Magnetism, Introduction!

(K) 29.1-29.4; (OS) 11.1 and parts of 11.2, 12.1-12.2

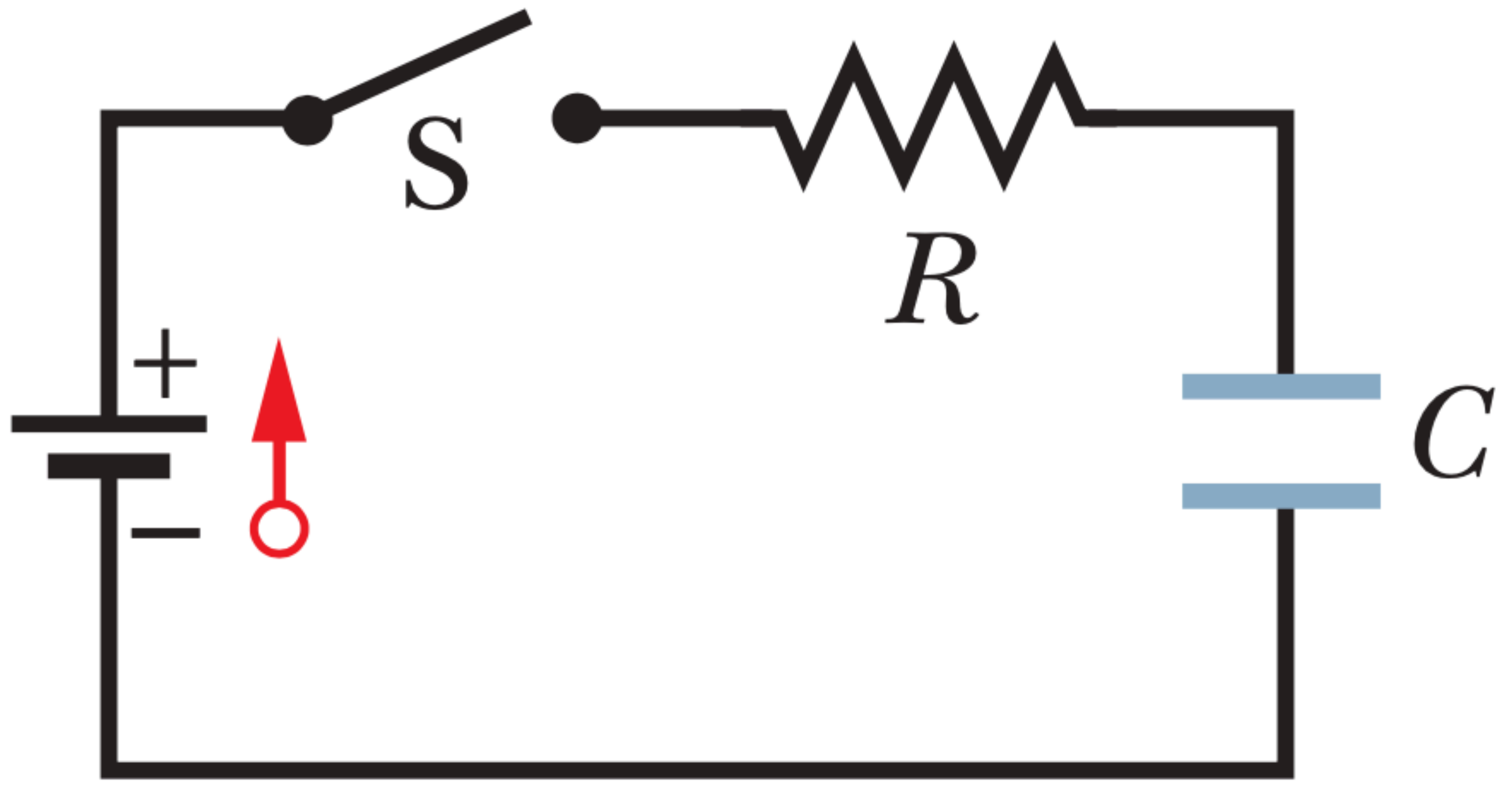
Brian Shotwell, Spring 2023

Agenda Today (May 12, 2023)

- Magnetism! Basic Phenomena
  - Compass needles, Earth’s mag. Field
  - Deflection of a compass needle by a wire
- Direction of the Magnetic field
  - Due to a long, straight current-carrying wire
  - Due to a moving point charge
- Cross Product
- Introduction to the Biot-Savart Law

Clicker/Poll Question

In the following circuit, switch S is closed at time t=0. What is the voltage across the capacitor a long time after the switch is closed?

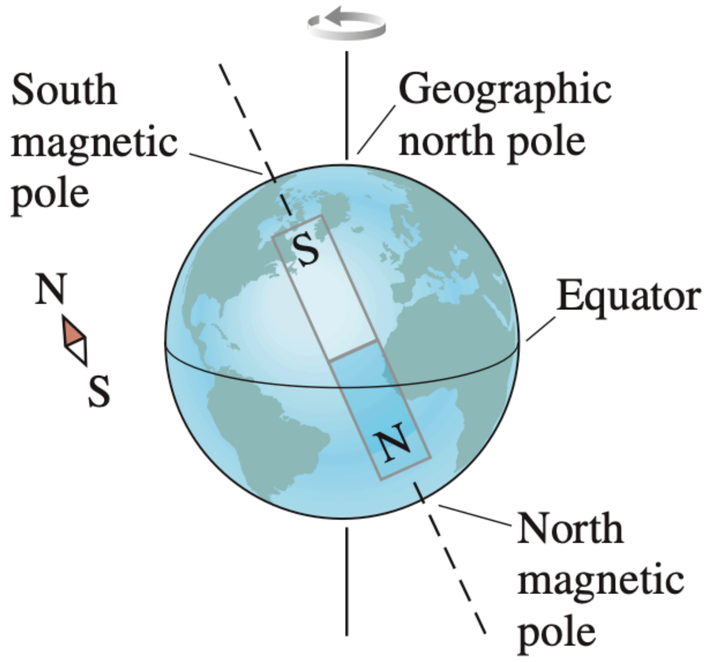


$\mathcal{E} = 12.0\,\text{V}, C = 2.0\,\text{mF},$ and $R = 1.0\,\Omega$

A. 0.0 Volts
B. 6.0 Volts
C. 12.0 Volts
D. None of the above

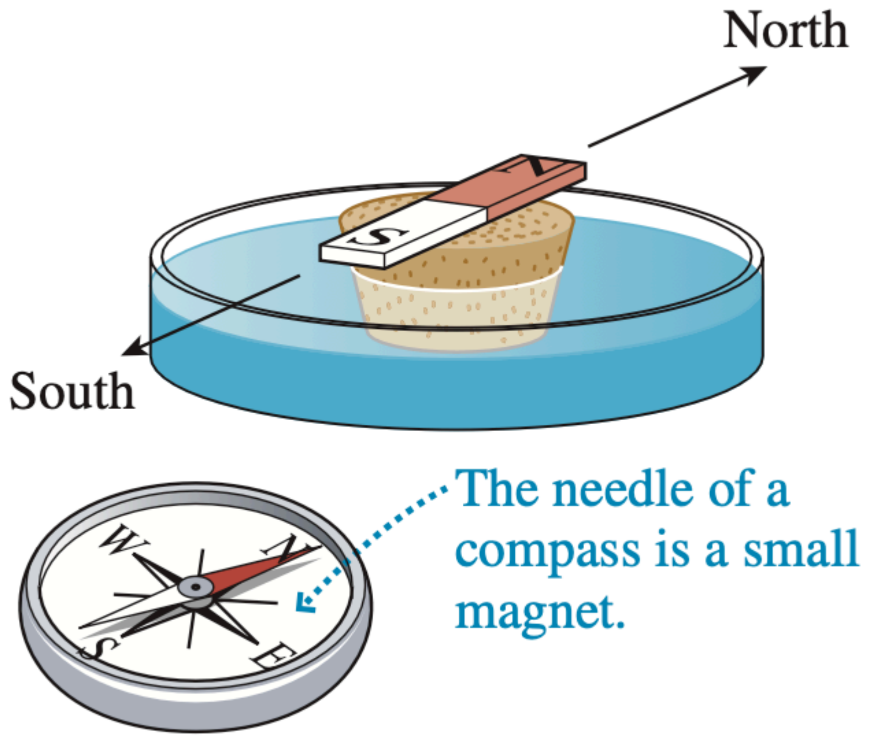
Experiments / Magnetism Basics

FIGURE 29.1 The earth is a large magnet.

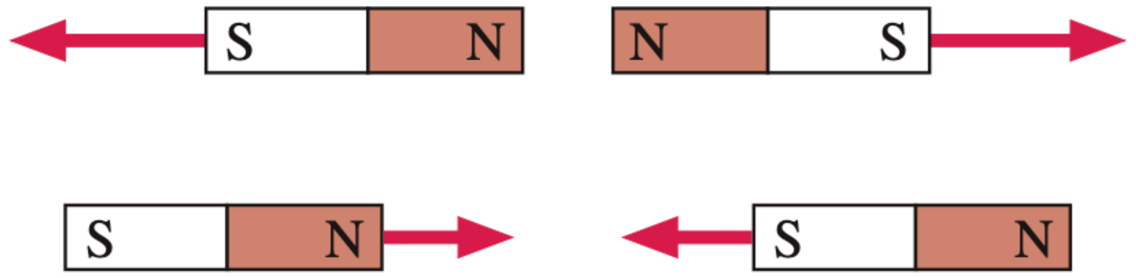


Experiment 1

If a bar magnet is taped to a piece of cork and allowed 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 other end is the **south pole.**



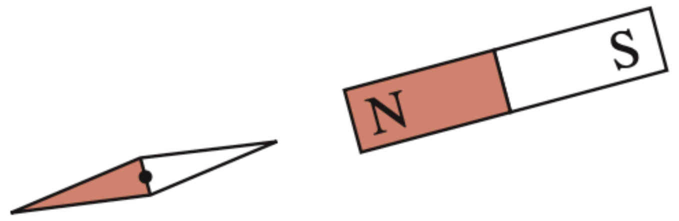
Experiment 2



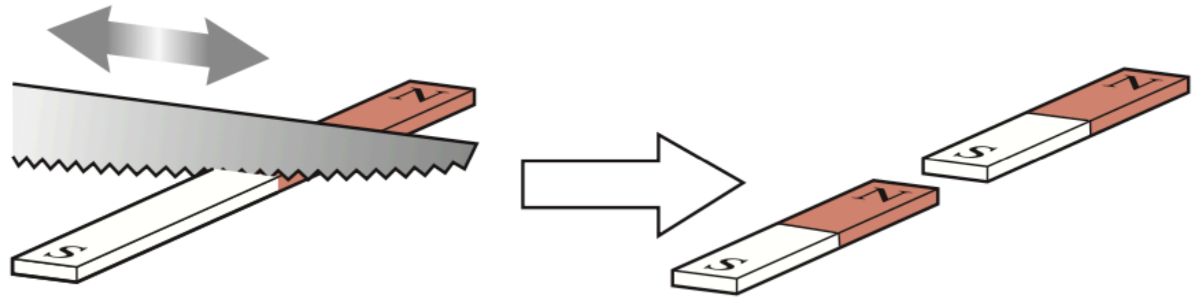
If the north pole of one magnet is brought near the north pole of another magnet, they repel each other. Two south poles also repel each other, but the north pole of one magnet exerts an attractive force on the south pole of another magnet.

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.



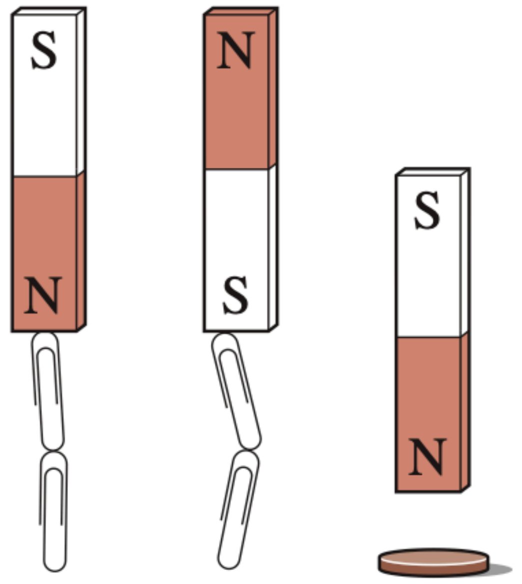
Experiment 4



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.

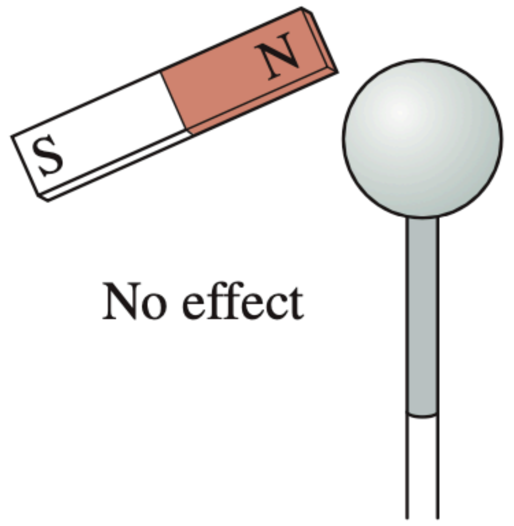
Experiment 5

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.



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.



Currents create magnetic fields

Permanent magnets (discussed on the previous slide) are somewhat complicated. We'll come back to them. The simplest way to create a magnetic field is from a current-carrying wire:

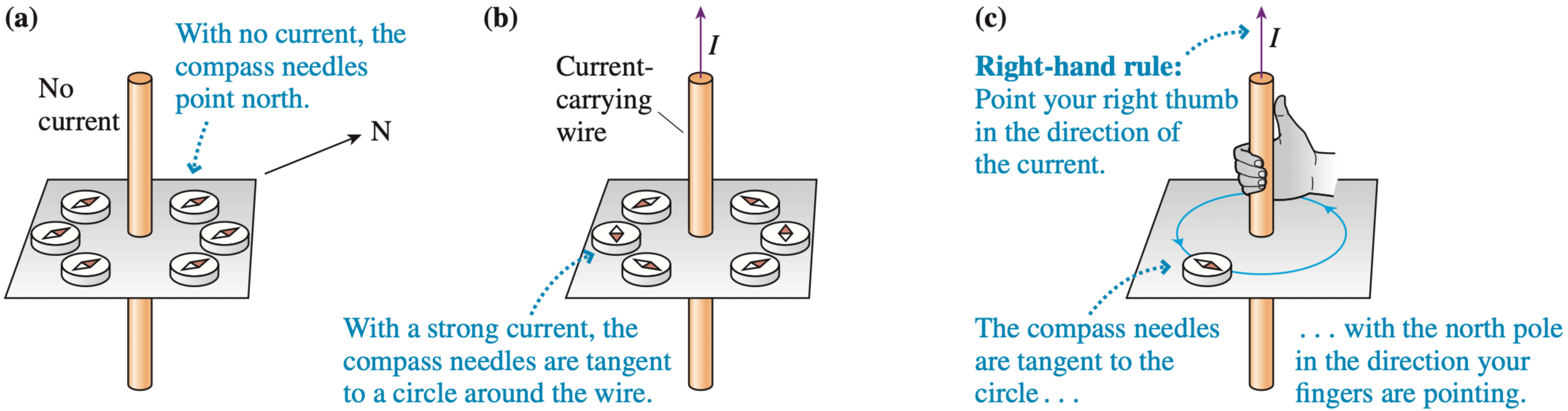


FIGURE 29.2 Response of compass needles to a current in a straight wire.

Currents create magnetic fields

Let us define the **magnetic field** $\vec{B}$ as having the following properties:

1. A magnetic field is created at *all* points in space surrounding a current-carrying wire.
2. The magnetic field at each point is a vector. It has both a magnitude, which we call the *magnetic field strength B*, and a direction.
3. The magnetic field exerts forces on magnetic poles. The force on a north pole is parallel to $\vec{B}$; the force on a south pole is opposite $\vec{B}$.

FIGURE 29.3 The notation for vectors and currents perpendicular to the page.

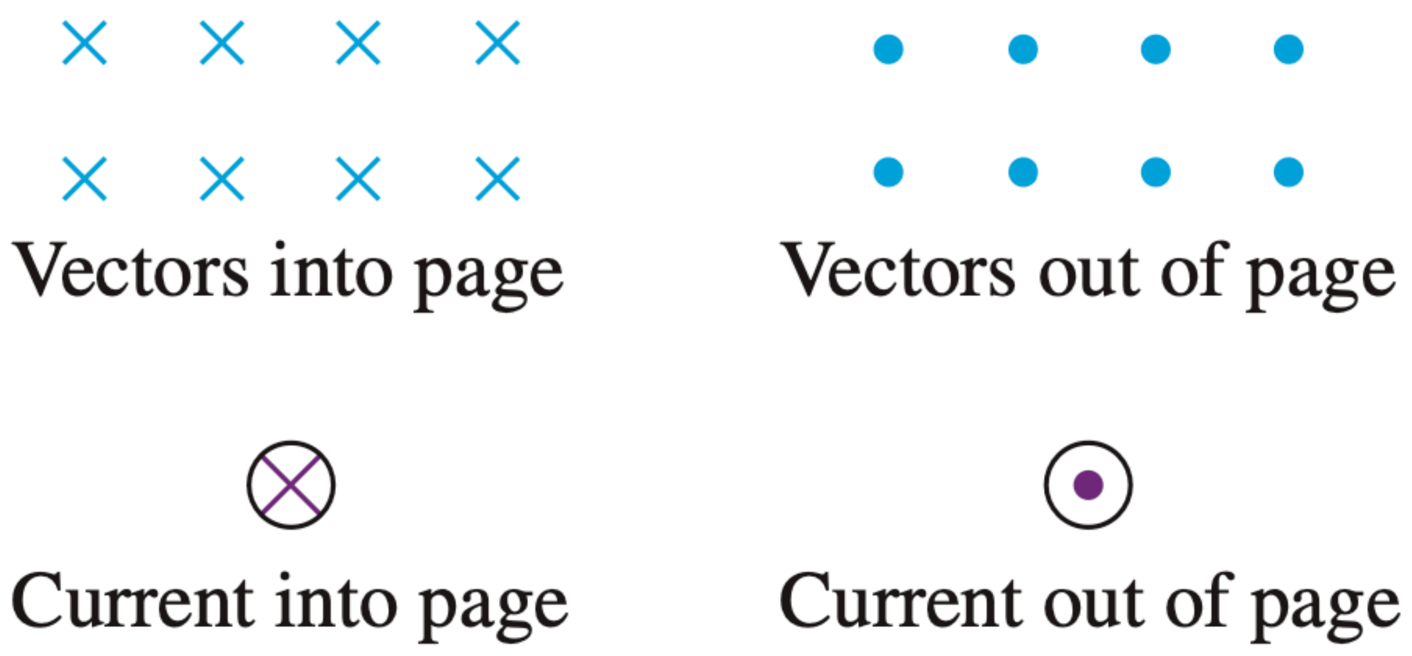
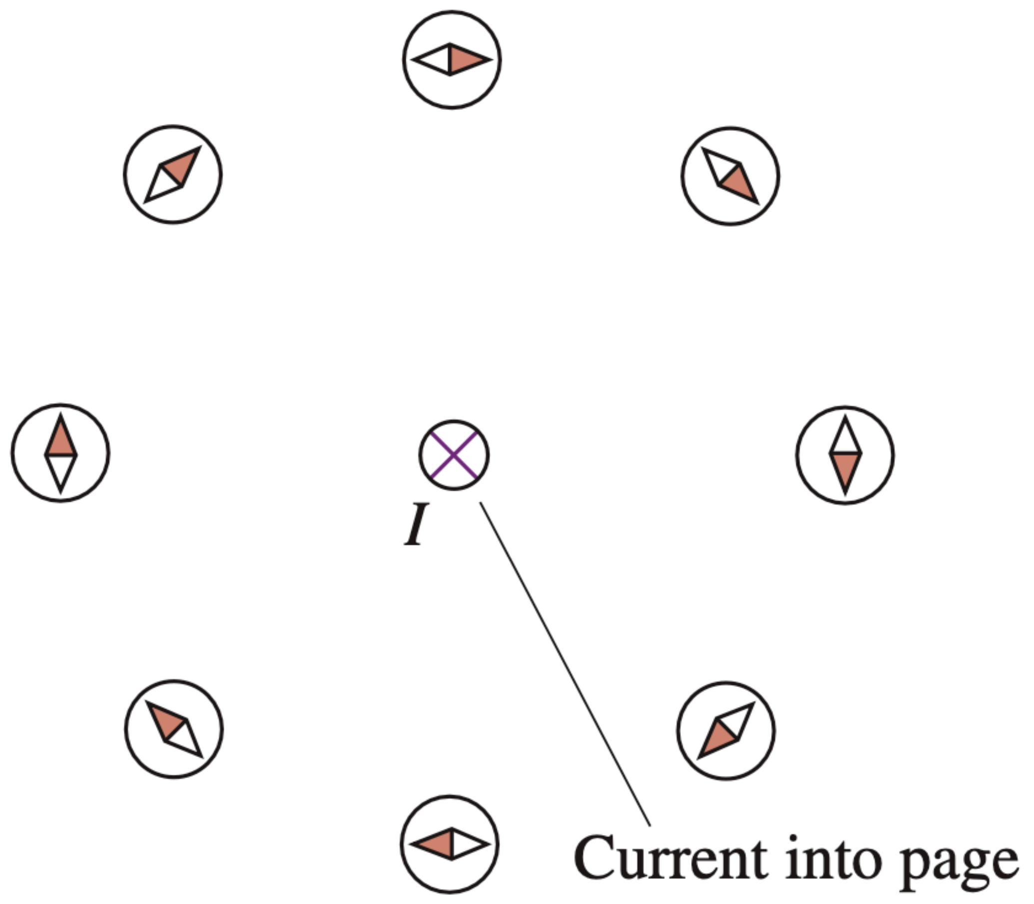


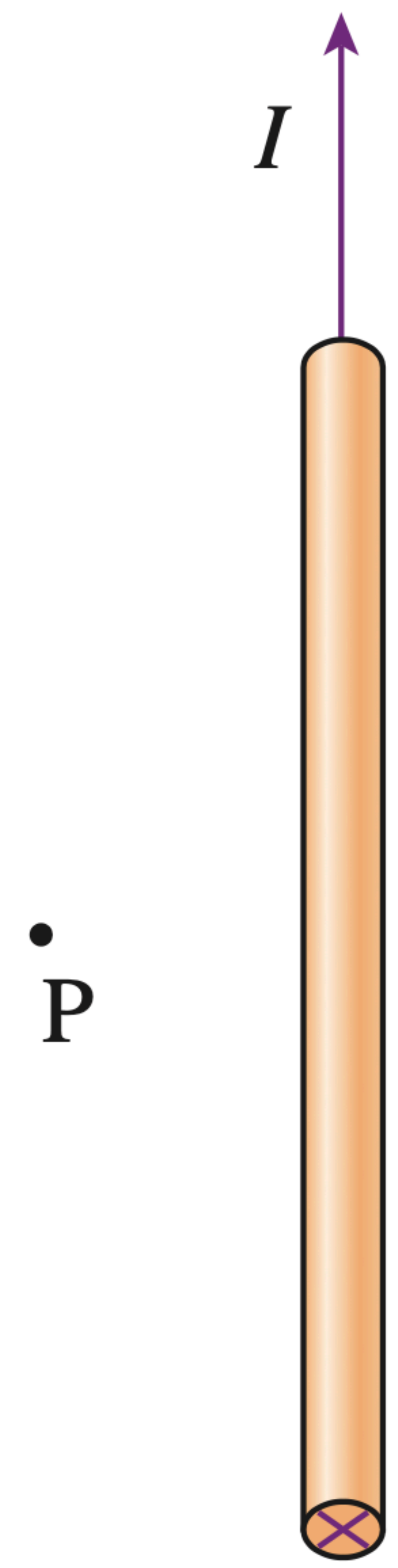
FIGURE 29.4 The orientation of the compasses is given by the right-hand rule.



