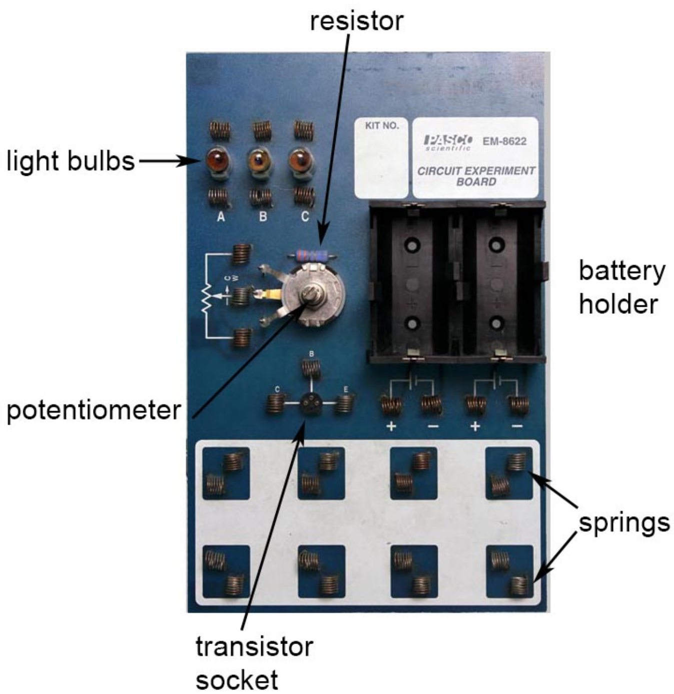
Electrical Circuits

APPARATUS

- Computer and interface
- Voltage sensor
- Fluke 8010A multimeter
- Pasco circuit board with two D-cells
- Box with hook-up leads and components

INTRODUCTION

This experiment is an introduction to the wiring of simple electrical circuits, the use of ammeters and voltmeters, series and parallel circuits, and RC circuits. The circuits will be wired up on the Pasco circuit board.



BRIEF REVIEW OF DC CIRCUIT THEORY

In a metal conductor, each atom contributes one or two electrons that can move freely through the metal. An electric current in a wire represents a flow of these electrons. The flow is quite chaotic since the electrons have a large thermal component to their motion; they are always "jittering" around randomly. When a current flows, however, there is a general drift velocity of the electrons in one direction superimposed on the random motion.

The total charge (which is proportional to the number of electrons) that passes one point in the circuit per unit time is the *current*. Current is measured in units of coulombs per second, which is also known as *amperes* (with unit symbol A).

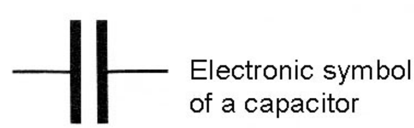
An electric field is needed to keep the electrons flowing in the metal (unless the metal is a superconductor). This field is normally provided by the chemical action of a cell or battery, or by a DC power supply. The electric field is the change in the *voltage* per unit distance. The unit of *volt* (V) is also energy per unit charge, or joules per coulomb. Voltage can be viewed as a pressure pushing the charges through the circuit, and current can be viewed as a measure of the charge that passes one point in the circuit per unit time.

Normal metals have a *resistance* to this flow of charges, and thus voltage is needed to maintain the current. It is found experimentally that for many materials over a wide range of conditions, the current is proportional to the voltage: $i = kV$. The symbols i for current and V for voltage are standard notation. However, we can write $k = 1/R$ and define a new quantity — the *resistance* R — measured in *ohms* (Ω). Ohm's Law, $i = V/R$, is not a fundamental law of physics in the same manner as Coulomb's Law, but is found to be approximately true in many circumstances. We will test Ohm's Law below.

Oftentimes in circuits, we want to reduce or limit the current with *resistors*. A typical resistor is a small carbon cylinder with two wire leads. The cylinder is encircled with colored rings which code its value of resistance. Figure 8 below shows the color code.

