Unit 3: Bulbs and Batteries--an Introduction to Electricity

In this unit, we will get some first exposure to electricity in the form of some familiar objects: light bulbs and batteries. Even with these everyday items, most people are still confused about how the electricity in them operates. This is not surprising, since although we can see the *effects* of the electricity, we are still unable to see the electricity itself. This units follows on the heels of the fluids units so that you can use the concepts developed there as visual, mental models to take the place of the electrical aspects that we cannot see.

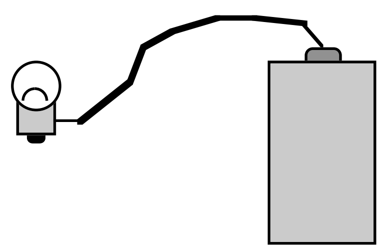
[This unit adapts many ideas and exercises developed originally at the University of Washington by A. Arons and L. McDermott and collaborators, which were further extended by P. Laws and J. Luetzelschwab at Dickinson College.]

Session 1: Seeing the Light!

In this session, you will simply attempt to make a battery light a small flashlight bulb. In this effort, you will also develop your own mental pictures of what is happening to the electricity in analogy to your work with fluids, test that model. In the process, you will also learn a bit about the electrical properties of materials.

Guidebook Entry III.1: How to Light a Bulb.

Take one of the flashlight bulbs, a battery, and a few of the plain connecting wires. The goal is to take these objects and make the bulb light. You may need more than one person to hold all the connections together. One possible way you could try might be as shown below.



Try this out; does it light the bulb?

Draw a different scheme that you think might light the light bulb.

Try it out. Is it successful--does the bulb light?

Draw several more possible arrangements that could conceivably light the bulb. Test them. Make sure to get at least two that do light the bulb, and one that fails to light the bulb. Label each sketch as "works" or "fails."

Summarize the common features of those arrangements that work.

Now that you know how to make a light bulb light, we will now use this bulb and battery as a way of testing some of the electrical properties of common materials. In particular, we want you to examine what common materials can substitute for the wires.

Guidebook Entry III.2: Electrical Properties of Common Materials.

Take any handy materials (coins, pens, pencils, tape, rulers, staples, rubber bands, keys, fingers...) and place them between the connections on the working arrangements. Which materials allow the bulb to light?

Which materials do not allow the bulb to light?

We refer to materials that allow the bulb to light as electrical conductors; those that don't are non-conductors, or insulators. What do the conductors have in common?

Now predict one additional item that you have not yet tested that you think is a conductor, and one that you think will be an insulator.

Test each item. Were you correct in your prediction? If not, do you need to amend your description above of conducting materials?

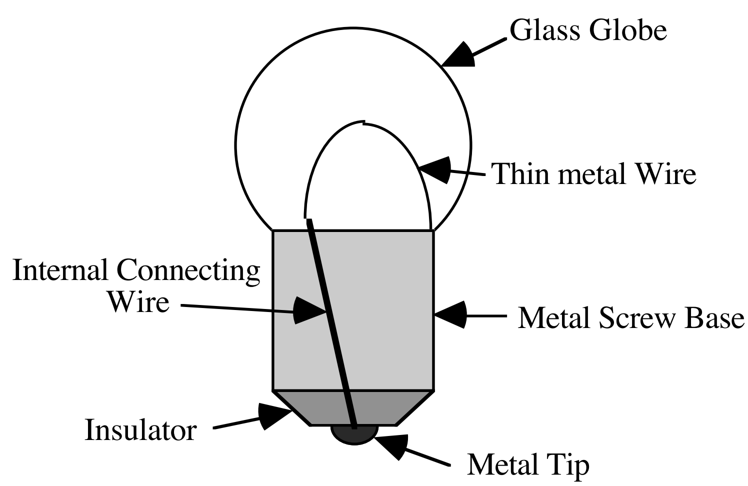
Now that you have some idea of the difference between conductors and insulators, you can use this to put together a model of electrical apparatus.

Guidebook Entry III.3: Understanding Electrical Equipment

Look at the wires carefully. Describe which parts are conductors, and which are insulators.

