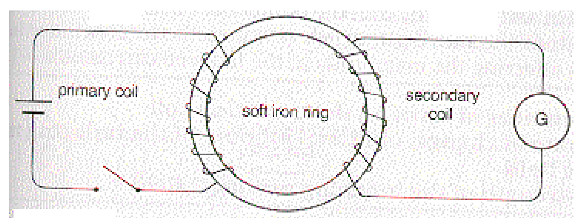
Physics 30 Lesson 22 The Generator Effect

I. Electromagnetic induction – Michael Faraday

Refer to Pearson pages 609 to 620 for a conceptual discussion of electromagnetic induction and the generator effect. Pay particular attention to the technologies described on pages 614 and 615.

In 1821, Michael Faraday invented the first electric motor. He publicly stated that if current had an effect on magnetism, then magnetism might have a corresponding effect on current. Faraday began to investigate the possibilities, but it would be ten years before the phenomena would be successfully demonstrated.

In the early months of 1831, Joseph Henry would be the first to observe the phenomenon at Albany, New York. He did not publish his results because he was working in an American College where teaching responsibilities came first and research second. He intended to publish his results in the summer months. Henry would soon regret his decision, as Faraday finally made the breakthrough himself in England. Faraday immediately published his results and is historically credited as the first man to successfully demonstrate **electromagnetic induction** or the **generator effect**.



Faraday discovered the generator effect while he was working with an iron ring apparatus as diagrammed to the right. He found that while a constant current was flowing in the left side (primary) coil no current was generated in the right side (secondary) coil. Then one day he noticed that there was a short lived current in the secondary coil as the primary coil was being turned on or turned off.

Faraday concluded that the turning on of the current in the primary coil caused a magnetic field to be **induced** or built up inside the iron ring and around to the secondary coil. This **changing magnetic field** would cause an **induced current** to be **generated** in the secondary coil. Once the current in the primary coil was constant, there could no longer be a **changing** magnetic field in the secondary coil and no current could be generated in the secondary coil. When the current in the primary coil was turned off, the magnetic field would collapse. This changing magnetic field would generate a current in the secondary coil, but in the opposite direction.

The key element necessary for the generator effect was a **changing** (or moving) magnetic field.

After further experiment, Faraday found that the iron ring was not necessary – the phenomena would occur with just two coils in close proximity. Faraday concluded that the magnetic field traveled through the air from the first coil to the second coil. As we shall see, James Clerk Maxwell would use this observation to show that light energy was in fact electromagnetic wave energy (see Lesson 24).

Faraday discovered the basic principles of electromagnetic induction. He experimented with three basic situations:

1. Moving a wire through the jaws of a horseshoe magnet.
   - ⇒ Electron flow occurred only when the conductor was moving.
   - ⇒ The direction of electron flow depended on the direction of movement of the wire.
   - ⇒ Multiple loops of wire multiplied the voltage produced.

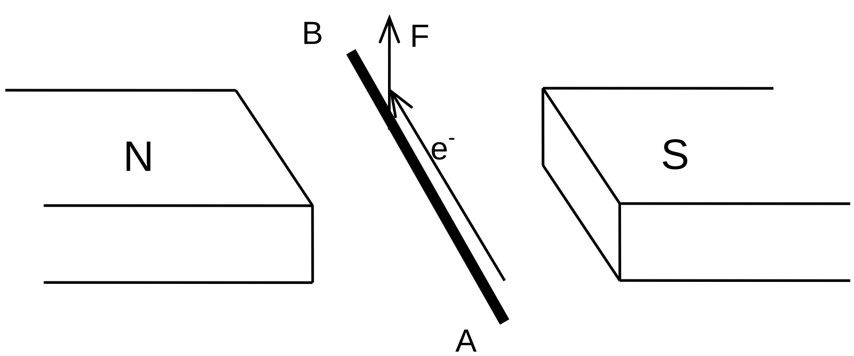
2. Plunging a bar magnet into and out of the core of a solenoid.
   - ⇒ The relative motion of the magnet and the coil produced a current in the coil wire.

