (100\,\Omega)\,I_3 - (200\,\Omega)\,I_2 = 0$$

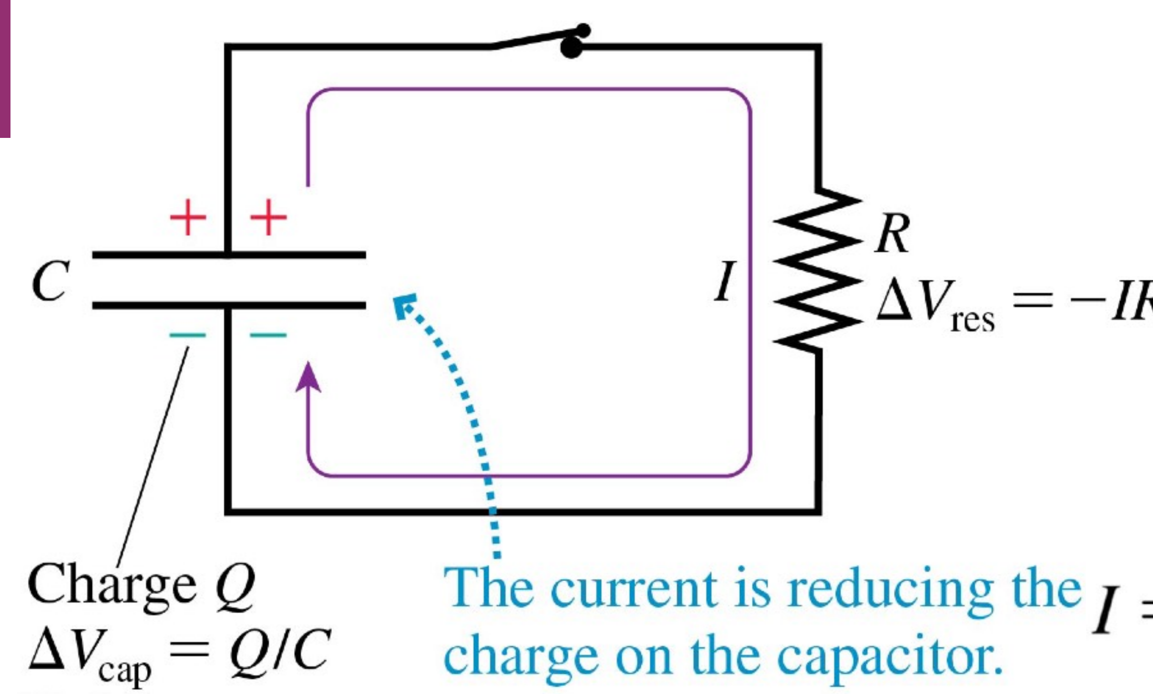
Current opposite to direction of travel!

Summary: RC Circuits

Before the switch closes



After the switch closes

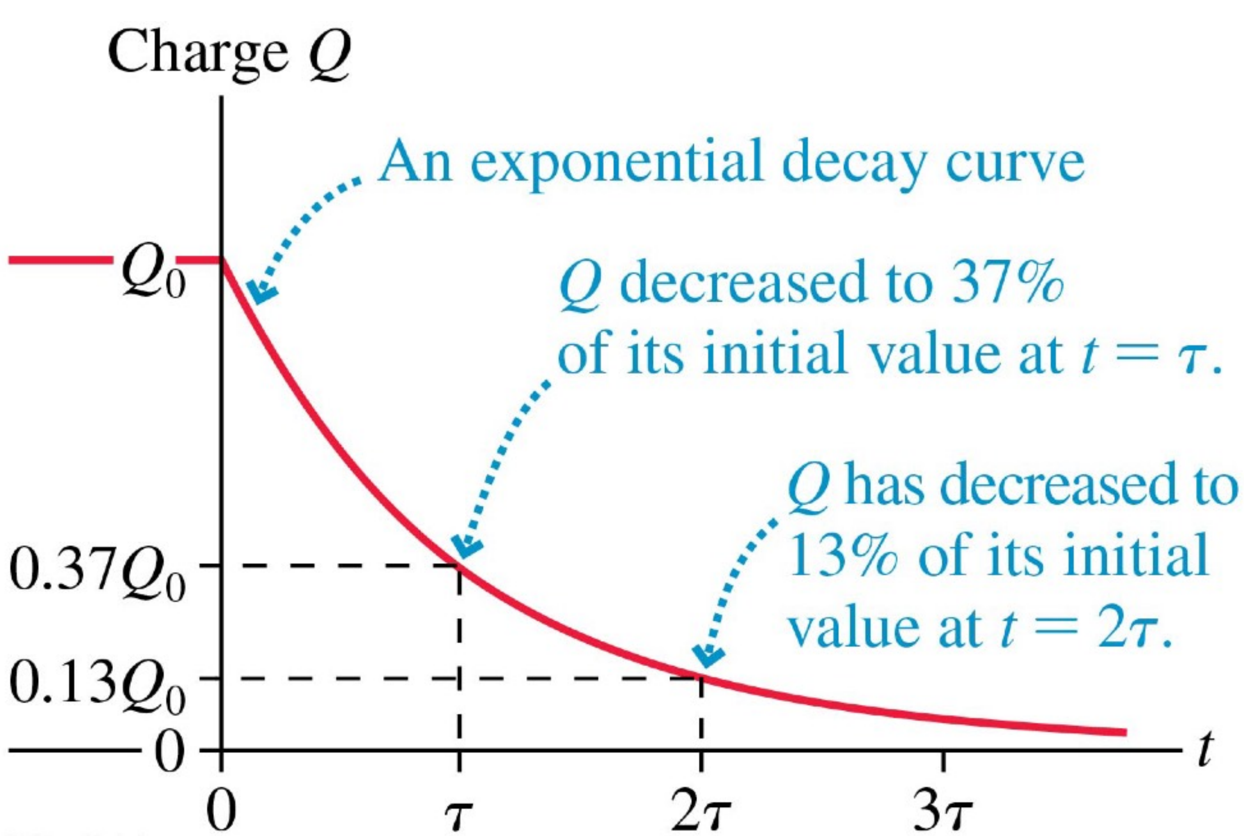


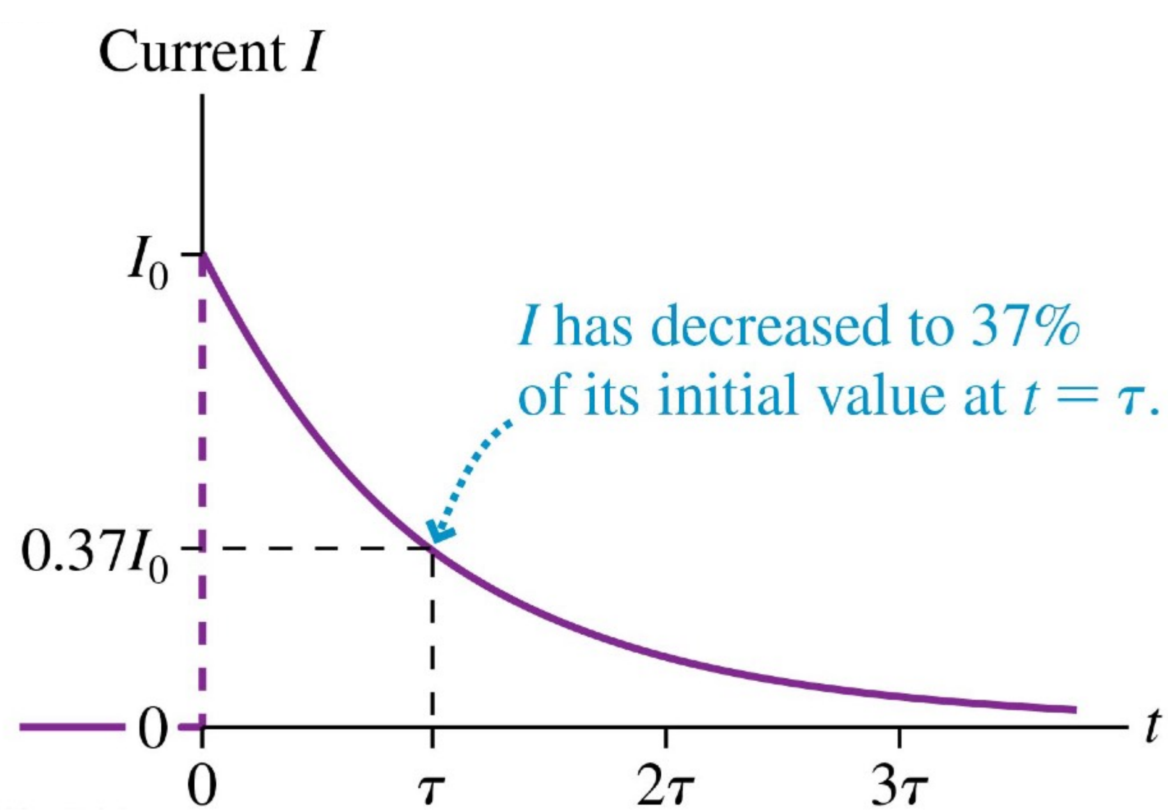
$$I = -\frac{dQ}{dt}$$

- Kirchhoff's loop law $\Delta V_{cap} + \Delta V_{res} = \dfrac{Q}{C} - IR = 0$

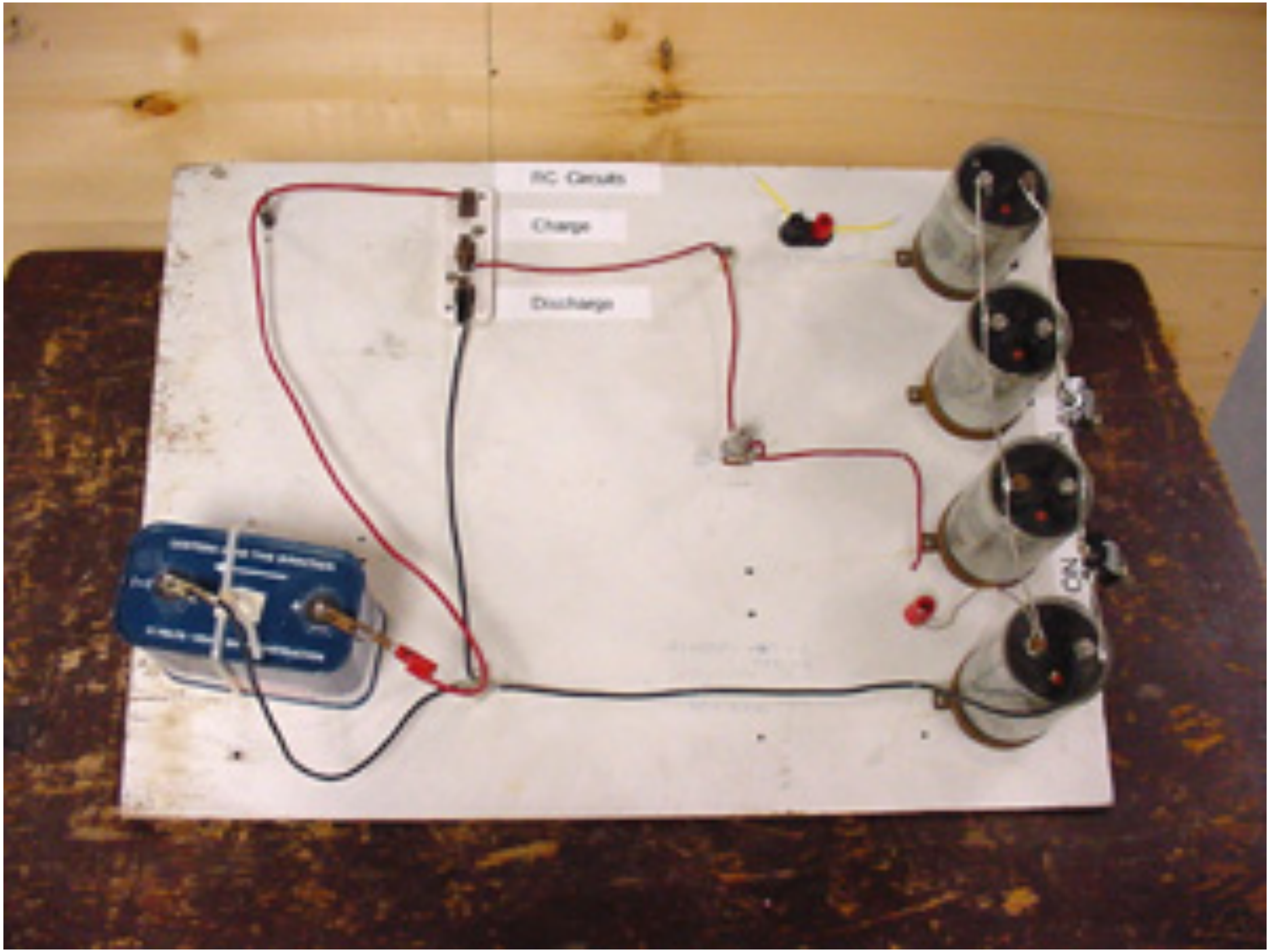
$$\boxed{Q = Q_0 e^{-t/\tau}}$$

$$\tau = RC$$



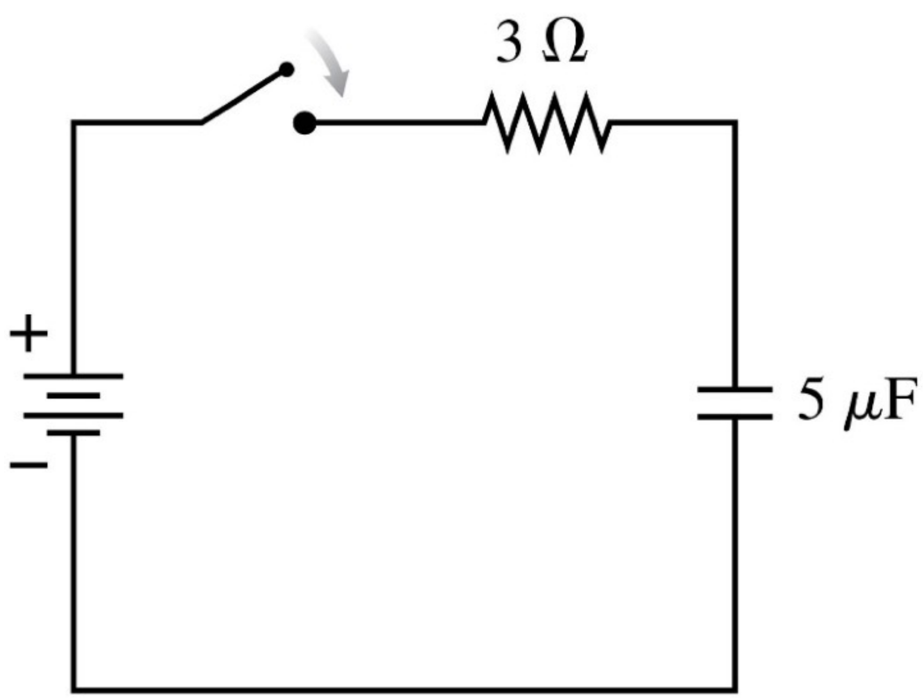


RC time constant demo



Review iclicker question:

The capacitor is initially unchanged. Immediately after the switch closes, the capacitor voltage is



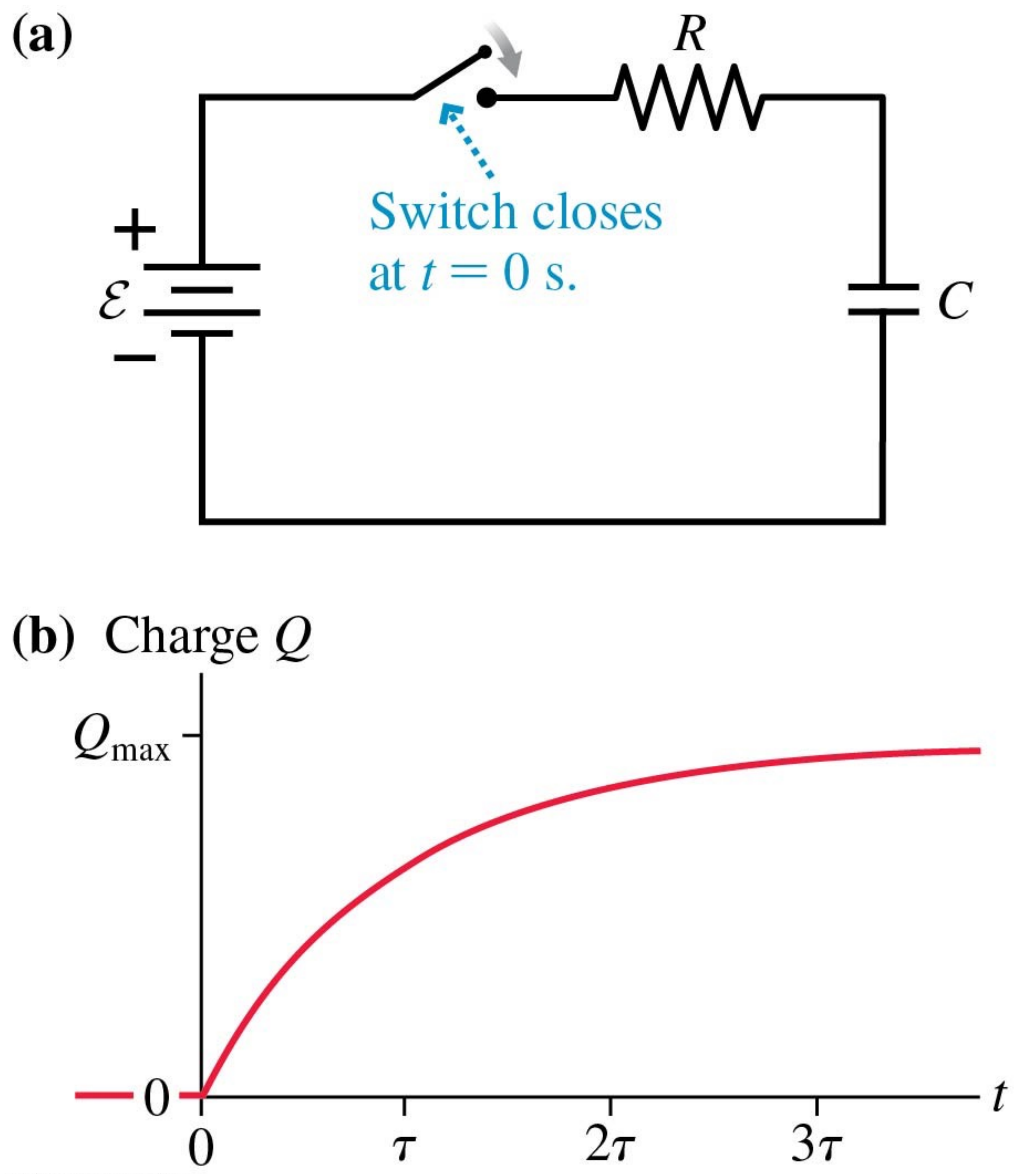
✔ A. **0 V**

B. Somewhere between 0 V and 6 V

C. 6 V

D. Undefined.

Charging a Capacitor



- Figure (a) shows a circuit that charges a capacitor.
- The capacitor charge and the circuit current at time t are

