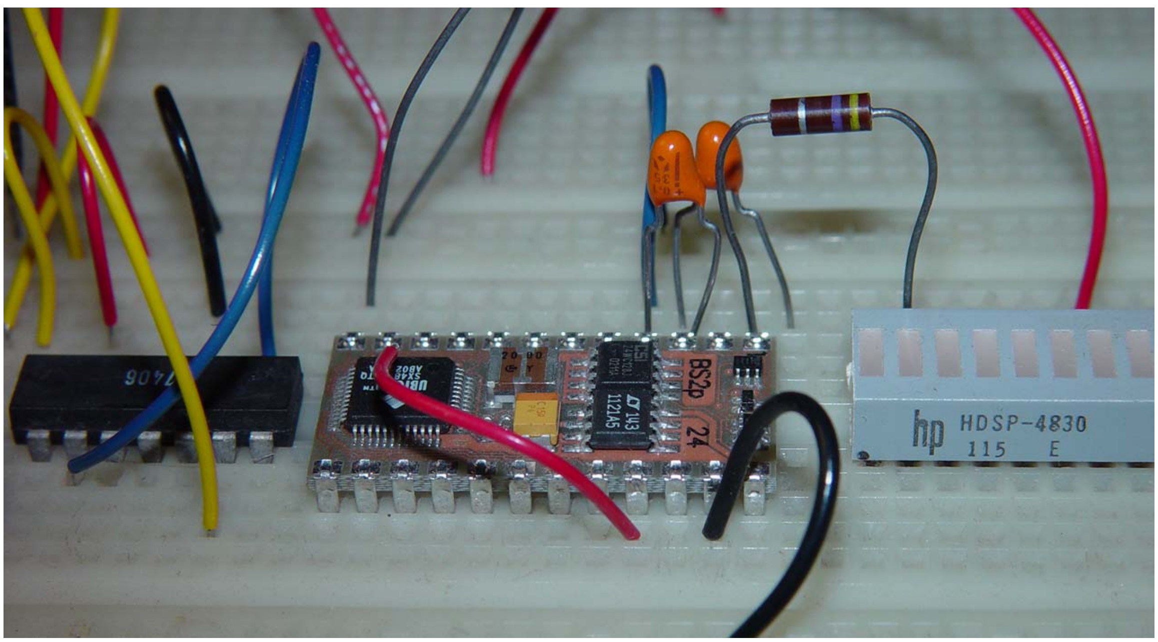
Introduction to Electronics for Rehabilitation Scientists



Written and Illustrated By

George T. Timberlake, Ph.D.
University of Kansas Medical Center

Second Edition. October 2002

Introduction

The purpose of this short laboratory course is to introduce the student to the basic electronics of instruments commonly used by rehabilitation scientists. As researchers, we frequently use commercial instruments such as force transducers and motion monitors. Most often these devices come connected to a computer and magically, numbers show up on the computer screen corresponding to some physical change we are interested in. We may not know, however, how physical variables such as force are changed into voltage signals or how those continuous voltage signals are turned into numbers in the computer. Understanding the electronics and physics behind our instruments is useful for several reasons. First, knowing how the electronics works (or doesn't) provides a useful dose of skepticism concerning computer-generated data. You can't always believe what shows up on the computer screen if the electronics providing those numbers has problems. In other words, it is highly useful to understand the limitations and pitfalls of the instrument. Second, equipment fails. When a device is not working or not working to specifications, a little electronics "troubleshooting" will often solve the problem or at least give you some information with which to talk to the company that made the equipment. Finally, you may find that you need a piece of equipment that is simply not manufactured. Rather than limit your research and experimentation to what can be performed with commercial instruments, you may wish to build your own gadget to get the research done.

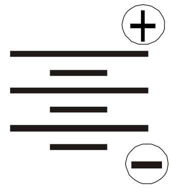
Basic concepts of electronics will be introduced by constructing a strain gauge. Strain gauges are devices that change a force into an electronic signal, that is, they are force transducers. There are many physical methods of making strain gauges, but we will consider only one type here, the resistive strain gauge. After an introduction to current, resistance, and voltage, we will construct a resistive strain gauge. Finally, the strain gauge voltage output will be transformed into digital, binary numbers using an Analog-to-Digital converter.

This is a laboratory course. I have developed and constructed equipment that will allow you to build and test various circuits. This equipment is provided in a kit. You will also need an oscilloscope and a digital multimeter. Please return the equipment to the boxes in an organized manner since others will use it after you. **Disconnect the batteries at the end of each experimental session. If they are left connected, they will drain.**

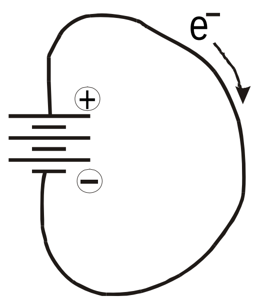
I. Linear Electronic Circuits

Current and voltage

Electrical current is the flow of electrons in a conducting medium such as a metal wire. Current will flow in a wire when a voltage is applied to the two ends of the wire. The simplest (and oldest) voltage source is the battery. The symbol for a battery is



This symbol came from early batteries that were made from alternating zinc and carbon plates immersed in an acid bath. When a metal wire is connected from the plus (+) to the negative (-) side of the battery, electrons flow from the + side to the – side:



The "strength" of a battery is measured in Volts ("V" or "v") named after Allesandro Volta (Italian physicist, 1745 – 1827). The greater the voltage, the greater the ability of the battery to make electrons flow.