Clicker/Poll Question

The wire has a upwards current through it. What is the direction of the magnetic field at the indicated point?

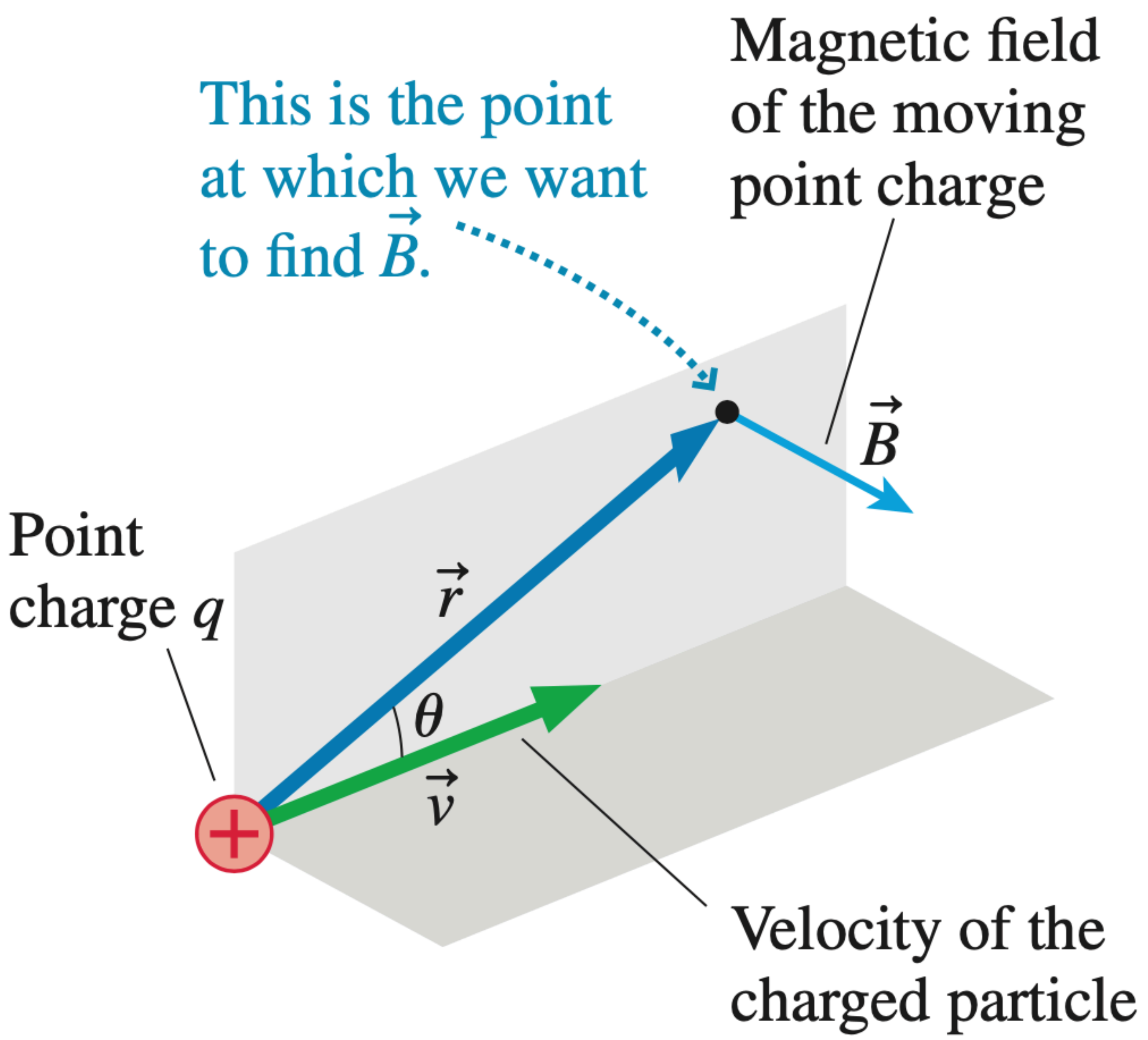
A. Rightwards
B. Downwards
C. Into the screen
D. Out of the screen
E. None of the above



Moving Point Charges make B-fields

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

FIGURE 29.7 The magnetic field of a moving point charge.



This is called the "Biot-Savart" Law (B.O. suh-vhar)

We'll talk about the right-hand rule in the next slide.

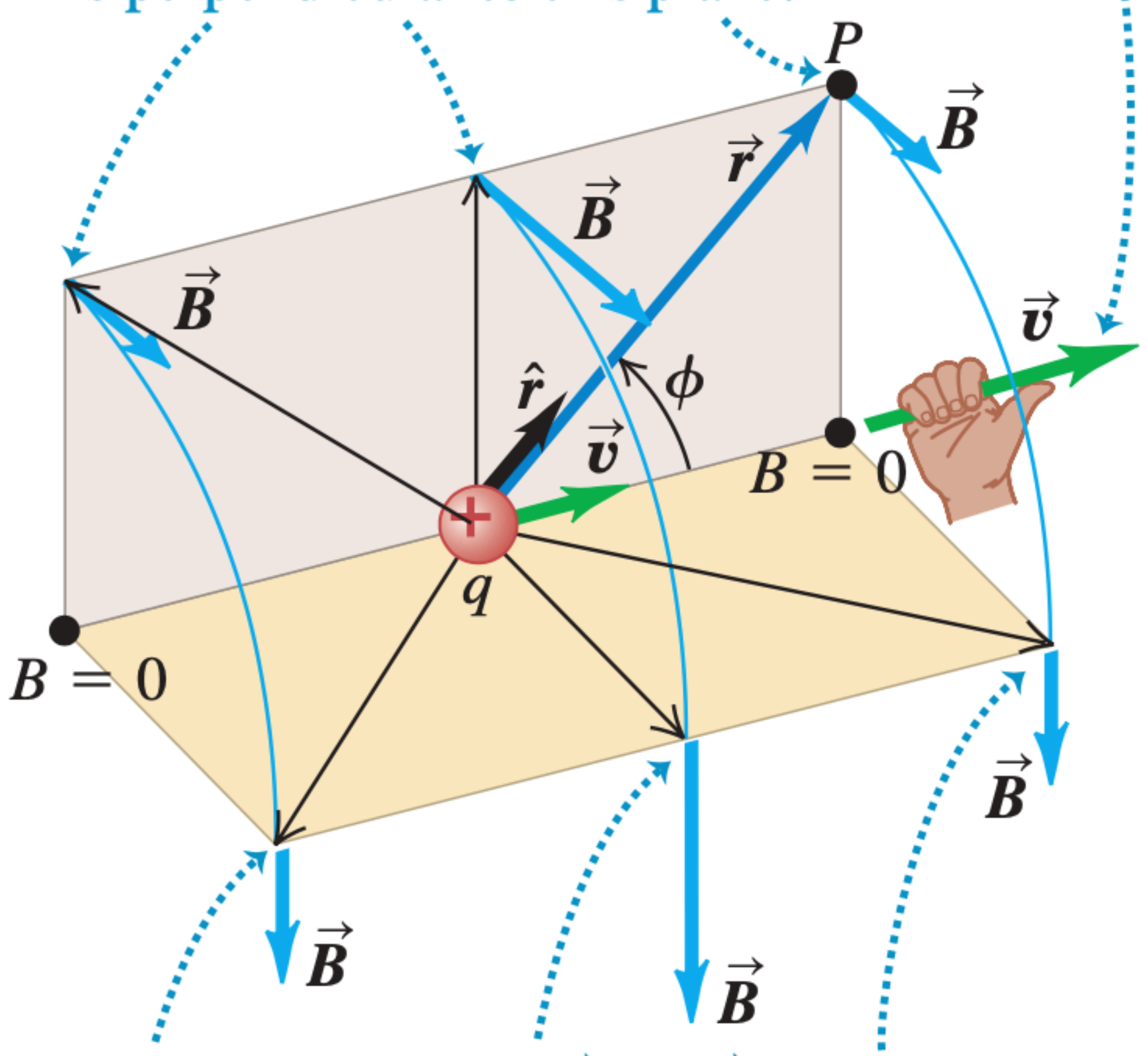
New SI unit: "tesla" (T) is the unit for magnetic field, where 1T = 1N/(A·m).

$\mu_0 = 4\pi \times 10^{-7}\,\dfrac{\mathrm{T\cdot m}}{\mathrm{A}}$ is a constant appearing often in magnetism (just like ϵ_0 for electricity)

(a) Perspective view

Right-hand rule for the magnetic field due to a positive charge moving at constant velocity: Point the thumb of your right hand in the direction of the velocity. Your fingers now curl around the charge in the direction of the magnetic field lines. (If the charge is negative, the field lines are in the opposite direction.)

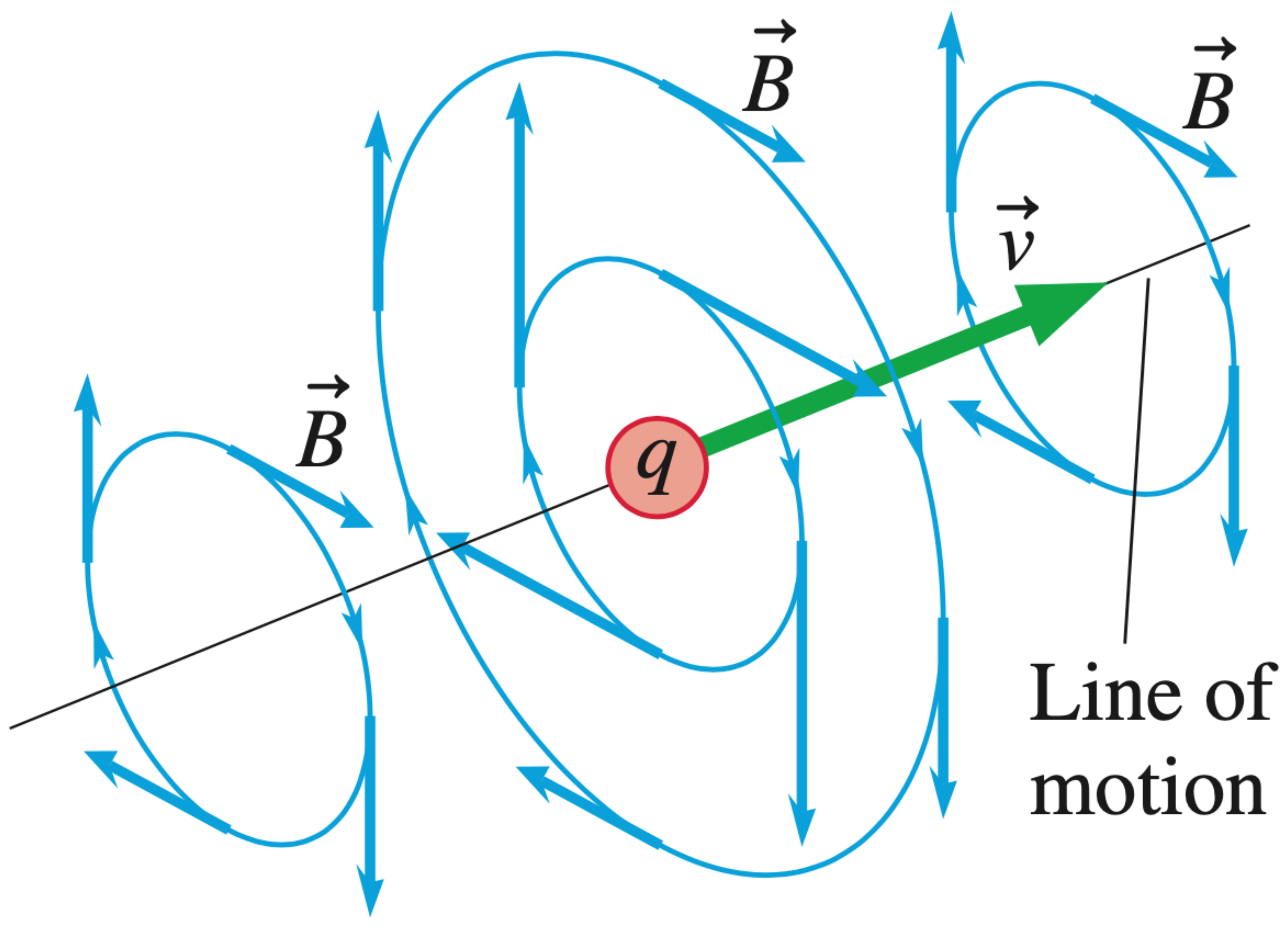
For these field points, $\vec{r}$ and $\vec{v}$ both lie in the beige plane, and $\vec{B}$ is perpendicular to this plane.



For these field points, $\vec{r}$ and $\vec{v}$ both lie in the gold plane, and $\vec{B}$ is perpendicular to this plane.

Right-Hand Rule for the direction of a Mag. Field from a moving charge

(b) View from behind the charge



The direction of **B** (the magnetic field) is perpendicular to both **v** and $\mathbf{\hat{r}}$.

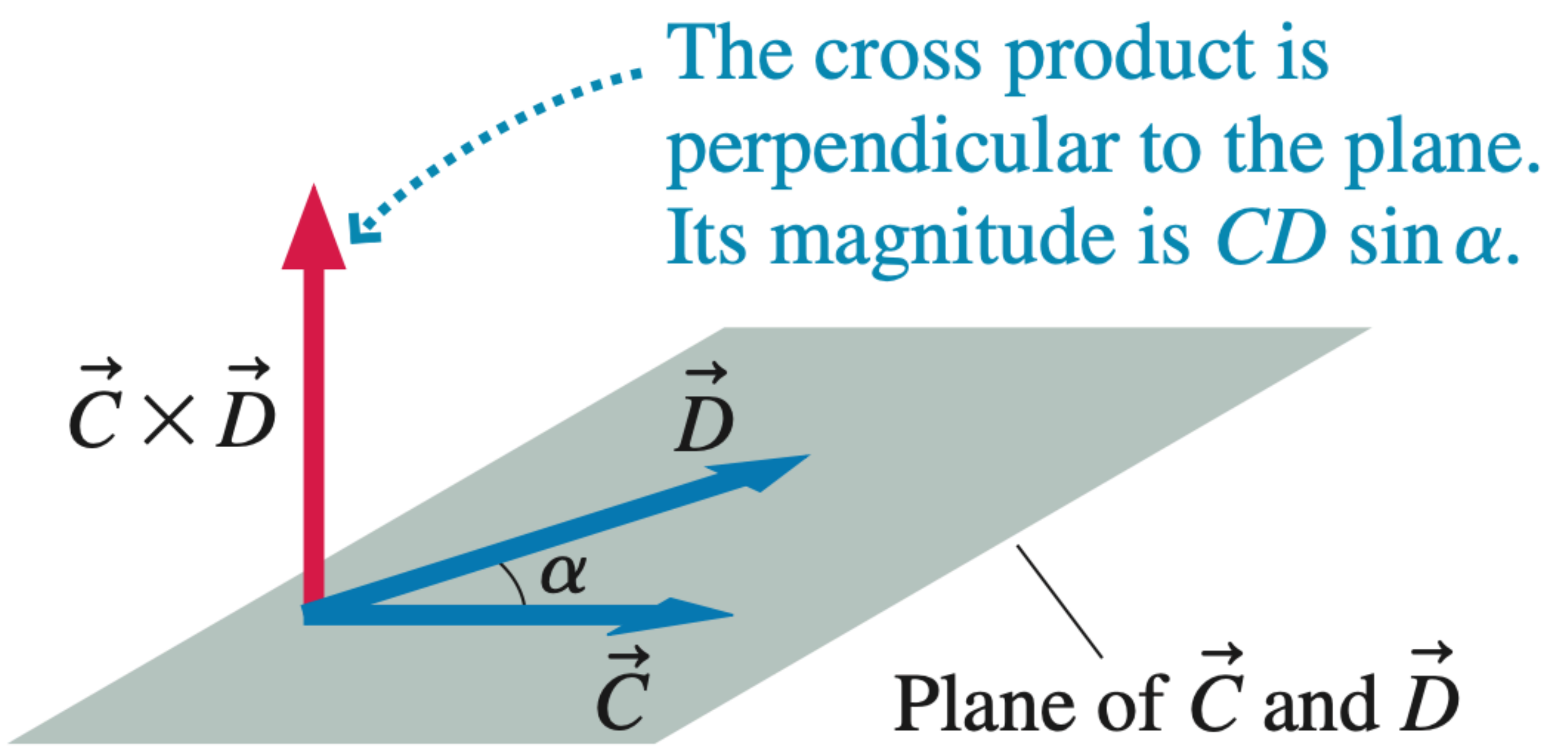
There is something in vector calculus that describes this perfectly.. the “cross product” of two vectors.

Cross Product Between Two Vectors

The cross product is a way of multiplying two vectors and getting another vector as a result.

- The resultant cross product is perpendicular to each of the input vectors, with direction determined by the right-hand rule.
- The magnitude of the result is $|\vec{C} \times \vec{D}| = CD \sin \alpha$

FIGURE 29.10 The cross product $\vec{C} \times \vec{D}$ is a vector perpendicular to the plane of vectors $\vec{C}$ and $\vec{D}$.



Note that if the vectors are parallel or antiparallel, the cross product is zero.
Also, it is true that $\vec{C} \times \vec{D} = -\vec{D} \times \vec{C}$

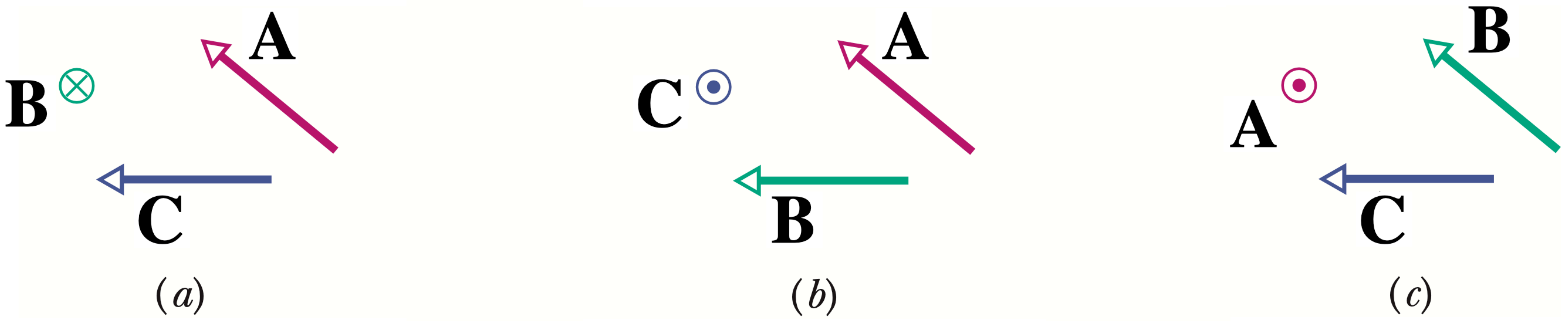
Clicker/Poll Question

What's the direction of **A** x **B** if **A** is pointing into the screen and **B** is pointing to the right?

A. Upwards
B. Downwards
C. To the left
D. Out of the screen
E. None of the above

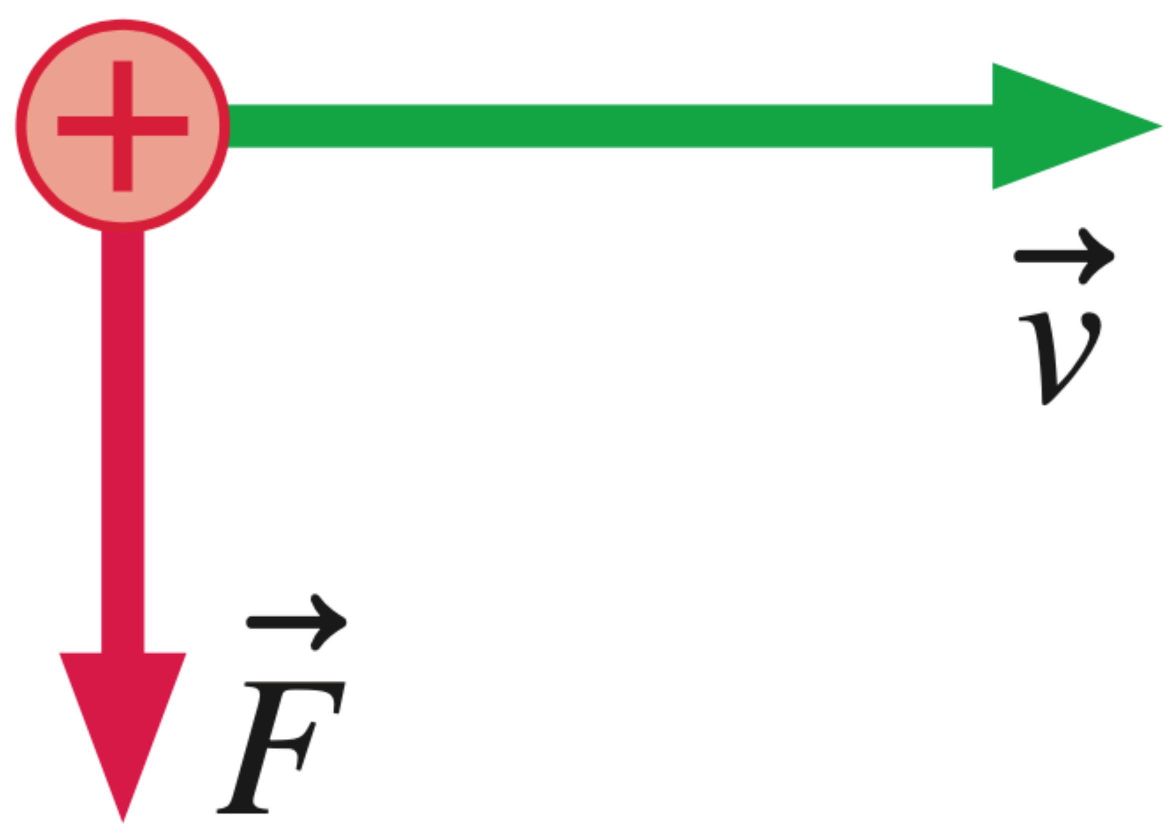
Try it Yourself

Your friend claims that $\mathbf{C} = \mathbf{A} \times \mathbf{B}$ for each of the following three pictures. Which do you agree with? What's wrong with the other(s)?