Why might the wires by designed this way? In particular, what would it be like using wires without the insulation? Why might uninsulated wires be dangerous if carrying the power in your house or dorm?

The bulbs themselves, if one were to cut one open, look like the sketch below:

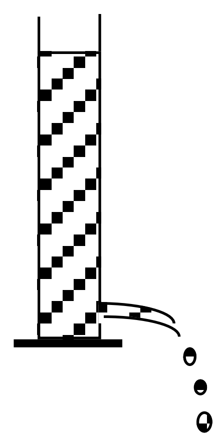


The thin metal wire, called the filament, conducts electricity only reluctantly, and gets hot in the process--so hot that it glows. Can you now explain the different purposes of the various parts of the light bulb? Write your thoughts below, and you might wish to check with your instructor.

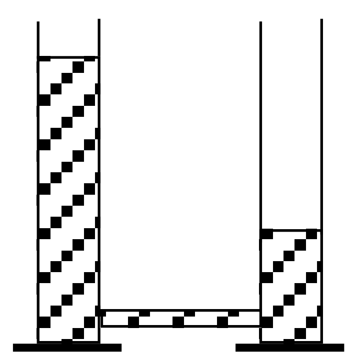
The battery is a somewhat more complicated object, and we will return to that after we have learned a bit more about such ideas as electrical currents, charges, and forces. However, at this point we will summarize its operation as follows: when conducors connect the bottom to the top in a complete circuit, electrons (subatomic particles that form the outsides of atoms) come out of the bottom of the battery (the flat end, marked with a negative sign), travel through the conductors, and return to the top (the end with the raised button, marked positive).

We studied fluids before this topic in part to allow us to make analogies between fluids and electrical systems. In particular, we studied three categories of fluid flow:

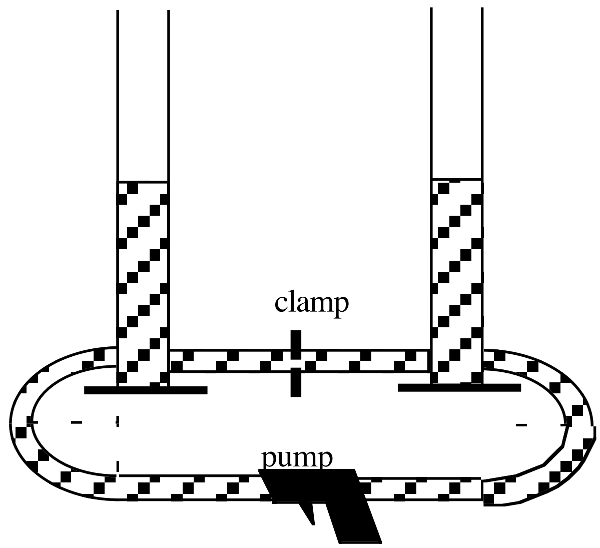
Flow into the air (hopefully caught by a bucket):



flow from one tube to another:



and flow in a circuit



Which of these is most like the electrical system you created to light the bulb? Why?

Describe each one of the elements of the electrical system in terms of an analogous element in our study of fluids. Then discuss your analogy with the instructor.

It should have become clear that holding batteries and wires together with your hands has limited appeal. In the next exercise, you will become familiar with some equipment designed to make your connections easier and more permanent.

Guidebook Entry III.4: Some Electrical Equipment and a Wiring Project

Get one of the red bulb sockets. Examine the bulb socket, paying attention to which parts are conducting and which are insulating. Where do you think you need to connect your wires now to light a bulb if the bulb is screwed into the socket?

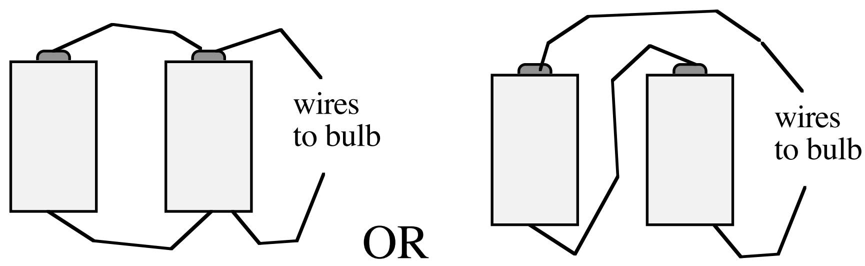
Test your hunch--does the bulb light? If not, persevere until it does.