The flow of electrons in a wire is called the <u>current.</u> The symbol for current is "I" or "i". The unit of current is the Ampere (A) or "amp" named after André Marie Ampere, a French physicist (1775 – 1836).

Resistors

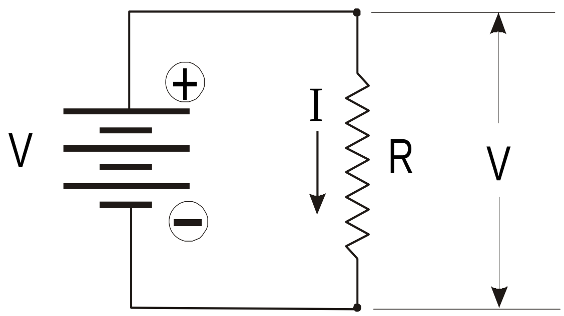
Materials that resist the flow of electrons are called "resistors." The symbol for a resistor is:

This symbol came from early resistors that were made by winding very fine wire on a cylinder. The symbol of resistance is "R" or "r." The units of resistance are Ohms (Georg Ohm, 1787 –1854. German physicist) and the symbol is Ω. Resistances in ohms can be measured using an ohmmeter.

Ohm's Law

When a battery is connected to a resistor as shown below, Ohm's Law relates the current, voltage, and resistance:

$$V \text{ (volts)} = I \text{ (amps)} \times R\text{(ohms)}$$
$$V = IR$$



Notice that the voltage "across" the resistor (i.e., from one end of the resistor to the other) is the same as the battery voltage, V. So, according to Ohm's Law, the voltage (V) across the resistor is equal to the current (A) flowing through the resistor times the resistance (Ω).

Example: In the drawing above, V = 10.0 v and R = 100 Ω. What is the current through the resistor, I?

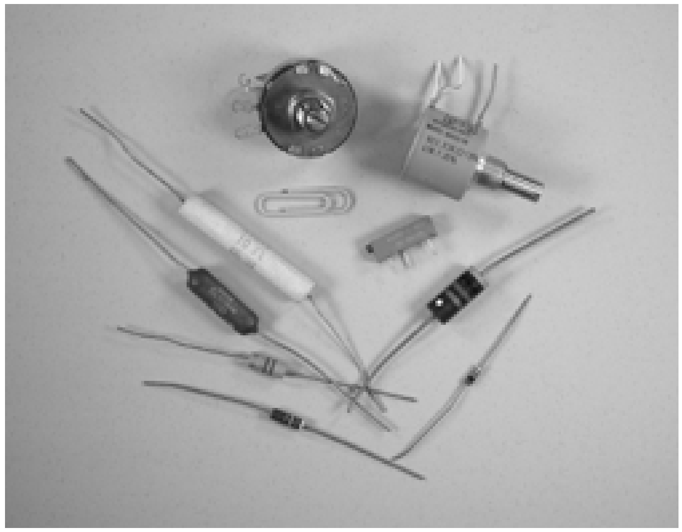
$$V = IR$$
$$10 \text{ v} = I \times 100\ \Omega$$
$$I = 10 \text{ v}/\ 100\ \Omega$$
$$I = 0.1 \text{ Amp} = 100 \times 10^{-3} = 100 \text{ mA}$$

Thus, 100 mA flows through the resistor (the "m" in mA stands for "milli" or 10^{-3}). The current is the same everywhere in the circuit.

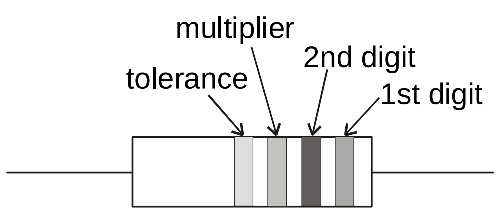
Problem: In the circuit shown above, the current is 0.5 A, and the resistance is 2,000 Ω. What is the battery voltage?

Real resistors

Modern resistors come in a wide variety of shapes and sizes as shown in the figure below. Fixed resistors shown in the figure have two wires coming from the resistor body. Most fixed resistors are made from carbon film. Variable resistors of “potentiometers” (also called “pots”) have three wires. The resistive material is usually a plastic compound, but precision pots often use wire as the resistive material. The two largest, cylindrical resistors in the figure are pots.



Fixed resistors have color-coded stripes that show their resistance. The color code gives two digits and the base-10 exponent of the multiplier as follows.



The color code is as follows.

COLOR	
Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Violet	7
Gray	8
White	9

The fourth color stripe refers to the tolerance of the resistor, from 2% to 20%. This number means that the true resistance is within x% of the color-coded resistance

	Tolerance
Red	2%
Gold	5%
Silver	10%
None	20%

Example: A resistor has the colors Brown, Black, Red, Gold. What is its resistance? Brown = 1 and Black = 0, so the first two digits are 10. Red = 2, so the multiplier is 10^2. The resistance is thus $10 \times 10^2 = 10 \times 100 = 1000\ \Omega$ or 1 kΩ. The tolerance is 5%, so the measured resistance should be within 5% of 1000Ω. Thus, the real resistance should be between 950 and 1050Ω.

Problem: A resistor has the color code Green, Violet, and Yellow. What is its resistance?