Clicker/Poll Question

As we'll see a few lectures from now, if a positive charge q is moving with velocity v in a magnetic field B, then it feels a force $\overrightarrow{F} = q(\overrightarrow{v} \times \overrightarrow{B})$. Given this info, find the magnetic field for the situation shown to the right.



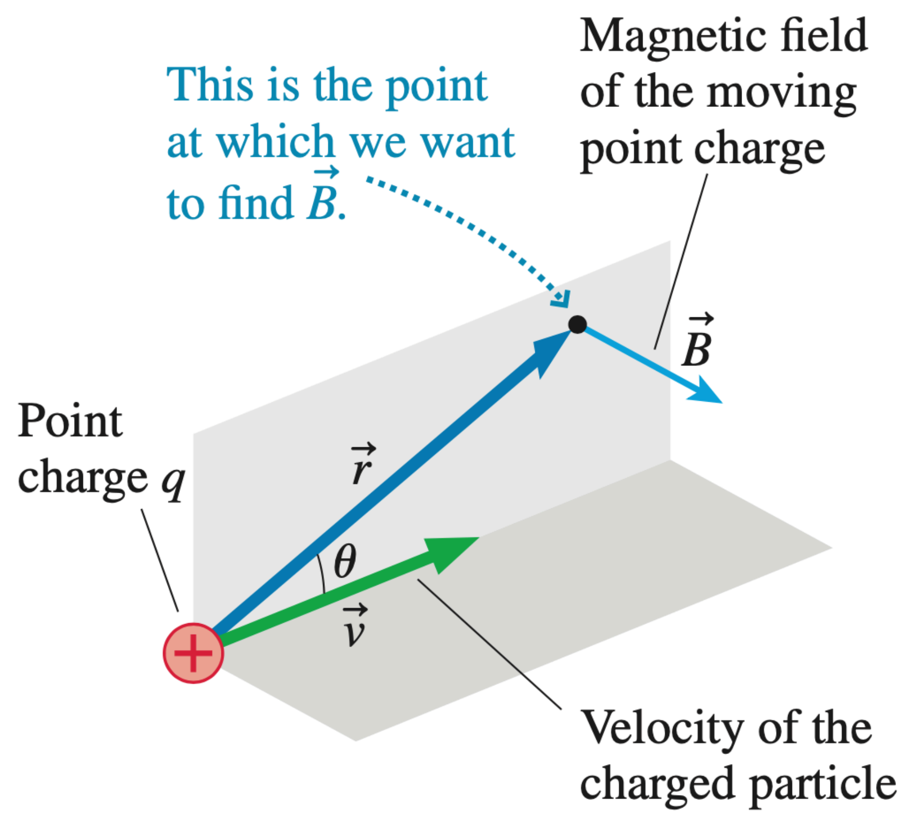
A. Upwards
B. To the left
C. Into the screen
D. Out of the screen
E. None of the above

Biot-Savart Law, Cross-Product Form

We previously wrote the Biot-Savart ("B.O. suh-vhar") law as the combination $B = \frac{\mu_0}{4\pi}\frac{qv\sin\theta}{r^2}$ (magnitude), and direction determined by the right-hand rule.
There is another way of expressing this information in terms of the cross product:

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

FIGURE 29.7 The magnetic field of a moving point charge.



As was the case with Coulomb's law, the $\hat{r}$ vector points from the source charge to the point where we want to find the field.

Also, remember $\mu_0 = 4\pi\times10^{-7}\,\frac{\mathrm{T\cdot s\cdot m}}{\mathrm{C}}$

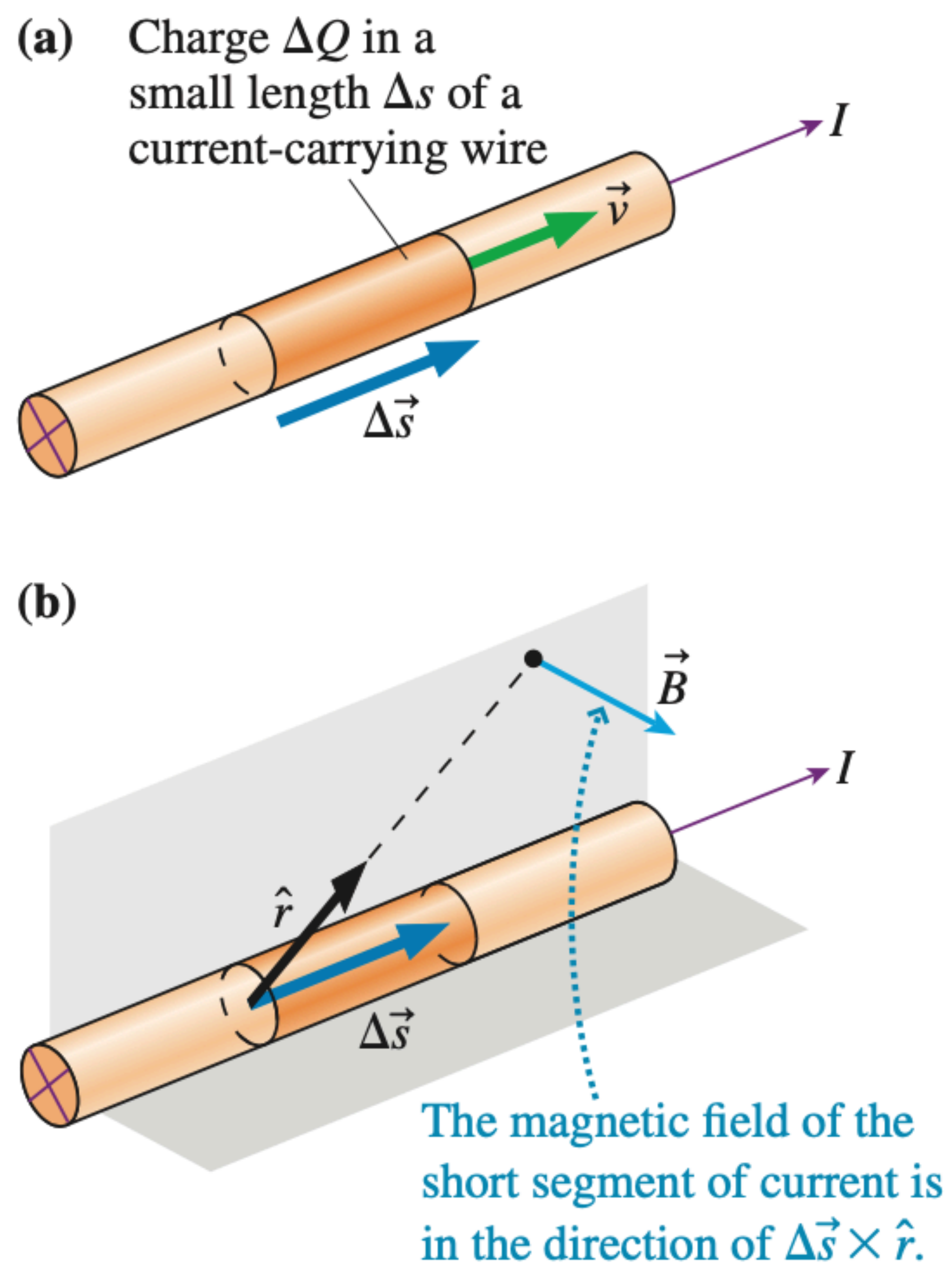
Biot-Savart Law for Currents

The magnetic field of a single point charge is very small. It takes a lot of charges moving to get an appreciable magnetic field. **A better form of the Biot-Savart law is one where the source is 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)

FIGURE 29.13 Relating the charge velocity $\vec{v}$ to the current I.



As was the case with Coulomb's law, the $\hat{r}$ vector points from the source charge to the point where we want to find the field.

Also, remember $\mu_0 = 4\pi\times10^{-7}\,\dfrac{\mathrm{T\cdot m}}{\mathrm{A}}$

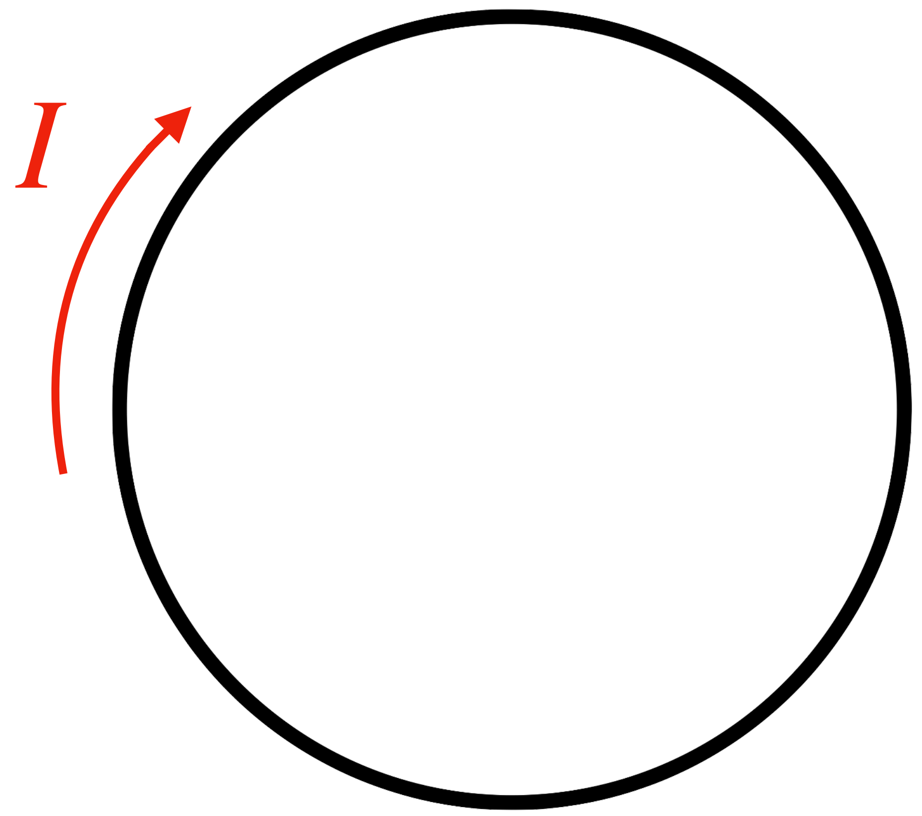
Biot-Savart Law: Main Results

The Biot-Savart law can be used to find the B-field from any current configuration. Two of the most important results are the following:

B-Field due to an infinite straight line

$$B_{\text{inf. wire}} = \frac{\mu_0 I}{2\pi r}$$

B-Field due to an circle



$$B_{\text{circle}} = \frac{\mu_0 I}{2R}$$

Note: any fraction of a circle is the corresponding fraction of this value. For example, a quarter-circle produces a field $B_{\text{1/4 circle}} = \frac{\mu_0 I}{8R}$ at the point the arc is centered around.

Biot-Savart Law, Ampere's Law

(Including magnetic dipoles and solenoids)

(K) 29.4-29.6; (OS) 11.1 and parts of 11.2, 12.1-12.2

Brian Shotwell, Spring 2023

Agenda Today (May 15, 2023)

- Biot-Savart Law, 2 Main Results
- Magnetic Dipoles (Current Loops)
- Ampere’s Law
  - In general
  - To solve for B(r) in a current-carrying wire of const. J
- Solenoids

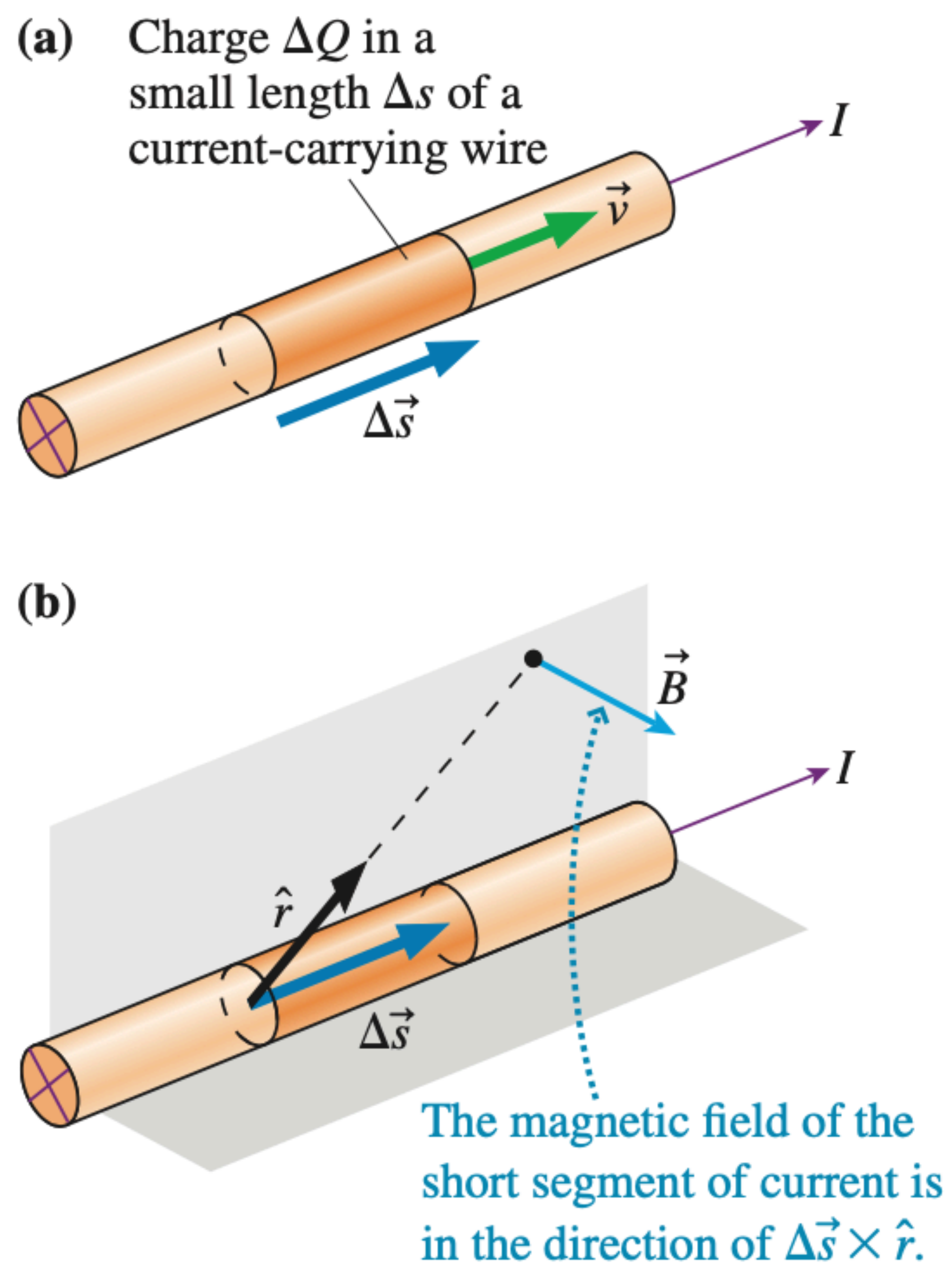
Biot-Savart Law for Currents

The magnetic field of a single point charge is very small. It takes a lot of charges moving to get an appreciable magnetic field. **A better form of the Biot-Savart law is one where the source is 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)

FIGURE 29.13 Relating the charge velocity $\vec{v}$ to the current I.



As was the case with Coulomb's law, the $\hat{r}$ vector points from the source charge to the point where we want to find the field.

Also, remember $\mu_0 = 4\pi \times 10^{-7} \, \frac{\text{T} \cdot \text{m}}{\text{A}}$

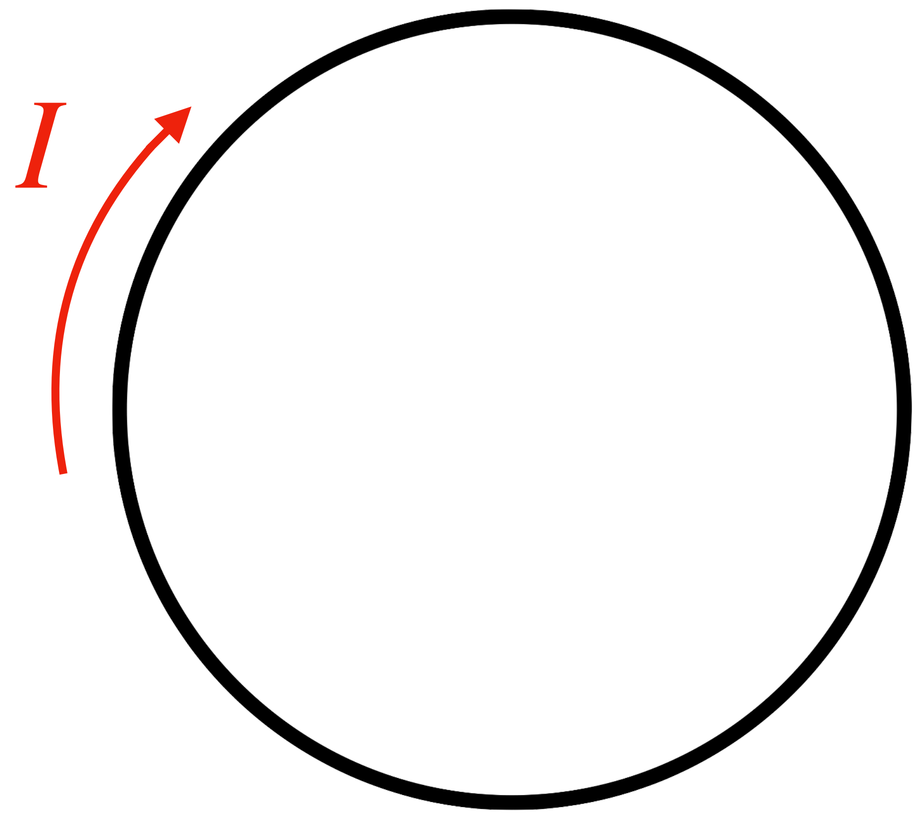
Biot-Savart Law: Main Results

The Biot-Savart law can be used to find the B-field from any current configuration. Two of the most important results are the following:

B-Field due to an infinite straight line

$$B_{\text{inf. wire}} = \frac{\mu_0 I}{2\pi r}$$

B-Field due to an circle

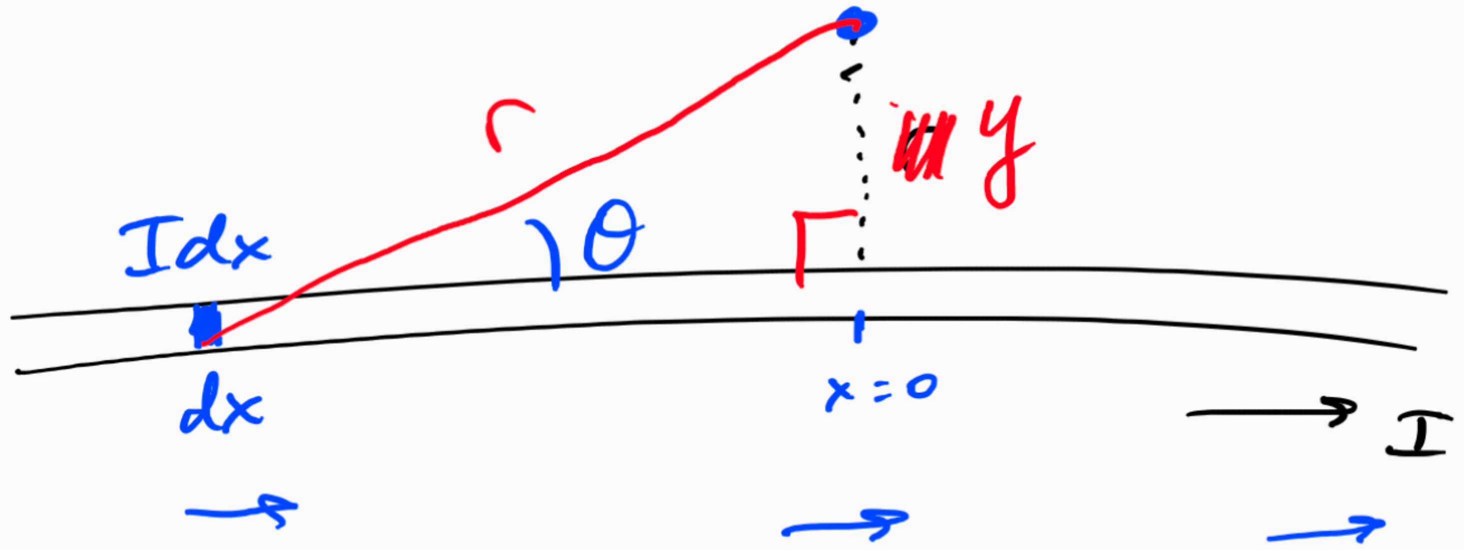


$$B_{\text{circle}} = \frac{\mu_0 I}{2R}$$

Note: any fraction of a circle is the corresponding fraction of this value. For example, a quarter-circle produces a field $B_{1/4 \text{ circle}} = \frac{\mu_0 I}{8R}$ at the point the arc is centered around.