3. Touching the iron core of a coil with a bar magnet and then removing the magnet.
   - ⇒ Electron flow occurred only when the core was *becoming* magnetized or demagnetized.
   - ⇒ A changing magnetic field produced a current.

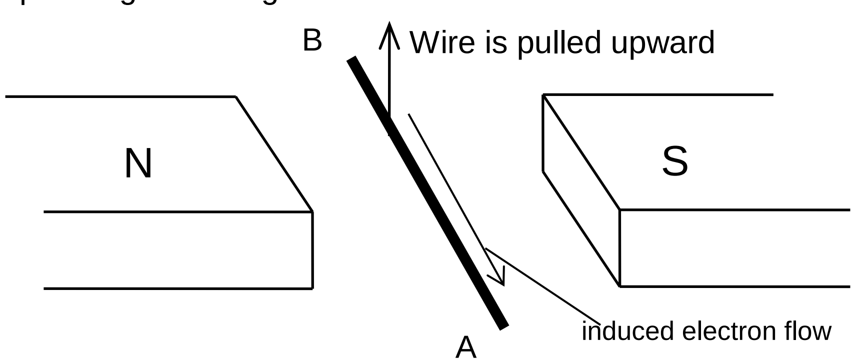
Faraday's Law of Electromagnetic Induction

A changing magnetic field induces a current in a conductor.

How does the generator effect compare with the motor effect? Consider the diagram below. If the **motor effect** is applied and electrons flow from A to B then the left flat hand rule indicates that the primary motion (electron flow into the page) causes a secondary motion (an upward force on the wire). This is the normal motor effect.



What happens if we **disconnect the power source** from the wire and then **pull the wire** up through the magnetic field?



The **generator effect** comes into play because we have a conductor moving through a magnetic field. When we measure the induced electron flow we find that it is opposite (from B to A) to the motor effect.

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II. Lenz's Law

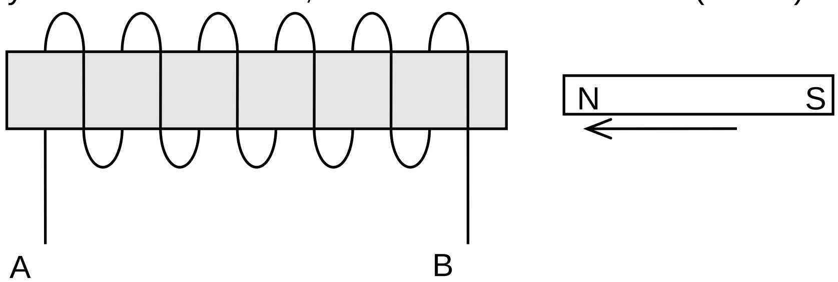
Heinrich F. Lenz was a German physicist who was investigating electrical induction about the same time as Faraday. In 1834, Lenz formulated a law for determining the direction of the induced current:

Lenz's Law

An induced current flows in such a direction that the induced magnetic field it creates opposes the action of the inducing magnetic field.

If you find this statement of Lenz's law confusing, you are not alone. The problem stems from the number of events which are occurring simultaneously. This may best be explained using an example.

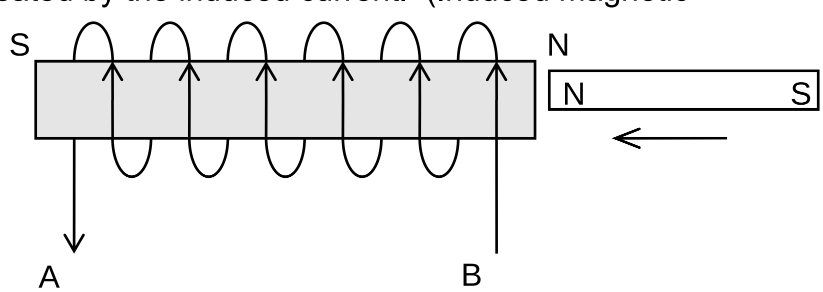
If the North pole of a magnet is pushed into a coil as indicated in the diagram below, which way will the current flow, and which end of the wire (A or B) will be positive?