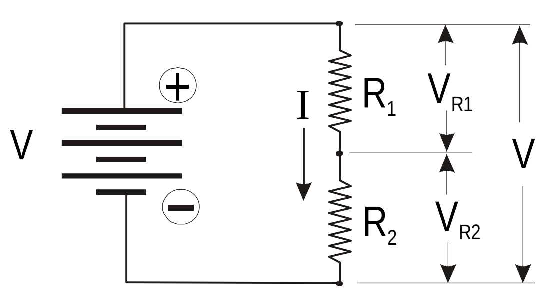
Resistor power

Resistors heat up when current flows through them. The amount of power is P=IV, where I is the current and V the voltage. Resistors come in different sizes depending on how much power they must dissipate. The smallest resistors in the photo above are ¼ Watt, while the next largest are ½ Watt. The largest resistors shown can dissipate several Watts of power. For the low-current and low-voltage circuits we will construct, ¼ Watt resistors are sufficient.

Experiment 1. Digital multimeters are indispensable electronic tools. They accurately measure resistance, voltage and current, and some can measure capacitance. Use your multimeter to measure three or four resistors selected from those supplied. Does the multimeter reading agree with the color code? Is the measured value within the tolerance of the resistor?

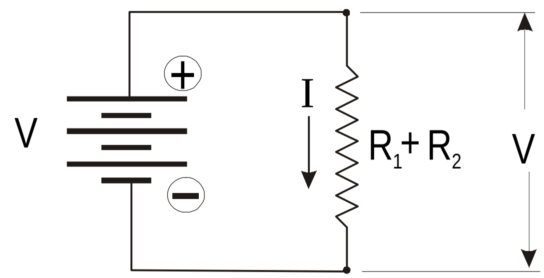
Resistors in series

Resistors connected end-to-end are connected "in series." In the diagram below, two resistors are connected in series. Each resistor has a voltage across it. The two voltages across the resistors must sum to the supply voltage, V.



$$V = V_{R1} + V_{R2}$$

When resistors are connected in series, the resistances ADD. In the diagram above, the two resistors in series have resistances R_1 and R_2, so the total resistance, R_T, is $R_1 + R_2$. Thus, the circuit is the same as a single resistor whose value is $R_1 + R_2$ ohms as shown below.



$$R_T = R_1 + R_2$$

How can we find the voltages across each of the resistors shown above? The key is first to calculate the current, I, using the total resistance, $R_1 + R_2$. We know that I flows through both R_1 and R_2, so we can then calculate the voltage across each resistor using Ohm's Law. As a practical example, let's assume V = 10 v, R_1 = 100 Ω, and R_2 = 300 Ω.

1. Find the current, I

$$V = IR$$

$$I = V/R$$

$$I = V/(R_1+R_2)$$

$$I = 10\text{ v}/ (100 + 300)\ \Omega$$

$$\underline{I = 10/400 = 1/40 = 0.025\text{ Amp} = 25\text{ mA}}$$

2. Find the voltage across R_1, V_{R1}.

$$V_{R1} = I \times R_1$$

$$V_{R1} = 0.025\text{ A} \times 100\ \Omega$$

$\underline{V_{R1} = 2.5\ v}$

3. Find the voltage across R_2, V_{R2}.

$$V_{R2} = I \times R_2$$

$$V_{R2} = 0.025\ A \times 300\ \Omega$$

$$\underline{V_{R2} = 7.5\ v}$$

Notice that the two voltage "drops" across the resistors sum to the supply voltage. In essence, the two resistors have "divided" the supply voltage according to the ratio of each resistance to the total resistance:

$$\frac{R_1}{R_T} = \frac{100}{400} = \frac{1}{4} \quad \text{and} \quad \frac{1}{4} \times 10.0\ V = 2.5\ V$$

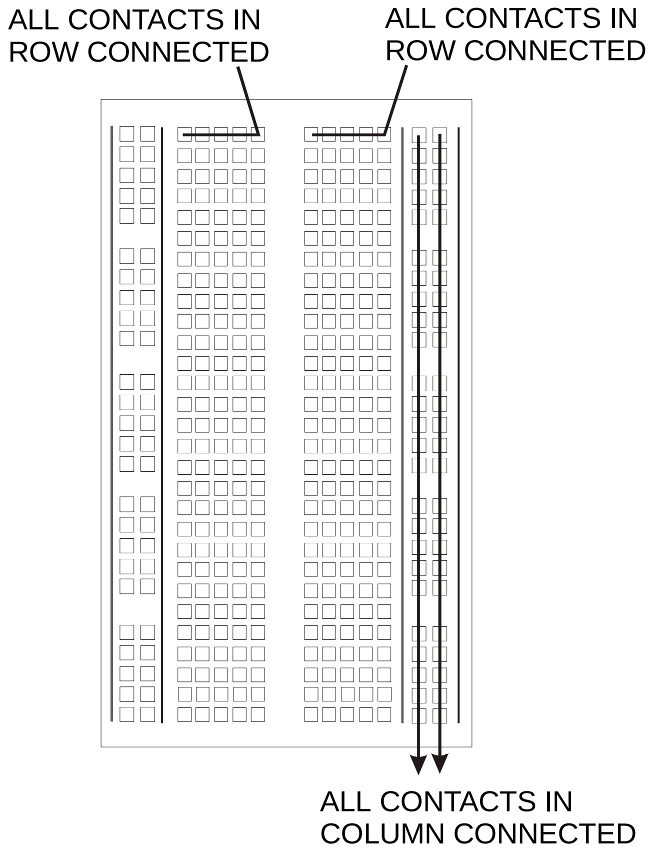
$$\frac{R_2}{R_T} = \frac{300}{400} = \frac{3}{4} \quad \text{and} \quad \frac{3}{4} \times 10.0\ V = 7.5\ V$$

For this reason, resistors in series are sometimes called "voltage dividers" when they are used in a circuit to provide only a part of the supply voltage.

