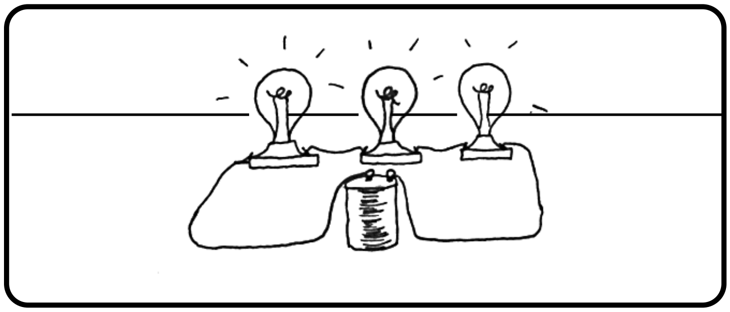
Name ______________________ Date(YY/MM/DD) ______/_________/_______
St.No. __ __ __ __ __-__ __ __ __ Section__________

UNIT 102-3: BATTERIES, BULBS, AND CURRENT FLOW*



We have in us somewhere knowledge... of the taste of strawberries... When we bite into a berry, we are ready to taste a certain kind of taste; if we taste something very different, we are surprised. It is this – what we expect or what surprises us – that tells us best what we really know.

– John Holt

OBJECTIVES

1. To understand how a potential difference results in a current flow through a conductor.

2. To learn to design and wire simple circuits using batteries, wires, and switches.

3. To learn to use symbols to draw circuit diagrams.

4. To understand the use of ammeters and voltmeters for measuring current and voltage respectively.

5. To understand the relationship between the current flows and potential differences in series and parallel circuits.

6. To understand the concept of resistance.

* Portions of this unit are based on research by Lillian C. McDermott & Peter S. Shaffer published in AJP 60, 994-1012 (1992).

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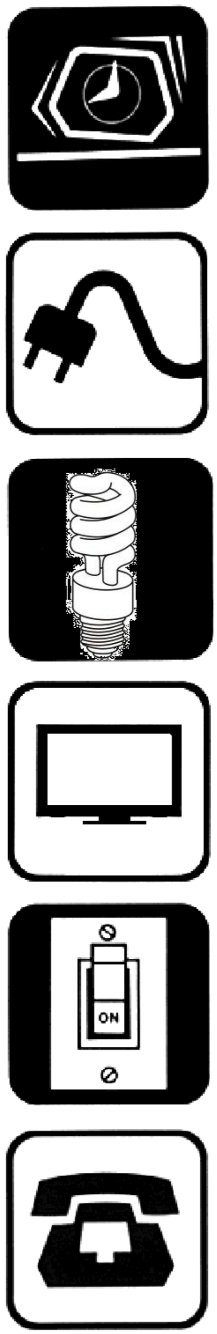
OVERVIEW



In the following sessions, we are going to discover, extend, and apply theories about electric charge and potential difference to electric circuits. The study of circuits will prove to be one of the more practical parts of the whole physics course, since electric circuits form the backbone of much of twentieth century technology. Without circuits we wouldn't have electric lights, air conditioners, automobiles, cell phones, TV sets, dishwashers, computers, or DVD players.

In the last unit you used a battery to establish a potential difference (or voltage) across two electrodes. *Battery* is a term applied to any device that generates an electrical potential difference from other forms of energy. The type of batteries you are using in this course are known as chemical batteries because they convert internal chemical energy into electrical energy.

As a result of a potential difference, an electrical charge can be repelled from one terminal of the battery and attracted to the other. No charge can flow out of a battery unless there is a conducting material connected between its terminals. A flow of charge can cause a small light bulb to glow.

In this unit, you are going to explore how charge originating in a battery flows in wires and bulbs. You will be asked to develop and explain some models that predict how the charge will flow in series and parallel circuits. You will also be asked to devise ways to test your models using a computer-based laboratory device that can measure the rate of flow of electrical charge through it or the potential difference between two points in a circuit.

SESSION ONE: CURRENT FLOW AND POTENTIAL DIFFERENCE

What is Electric Current?

The rate of flow of electric charge is more commonly called *electric current*. If charge is flowing through a conductor then the official mathematical definition of the average current is given by

$$< i > \equiv \frac{\Delta Q}{\Delta t}$$

Instantaneous current is defined in the usual way with a limit:

$$i \equiv \lim_{\Delta t \to 0} \frac{\Delta Q}{\Delta t} = \frac{dQ}{dt}$$

The unit of current is called the ampere (A). One ampere represents the flow of one coulomb of charge through a conductor in a time interval of one second.

15 min

Circuit Diagrams

Now that you have been wiring circuits and drawing diagrams of them you may be getting tired of drawing pictures of the batteries, bulbs, and switches in your circuits. There are a series of symbols that have been created to represent circuits. These symbols will enable you to draw the nice neat square looking circuits that you see in physics textbooks. A few of the electric circuit symbols are shown below.

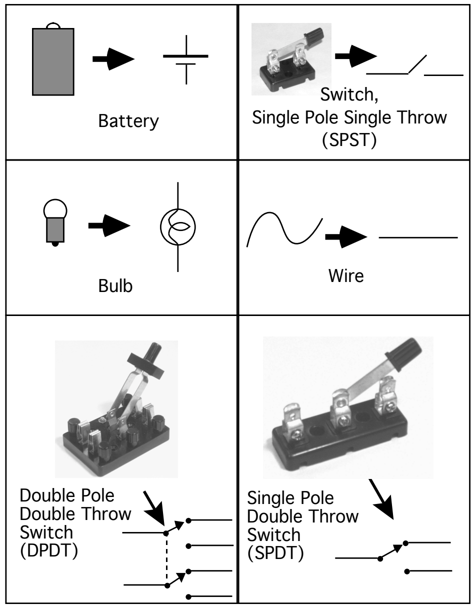


Figure 3-3: Circuit Symbols

Using these symbols, the standard circuit with a switch, bulb, wires, and battery can be represented as in the diagram below.

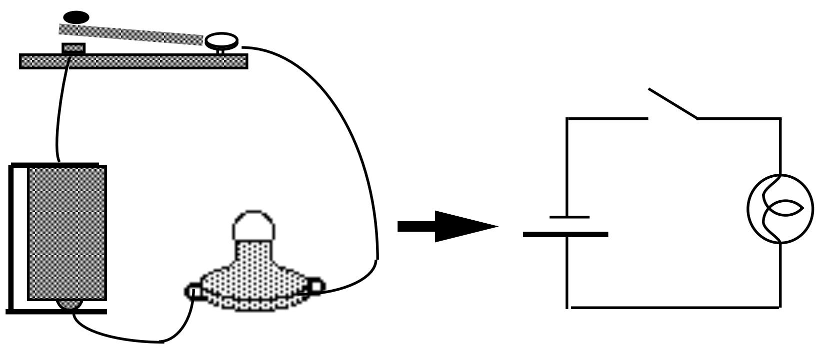
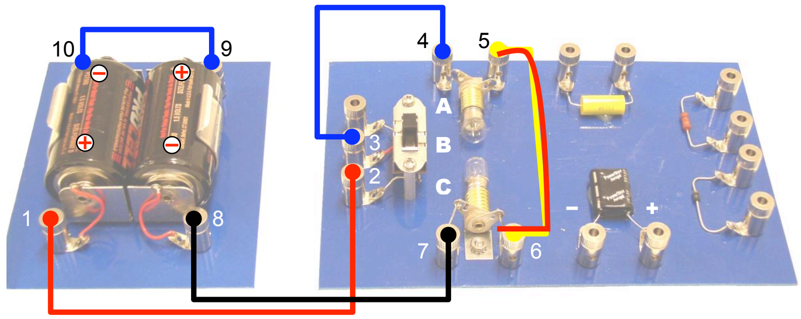


Figure 3-4: A circuit sketch and corresponding diagram

✍ Activity 3-2: Drawing Circuit Diagrams

(a) On the battery symbol, which line represents the positive terminal? The long one or the short one? **Note**: You should try to remember this convention for the battery polarity because some circuit elements, such as *diodes*, behave differently if the battery is turned around so it has opposite polarity.

(b) Below is a photograph of a circuit that is built on a circuit construction kit. The wires are shown as blue and red lines. Draw a textbook circuit diagram of the circuit using the correct schematic symbols. (Each battery cell should use one battery symbol.)


10
9
4
5
3
2
1
8
A
B
C
7
6
–
+

30 min

Developing a Model for Current Flow in a Circuit

Several models for current flow in the circuit might be proposed. Four are diagrammed below.

After you have discussed the various ideas you will be asked to figure out how to use one or more ammeters in your circuit to measure current and test your model.

