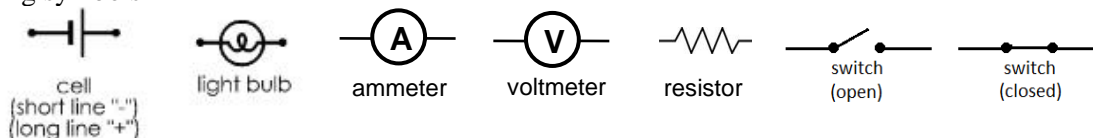


## SPH3U - Simple Circuits

Use the following website to build circuits: <https://phet.colorado.edu/en/simulation/circuit-construction-kit-dc>

A circuit diagram is a simplified drawing of an electric circuit. Circuit diagrams use straight lines for wires and the following symbols



**Represent.** Draw a circuit diagram for a simple circuit using a cell, resistor/light bulb, wires and a switch.

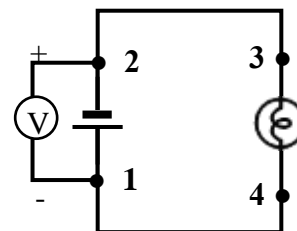
The flow of electricity is called the *electron current*, or just simply, the *current*. It is the movement of electrons through the circuit. An *ammeter* measures the current in *amperes* (A). To measure the current travelling through one point in a circuit, simply “insert” the ammeter into that location in the circuit.

**Represent.** Draw a circuit diagram showing how to connect an ammeter. Then measure the current at different points in your circuit.

A *voltmeter* measures the change in energy of a unit of charge as it moves between two points in a circuit. To use a voltmeter, you must connect the meter’s two leads to two different points in a circuit. A voltmeter connects across two points, without disconnecting the original circuit (connected in *parallel*).

**Test.** Construct a simple circuit. Connect the voltmeter across different parts of the circuit with the pair of leads connected at the points numbered in the chart below. Complete the chart.

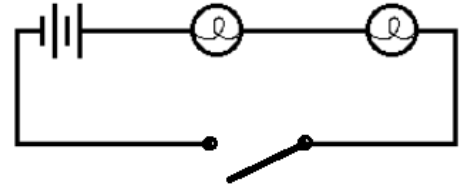
Voltmeter leads connected at points	Part of circuit charge moves through	Observed meter reading
1 and 2		
2 and 3		
3 and 4		
4 and 1		



**Explain.** According to your measurements, what is happening to the amount of energy carried by the electrons moving in this circuit between each pair of points?

## Series Circuits

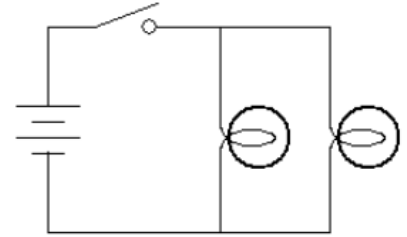
Construct the circuit shown in the diagram, and make sure “Show Current” is checked showing electrons.



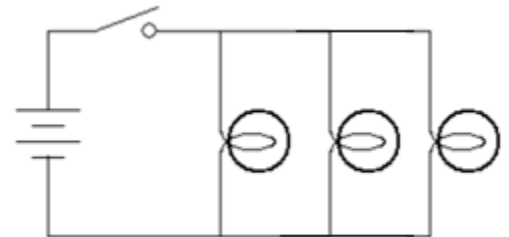
1. Close the switch. Observe and Explain.
2. Open the switch. Observe and explain.
3. Close the switch, then break one of the connections between a wire and a lightbulb. Observe and explain.
4. Reattach the wire to the lightbulb so that both lights work. Now use an ammeter to measure the current at a variety of locations along your circuit. Summarize your findings.
5. Use a voltmeter to measure the voltage between a variety of points of your circuit. Summarize your findings.
6. Take a moment to observe the brightness of the bulbs (shown by the yellow lines) and the speed of energy flow. Now add a third lightbulb to your circuit, also in series (“in a row”), and again observe the brightness of the bulbs and speed of energy flow. Explain.
7. Suppose you re-did steps 4 and 5 above. What would you expect to find? Explain briefly, then confirm.
8. Add a second battery in the same direction as the first. Observe and explain.
9. Change the direction of your second battery. Observe and explain.

## Parallel Circuits

Construct the circuit shown in the diagram, and make sure “Show Current” is checked showing electrons.



1. Close the switch so that both lights are on. Use an ammeter to measure the current at various places in your circuit. Summarize your findings.
2. Use a voltmeter to measure the voltage across a variety of locations in your circuit. Summarize your findings.
3. Take a moment to observe the brightness of the bulbs. Now break one of the connections between a wire and a lightbulb. Observe and explain.
4. Reconnect the lightbulb.
5. Now you will now add a third lightbulb to your circuit, also in parallel (see picture). What do you expect to happen to the current, voltage, brightness, etc. in your circuit? Test your hypothesis.



6. As you add bulbs in parallel, why does their brightness stay constant?
7. As you add bulbs in parallel, how does this affect the battery?

# Circuit Analysis

**Calculate.** For each loop in the circuits below, use Kirchhoff's voltage law to determine any missing voltage values.

<p>(a)</p> <p><math>V_s = 9\text{ V}</math></p> <p><math>V_1 = 4\text{ V}</math></p> <p><math>V_2 =</math></p>	<p>(b)</p> <p><math>V_s = 9\text{ V}</math></p> <p><math>V_1 = 18\text{ V}</math></p> <p><math>V_t =</math></p>
<p>(c) Hint: which loop should you do first?</p> <p><math>V_s = 1.5\text{ V}</math></p> <p><math>V_1 =</math></p> <p><math>V_2 =</math></p> <p><math>V_3 = 0.5\text{ V}</math></p>	<p>(d)</p> <p><math>V_s = 1.5\text{ V}</math></p> <p><math>V_1 =</math></p> <p><math>V_2 =</math></p> <p><math>V_3 = 0.3\text{ V}</math></p>

**Calculate.** For each loop in the circuits below, use Kirchhoff's current law to determine any missing current values.

<p>(a)</p> <p><math>I_s = 4\text{ A}</math></p> <p><math>I_1 =</math></p> <p><math>I_2 =</math></p>	<p>(b)</p> <p><math>I_s =</math></p> <p><math>I_1 = 3\text{ A}</math></p> <p><math>I_t =</math></p>
<p>(c) Hint: which loop should you do first?</p> <p><math>I_s =</math></p> <p><math>I_1 = 6\text{ A}</math></p> <p><math>I_2 =</math></p> <p><math>I_3 = 2\text{ A}</math></p>	<p>(d)</p> <p><math>I_s = 8\text{ A}</math></p> <p><math>I_1 =</math></p> <p><math>I_2 = 2\text{ A}</math></p> <p><math>I_3 =</math></p>

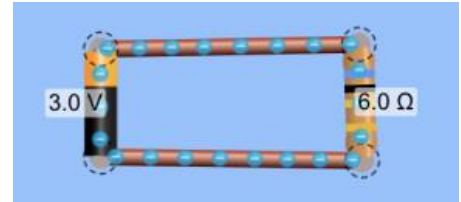
## SPH 3U – Electricity – Circuit simulation

Answer the questions below using the circuit simulation. No need to do any calculations!