Biot-Savart Law: Main Results (Proofs in Vid)

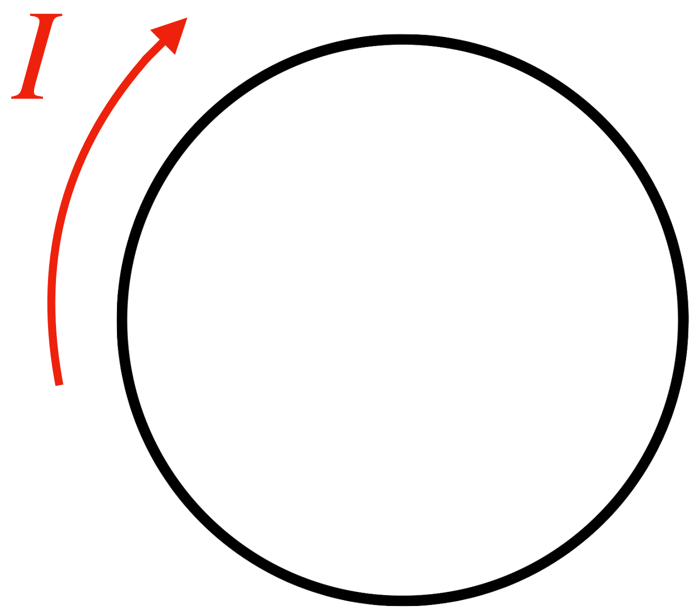
$\vec{B}$ due to a long wire $\qquad \odot\ \hat{z}$



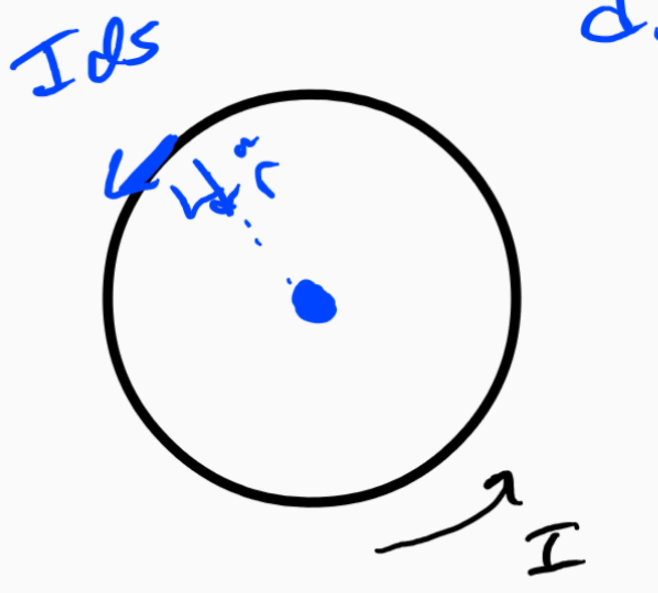
$$dB_z = \frac{\mu_0}{4\pi}\frac{(I\,dx)\sin\theta}{r^2} \qquad \sin\theta = \frac{y}{r} = \frac{y}{\sqrt{x^2+y^2}}$$

$$B_z = \frac{\mu_0}{4\pi}\int \frac{(I\,dx)\,y}{(x^2+y^2)^{3/2}}$$

$$B_z = \frac{\mu_0}{4\pi} I y \int_{-\infty}^{\infty} \frac{dx}{(x^2+y^2)^{3/2}} = \frac{\mu_0 I}{2\pi y}$$



$\vec{B}$ due to a current loop @ center of loop



radius R

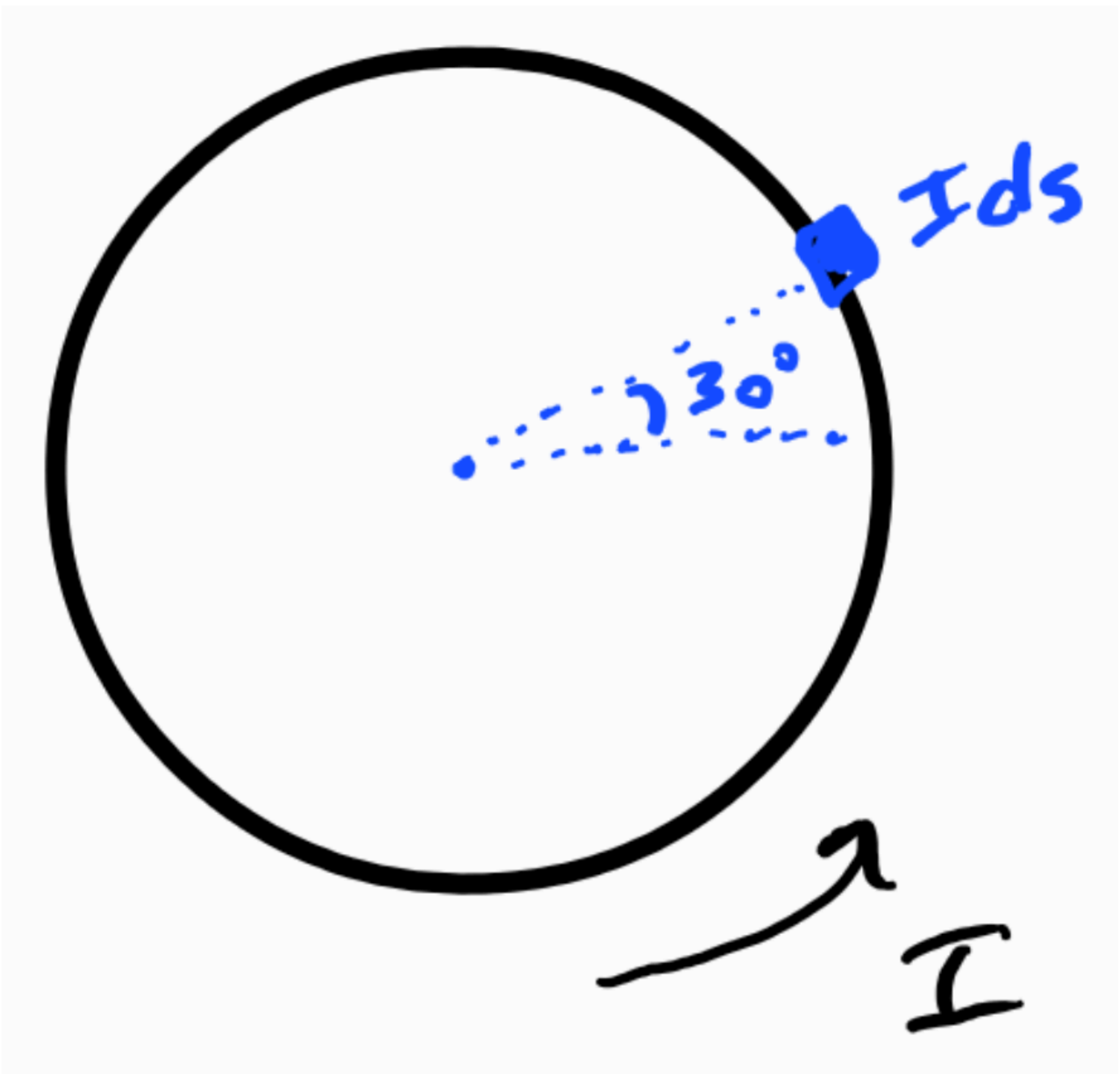
$$dB_z = \frac{\mu_0}{4\pi}\frac{I\,ds}{R^2}$$

$$B_z = \frac{\mu_0}{4\pi}\int_{\text{circle}} \frac{I\,ds}{R^2}$$

$$= \frac{\mu_0 I}{4\pi R^2}\underbrace{\int_{\text{circle}} ds}_{2\pi R} = \boxed{\frac{\mu_0 I}{2R}}$$

Clicker/Poll Question

The picture to the right shows a loop of current I with a small segment Ids labeled. What is the contribution to the magnetic field dB_z at the center of the loop due to this current segment? Let the +z direction point out of the screen (towards you).



A. $\dfrac{\mu_0}{4\pi}\dfrac{Ids}{R^2}$

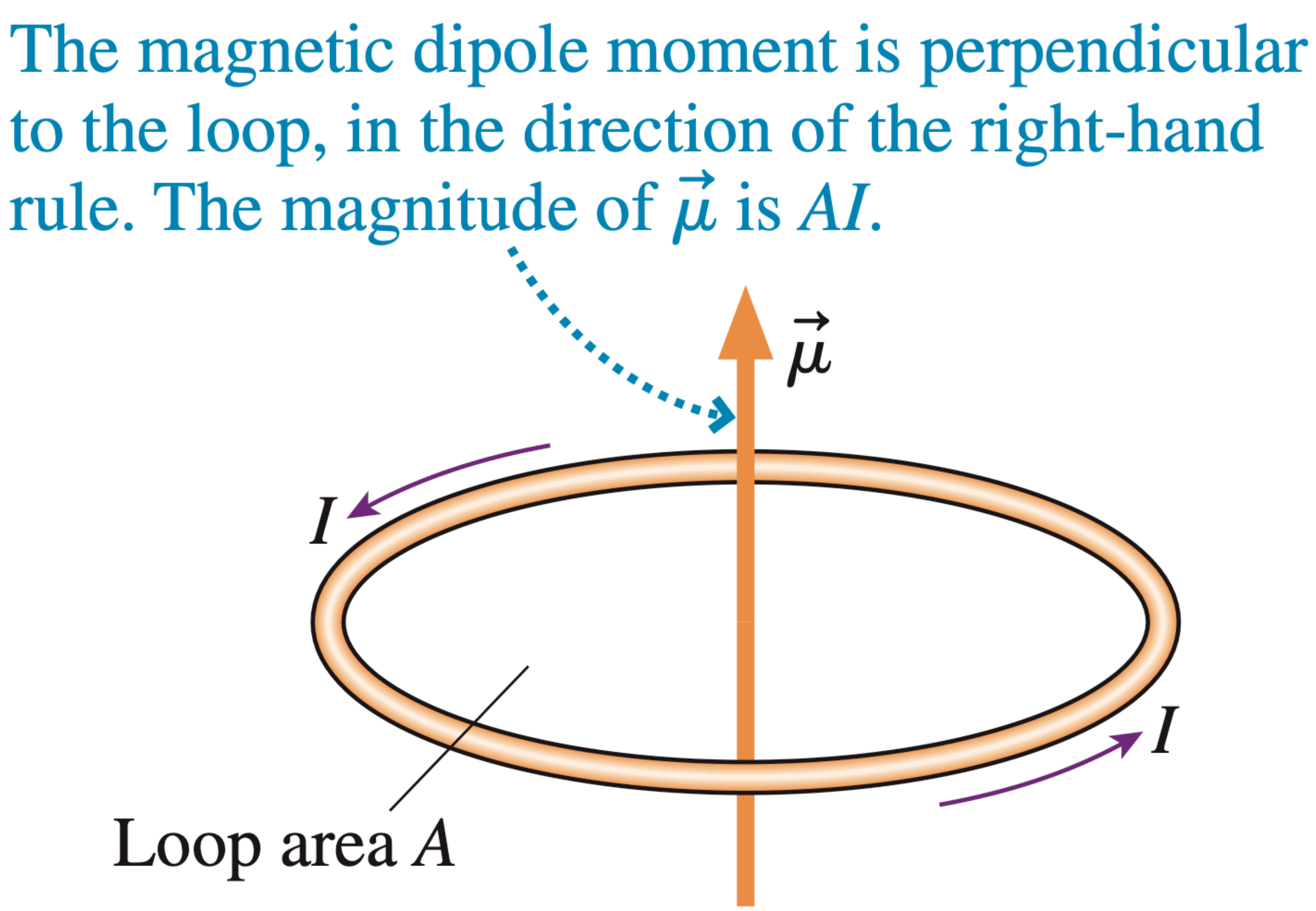
B. $-\dfrac{\mu_0}{4\pi}\dfrac{Ids}{R^2}$

C. $+\dfrac{\mu_0}{4\pi}\dfrac{Ids}{R^2}\sin 30°$

D. $-\dfrac{\mu_0}{4\pi}\dfrac{Ids}{R^2}\cos 30°$

Magnetic Dipole

A current loop is an example of a "magnetic dipole" (a magnetic object with a north and south pole).



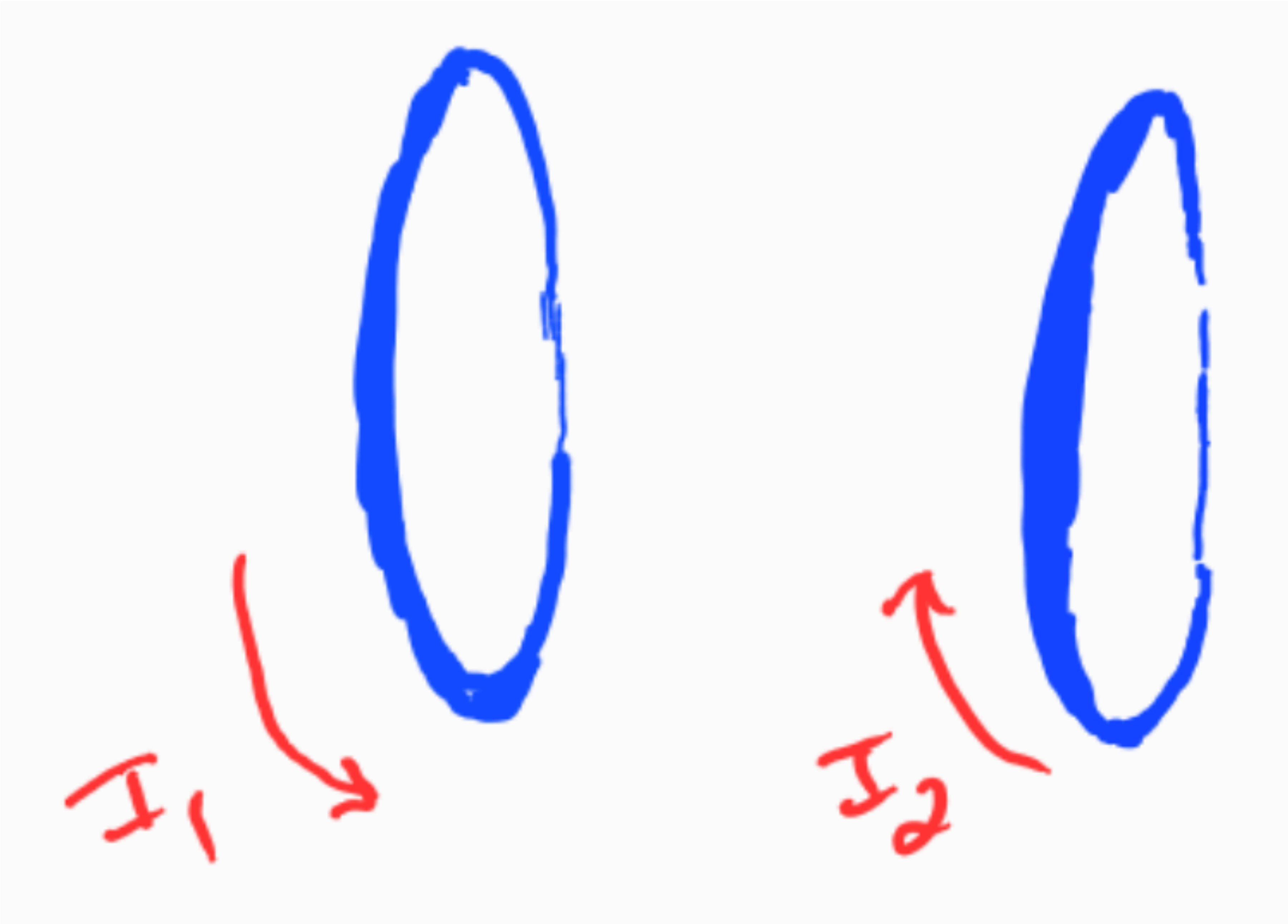
The magnetic field created by a magnetic dipole, on the axis of the dipole, looks similar to the result for the electric field due to an electric dipole:

$$\mathbf{B}_{\text{due to } \mu,\text{ on axis of } \mu} = \frac{\mu_0}{4\pi}\frac{2\overrightarrow{\boldsymbol{\mu}}}{z^3}$$

Clicker/Poll Question

Two current loops are placed side-by-side, as shown. The currents are going in opposite directions. The magnetic force between the two loops is…

A. Attractive
B. Repulsive



Ampere's Law

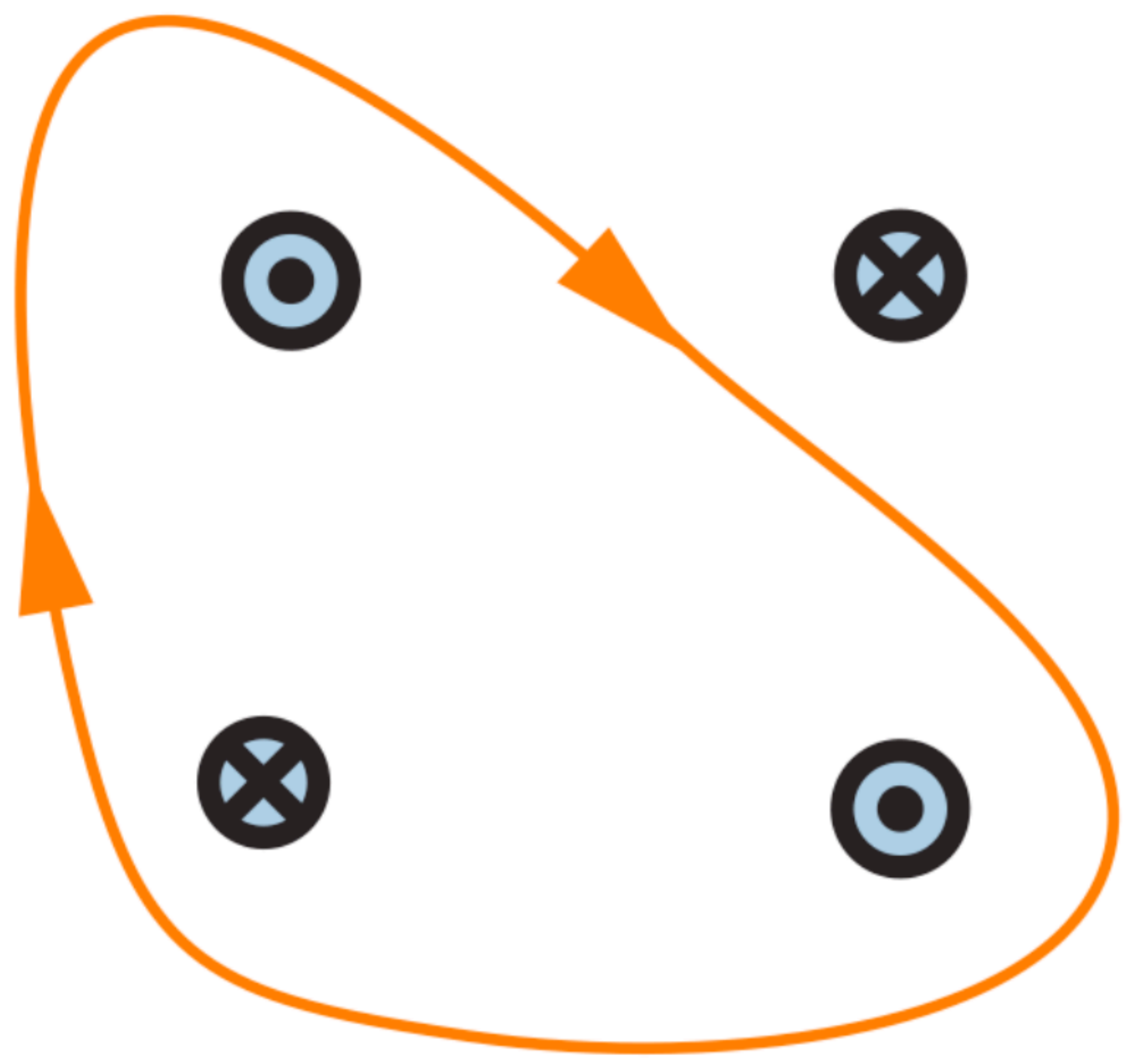
Ampere's Law: The line integral of the magnetic field around a closed curve is proportional to the current going through the loop:

$$\boxed{\oint \vec{B} \cdot d\vec{s} = \mu_0 I_{\text{through}}}$$

Ampere's Law is useful for magnetic fields in the same way Gauss's Law is useful for electric fields — if there is some symmetry in the source distribution (charges for E and currents for B), then we can use the law to easily calculate the field.

Clicker/Poll Question

What is the value of $\oint_{\text{cw}} \mathbf{B} \cdot d\mathbf{s}$ for the current distribution and loop shown? Each wire carries a current 1A.



A. $\mu_0\,(+1\text{ A})$

B. $\mu_0\,(-1\text{ A})$

C. $\mu_0\,(+3\text{ A})$

D. $\mu_0\,(-3\text{ A})$

E. None of the above

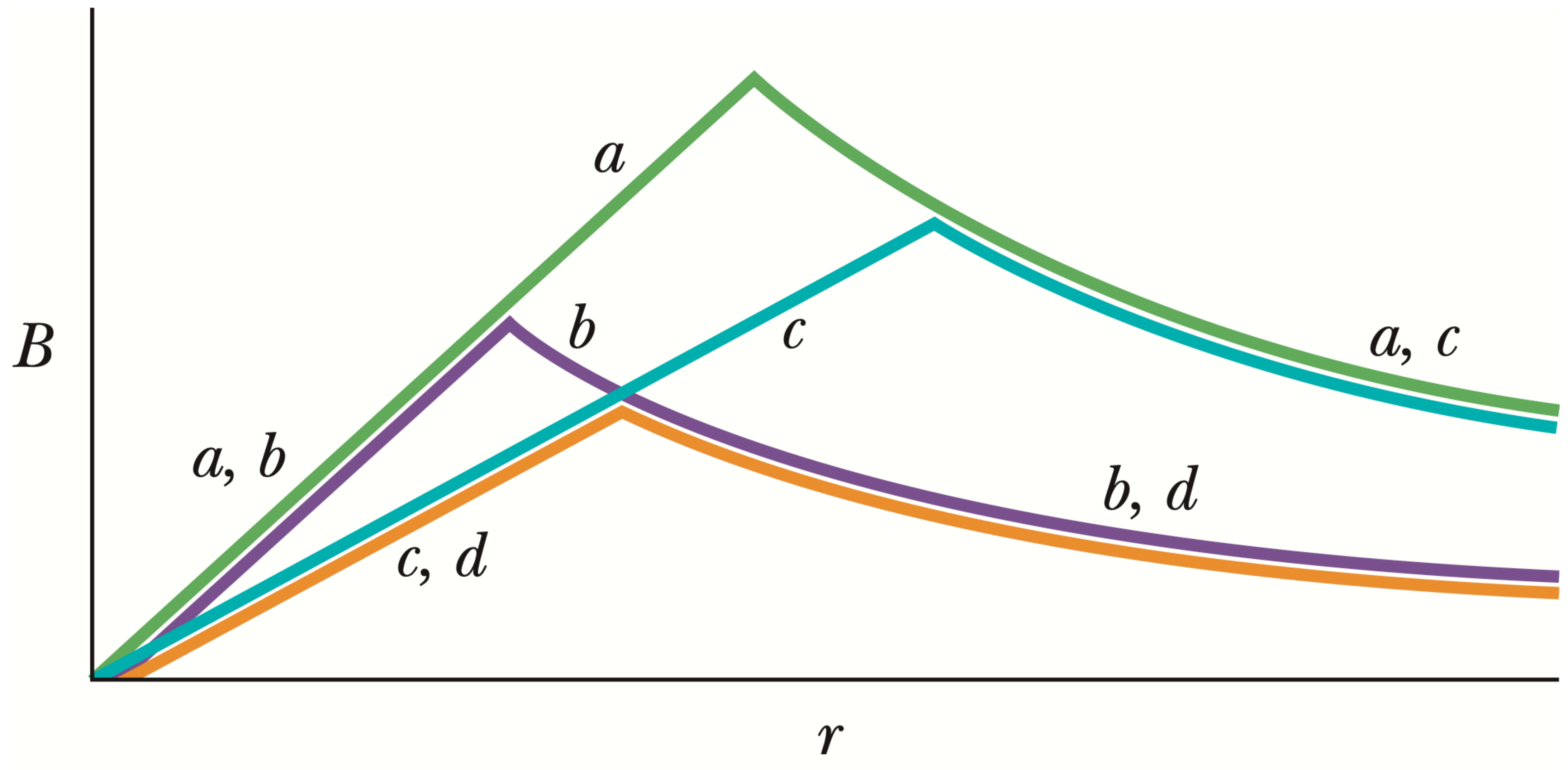
Ampere's Law to find B(r) inside a wire

Let's see how Ampere's Law can be useful: what is the magnetic field as a function of r for a long, straight wire of radius R carrying a total current I that is uniformly distributed over the interior of the wire?