RC CIRCUIT THEORY

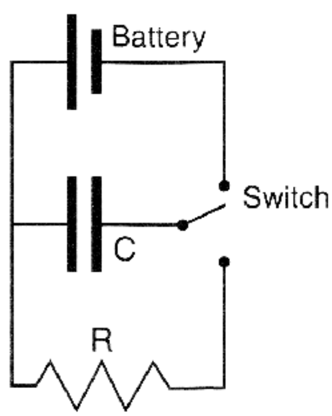
A capacitor consists of two conductors separated by an insulator (e.g., two parallel metal plates separated by an air gap).



It is found that when the two plates are connected to a source of DC voltage, the plates "charge up", with one becoming negative and the other becoming positive. If the DC voltage is now disconnected, the charge remains on the plates, but drains off slowly through the air. If the plates are now shorted by a wire, the charge will neutralize — with a spark and a bang, if the stored energy is large. A capacitor therefore stores charge and energy. For a given voltage, the capacitor will store more charge if the area of the plates is larger and/or if the plates are positioned closer together.

The equation for the charge in a capacitor is $Q = CV$: the stored charge Q is proportional to the voltage V and the capacitance C. Capacitance is a quantity determined by the physical characteristics of the capacitor, the area and separation of the plates, and the type of insulator. Capacitance is measured in farads (with unit symbol F): a one-farad capacitor stores one coulomb of charge at a potential of one volt. The farad is a large unit; most capacitors used in electrical circuits have capacitances measured in millionths of a farad (microfarads, or µF), billionths of a farad (nanofarads, or nF), or even trillionths of a farad (picofarads, or pF).

The circuit below would permit charging of the capacitor C by the battery and discharging of the capacitor through the resistor R.



Let us study the discharging process. When discharging through the resistor, the voltage across the capacitor is $V = -iR$. (The negative sign indicates that the capacitor voltage is opposite the resistor voltage.) However,

$$i = \mathrm{d}Q/\mathrm{d}t = C\,\mathrm{d}V/\mathrm{d}t \quad \text{(from } Q = CV\text{)}, \tag{1}$$

so we have

$$V = -iR = -RC\mathrm{d}V/\mathrm{d}t, \tag{2}$$

or

$$\mathrm{d}V/V = -\mathrm{d}t/RC. \tag{3}$$

The equation above integrates to $V = V_0 e^{-t/RC}$, where V_0 is the voltage at $t = 0$. The voltage on the discharging capacitor decreases exponentially with time, and its exponential slope is $1/RC$. We will find the exponential slope for an RC circuit below by using the curve fitting features of Capstone.

MULTIMETER

A multimeter is an important tool for anyone working with electrical circuits. A typical multimeter has different scales and ranges for voltage, current, and resistance. Some multimeters will also measure other quantities such as frequency and capacitance. In this experiment, we will be using the Fluke 8010A digital multimeter.

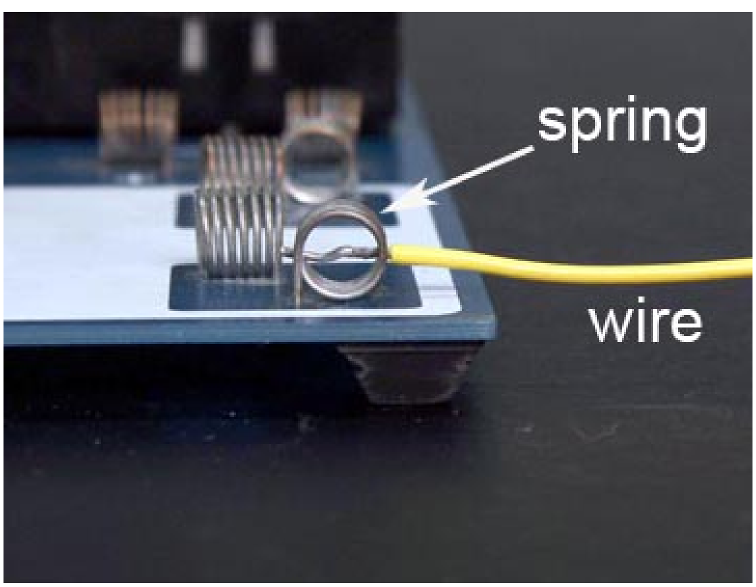
Take a moment to study this instrument. The green push-button power switch is at the lower right. The left-most button changes the measurements between AC and DC (alternating and direct current). This button should be out, as all of our measurements for this experiment are in DC.