Now grab one of the metal battery clips. Again examine it carefully to look for conducting and non-conducting parts. Does the metal frame of the clip appear to be electrically connected to the positive end, the negative end, or neither end?

How can you test to see if it is connected to either end? Do so, and record your results.

The clip is made to hold two batteries. Insert two batteries. Pick up several of the lengths of wire with clips (called alligator clips) on each end. With these, you can now make many connections, and not need your hands to keep them made.

Below are two ways you could use the two batteries simultaneously on the same light bulb:



Make these circuits using the wires with clips, the battery clips, and a bulb in a socket. Which way makes the light bulb burn more brightly? (By the way, there are several more ways to connect the two batteries together, some that will give no light, and some that will even cause the batteries to expend all of their electrical energy and get very hot!) Once you have found how to make the light brighter, use that configuration for the rest of your work today.

There are also some very old-fashioned switches, called knife switches. These allow you to make or break an electrical connection without having to move any wires. Examine them carefully, especially looking for conducting and insulating materials. Once you think you know how one works, use it to turn a light off and on with the switch. Sketch your circuit below

Now for the wiring project. A deaf person has little use for a doorbell, but still needs to have a way of knowing someone is calling. Design a light bulb caller system that will turn on one light when a person closes a switch at the back door, but two lights when someone closes the switch at the front door. You may use one battery, two switches, two lights, and as many wires as you like. Sketch your circuit below.

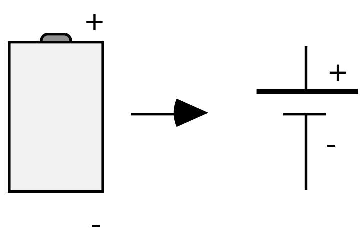
Build your circuit and test it. (You should use the two batteries in series instead of a single battery--they work better than a single battery in many designs.) Does your system work?

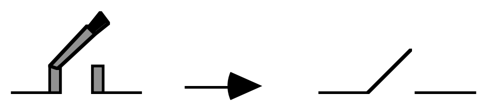
Session 2: Drawing Circuits and Conceptualizing Current Flow

In this session we will investigate some of the properties of electrical current flow by investigating parallel and series combinations of batteries and bulbs. Our working assumption is that the brightness of a bulb is indicative of the amount of electricity (or to be more careful with our language, electrical current) flowing through it.

Guidebook Entry III.5: Circuit Diagrams.

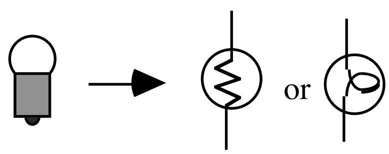
It is a bit tedious to be drawing bulbs and batteries in such detail, so we will adopt the standard convention for symbols for circuit elements:

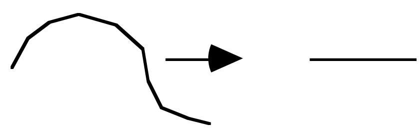




Switch

Battery

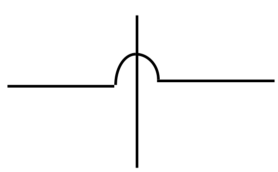




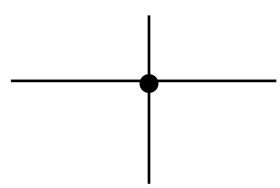
Wire

Bulb

When drawing the connections, it is conventional to use straight vertical or horizontal lines for wires. Since the drawing is required to stay on a two dimensional surface, lines will often have to cross, even if they are not connected. The rule is to make a loop over an unconnected wire, and a dot on a connected wire.