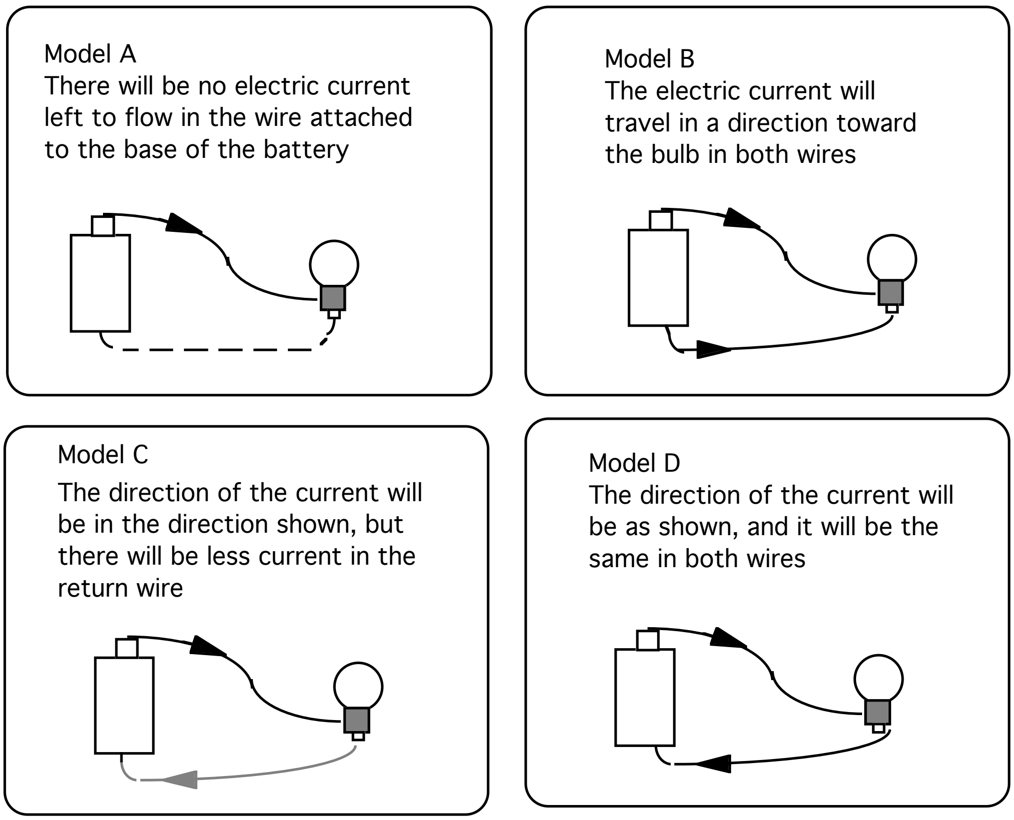
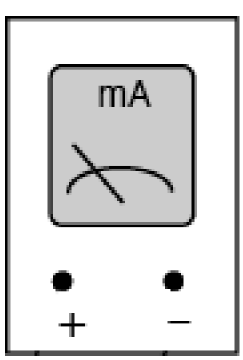


Figure 3-5: Four alternative models for current flow

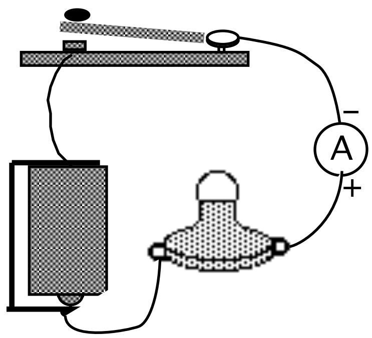
Measuring Current with an Ammeter



The ammeter is a device that measures current and displays it. It will allow you to explore the current flowing at different locations in an electric circuit.

Current is typically measured in amperes (A) or milliamperes (mA). (1 ampere = 1000 milliamperes.) Usually we just refer to current as "amps" or "milliamps".

To measure the current flowing through a part of the circuit, you must "insert" the ammeter at the point of interest. Disconnect the circuit, put in the ammeter, and reconnect with it in place. For example, to measure the current in the right-hand wire of the circuit in Figure 3-4 the ammeter could be connected as shown below (We will be using a circle with a capital A on it to represent an ammeter.):



The ammeter measures both the *magnitude* and *direction* of current flow. A current flowing in through the positive (+) terminal and out through the negative (–) terminal will be displayed as a positive current.

Discovering Models for Current Flow that Work

Discuss the various current flow models with your partners, and design measurements that will allow you to choose the model or models that best describe the actual current flowing through the circuit. (For example, to see if the current has a different magnitude or direction at different points in a circuit (e.g. model B or model C) you should connect two ammeters in various locations around the circuit.

To investigate current flow models you will need:

- 1 ammeter, 0.25 A
- 1 digital multimeter
- 2 #14 bulbs with holder
- 1 D-cell battery and holder
- 1 SPST switch
- 6 alligator clip wires

Describe your test (or tests) in the space below as well as your choice of the best model as a result of these tests.

✍ Activity 3-3: Picking a Model for Current Flow

(a) Describe your tests. Include drawings of the circuits you used, showing where the ammeters were connected.

(b) Which model or models seem to work? Is the current different at different locations in the circuit? Explain how you reached your conclusion based on your observations.

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30 min

Measuring Potential Difference with a Voltmeter

Since a battery is a device that has a potential difference across its terminals, it is capable of giving energy to charges, which can then flow as a current through a circuit. Exploring the relationship between the potential differences in a circuit and the currents that flow in that circuit is a fundamental part of developing an understanding of how electrical circuits behave.

Because potential differences are measured in volts, a potential difference is often informally referred to as a *voltage*.

Let's measure voltage in a familiar circuit. Besides the ammeters you have been using so far to measure current, there are voltmeters to measure voltage. Figure 3-6 shows the symbols we will use to indicate a voltmeter and an ammeter.

Figure 3-6: Symbols for a voltmeter (left) and an ammeter (right). The + sign on the voltmeter should be at the higher potential if the voltmeter reads positive. If the current in the ammeter flows from + to – then the ammeter reads positive.

Figure 3-7 shows a simple circuit with a battery, a bulb, and two voltmeters connected to measure the voltage *across* the battery and the voltage *across* the bulb. The circuit is drawn again symbolically on the right. Note that the word *across* is very descriptive of how the voltmeters are connected to measure voltage.

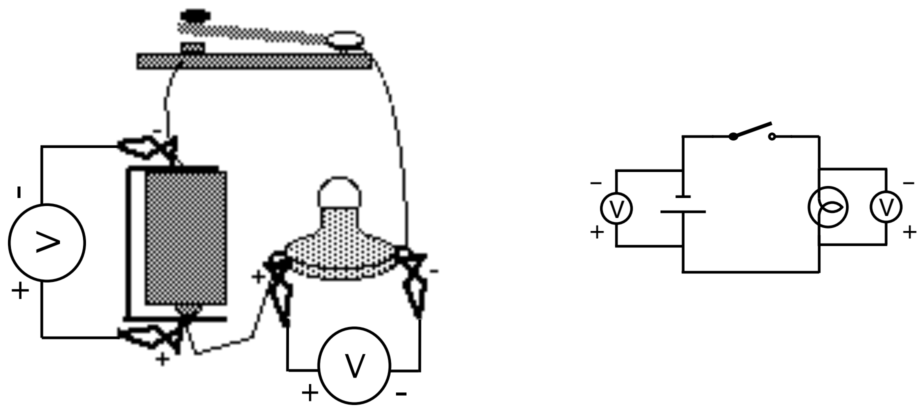
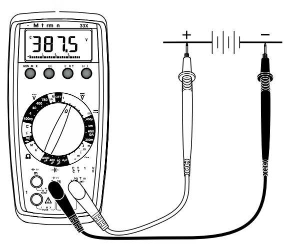


Figure 3-7: Two voltmeters connected to measure the voltage across the battery and the bulb.

To do the next few activities, you will need:

- a D-cell alkaline battery and holder
- 2 #14 light bulbs
- a SPST switch
- a digital voltmeter
- an ammeter, 0.25 A



A Digital Multimeter (DMM) used as a voltmeter and connected to a battery.

✍ Activity 3-4: Voltage Measurements in a Simple Circuit

(a) First connect both the + and the - clips of the voltmeter to the same point in the circuit. Observe the reading. What do you conclude about the voltage when the leads are connected to each other (i.e. not across anything else)?

(b) In the circuit in Figure 3-7, predict the voltage across the battery compared to the voltage across the bulb. Explain your predictions.

(c) Now test your prediction. Connect the circuit in Figure 3-7. Use the voltmeter to measure the voltage *across* the battery and then use it to measure the voltage *across* the bulb.

Voltage across the Battery	Voltage across the bulb

What do you conclude about the voltage across the battery and the voltage across the bulb?

Now let's measure voltage and current in your circuit at the same time. To do this, connect a voltmeter and an ammeter so that you are measuring the voltage *across* the battery and the current *entering* the bulb at the same time. (See Figure 3-8.)

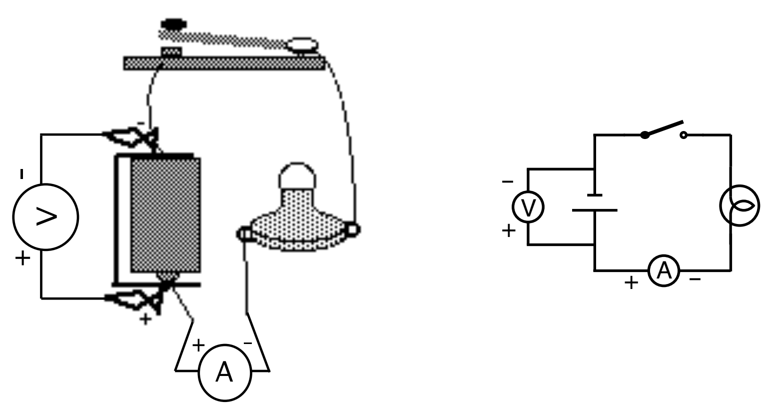


Figure 3-8: Meters connected to measure the voltage across the battery and the current through it. (The positive terminal of the battery is at the bottom.)

✍ Activity 3-5: Current and Voltage Measurements

(a) Measure the voltage across the battery when the switch is closed and the light is lit. Enter the value in the table below in Activity 3-6d

(b) Measure the current through the circuit when the switch is closed and the light is lit. Enter the value in the table below in Activity 3-6d

Now suppose you connect a second bulb, as shown in Figure 3-9.

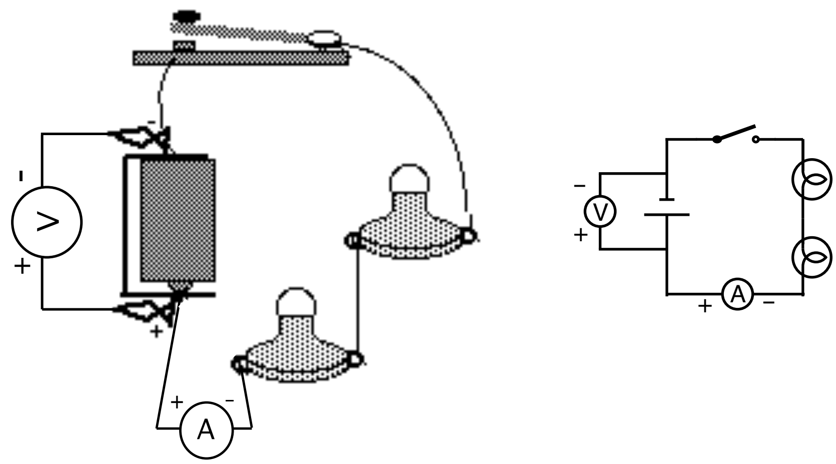


Figure 3-9: Two bulbs connected in series with a voltmeter and an ammeter.