To measure voltages, press the "V" button, and connect your test leads to the "common" and V/kΩ/S sockets. Push in a button for the appropriate scale: 2 V or 20 V in this experiment. To measure resistances, use the "kΩ" button and an appropriate scale. (Here kΩ represents thousands of ohms.)

You must be careful when measuring currents. Double-check your circuit when using the current meter. The meter must be hooked into the circuit so the current flows through the meter. The test leads are connected to the mA (milliampere) and common sockets. Before hooking the meter into the circuit, estimate first whether you expect the current to exceed 2 A. The meter has a 2-A fuse which will "blow" if this current is exceeded. All of our circuits below use smaller currents, provided they are wired correctly.

HOOKING UP WIRES

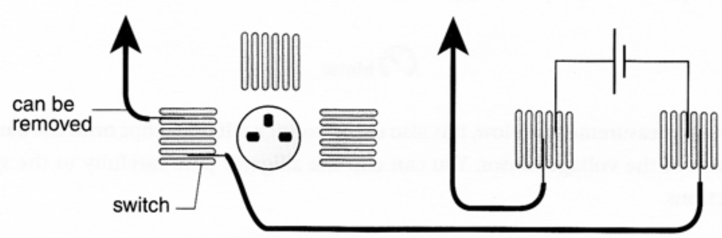
Connections are made on the circuit board by pushing a stripped wire or lead to a component into a spring. For maximum effect, the striped part of the wire should extend in such a way that it passes completely across the spring, making contact with the spring at four points. This extension produces the most secure electrical and mechanical connection.



If the spring is too loose, press the coils firmly together to tighten it up. The coils of the spring should not be too tight, as this may result in the bending or breaking of the component leads when they are inserted or removed. If a spring is pushed over, light pressure will straighten it back up.

MAKING A SWITCH

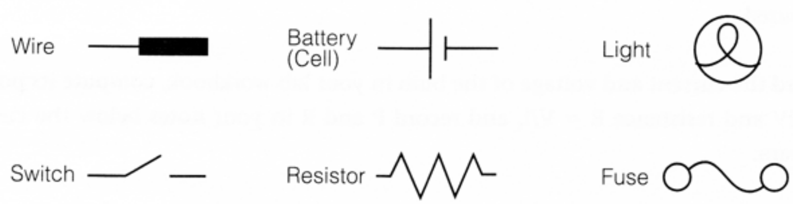
Use a vacant spring connection (such as one of the three around the transistor socket, as shown below) for a switch.



Connect one lead from the battery to this spring, and take a third wire from the spring to the light. You can now switch the power "on" and "off" by connecting or disconnecting the third wire.

PROCEDURE

For each of the circuits below (except the first), discuss the circuit with you lab partner and agree upon a design. Then sketch the circuit neatly on a blank piece of paper using standard electrical symbols. Finally, hook up the circuit on the circuit board.



To be checked off as completing this experiment, your TA will glance at all your circuits, notes, and data, and look closely at the graphs of circuits 7 and 8.

- **CIRCUIT 1: CHECK YOUR COMPUTER VOLTAGE SENSOR**

  Plug a voltage sensor (just a pair of leads connected to a multi-pin socket) into the Science Workshop interface, turn on the interface and computer, call up Capstone and choose "Graph & Digits". Under "Hardware Setup", click on channel A and select "Voltage Sensor". Click the "Select Measurement" button in the digits box and select "Voltage (V)".

In certain applications below, it is useful to have an analog meter on the computer screen linked to the voltage sensor. This permits you to determine quickly whether a voltage is present and what its approximate size is. This can be found at the right of the screen.

For certain measurements below, it is also useful to stick alligator clips onto the banana plug ends of the voltage sensor. You can clip the alligator jaws carefully to the spring connections.

Check the voltage of one D-cell with both the voltage sensor and the digital multimeter to make sure the readings are in reasonable agreement. Record these readings. (Label your notes and circuit diagrams with the circuit number, 1 in this case.)