<https://phet.colorado.edu/en/simulation/circuit-construction-kit-dc>

- 1) **Verify Ohm's law:** Use a voltmeter and an ammeter to find the current and voltage across a 6 ohm resistor in a simple circuit. Enter your results in the table below. Using your results, find an equation for voltage, current and resistance?

Voltage (V)	Current (I)	Resistance (Ohms)
3		6
6		6
12		6
18		6
24		6



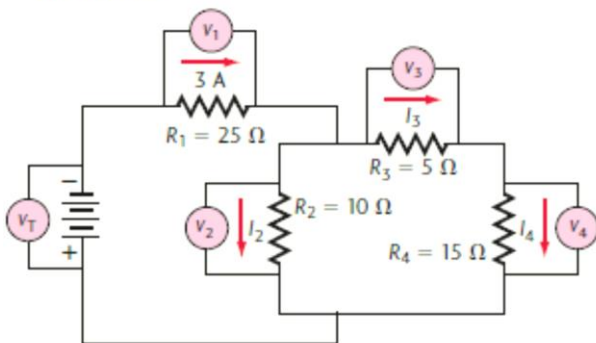
- 2) Use a voltmeter and an ohmmeter to find the current and voltage across the resistors for the following circuits:
- A simple circuit: a 12 V battery connected to one 6 ohm resistor
  - A series circuit: a 12V battery connected to one 9 ohm and one 3 ohm resistor
  - A parallel circuit: a 12V battery connected to 6 ohm and 3 ohm resistors in parallel
  - A complex circuit: a battery with resistors in series and parallel

Draw your 4 circuits on the next page using the following symbols, find and label the voltage and the current across each resistor. Make conclusions based on your observations.

 Battery	 Resistor	 wire	 Voltmeter	 Ammeter
-------------	--------------	----------	---------------	-------------

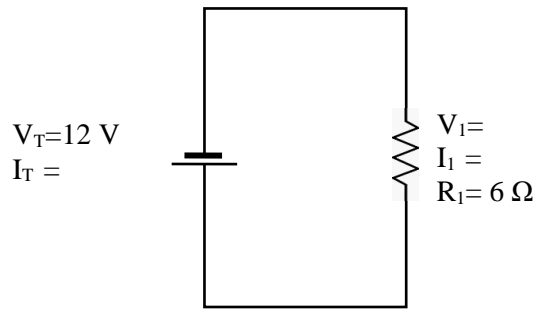
- 3) Build the following circuit and determine all the unknown voltages, resistances and currents.

d) Fig.16.26



Name	V (V)	I (A)	R (Ω)
R <sub>1</sub>			
R <sub>2</sub>			
R <sub>3</sub>			
R <sub>4</sub>			
Total, R <sub>0</sub>			

3a) A simple circuit: a 12 V battery connected to one 6 ohm resistor.



3b) A series circuit: a 12V battery connected to one  $9 \Omega$  and one  $3 \Omega$  resistor

3c) A parallel circuit: a 12V battery connected to a 6 ohm and a 3 ohm resistors in parallel

3d) A complex circuit: a battery with resistors in series and parallel

# Circuits Analysis

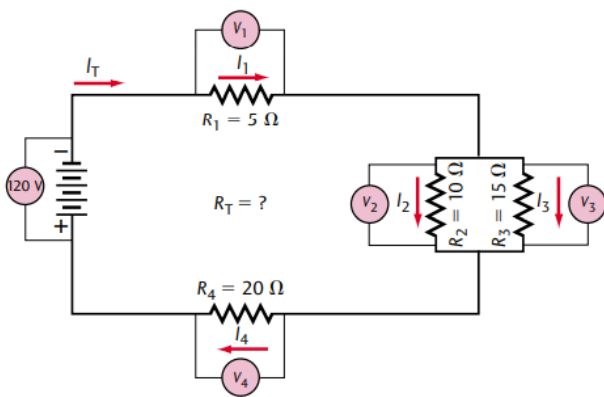
We don't always want to have to build circuits in order to predict current, voltage, etc, so we can apply some of our findings from the previous pages in circuit analysis. Some general strategies:

Here is a summary of some strategies that will be useful when analyzing circuits:

- **Identify quantities we know already**
- **Look for quantities we can easily obtain (ex. current in series remains constant)**
- **Replace resistances in series or parallel with their equivalent resistances**
- **Use  $V = IR$  when you know two out of the three**
- **You guessed it – persistence and determination!**

And some useful formulas...

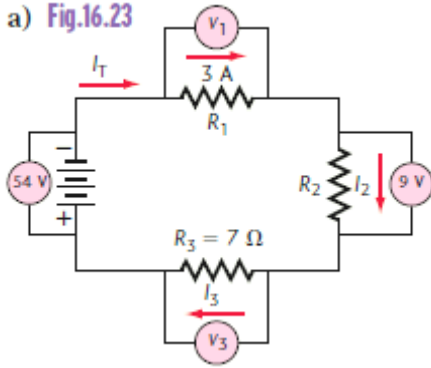
Series Circuits	Parallel Circuits	Other
$V_T = V_1 + V_2 + V_3$ $I_T = I_1 = I_2 = I_3$ $R_T = R_1 + R_2 + R_3 \dots + R_N$	$I_T = I_1 + I_2 + I_3$ $V_T = V_1 = V_2 = V_3$ $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \dots + \frac{1}{R_N}$	$V = IR$