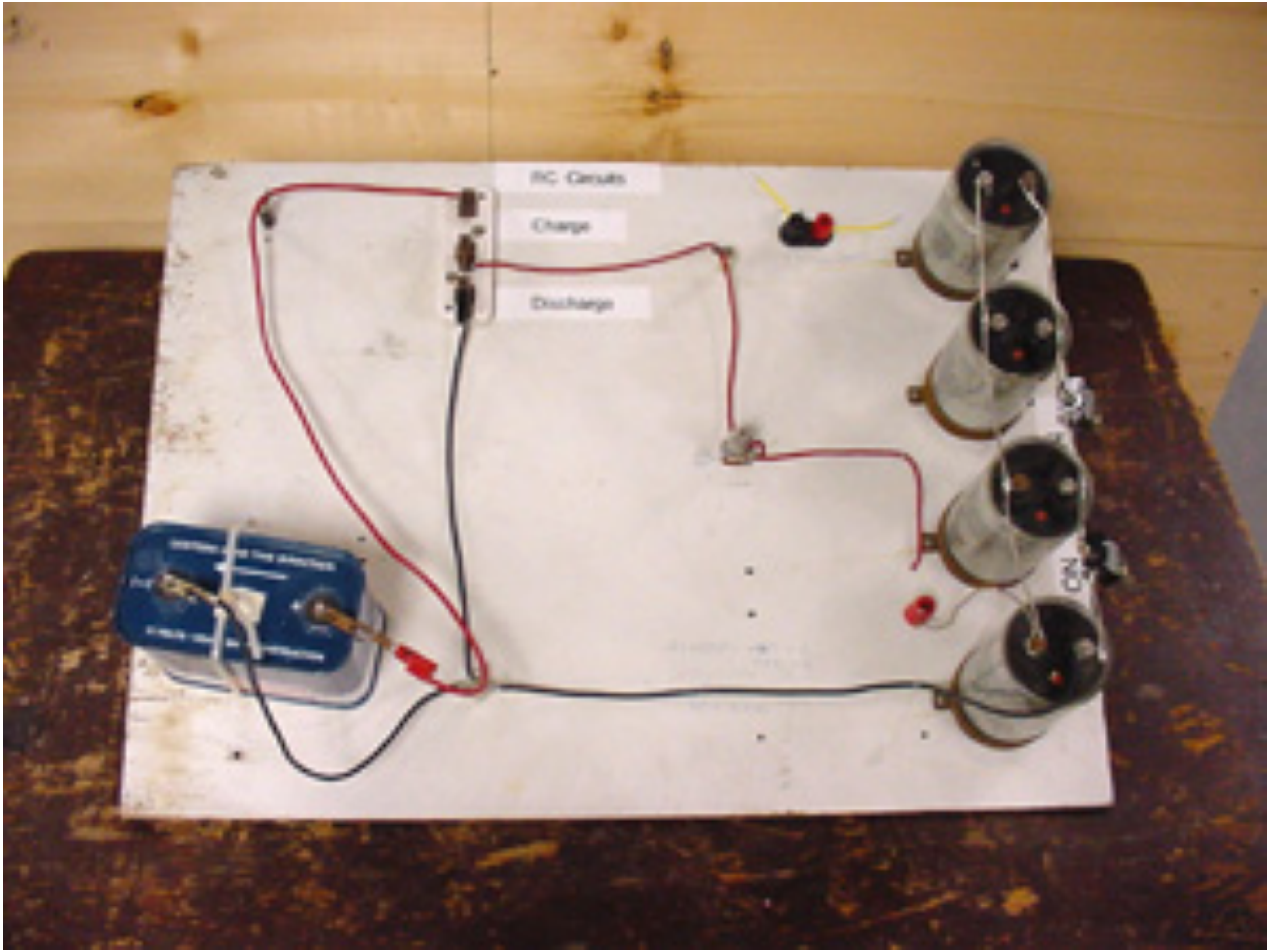
$$Q = Q_0(1 - e^{-t/\tau})$$

$$I = I_0 e^{-t/\tau}$$

where $I_0 = \mathcal{E}/R$ and $\tau = RC$.

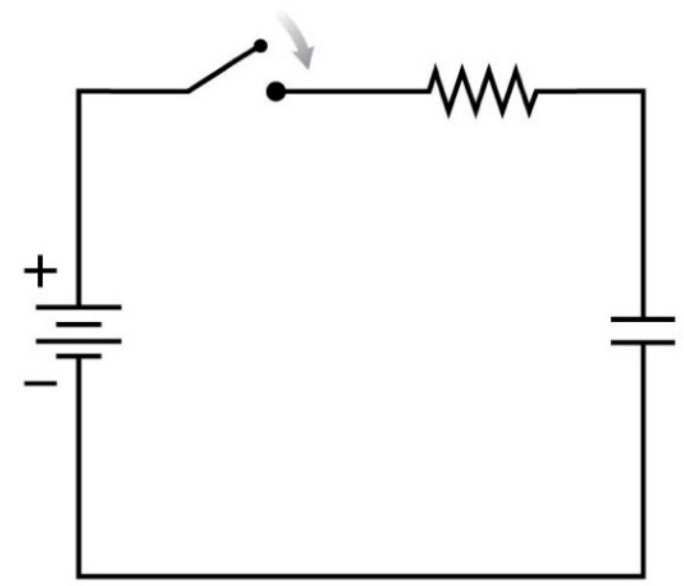
- This "upside-down decay" is shown in figure (b).

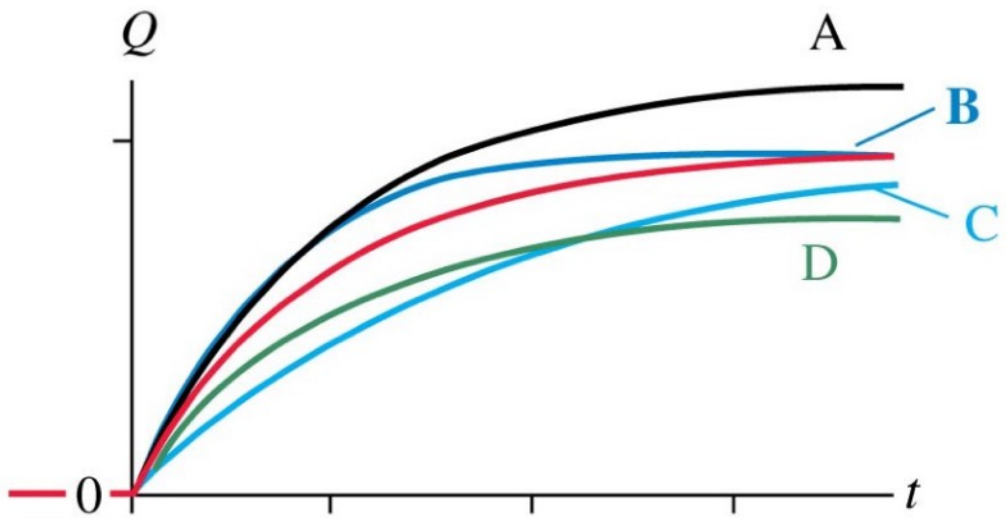
RC time constant demo



iClicker question #13-1

The red curve shows how the capacitor charges after the switch is closed at $t = 0$. Which curve shows the capacitor charging if the value of the resistor is reduced?

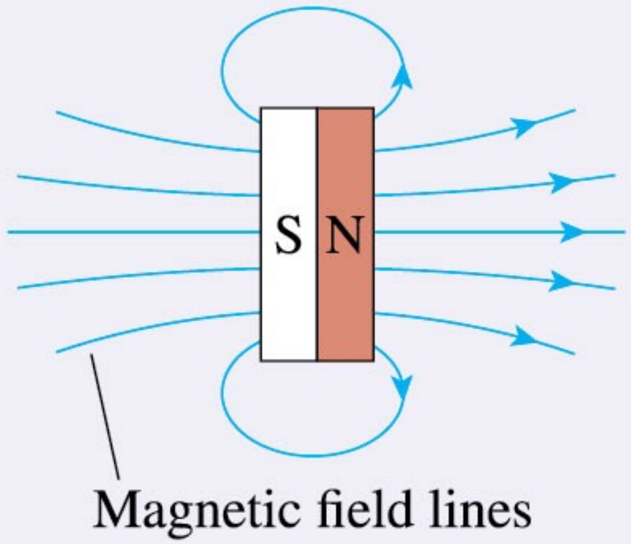




What is magnetism?

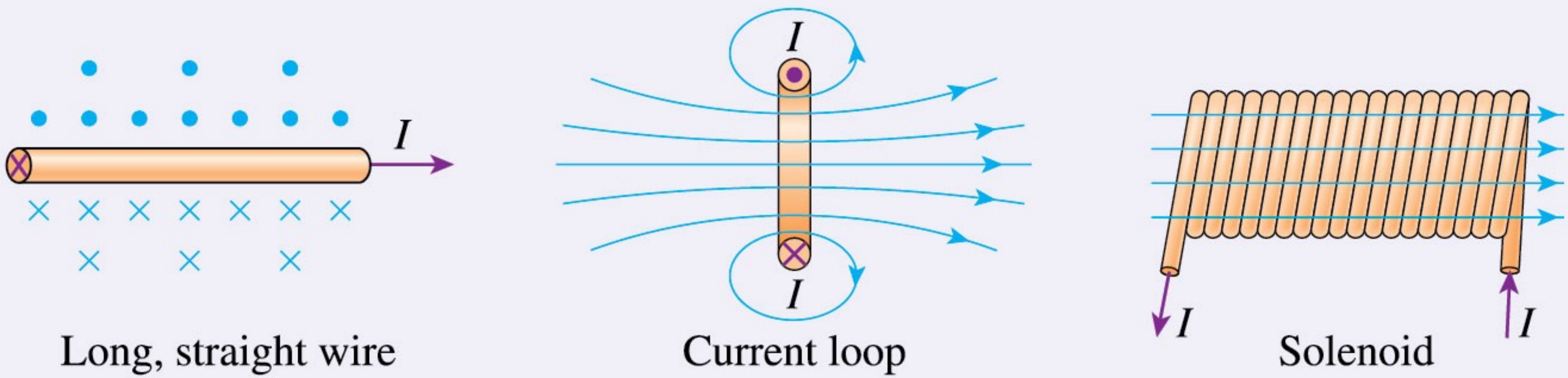
Magnetism is an interaction between *moving* charges.

- Magnetic forces, similar to electric forces, are due to the action of magnetic fields.
- A magnetic field $\vec{B}$ is created by a moving charge.
- Magnetic interactions are understood in terms of magnetic poles: north and south.
- Magnetic poles never occur in isolation. All magnets are dipoles, with two poles.
- Practical magnetic fields are created by currents—collections of moving charges.
- Magnetic materials, such as iron, occur because electrons have an inherent magnetic dipole called electron spin.



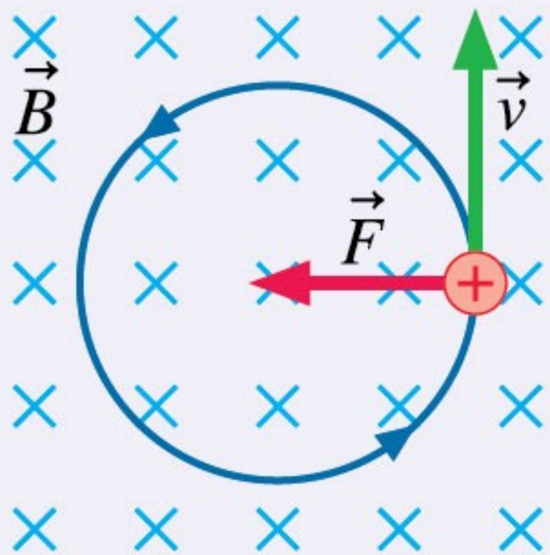
What fields are especially important?

We will develop and use three important **magnetic field models**.



How do charges respond to magnetic fields?

A charged particle *moving* in a magnetic field experiences a force perpendicular to both $\vec{B}$ and $\vec{v}$. The perpendicular force causes charged particles to move in circular orbits in a uniform magnetic field. This cyclotron motion has many important applications.



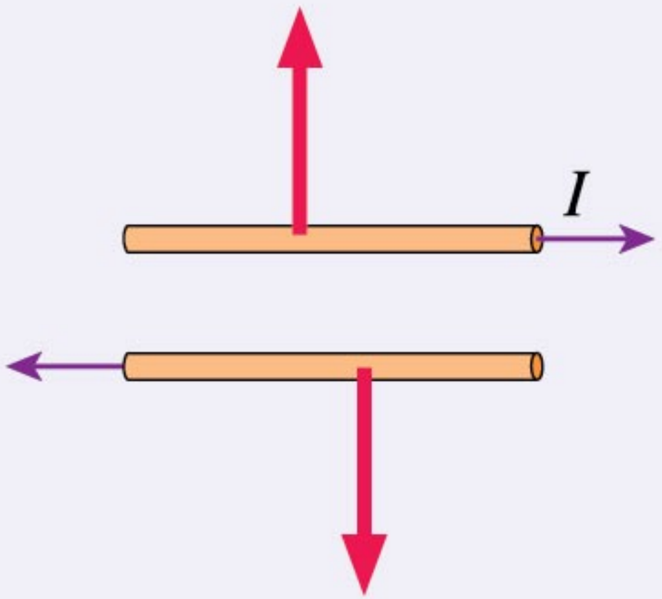
« LOOKING BACK Sections 8.2–8.3 Circular motion

« LOOKING BACK Section 12.10 The cross product

How do currents respond to magnetic fields?

Currents are moving charged particles, so:

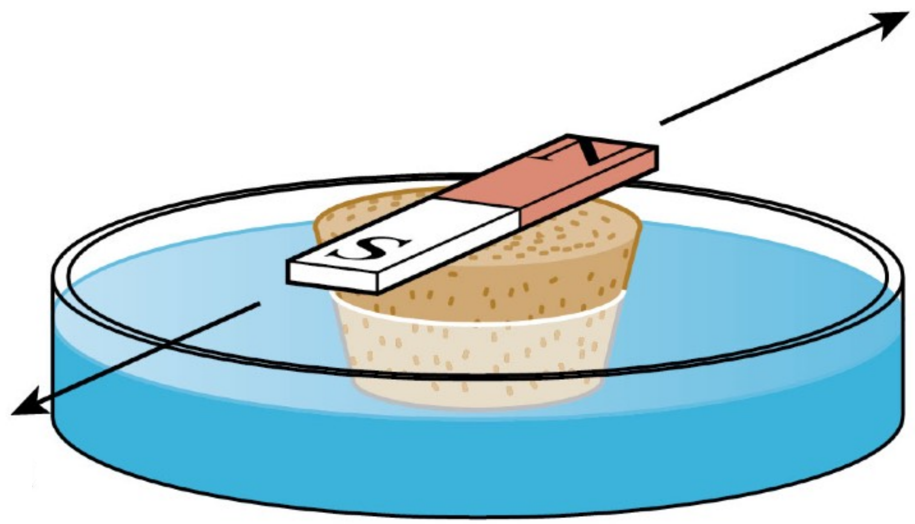
- There's a force on a current-carrying wire in a magnetic field.
- Two parallel current-carrying wires attract or repel each other.
- There's a torque on a current loop in a magnetic field. This is how motors work.



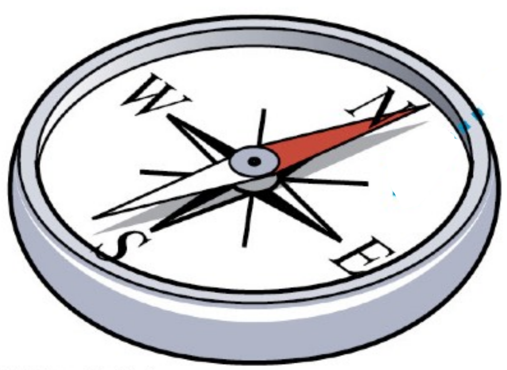
Why is magnetism important?

Magnetism is much more important than a way to hold a shopping list on the refrigerator door. Motors and generators are based on magnetic forces. Many forms of data storage, from hard disks to the stripe on your credit card, are magnetic. Magnetic resonance imaging (MRI) is essential to modern medicine. Magnetic levitation trains are being built around the world. And the earth's magnetic field keeps the solar wind from sterilizing the surface. There would be no life and no modern technology without magnetism.

Discovering Magnetism: Experiment 1



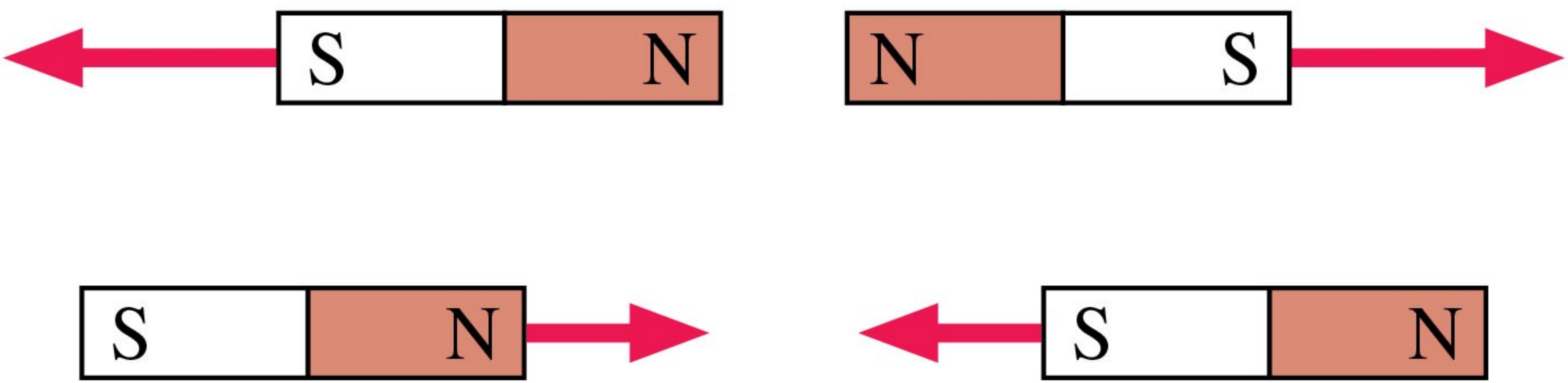
- Tape a bar magnet to a piece of cork and allow it to float in a dish of water.
- It always turns to align itself in an approximate north-south direction.



- The end of a magnet that points north is called the *north-seeking pole*, or simply the **north pole**.
- The end of a magnet that points south is called the **south pole**.

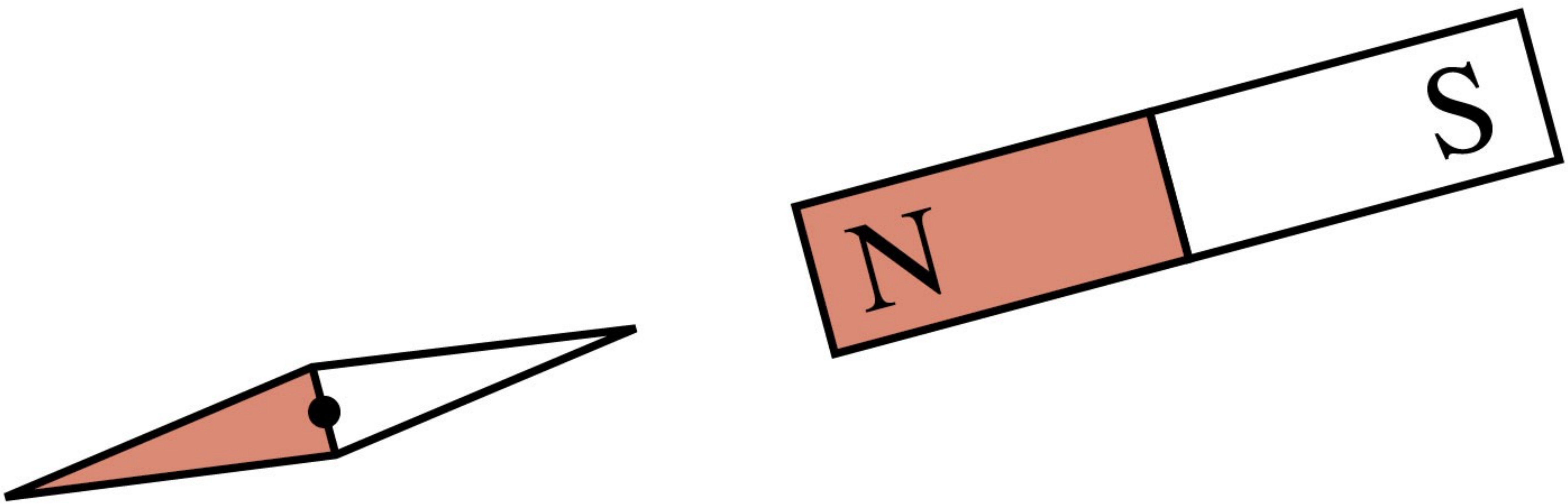
Discovering Magnetism: Experiment 2

- If the north pole of one magnet is brought near the north pole of another magnet, they repel each other.
- Two south poles also repel each other, but the north pole of one magnet exerts an attractive force on the south pole of another magnet.