- **CIRCUIT 2: SINGLE BULB WITH VOLTMETER AND AMMETER**

  Design a circuit that will light a single light bulb with a single D-cell through a switch. (See "Making a Switch" above.) Try out the circuit and check that it works.

  Use the digital multimeter on a milliammeter scale, and wire it in series with the light bulb to measure the current flowing through the bulb. An ammeter must always be in series with the component whose current is being measured.

  Connect the leads of the voltage sensor across the light bulb to measure its voltage. A voltmeter must always be in parallel with the component whose voltage is being measured.

  Record the current and voltage of the bulb, compute its power $P = Vi$ and resistance $R = V/i$, and record P and R in your notes below the circuit diagram.

- **CIRCUIT 3: ADD A POTENTIOMETER**

  Rearrange your circuit so that you add a potentiometer in series with the light bulb whose current and voltage are still being measured. First, sketch the circuit in your notes. The potentiometer is the circular component with the screwdriver slot control (see Figure 1). Use the middle lead of the potentiometer and one of the end leads.

  Experiment with controlling the brightness of the bulb while observing the ammeter and voltmeter readings. (No data need be taken.)

- **CIRCUIT 4: BULBS IN PARALLEL**

  Design and wire up a circuit that will light all three bulbs in parallel. You may use one or both D-cells. Measure and record the battery voltage and the voltage across each bulb.

  Measure and record the current to each bulb separately, as well as the total current output of the battery. (Although the bulbs are labeled identically as #14 bulbs, their electrical characteristics may vary up to 30%, owing to relatively large variations allowed by the manufacturer.) One consequence of Kirchhoff's Current Law is that the sum of the currents of several components in parallel must be equal to the total current. Compare the sum of the three individual currents with the total current. Enter the comparison clearly in your notes below the data and circuit for this part. Upon what fundamental law of physics is Kirchhoff's Current Law based?

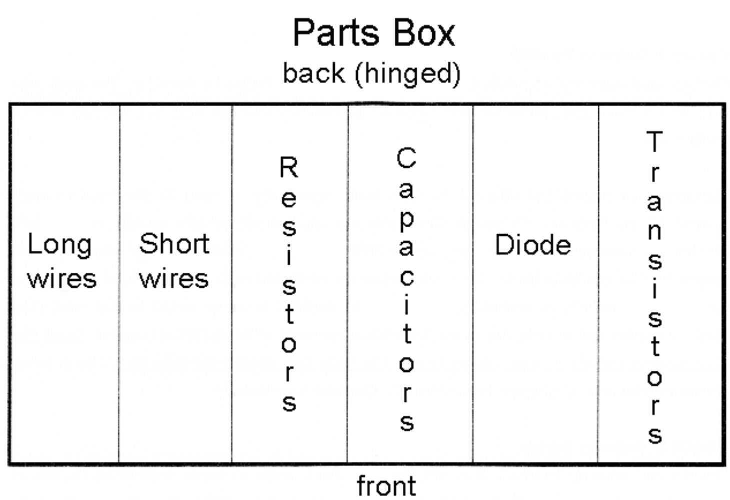
- **CIRCUIT 5: BULBS IN SERIES**

Design and wire up a circuit that will light all three bulbs in series with both D-cells in series. Measure and record the current output of the battery. What would you expect to obtain if you measured the current to each bulb?

Measure and record the voltage across each bulb separately, as well as the total voltage of the battery. One consequence of Kirchhoff's Voltage Law is that the sum of the voltages of several components in series must be equal to the total voltage. Compare the sum of the three individual voltages with the total voltage. Enter the comparison clearly in your notes. Upon what fundamental law of physics is Kirchhoff's Voltage Law based?

For Circuit 4, you should have entered in your notes the measured individual currents to each bulb and the measured total battery current; and for Circuit 5, similar entries for the voltages. Your current comparison may show a difference of 10% or more. Some meters on the current setting have significant internal resistance of their own (partly because of the fuse), so they actually reduce the current to the component when wired into the circuit. On the voltage settings, however, the meters do not change the circuit voltages significantly when they are wired in, so your voltage comparison should agree quite closely.