Name	V (V)	I (A)	R ( $\Omega$ )
$R_1$			
$R_2$			
$R_3$			
$R_4$			
Total, $R_0$			

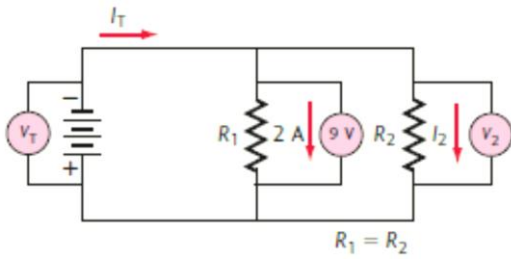
35. Determine all missing values. You might need to use other paper.

a) Fig.16.23



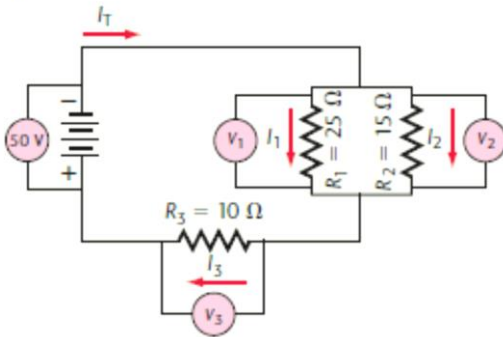
Name	V (V)	I (A)	R (Ω)
R <sub>1</sub>			
R <sub>2</sub>			
R <sub>3</sub>			
Total, R <sub>0</sub>			

b) Fig.16.24



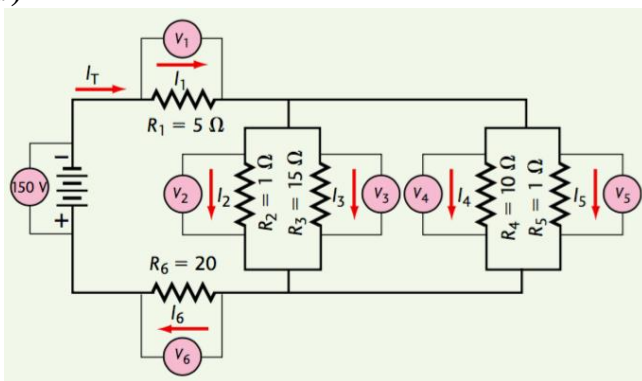
Name	V (V)	I (A)	R (Ω)
R <sub>1</sub>			
R <sub>2</sub>			
Total, R <sub>0</sub>			

c) Fig.16.25



Name	V (V)	I (A)	R (Ω)
R <sub>1</sub>			
R <sub>2</sub>			
R <sub>3</sub>			
Total, R <sub>0</sub>			

d)



Name	V (V)	I (A)	R (Ω)
R <sub>1</sub>			
R <sub>2</sub>			
R <sub>3</sub>			
R <sub>4</sub>			
R <sub>5</sub>			
R <sub>6</sub>			
Total, R <sub>0</sub>			



The following simulations will help us learn some basic concepts of electromagnetism...

**A. Classifying materials**

Visit [www.explorellearning.com](http://www.explorellearning.com), then log in and find the Magnetism activity. Choose the magnetic forces tab. You have access to different types of objects: magnetic objects, ferromagnetic objects, non-magnetic objects. Learning Goal: To learn about the magnetic interaction between any two objects.

**B. Field Lines**

Option 1: Remain in Magnetism activity of [www.explorellearning.com](http://www.explorellearning.com), but choose the Magnetic Field Lines tab.  
Option 2: <https://phet.colorado.edu/en/simulation/legacy/magnet-and-compass>  
Learning Goal: To learn about the characteristics of magnetic field lines created by magnets.

**C. Earth's Magnetic Field**

Visit the following simulation: <https://phet.colorado.edu/en/simulation/legacy/magnet-and-compass>. Click on "Show Planet Earth"  
Learning Goal: To learn about the magnetic fields surrounding planet earth

**D. Oersted's Principle**

Option 1: [www.explorellearning.com](http://www.explorellearning.com), then find the Magnetic Induction activity  
Option 2: [https://javalab.org/en/oersteds\\_experiment\\_en/](https://javalab.org/en/oersteds_experiment_en/)  
Learning Goal: To discover what Hans Christian Oersted discovered (by accident) in 1820

**E: Faraday's Law of Induction**

First visit <https://phet.colorado.edu/en/simulation/legacy/faraday> and select Electromagnet  
Visit <https://phet.colorado.edu/en/simulation/faradays-law>  
Learning Goal: To discover Faraday's Law of Induction

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## ***SO WHAT?***

### LET'S LOOK AT A FEW PRACTICAL APPLICATIONS

**F: Step-up/Step-down Transformer**

Visit [https://javalab.org/en/electric\\_transformer\\_en/](https://javalab.org/en/electric_transformer_en/)

**G: Electromagnetic Generator**

Visit <https://phet.colorado.edu/sims/cheerpj/faraday/latest/faraday.html?simulation=generator>

**H: DC Motor**

Visit [https://javalab.org/en/dc\\_motor\\_en/](https://javalab.org/en/dc_motor_en/)

**I: And just because it made me laugh...**

Visit <https://phet.colorado.edu/en/simulation/john-travoltage>

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## SPH 3U – Electricity & Magnetism Directions

Note: The rules below assume we are looking at the direction of the flow of electrons (negative to positive). Many textbooks will use "conventional current" which is current flow from positive to negative, in which case the right hand rule is used. When electricity was discovered there was no way to know *what* was actually moving and in what direction, and Benjamin Franklin guessed wrong.

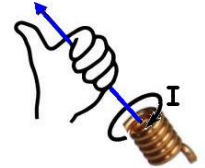
### LHR (for straight conductors)

Using your left hand, point your thumb in the direction of the electron current and the fingers curl in the direction of the magnetic field.

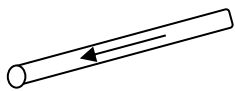


### LHR (for coiled conductors – solenoids)

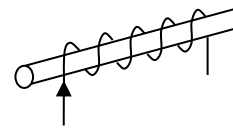
Curve fingers of left hand point in the direction of electron current and the thumb points in the direction of the magnetic field inside the coil



- 1) Draw the magnetic fields around the following objects. The arrows indicate the direction of electron current flow.