Ampere’s Law to find B(r) inside a wire

Clicker/Poll Question

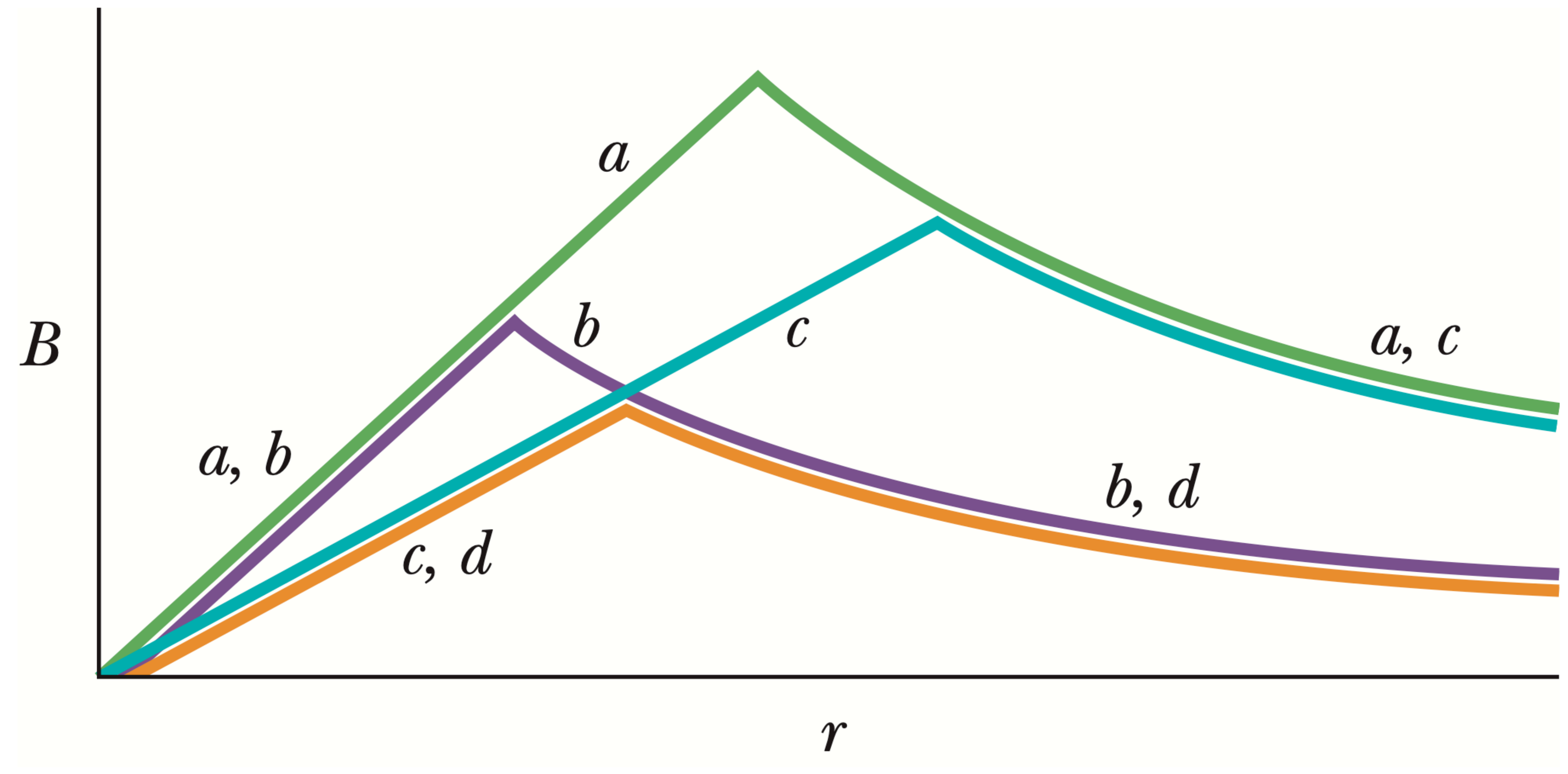
$B_r(r)$ for four different wires (a-d) is shown to the right. Which wire(s) have the largest current density, J?



A. Wire a
B. Wires a and b
C. Wires a and c
D. Wires b and d
E. ???

Clicker/Poll Question

$B_r(r)$ for four different wires (a-d) is shown to the right. Which wire(s) have the largest current, I?



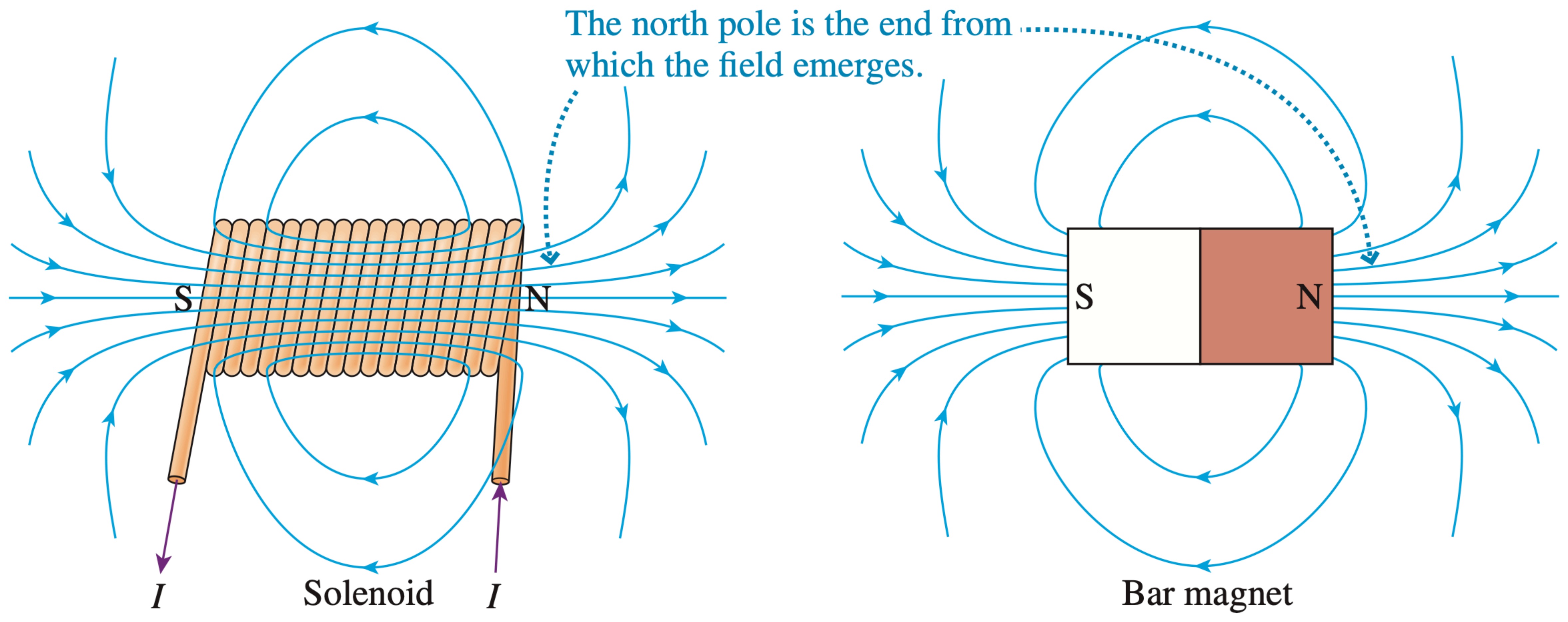
A. Wire a
B. Wires a and b
C. Wires a and c
D. Wires b and d
E. ???

Ampere’s Law to find B(r) inside a solenoid

A “solenoid” is a coil of wire.
(Several loops of wire.)

Without proof, a(n ideal) solenoid (very long, lots of turns) produces a strong, near-constant magnetic field inside of it, and a weaker field outside.

FIGURE 29.32 The magnetic fields of a finite-length solenoid and of a bar magnet.



You can use Ampere’s law along with the above fact to show that the magnetic field inside the solenoid is

$$\boxed{B_{\text{in solenoid}} = \mu_0 n I}$$

I: current in the wire, [A]

n: number of loops per unit length, [1/m]

Try it yourself…

A slinky is a solenoid. Suppose a slinky has length 10cm and 50 turns. If we are able to get a current 100mA passing through the slinky, what is the magnetic field at the center (in Tesla)?

Magnetic Forces (on charges and wires); Magnetic Torques (on mag. Dipoles)

(K) 29.7-29.9; (OS) 11.2-11.7, 12.3

Brian Shotwell, Spring 2023

Agenda Today (May 17, 2023)

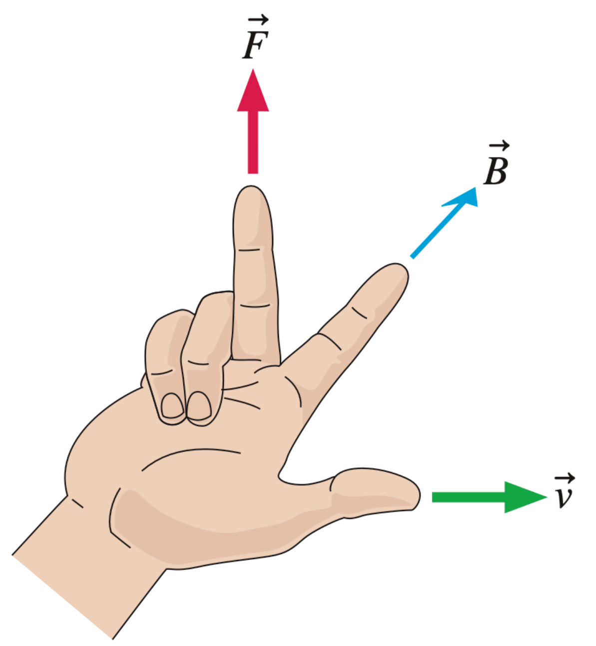
- Magnetic Forces on Charges
  - Circular Motion in uniform **B**-field; Cyclotron Frequency
  - Lorentz Force: $\mathbf{F}_{\text{EM}} = \mathbf{F}_e + \mathbf{F}_m$
  - Crossed Fields “The Hall Effect”
- Magnetic Forces on Wires
  - Force between two wires
- Magnetic Torque on a current-loop (i.e., on a magnetic dipole)

Magnetic Force on a Charge

A charge q moving with velocity **v** in a magnetic field **B** feels a magnetic force given by

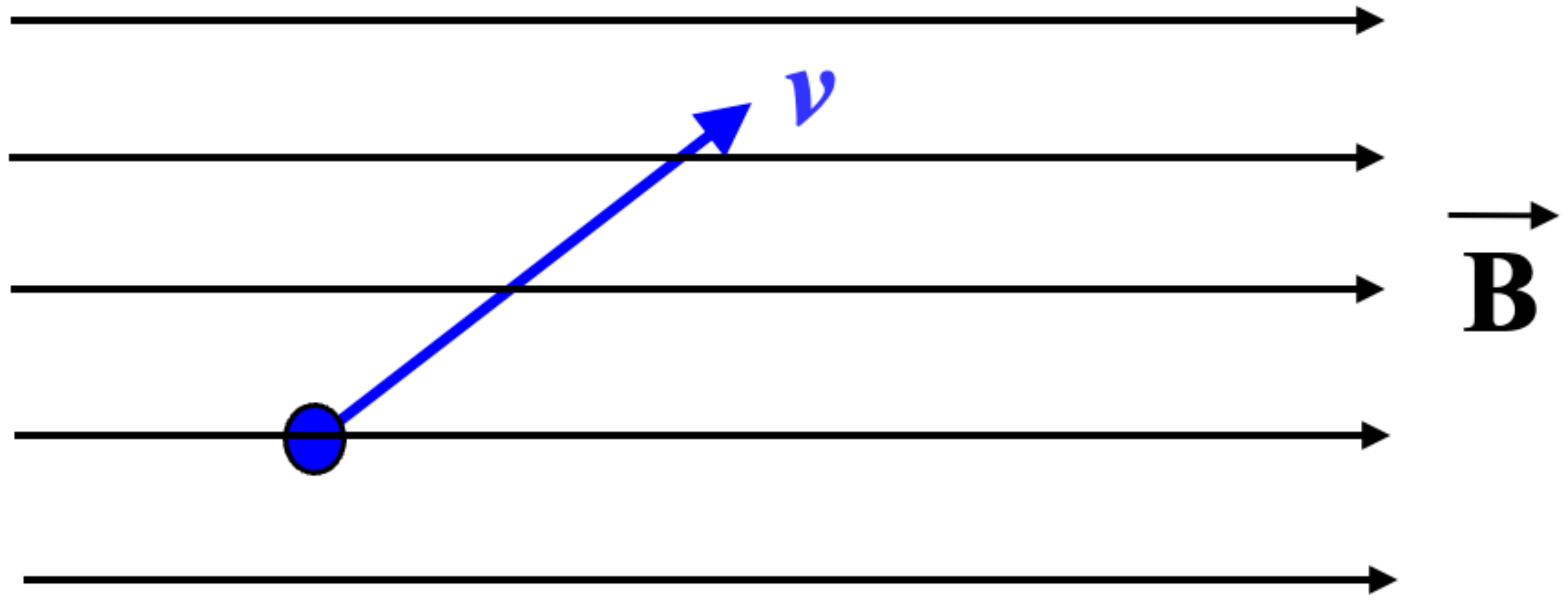
$$\boxed{\vec{F}_{\text{on } q} = q\vec{v} \times \vec{B}}$$

FIGURE 29.34 The right-hand rule for magnetic forces.



WARNING: this figure from the textbook only works if q is positive… if the charge is negative, the force would be in the opposite direction! For this reason, I avoid gang signs.

Clicker/Poll Question



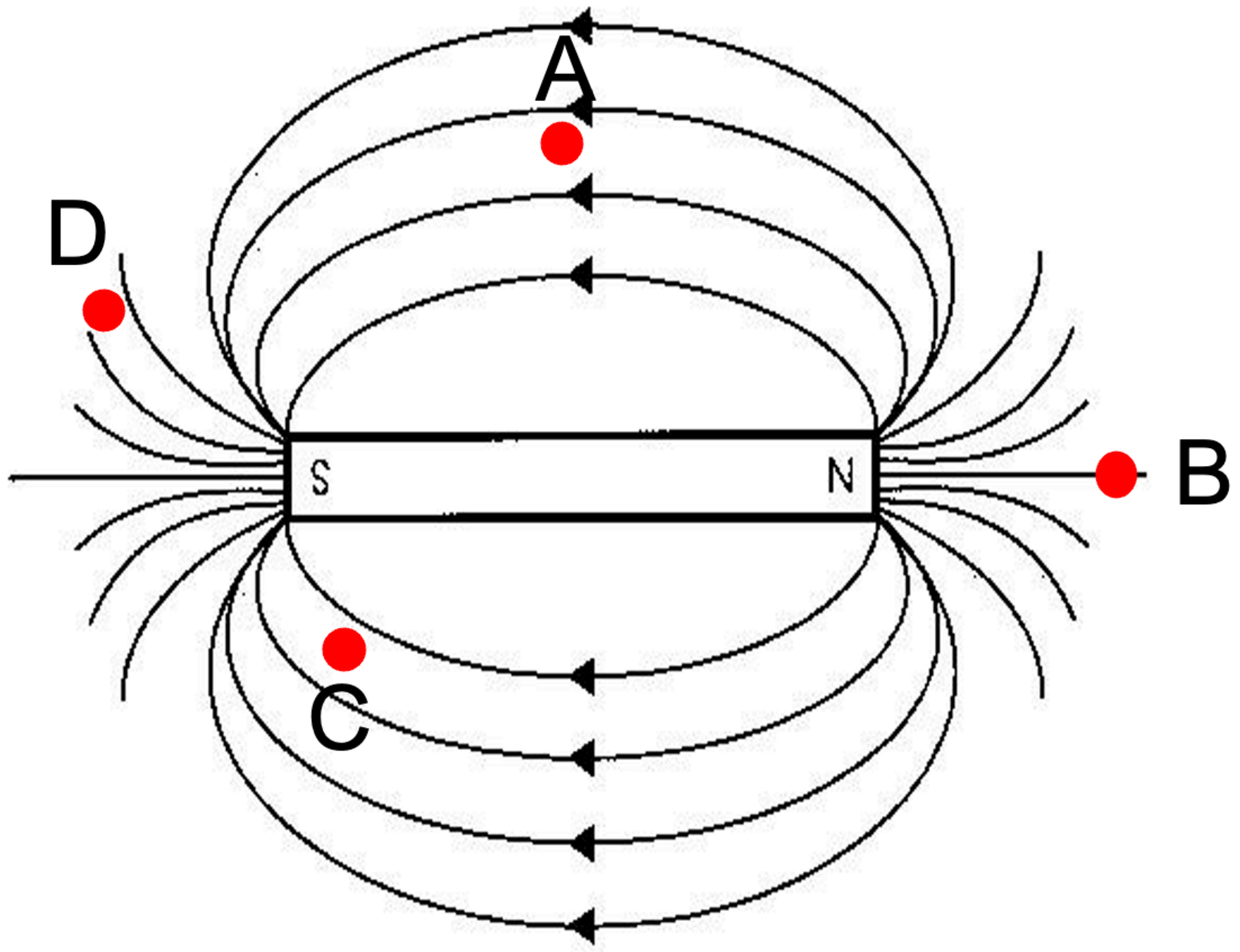
An electron with velocity **v** moves through the uniform mag. field B as shown. What is the direction of the force on the electron?