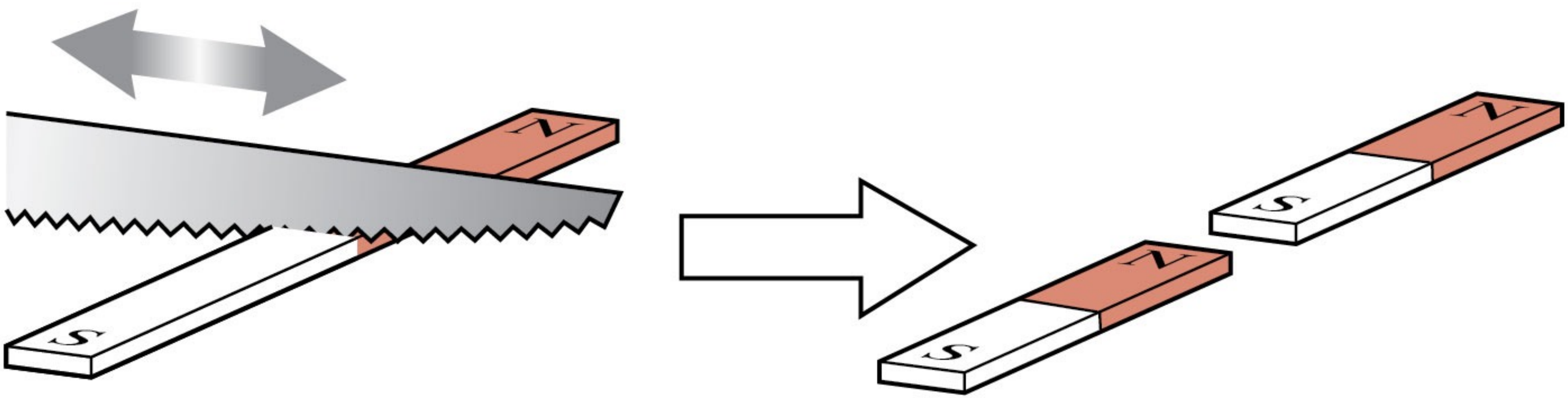
Discovering Magnetism: Experiment 3

- The north pole of a bar magnet attracts one end of a compass needle and repels the other.
- Apparently the compass needle itself is a little bar magnet with a north pole and a south pole.

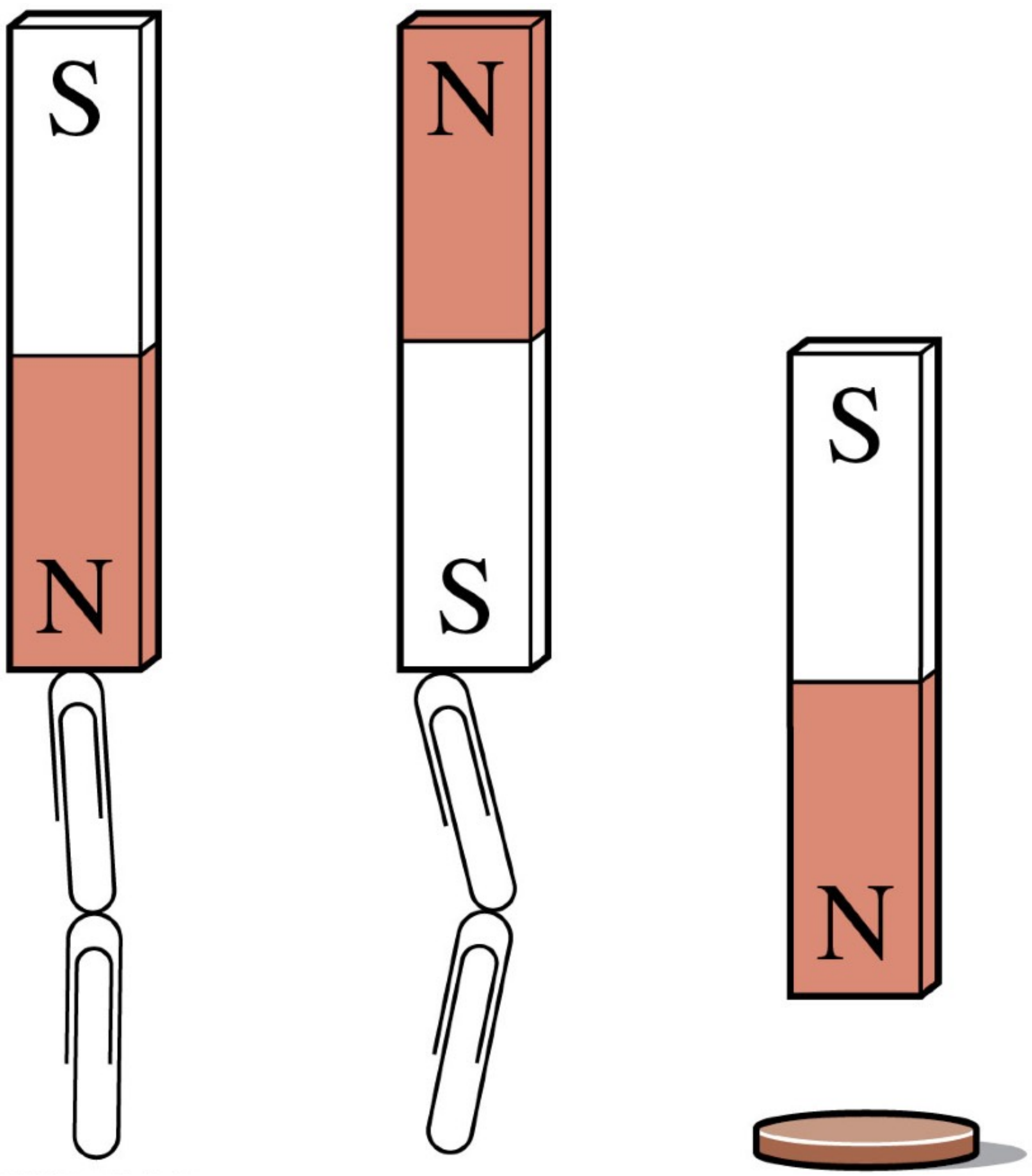


Discovering Magnetism: Experiment 4

- Cutting a bar magnet in half produces two weaker but still complete magnets, each with a north pole and a south pole.
- No matter how small the magnets are cut, even down to microscopic sizes, each piece remains a complete magnet with two poles.



Discovering Magnetism: Experiment 5

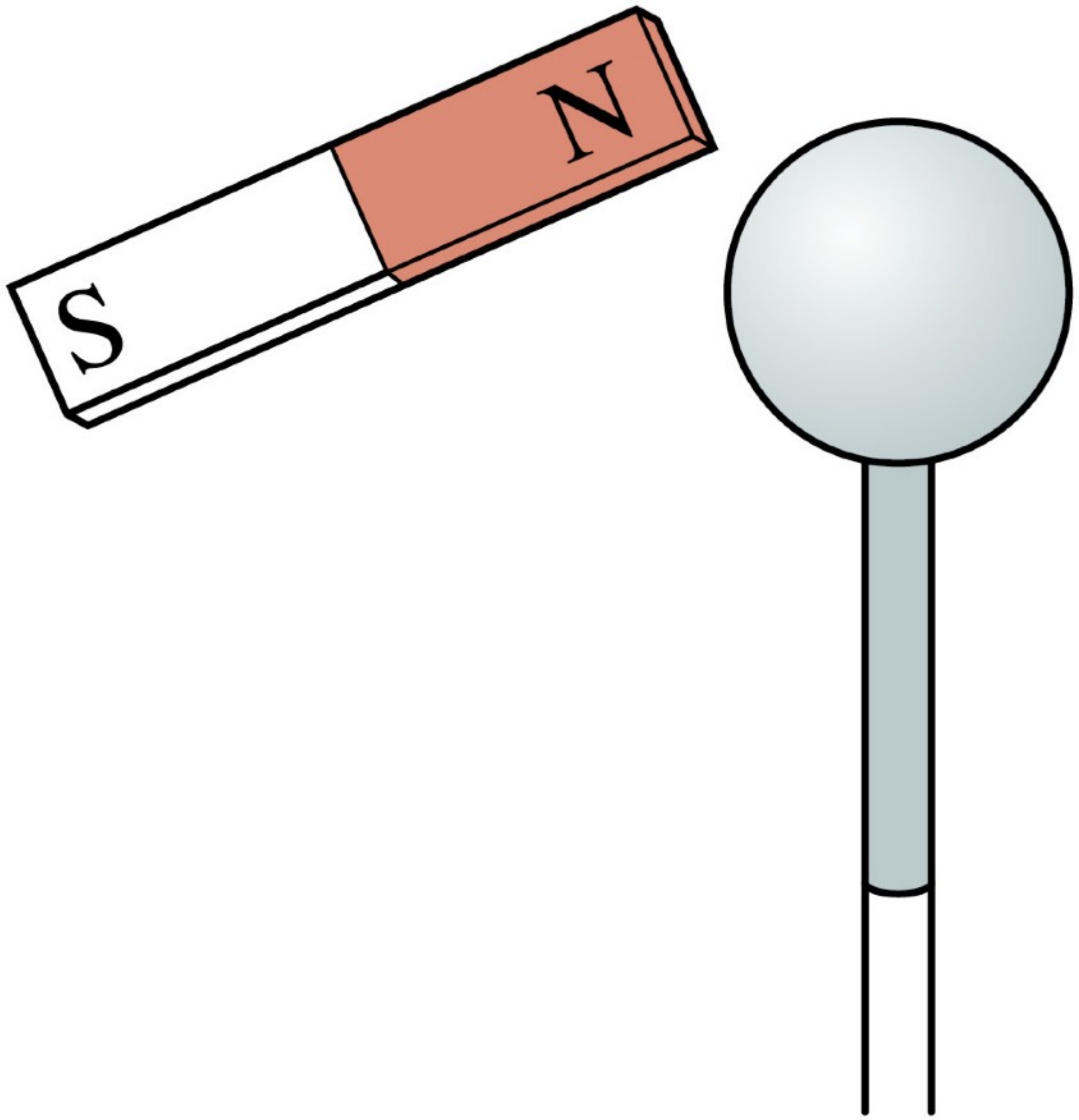


- Magnets can pick up some objects, such as paper clips, but not all.
- If an object is attracted to one end of a magnet, it is also attracted to the other end.
- Most materials, including copper (a penny), aluminum, glass, and plastic, experience no force from a magnet.

Ferromagnetism

"Paperclips on Magnet"
(Source: Robert Fornal)
http://www.flickr.com/photos/fornal/369978120/

Discovering Magnetism: Experiment 6



- A magnet does not affect an electroscope.
- A charged rod exerts a weak *attractive* force on *both* ends of a magnet.
- However, the force is the same as the force on a metal bar that isn't a magnet, so it is simply a polarization force like the ones we studied in Chapter 22.

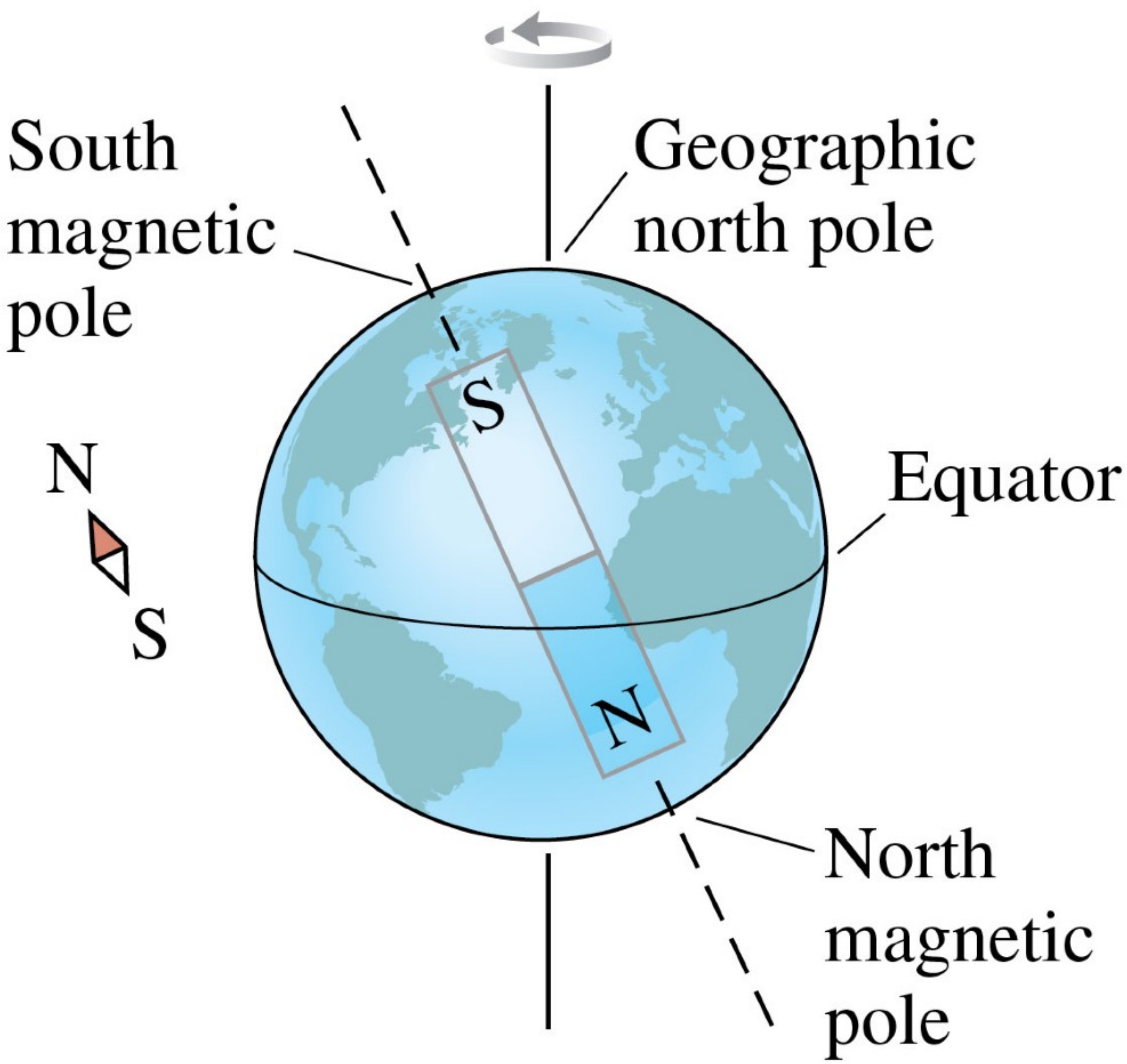
- Other than polarization forces, charges have *no effects* on magnets.

What Do These Experiments Tell Us?

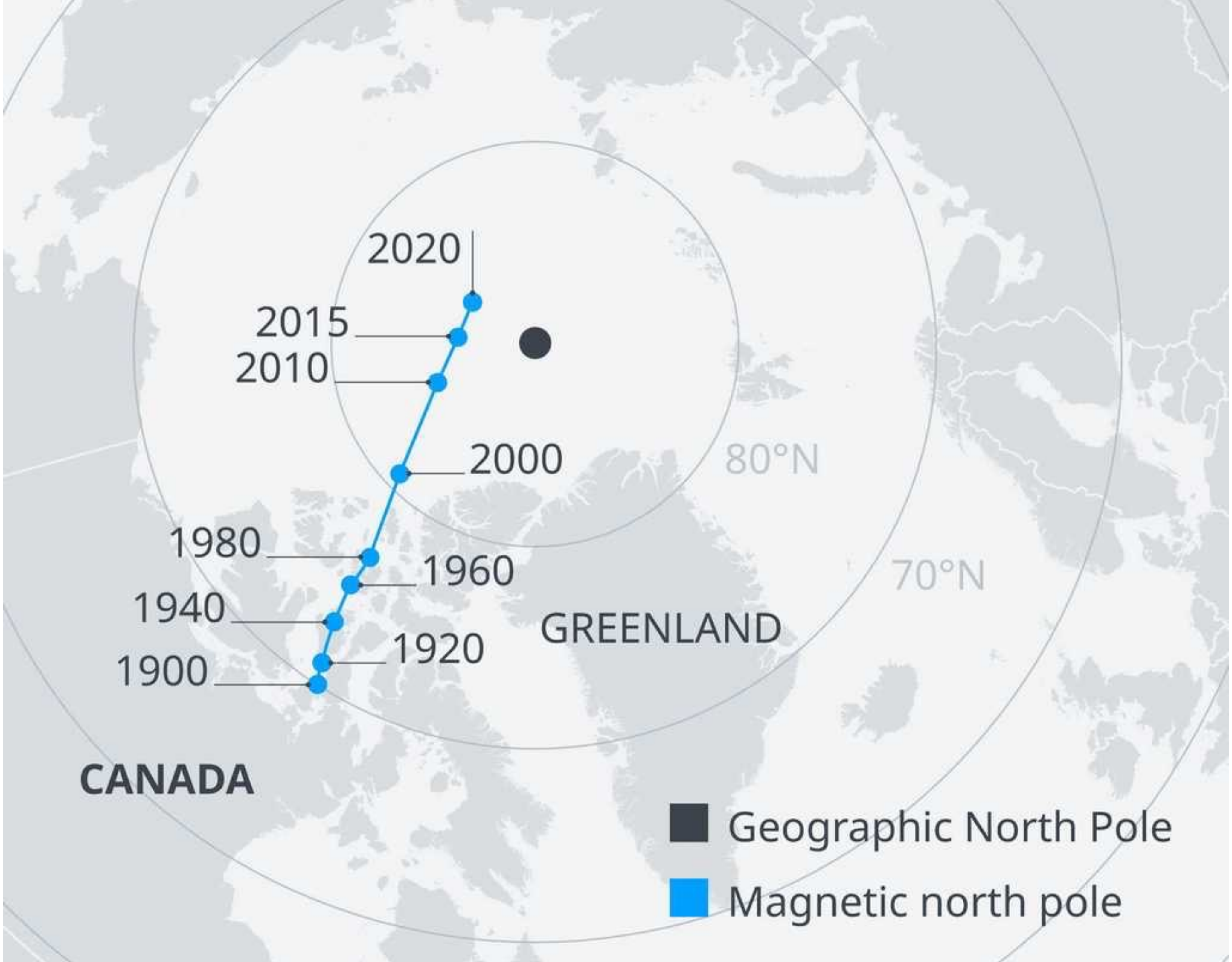
1. Magnetism is *not* the same as electricity.
2. Magnetism is a <u>long range force</u>.
3. All magnets have <u>two poles</u>, called north and south poles. Two like poles exert repulsive forces on each other; two opposite poles attract.
4. The poles of a bar magnet can be identified by using it as a compass. The north pole tends to rotate to point approximately north.
5. Materials that are attracted to a magnet are called **magnetic materials**. The most common magnetic material is iron.

Compasses and Geomagnetism

- Due to currents in the molten iron core, the earth itself acts as a large magnet.
- The poles are slightly offset from the poles of the rotation axis.
- The geographic north pole is actually a *south* magnetic pole!