Keep your parts in the order shown. After finishing the experiments, put all parts back in their proper slots.

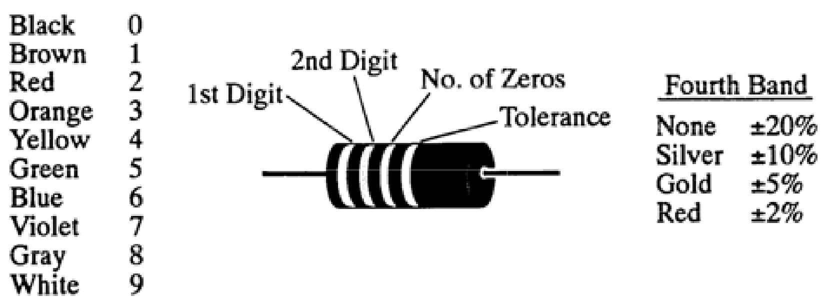


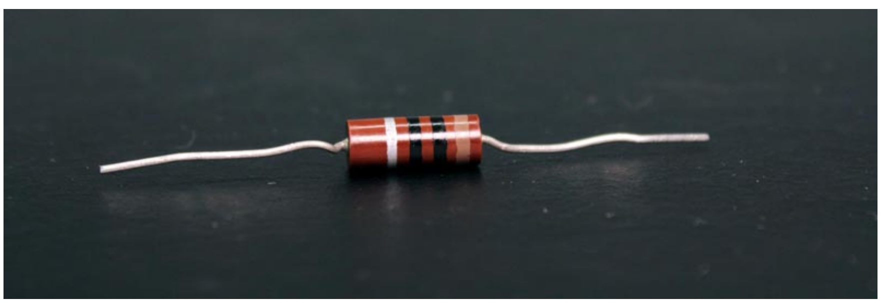
- **CIRCUIT 6: ADDITIONAL CREDIT (1 mill)**

Devise a circuit that will light two bulbs at the same intensity, but a third bulb at a different intensity. Try it. If one lab partner has been doing all the wiring on the circuit board, change tasks now so that both partners gain experience in wiring a circuit. When successful, draw the circuit diagram in your notes. Indicate what happens when you unscrew each bulb, one at a time. Your TA will award the mill when he or she checks your notes at the end of the lab.

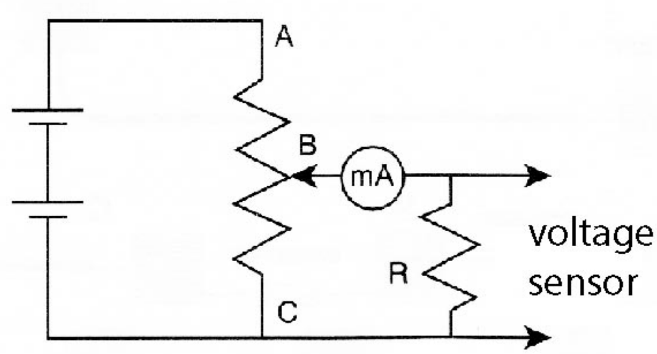
- **CIRCUIT 7: OHM'S LAW**

Choose one of the three resistors. Using the chart below, decode the values of the resistance and tolerance range of the resistor, and record them. Measure and record the resistance directly with your multimeter. Is the measured value within the tolerance range of the coded value?





Wire up the voltage divider circuit shown below on your circuit board with your chosen resistor in position R.