According to Faraday's law of induction, a current will be induced in the coil wire by the motion of the bar magnet into the coil. However, as we learned in Lesson 19, a current through a coil of wire induces a magnetic field. Therefore, the induced current in the coil will, in turn, produce a **new induced magnetic field** in the coil. And, according to Lenz's law, the induced magnetic field of the coil will oppose the original inducing magnetic field.

Three distinct phenomena are involved in the process of electromagnetic induction, and they must be clearly distinguished:

1. The action of the "inducing field". (In this case, the bar magnet.)
2. The resulting "induced current". (The induced current in the coil.)
3. The "induced magnetic field" created by the induced current. (Induced magnetic field of the coil.)



Returning to the problem at hand, the solenoid will have an induced magnetic field which opposes the inducing magnetic field (the bar magnet). Therefore, we indicate that a north pole will be induced on the right end of the solenoid since it will oppose the motion of the bar magnet. Using our left hand rule for wires and solenoids, the thumb points in the north direction while the fingers wrap around the coil in the direction of the electron flow. Therefore, **the electrons must be flowing from B to A**. Further, since electron flow is the movement of negative charges, they will be forced to accumulate at the A end of the coil wire. Therefore **A is negative** and **B is positive**.

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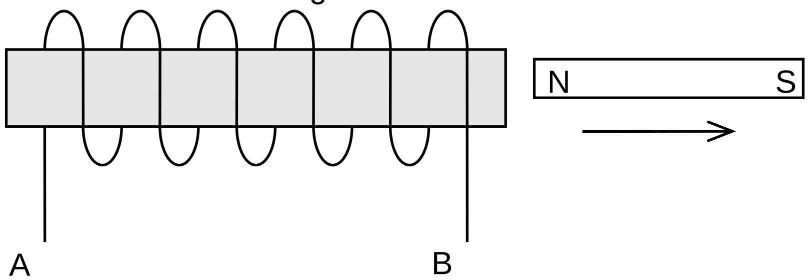
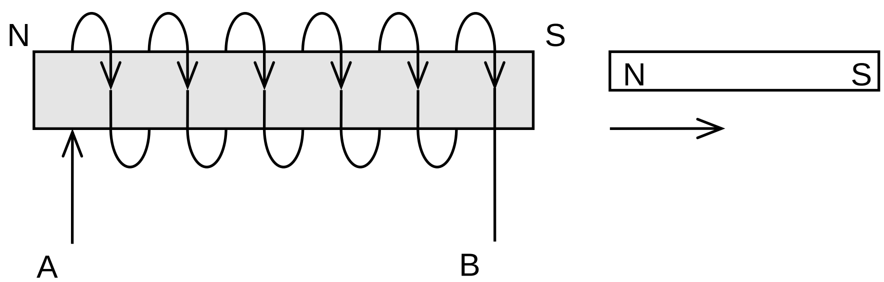
Review: When a magnet is being pushed through a coil, first indicate the appropriate induced magnetic field for the coil that will oppose the inducing magnetic field. Then use the appropriate hand rule to predict the direction of the current or electron flow.

Let us also consider the situation when a magnet is being **pulled out** of a solenoid. What will be the resulting electron flow direction for the following system?



According to Lenz's law, the solenoid will have an induced magnetic field which opposes the motion of the inducing magnetic field (the bar magnet). Therefore, we indicate that a south pole will be induced on the right end of the solenoid – the solenoid is trying to pull or attract the magnet back. A north pole will be induced on the left. Using our left hand rule, **the electrons must be flowing from A to B**.