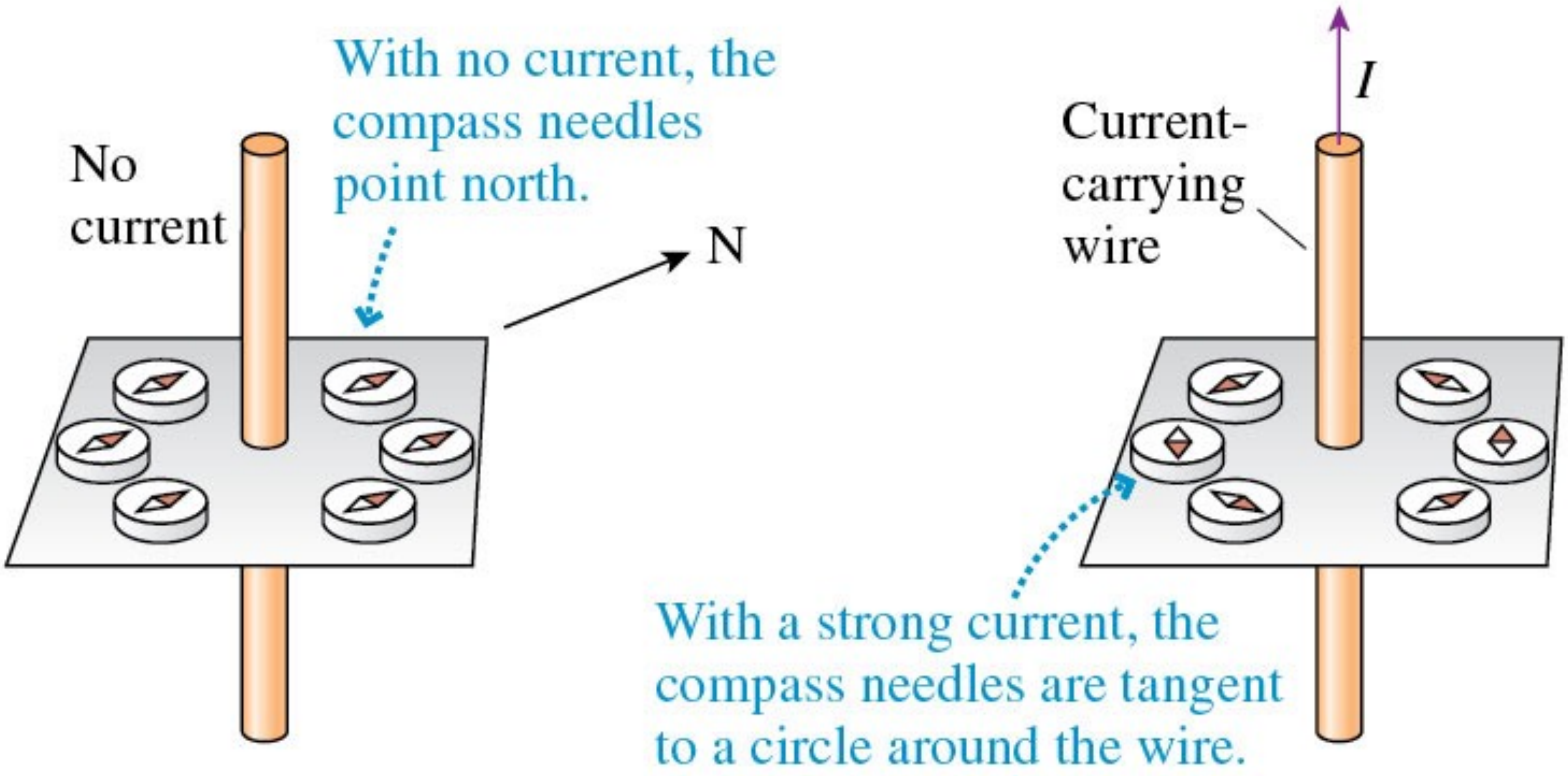
Magnetic north in motion



Source: Nature; World Data Center for Geomagnetism ©DW

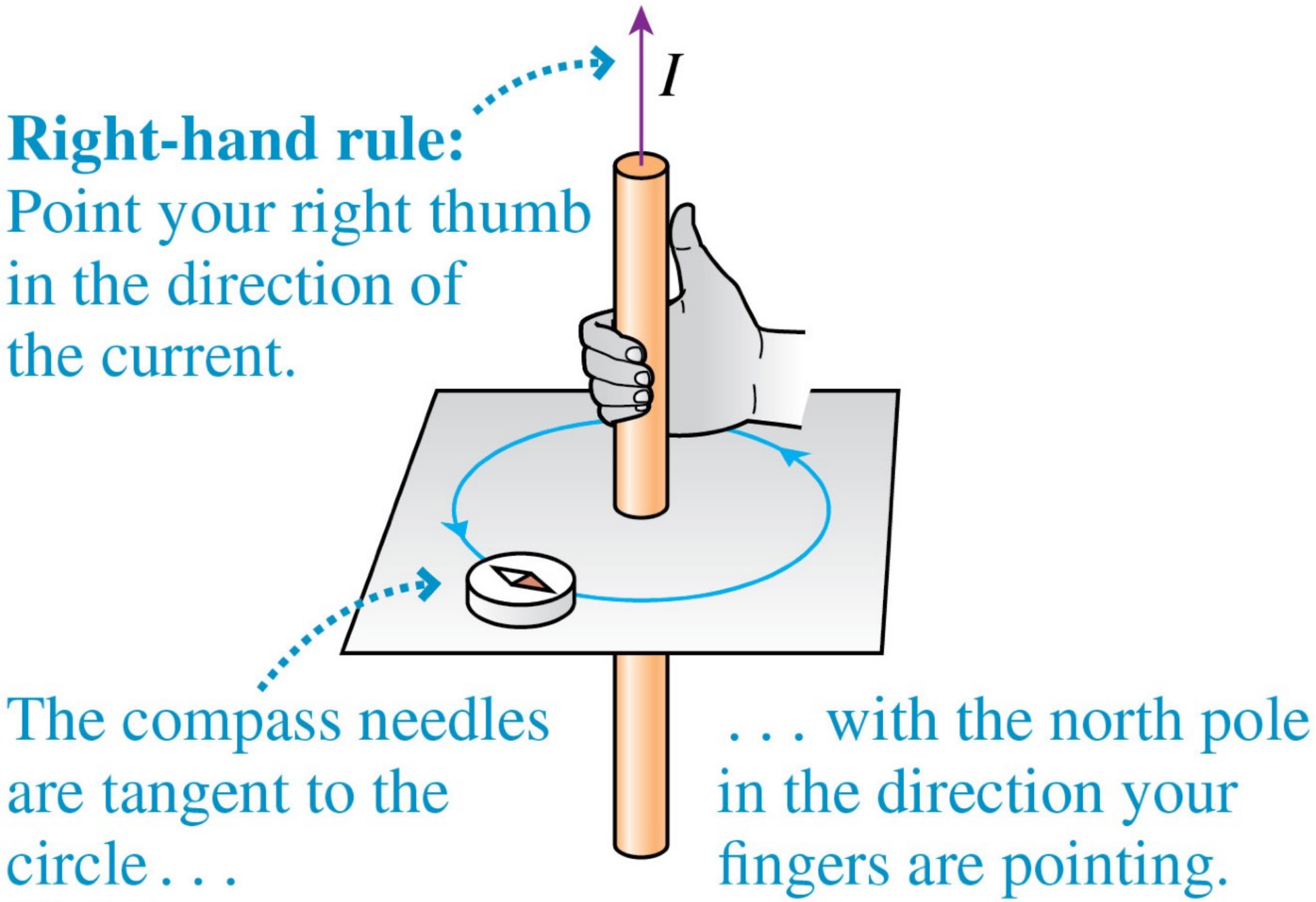
Electric Current Causes a Magnetic Field

- In 1819 Hans Christian Oersted discovered that an electric current in a wire causes a compass to turn.



Electric Current Causes a Magnetic Field

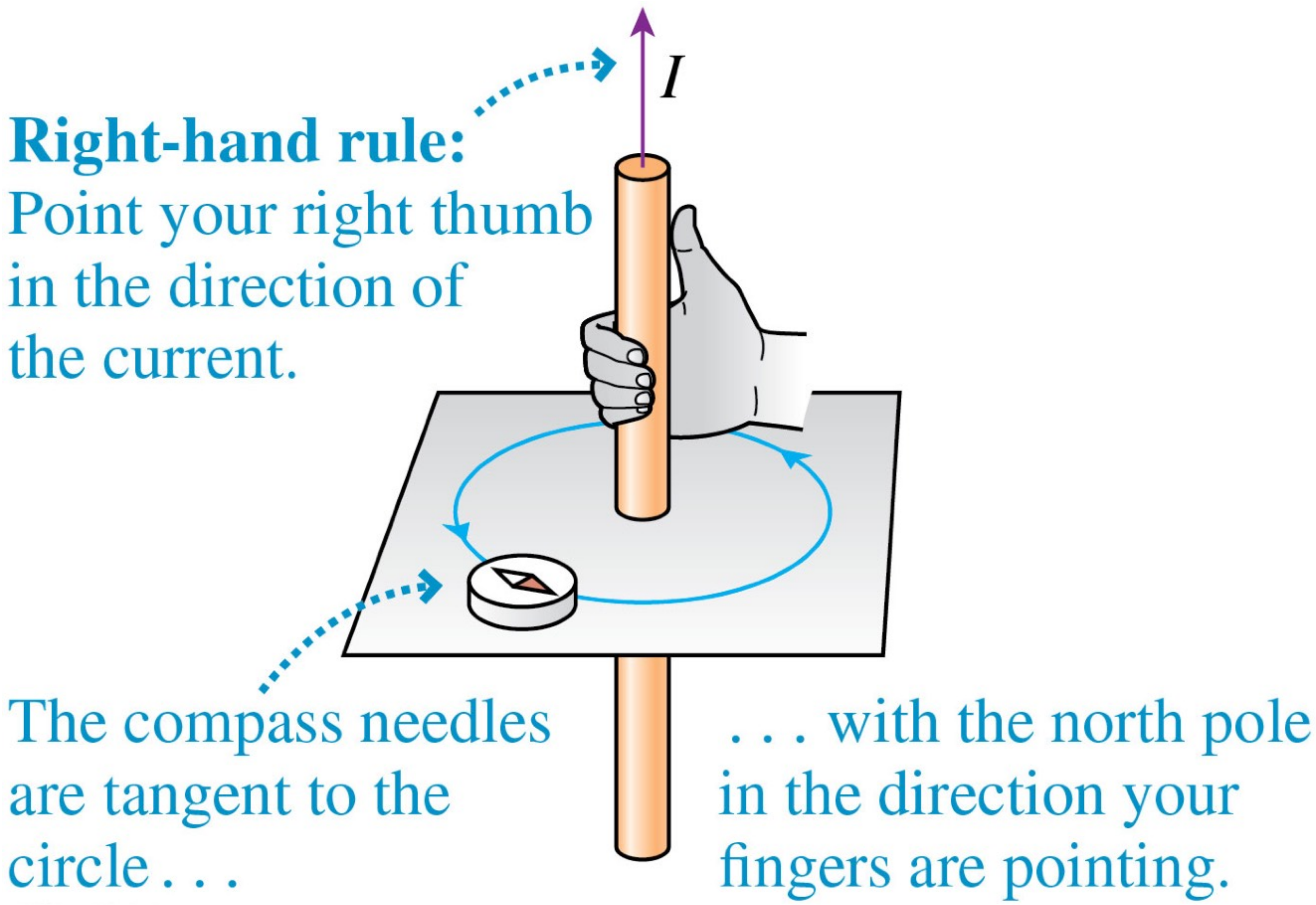
- The **right-hand rule** determines the orientation of the compass needles to the direction of the current.



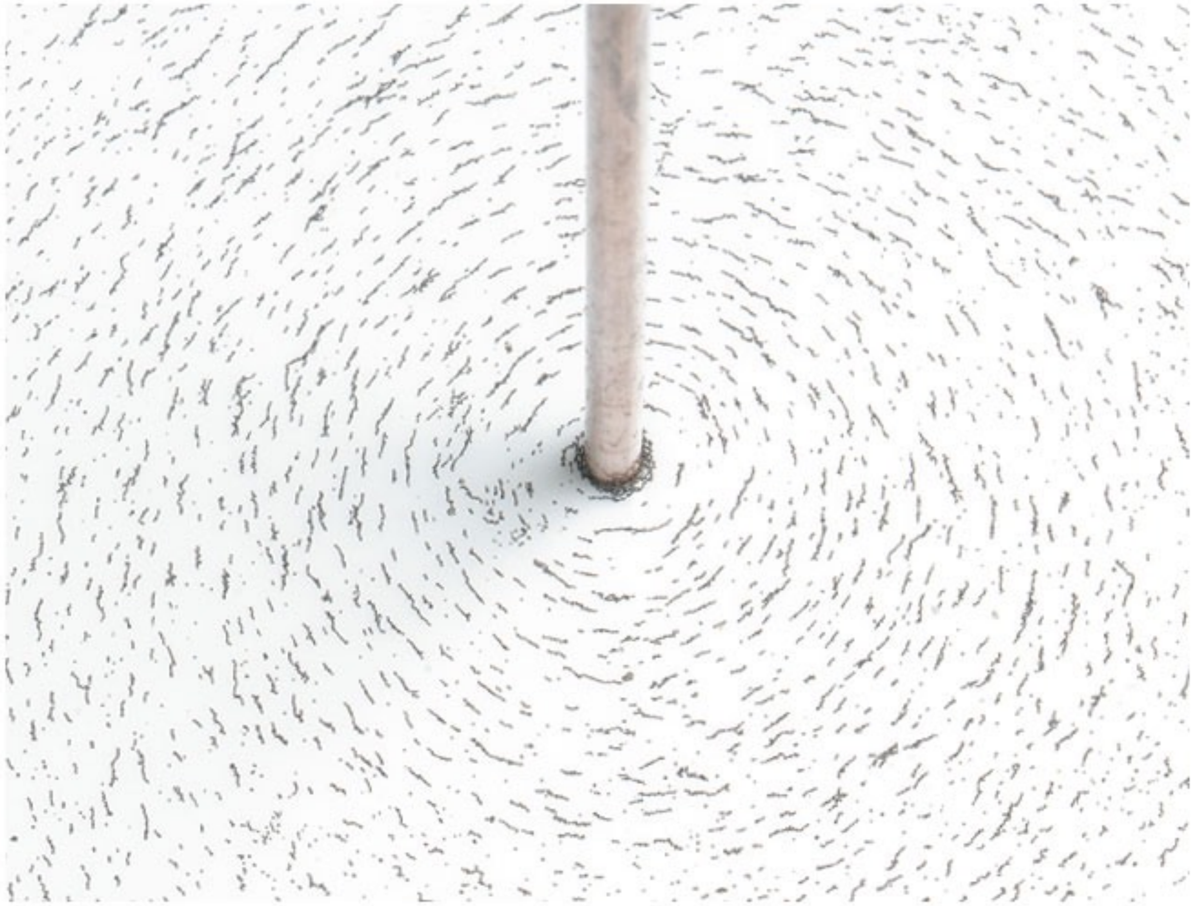
iClicker survey #13-2: Did you know this?

A. YES
B. NO
C. I don't care
D. Where am I?
E. Who am I?

- The **right-hand rule** determines the orientation of the compass needles to the direction of the current.



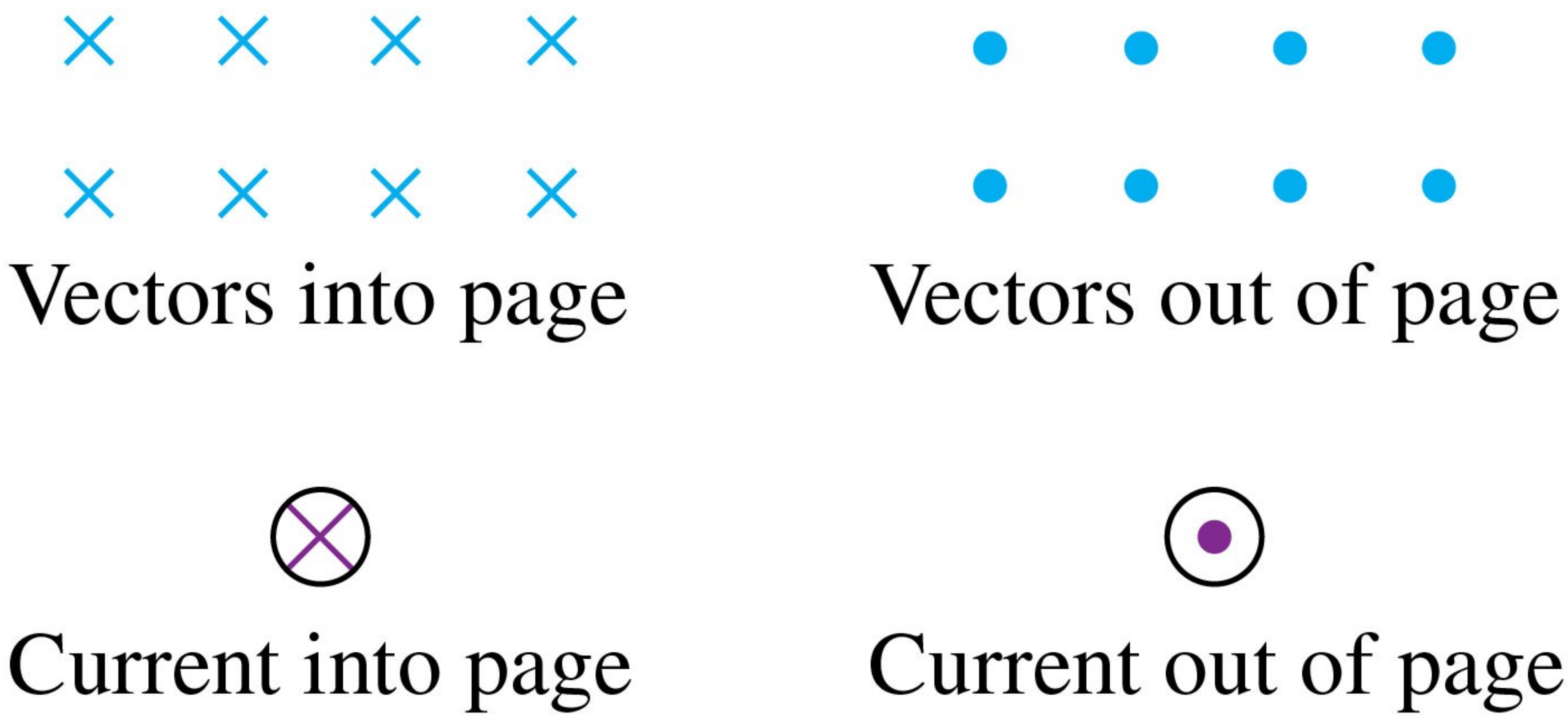
Electric Current Causes a Magnetic Field



- The magnetic field is revealed by the pattern of iron filings around a current-carrying wire.