✍ Activity 3-6: Current and Voltage Measurements with Two Bulbs

The predictions below should be completed before class.

(a) How do you think the voltage across the battery will compare to that with only one bulb? (More, less or the same within measurement error?)

(b) What do you think will happen to the brightness of the first bulb when you add a second bulb? Explain.

(c) What will happen to the current drawn from the battery? Explain.

(d) Connect a second bulb as shown, and test your predictions. Measure the voltage across both the bulbs and the current entering both bulbs with the switch closed and record in the table.

Measurements 3-5 and 3-6	1 bulb	2 bulbs
voltage		
current		

(e) Did the addition of the second bulb seem to affect the battery voltage very much?

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(f) Did the first bulb dim when you added the second one to the circuit? What happens to the current drawn from the battery?

(g) Explain what you think the battery is doing and why the differences in voltage and current (if any) occur when a second bulb is added.

(h) Is the battery more like a “constant current source” or a “constant voltage source”?

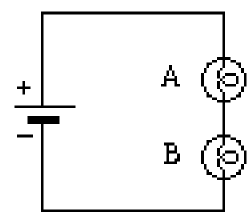

Figure 3-10: A series circuit with one battery and two bulbs. (Note that the battery polarity is reversed from the previous figures. This is the conventional orientation for schematic diagrams.)

✍ Activity 3-7: More Current and Voltage Measurements with Two Bulbs

(a) Explore the current flowing at various points in the series circuit of 3-10. Use an ammeter and insert the ammeter at various places, removing the wires as necessary. to find

The current entering Bulb A
The current flowing from Bulb A to Bulb B
The current leaving Bulb B

Enter the data in the following table:

Current flowing into Bulb A	Current flowing from Bulb A to B	Current flowing out of Bulb B

(b) Formulate a rule about the current flowing through the different parts of a series circuit.

(c) Now measure the voltages across both bulbs and compare to the voltage of the battery.

Element	Voltage
Bulb A	
Bulb B	
Battery	

(d) Formulate a rule about voltages across the elements of a series circuit.

SESSION TWO: SERIES AND PARALLEL CIRCUITS

In the last session you saw that, when an electric current flows through a light bulb, the bulb lights. You also saw that to get a current to flow through a bulb you must connect the bulb in a complete circuit with a battery. A current will only flow when it has a complete path from the positive terminal of the battery, through the connecting wire to the bulb, through the bulb, through the connecting wire to the negative terminal of the battery, and through the battery.

By measuring the current at different points in the simple circuit consisting of a bulb, a battery and connecting wires, you discovered a model for current flow, namely that the electric current was the same in all parts of the circuit. By measuring the current and voltage in this circuit and adding a second bulb, you also discovered that a battery supplies essentially the same voltage whether it is connected to one light bulb or two.

In this session you will examine more complicated circuits than a single bulb connected to a single battery. You will compare the currents through different parts of these circuits by comparing the brightness of the bulbs, and also by measuring the currents with ammeters.

Devising Your Own Rules to Explain Current Flow
In the next series of exercises you will be asked to make a number of predictions and then to confirm your predictions with actual observations. Whenever your observations and predictions disagree you should try to develop new concepts about how circuits with batteries and bulbs actually work. In order to make the required observations you will need:

- A fresh D-cell alkaline battery in a holder
- 6 wires with alligator clip leads
- 4 #14 bulbs in sockets
- a SPST switch
- one ammeter, 0.25A

Consider the two circuits shown in Figure 3-13. Assume that all batteries are identical and that all bulbs are identical. What do you predict the relative brightness of the various bulbs will be? (Remember that you saw in the last session that the battery supplies essentially the same voltage whether there is one light bulb or two.)

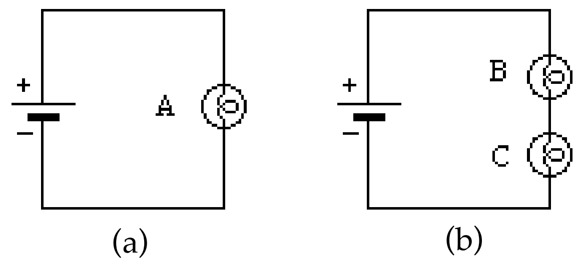

Figure 3-13: Two different circuits with identical components–**(a)** a battery with a single bulb; **(b)** a battery with two bulbs

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25 min

Current and Voltage In Parallel Circuits

There are two basic ways to connect resistors (such as bulbs) in a circuit – *series* and *parallel.* So far you have been dealing with bulbs wired in series. To make predictions involving more complicated circuits we need to have a more precise definition of series and parallel. These are summarized in the box below.

Series Connection:
Two resistors are in series if they are connected so the *same* current that passes through one bulb passes through the other.

Parallel Connection:
Two resistors are in parallel if their terminals are connected together so that *at each junction* one terminal of the one bulb is *directly* connected to the terminal of the other.

Figure 3-14 Series and Parallel Connections

Let's compare the behaviour of a circuit with two bulbs wired in parallel to the circuit with a single bulb. (See Figure 3-15.)

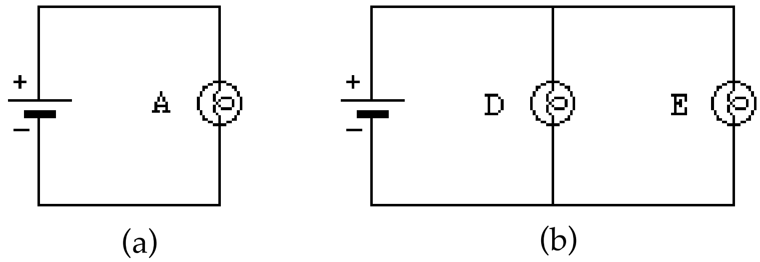

Figure 3-15: Two different circuits with identical components–**(a)** a single bulb circuit and **(b)** a parallel circuit.

Note that if bulbs A, D and E are identical, then the circuit in Figure 3-16 (below) is equivalent to circuit 3-15(a) when the switch is open (as shown) and equivalent to circuit 3-15(b) when the switch is closed.

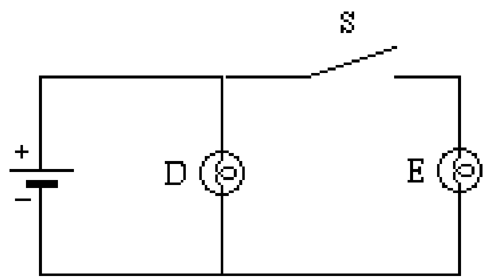

Figure 3-16: When the switch is open, only bulb D is connected to the battery. When the switch is closed, bulbs D and E are connected to the battery *in parallel*.

Now, let's make some predictions about the currents in the branches of a parallel circuit.

✍ Activity 3-9: Predicting Currents in a Parallel Circuit

(a) Predict the relative brightness of bulb A in Figure 3-15a with the brightness of bulbs D and E in Figure 3-15b. Which of the three bulbs will be the brightest? The dimmest? Explain the reasons for your predictions.

(b) How do you think that closing the switch in Figure 3-16 will affect the current through bulb D? Explain.

You can test your predictions in (a) and (b) by wiring up the circuit shown in Figure 3-16 and looking at what happens to the brightness of the bulbs as the switch is closed.

Note: Before you start the next activity make sure that (1) bulbs D and E have the same brightness when placed in series with the battery and (2) use a very fresh alkaline D-cell battery so it behaves like an "ideal" battery.

✍ Activity 3-10: Actual Currents in a Parallel Circuit

(a) Wire up the circuit in Figure 3-16 and, by opening and closing the switch, describe what you observe to be the actual relative brightness of bulbs A, D and E. (Very small changes may be due to your non-ideal battery.)

(b) Were the relative currents through bulbs A, D and E what you predicted? If not, can you now see why your prediction was incorrect?

(c) Did closing the switch and connecting bulb E in parallel with bulb D significantly affect the current through bulb D? How do you know?

What about the current from the battery? Is it always the same no matter what is connected to it, or does it change depending on the circuit? Is the current through the battery the same whether the switch in Figure 3-16 is open or closed? Make predictions based on your observations of the brightness of the bulbs, and test it using meters.

✍ Activity 3-11: Predicting Changes in Battery Current and Voltage

(a) Based on your observations of the brightness of bulbs D and E in Activity 3-11, how do you think that closing the switch in Figure 3-16 will affect the current from the battery? Explain.

(b) Based on your observations in Activity 3-11, how do you think that closing the switch in Figure 3-16 will affect the current through bulb D? Explain.

(c) Based on your observations in Activity 3-11, how do you think that closing the switch in Figure 3-16 will affect the voltage across the battery? Explain.

You can test your predictions by placing the voltmeter across the battery and inserting the ammeters in the circuit as shown in the following diagram.

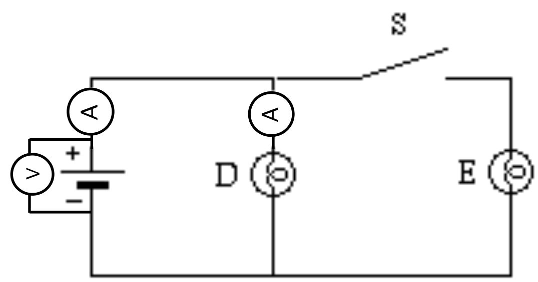

Figure 3-17: Meters connected to measure the current through the battery and the current through bulb D and the voltage of the battery when the switch is opened and closed.

✍ Activity 3-12: Observing Battery Voltage and Current

(a) Collect data while closing and opening the switch as before. Measure the currents through the battery and through bulb D. How does closing the switch in the circuit affect the voltage across the battery?