III. Predicting the direction of current flow – straight conductors

As we learned in lessons 20 and 21, the flat hand rule is:

For current or particle motion, the **fingers** point in the direction of the magnetic field lines, the **thumb** points in the direction of the current or electron, and the **palm** points in the direction of the resulting force.

Lenz's law predicts results which are opposite to the motor effect if we move the wire instead. To account for this we can make the following adjustment:

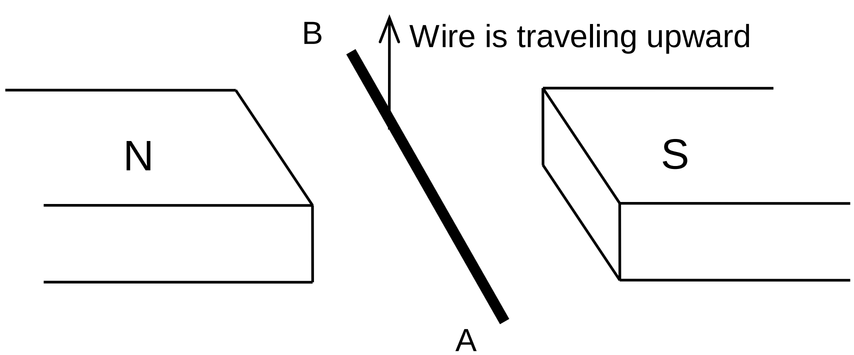
When a conductor passes through a magnetic field, the **fingers** point in the direction of the magnetic field lines, the **thumb** points in the direction of the motion, and the **palm** indicates the direction of the induced current or electron flow. The right hand is still conventional current and the left hand is for electron flow.

However, a **combined hand rule** may be used which **integrates the motor effect and the generator effect**. For the combined hand rule:

The **fingers** point in the direction of the magnetic field.
The **thumb** points in the direction of what is **input** or **primary**.
The **palm** points in the **output** or **secondary** direction.

Thus, if current is being input, the current is the thumb and the resulting force is the palm. Conversely, if the wire is being moved, the direction of motion is the thumb and the induced current/electron flow is the direction indicated by the palm.

For example, using the diagram below, if the conductor is pulled up through the magnetic field, which way will the electrons flow? Which end will become negative: A or B?



The magnetic field points to the right (fingers) and the wire is being pulled up the page (thumb). Using the left hand, the palm faces toward us indicating **that the electrons are flowing from B to A**. The negative electrons pile up on the A end of the wire, thus **A is negative**.

IV. Potential difference created by the generator effect

The motion of electrons toward one end of a conductor will result in a potential difference or voltage along the conductor within the magnetic field. To calculate the amount of potential difference (also called Electromotive Force – EMF) we use

$$V = B\,v\,L\sin\theta$$

where V potential difference (volts)
B magnetic field strength (T) or (N s / C m)
v speed of conductor (m/s)
L length of conductor (m)
θ angle between v and B, or B and L

Example 1

What voltage is generated by a 10.0 cm wire passing at 90° to a magnetic field of 4.0 T at 40 m/s? If the wire is connected to a 20 Ω resistor to form a circuit, what is the current?

$$V = BvL\sin\theta$$

$$V = (4.0\,T)(40\,\tfrac{m}{s})(0.100\,m)(\sin 90)$$

$$V = \mathbf{16V}$$

using Ohm's law:

$$I = \frac{V}{R}$$

$$I = \frac{16\,V}{20\,\Omega}$$

$$I = \mathbf{0.80A}$$

V. Electric generators

When a single wire is bent into a loop and rotated through a permanent magnetic field, we have the basis for a generator. If the loop or armature is turned by some mechanical means (hand crank, pedals, crankshaft of an engine, or a turbine using steam, wind or water) we can generate electric power. A generator generates electricity from mechanical work, which is the opposite of what a motor does. In fact, a generator is just the inverse of a motor.