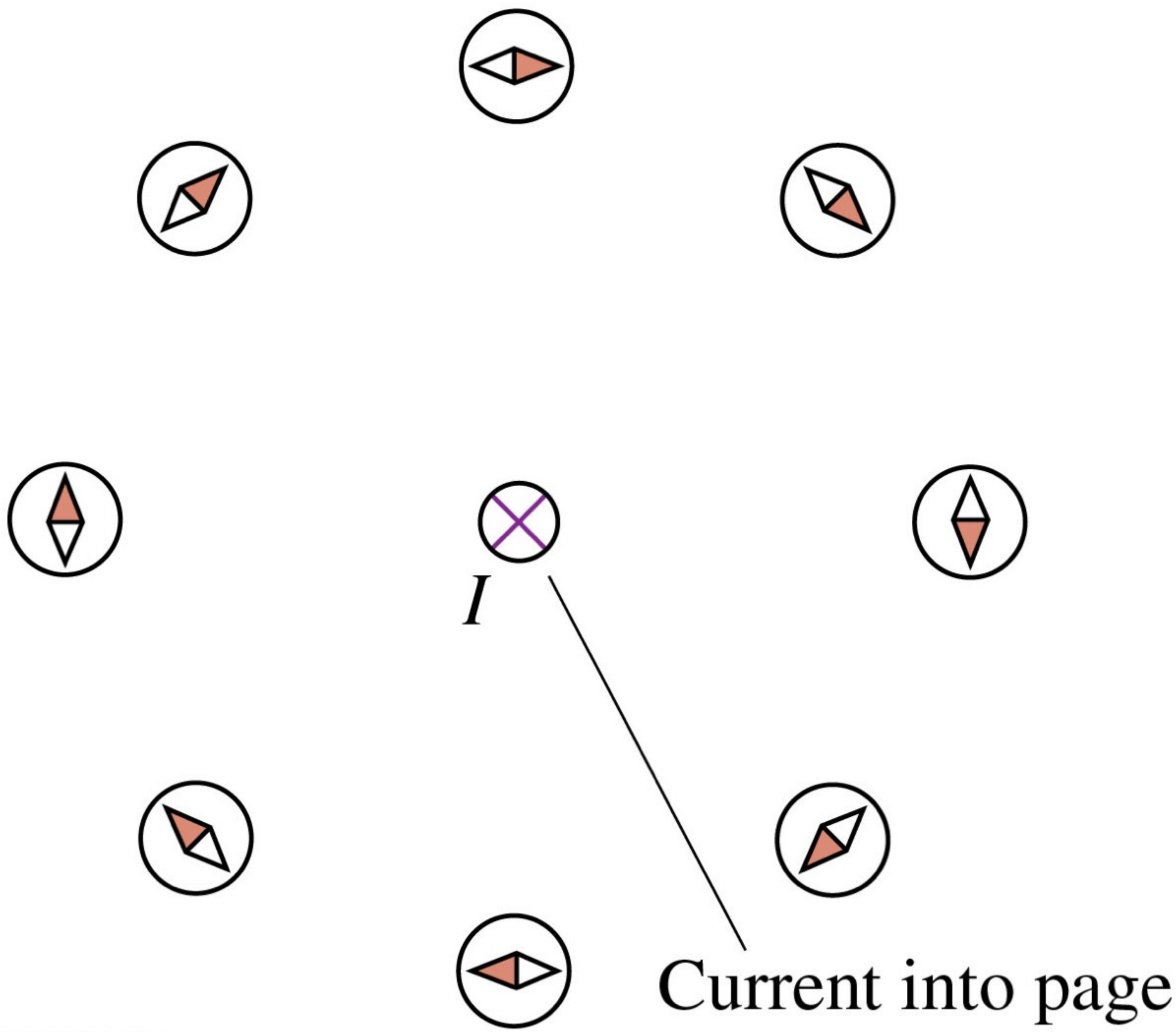
Notation for Vectors and Currents Perpendicular to the Page

- Magnetism requires a three-dimensional perspective, but two-dimensional figures are easier to draw.
- We will use the following notation:



Electric Current Causes a Magnetic Field

- The **right-hand rule** determines the orientation of the compass needles wrt the direction of the current.

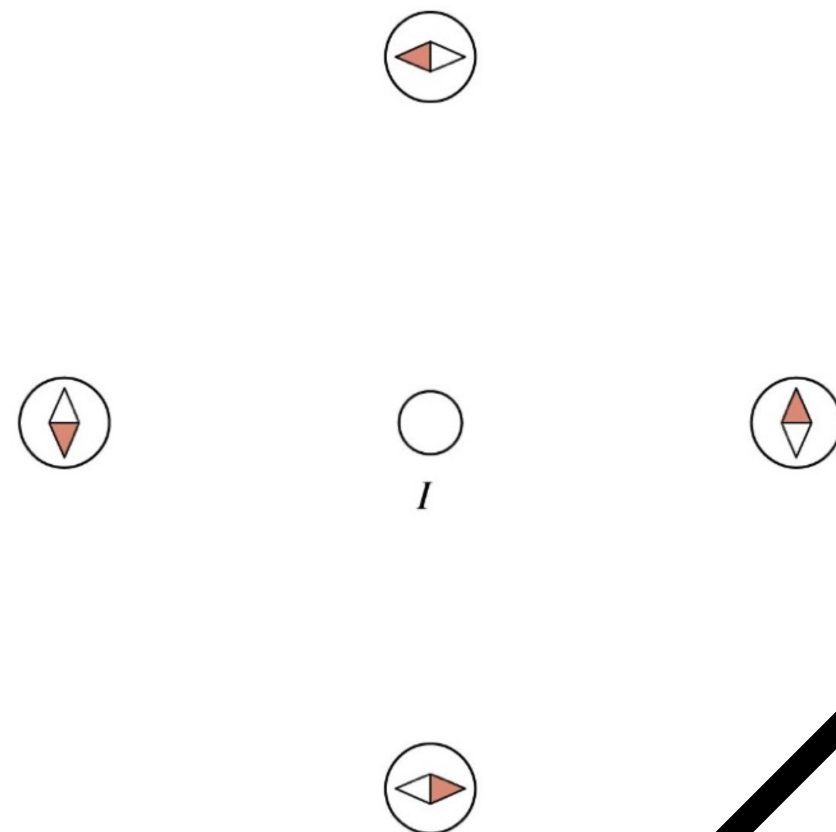


Mag. field of current

“Magnetic field around a wire”
(Source: VideoSASP)
http://www.youtube.com/watch?v=z5rLXjhlkjQ

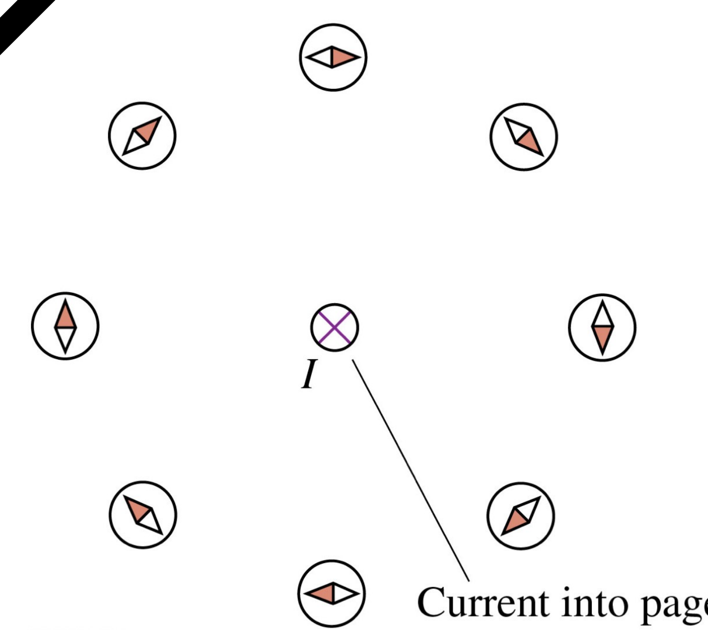
iClicker question #13-3

A long, straight wire extends into and out of the screen. The current in the wire is

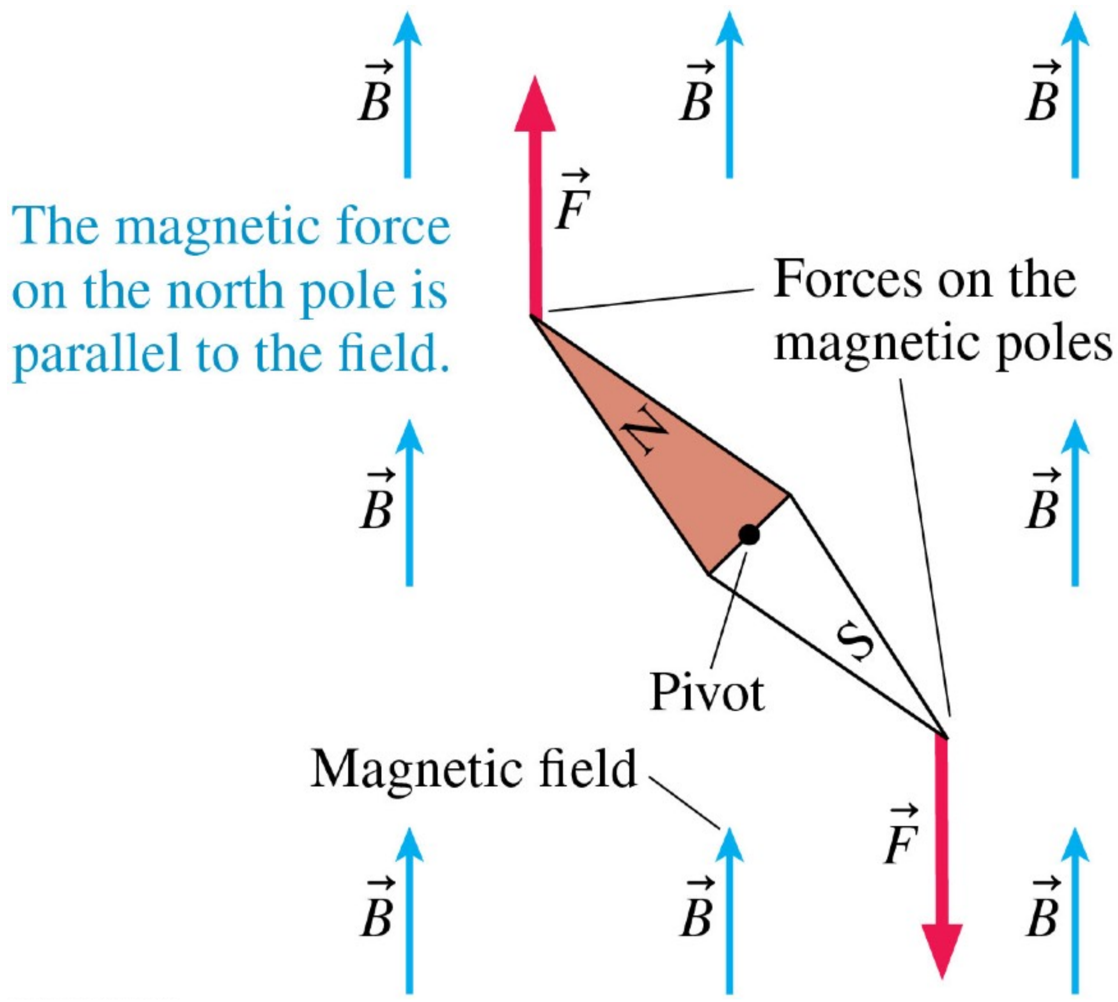


A. Into the screen.
B. Out of the screen.
C. There is no current in the wire.
D. Not enough info to tell the direction.

Earlier example:

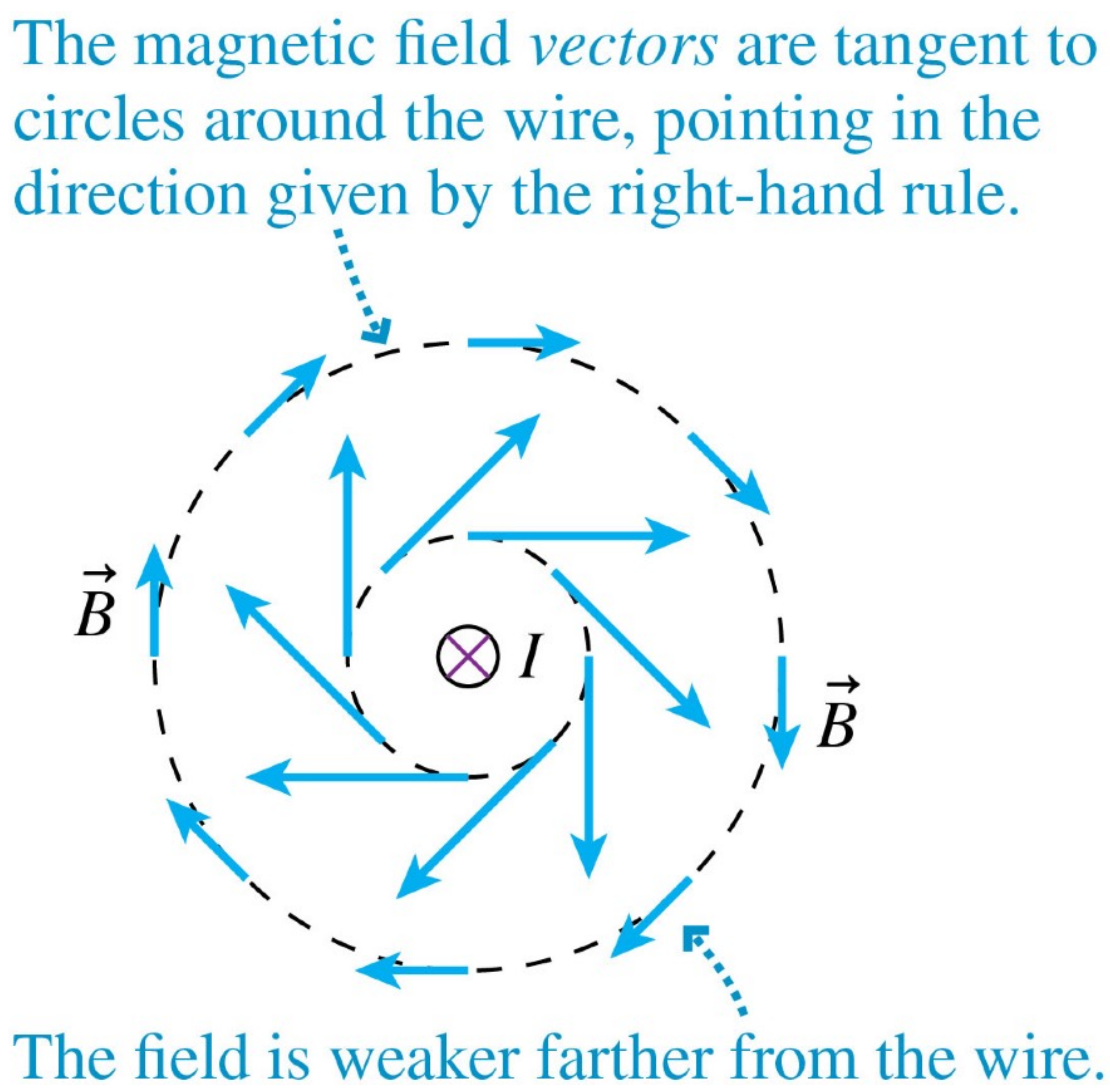


Magnetic Force on a Compass



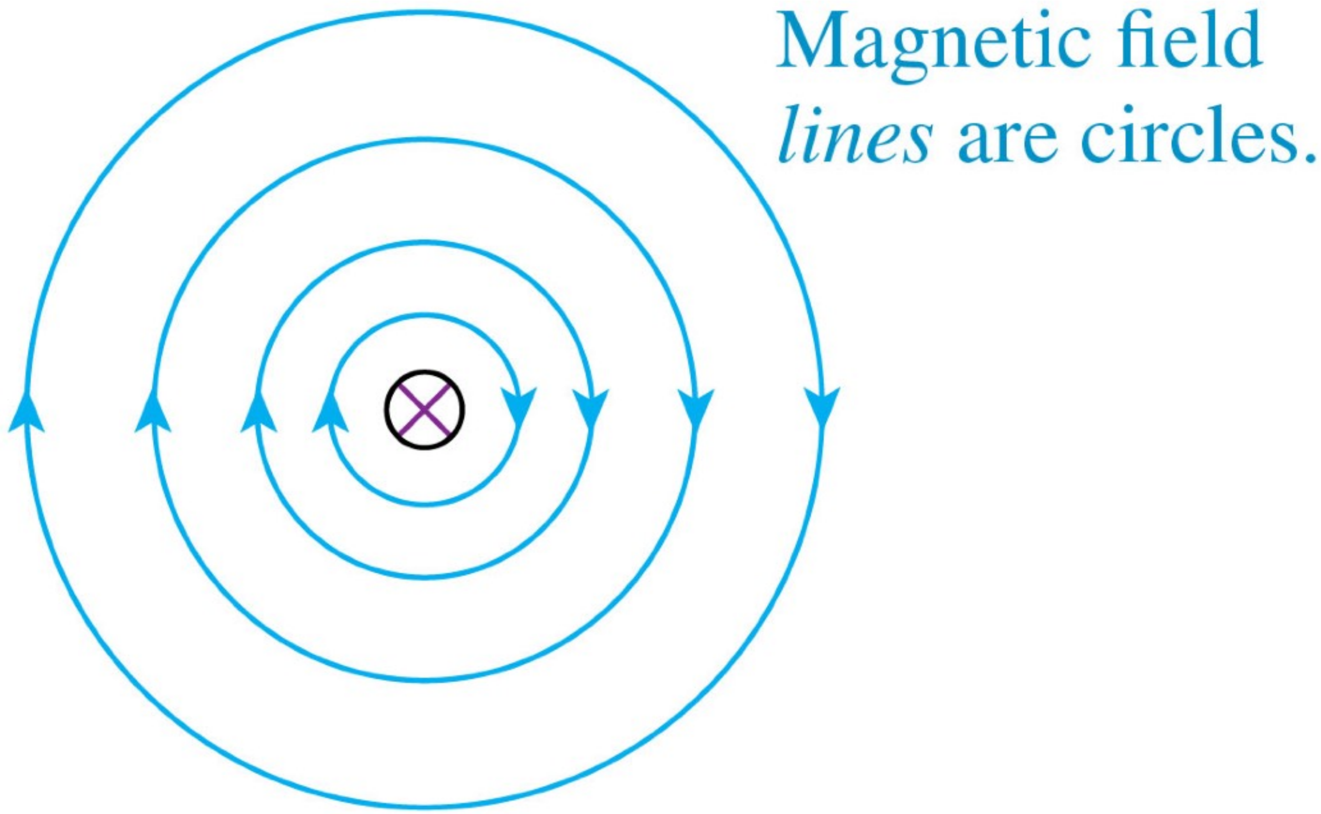
- The figure shows a compass needle in a magnetic field.
- A magnetic force is exerted on each of the two poles of the compass, parallel to $\vec{B}$ for the north pole and opposite $\vec{B}$ for the south pole.
- This pair of opposite forces exerts a torque on the needle, rotating the needle until it is parallel to the magnetic field at that point.

Electric Current Causes a Magnetic Field



- Because compass needles align with the magnetic field, the magnetic field at each point must be tangent to a circle around the wire.
- The figure shows the magnetic field by drawing field vectors.
- Notice that the field is weaker (shorter vectors) at greater distances from the wire.

Electric Current Causes a Magnetic Field



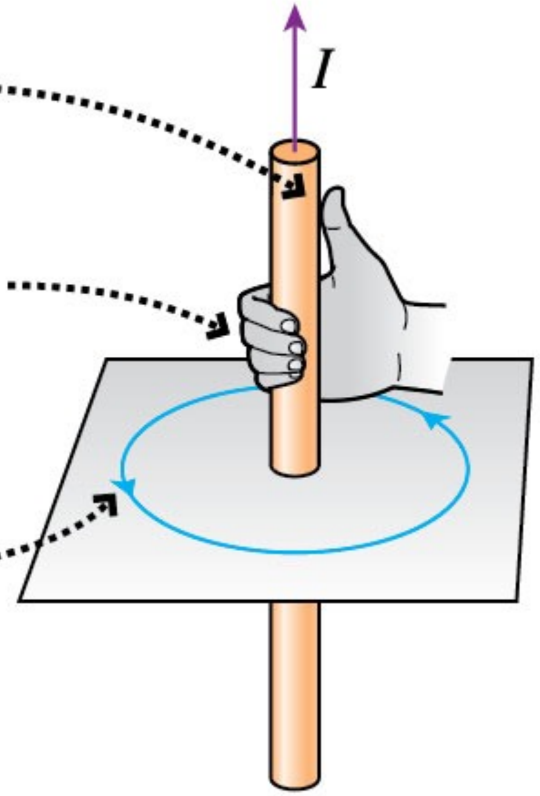
- Magnetic field lines are imaginary lines drawn through a region of space so that:
  - A tangent to a field line is in the direction of the magnetic field.
  - The field lines are closer together where the magnetic field strength is larger.