	Current from Battery	Current into Bulb D	Battery Voltage
Switch Open			
Switch Closed			

(b) Use your observations to formulate a rule to predict how the current through a battery will change as the number of bulbs connected *in parallel* increases. Can you explain why?

(c) Compare your rule in (b) to the rule you stated in Activity 3-9 (e) relating the current through the battery to the total *resistance* of the circuit connected to the battery. Does the addition of more bulbs in parallel increase, decrease, or not change the total *resistance* of the circuit?

(d) Explain your answer to (c) in terms of the number of paths available in the circuit for current flow.

(e) Does the amount of current through a battery appear to depend only on how many bulbs are in the circuit or does the arrangement of the bulbs matter also? (Don't forget your observations with bulbs in series in Activities 3-9 and 3-11!) Explain.

(f) Does the total resistance of a circuit appear to depend only on how many bulbs are in the circuit or does the arrangement of the bulbs matter also? Explain.

60 min

More Complex Series and Parallel Circuits

Applying your knowledge to a more complex circuit.
Consider the circuit consisting of a battery and two bulbs, A and B, in series shown in Figure 3-18(a). What will happen if you add a third bulb, C, in parallel with bulb B (as shown in Figure 3-18(b))? You should be able to answer this question about the relative brightness of A, B, and C based on previous observations. The tough question is: how does the brightness of A change?

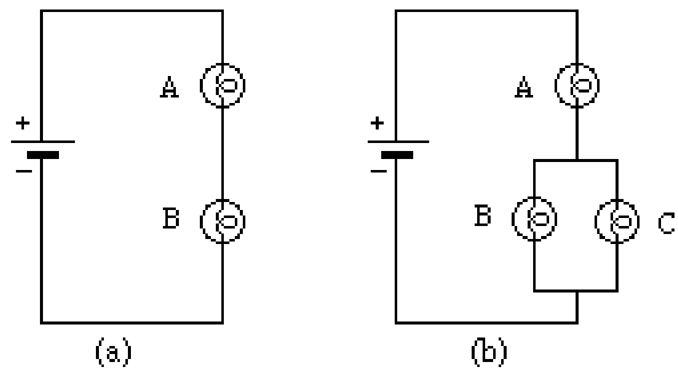

Figure 3-18: Two different circuits with identical components

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✍ Activity 3-13: Predictions About a More Complex Circuit

(a) In Figure 3-18 (b) is A in series with B alone, with C alone, or with a combination of B and C? (You may want to go back to the definitions of series and parallel connections given earlier in this session.)

(b) In Figure 3-18(b) are B and C in series or in parallel with each other? Explain.

(c) Is the resistance of the combination of B and C larger than, smaller than, or the same as B alone? Explain.

(d) Is the resistance of the combination of bulbs A, B and C in Figure 3-18(b) larger than, smaller than or the same as the combination of bulbs A and B in Figure 3-18(a)? Explain.

(e) Can you predict how the current through bulb A will change, if at all, when circuit 3-18 (a) is changed to 3-18 (b) (i.e. when bulb C is added in parallel to bulb B)? Explain the reasons for your answer.

(f) When bulb C is added to the circuit, what will happen to the brightness of bulb A? Explain.

(g) Finally, predict the relative rankings of brightness for all the bulbs, A, B, and C, after bulb C is added to the circuit. Explain the reasons for your answers.

Set up the circuit shown in Figure 3-19(a) below. You will need:

- 3 D-cell alkaline batteries
- 3 #14 light bulbs
- A SPST switch
- 2 ammeters, 0.25 A
- 1 digital voltmeter

Convince yourself that this circuit is identical to Figure 3-18(a) when the switch is open (as shown) and to 3-18(b) when the switch, S, is closed.

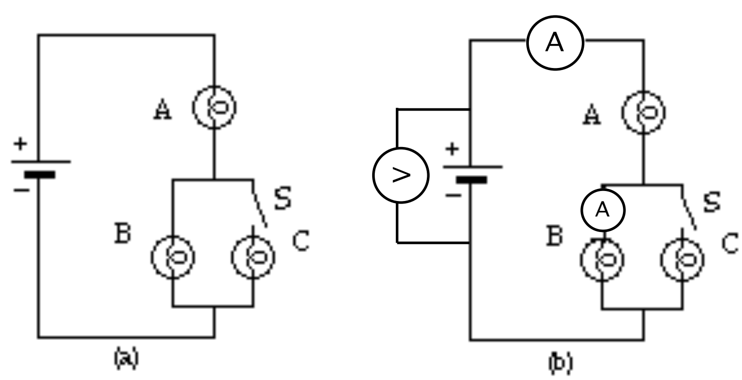


Figure 3-19: **(a)** Circuit equivalent to Figure 3-18(a) when the switch is open, and to Figure 3-18(b) when the switch is closed. **(b)** Same circuit with ammeters connected to measure the current through bulb A and the current through bulb B and a voltmeter to measure the battery voltage.

Now let's make some observations using this circuit.

✍ Activity 3-14: Observing a Complex Circuit

(a) Observe the brightness of bulbs A and B when the switch is open, and then the brightness of the three bulbs when the switch is closed (when bulb C is added). Compare the brightness of bulb A with and without C added, and rank the brightness of bulbs A, B, and C with the switch closed.

	Brightest		Dimmest
Switch Open			
Switch Closed			

If two bulbs have equal brightness, list them in the same box.

(b) If your observations and predictions of the brightness were not consistent, what changes do you need to make in your reasoning? Explain!

(c) Connect the two ammeters and the voltmeter as shown in Figure 3-19b. Measure what happens to the battery voltage and the voltage across bulb A. Also measure the current through bulb A and the current through bulb B when the switch is opened and closed. Record your measurements below:

Measurement	Switch Open	Switch Closed
Battery Voltage		
Bulb A Voltage		
*Bulb B Voltage**		
Bulb A Current		
Bulb B Current		

*This can be deduced from the other voltage measurements.

(d) What happens to the current from the battery and through bulb A when bulb C is added in parallel with bulb B? What do you conclude happens to the total resistance in the circuit? Explain.

Power

The brightness of a bulb depends on the product of the voltage across the bulb and the current through it. This product represents the power, or the electrical energy per unit time, used by the bulb:

Power: $P = VI$

If V is in volts and I in amperes then P is in watts.The electrical energy is converted to both heat and light so that the relationship of power to the brightness is not necessarily linear. Nevertheless, one should observe that the qualitative brightness increases with the power if the light bulbs are of the same manufacture. [1]

✍ Activity 3-15: Calculate the power of the light bulbs

(a) Use the voltage and current values in the table of 3-14 to calculate the power usage of the bulbs with both switch open and switch closed.

Power	Switch Open	Switch Closed
Bulb A		
Bulb B		
Bulb C		

(b) Does the power consumption of the bulbs correspond to the brightness ranking?

[1] Note that commercial light bulbs are rated by the power they dissipate when used at the standard voltage, e.g., 110 V in N. America or 220 V in Europe. If a light bulb is used at a voltage for which it was not intended then its power dissipation will not be the rated value. For example, if a 60 W bulb bought in Europe is used in N. America, its power usage is much less than 60 W.

Series and Parallel Networks

Let's look at a somewhat more complicated circuit to see how series and parallel parts of a complex circuit affect one another. The circuit is shown below.

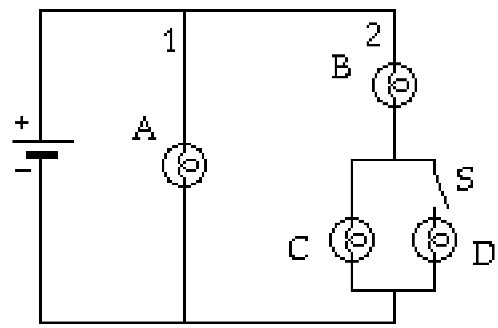


Figure 3-20: A complex circuit with series and parallel connections.

From your knowledge of current and voltage in parallel and series circuits you should be able to figure out what happens when the switch is closed.

✍ Activity 3-15: Series and Parallel Network

(a) Predict the effect on the current in branch 1 of each of the following alterations in branch 2: (i) unscrewing bulb B, and (ii) closing switch S.

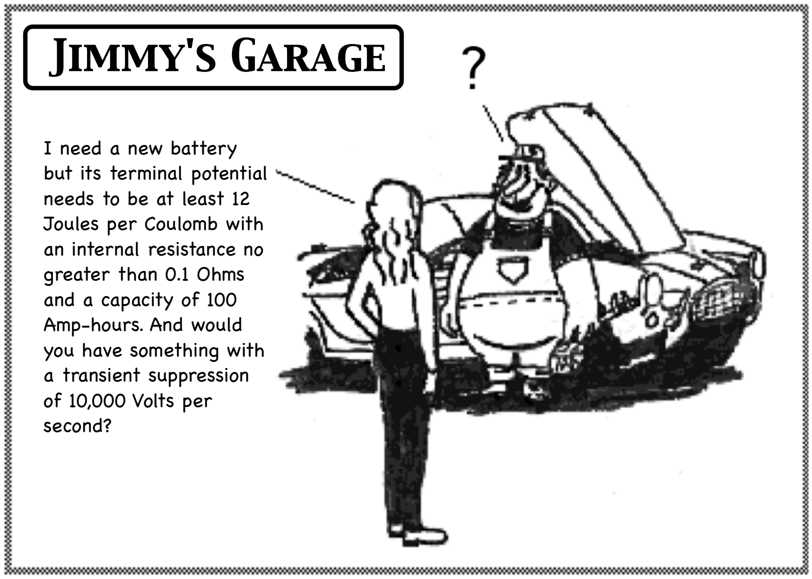
(b) Predict the effect on the current in branch 2 of each of the following alterations in branch 1: (i) unscrewing bulb A, and (ii) adding another bulb in series with bulb A.

(c) Connect the circuit in Figure 3-20, and observe the effect of each of the alterations in (a) and (b) on the brightness of each bulb. Record your observations for each case.