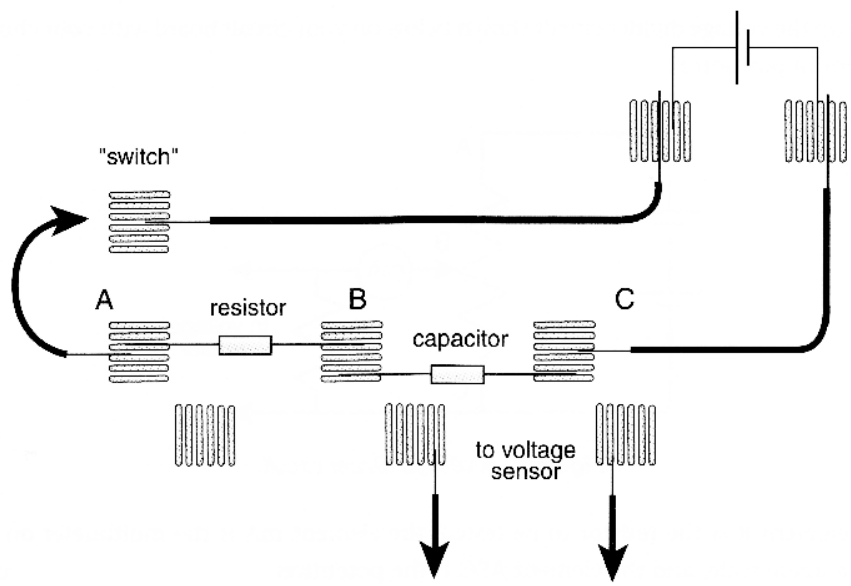
The element R is the resistor to be tested, the element mA is the multimeter on the milliampere scale, and the element ABC is the potentiometer, with B the middle connection (i.e., the sliding contact of the potentiometer). For the position of the potentiometer on your circuit board, see Figure 1. As you turn the potentiometer knob, the sliding contact B moves along the resistance of the potentiometer, allowing you to pick any voltage from zero to the full battery voltage V. This circuit permits you vary the voltage to the chosen resistor with the potentiometer, and to measure the voltage and current to it. Does it make any difference if its resistance R is much larger or much smaller than that of the potentiometer? Your TA may award you a mill or two for a well-reasoned discussion of this point.

Set your computer to take data in a table of voltage from the voltage sensor while you input the current reading of the ammeter as a keyboard entry. To do this, Click on "Continuous Mode" at the bottom of the screen and change this to "Keep Mode". Drag a new table over from the right side of the screen. select "Voltage (V)" for the first column. For the second column, click on "Select Measurement". Under "Create New", Choose "User-Entered Data" and then change the title to "current". Take data every 0.5 V between 0 V and 3 V by clicking the "Keep Sample" button. Remember to record the current (with units) for each voltage data point you keep.

Graph the data of V as a function of i in Capstone or Excel. Create a best-fit line and record the slope. Compare the slope ($R = V/i$) with your previously measured value of R. (You should have three entries of resistance compared in your notes: the "nominal" value read from the color code, the value measured by the multimeter, and the value determined from the slope of your graph.)

- **CIRCUIT 8: RC CIRCUIT**

  Use the color-code chart above to locate a 100-kΩ (100,000-ohm) resistor. Measure and record its resistance with the ohmmeter scale of the multimeter. Wire (all in series) a D-cell, a switch, the 100-kΩ resistor, and the 100-µF capacitor, as in Figure 10 below. Connect the leads of the voltage sensor across the capacitor. Call up a meter scale linked to the voltage sensor on the computer screen, and set its limits to ± 2 V (to do this, click the "properties" button and then adjust "Meter Scale"). Make sure you are in "Continuous Mode" and not "Keep Mode".



With the switch open, briefly short the terminals of the capacitor to drain any residual charge. (Touch the capacitor leads simultaneously with the two leads of a loose wire.)

Click "Record", close the switch, and observe the charging of the capacitor on the screen meter. When the capacitor is charged up to nearly the full battery voltage, open the switch. The capacitor should remain at its present voltage, with a very slow drop over time. This indicates that the charge you placed on one of the capacitor plates has no way to move over and neutralize the opposite charge on the other plate.

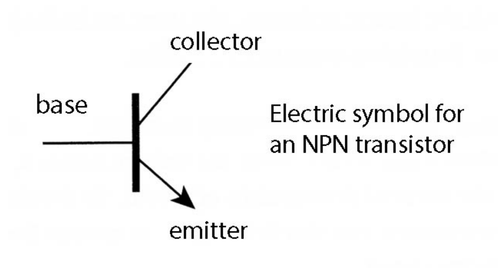
Click "Stop". Prepare the computer to take data in a table of voltage as a function of time. At the bottom of the screen, set the sampling rate at 2 Hz. (The interface will then take a voltage reading every 0.5 second.) Close the switch, charge the capacitor to about 1.5 V, and switch the battery "off". Click "Record", and connect points A and C with a lead so the capacitor discharges through the resistor. Take data until the voltage of the capacitor drops below 0.05 V. Graph this data in Capstone or Excel. There may be a short section of curve at the beginning, before you completed the RC circuit, where the charge is decreasing very slowly, and then a more rapid decrease as the capacitor discharges through the resistor.