Tactics: Right-Hand Rule for Fields

TACTICS BOX 29.1

Right-hand rule for fields

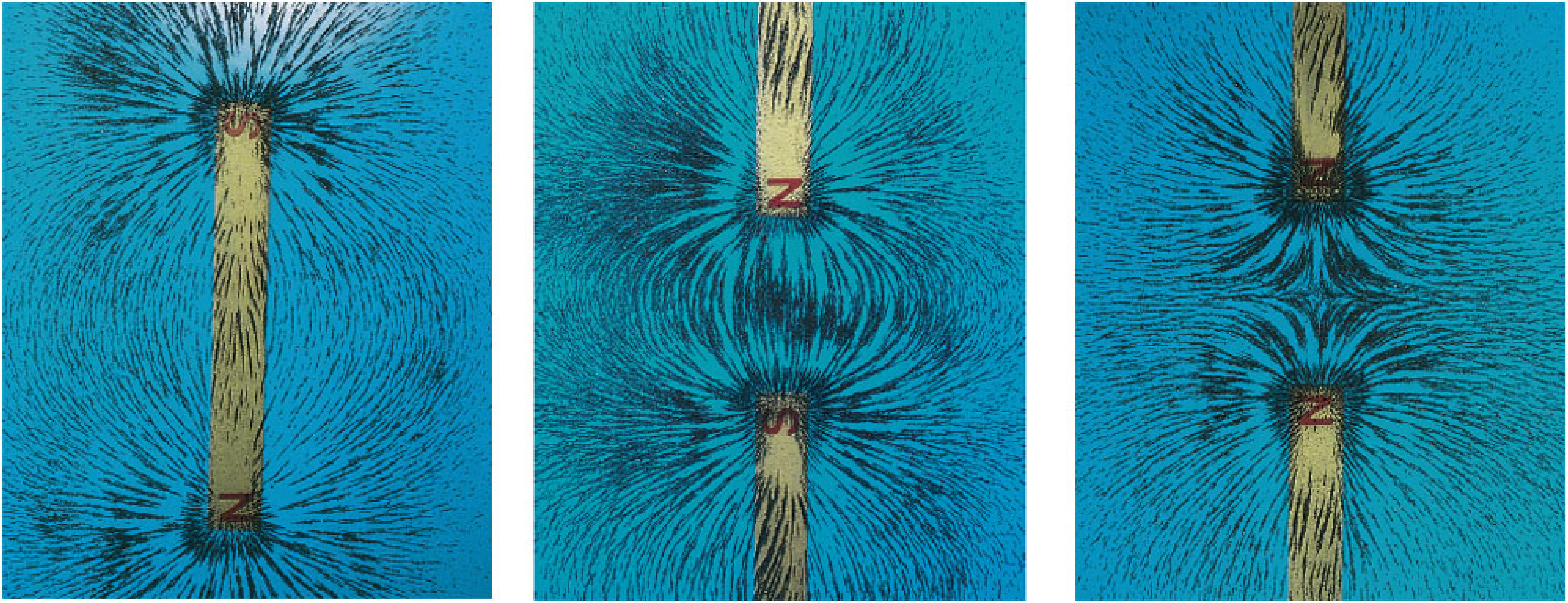
1. Point your *right* thumb in the direction of the current.
2. Curl your fingers around the wire to indicate a circle.
3. Your fingers point in the direction of the magnetic field lines around the wire.



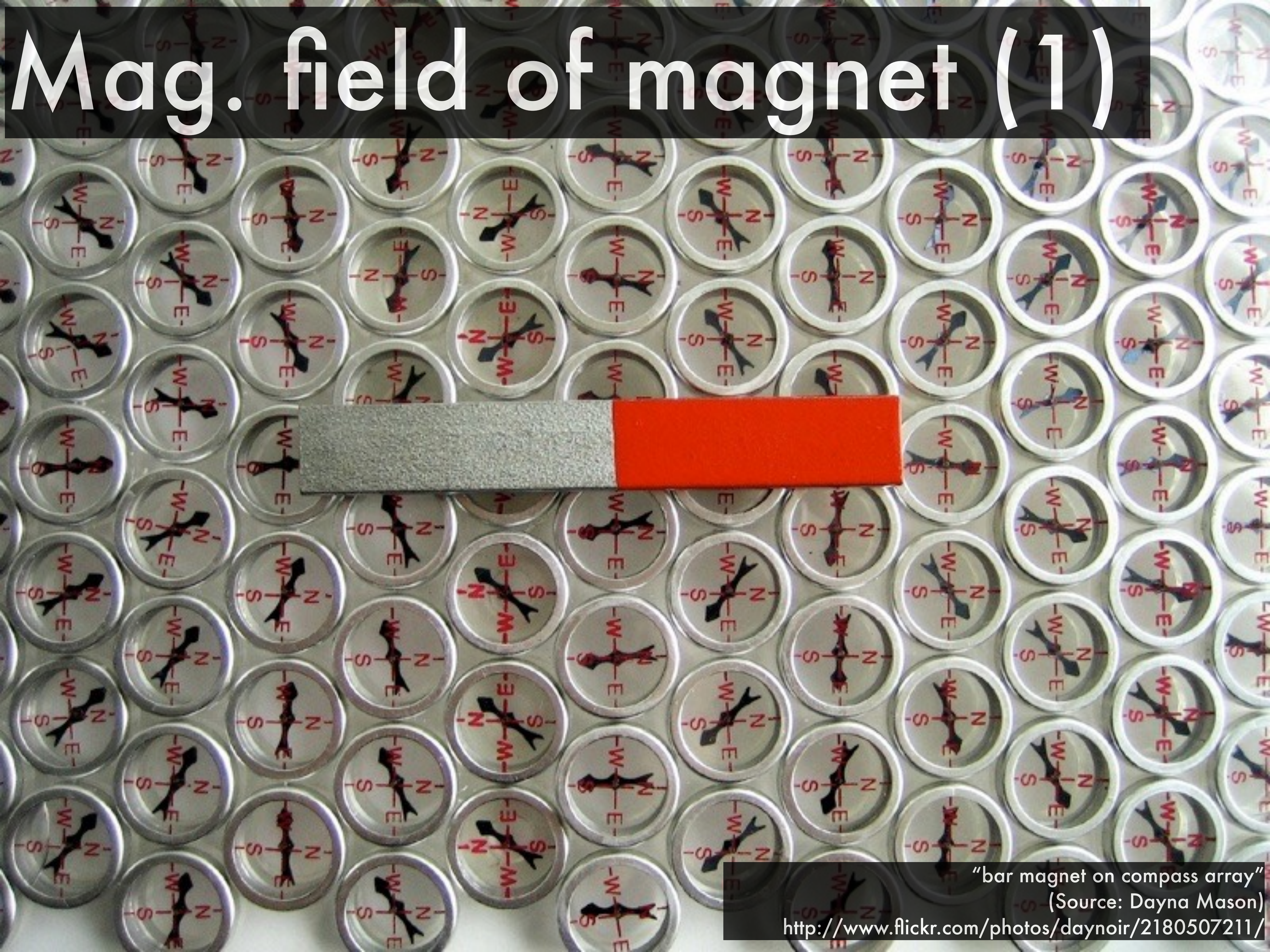
Exercises 6–8

History of Magnets

- Magnetic field lines are actually easier to visualize than electric field lines.
- Just put some iron filings next to a magnet and they will align themselves with the magnetic field.

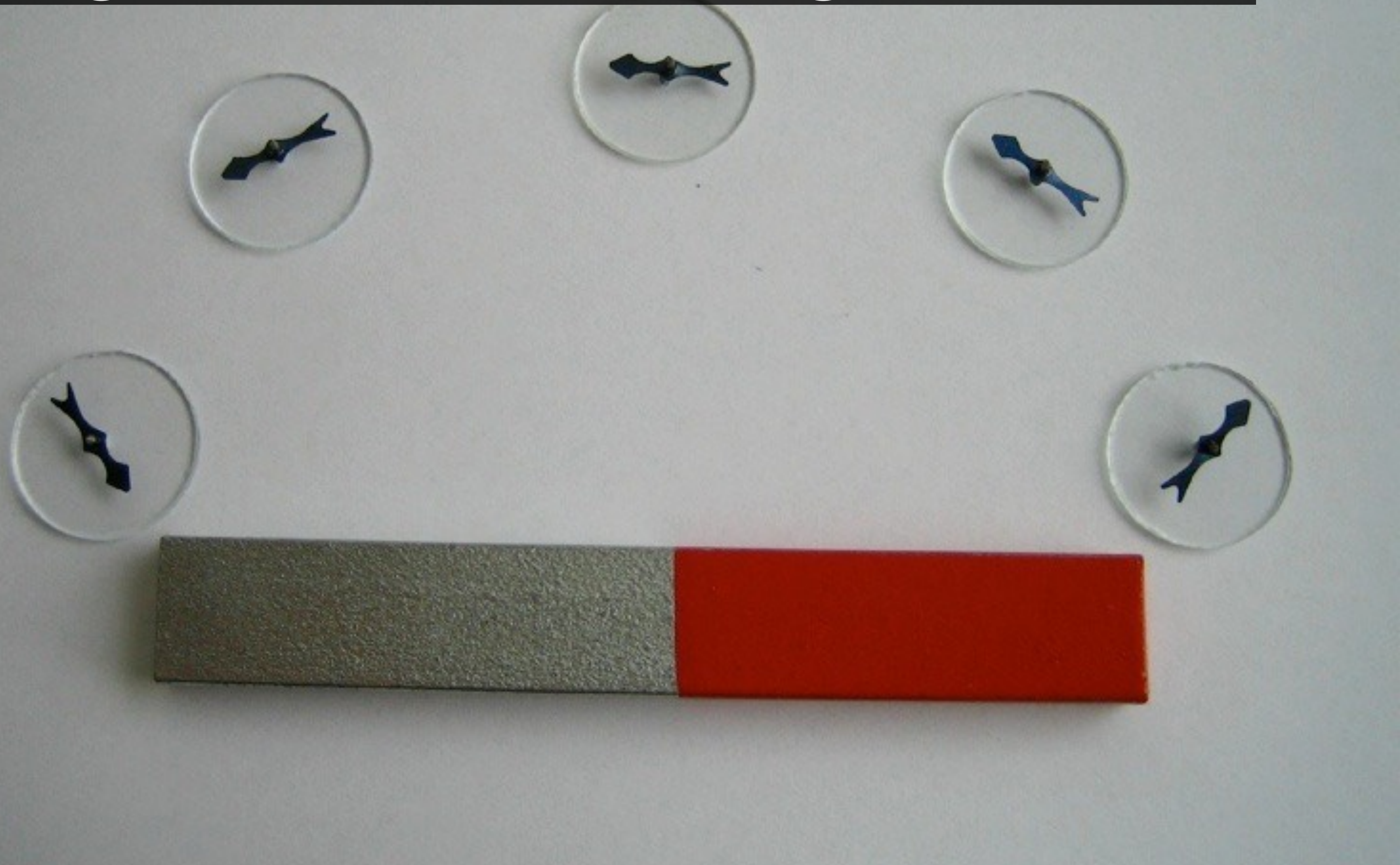


Mag. field of magnet (1)



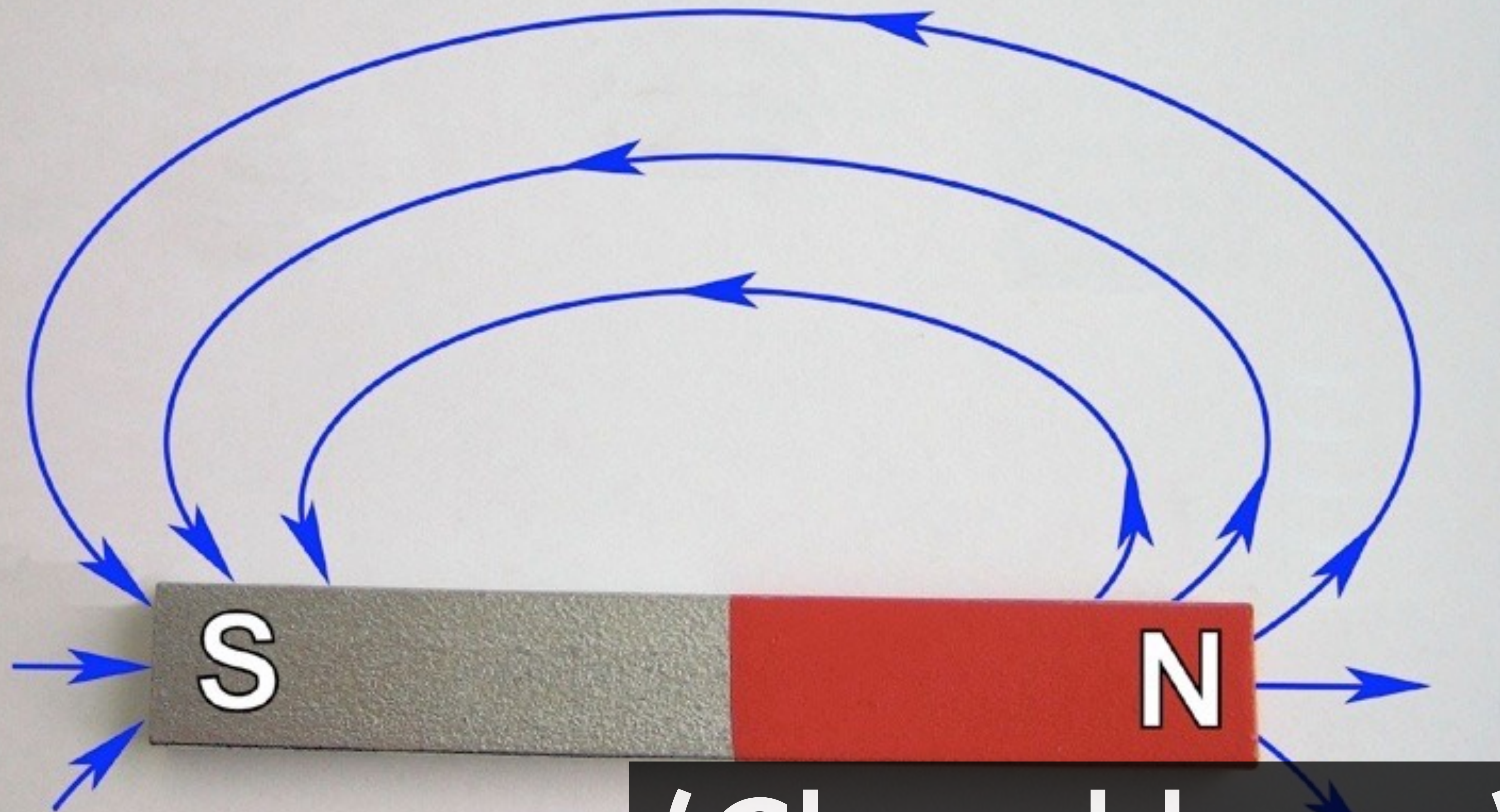
“bar magnet on compass array”
(Source: Dayna Mason)
http://www.flickr.com/photos/daynoir/2180507211/

Mag. field of magnet (2)



“Magnetism pictures–a set on Flickr”
(Source: Dayna Mason)
http://www.flickr.com/photos/daynoir/sets/72157603674410770/

N,S = source, sink



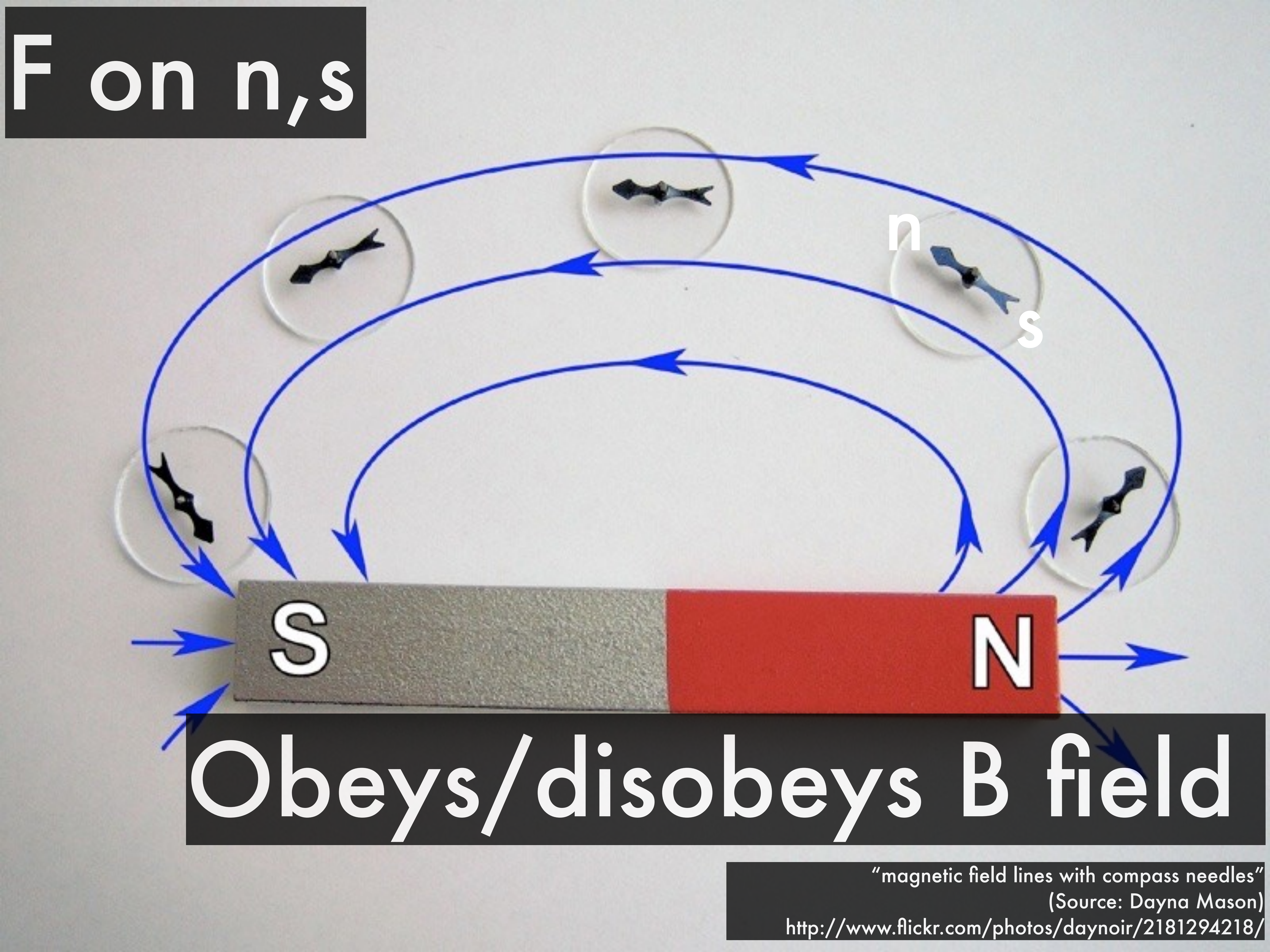
(Closed loops)

"magnetic field lines"
(Source: Dayna Mason)
http://www.flickr.com/photos/daynoir/2180507487/

Direct Model

$$\text{Source N-S } \boxed{\text{exerts } \vec{F} \text{ on}} \text{ test n-s}$$

$$\text{dir.} = \left\{ \begin{array}{l} \text{attractive (N-s, S-n)} \\ \text{repulsive (N-n, S-s)} \end{array} \right\}$$


F on n,s
n
s
S
N
Obeys/disobeys B field
“magnetic field lines with compass needles”
(Source: Dayna Mason)
http://www.flickr.com/photos/daynoir/2181294218/

Magnetic Fields

- We will treat magnetic forces and fields how we treated electric forces and fields.
- We will use a two-step process:
- step (i): Moving charges, I, creates a B field.
- step (ii): Moving charge, q, experiences magnetic force from the field.