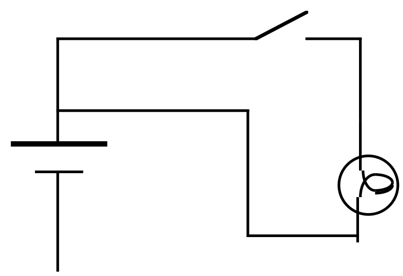


Not connected



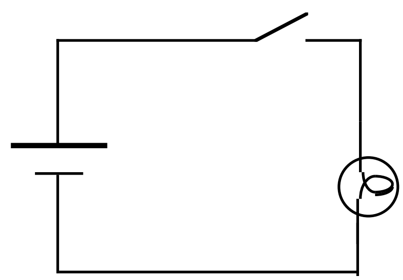
Connected

To get some practice, look at the circuit diagrams on the next page. Which do you think will cause the bulb(s) to light? Does the switch need to be open or closed? Which won't work at all? Build them and test them.



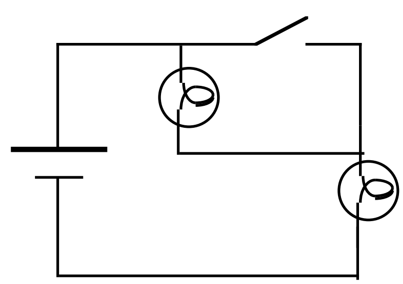
Prediction?

Experiment?



Prediction?

Experiment?



Prediction?

Experiment?

Make up your own circuit, using batteries, switches, and bulbs. Sketch it using pictures of the components (like we did in the last unit), and then using our new circuit symbols.

Using Pictures:

Using symbols:

One question that probably occurred to some of you in the last session is whether or not the orientation of the battery mattered. Check that quickly in the next activity.

Guidebook Entry III.6: Bulb Brightness and Direction of Current Flow

Is there a difference between one end of the battery and the other?

What significance do you expect this has in terms of the current flow?

Does the symbol for a bulb distinguish one end from the other?

Do you expect the brightness of a bulb to depend on the direction the battery is placed in the battery clip? How about the orientation of the connections to the bulb?

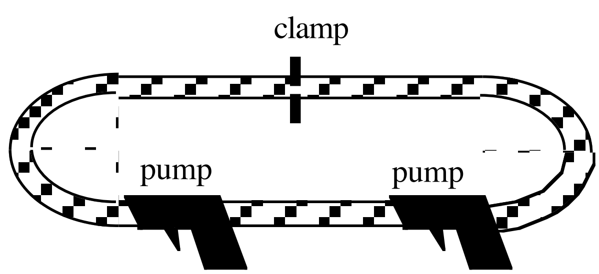
Test the dependence experimentally. Does it agree with your prediction?

In the next activity, you will gain some intuition about the nature of current flow, and about the ability of batteries to supply current. This activity will depend on your understanding of fluid flow from the previous unit.

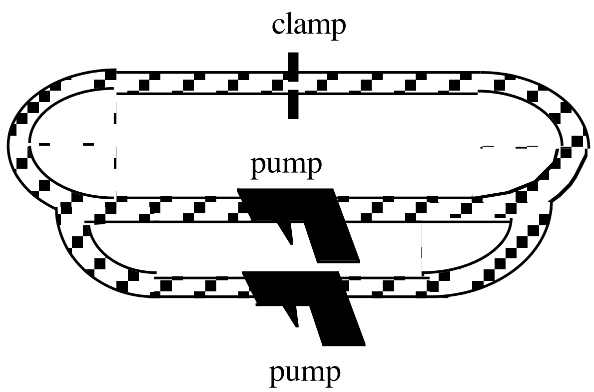
Guidebook Entry III.7: Parallel and Series Batteries

You determined last session that the battery was analogous to our pump in Unit II, session 2. That pump was a constant flow pump; that is, if it was at all possible, it would pump the same amount of fluid per unit time (actually per stroke of the trigger) no matter what was connected to it. Now imagine that we had two pumps, and we had the choice of connecting them in series or in parallel.

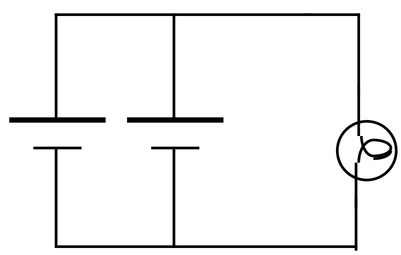
Series: How does the flow through the clamp change in this case from what it would be with a single pump?