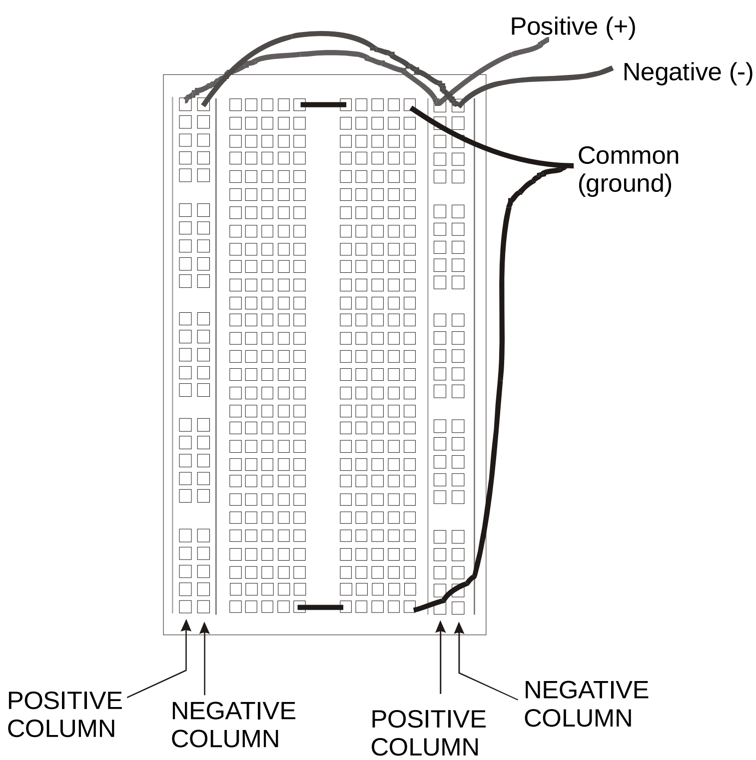
Problem. The following resistors are connected in series: 100, 200, 500, 800 Ω. The 100 Ω resistor is connected to the + of a 10 v battery and the 800 Ω resistor is connected to the – of the battery. What are the voltage drops across each resistor?

The prototype board

The prototype board is a convenient way to make electrical connections to resistors, wires, and integrated circuits. The overall layout of the board is shown below. The four vertical columns are used for + and – voltages.

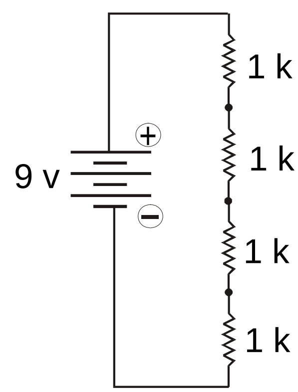


Wire the power from the two 9 volt batteries as shown below

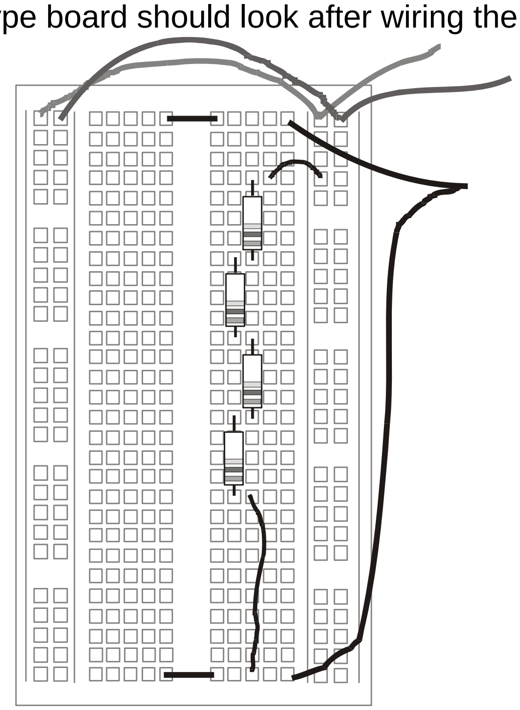


This wiring provides a convenient way to provide a positive or negative voltage or ground to any component on the board. Simply connect a wire from the appropriate column or ground row to the component.