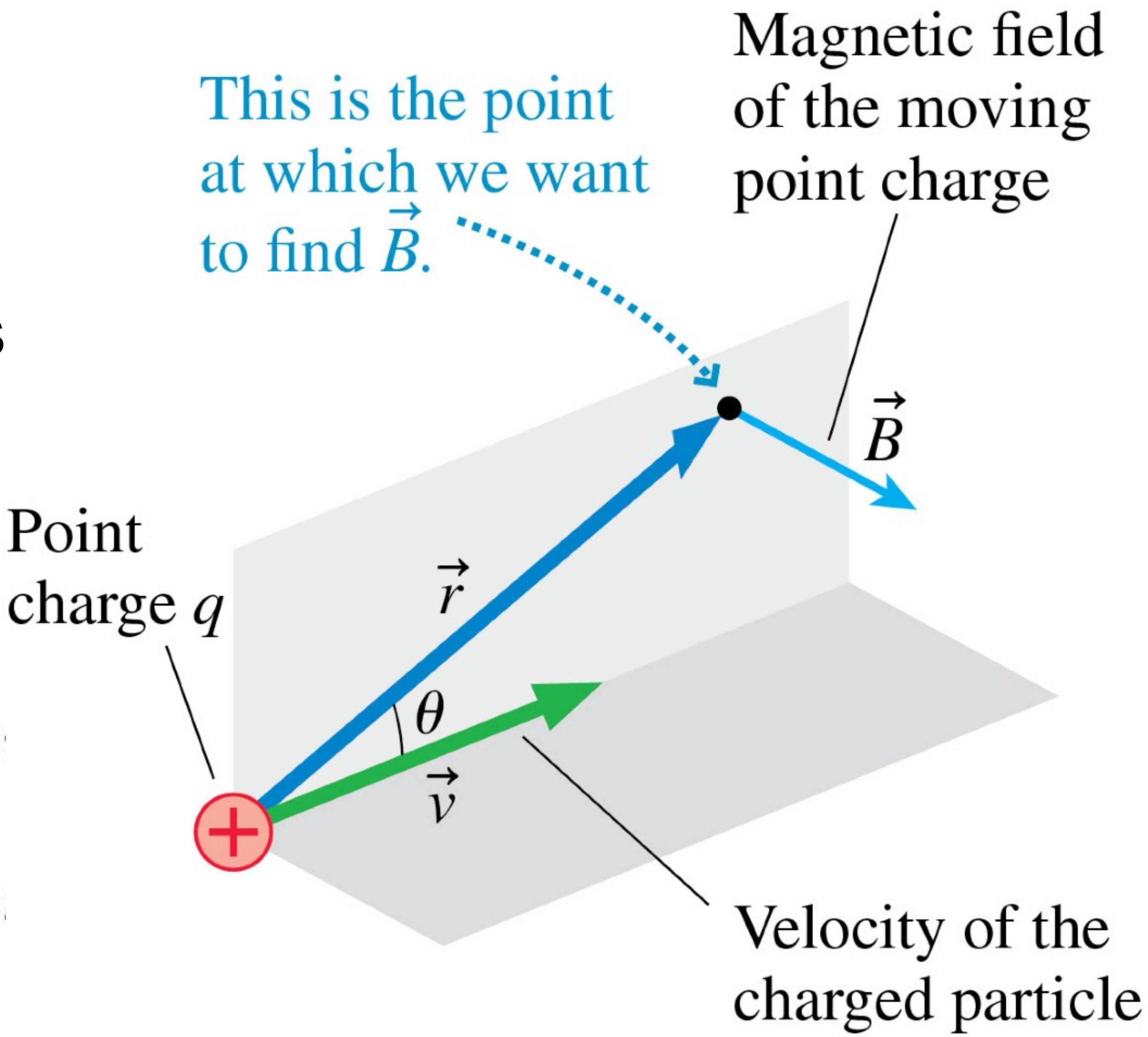
Moving charges (current I) [Amps] $\xrightarrow{\text{creates}}$ B field [Teslas] $\xrightarrow{\text{exerts force on}}$ other moving charges q [Coul]

A Source of the Magnetic Field: Moving Charges

- The magnetic field of a charged particle q moving with velocity v is given by the **Biot-Savart law**:

$$\vec{B}_{\text{point charge}} = \left(\frac{\mu_0}{4\pi} \frac{qv\sin\theta}{r^2}, \right.$$

direction given by the right-hand rule



$$\vec{B}_{\text{point charge}} = \frac{\mu_0}{4\pi} \frac{q\vec{v} \times \hat{r}}{r^2} \quad \text{(magnetic field of a point charge)}$$

The Magnetic Field

$$\vec{B}_{\text{point charge}} = \left(\frac{\mu_0}{4\pi} \frac{qv \sin\theta}{r^2}, \text{ direction given by the right-hand rule} \right)$$

- The constant μ_0 in the Biot-Savart law is called the **permeability constant**:

$$\mu_0 = 4\pi \times 10^{-7} \text{ T m/A} = 1.257 \times 10^{-6} \text{ T m/A}$$

- The SI unit of magnetic field strength is the tesla, abbreviated as T:

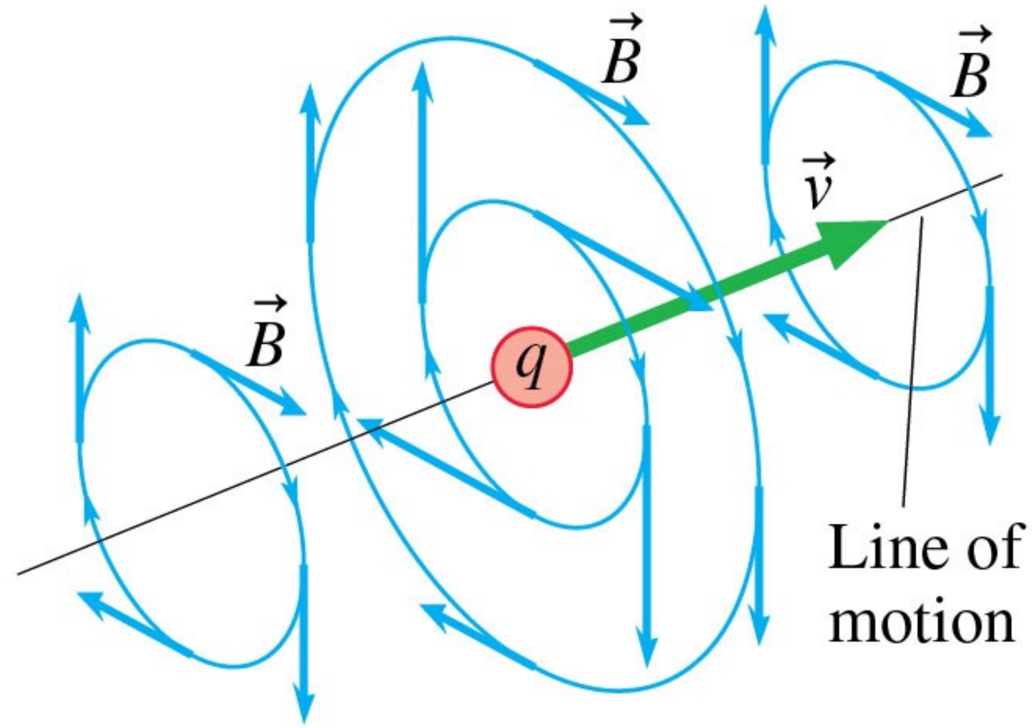
$$1 \text{ tesla} = 1 \text{ T} = 1 \text{ N/A m}$$

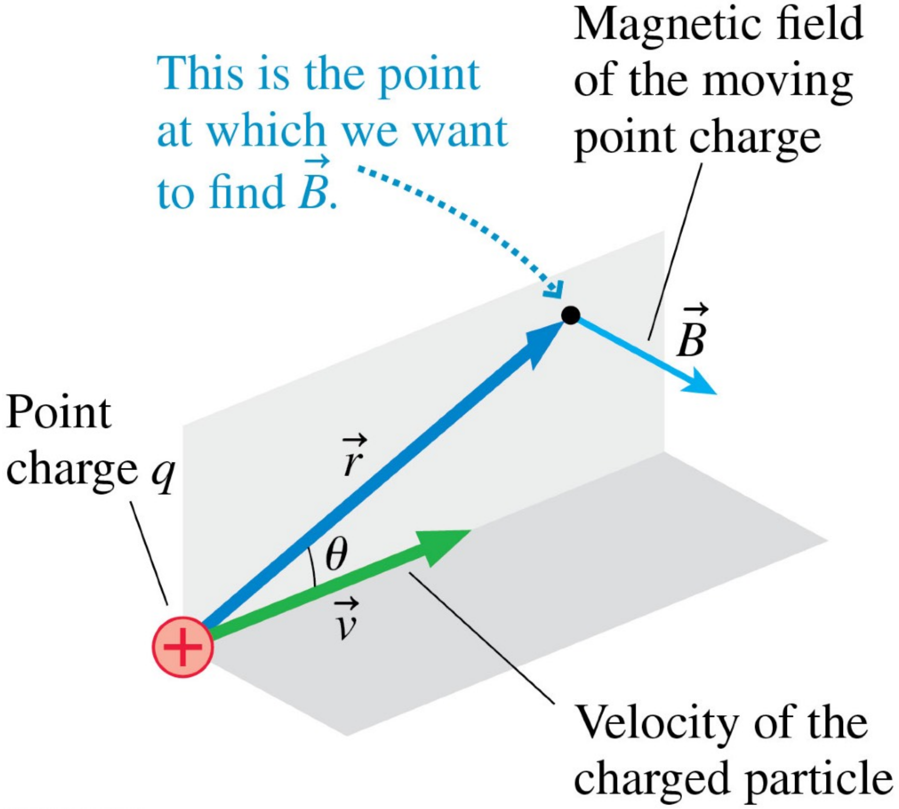
TABLE 29.1 Typical magnetic field strengths

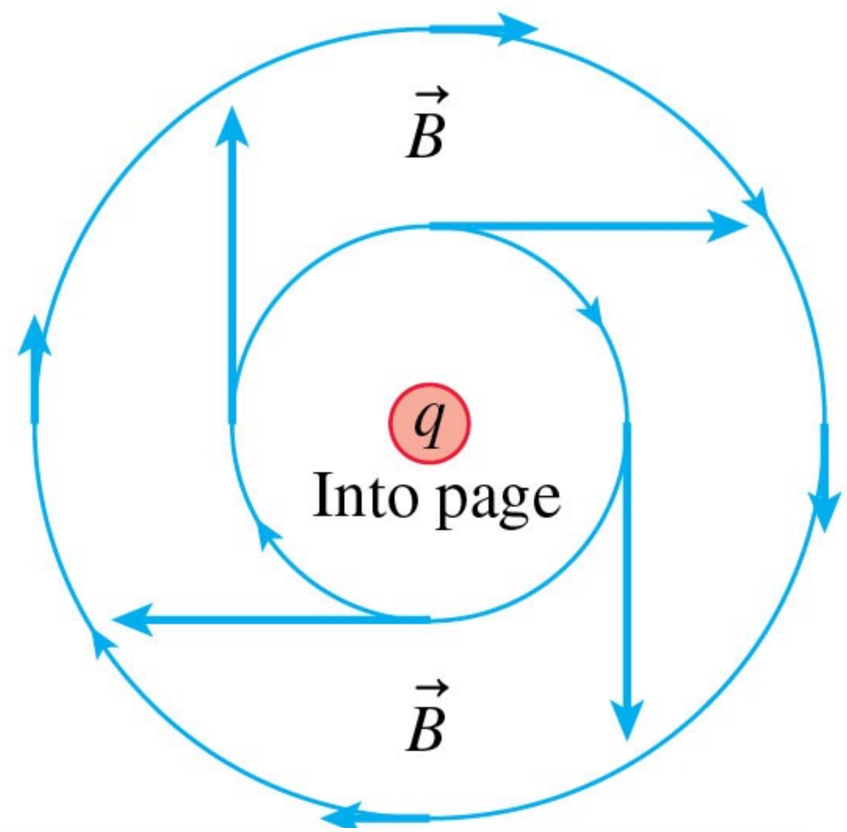
Field source	Field strength (T)
Surface of the earth	5×10^{-5}
Refrigerator magnet	5×10^{-3}
Laboratory magnet	0.1 to 1
Superconducting magnet	10

Magnetic Field of a Moving Positive Charge

- The right-hand rule for finding the direction of $\vec{B}$ due to a moving positive charge is similar to the rule used for a current carrying wire.
- Note that the component of $\vec{B}$ parallel to the line of motion is zero.







$$\vec{B}_{\text{point charge}} = \frac{\mu_0}{4\pi}\frac{q\vec{v}\times\hat{r}}{r^2} \quad \text{(magnetic field of a point charge)}$$

Example 29.1 The Magnetic Field of a Proton

EXAMPLE 29.1 **The magnetic field of a proton**

A proton moves with velocity $\vec{v} = 1.0 \times 10^7\, \hat{\imath}$ m/s. As it passes the origin, what is the magnetic field at the (x, y, z) positions (1 mm, 0 mm, 0 mm), (0 mm, 1 mm, 0 mm), and (1 mm, 1 mm, 0 mm)?

MODEL The magnetic field is that of a moving charged particle.

Example 29.1

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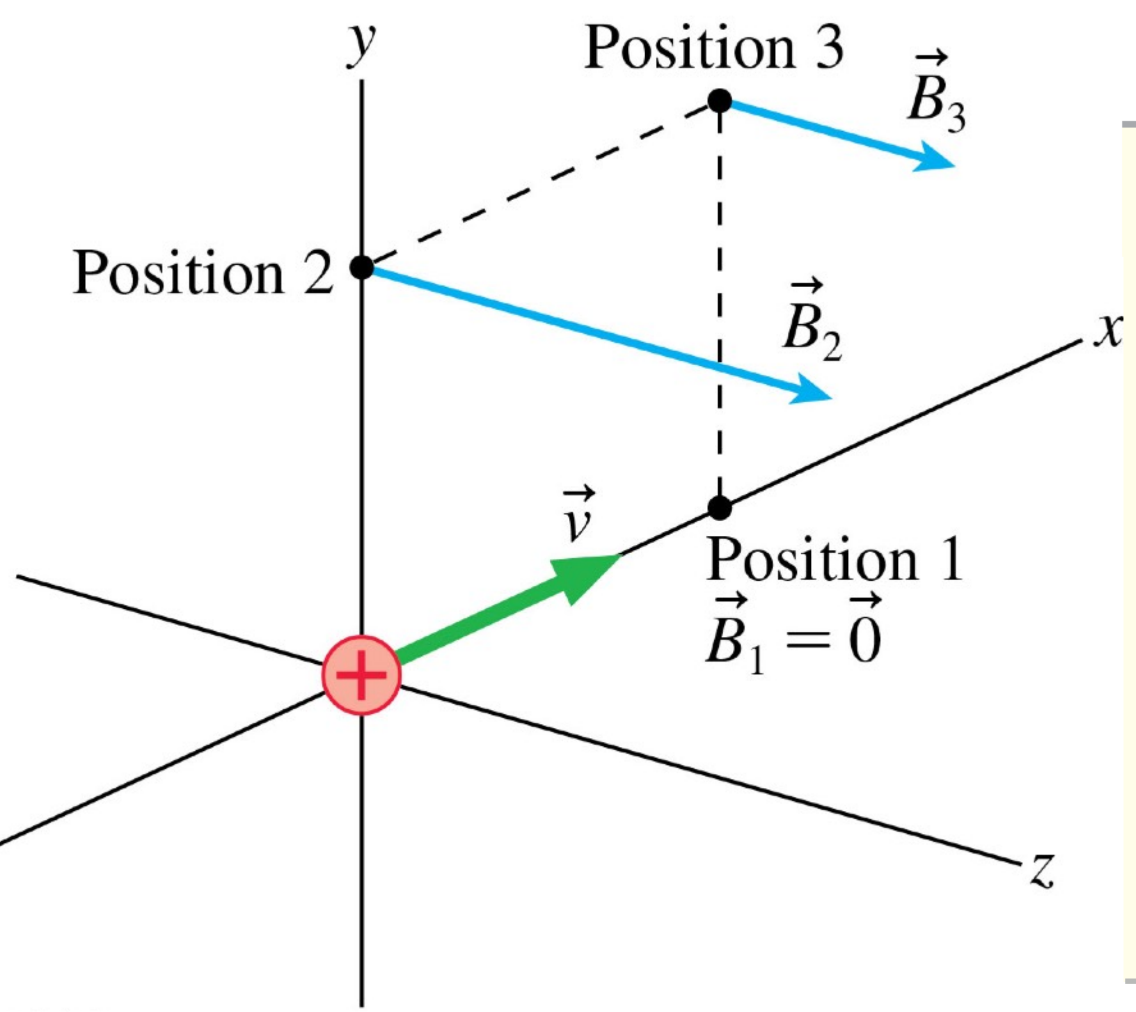
MODEL The magnetic field is that of a moving charged particle.

EXAMPLE 29.1 | **The magnetic field of a proton**

VISUALIZE **FIGURE 29.9** shows the geometry. The first point is on the x-axis, directly in front of the proton, with $\theta_1 = 0°$. The second point is on the y-axis, with $\theta_2 = 90°$, and the third is in the xy-plane.