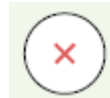
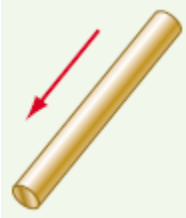
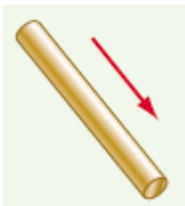
Out of the page      Into the page



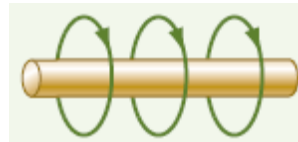
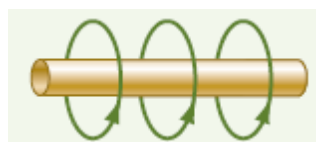
### Magnetic fields in coiled conductors

- The magnetic field inside the solenoid is uniform (same strength and same direction)
- Magnetic field  $B$  can be adjusted depending on the current (double the current  $\rightarrow$  double the magnetic field)
- Magnetic field can be adjusted depending on the number of turns (if you double the number of turns, you double the magnetic field)

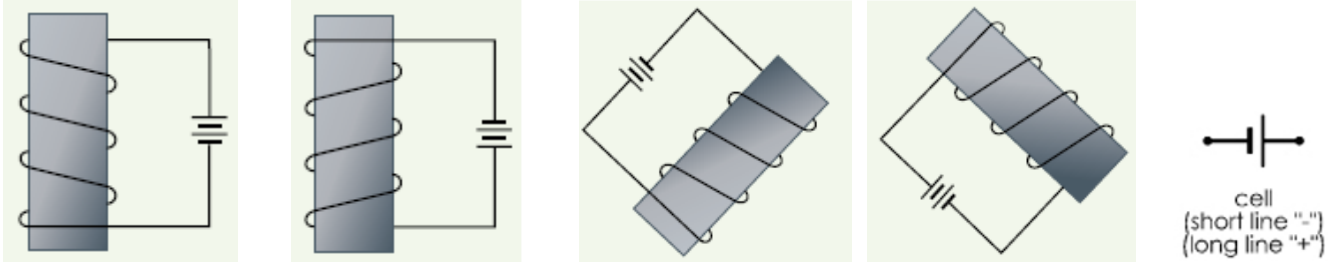
1. For each current-carrying conductor, sketch a view of the magnetic field, based on the direction of the current shown (current represents electron flow)



2. For each current-carrying conductor, show the direction of current (electron flow), based on the magnetic field shown.



3. For each current-carrying solenoid (an electromagnetic coil), sketch a view of the magnetic field around the coil, based on the direction of current flow shown. On each, label the polarity (north and south) of the electromagnet.



4. For each coil, show the direction of current (electron flow) that would cause the labelled magnetic polarity.



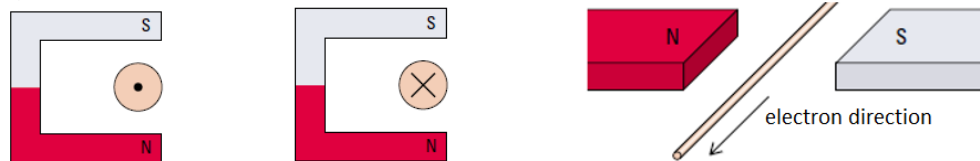
**SPH 3U – Electricity & Magnetism – Motor Principle**      Name: \_\_\_\_\_

**The motor principle:** A current-carrying conductor experiences a force when it is placed in an external magnetic field. The force exerted is perpendicular to the direction of current and the external magnetic field.

**LHR (for the motor principle)**  
 On the left hand, the fingers point in the direction of the magnetic field, the thumb points in the direction of the electron current flow. The palm points in the direction of the force produced.

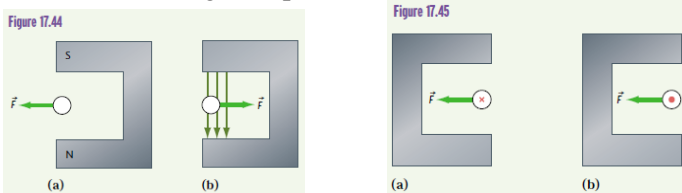
**Examples**

1) Find the direction of the force

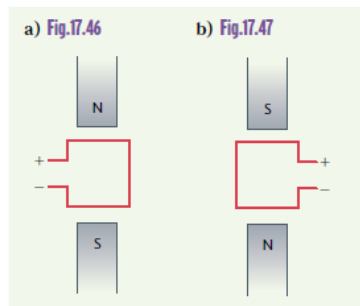


Recall: Magnetic poles are drawn from north to south

2) Label the magnetic poles, the magnetic field and the direction of electron current



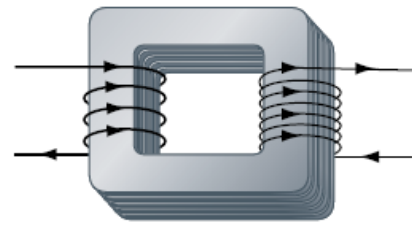
3) Show which way the loops will turn



**18.4 Transformers and the Distribution of Electrical Power** (from Irwin Physics 11 p615)

The simple transformer, shown in Fig. 18.13, uses both Faraday’s principle and Oersted’s principle to transform current and voltage in a circuit. The primary side uses an alternating current to produce an electromagnet. The changing magnetic field in the secondary side uses Faraday’s principle to produce a new alternating current. If the number of turns in the primary and secondary sides of the transformers is different, then the voltage on the primary and secondary is different. Increasing the number of turns ( $N$ ) in the secondary compared to the primary increases the secondary voltage proportionally.