A. Down and right
B. Up and left
C. Into the screen (exactly)
D. Out of the screen (exactly)
E. None of the above

Try it yourself…

For each of the following, find the direction of the magnetic force on the particle:

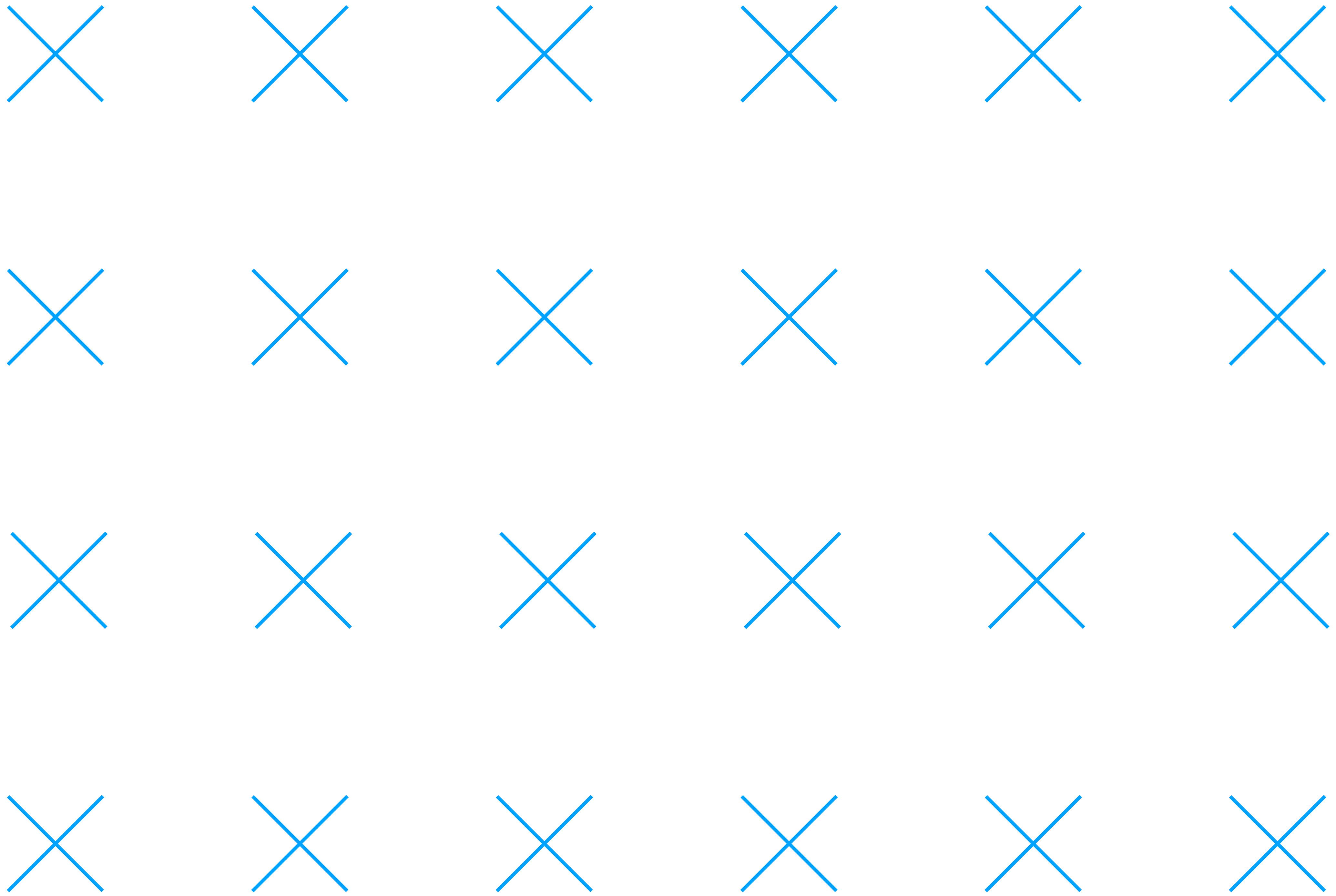
A. A proton moving upwards at pt. A
B. An electron at rest at pt. B
C. An electron into the screen at pt. C



Charge Moving in a uniform B-field

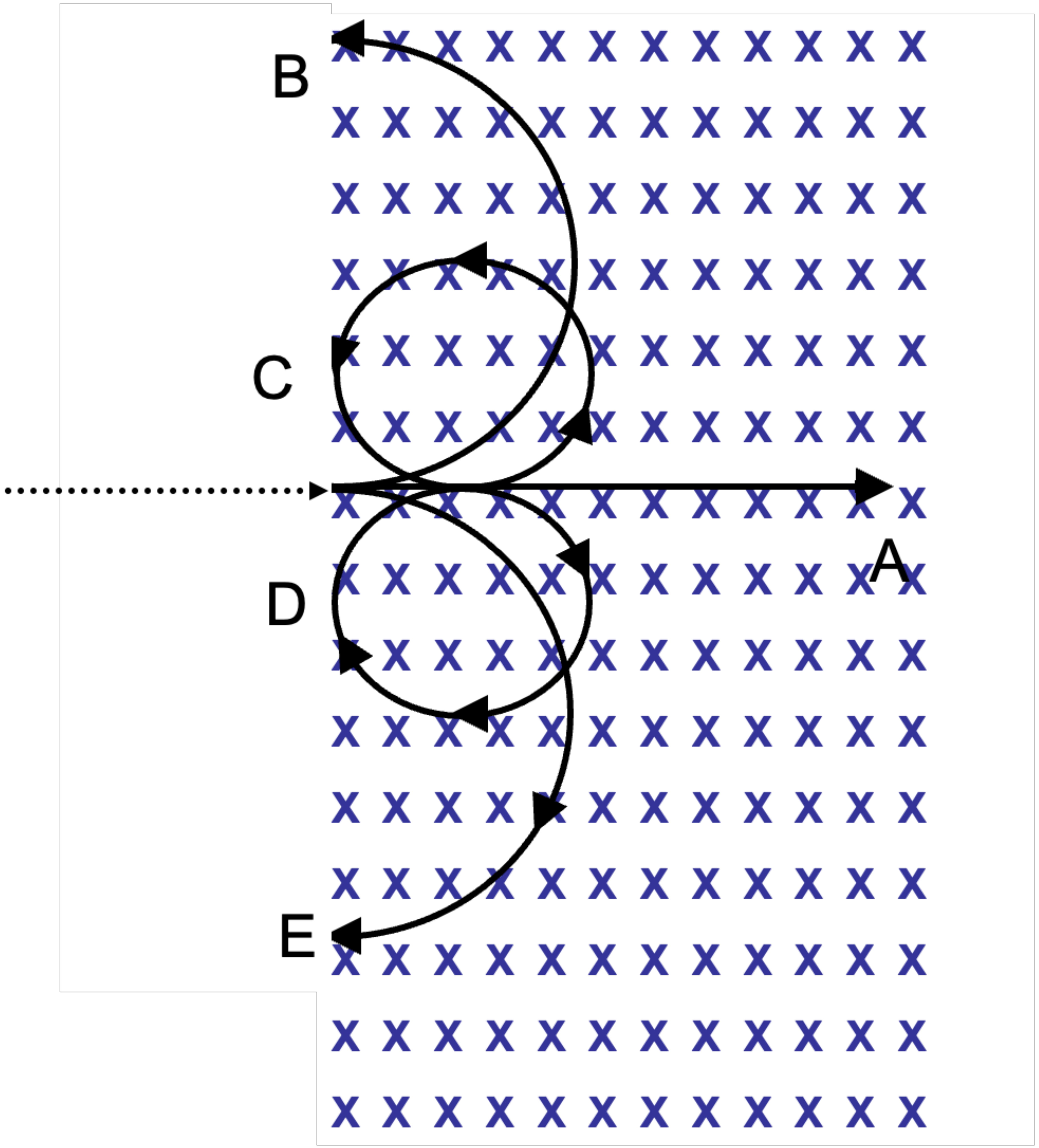
A particle moving perpendicular to a magnetic field will undergo circular motion:

Since $F_B = qvB = \frac{mv^2}{r}$, we know…



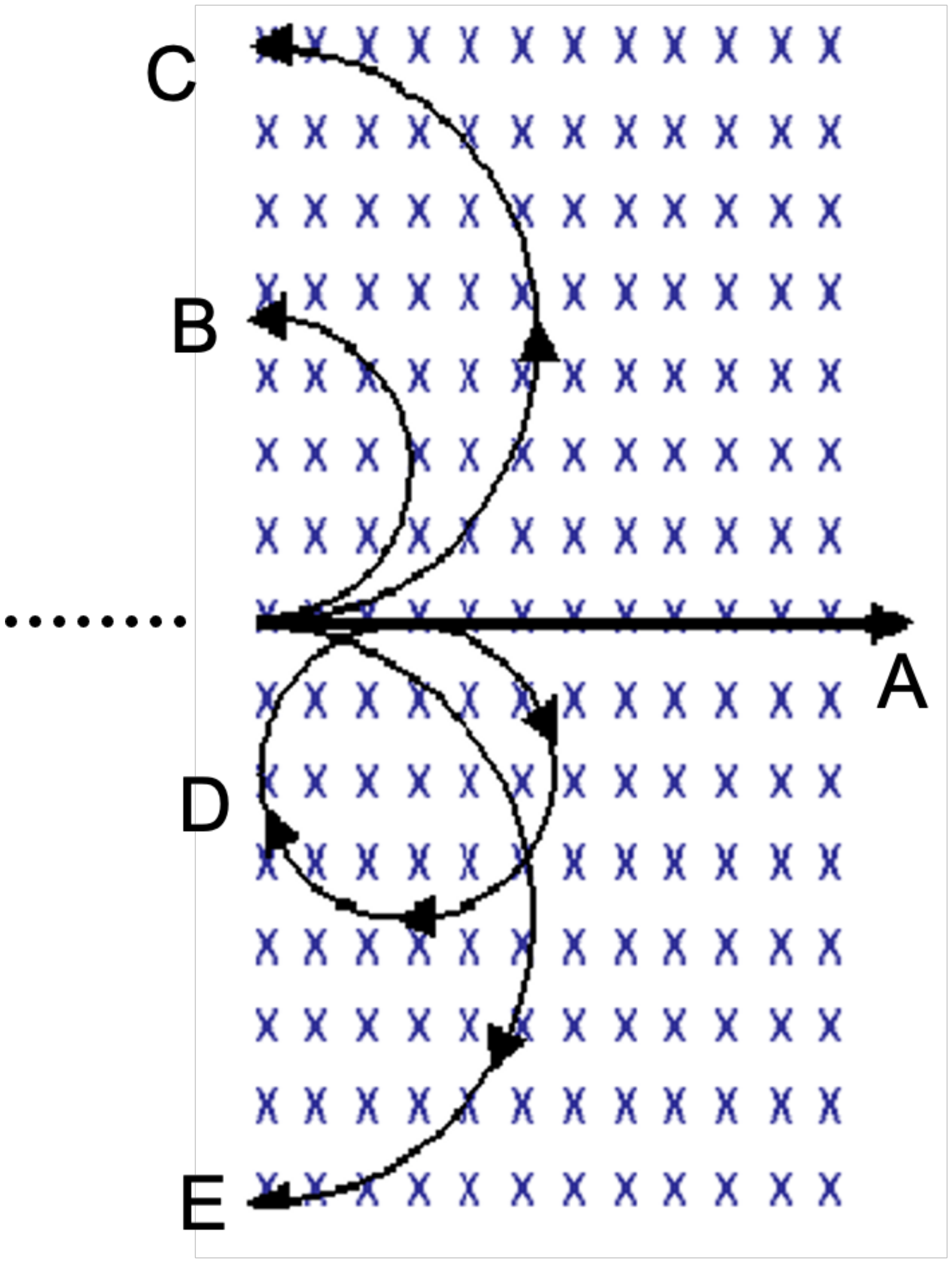
Clicker/Poll Question

A proton enters a uniform magnetic field into the screen as shown. Which of the indicated options could be its subsequent trajectory?



Clicker/Poll Question

A proton enters a magnetic field and follows trajectory B. An isotope of deuteron (same charge but twice the mass) enters the same magnetic field in the same way and with the same velocity as the proton. Which of the following is the right trajectory for the deuteron?

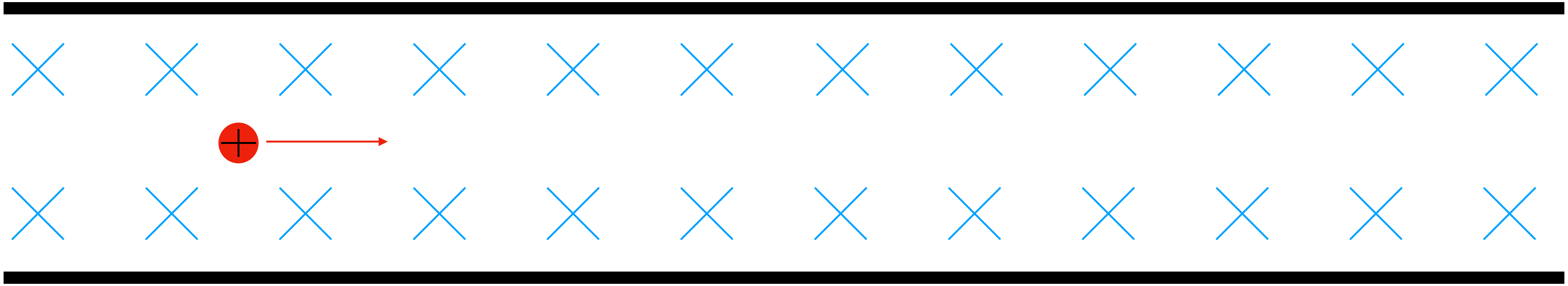


The Lorentz Force

The total force on a charged particle is a sum of contributions from the electric and magnetic forces; the total is called the Lorentz Force:

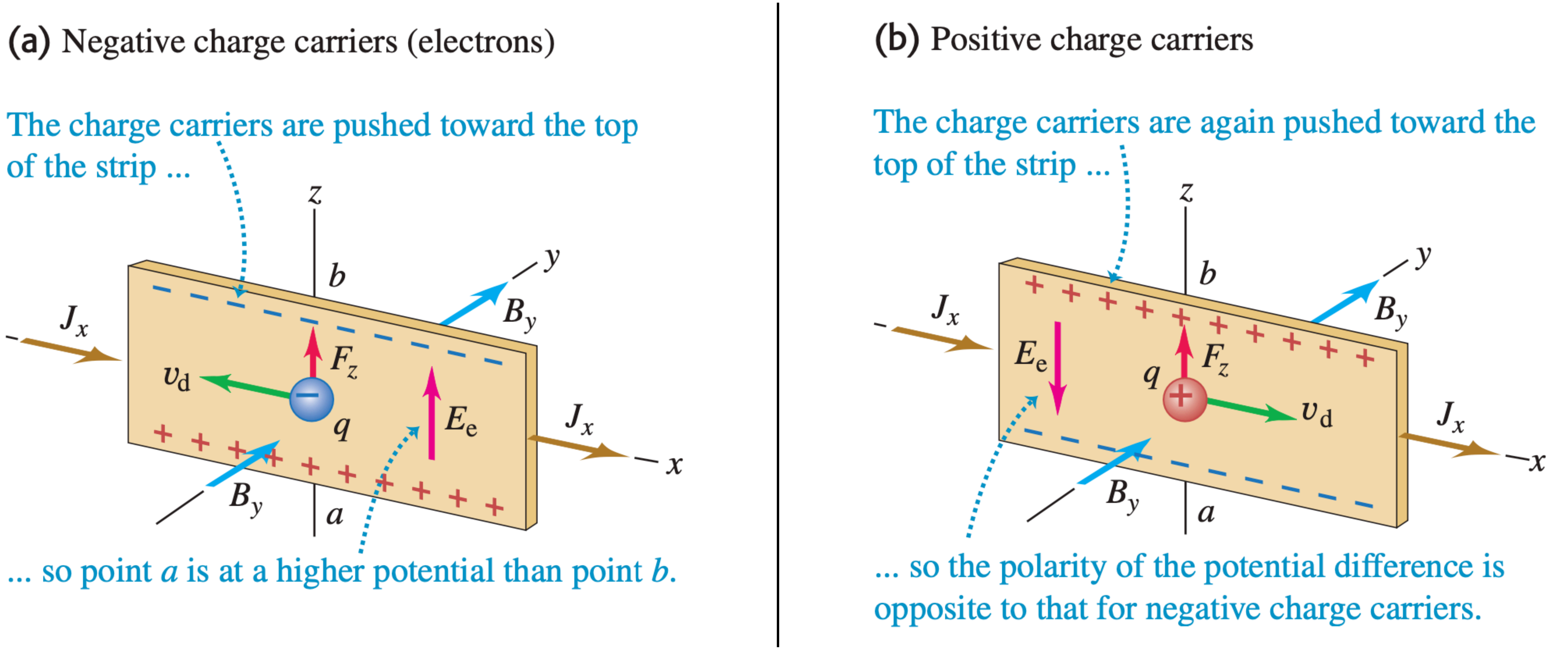
$$\boxed{\mathbf{F}_{\text{tot}} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})}$$

Imagine you had a positive particle moving to the right in the fields shown… what happens? What if the charge collected on the boundary?



The Hall Effect

(As a continuation of the picture in the previous slide)… there's a difference in a positive charge going up and a negative charge going down!



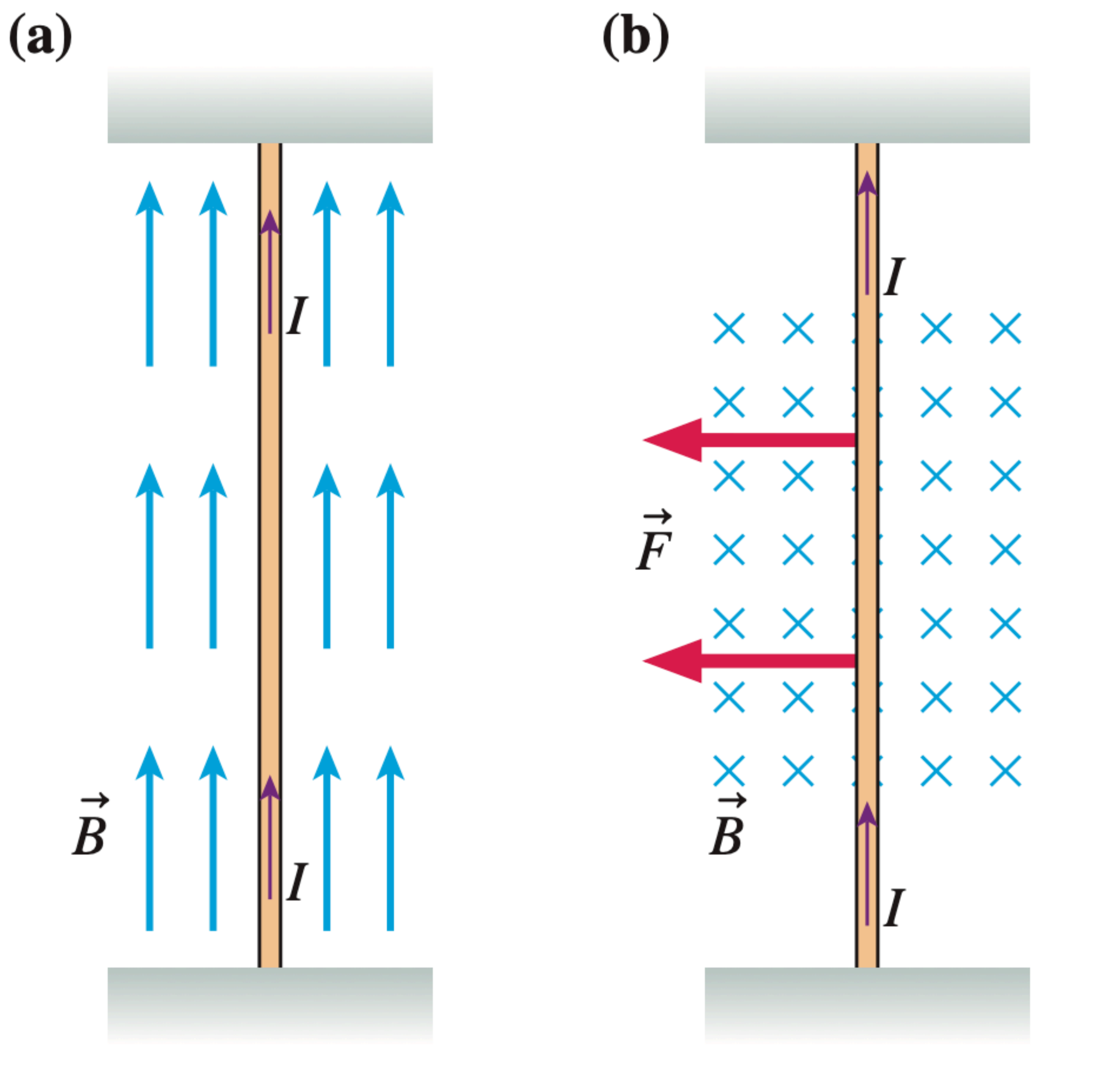
When will there be no more net EM force on the charge? When there is enough potential difference so that E=vB!

Magnetic Force on a Current-Carrying Wire

A wire carrying current I and length vector $\vec{l}$ (pointing in the direction of the current) in a magnetic field **B** feels a magnetic force given by

$$\boxed{\vec{F}_{\text{wire}} = I\vec{l} \times \vec{B}}$$

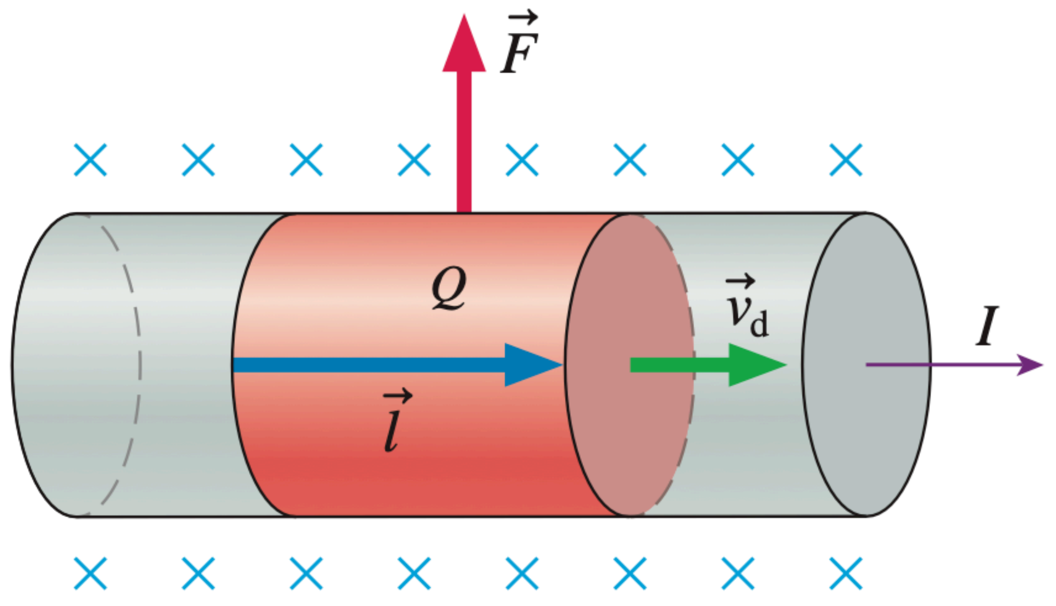
FIGURE 29.42 Magnetic force on a current-carrying wire.



There's no force on a current parallel to a magnetic field.

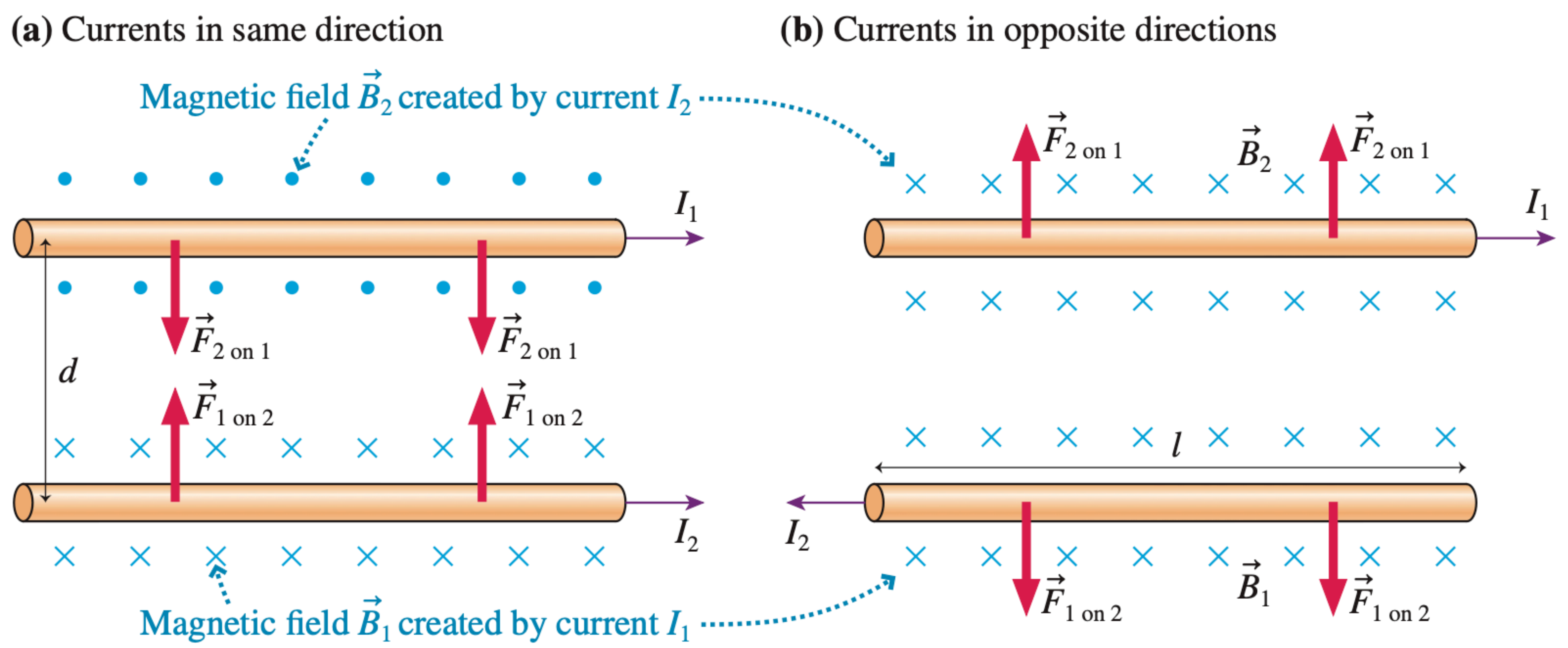
There is a magnetic force in the direction of the right-hand rule.