(d) Compare your results with your predictions. How do you account for any differences between your predictions and observations?

(e) In this circuit, two parallel branches are connected across a battery. What do you conclude about the effect of changes in one parallel branch on the current in the other?

SESSION THREE: OHM'S LAW & KIRCHHOFF'S LAWS



When a battery is fresh, the voltage marked on it is actually a measure of the electrical *potential difference* between its terminals. *Voltage* is an informal term for potential difference. If you want to talk to physicists you should refer to potential difference. Communicating with a sales person at the local store is another story. There you would probably refer to voltage. We will use the two terms interchangeably.

Let's explore potential differences in series and parallel circuits, and see if you can develop rules to describe its behaviour as we did earlier for currents. How do the potential differences of batteries add when the batteries are connected in series or parallel? Figure 3-11 shows a single battery, two batteries identical to it connected in series, and then two batteries identical to it connected in parallel.

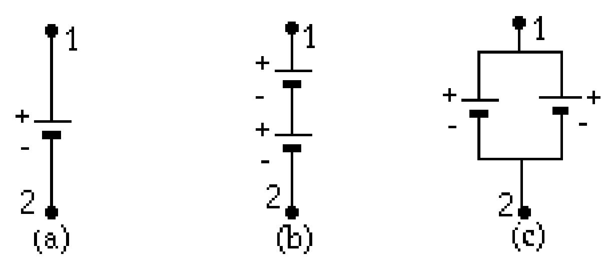


Figure 3-11: Identical batteries: **(a)** single, **(b)** two connected in series and **(c)** two connected in parallel.

You can measure potential differences with a voltmeter connected as shown in Figure 3-12.

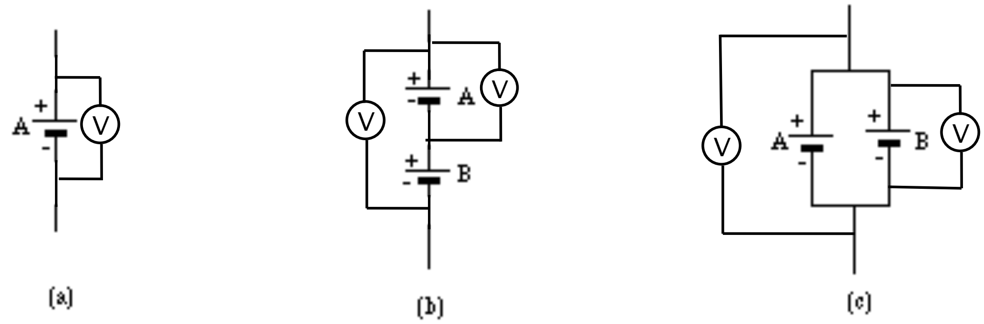


Figure 3-12: Voltmeters connected to measure the potential difference across **(a)** a single battery, **(b)** a single battery and two batteries connected in series, and **(c)** a single battery and two batteries connected in parallel.

✍Activity 3-12: Combinations of Batteries

(a) Predict the voltage for each combination of batteries in Fig 3-12. Write you prediction beside the meter symbols.
(b) Measure the voltages you predicted and write them below the predicted values on the figure.

Using a Multimeter

A digital multimeter (DMM) is a device that can be used to measure either current, voltage or resistance depending on how it is set up. We have already used one to measure voltage and current. The following activity will give you some practice in using it as an ohmmeter. You will need:

- A digital multimeter
- A D-cell alkaline battery w/ holder
- A SPST switch
- 4 alligator clip wires
- 1 resistor, 10 Ω

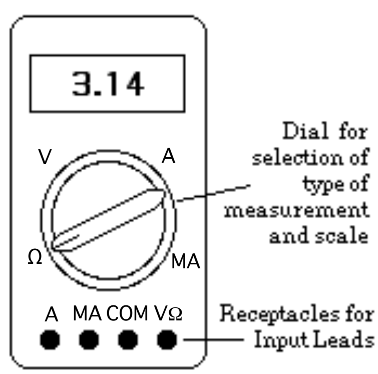


Figure 3-16: Diagram of a typical digital multimeter that can be used to measure resistances, currents, and voltages

By putting the input leads (red for positive, black for negative) into the proper receptacles and setting the dial correctly, you can measure resistances (Ω) as well as direct-current voltages (DCV) and currents (DCA).

Figure 3-17 shows two simple circuits to remind you how to take voltage and current readings with the multimeter which here acts as a voltmeter on the left and as an ammeter on the right.

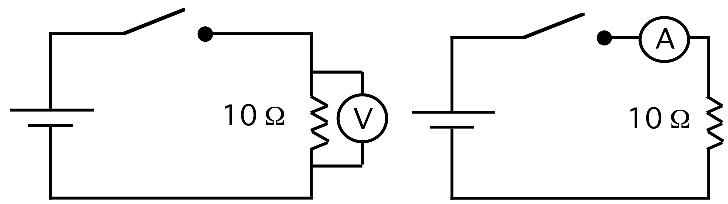


Figure 3-17: Simple circuits for using a multimeter to measure voltage and current.

Uncertainty of Multimeter Measurements

There are two sources of error to consider when measuring with a multimeter:

1. The effect of the meter on the circuit being measured and the consequent deviation of the value measured from what it was without the meter connected and
2. The possible error in calibration and the sensitivity of the meter's digital reading.

Voltage Measurements

Digital multimeters are usually designed so that very little current flows through them while they are being used. The technical jargon for this is "high input impedance" which means in practice that it acts like a very large resistor. Most digital multimeters can be assumed to have an input impedance of 1 MΩ or 10 MΩ. Thus if you measure the potential difference across a component with resistance comparable to the meter's then the effect of the parallel resistance of the meter should be considered. For components whose resistances are much smaller, then one can ignore the meter's effective resistance.

The meter reading is subject to uncertainty caused by two influences:
(1) the calibration of the meter and
(2) the digitization error of the numerical reading.

Normally calibration error is expressed as a percentage of the value. The digitization error is usually expressed as a ± range on the last digit. For example the technical specifications of our Meterman 33XR multimeters state that for DC voltage measurements the error is

$$\pm(0.7\% + 1 \text{ digit})$$

One calculates the uncertainty as 0.7% of the reading plus one digit in rightmost digit of the reading. For example

2.47 V would have an error of

	±0.7% × 2.47 V =	±0.02 V added to
		±0.01 V
resulting in a total error of		±0.03 V.

(We do not add these two contributions in quadrature.)

Current Measurements

Current measurements need to have the meter inserted in series with the circuit elements. Digital multimeters are apt to have a significant resistance compared to the other circuit elements, and the amount of resistance depends on the scale setting. For higher currents such as around 1 A the resistance could be a few ohms, but for milliampere ranges internal resistances could be as high as a kΩ. (Sometimes this is specified as "voltage burden" because there's an unwanted voltage across the meter while it's being used.) The result is that the meter causes the current being measured to be smaller than it would be without the meter.

The error on current measurements depends on the scale. For most scales it is listed as ±(1%+1digit) for the 33XR Meterman DMM

Resistance Measurements

Resistance measurements combine both voltage and current measurement. A meter has to provide a voltage and measure the current for that voltage and then presents the ratio of voltage to current as the resistance value. Because the meter has to provide an exact voltage across the component being measured it's important to ensure that no other sources of voltage are connected which would interfere with the measurement. Similarly, the current from the meter must flow only through the component being measured. Therefore, the component must be disconnected from any other circuit element while the resistance is being measured. If the component is being tested in circuit, at least one end must be disconnected while measuring its resistance. While you're measuring the resistance of something you must make sure that it is not connected to anything else. Even having your fingers touching the leads can cause an erroneous measurement due to the body's resistance in parallel.

Because both voltage and current are involved in measuring resistance, it is normal that the uncertainty is somewhat more than that for voltage or current. Most scales have a listed error of ±(1%+4 digits) for the 33XR Meterman DMM.

AC/DC

Both current and voltage functions of a multimeter have alternating current and direct current scales. Most of our measurements should use the direct current setting. If you get reading of almost zero when you expect a larger value, then check if the meter is set on AC instead of DC. The specified error on AC measurements is typically larger than for DC measurements.

Other Measurements

Many DMMs have the ability to make various other measurements depending on the model. Some can measure frequency, capacitance, temperature, inductance or transistor current amplification. These may be very useful in some situations, but the three basic measurements are essential and should be mastered first.

✍Activity 3-15: Using a Multimeter

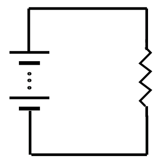
(a) Set up the circuit shown in Figure 3-17 with the switch open. Figure out what settings you need to use to measure the actual resistance of the "10Ω" resistor. Record your measured value below.

(b) Now close the switch and measure the actual resistance of the "10Ω" resistor again. Is your result different? If so, what do you think is the cause of this difference?

Ohm's Law: Relating Current, Potential Difference and Resistance

You have already seen on several occasions that there is only a potential difference across a bulb when there is a current flowing through the bulb. In this activity we are going to use a resistor and compare its characteristics to a light bulb. Resistors are designed to have the same resistance value no matter how much current is passing through. How does the potential difference across a resistor depend on the current through it? In order to explore this, you will need the following:

- 2 digital multimeters
- 4 D-cell alkaline batteries with holders
- 1 resistor, 68 Ω
- 1 SPST switch



Use 1 to 4 batteries to vary the voltage, ΔV applied to a resistor. After measuring I and ΔV, plot the I vs ΔV graph for each. A graph of I vs. ΔV is called the "characteristic curve" and the resistance is the inverse of its slope.

✍Activity 3-16 Experimental Relationship of *I* and ΔV

a) Set up a circuit to test your prediction by placing the resistor in series with one, two, three and then four batteries. Set up the multimeters as a voltmeter and ammeter to measure the voltage across the resistor and the current through it. Carefully describe your procedures and sketch your circuit diagram.

b) Record your data for I vs ΔV in the table below. Record values and uncertainties.