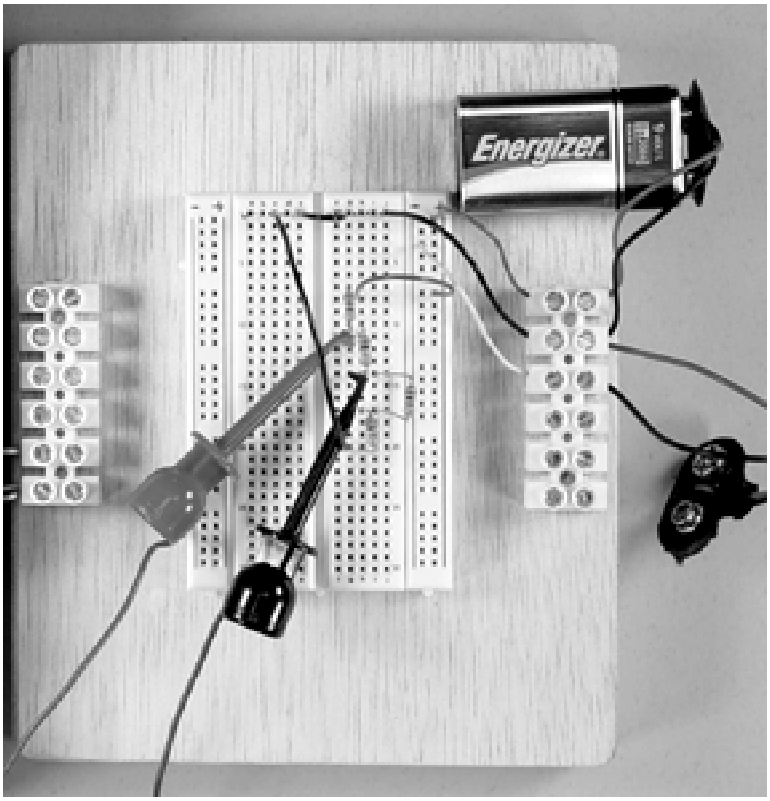
Experiment 2. Construct a 4-element resistive voltage divider and measure the voltage drops. Using the prototype board and four 1 kΩ resistors, wire the circuit shown below. The minus 9 volts (-9 v) connection from the battery is not used here. (The "k" in "1 kΩ" stands for "kilo" or 10^3. Thus, 1kΩ is the same as 1,000 Ω.) Your circuit has four 1 k resistors in series and the applied voltage is 9 v. Calculate the voltage drop across each resistor. Using the VOLTAGE function of your digital multimeter, measure the voltage across each resistor. Do the voltages agree with your calculations? Now measure the voltage drop from the "top" of the first resistor to the "end" of the second and third resistors. How has the resistive series "divided" the battery voltage?



Here's how your prototype board should look after wiring the resistors



Wire Colors: Generally RED wire is used for + voltages, and BLACK for ground. YELLOW is often used for negative (-) voltages.



Resistors in parallel

Resistors wired together as shown below are said to be "in parallel." Unlike series resistors, the resistances do not add. Rather, the total resistance, R_T, is

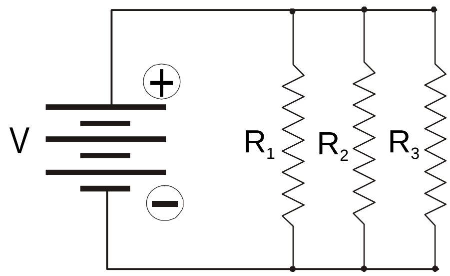
$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

For example, suppose all of the resistors are 1 kΩ. Then

$$\frac{1}{R_T} = \frac{1}{1000} + \frac{1}{1000} + \frac{1}{1000} = \frac{3}{1000}$$

or

$$R_T = \frac{1000}{3} = 333.33\Omega$$

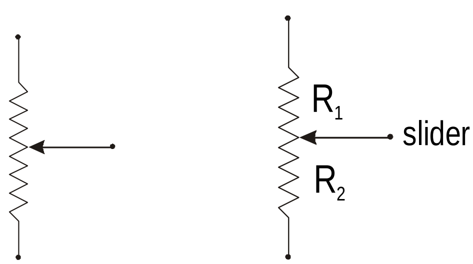


You can see that the more 1 k resistors added in parallel, the lower the total resistance.

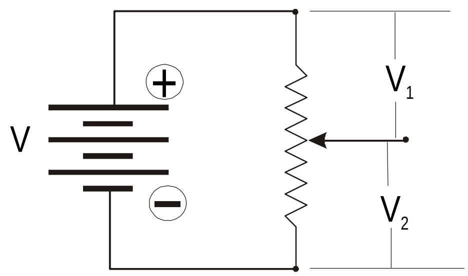
Experiment 3. Wire several 1 k resistors in parallel as shown above. Do not connect the battery. Measure the total resistance.

Variable resistors or "potentiometers"

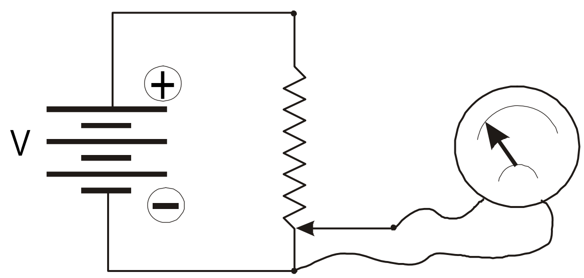
You can envision making a voltage divider that produces a large number of small voltage drops by connecting a lot of resistors in series. Fortunately, there is an easier way to accomplish this, namely by using variable resistors. The symbol for a variable resistor or "potentiometer" is shown below

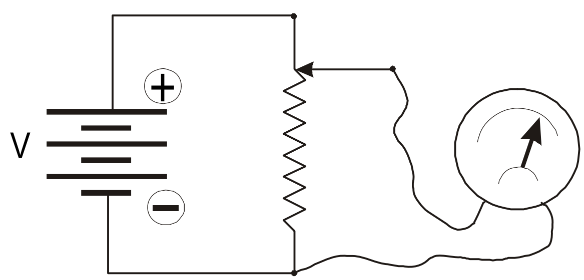


The symbol comes from old variable resistors that were made of fine wire wound onto a cylinder. A mechanical slider moved along the top of the cylinder, making contact at different parts of the wire coil, thus varying the resistance. You can see that a variable resistor is just like a voltage divider since the resistance from the top terminal to the slider is one resistance, and the resistance from the bottom to the slider is another.