Motors and generators have the same basic design, multiple loops of wire turning in an external magnetic field, but they perform opposite processes. A motor converts electric energy into mechanical energy. A generator converts mechanical energy into electrical energy.

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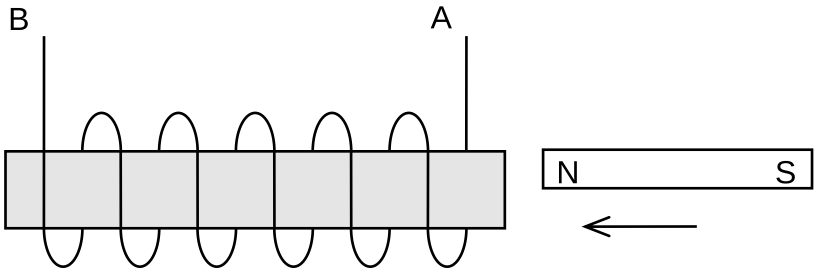
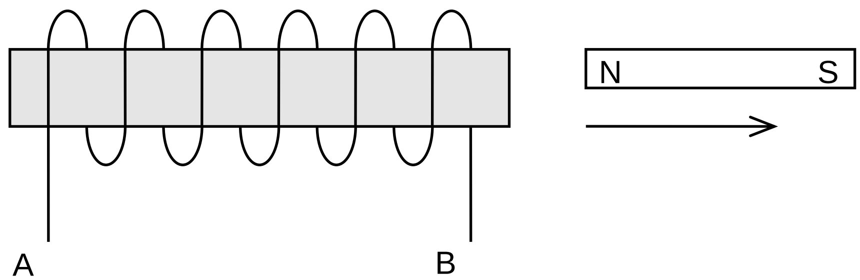
VI. Practice problems

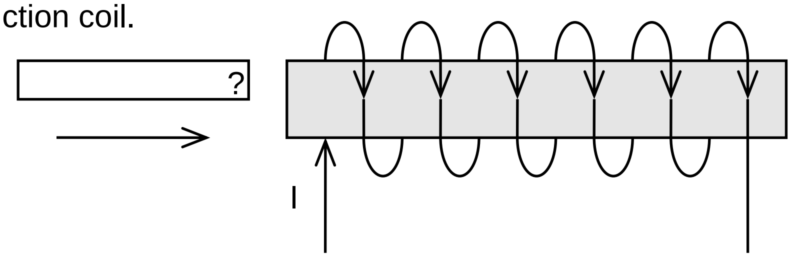
1. Which end will become negatively charged, A or B?



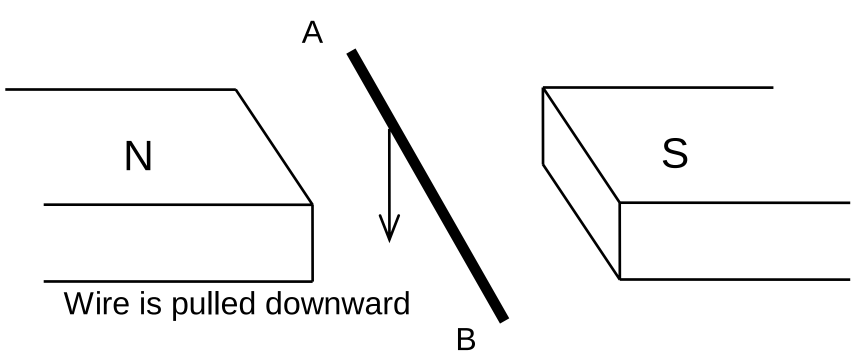
2. Determine the direction of the induced current for the following coil. Is A positive or negative?