Fig.18.13 A step-up transformer



Output power in the secondary coil must be equal to the input power in the primary coil. (Energy must be conserved!) Note that  $P = VI$  where  $P$  = power (Watts, 1 W = 1 J/s)

$v$  = voltage or electric potential difference (Volts)

$I$  = current (Amperes)

$$P_{primary} = P_{secondary}$$

$$I_{primary} V_{primary} = I_{secondary} V_{secondary}$$

Rearranging yields:  $\frac{V_{primary}}{V_{secondary}} = \frac{I_{secondary}}{I_{primary}}$

Fig.18.14 Voltage and Current Changes in a Transformer

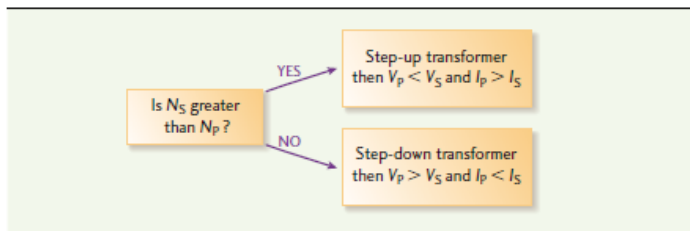
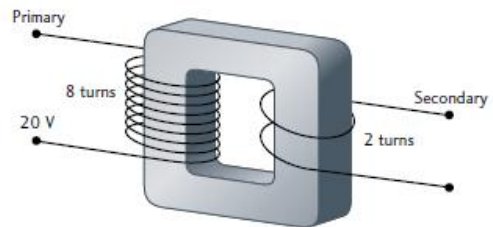


Fig.18.15



Factor in the number of turns,  $N$ , on the primary and secondary sides ( $N_p$  and  $N_s$ )

$$\frac{V_{primary}}{V_{secondary}} = \frac{I_{secondary}}{I_{primary}} = \frac{N_{primary}}{N_{secondary}}$$

1. A step-up transformer with 50 primary turns and 250 secondary turns is used to generate a current of 2.5 A at a voltage of 10 V. Find
  - a) the turns ratio.
  - b) the primary voltage.
  - c) the primary current.
  - d) the average power delivered to the secondary side.
  - e) the average power of the primary side
  - f) the resistance of the load on the output side.

2. A step-down transformer is used to convert 120 V from the wall source to an audio receiver voltage. If there is a 0.80 A current on the primary side and the turns ratio is 13:1, find
  - a) the voltage across the secondary side.
  - b) the current delivered to the stereo.
  - c) the resistance of the stereo components.
  - d) the power delivered to the secondary side.
  - e) the power delivered to the primary side.

Answers:

1a) 1:5 b) 2V c) 12.5 A d) 25W e) 25W f) 4 Ω

2a) 9.23V b) 10.4A c) 0.89 Ω d) 96W e) 96W

1) Complete the following statements:

**Kirchhoff's Voltage Law (KVL):** In a complete circuit loop, the total of all electric potential increases is equal to ...

**Kirchhoff's Current Law (KCL):** At any junction point in an electric circuit, the total electric current into a junction point is equal to ...

**Ohm's Law:**  $V = IR$  or  $I =$

**Oersted's Principle:** Current moving through a conductor produces (or induces) ...

**Faraday's Law:** A magnetic field that is moving or changing intensity near a conductor causes (or induces) ...

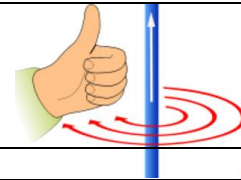
**Lenz's Law:** The direction of the induced current creates an induced magnetic field that \_\_\_\_\_ the motion of the inducing magnetic field.

**The Motor Principle:** A current-carrying conductor experiences a \_\_\_\_\_ when it is placed in an external magnetic field. This is because the conductor creates its own \_\_\_\_\_ as well.

**Magnetic Fields:** Magnetic field lines come out of the \_\_\_\_\_ pole and go into the \_\_\_\_\_ pole. They are 3D, and do not cross.

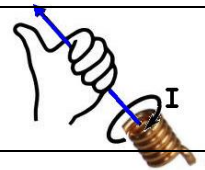
**LHR #1 straight conductors:** Grasp a conductor with the *left* hand.

The thumb points in the direction of ...  
and the curved fingers point in the direction of ...



**LHR #2 coiled conductors:** Grasp a conductor with the *left* hand.

The curved fingers point in the direction of ...  
and the thumb point in the direction of ...



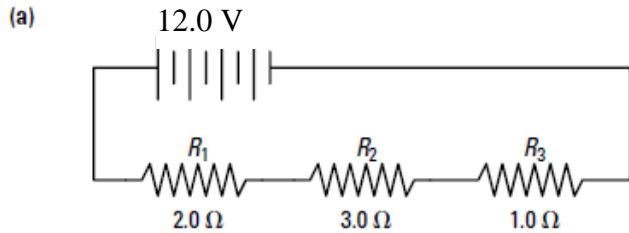
**LHR #3 the motor principle:** Open the *left* hand,

the fingers point in the direction of the ...  
the thumb points in the direction of ...  
and the palm points in the direction of the ...

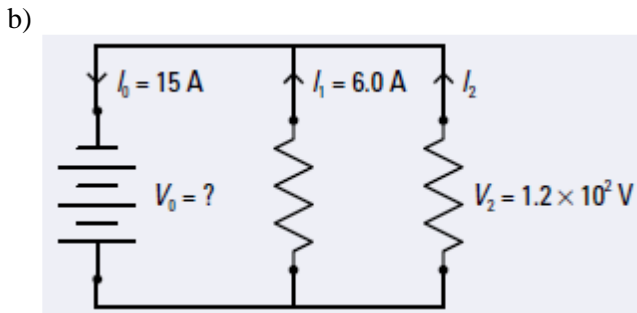
- 1) A small light bulb with a resistance of  $15.0\ \Omega$  is connected to a  $9.0\text{-V}$  battery for  $30.0\ \text{s}$ .
  - a) What is the current through the bulb?
  - b) What power is dissipated by the bulb?
  - c) How much energy is used by the bulb?
  - d) How much charge is transferred through the bulb?
  - e) How many electrons pass through the bulb?

- 2) The following appliances are operated in a  $120.0\text{-V}$  circuit for a thirty-day month:
  - six  $100.0\ \text{W}$  light bulbs for  $8.0\ \text{h/d}$
  - a  $10.0\ \Omega$  kettle for  $10.0\ \text{min/d}$
  - a bread machine drawing on  $6.0\ \text{A}$  for  $1.0\ \text{h/d}$
 Calculate the electric bill for the month at an average cost of  $8.5\text{¢/kW}\cdot\text{h}$ .

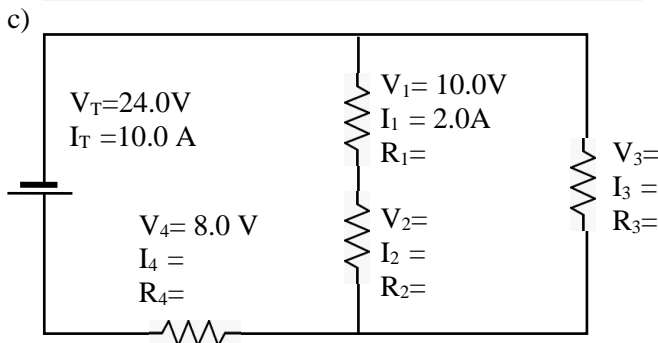
- 3) For each of the electric circuits, solve for all  $V$ ,  $I$ , and  $R$ 's.