FIGURE 29.43 The force on a current is the force on the charge carriers.



Magnetic Force between Current-Carrying Wires

FIGURE 29.45 Magnetic forces between parallel current-carrying wires.



Clicker/Poll Question

You have two parallel wires carrying currents in the same direction. What is the direction of the magnetic field at the position where I_2 is located that is created by I_1?

A.

B.

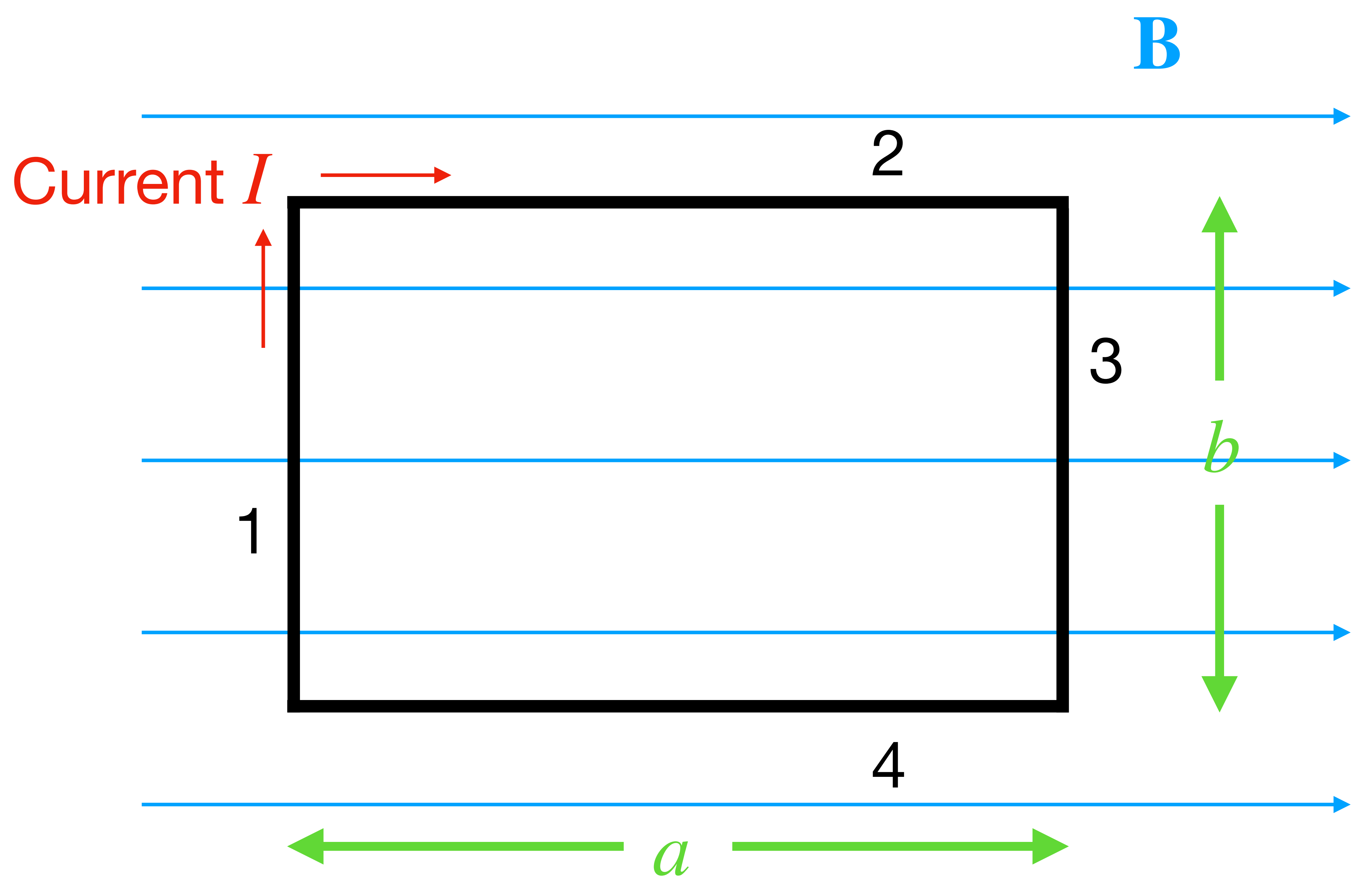
C.

D.

E.
None of these

Magnetic Torque on a Current Loop

Find the force on each straight-line segment (numbered 1-4) for the following rectangular current loop:



OVERALL RESULT: $\boldsymbol{\tau} = \boldsymbol{\mu} \times \mathbf{B}$

Try it yourself…

38. || A square current loop 5.0 cm on each side carries a 500 mA current. The loop is in a 1.2 T uniform magnetic field. The axis of the loop, perpendicular to the plane of the loop, is 30° away from the field direction. What is the magnitude of the torque on the current loop?

Magnetic Properties of Matter, Review of Ch. 29 / Ex. Problems

(K) 29.10 / Review of CH. 29

Brian Shotwell, Spring 2023

Agenda Today (May 19, 2023)

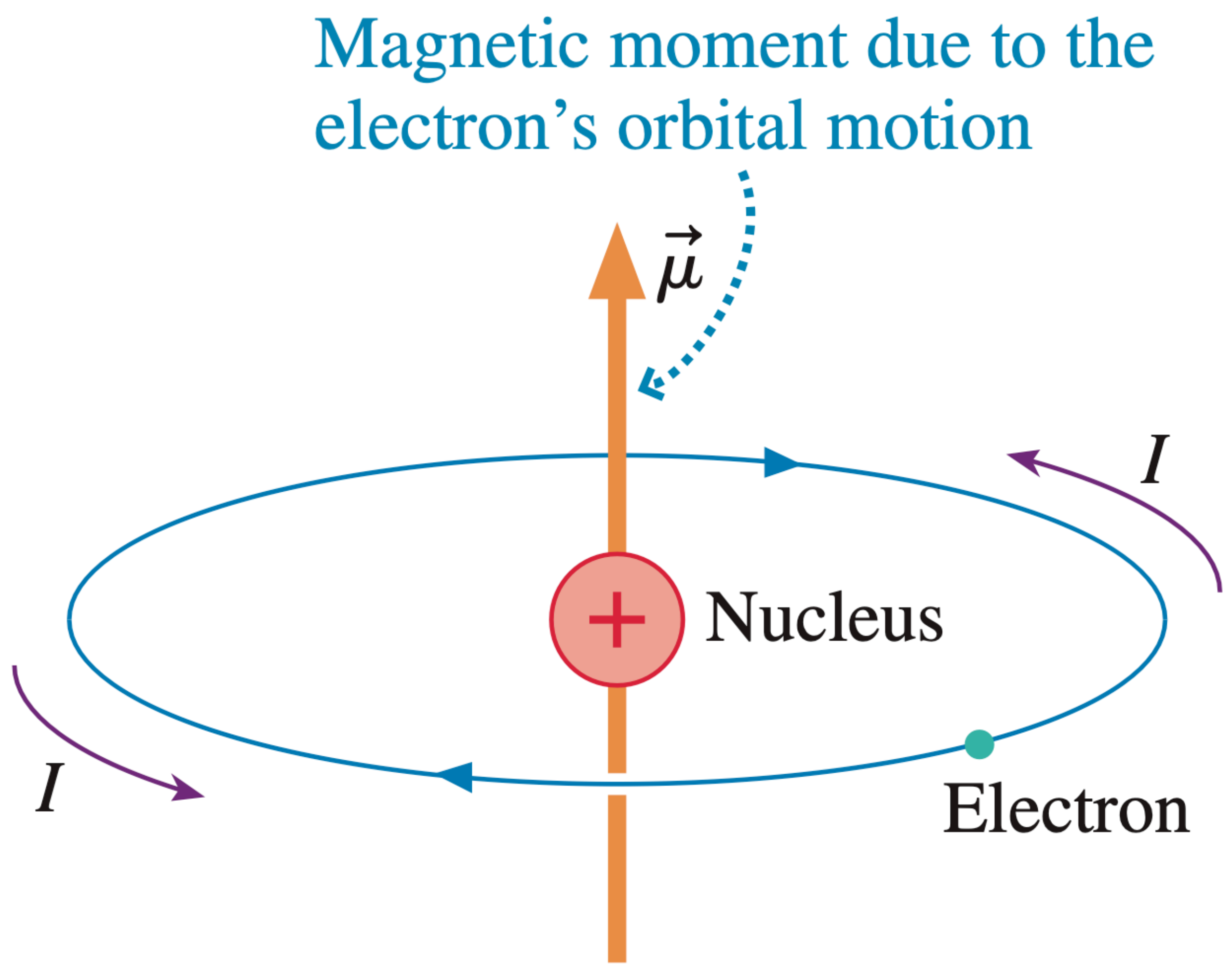
- Electron Orbital Motion vs. Intrinsic Spin
- Ferromagnetism, including magnetic domains
- Review of earlier material
    - Questions?
    - Example problems

Orbital vs. Intrinsic Magnetic Moments

Two weak sources of magnetism present in all kinds of materials (not just for ferromagnetic materials, i.e., Fe/Ni/Co at room temp):

Very very weak (not strong): electron orbits

FIGURE 29.50 A classical orbiting electron is a tiny magnetic dipole.



Very weak (lots of cancellations): electron spin

FIGURE 29.51 Magnetic moment of the electron.

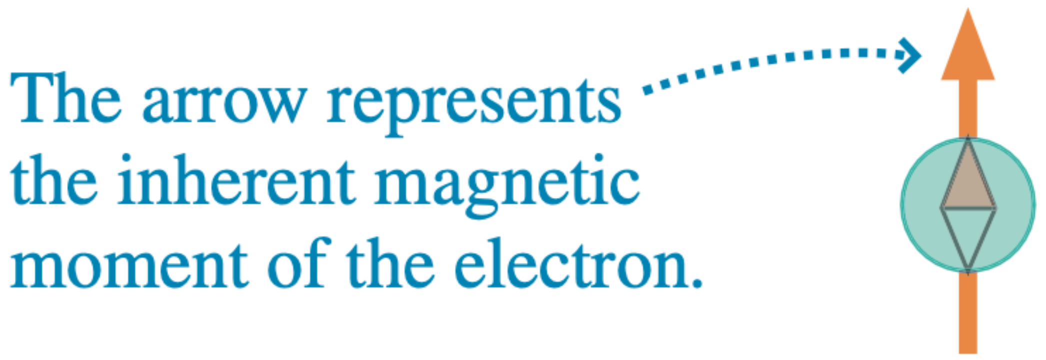
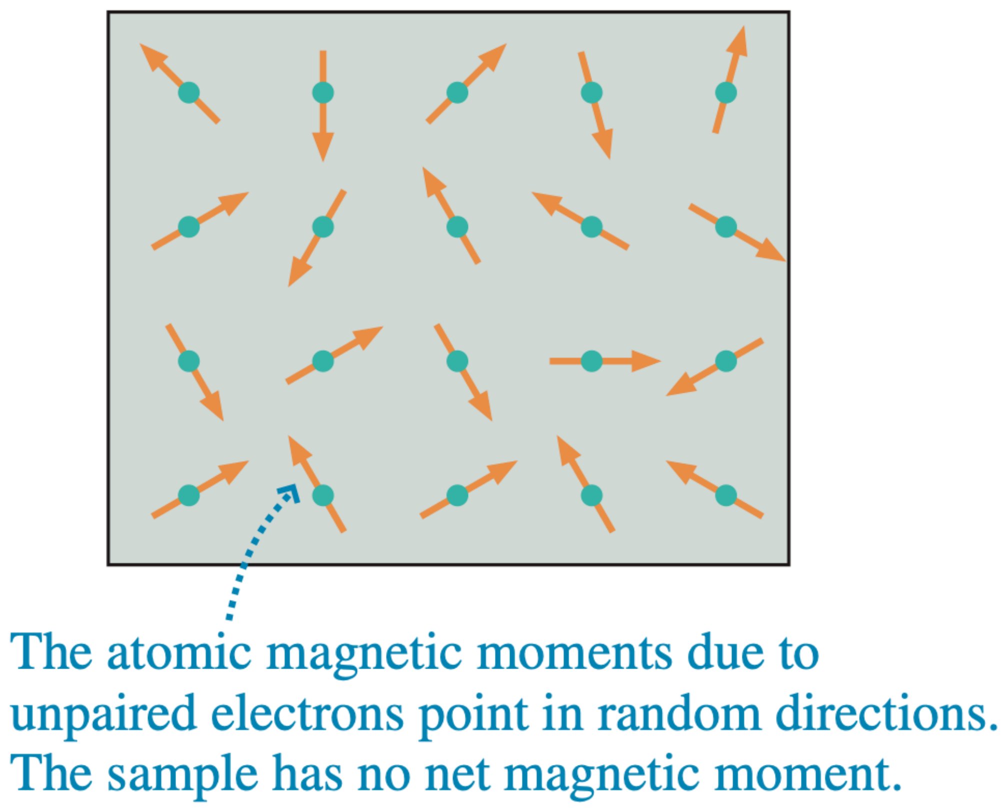


FIGURE 29.52 The random magnetic moments of the atoms in a typical solid.

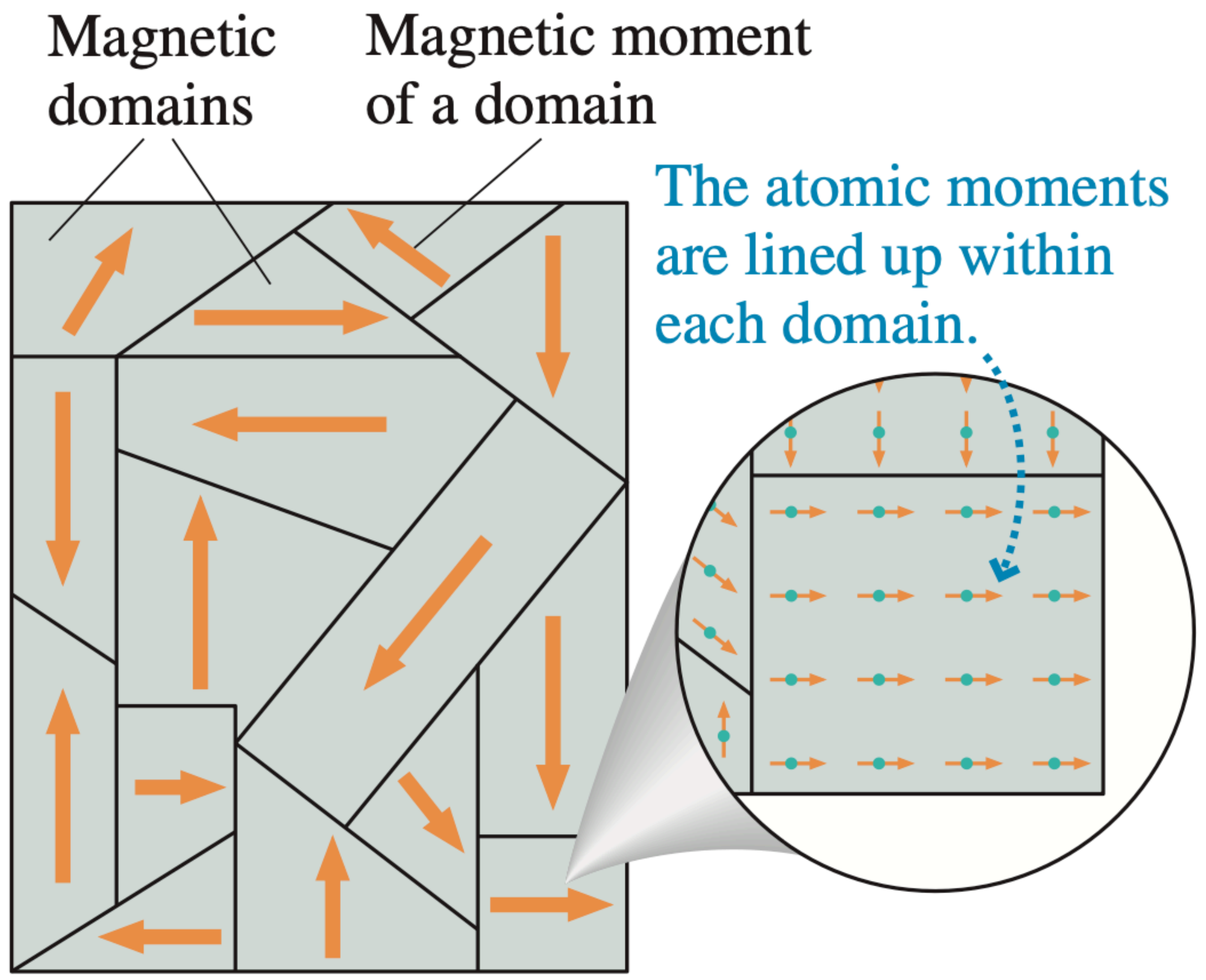


Ferromagnetism: Materials where it's possible for the electron spins to line up

What makes Fe/Ni/Co special (at room temperature) is that the electrons tend to line up with their nearest neighbors, forming "magnetic domains" of size small compared to what we can see, but large compared to the size of an atom.

For example, one domain is maybe a billion or a trillion spins lined up — large compared to one spin, but small compared to Avogadro's number.

FIGURE 29.54 Magnetic domains in a ferromagnetic material. The net magnetic dipole is nearly zero.

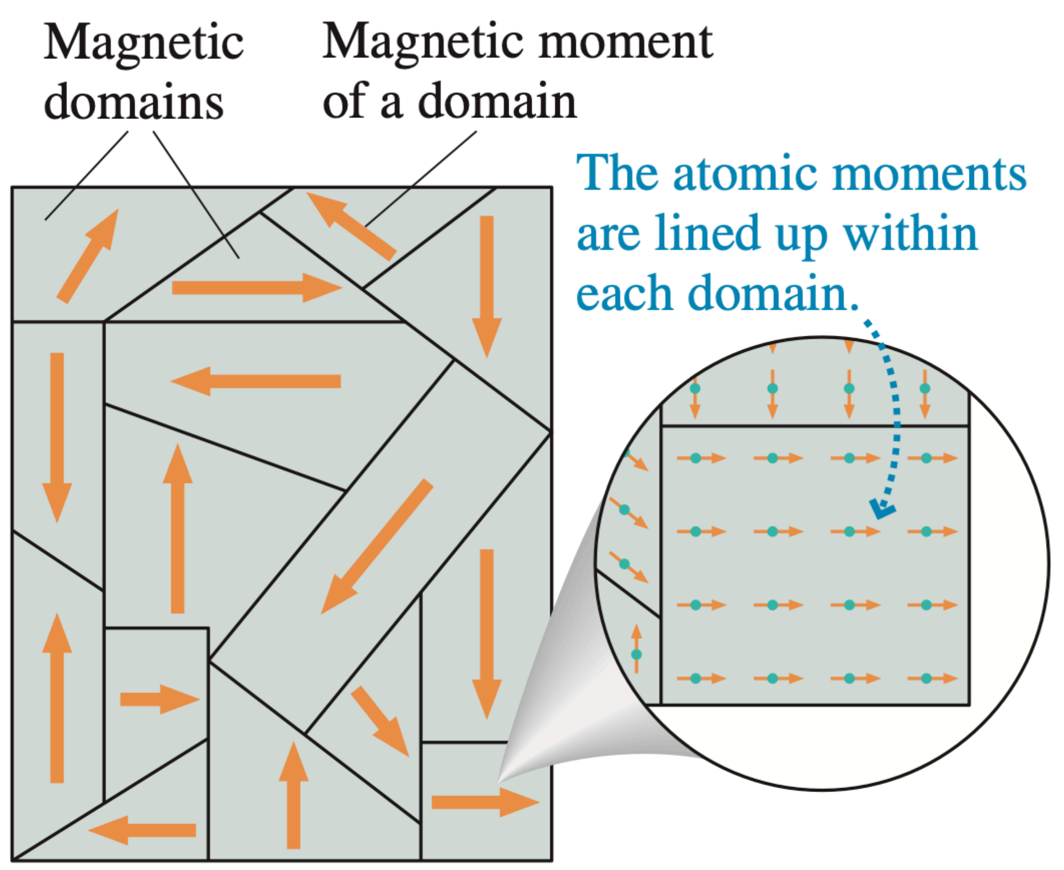


We can make a permanent magnet by getting the magnetic domains to line up with each other.

Clicker/Poll Question

A material has magnetic domains with directions indicated. Which of the following is probably the object?

FIGURE 29.54 Magnetic domains in a ferromagnetic material. The net magnetic dipole is nearly zero.