3. Determine the pole of the bar magnet that is being inserted into the illustrated induction coil.



4. Which end of the conductor will become negative? What is the direction of current flow?



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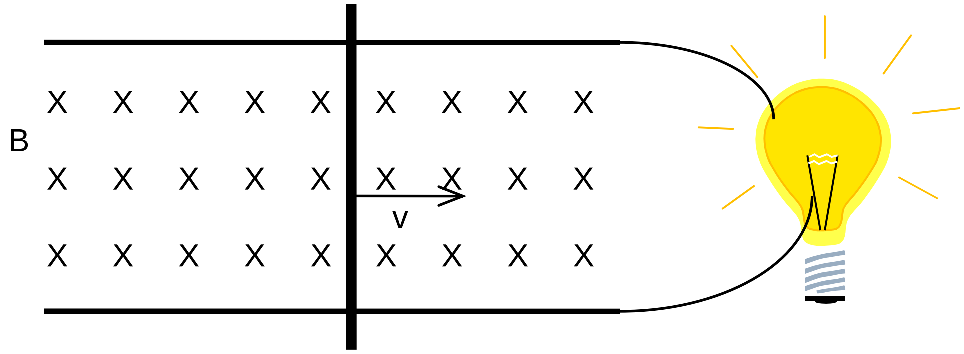
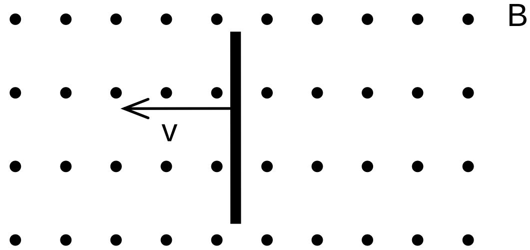
5. Which way will the electrons flow in the circuit below?

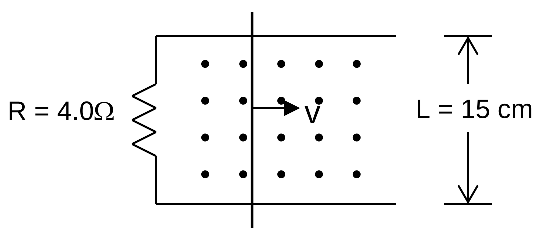


6. Which end of the conductor will become negative?



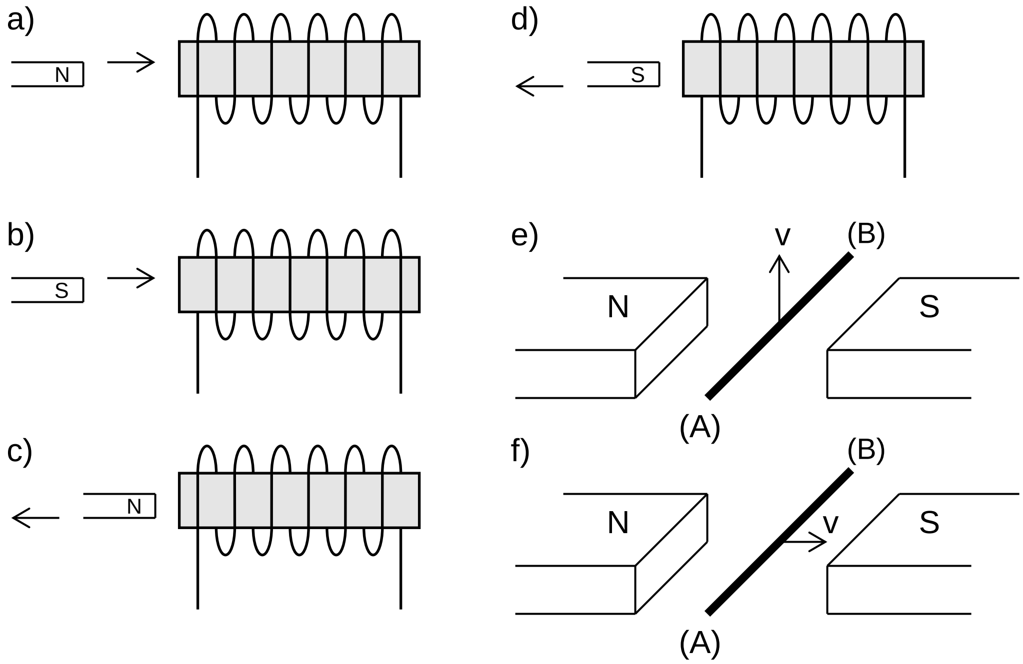
7. What is the voltage generated when a 50 cm wire passes through a 6.0 T field at 30^o to the field with a speed of 30 m/s? (45 V)