Name	V (V)	I (A)	R ( $\Omega$ )
$R_1$			
$R_2$			
$R_3$			
Total			



Name	V (V)	I (A)	R ( $\Omega$ )
$R_1$			
$R_2$			
Total			



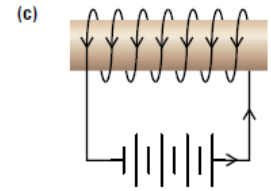
Name	V (V)	I (A)	R ( $\Omega$ )
$R_1$			
$R_2$			
$R_3$			
$R_4$			
Total			

4) Draw the magnetic lines for each of the diagrams.

(a) one bar magnets

(b) a current-carrying conductor

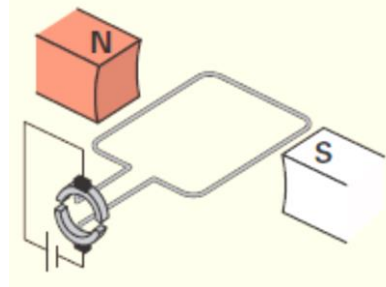
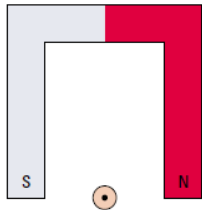
(c) current through a solenoid



5) Indicate the magnetic field and the direction of the force on each current-carrying conductor.

(a) a conductor near a U-shaped magnet

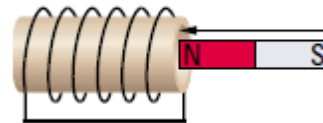
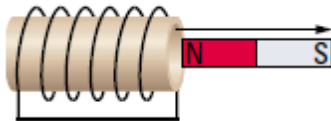
(b) loop conductor in a uniform magnetic field



6) Indicate the direction of the induced current (electron flow).

(a) a magnet being pulled out of a solenoid

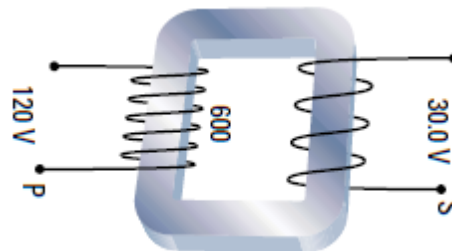
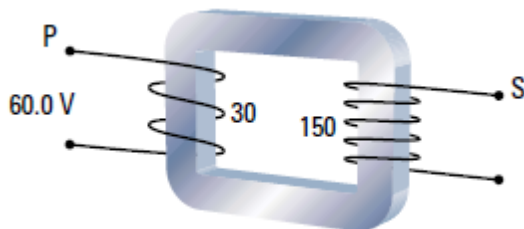
(b) a magnet being pushed into a solenoid



7) For each of the following transformers, state whether it is a step-up or step-down transformer and calculate the

(a) electric potential difference in the secondary circuit

(b) number of windings in the secondary circuit

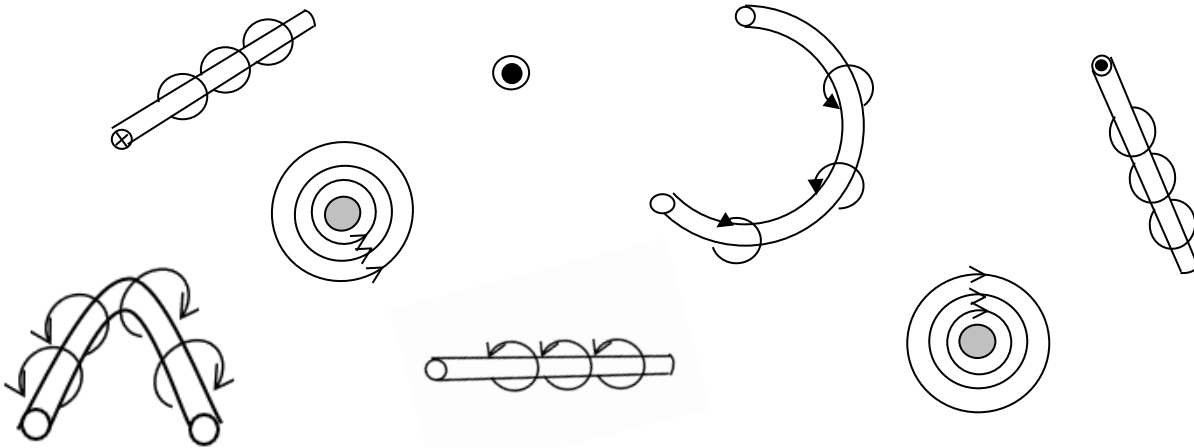


Answers

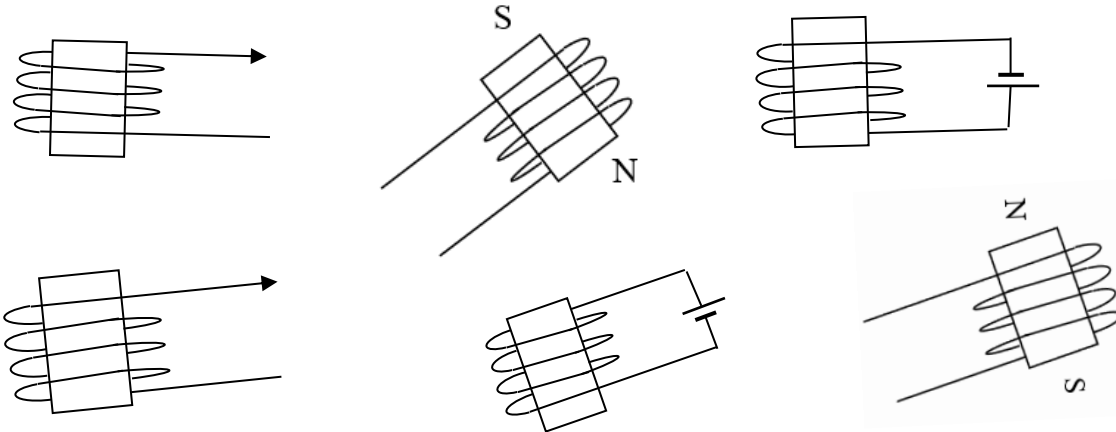
1a) 0.6A 1b) 5.4 W 1c) 162 J 1d) 18C 1e)  $1.125 \times 10^{20} e$  2) \$14.69