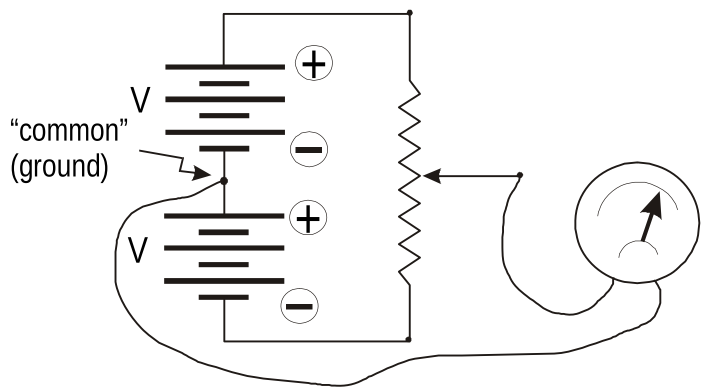


Experiment 4. Use the 5 k pot attached to the prototype board. This pot is a 10-turn, wire-wound pot. Identify the slider terminal and connect the multimeter to the slider and another terminal. Measure the resistance while turning the knob. Do the same thing with the other terminal. Then connect a 9 v battery across the terminals of the pot and change the multimeter setting to voltage. Connect the voltmeter from the slider to negative. Turn the knob on the pot and notice the voltage changes. The extremes are shown below.



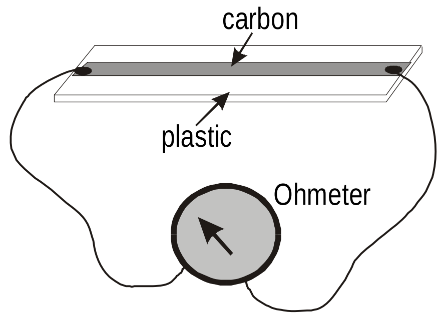


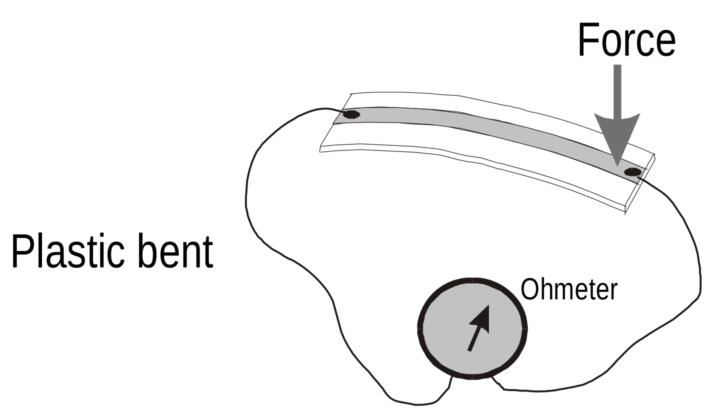
Experiment 5. Repeat the previous experiment, but use a “dual” power supply. A dual power supply provides both negative and positive voltages <u>with respect to ground.</u> Notice that the dual supply uses two 9 v batteries with the + of one battery connected to the – of the other. This connection is referred to as “common” and will also be referred to as “ground.” The term “ground” means that this point is ultimately connected to the earth. In some countries the term “earth” is used instead of “ground.” Rotate the shaft of the pot and observe how the voltage changes.



Strain Gauge

Strain gauges are devices for measuring forces and are ubiquitous in human performance laboratories. The functions of resistors described above suggest a possible method of constructing a strain gauge. Suppose, for example, you had a material whose resistance changed when a force was applied. Many commercial resistors are made of a carbon film. Carbon films change their resistance when deformed. To make a resistive strain gauge, we can form a carbon film on a piece of non-conductive, bendable plastic as shown below.

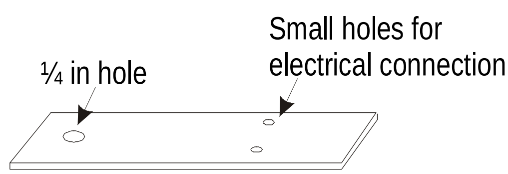


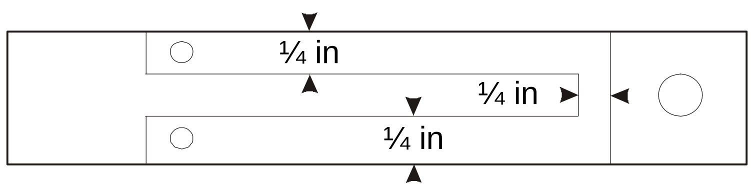


When a force is applied to one end of the plastic, it bends, stretching the carbon film and increasing the resistance. Thus, by measuring the change in resistance (and calibrating), we can measure the applied force. (In practice, it is better to measure a voltage change produced by the changing resistance, described later.)