8. The conducting rod in the diagram is 15 cm long and is moving at a speed of 4.0 m/s perpendicular to a 0.30 T magnetic field. The conducting rod slides across two wires which forms a circuit. If the resistance in the circuit is 4.0 Ω, what is the magnitude and direction of the current through the circuit? (0.045 A clockwise)



VII. Hand-in assignment

1. For each situation below, determine the polarity of the induced magnetic field and the direction of induced electron flow for each of the following cases. Indicate which end of the “generator” wire becomes a negative terminal in each case.



2. In table form, describe the three hand rules that you have learned for current carrying wires, solenoids and the motor/generator effect. Which parts of the hand are used for each hand rule?

3. A bar magnet inserted into a coil of 500 turns produces an induced potential of 1.5 V, Determine the potential difference induced when each of the following changes are made. Consider each change separately.
   a) A 250 turn coil is used. (0.75 V)
   b) The bar magnet is moved twice as fast. (3.0 V)
   c) Three identical magnets are inserted at once, side by side. (4.5 V)
   d) All three of the above changes occur together. (4.5 V)

4. For a generator, where does the electrical energy of the induced current and potential difference come from? What form of energy provides the work for the electrical energy being made?

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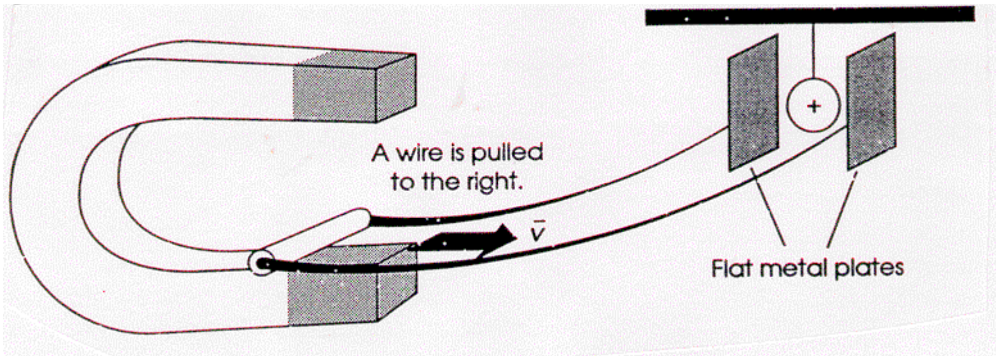
5. A positively charged sphere is suspended between two large metal plates as shown in the diagram. A wire is placed between the poles of a horseshoe magnet and connected to the metal plates. When the wire is drawn horizontally to the right the charged ball is observed to swing toward the right-hand metal plate.



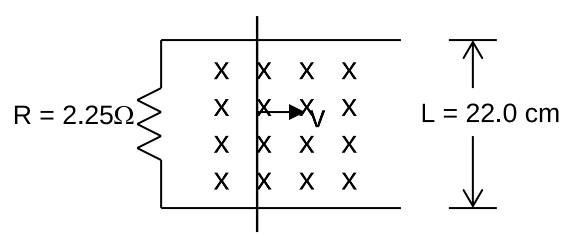
a) Determine the direction of the induced electron flow in the wire in the horseshoe magnet. Explain.
b) Is the top pole of the magnet a north pole or a south pole? Explain.