Number of Batteries	ΔV (Volts)	I (Amps)
1		
2		
3		
4		

c) Using a spreadsheet create a graph of I vs ΔV for both resistor. Draw a line through the points that starts at 0,0. Submit your graphs to WebCT.

Ohm's Law and Resistance

The relationship between potential difference and current which you have observed for a resistor is known as Ohm's law. To put this law in its normal form, we must now define the quantity known as resistance. Resistance is defined by:

$$R \equiv \Delta V/I$$

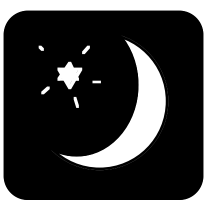
If potential difference (ΔV) is measured in volts and current (I) is measured in amperes, then the unit of resistance (R) is the ohm, which is usually represented by the Greek capital letter Ω, "omega."

✍Activity 3-17: Statement of Ohm's Law

a) State the mathematical relationship found in Activity 3-16 between potential difference and current for a resistor in terms of ΔV, I, and R.

b) Based on your graph, what can you say about the value of R for a resistor — is it constant or does it change as the current through the resistor changes? Explain.

c) From the slope of your graph, what is the experimentally determined value of the resistance of your resistor in ohms? How does this agree with the rated value of the resistor?



d) Complete the famous pre-exam rhyme used by countless introductory physics students throughout the English speaking world:

Twinkle, twinkle little star, ΔV equals ______ times ______

Note: Some circuit elements do not obey Ohm's law. The definition for resistance is still the same, but, as with a light bulb, the resistance changes because of temperature changes resulting from the flow of current. Circuit elements which follow Ohm's law over a wide range of conditions--like resistors--are said to be *ohmic*, while circuit elements which do not--like a light bulb--are *nonohmic*.

Resistance and Its Measurement

In the series of observations you have been making with batteries and bulbs it is clear that electrical energy is being transferred to light and heat energy inside a bulb, so that even though all the current returns to the battery after flowing through the bulb, the charges have lost potential energy. We say that when electrical potential energy is lost in part of a circuit, such as it is in the bulb, it is because that part of the circuit offers *resistance* to the flow of electric current.

A battery causes charge to flow in a circuit. The electrical resistance to the flow of charge can be compared to the mechanical resistance offered by the pegs and the barrier in a mechanical model depicted by a ramp with balls travelling down it as described in Unit 22.

A light bulb is one kind of electrical resistance. Another common kind is provided by a resistor manufactured to provide a constant resistance in electrical circuits.

Resistors are the most standard sources of resistance used in electrical circuits for several reasons. A light bulb has a resistance which increases with temperature and current and thus doesn't make a good circuit element when quantitative attributes are important. The resistance of resistors doesn't vary with the amount of current passing through them. Resistors is that they are inexpensive to manufacture and can be produced with low or high resistances.

A typical resistor contains a form of carbon, known as graphite, suspended in a hard glue binder. It usually is surrounded by a plastic case with a colour code painted on it. It is instructive to look at samples of resistors that have been cut down the middle as shown in the diagram below.

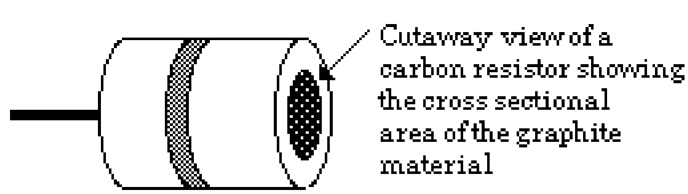


Figure 3-18: A cutaway view of a resistor

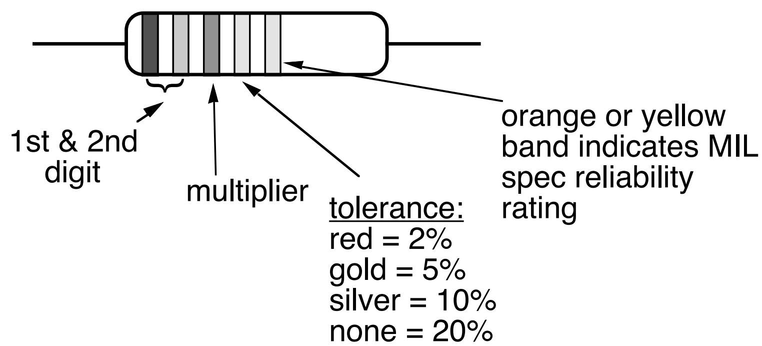
As you found in the previous activity on Ohm's Law, a simple equation can be used to define electrical resistance in terms of of potential difference, ΔV, across it and the current, I, through it. It is

$$R \equiv \Delta V/I$$

A resistor is usually marked with coloured bands to

signify its resistance value in ohms.

Resistor Colour Code



digit	colour	multiplier	# zeros
	silver	0.01	–2
	gold	0.1	–1
0	black	1	0
1	brown	10	1
2	red	100	2
3	orange	1k	3
4	yellow	10k	4
5	green	100k	5
6	blue	1M	6
7	violet	10M	7
8	grey		
9	white		

For example, a resistor with bands of yellow-violet-red-silver has a value of: $47\times10^2 \pm 10\%\ \Omega$ or 4.7 kΩ.

Suppose you have finally graduated and taken a job as a quality control inspector for a company that makes resistors. Your task is to determine the rated resistance in ohms of a batch of five resistors and then check your decoding skills by measuring the resistance with a digital multimeter. For this activity you'll need:

• A digital multimeter
• 5 assorted colour-coded resistors

✍Activity 3-18: Decoding and Measuring Resistors

a) Decode the 3 resistors and write their colour codes and "Coded R" values in the first two columns of the following table.

Colour Sequence	Coded R Ω	Measured R Ω	Calculated Percent Difference	Percent Tolerance	Within rated tolerance? Yes No
					☐ ☐
					☐ ☐
					☐ ☐

b) Measure the resistance of each of your resistors with the multimeter. Fill in the values in the third column of the table above. (Include uncertainties.)

c) Calculate the percent difference between the coded *R* and the measured *R* for each resistor using the following formula:

$$\text{percent difference} = \frac{|\text{coded } R - \text{measured } R|}{\text{coded } R} \times 100\%$$

Record this result for each resistor in the fourth column.

d) Record the percent tolerance of each resistor in the fifth column.

e) Are your resistor values correct within the rated tolerance values? Record your results in the last column and comment on whether this resistor manufacturer did a good job below.

Resistors in Parallel and Series

The resistance of a wire is directly proportional to length. The resistance also depends on the cross-sectional area of the wire. It is possible to control the *R*-value of a wire fairly precisely by varying these quantities.

Several identical resistors can be wired in *series* to increase their effective length and in *parallel* to increase their effective cross-sectional area as shown in the next diagram.

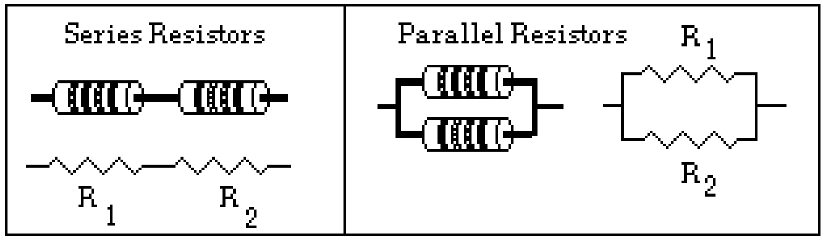


Figure 3-19: Resistors wired in series and in parallel

In order to test your predictions and do some further exploration of equivalent resistances of different combinations of resistors you will need the following

- 2 resistors, ~100 Ω
- 2 resistors, ~220 Ω
- 2 resistors, ~330 Ω
- 1 digital multimeter
- 6 connecting wires with alligator clips

Using the items listed above, you will devise a way to measure the equivalent resistance when three or more resistors are wired in series.

✍Activity 3-19: Resistances for Series Wiring

(a) If you have three different resistors, what do you think the equivalent resistance to the flow of electrical current will be if the resistors are wired in *series*? Explain the reasons for your prediction based on your previous observations with batteries and bulbs.

(b) Compare the calculated and measured values of equivalent resistance of the series network as follows:

Write down the *measured* values of each of the three resistors:

R_1 = _________ Ω
R_2 = _________ Ω

R_3 = _________ Ω

Describe the method you are using to predict the equivalent resistance and calculate the predicted R value:

Predicted R_{eq} =_________ Ω

(c) Draw a diagram for the resistance network for the three *different* resistors *wired in series*. Mark the measured values of the three resistances on your diagram.

(d) Measure the actual resistance of the series resistor network and record the value:

Measured R_{eq} = _________ Ω

(e) How does this value compare with the one you calculated?

(f) On the basis of your experimental results, devise a *general* mathematical equation that describes the equivalent resistance when n resistors are wired in series. Use the notation R_{eq} to represent the equivalent resistance and $R_1, R_2, R_3, \ldots R_n$ to represent the values of the individual resistors.

Now you're going to devise a way to measure the equivalent resistance when two or more resistors are wired in *parallel*, Draw a symbolic diagram for each of the wiring configurations you use.

✍Activity 3-110: Resistances for Parallel Wiring

(a) If you have two *identical* resistors what to you think the resistance to the flow of electrical current will be if the resistors are wired in *parallel*? Explain the reasons for your prediction.

(b) Pick out two resistors with an identical colour code and draw a diagram for these two resistors *wired in parallel*. Label the diagram with the measured values R_1(measured) and R_2 (measured). Predict the equivalent resistance of the parallel circuit and record your prediction below. Measure the value of the equivalent resistance of the network. Explain your reasoning and show your calculations in the space below.

Predicted value: R_{eq} =_________ Ω

Measured value: R_{eq} = _________ Ω

(c) Pick out three *different* resistors and draw a diagram for these three resistors *wired in parallel*. Label the diagram with the measured values R_1 (measured) , R_2 (measured) and R_3 (measured). Measure the value of the equivalent resistance of the network and record it below.