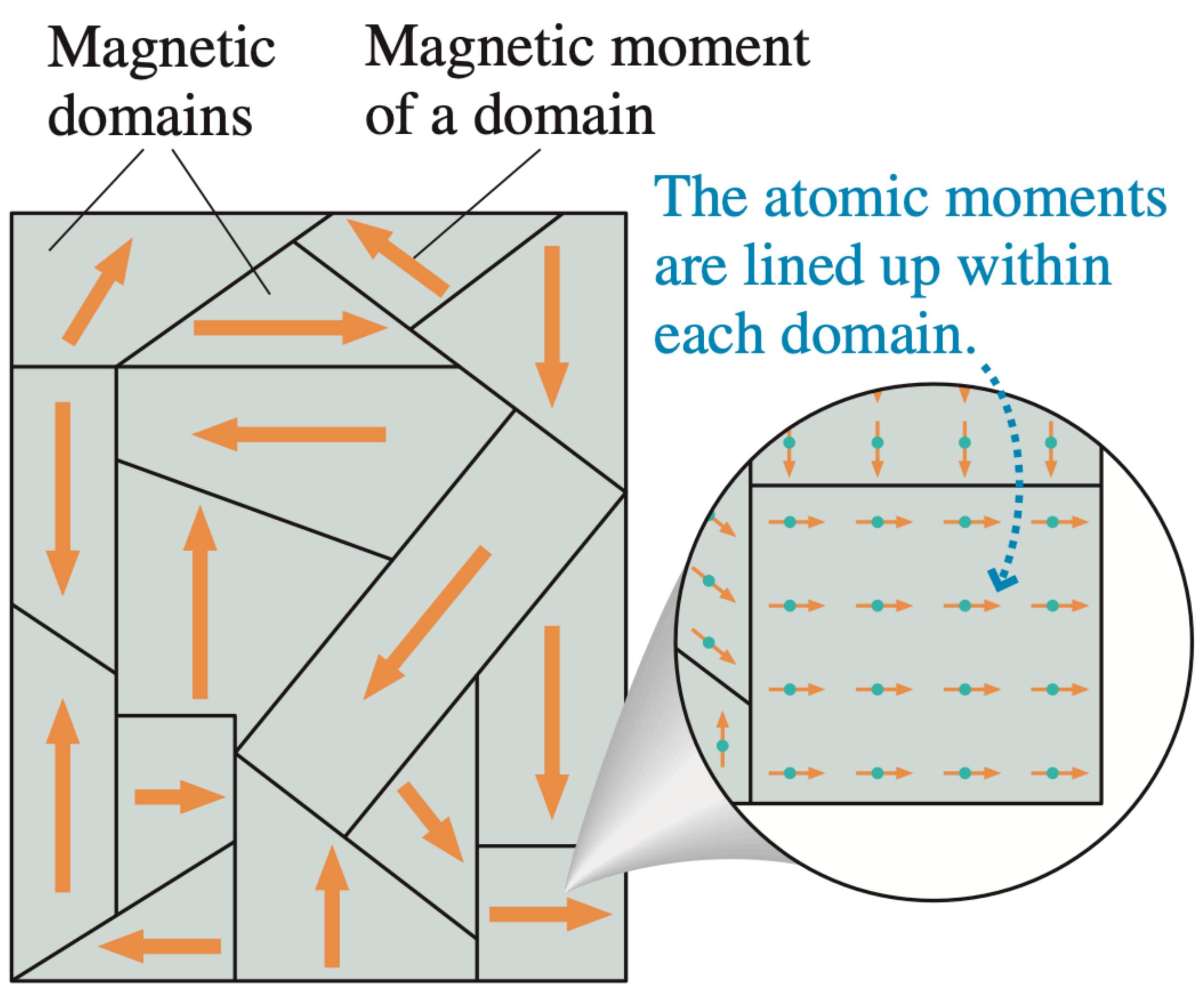
A. Zinc (no unpaired electrons)
B. Titanium (unpaired electrons, but not ferromagnetic)
C. An unmagnetized Nickel paperclip
D. A magnetized Iron bar magnet
E. ???

Why is a paperclip attracted to a magnet?

If you put a permanent magnet near a paperclip, the domain walls move a little bit, so that domains with spins parallel to the ext. B-field grow in size, and those with spins antiparallel shrink.

This leaves a net induced dipole moment on the paperclip that is attracted to the bar magnet.

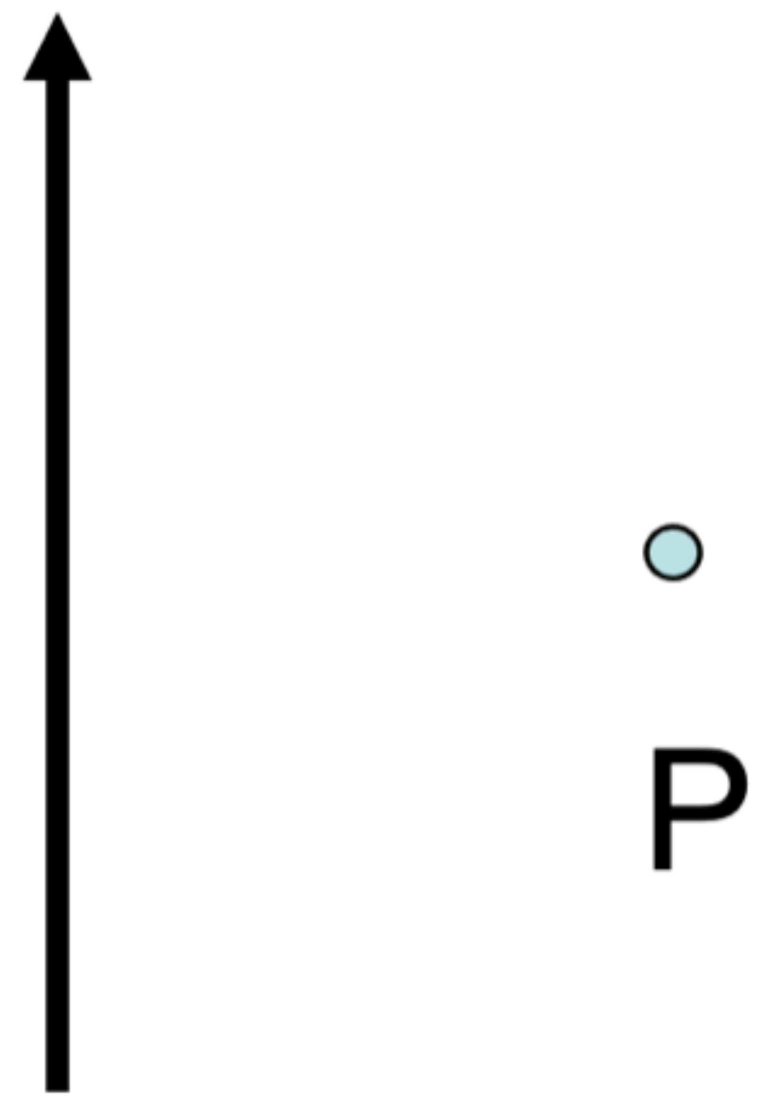
FIGURE 29.54 Magnetic domains in a ferromagnetic material. The net magnetic dipole is nearly zero.



Clicker/Poll Question

A proton moves into the screen at point P.
What is the direction of the force on the proton?

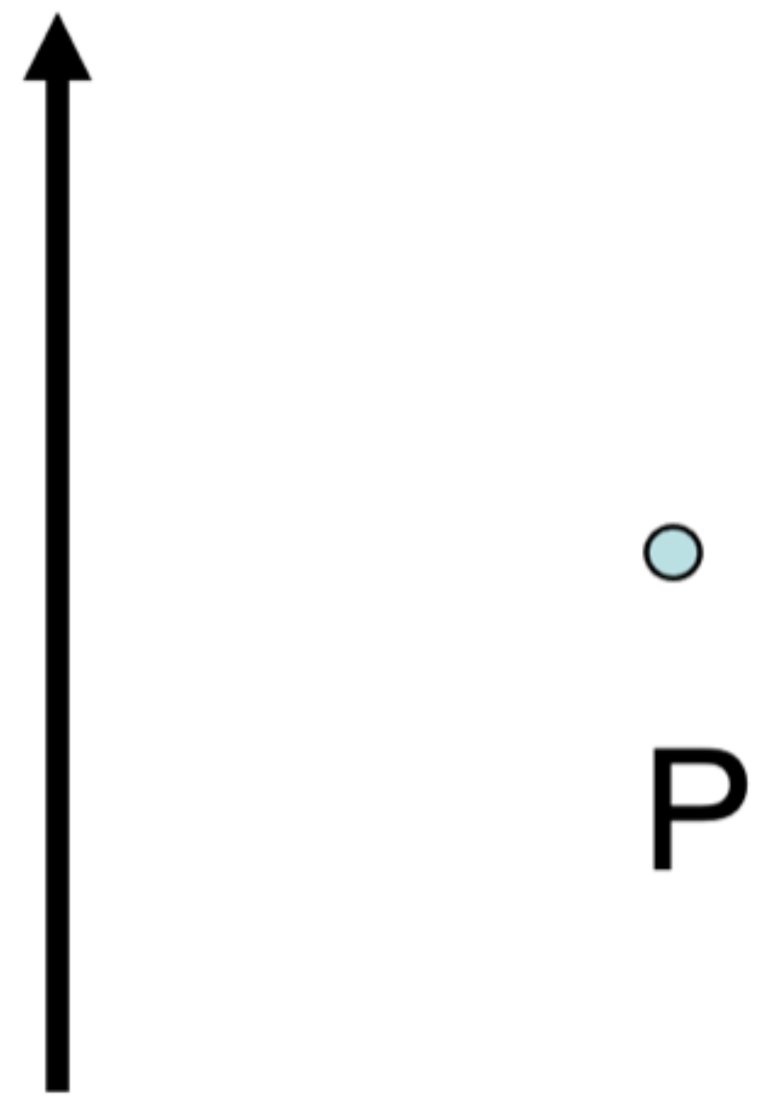
A. Into the page
B. Out of the page
C. Left
D. Right
E. (There is no magnetic field at point P)



Clicker/Poll Question

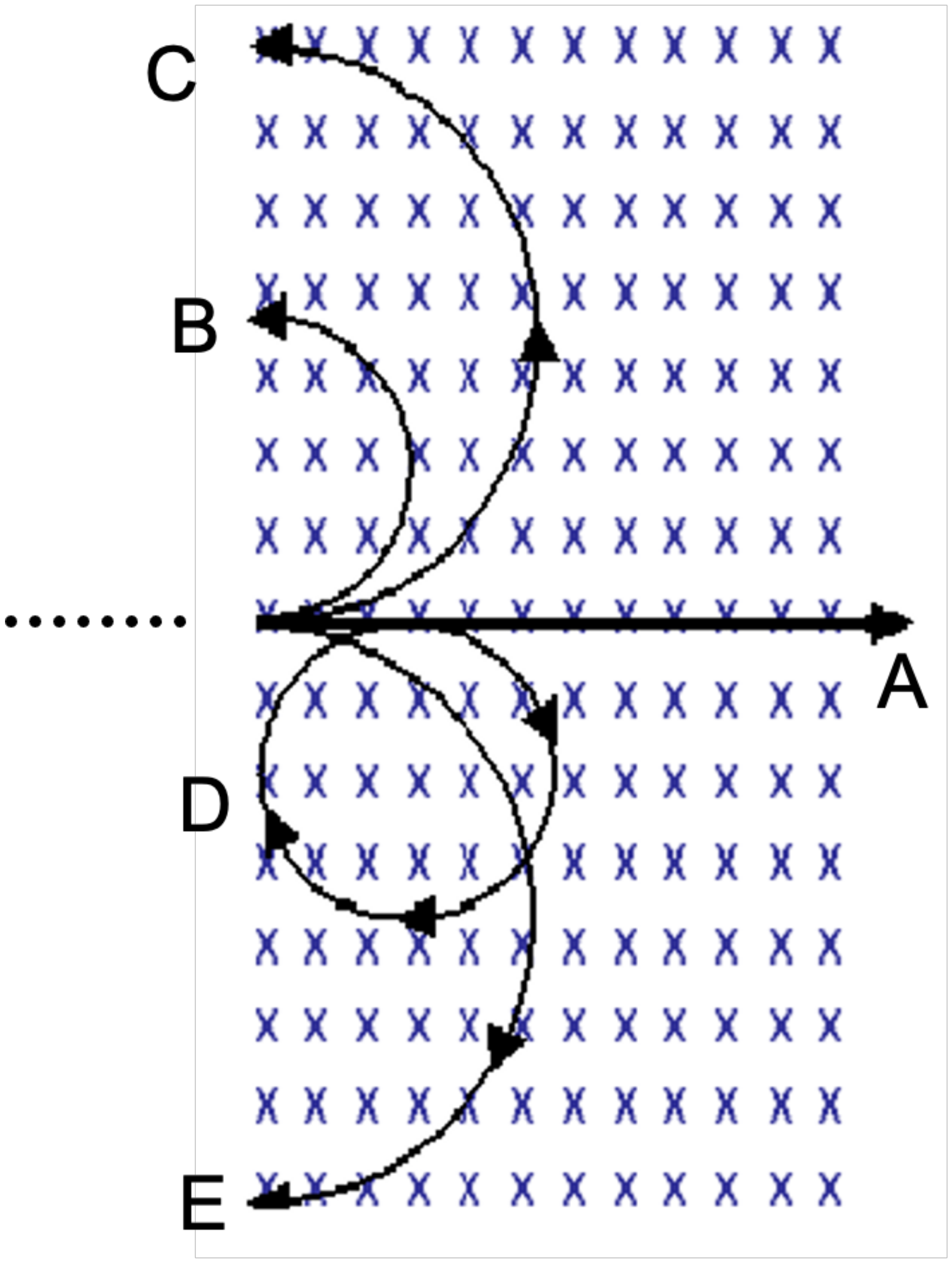
An electron moves upwards at point P.
What is the direction of the force on the electron?

A. Into the page
B. Out of the page
C. Left
D. Right
E. (There is no magnetic field at point P)



Clicker/Poll Question

A proton enters a magnetic field and follows trajectory B. An alpha particle (twice the charge and 4 times the mass) enters the same magnetic field in the same way and with the same velocity as the proton. Which of the following is the right trajectory for the alpha?

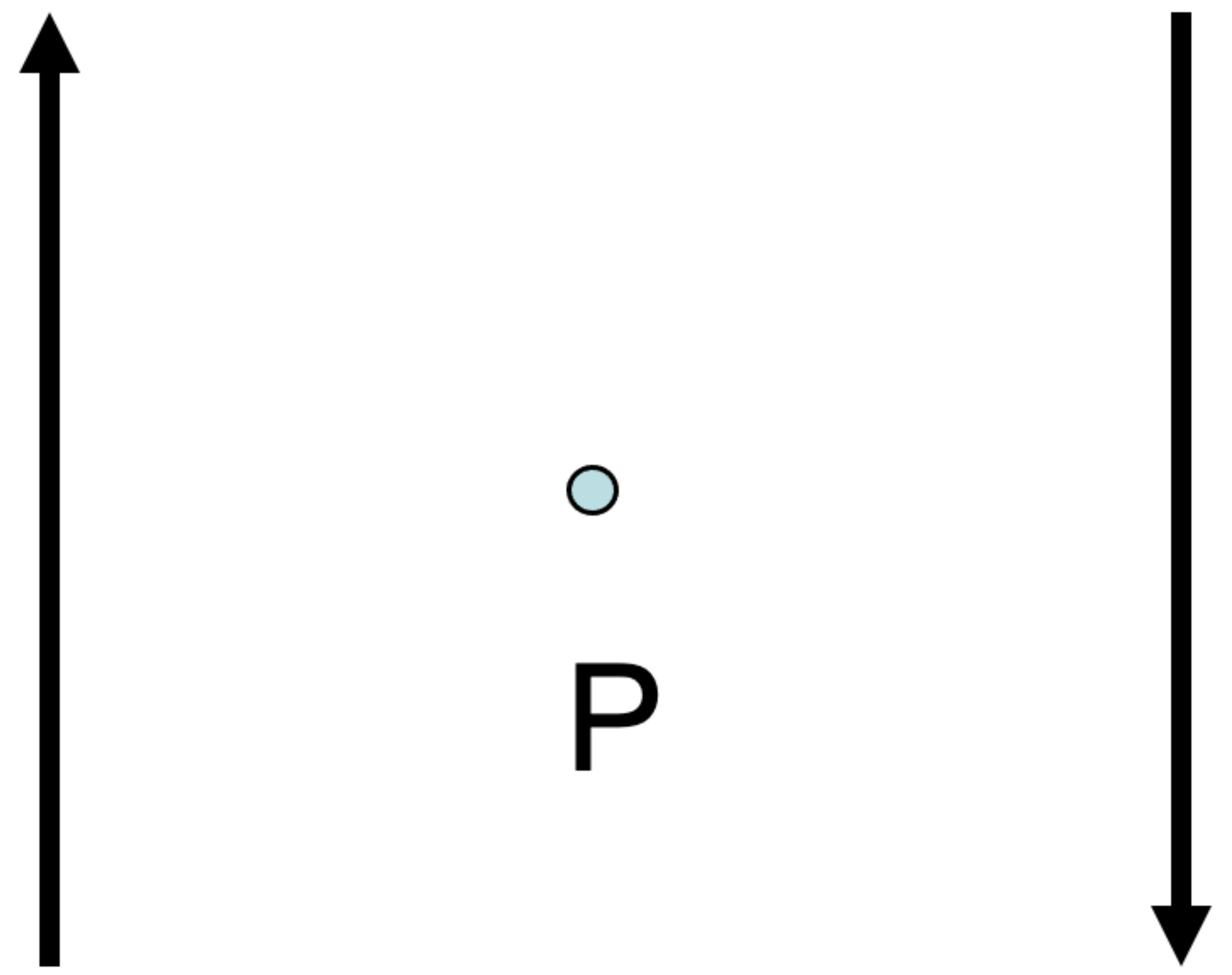


Try it yourself…

Given the mass of the alpha particle in the last problem is $4m_p$, and given that it has charge $+2e$, find how long the particle spends in the magnetic field region in the previous clicker

Clicker/Poll Question

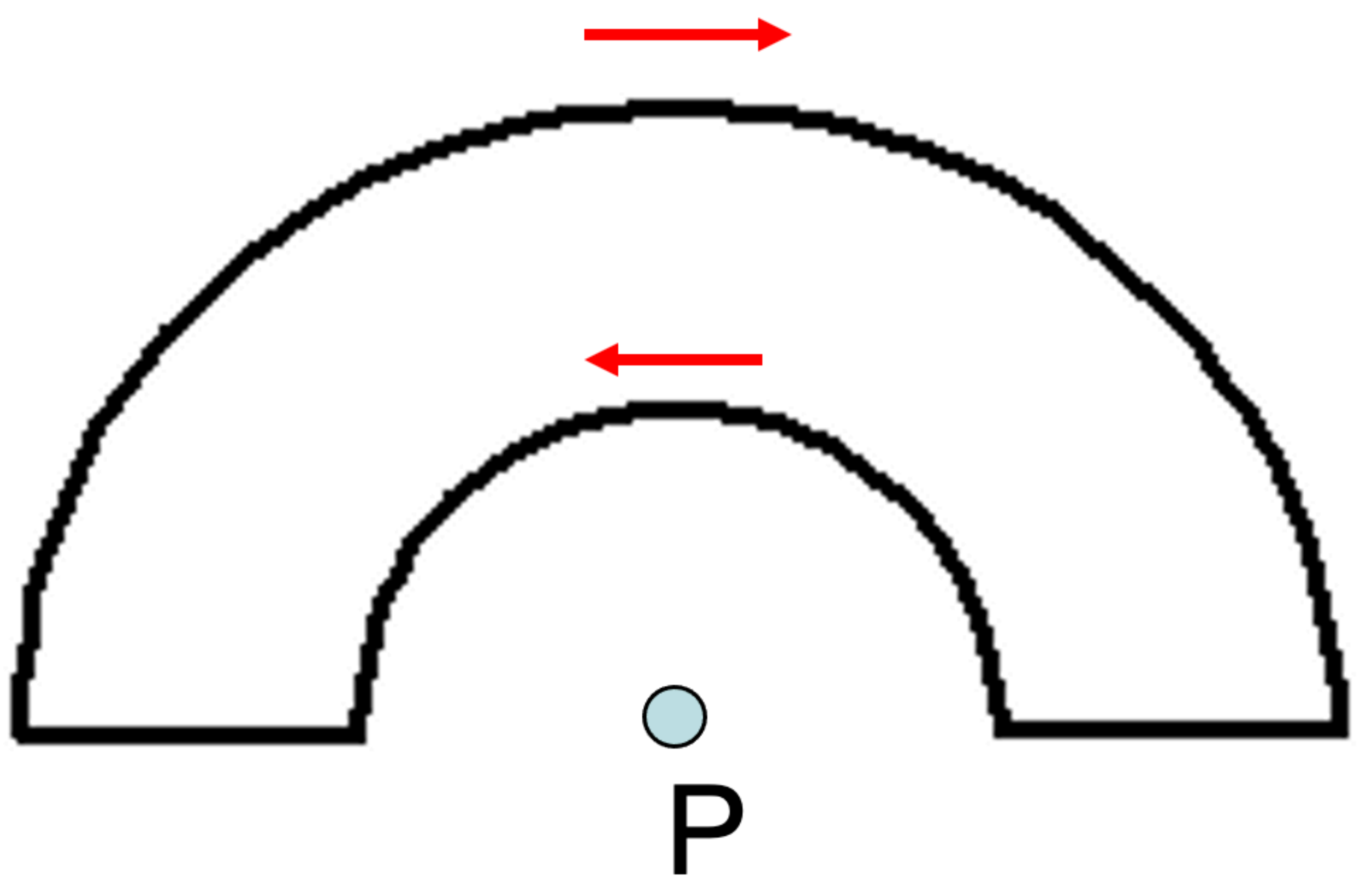
What is the direction of the magnetic field at point P, which is exactly in the middle of two parallel wires carrying equal currents I in opposite directions?



A. Into the page
B. Out of the page
C. Left
D. Right
E. (There is no magnetic field at point P)

Clicker/Poll Question

What is the direction of the magnetic field at point P, which is at the center of a semicircular loop of wire carrying a current I as shown?



A. Into the page
B. Out of the page
C. Left
D. Right
E. (There is no magnetic field at point P)

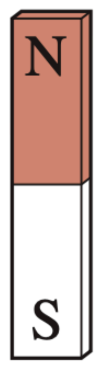
Try it yourself…

A current-carrying wire of radius R has current I uniformly distributed on its surface. Find the magnetic field everywhere.

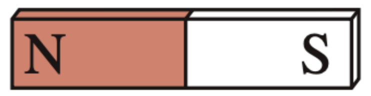
Clicker/Poll Question

Suppose you had two bar magnets (A and B) oriented as shown. What is the direction of the torque on each magnet? *Hint: how do you find the torque on a magnetic moment?*

A



B



A. $\boldsymbol{\tau}_A$ is into the screen; $\boldsymbol{\tau}_B$ is to the right.

B. $\boldsymbol{\tau}_A$ is into the screen; $\boldsymbol{\tau}_B$ is to the left.

C. $\boldsymbol{\tau}_A$ is to the left; $\boldsymbol{\tau}_B$ is out of the screen.

D. $\boldsymbol{\tau}_A$ is to the right; $\boldsymbol{\tau}_B$ is out of the screen.

E. (None of the above is totally correct.)