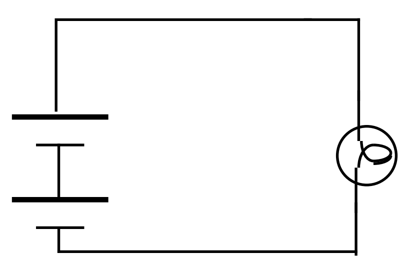
parallel: How does the flow through the clamp change in this case from what it would be with a single pump? Discuss your results with an instructor.



Now consider the case of two batteries. Compare the brightness of the following cases:



Parallel



Series

Try each of these configurations. Which one has more current flowing through it, as evidenced by a brighter bulb? Is this the same as the conclusion you reached for the fluid case? Discuss your results with an instructor.

Consider the fluid case again. How would your analysis of the parallel and series cases change if the pumps, rather than being constant flow rate devices, produced a constant pressure difference?

Parallel case:

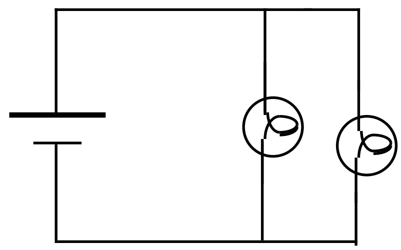
Series case:

Which is the most appropriate analogy for a battery when producing electric current through a bulb--constant pressure or constant flow?

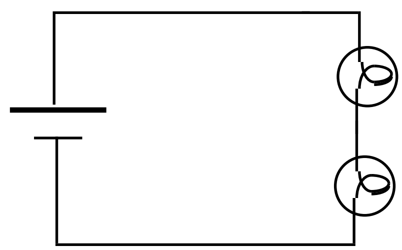
We have rightly assumed that the analogous quantity for fluid flow in the electrical case is electrical current. We will learn to measure this quantity in the next session. However, what is the correct analogy for pressure, which seems to be so important in describing batteries? While it does not define it, it is known as electric potential, or more commonly, voltage. Like pressure, it is related to the driving force that moves electrical currents, and we will find conservation laws like Bernoulli that will depend on this quantity.

Guidebook Entry III.8: Series and Parallel Bulbs.

Now that you have some intuition about the nature of electrical current, use it to predict what will happen with series and parallel bulbs. In which case do you expect the bulbs to be brighter? Explain your reasoning.



Parallel

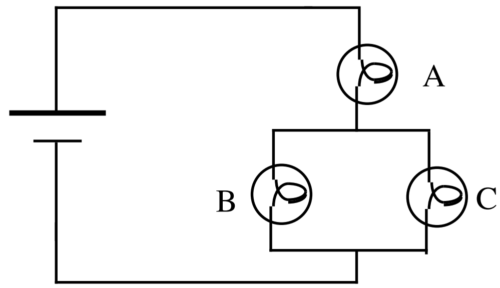


Series

How do you expect each of the above cases to compare for brightness (and hence current flow through each bulb) relative to a single bulb case?

Compare the single bulb case experimentally to the series and parallel cases. What do you find? Discuss your results with an instructor.

Finally, as a test of your understanding of current flow, consider this case.



What do you predict will be the relative brightness of bulbs A, B, and C?

What do you actually observe experimentally? (You will need at least three batteries in series to get all bulbs to light; four works well.)

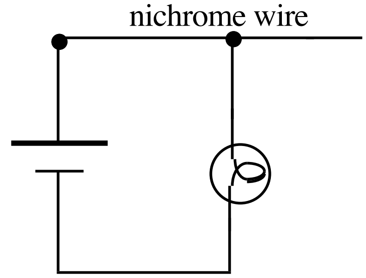
Session 3: Measuring Current, Voltage, and Resistance

In the previous sessions, we observed that bulbs behaved in a manner similar to constrictions in fluid circuits. That is, they limited flow when a constant voltage difference (or pressure difference for fluids) was applied across them. We concluded this because, for example, placing two bulbs in series reduced the amount of current flowing through the circuit relative to a single bulb, as evidenced by the brightness of the bulb. In the fluid case, we defined a quantity we called the flow resistance; in the electrical system we will also define an electrical resistance. In addition, as we investigate this resistance, we will find it necessary to work with more precise measuring tools than our eyes estimating the brightness of bulbs; you will gain some experience using two different types of multi-purpose electrical meters.