We now want to determine the exponential slope of the curve: that is, to find the parameter "a" in a curve fit of e^{-at}. Click the "Highlight range of points..." button on top of the graph. A selection box will appear. Drag this box over the data of interest and then click inside the box to highlight the data. Click the "Apply selected curve fits..." button and choose "Natural Exponential". the inverse of "a" should be RC. Make sure your graph is titled and the axes are labeled. <u>Beneath the graph, compare the experimentally determined value of RC with that obtained from the product of the measured resistance and the nominal capacitance.</u>

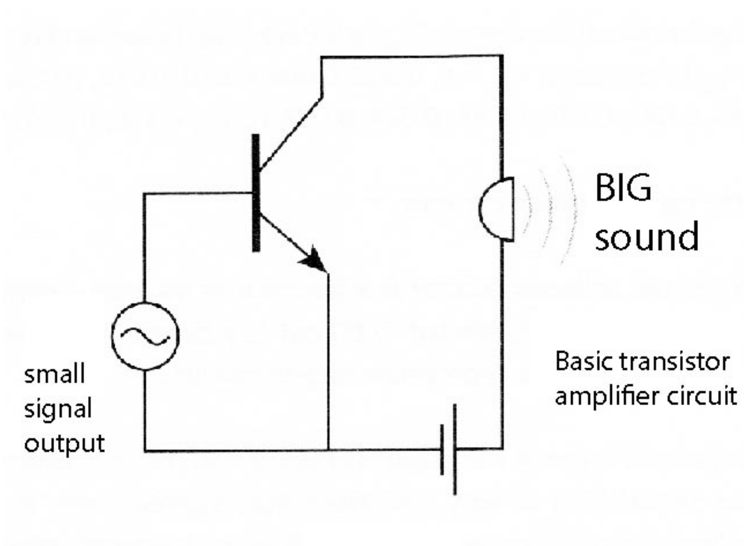
- **CIRCUIT 9: TRANSISTOR (additional credit up to 5 mills)**

This is a complicated additional credit assignment. Get yourself checked off on the rest of the experiment before starting it.

Transistors were probably not covered in class, so here is a brief introduction. A junction transistor has three connections: emitter, base, and collector.



Basically, a small current at the base controls a large current flowing in the emitter-collector circuit. For example, a small signal from a microphone input at the base can control a large current to a speaker. The transistor can therefore operate as an *amplifier*.



You don't get something for nothing; the large working current in the collector circuit must be supplied by an external source (in this case, the battery). The circuit above is barely functional. Normally, there would be resistors in the circuit to set the operating voltages of the transistor, capacitors to isolate the DC of the battery, and so forth. A stereo amplifier would have many amplification stages, with feedback and other arrangements to ensure that the amplification is linear (i.e., that the output is a faithful copy of the input, only larger).

A transistor can also operate as a switch. A small current at the base can switch on or off a larger current flowing in the emitter-collector circuit. A computer has thousands, perhaps millions, of transistors printed microscopically small on tiny circuit boards enclosed in the "chips" performing this function.

In this additional credit assignment, we will study the amplification property of a transistor. (Refer to the instructions below and the diagram on the following page.)

1. Wire up the circuit of Figure 13 on your circuit board. Use $R_1 = 1000\ \Omega$ and $R_2 = 100\ \Omega$. Be sure your transistor is oriented as shown in the picture and connected properly. Also, double check the battery polarities; the short bar in the battery symbol is the negative terminal. Transistors are easy to burn out.