3a)  $I_T = I_1 = I_2 = I_3 = 2A$  3b)  $I_2 = 9.0A$   $R_T = 9.0 \text{ Ohms}$  3c)  $I_T = 1.0 A$   $I_1 = 1.0A$   $I_2 = I_3 = I_4 = 0.5A$

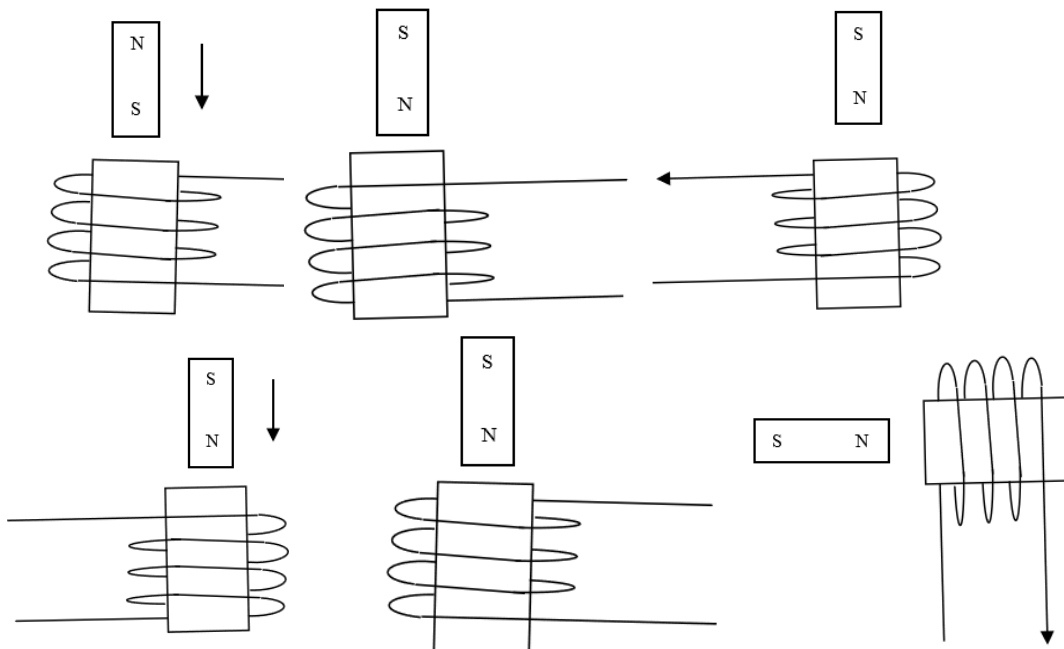
1) Complete the diagrams by drawing the direction of current (electron flow) or magnetic field lines.



2) Complete the missing parts of the diagrams: current (electron flow) or polarity



3) Complete the missing parts: current (electron flow), polarity and direction of magnet motion



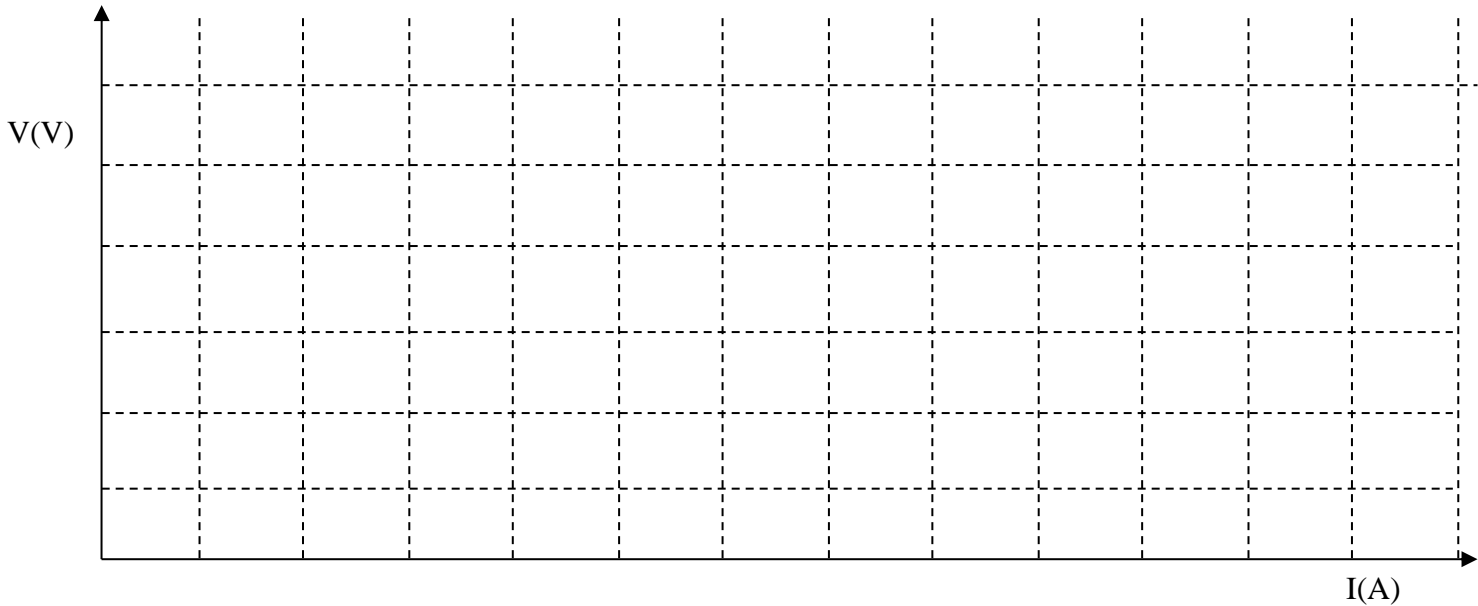


## Resistance & Ohm's Law

(from RTevlin)

- 1) **Ohm's Law:** Set up four batteries in series. Check that they each have around 1.5 V. Set up a circuit with an ammeter, four batteries and a 10 ohm resistor but leave one connection open. Have the teacher check your circuit before proceeding. You can change the voltage by moving one alligator clip along the line of batteries. Enter and graph the data for the three loads.