Experiment 6. Building a resistive strain gauge

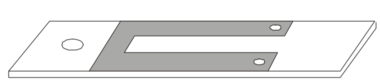
Use a piece of plastic about 2 mm thick, such as that used for window repair (can be found at most hardware stores). Cut the plastic into a piece 5 in X ¾ in. Drill holes as shown below.



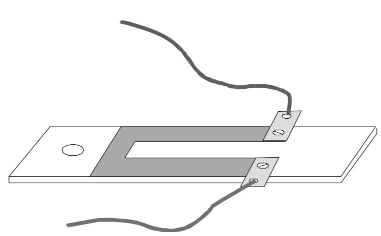


Sand the surface of the plastic using fine sandpaper. (The plastic strip has been cut and drilled for you.)

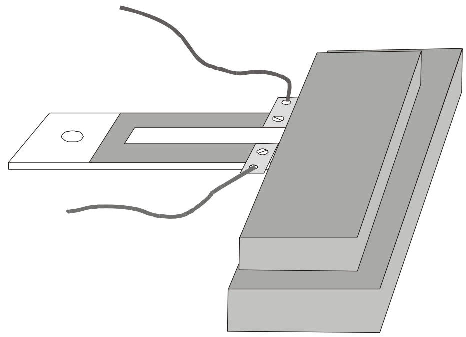
Using a soft (No. 2) pencil, outline the area shown in the drawing above *on the sanded (rough) side of the plastic*. Fill in the outlined area with the #2 pencil as shown below. Make sure that the plastic in the area indicated is completely covered with the carbon from the pencil.



Connect the carbon film to the two wires from the RG-174 coaxial cable provided using small pieces of copper or brass. Use 2-56 screws, nuts, and lock washers to tightly secure the metal to the carbon film.



Clamp the end of the strain gauge with the *carbon film side down* in the clamp provided:



Experiment 7. Connect the leads from the strain gauge to an your multimeter and measure the resistance (record the resistance). Press the end of the strain gauge downward or upward and record the resistances. What was the resting (no force) resistance of the strain gauge? What were the maximum and minimum resistances with force?

You probably found that the total resistance was about 100 - 200 kΩ and that it varied about 100 Ω with finger pressure applied. These small changes in resistance are difficult to measure and use in experiments. It would be desirable to make larger changes in resistance (or voltage) with applied force, that is, to amplify the signal. To do this, we need to learn about “operational amplifiers” or “op-amps.”

Operational amplifiers

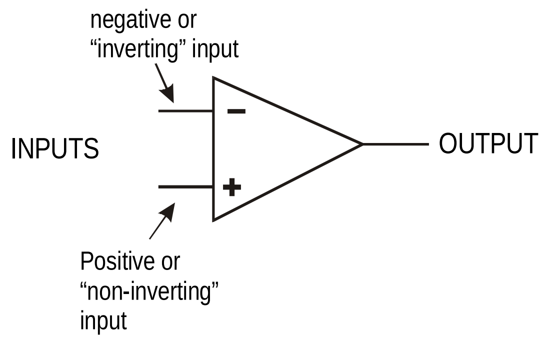
Op amps are d.c. (direct current) amplifiers, unlike your a.c. (alternating current) home stereo. The symbol for an op-amp is shown below. This symbol comes from the “greater than” symbol (>) since the output is greater than the input. The output voltage of an op amp is simply the input voltage multiplied by a factor called the “gain.” Thus,

$$V_{output} = V_{input} \times \text{Gain}$$

In fact, the gain is defined as the ratio of the output voltage to the input voltage:

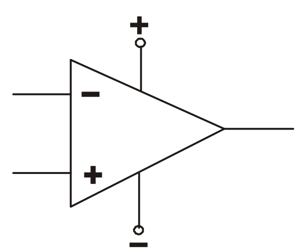
$$\text{Gain} = V_{out}/V_{in}$$

Most common op amps have very high gains of ~ 10^6, but as we will see, the gain can be set to be less than this.

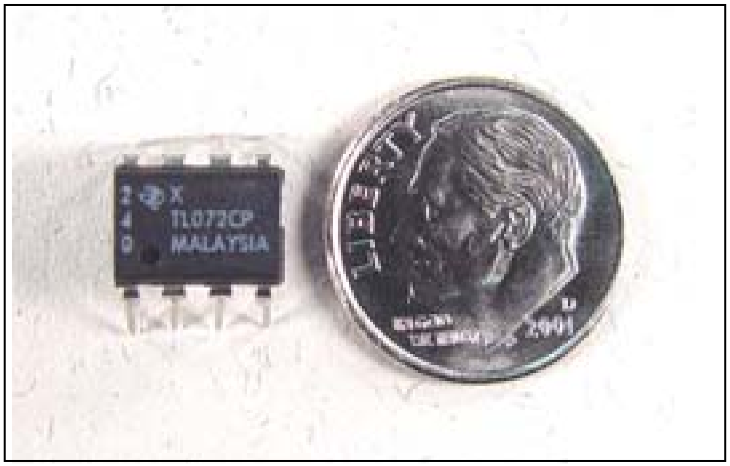


Notice that the op amp has a negative (-) and a positive (+) input. Op amps multiply the ***difference in voltage at the + and – inputs*** by the gain. Thus, even a few millivolts difference between the + and – inputs would result in many volts at the output when the gain is ~ 10^6