Guidebook Entry III.9: A Variable Electrical Resistance

We saw with fluid circuits, flow resistance increased as you cut the cross-sectional area of a section of the circuit (as in case of the capillary, or as we did by clamping the tube nearly closed), and as you increased the length (as we saw with long lengths of thin tubing between two cylinders). Both of these effects are important for electrical conductors as well, as is a third variable: the material out of which the conductor is fabricated. We will use a thin metal wire that is made from a nickel-chromium alloy that is only a so-so electrical conductor.

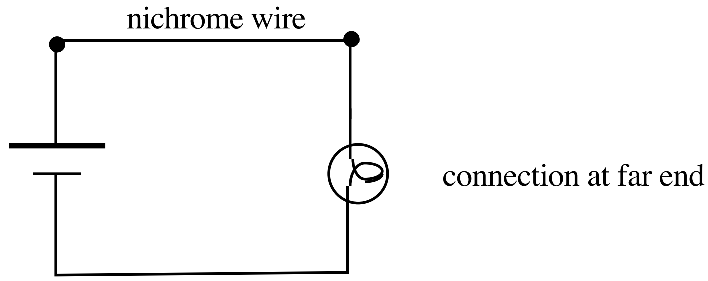
Take one of the nichrome wires, and wire it in series with one of the round bulbs and two batteries in series.



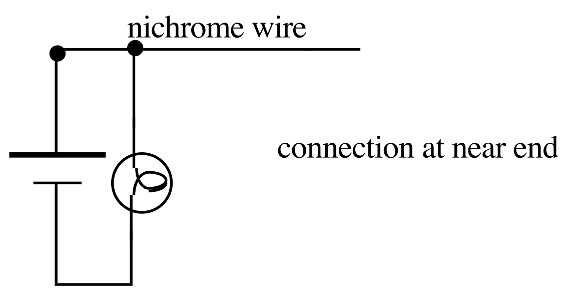
As is suggested in the wiring diagram above, make the connections to the nichrome wire at one end, and somewhere in the middle of the wire.

Note the brightness of the bulb. How does it compare to a circuit with no nichrome wire?

What happens to the brightness if you reconnect the connection in the middle near the far end of the nichrome wire?



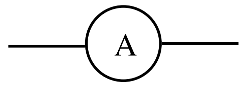
What happens to the brightness if you remake the connection near the other connection, as shown?



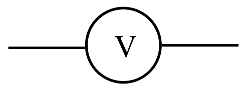
What do your results indicate about the current flow as a function of the length of nichrome wire included in the circuit?

How would you interpret this result in terms of the dependence of the electrical resistance of the nichrome on its length ?

Before we can delve into the concept of electrical resistance, we must first learn how to make measurements of current and voltage. The tools we will use are the digital BK ToolKit for voltage measurements, and the analog Simpson meter for current measurements. In fact, either of these meters can measure voltage or current, but they have somewhat different properties that make them more suitable for these two different duties in this set of exercises. We will symbolize the current meter, or ammeter, as an A in a circle,

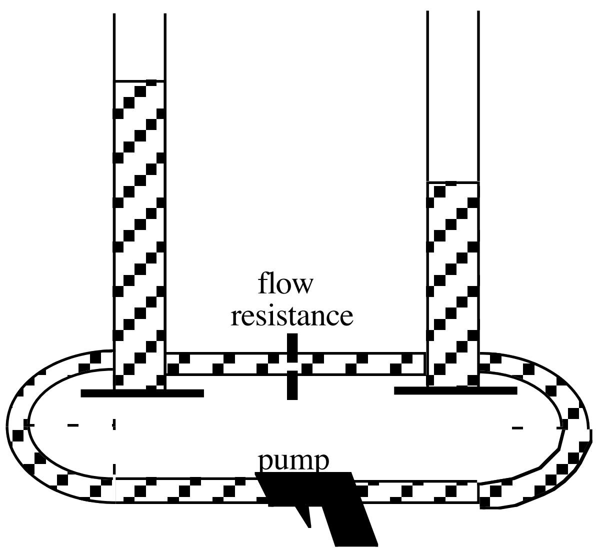


and the voltmeter in a similar diagram:

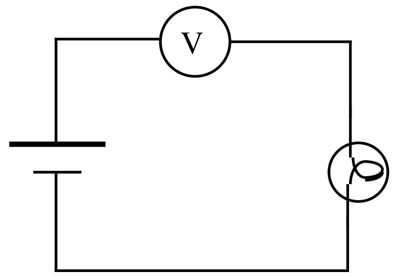


Guidebook Entry III.10: Measuring Voltage and Current

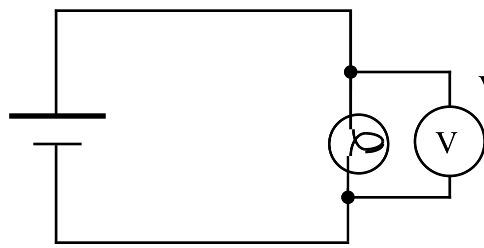
The analogue of voltage in the fluid case was pressure, which we measured by measuring the height of a fluid column. So, if we wanted to measure the pressure drop caused by flow through a constriction, we looked at the difference in fluid heights between the cylinders on either side.



With this in mind, which of the two ways shown below do you think will allow you to measure the voltage across the light bulb without significantly disturbing the current flow? Explain. (Use the BK digital meter set on the 20 V scale.)



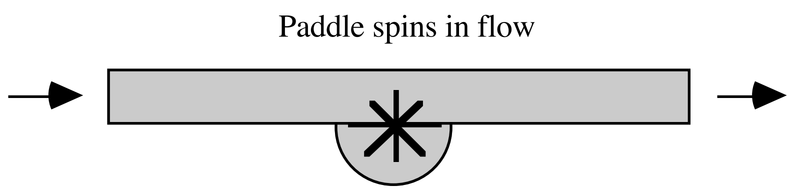
Voltmeter in series



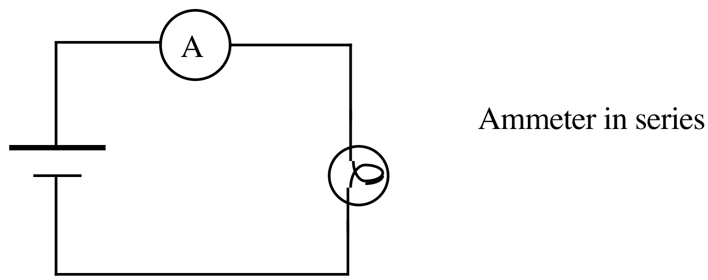
Voltmeter in parallel

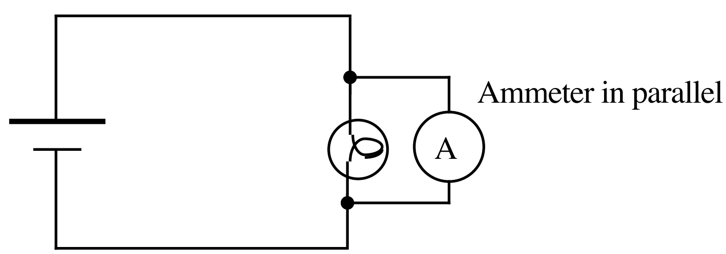
Which method seems to work in practice? Describe what you observe in each case.

When we wanted to measure fluid flow, we had the luxury of being able to simply disconnect one end of the tubing, and letting the fluid flow into a closed cylinder. Electrical current is not inclined to collect in quite the same way; we need a complete circuit to get current to flow continuously. There are fluid flow measuring devices that can be inserted into a fluid stream to measure flow without interrupting the flow. These devices usually have a propeller or paddle wheel that turns at a rate proportional to the flow, as shown.



With this in mind, which of the following diagrams do you think is more likely to measure electrical current flow without significantly disrupting the current? Explain.