2. Wire your multimeter on the millivolt scale to measure the voltage across R_1, and the computer voltage sensor to measure the voltage across R_2 on a digital scale to two places after the decimal (hundredths of a volt). By dividing these voltages by their respective resistances, you can determine the current flowing in the base circuit and the collector circuit.

3. Prepare a data table in your notes (or use Excel) with at least four columns and 20 rows. We will take data for V_{AB} and V_{CD}, and compute their respective currents.

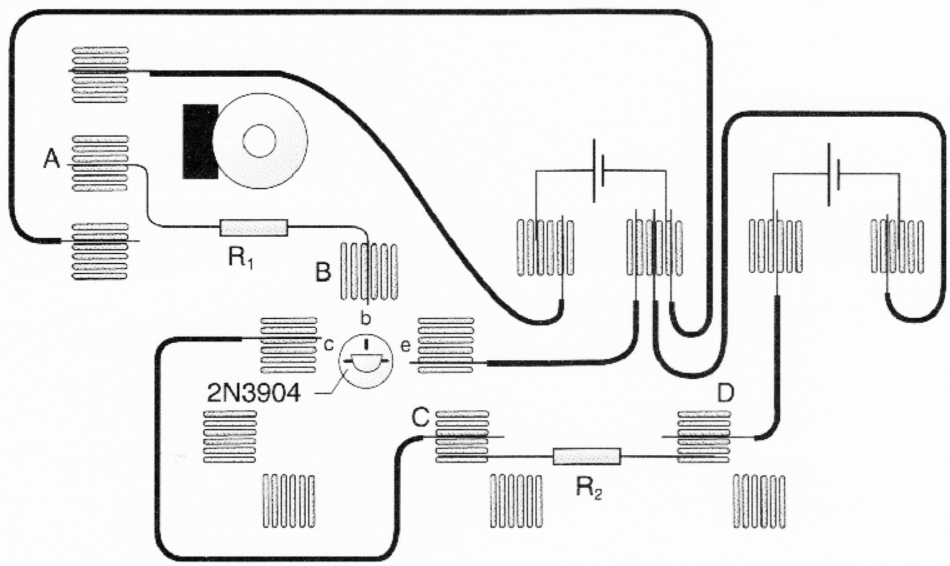
4. By adjusting the potentiometer, set V_{AB} to the readings below, and record the corresponding V_{CD} in the table: $V_{\text{AB}} = 0$, 0.002, 0.006, 0.010, 0.015, 0.020, 0.025, 0.030, 0.035, 0.040, 0.045, 0.050, 0.055, 0.060, 0.080, 0.100, 0.150, 0.200, 0.250 V.

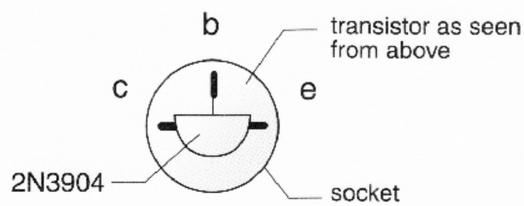
5. Calculate the corresponding currents.

6. Plot a graph of the collector current as a function of the base current. If you find areas where more points are needed to fill out any curves or sudden changes, return to step 4 and make the appropriate measurements.

7. What is the general shape of the graph? Is there a straight-line region? Does it pass through the origin? Why or why not? Electronic engineers refer to the region of the curve where the collector current levels off as the transistor being *saturated*. At what current does this transistor saturate? What determines the saturation current?

8. The slope of the straight-line region is the current amplification of the transistor. Determine and record the current amplification.


A
R1
B
b
c
e
2N3904
C
D
R2


b
transistor as seen
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e
2N3904
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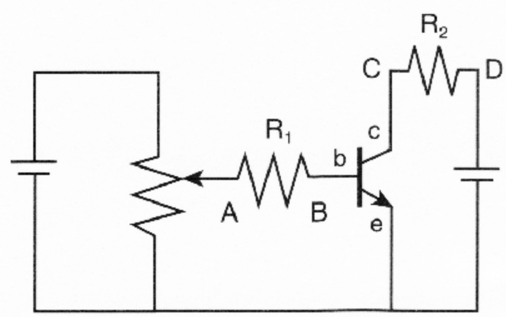
R2
C
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