Measured Value of the equivalent resistance of the network:

R_{eq} =_________ Ω

(d) Use the notation R_{eq} to represent the equivalent resistance and R_1, R_2, R_3, …, etc. to represent the values of the individual resistors. Show that, within the limits of experimental uncertainty, the results of the measurements you made with parallel resistors are the same as those calculated using the equation:

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots$$

1. For the two identical resistors wired in parallel:

Calculated Value: R_{eq} = _________ Ω

Measured Value: R_{eq} = _________ Ω

2. For the three resistors wired in parallel:

Calculated Value: R_{eq} = _________ Ω

Measured Value: R_{eq} = _________ Ω

(e) Show mathematically that if

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} \text{ then } R_{eq} = \frac{R_1 R_2}{R_1 + R_2}$$

Equivalent Resistances for Networks

Now that you know the basic equations to calculate equivalent resistance for series and parallel resistances, you can tackle the question of how to find the equivalent resistances for complex networks of resistors. The trick is to be able to calculate the equivalent resistance of each segment of the complex network and use that in the calculation of the next segment. For example, in the network shown below there are two resistance values R_1 and R_2. A series of simplifications is shown in the diagram below.

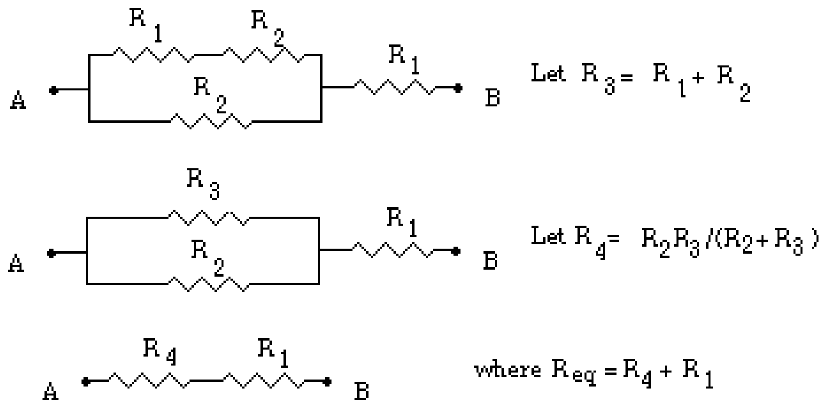


Figure 3-111: A sample resistor network

In order to complete the equivalent resistance activities you will need the following apparatus:

- 3 resistors, ~100 Ω
- 3 resistors, ~220 Ω
- 1 digital multimeter

✍Activity 23-11: The Equivalent Resistance for a Network

(a) In the following activity, use the 100 Ω resistor for R_1 and the 220 Ω resistor for R_2. Calculate the equivalent resistance between points A and B for the first network shown in Figure 3-111. *You must show your calculations on a step-by-step basis*.

(b) Set up the network of resistors and check your calculation by measuring the equivalent resistance directly. (Hint: Build the circuit in stages and check the equivalent resistance for each stage.)

Calculated Value: R_{eq} = _________ Ω

Measured Value: R_{eq} = _________ Ω

Theoretical Application of Kirchhoff's Laws

Suppose we wish to calculate the currents in various branches of a circuit that has many components wired together in a complex array. In such circuits, simplification using series and parallel combinations is often impossible. Instead we can apply a formal set of rules known as Kirchhoff's laws to use in the analysis of current flow in circuits. These rules can be summarized as follows:

Kirchhoff's Laws

1. ***Junction (or node) Rule (based on charge conservation):*** The sum of all the currents entering any node or branch point of a circuit (i.e. where two or more wires merge) must equal the sum of all currents leaving the node.

2. ***Loop Rule (based on energy conservation):*** Around any closed loop in a circuit, the sum of all emfs (voltage gains provided by batteries or other power sources) and all the potential drops across resistors and other circuit elements must equal zero.

Steps for Applying Rules

1. Assign a current symbol to each branch of the circuit and label the current in each branch I_1, I_2, I_3, etc.; then *arbitrarily* assign a direction to each current. (The direction chosen for the circuit for each branch doesn't matter. If you chose the "wrong" direction the value of the current will simply turn out to be negative.) Remember that the current flowing out of a battery is always the same as the current flowing into a battery.

2. Apply the loop rule to each of the loops by: (a) letting the potential drop across each resistor be the negative of the product of the resistance and the net current through that resistor (reverse the sign to "plus" if you are traversing a resistor in a direction opposite that of the current); (b) assigning a positive potential difference when the loop traverses from the – to the + terminal of a battery. (If you are going through a battery in the opposite direction assign a *negative* potential difference to the trip across the battery terminals.)

3. Find each of the junctions and apply the junction rule to it. You can place currents leaving the junction on one side of the equation and currents coming into the junction on the other side of the equation.

In order to illustrate the application of the rules, let's consider the circuit in Figure 3-112 below.

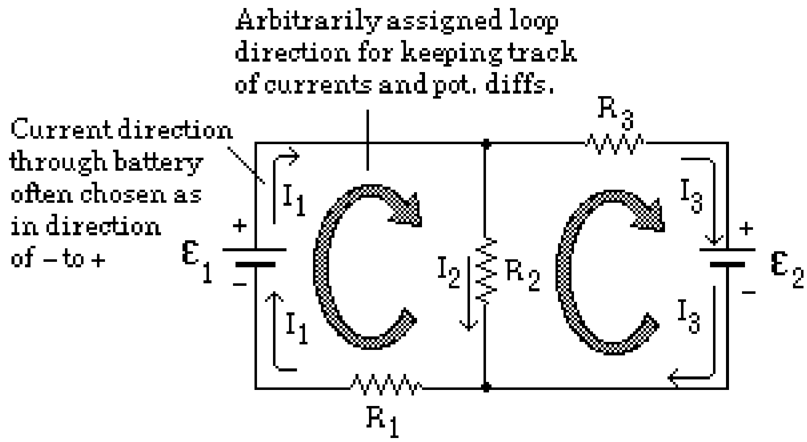


Figure 3-112: A complex circuit in which loops 1 and 2 share the resistor R_2. The currents I_1 and I_3 flow through R_2 in opposite directions and the net current through R_2 is denoted by I_2.

In Figure 3-112 the directions for the currents through the branches and for I_2 are assigned arbitrarily. *If we assume that the internal resistances of the batteries are negligible*, then by applying the loop and junction rules we find that

Loop 1 Eq.: $\mathcal{E}_1 - I_2 R_2 - I_1 R_1 = 0$ [Eq. 3-11]

Loop 2 Eq.: $-\mathcal{E}_2 + I_2 R_2 - I_3 R_3 = 0$ [Eq. 3-12]

Node 1 Eq.: $I_1 = I_2 + I_3$ [Eq. 3-13]

It is not obvious that the loops and their directions can be chosen arbitrarily. Let's explore this assertion theoretically for a simple situation and then more concretely with some specific calculations. In order to do the following activity you'll need a couple of resistors and a multimeter as follows:

- two resistors (rated values of ~39 Ω and ~68 Ω)
- A digital multimeter
- 3 D-cell batteries in holder
- 1 D-cell battery in holder

✍Activity 3-114: Applying the Loop Rule Several Times

(a) Use the loop and node rule along with the new arbitrary direction for I_2 to rewrite the three equations relating values of battery emfs, resistance, and current in the circuit shown in Figure 3-113 below.

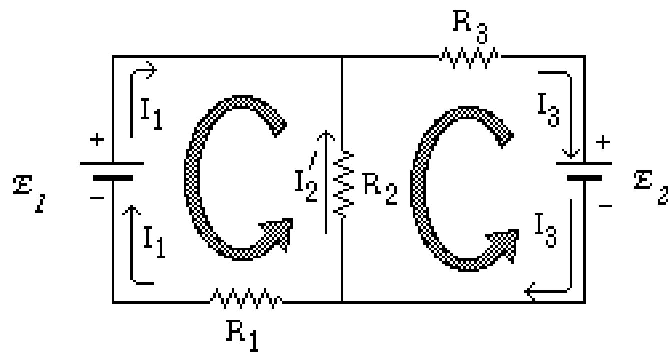


Figure 3-113: A similar complex circuit

(b) Show that if $I_2' = -I_2$ then the three equations you just constructed can be rearranged algebraically so they are *exactly the same* as Equations 3-11, 3-12 and 3-13.

(c) Suppose the values of each component for the circuit shown in Figure 3-113 shown above are rated as

$$\varepsilon_1 = 4.5 \text{ V}$$
$$\varepsilon_2 = 1.5 \text{ V}$$

Rated Fixed Resistances: $R_1 = 68\ \Omega$
$R_3 = 39\ \Omega$

Variable Resistance: $R_2 = 100\ \Omega$

1. Since you are going to test your theoretical results for Kirchhoff's law calculations for this circuit experimentally, you should measure the actual values of the two fixed resistors (rated at 68Ω and 39Ω) and the two battery voltages with a multimeter. List the results below.

Measured value of the battery emf rated at 4.5 V $\varepsilon_1 =$ ________

Measured value of the battery emf rated at 1.5 V $\varepsilon_2 =$ ________

Measured value of the resistor rated at 68 Ω: $R_1 =$ ________

Measured value of the resistor rated at 39 Ω: $R_3 =$ ________

2. Carefully rewrite Equations 3-11, 3-12 and 3-13 with the appropriate *measured* (not rated) values for emf and resistances substituted into them. Use 100 Ω for the value of R_2 in your calculation. You will be setting a variable resistor to that value soon.

(d) Solve these three equations for the three unknowns I_1, I_2 and I_3 in amps using one of the following methods: (1) substitution or (2) determinants.

(e) Show by substitution that your solutions actually satisfy the equations.

Verifying Kirchhoff's Laws Experimentally

Since circuit elements have become smaller in the past 30 years or so, it is common to design and wire simple circuits on a device called a breadboard. A breadboard has hundreds of little plastic holes in it that can have small diameter (22AWG) wire poked into them. In the breadboard model shown in Figure 3-114 below, these holes are electrically connected in vertical columns of 5 near the middle. The top of the breadboard has two horizontal rows of connected holes. There is a similar arrangement at the bottom.