EXAMPLE 29.1 | **The magnetic field of a proton**

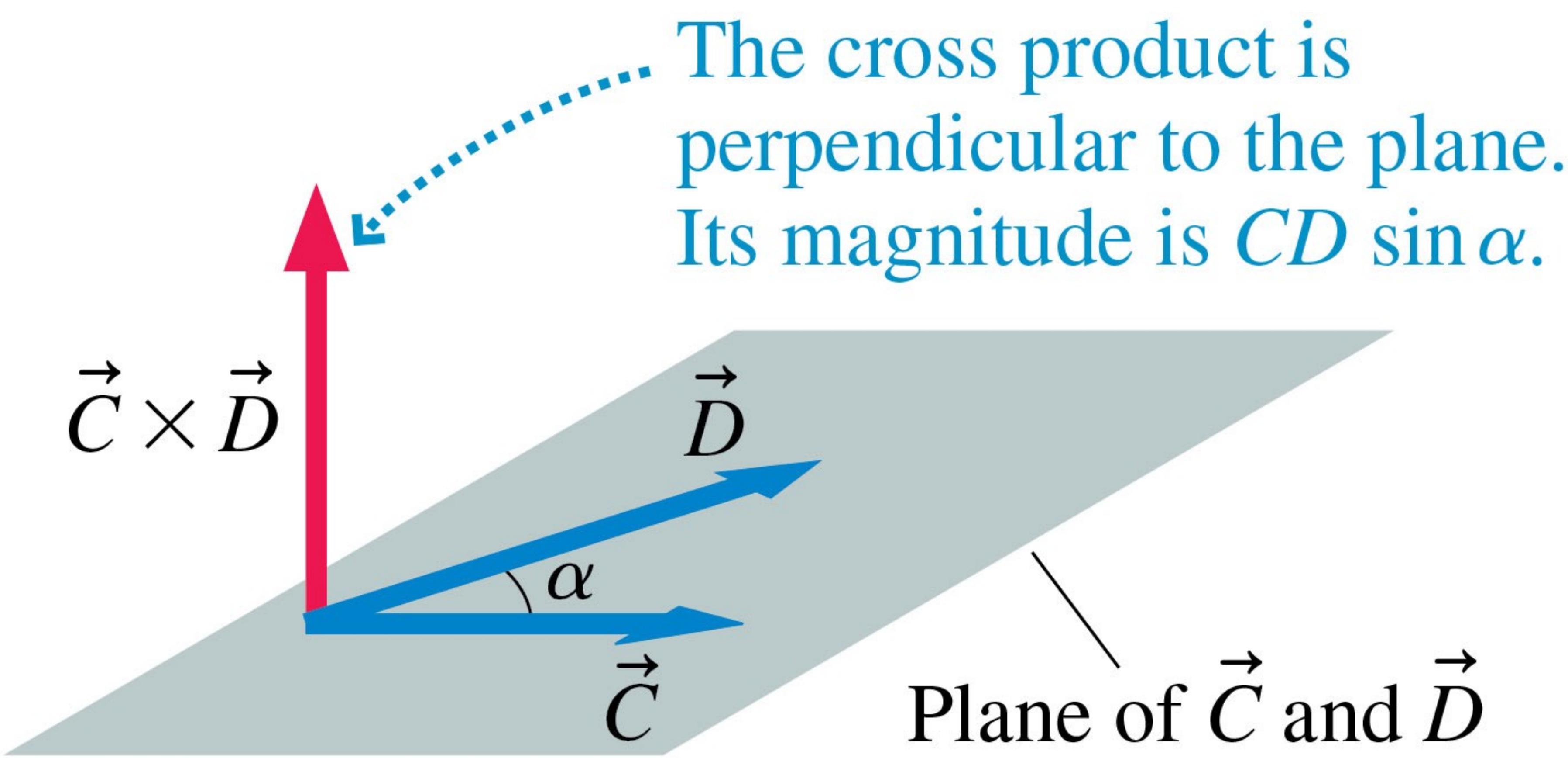
SOLVE Position 1, which is along the line of motion, has $\theta_1 = 0°$. Thus $\vec{B}_1 = \vec{0}$. Position 2 (at 0 mm, 1 mm, 0 mm) is at distance $r_2 = 1\text{ mm} = 0.001$ m. Equation 29.1, the Biot-Savart law, gives us the magnetic field strength at this point as

$$B = \frac{\mu_0}{4\pi}\frac{qv\sin\theta_2}{r_2^{\,2}}$$

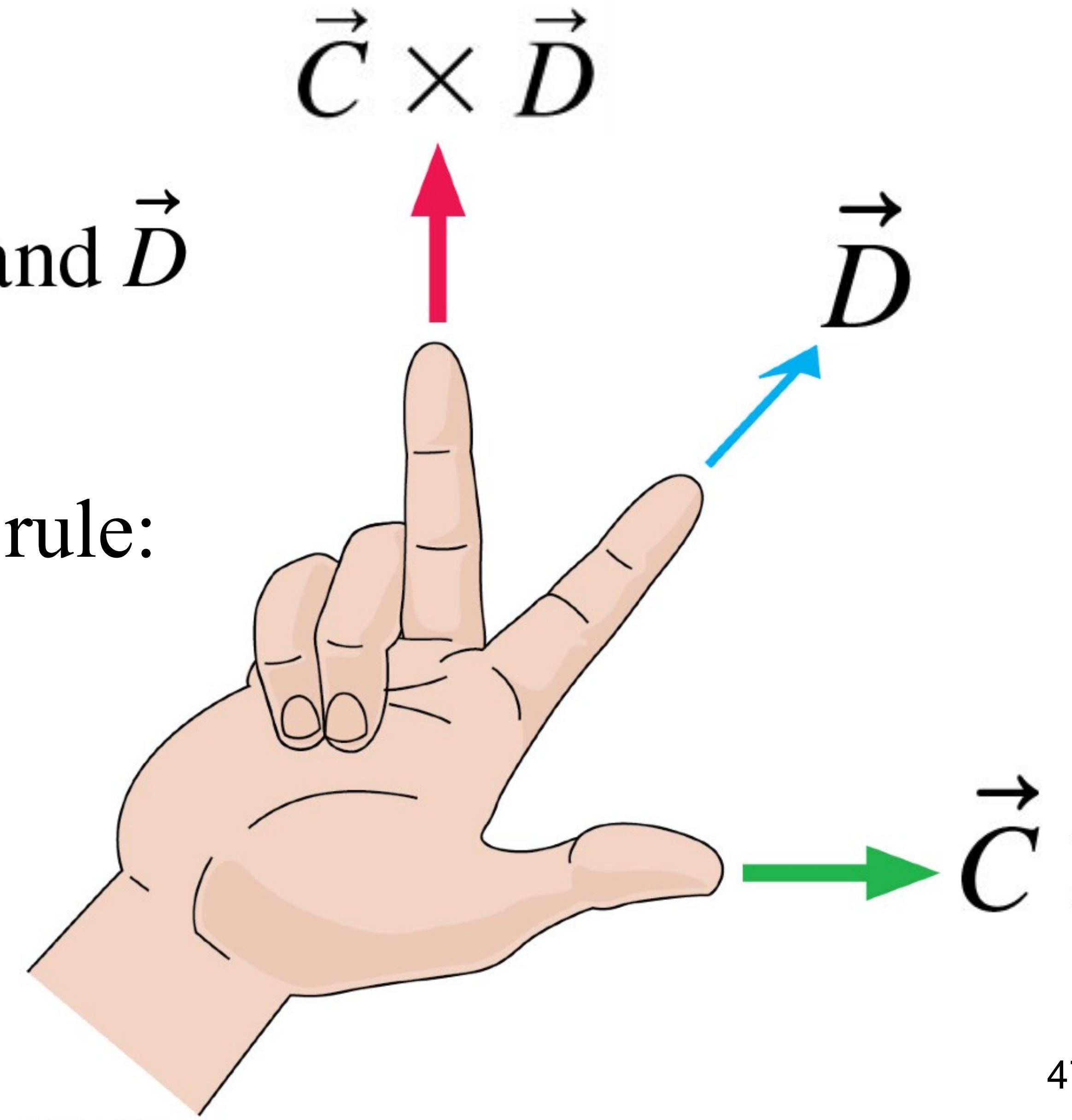
$$= \frac{4\pi \times 10^{-7}\ \text{T m/A}}{4\pi}\frac{(1.60 \times 10^{-19}\ \text{C})(1.0 \times 10^7\ \text{m/s})\sin 90°}{(0.0010\ \text{m})^2}$$

$$= 1.60 \times 10^{-13}\ \text{T}$$

The Cross Product



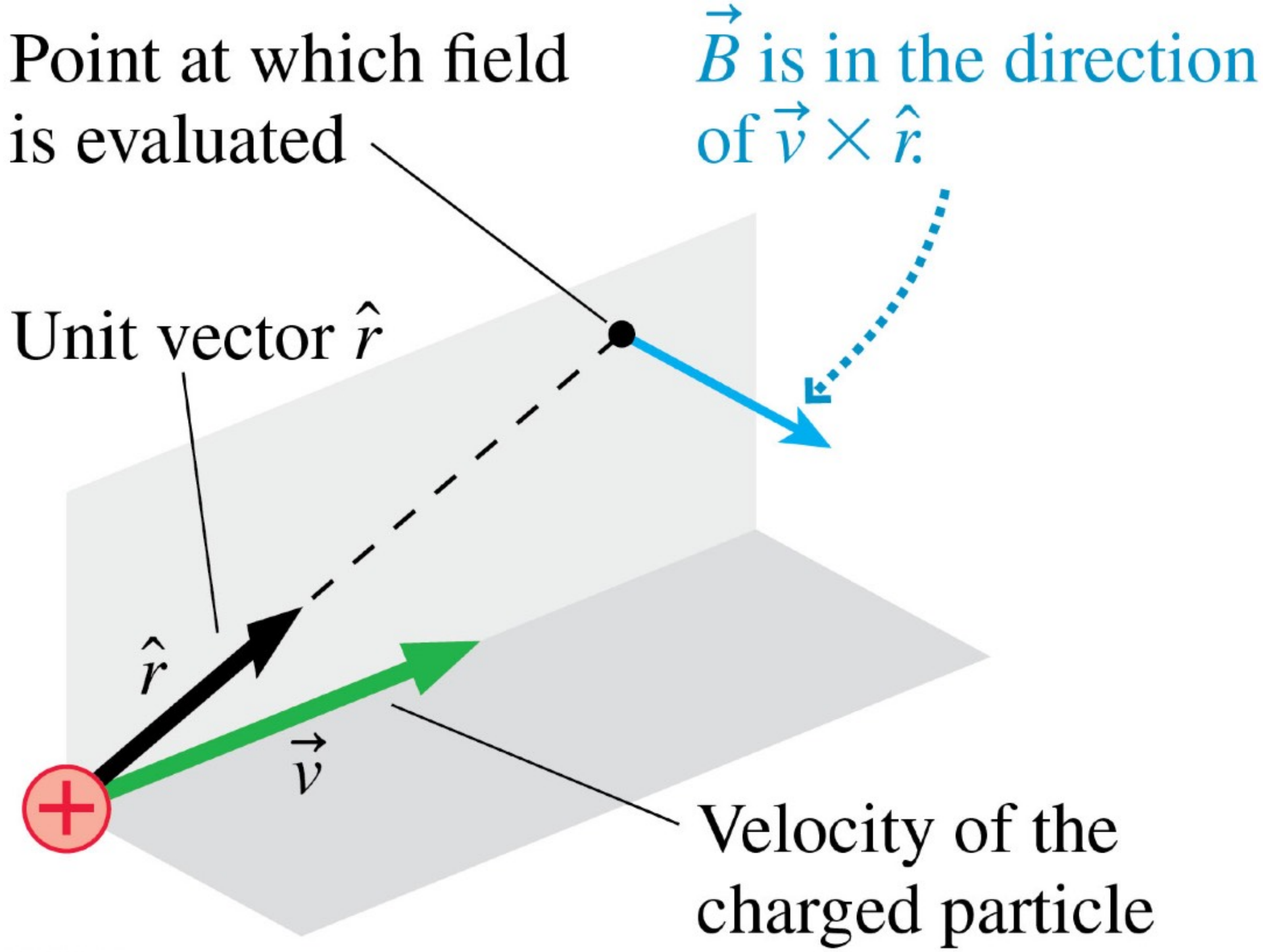
$\vec{C} \times \vec{D} = (CD \sin \alpha,$
direction given by the right-hand rule:



Magnetic Field of a Moving Charge

- The magnetic field of a charged particle q moving with velocity $\vec{v}$ is given by the **Biot-Savart law**:

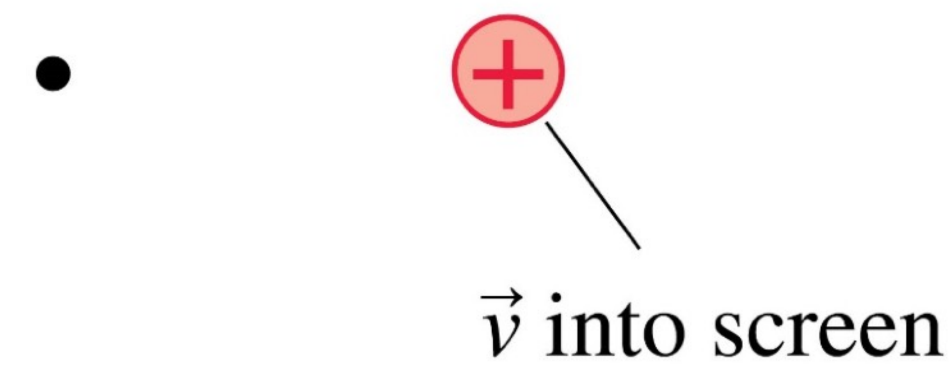
$$\vec{B}_{\text{point charge}} = \frac{\mu_0}{4\pi}\frac{q\vec{v}\times\hat{r}}{r^2} \quad \text{(magnetic field of a point charge)}$$



- Write in BB

What is the direction of the magnetic field at the position of the dot?

A. Into the screen
B. Out of the screen
C. Up
D. Down
E. Left



$$\vec{B}_{\text{point charge}} = \frac{\mu_0}{4\pi}\frac{q\vec{v}\times\hat{r}}{r^2} \qquad \text{(magnetic field of a point charge)}$$

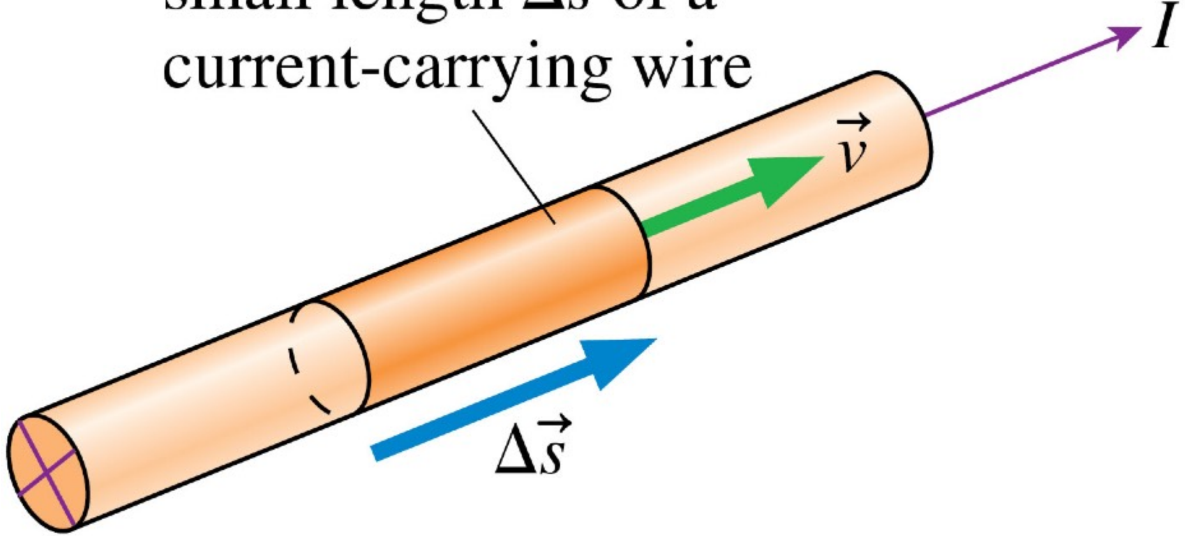
Superposition of Magnetic Fields

- Magnetic fields, like electric fields, have been found experimentally to obey the principle of superposition.
- If there are *n* moving point charges, the net magnetic field is given by the vector sum:

$$\vec{B}_{\text{total}} = \vec{B}_1 + \vec{B}_2 + \cdots + \vec{B}_n$$

- The principle of superposition will be the basis for calculating the magnetic fields of several important current distributions.

The Magnetic Field of a Current



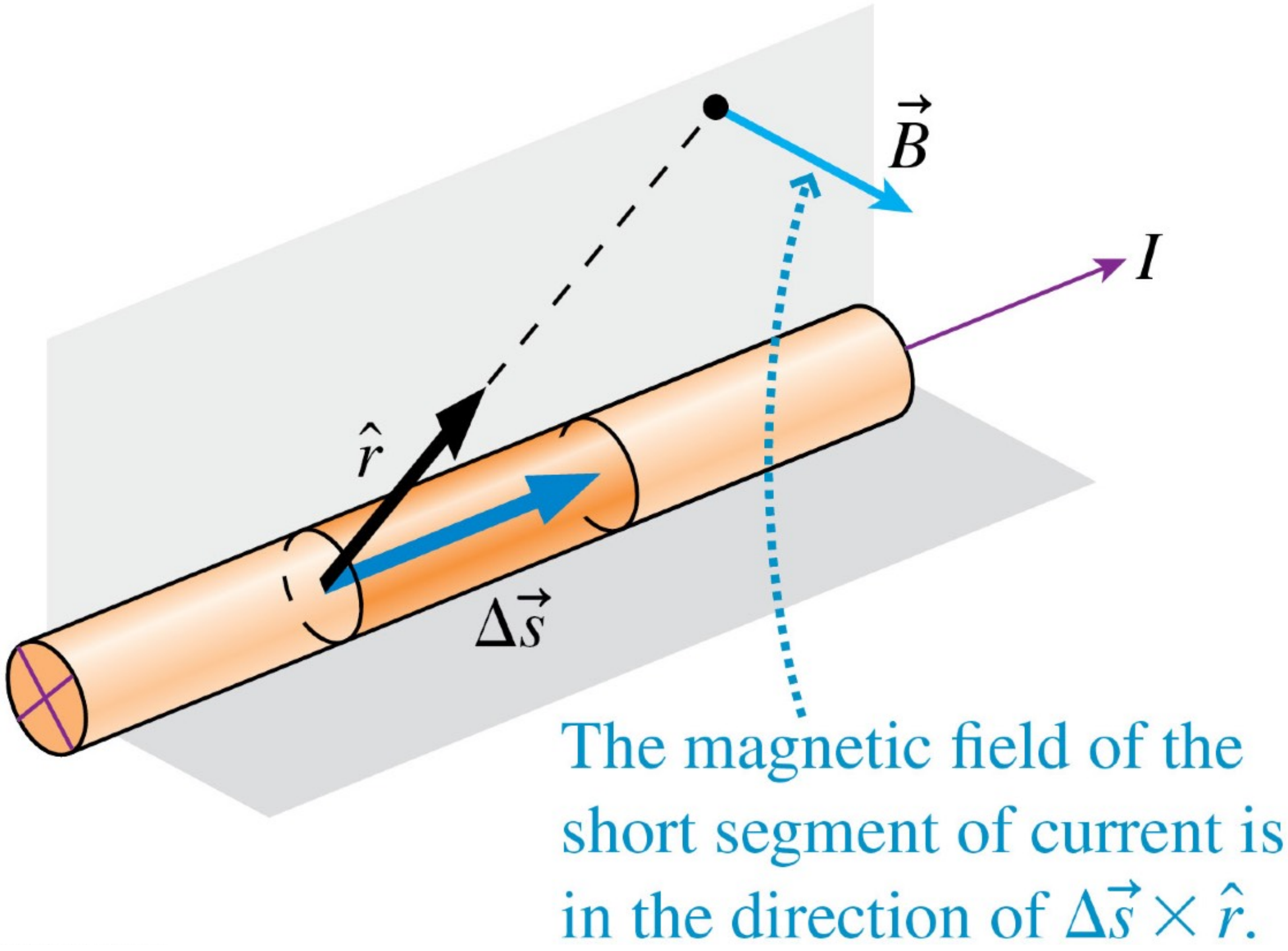
- The figure shows a current-carrying wire.
- The wire as a whole is electrically neutral, but current I represents the motion of positive charge carriers through the wire:

$$(\Delta Q)\vec{v} = \Delta Q \frac{\Delta\vec{s}}{\Delta t} = \frac{\Delta Q}{\Delta t}\Delta\vec{s} = I\,\Delta\vec{s}$$

The Magnetic Field of a Current

$$\vec{B}_{\text{current segment}} = \frac{\mu_0}{4\pi}\frac{I\,\Delta\vec{s} \times \hat{r}}{r^2}$$

(magnetic field of a very short segment of current)



The Magnetic Field of a Current

- Examples 29.3 and 29.5 in the book will be covered in discussion section, deriving:
- The magnetic field of a long, straight wire carrying current I at a distance r from the wire is

$$B_{\text{wire}} = \frac{\mu_0}{2\pi}\frac{I}{r} \quad \text{(long, straight wire)}$$

- The magnetic field at the center of a coil of N turns and radius R, carrying a current I is

$$B_{\text{coil center}} = \frac{\mu_0}{2}\frac{NI}{R} \qquad (N\text{-turn current loop})$$

- Write in BB

iClicker question #13-5

Compared to the magnetic field at point A, the magnetic field at point B is

A. Half as strong, same direction.
B. Half as strong, opposite direction.
C. One-quarter as strong, same direction.
D. One-quarter as strong, opposite direction.
E. Can't compare without knowing I.