B10 · Fields around currents

Completed notes

Use the right-hand rules for a straight wire, a loop and a solenoid.

Slide 1 of 6 · Currents make magnetic fields

In 1820 Oersted found that a compass near a wire turns only while the wire carries a **current**. The cause is **moving charge**: every moving charge has its own magnetic field, and in a wire the fields of billions of electrons add up. Current has symbol **I** and is measured in **amperes (A)**. One ampere is one **coulomb** of charge passing a point each **second**.

Conventional current is the way positive charge would move: out of the **positive** terminal (the positive plate of the battery), through the wire and back to the negative terminal. **Electron** flow is the real motion in a metal and points the **opposite** way.

This course uses **conventional** current for every hand rule, unless the question says otherwise.

Into the page is drawn as a circle with a **cross**. Out of the page is drawn as a circle with a **dot**. On the diploma: if a question says “electrons”, convert to conventional current **before** you apply a hand rule.

Example. A battery is in the middle of the bottom wire of a rectangular circuit, with its positive plate on the left and its negative plate on the right. Along the top wire, which way does conventional current flow, and which way do the electrons flow?

1. Conventional current leaves the positive plate on the left, goes up the left side and then along the top wire from left to right.

2. Electrons move the opposite way, from right to left along the top wire.

Try it. In a straight wire on the page, electrons flow down the page. Which way does conventional current flow? A compass beside the wire turns when the battery is connected and settles back when it is disconnected. What does that show?

1. Conventional current is opposite to the electron flow, so it flows up the page.

2. The compass turns only while there is a current. This shows that a moving charge (a current) makes a magnetic field.

Slide 2 of 6 · The right-hand rule for a straight wire

The field of a straight wire is a set of **circles** around it (look at the dot or cross picture for end-on views). Grip the wire loosely with your **right** hand, with your **thumb** along the conventional current. Your curled **fingers** show the direction of the field.

If the thumb points up the page, the fingers move across to the **right** in front of the wire and to the **left** behind it. So a point to the right of the wire has the field **into** the page and a point to the left has it **out of** the page. Thumb down reverses both. Thumb right gives **out of** the page above the wire and **into** the page below; thumb left reverses those.

The circles are closer together near the wire, so the field is **stronger** there. End-on means you look straight along the wire, so it looks like a dot or cross. With the current out of the page, the thumb points at you and the circles go **counterclockwise**.

At any point the field is **tangent** to the circle through that point. On the diploma: a wrong choice uses the **left** hand or the **electron** direction.

Example. A long wire lies in the plane of the page. Conventional current flows through it from left to right. P is a point above the wire and Q is a point below it, both in the plane of the page. At P and at Q, is the magnetic field into the page or out of the page?

1. Point the right thumb to the right, along the current.

2. At P (above the wire) the fingers curl toward you, so the field is out of the page.

3. At Q (below the wire) the fingers curl away from you, so the field is into the page.

Try it. A wire is seen end-on and its electrons flow into the page. R is a point to the right of the wire and S is a point directly above it, both in the plane of the page. Which way does the magnetic field point at R and at S: up, down, left, right, into the page or out of the page?

1. Electrons flow into the page, so conventional current is out of the page. The right thumb points toward you and the field circles are counterclockwise.

2. Picture a clock face with the wire in the middle: R is at 3 o’clock, where a counterclockwise circle goes up, so the field points up the page.

3. S is at 12 o’clock, where a counterclockwise circle goes left, so the field points left.

Slide 3 of 6 · Loops add their fields

Bend a straight wire into a loop and every piece of wire adds a field through the middle that points the **same** way. Fields are vectors, so adding them gives a **strong** field inside the loop. Outside the loop the field is weaker and points the other way. If the current in the loop is counterclockwise, the field in the middle is **out of** the page (check: on top of the loop the current goes left, so thumb left puts the field below that wire, inside the loop, out of the page).

The field B of a solenoid depends on the current I (amperes, A) and on the number of turns N. Both are direct proportions: B ∝ **I** and B ∝ **N**. The sign ∝ means “is directly proportional to”: if one doubles, the other doubles. B is in **tesla (T)**.

A **smaller** radius makes the field at the middle stronger, because the wire is **closer** to the middle. A coil of many turns is called a **solenoid**.

When two quantities change at once and both are direct proportions, the factors **multiply**. On the diploma: “in terms of B” answers look like **6B** or B/2, so write each factor out.

Example. A solenoid with a given current and number of turns makes a magnetic field of strength B at its centre. The current is doubled and the number of turns is multiplied by three. What is the new field, in terms of B?