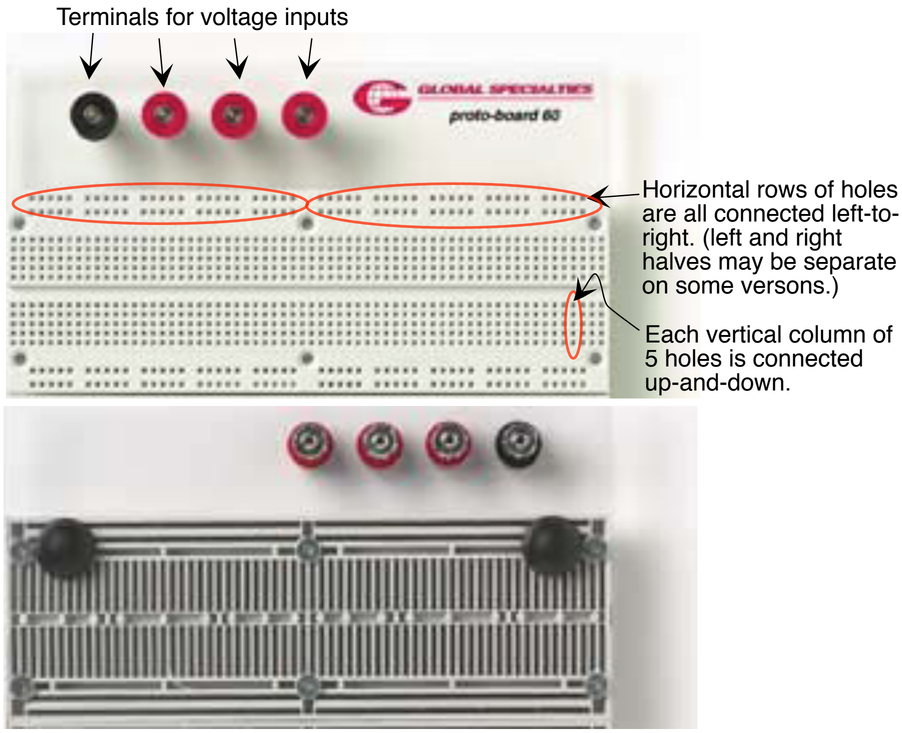


Figure 3-114: A "Proto-Board" breadboard. Top View and Bottom View. The bottom view reveals the connections among the holes.

Usually, one connects the voltage inputs to the long rows of connected dots toward the outside of the circuit; these rows can then serve as power supplies. As part of the next project with the breadboard you will be using some simple circuit elements to design a tricky circuit with more than one battery and several branches in it! To design this circuit you will be using the following items:

- 1 pot (200 Ω DIP style set at 100 Ω)
- 2 resistors (rated at 39 Ω and 68 Ω)
- 4 D-cell alkaline batteries in two holders (1,3)
- A "Proto-Board" breadboard
- A digital multimeter
- A small screw driver
- Assortment of small lengths of #22 wire

The word "pot" stands for potentiometer. It is a variable resistor. There is a 200 Ω pot already installed on your breadboard. The pot has three leads. The two outside leads are across the 200 Ω resistor while the centre lead taps off part of the 200 Ω . The resistance between an outside lead and the centre tap can be adjusted from 0 to 200 Ω with a screwdriver; the resistance between the two outside leads is always 200Ω. The circuit symbol for the pot is shown below.

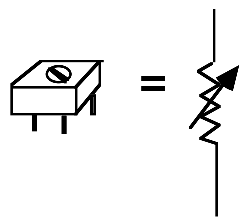


Figure 3-115: A breadboard pot

To wire up the circuit shown in Figure 3-112 on the breadboard, you will need to examine the details of how the breadboard is arranged, as shown in Figure 3-114.

✍Activity 3-115: Testing the Loop Rule with a Real Circuit

(a) Use the ohmmeter feature of the digital multimeter to measure the total resistance across a pot that is labelled 200 Ω. Then measure the resistance between the centre tap on the pot and one of the other taps. What happens to the ohmmeter reading as you use a small screwdriver to change the setting on the pot?

(b) Set the pot so that there is 100 Ω between the centre tap and one of the other taps.

(b) Wire up the circuit pictured in Figure 3-112 above; use a breadboard and the pot (set at 100 Ω) as R_2. Measure the current in each branch of the circuit and compare the measured and calculated values of the current by computing the % difference in each case.

Note: The most accurate way to measure current with a digital multimeter is to measure the potential difference across each of the resistors and use Ohm's law to calculate I from ΔV and R.

	Measured R	Measured ΔV	Measured $I = \Delta V/R$	Theoretical i	%Diff
1					
2					
3					

(c) What do you predict will happen to each of the currents as the resistance on the pot is decreased? That is, will the currents I_1, I_2, and I_3 increase or decrease? Explain your predictions.

(d) What actually happens to each of the currents as you decrease R_2? How good were your predictions?

PLEASE READ THE FOLLOWING OUTSIDE OF CLASS:

We will not be doing the following activity, but please read this section on your own time.

An Analogy to Potential Difference and Current Flow

The fact that you found that a current is not "used up" in passing through a bulb seems counterintuitive to many people trying to understand how circuits work. Many physics teachers have invented analogies to help explain this idea for an electric circuit. One obvious approach is to construct a model of a gravitational system that is in some ways analogous to the electrical system we are studying.

It is believed that the electrons flowing through a conductor collide with the atoms in the material and scatter off of them. After colliding with an atom, each electron accelerates again until it collides with another atom. In this manner, the electron finally staggers through the material with an average drift velocity v_d.

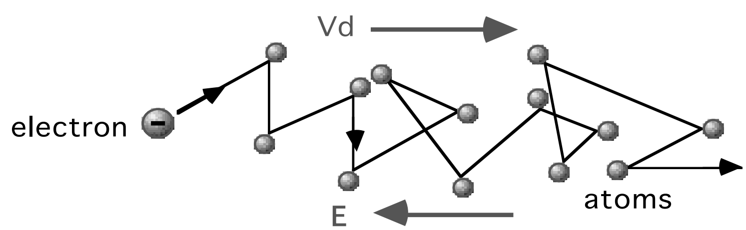


Figure 3-10: An electron in a uniform electric field staggering through a conductor as a result of collisions with atoms. Instead of accelerating it has an average drift velocity, v_d.

We can talk about the *resistance* to flow of electrons that materials offer. A thick wire has a low resistance. A light bulb with a thin filament has a much higher resistance. Special electric elements that resist current flow are called *resistors*. We will examine the behaviour of resistors in electric circuits in future sessions.

It is possible to use a two-dimensional mechanical analogue to model this picture of current flow through conductors. You should note that the real flow of electrons is a three-dimensional affair. The diagram for the two-dimensional analogue is reproduced in Figure 3-11.

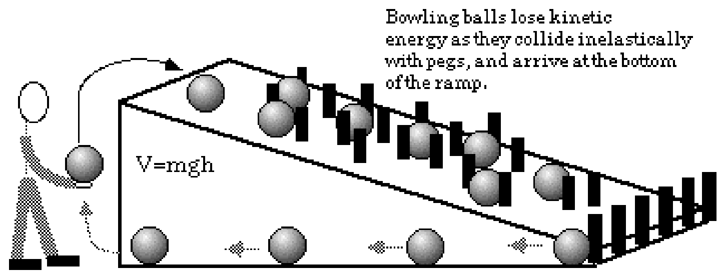


Figure 3-11: An analogue to electrical current flow.

Building a Working Model for Current Flow

In order to see how the model works, you should build it and play with it to see how it works.

To build the model you can take an adjustable wooden ramp and mount a piece of insulation board on it. Then push pins can be poked into the soft insulation board to simulate atoms. Graph paper can be placed on top of the insulation board to facilitate the spacing of the atoms. A marble can be used to represent an electron flowing through the circuit. Strips of poster board can be pinned into the sides of the insulation board to make side rails.

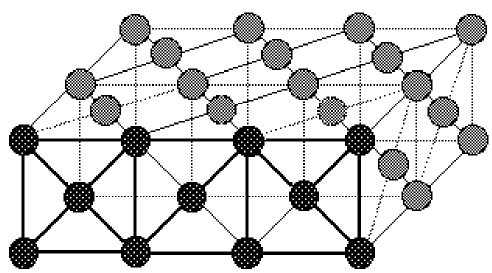


Figure 3-12: Arrangement of atoms in a face centred cubic crystal. The atoms in the foreground are represented by the dark circles.

By placing the board with face-centred pegs on the ramp and tilting it at an angle you can investigate the analogy between gravitational potential energy and the electrical potential energy stored in a battery. Suppose that the ramp is propped up so that one end is a height h above the other end and that a ball is rolled down the ramp with the pegs providing resistance to the flow of balls, and that a little person keeps lifting up a ball to the top to the ramp as soon as it reaches the bottom.

✍ Activity 3-7: Explaining the Features of the Model

(a) What would happen to the ball current (i.e. the rate of ball flow) if twice as many pegs were placed in the path of the ball?

(b) What would happen to the ball current if the ramp were raised to a height of 2*h*?

(c) Examine the list below and *draw lines between elements of the model and the corresponding elements of a circuit consisting of batteries and bulbs* (or other electrical resistors). In particular, what represents the electrical charge and current? What ultimately happens to the "energy" given to the bowling balls by the "battery"? What plays the role of the bulb? Where might mechanical energy loss occur in the circuit you just wired that consists of a battery, two wires, and a bulb?

Battery action	Rate of motion of bowling balls
Resistance of bulb	Person raising the balls
Current	Height of the ramp
Voltage of battery	Number of pegs

(d) How does this model help explain the fact that electric current doesn't decrease when it flows through the bulb?

(e)How does this ramp analogy support a model in which current doesn't accelerate when it flows through a circuit?

(f) In this model, what would happen to the "ball" current if the drift velocity doubles? What can you do to the ramp to increase the drift velocity?