Try out each arrangement. Use the Simpson meter set on the 500 mA scale. You will probably need help figuring out how to read the scales, so don't hesitate to ask. Which arrangement works? Describe what happened.

In the next exercise, you will get some practice measuring current and voltage, and in the process deduce the electrical resistance. In the fluid case, we found that current flow was often directly proportional to the pressure difference, so we could define a flow resistance as the ratio of pressure difference to flow:

$$R = P/f \ .$$

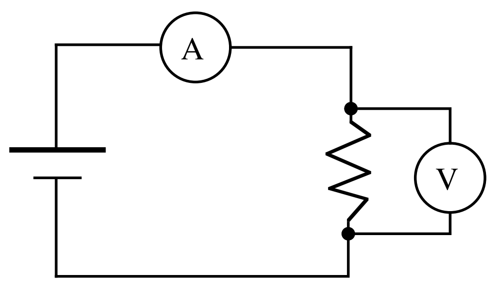
We will now do an analogous thing; we will define the electrical resistance* (R) as the ratio of voltage (V) to electrical current (I):

$$R = V/I \ .$$

The units of resistance are Volts/Ampere, which is almost always refered to as Ohms, symbolized by a capital omega Ω. Now that we have this new electrical component, we need also to have an electrical symbol for it. This is given below.

Guidebook Entry III.11: A First Resistance Measurement.

Take one of the small electrical components with several colored stripes on its body. This is a resistor. Connect it in the following circuit:



Measure the current and voltage with one battery, then two batteries in series, and then three and four batteries in series. Make a table of your data below.

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* The relationship shown is most commonly known as Ohm's Law. In fact, it is not a law at all in the conventional sense. It simply turns out that the resistance as defined by this relationship is constant for a number of materials over a wide range of voltages and currents.

Enter your data in Excel, and plot current versus voltage. Describe what you find, and either sketch your graph below, or attach a copy of your graph.

Now use Excel to calculate a resistance value for each of the four voltage values. Is the resistance reasonably constant?

Our meters will also measure resistance directly. Use the BK meter to measure the resistance of your resistor. How does this value compare with your calculated value?

If you are particularly fond of accurate measurements, and were displeased with discrepancies between your calculation and the BK meter's direct value, you should know that the most likely source of error is the current value from the Simpson meter. If you like, you may try making a measurement with two BK meters, one measuring current and the other measuring the voltage. You should get results to agree easily to 1% accuracy.

Now that we have an easy way to measure resistance, let's actually see if our initial assumption that resistance of a wire depended simply on the length of the wire is indeed valid.

Guidebook Entry III.12: Resistance Dependence on Wire Length

Take your BK meter and measure the resistance of several different lengths along the same nichrome wire. Make sure to press the probe tips firmly against the nichrome wire. If the values fluctuate, make sure to hold it tightly until you get a stable value that is the smallest one you see (additional resistance can be introduced by dirt and corrosion on the wire). Take your data, enter it into Excel, and plot resistance versus wire length. Sketch below.

How does the resistance seem to depend on length of wire? Does this agree with what you expected?

Finally, let's return to the case of the light bulbs. These were the first objects that we viewed as resistors. However, our definition of resistance implied current was directly proportional (i.e. linearly related with no offset) to the applied voltage. Let's now look at them more quantitatively, and see how well they fit this requirement.

Guidebook Entry III.13: Resistance of Light Bulbs.

Use the techniques of Guidebook Entry III.11 to measure the resistance. In particular, measure the voltage across and current through the bulb when connected to one battery. (Suggestion: it is sometimes difficult to connect cleanly to the bulb sockets. Touch your voltage probes directly to the bulb contacts and not just to the socket.) What are the voltage and currents values, and the corresponding resistance?

Voltage:

Current:

Resistance:

Now replace the single battery with two batteries in series and repeat the measurement.

Voltage:

Current:

Resistance:

Does the resistance agree with your previous value? Are they different enough to make you worried?

Now try measuring the resistance directly with the BK meter on the 200 Ω resistance scale. What do you get? How does this value compare with your other two?

Would you say that the approximation of Ohm's law is good for light bulbs over commonly used voltages and currents? Discuss your results with an instructor.