1. The field is directly proportional to current, so doubling the current gives 2B.

2. The field is also directly proportional to the number of turns, so tripling the turns multiplies by 3 again.

3. The new field is 2 × 3 × B = 6B.

Try it. Two flat circular coils carry the same current and have the same number of turns. Coil X has radius 4.0 cm and coil Y has radius 2.0 cm. Which coil has the stronger field at its centre, and why?

1. Coil Y has the stronger field at its centre.

2. Its wire is closer to the centre, and the field of a current is stronger closer to the wire. Current and turns are the same, so the radius is the only difference.

Slide 4 of 6 · Poles of a solenoid and an electromagnet

To find the north pole of a solenoid, grip a wire on the **front** of the coil with your **right** hand, with your thumb along the **conventional** current. Look at where your fingers go on the **inside** of the coil.

The field inside points toward the **north** end, because field lines leave a north pole. If the thumb points up on the front wires, that is the “behind the wire” case of the straight-wire rule: the fingers move **left**, and inside the coil is behind the front wire. So the field inside runs left and the **left** end is the north pole.

An air-core solenoid has just air inside. An **electromagnet** has an **iron** core: the coil’s field lines up the **domains** in the iron, so the magnet is much stronger. Turn off the current and the domains go back to random.

More current, more turns or a smaller radius also make it stronger. On the diploma: the **winding** and the current direction set the pole, not the terminal label. Trace the current from the **positive** plate first.

Example. A solenoid is wound the opposite way to the one in the slide. The positive plate of the battery is on the left and the leads go to the top of the coil. In which direction does the conventional current flow in the wires on the front of the coil, and which end of the solenoid is the north pole?

1. Starting at the left (positive) lead, the current enters at the top-left and goes down through the front wires.

2. With the thumb pointing down, the fingers inside the coil point right, so the right end is the north pole.

Try it. A solenoid with an iron core is wound with its front wires slanting up. This time the positive plate of the battery is on the right. (In the first example the positive plate was on the left and the front current went up.) Which end of the electromagnet is the north pole, and what two changes would make it stronger?

1. The positive plate is on the right, so the current reverses. The front wires carry conventional current down and the field inside points right.

2. The right end is the north pole.

3. Make it stronger with more current or more turns (or a smaller radius).

Slide 5 of 6 · Method: which right-hand rule do I use?

Step 1: convert to **conventional** current. If the question gives electron flow, **reverse** it. A moving negative charge counts as current the other way.

Step 2: name the shape: a straight **wire**, one moving **charge**, or a **coil**.

Step 3: make the grip with your **right** hand. Wire or charge: **thumb** along the current. Coil: grip one **front** wire, thumb along its current.

Step 4: read the **fingers**. Wire or charge: they curl the way the field goes around it. Coil: inside the coil they show the field, and the end the field leaves is **north**.

Check: right hand, conventional current in the thumb. Electron flow in the thumb reverses your answer. On the diploma: a wrong choice uses the **left** hand or the **electron** direction.

Example. A wire is seen end-on and its electrons flow into the page. R is a point to the right of the wire and S is a point directly above it, both in the plane of the page. Which way does the magnetic field point at R and at S?

1. Step 1: electrons flow into the page, so conventional current comes out of the page.

2. Steps 2 and 3: this is a straight wire. Make the right-hand grip with the thumb pointing out of the page, toward you.

3. Step 4: the fingers curl counterclockwise. R is at 3 o’clock, where a counterclockwise circle goes up, so the field at R points up the page. S is at 12 o’clock, where it goes left, so the field at S points left.

Try it. NEW, for teacher review. In a long vertical wire on the page, electrons flow down the page. Point U is to the left of the wire, in the plane of the page. Which way does the magnetic field point at U: into the page or out of the page?

1. Step 1: electrons flow down, so conventional current flows up the page.

2. Steps 2 and 3: a straight wire. Make the right-hand grip with the thumb pointing up.

3. Step 4: with the thumb up, the fingers move across to the right in front of the wire and to the left behind it. A point to the left of the wire has the field out of the page.

4. Check: right hand, and conventional current (not electron flow) in the thumb.

Slide 6 of 6 · How much charge flows? Current is charge per time

Current is charge per time: I = **q ÷ t**, so q = **It**. I is in **amperes**, q is in **coulombs** and t must be in **seconds**.

To count electrons, divide the charge by the charge of one electron: n = **q ÷ e**, with e = **1.60×10^{-19} C**.

To go the other way, from a count to a charge, **multiply**: q = **n × e**. Then divide by the time to get the **current**.

On the diploma: the number of electrons is a **count**, so it is a whole number or a power of ten, never a fraction of an electron.