V (V)	I(A) 10 ohm	I(A) 20 or 24 ohm	I(A) bulb
0	0	0	0
1.5			
3.0			
4.5			
6.0			



- a) Two of the graphs produce straight lines. Which are they?
- b) What are their equations of the two straight lines?
- c) What does the slope of the straight line measure?
- d) Ohm's Law is  $V = IR$ .  
Calculate the voltage that you would need in each case to get 0.7 A of current.

Calculate the current that you would get in each case with 10 batteries?

2) Two  $10\text{-}\Omega$  resistors are in a series circuit with four batteries. What current would you expect?

A)  $6/5\text{ A}$

B)  $6/10\text{ A}$

C)  $6/20\text{ A}$

Explain.

Observe

What is the **resistance** of the circuit?

3) A  $10\text{-}\Omega$  resistor and a  $20\text{-}\Omega$  resistor are in a series circuit with four batteries. The current will be

A)  $6/10\text{ A}$

B)  $6/15\text{ A}$

C)  $6/20\text{ A}$

D)  $6/30\text{ A}$

Explain

What is the resistance of the circuit?

4) Two  $10\text{-}\Omega$  resistors are in a parallel circuit with four batteries. What current would you expect?

A)  $6/5\text{ A}$

B)  $6/10\text{ A}$

C)  $6/20\text{ A}$

Explain

What is the resistance of the circuit?

5) Three  $10\text{-}\Omega$  resistors are in a series circuit with four batteries. What current would you expect?

A)  $6/3.3\text{ A}$

B)  $6/5\text{ A}$

C)  $6/7\text{ A}$

Explain

What is the resistance of the circuit?

6) A  $10\text{-}\Omega$  resistor and a  $20\text{-}\Omega$  resistor are in a parallel circuit with four batteries.

What will the current be?

What is the resistance of the circuit?

7) Draw a circuit diagram of four batteries in series with two  $10\text{-}\Omega$  resistors. Add another parallel path with two more  $10\text{-}\Omega$  resistors in series.

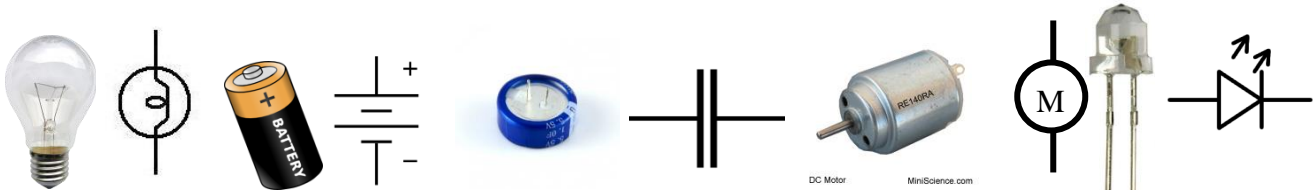
a) Label the voltage drop for each resistor and for the set of batteries.

b) Calculate and label the current passing through each resistor and through the batteries.

c) Trace the path of an electron as it passes from the battery through one path and back to the battery to where it started. Use conservation of energy to explain why the sum of the voltages along that path is zero. This is known as **Kirkhoff's voltage law**.

d) Look at any point where the circuit branches. Use conservation of electrons to explain why the sum of currents into junction equals the sum of the currents leaving that point. This is known as **Kirkhoff's current law**.

## Simple Circuits Adjustments

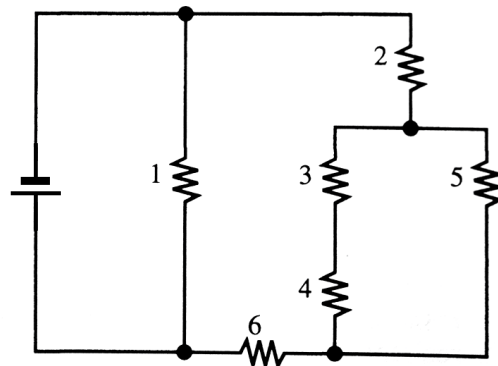


**Observe.** Connect a simple circuit to each different load the table below. Connect each of them individually to a single battery in both directions and then to two batteries in a row. Write your observations in the table.

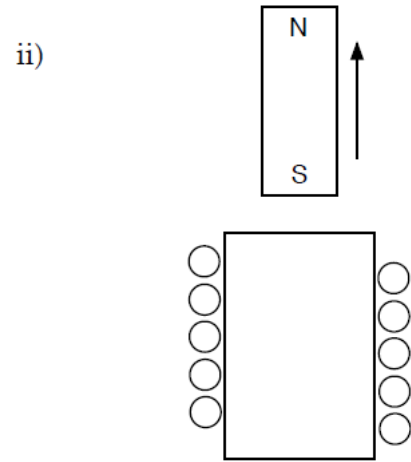
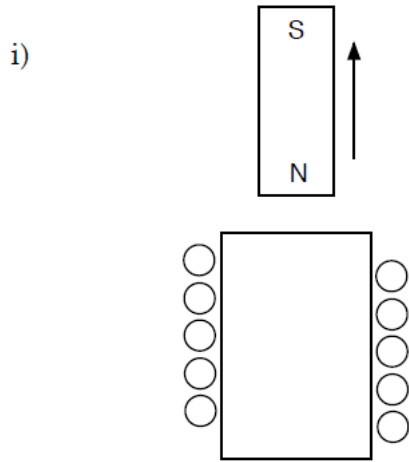
Load Type	Effect of reversing battery	Effect of adding a 2 <sup>nd</sup> battery
Light bulb		
Motor		
Red LED		
Buzzer		
Resistor		

## Equivalent Resistance Problem

**Calculate.** Each resistor in this circuit has a resistance of  $30\ \Omega$ . Find the equivalent resistance of the circuit to the right. The battery in this circuit has a voltage rise of  $10\ \text{V}$ . What is the current flowing through the battery?



1) For the following two diagrams, indicate the N and S poles of the coil, and the direction of the induced current (electron flow).



⊙ or ⊗ ?

2) For each of the inducing actions in the diagrams below, predict:  
 a) Which of the poles formed on the coiled conductor is the north pole  
 b) The direction of the induced current (electron flow)