6. An aluminium airplane is flying west, parallel to the ground, at 350 m/s. The Earth's magnetic field produces a downward component of 8.0×10^{-5} T. For this question, treat the wing as a conducting rod.
a) What is the magnitude of the potential difference induced across the plane's wingspan of 22 m? (0.62 V)
b) Which wing tip would be negatively charged, the wing on the north side or the south side of the plane? Support your answer with a diagram.

7. If a 24 cm conductor moves through a 27.5 T field at 75 m/s and produces a potential difference of 128 V, what is the angle at which conductor is passing through the field? (15^{o})

8. A certain conductor produces a voltage of 1.00 mv when it moves perpendicular to a magnetic field. What voltage is generated when it moves at the same speed across the field at an angle of 45^{o}? (0.707 mV)

9. The conducting rod in the diagram is 22.0 cm long and is moving at a speed of 1.25 m/s through a 0.150 T magnetic field. If the resistance in the circuit is 2.25 Ω, what is the magnitude and direction of the induced electron flow through the circuit? (18.3 mA, clockwise)



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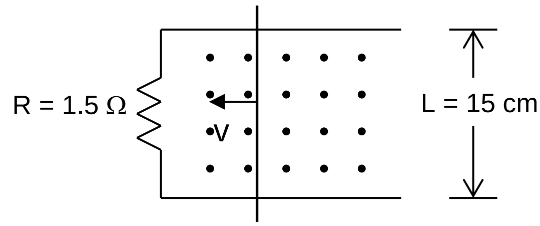
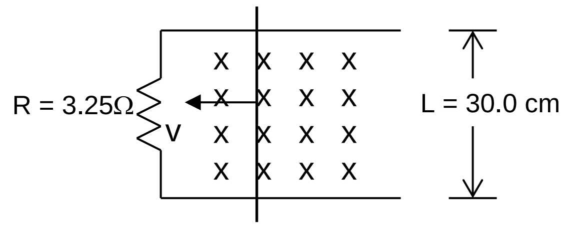
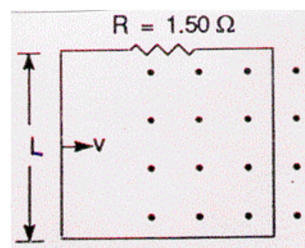
10. The conducting rod in the diagram is 15 cm long and is moving at a speed of 0.95 m/s through a magnetic field. If the resistance in the circuit is 1.5 Ω and a current of 56 mA is induced in the circuit, (a) what is the magnitude of the magnetic field? (b) what is the direction of the induced electron flow through the circuit? (0.59 T, clockwise)



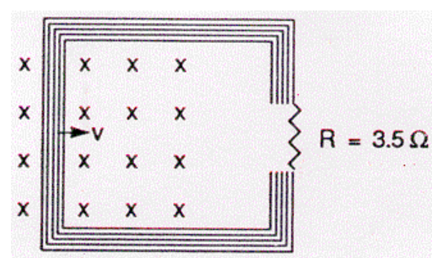
11. The conducting rod in the diagram is 30.0 cm long and is moving through a 0.950 T magnetic field. If the resistance in the circuit is 3.25 Ω, what force is required to move the rod at a constant speed of 1.50 m/s? (0.0375 N)



12. A rectangular loop of wire is moving at a speed of 0.95 m/s through a 1.30 T magnetic field as shown. If the length of the side moving perpendicular to the field is 0.625 m and the resistance in the circuit is 1.50 Ω, (a) what is the induced current? and (b) what is the direction of the induced electron flow through the circuit? (0.52 A, counterclockwise)



13. A rectangular coil of wire containing 5 loops is moving at a speed of 2.7 m/s through a 1.1 T magnetic field. If the length of the side of the coil moving perpendicular to the field is 0.18 m and the resistance in the circuit is 3.5 Ω, (a) what is the induced current? (b) what is the direction of the induced electron flow through the circuit? (0.76 A, counterclockwise)



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