Example. A wire carries a current of 2.5 A for 4.0 s. Find the charge that passes a point in the wire and the number of electrons. ($e = 1.60 \times 10^{-19}$ C)

1. q = It = (2.5 A)(4.0 s) = 10 C.

2. n = q ÷ e = 10 ÷ (1.60×10^{-19}) = 6.25×10^{19} electrons.

Try it. NEW, for teacher review. A wire carries 3.20×10^{19} electrons past a point in 2.0 s. Find the current. ($e = 1.60 \times 10^{-19}$ C)

1. q = ne = (3.20×10^{19})(1.60×10^{-19} C) = 5.12 C.

2. I = q ÷ t = 5.12 C ÷ 2.0 s = 2.56 A.

B10 · Worked practice

Fields around currents | Questions 1-2 of 8

Constants from the Alberta Physics 30 data sheets: $k = 8.99 \times 10^{9}$ N·m²/C², $e = 1.60 \times 10^{-19}$ C, electron mass $m_e = 9.11 \times 10^{-31}$ kg, proton mass $m_p = 1.67 \times 10^{-27}$ kg, $g = 9.81$ m/s².

Easy · B10-N01. Electrons flow through a wire from left to right. Which statement is correct?

A. Conventional current flows left to right, the same as the electrons.

B. Conventional current flows right to left, and we use the right-hand rule for conventional current.

C. Conventional current flows right to left, and we use the left-hand rule for electrons.

D. There is no current because electrons are very small.

1. Givens: electron flow left → right. Question: direction of conventional current.

2. Conventional current is the flow of positive charge, so it is opposite to the electron flow: right → left. The course uses conventional current with the right hand.

3. Answer: B. Conventional current flows right to left, and we use the right-hand rule for conventional current.

Easy · B10-N02. Conventional current flows up the page in a long vertical wire. Is the magnetic field into the page or out of the page (a) to the right of the wire, and (b) to the left of the wire?

1. Givens: current up the page. Question: field direction at the right and at the left.

2. Grip the wire with the right hand, thumb up the page. In front of the wire the fingers move to the left; behind it they move to the right.

3. So the field is into the page at a point to the right of the wire, and out of the page at a point to the left.

B10 · Worked practice

Fields around currents | Questions 3-4 of 8

Easy · B10-N03. Conventional current goes to the right in a horizontal wire in the plane of the page. At a point above the wire, the field points

A. into the page
B. up the page
C. to the right
D. out of the page

1. Givens: current right; point above the wire. Question: field direction.

2. Right thumb to the right; above the wire the fingers curl out of the page. Check: below the wire the field is into the page.

3. Answer: D. out of the page

Medium · B10-N04. Electrons flow from right to left along a long horizontal wire in the plane of the page. What is the direction of the field at a point below the wire?

1. Givens: electrons right → left. Question: field below the wire.

2. Conventional current flows left → right. Thumb to the right.

3. Below the wire the fingers curl into the page. The field is into the page.

B10 · Worked practice

Fields around currents | Questions 5-6 of 8

Medium · B10-N05. A solenoid’s current is doubled while the number of turns is cut in half (the solenoid keeps the same length). What happens to the field at the centre?

A. It doubles.

B. It stays about the same.

C. It is cut to one quarter.

D. It becomes four times larger.

1. Givens: I × 2; N ÷ 2; same length. Question: change in B.

2. The field depends on the number of turns times the current (per length). 2 × ½ = 1, so the field is unchanged.

3. Answer: B. It stays about the same.

Medium · B10-N06. A coil with an iron core has conventional current going down in the wires on the front of the coil. Which end is the north pole? Why does the iron help?

1. Givens: current down on the front. Question: north pole; role of iron.

2. Grip a front wire with the right hand, thumb down along the current. Inside the coil, behind the wire, the fingers point to the right.

3. The field inside runs right, so field lines leave from the right end: the right end is the north pole.

4. The iron’s domains line up in the coil’s field, adding their own field and making the magnet much stronger.

B10 · Worked practice

Fields around currents | Questions 7-8 of 8

Challenging · B10-N07. A proton moves to the right across the page. At a point above its path, its magnetic field points

A. into the page
B. up the page
C. to the left
D. out of the page

1. Givens: proton moving right. Question: field above the path.

2. A moving proton is a conventional current to the right. Same as a wire with current to the right: above, the field is out of the page.

3. Answer: D. out of the page

Challenging · B10-N08. Using the same moving charge, say what changes if an electron moves to the right instead, and why.

1. Givens: an electron moving right. Question: what changes.

2. An electron moving right is conventional current to the left.

3. The field direction reverses: into the page above the path.