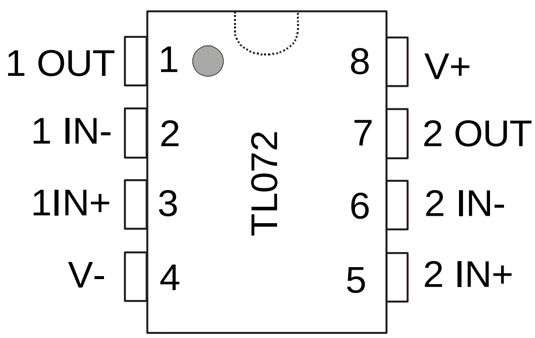
Op amps use a dual power supply, that is, one having negative and positive voltages referenced to ground (or "common") like the one you built earlier. The following diagram shows the dual voltage supply of an op amp.

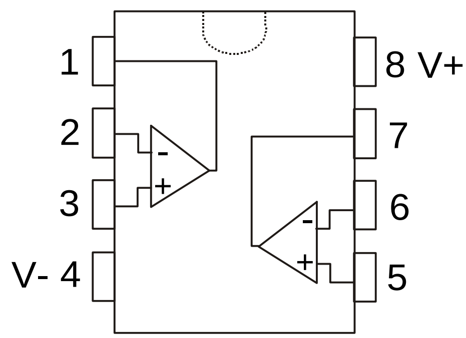


We will use the TL072 op amp (see photo below) made by Texas Instruments. This device is an integrated circuit in an 8-pin DIP (Dual Inline Package) configuration. Most of the integrated circuits you see are DIP's. The TL072 is readily available, inexpensive, and has excellent performance characteristics. You can find out more about the TL072 at the Texas Instrument Web site.



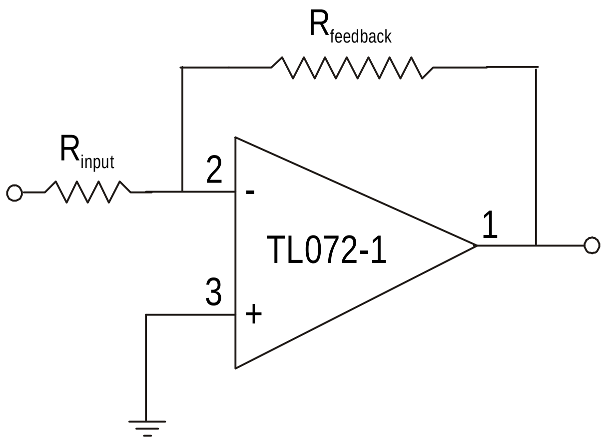
The pin configuration of the TL072 is illustrated below. The pins are numbered from 1 to 8 counterclockwise from the upper-left corner. The upper-left corner is usually marked with a small dot or the upper edge is marked with a recessed U-shaped area (shown by dotted line in diagram below). Notice that the TL072 contains two separate op amps. We will use both.





Inverting op amp

The basic op amp amplifier circuit is shown in the diagram below. It is called an "inverting" amplifier because the output is equal to the input times – G, where G is the gain. The output is connected back to the input (pin 2 to pin 1) through a "feedback" resistor, R_f. The input signal is coupled to the negative input through a resistor, R_{in}. The op amp output changes to whatever voltage is needed in to keep the difference between the plus and minus inputs zero. Since the plus input (pin 3) is connected to ground, it is 0 volts. Thus, the op amp feeds back a voltage through R_f to reduce the input voltage to zero.

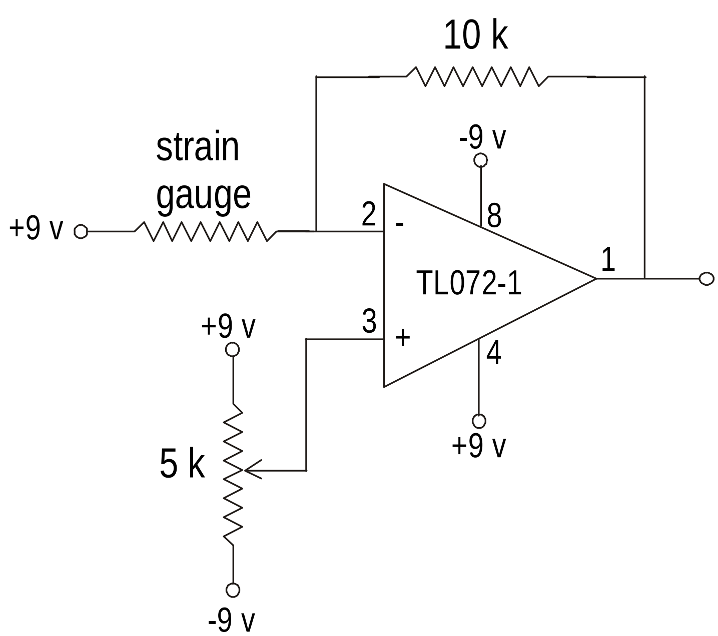


The gain, G, is simply $-R_f/R_i$. For example, if R_I were 1 kΩ and R_f 100 kΩ, the gain would be -100/1 = -100. So, if we apply an input signal of 10 mV to the input resistor, the output would be

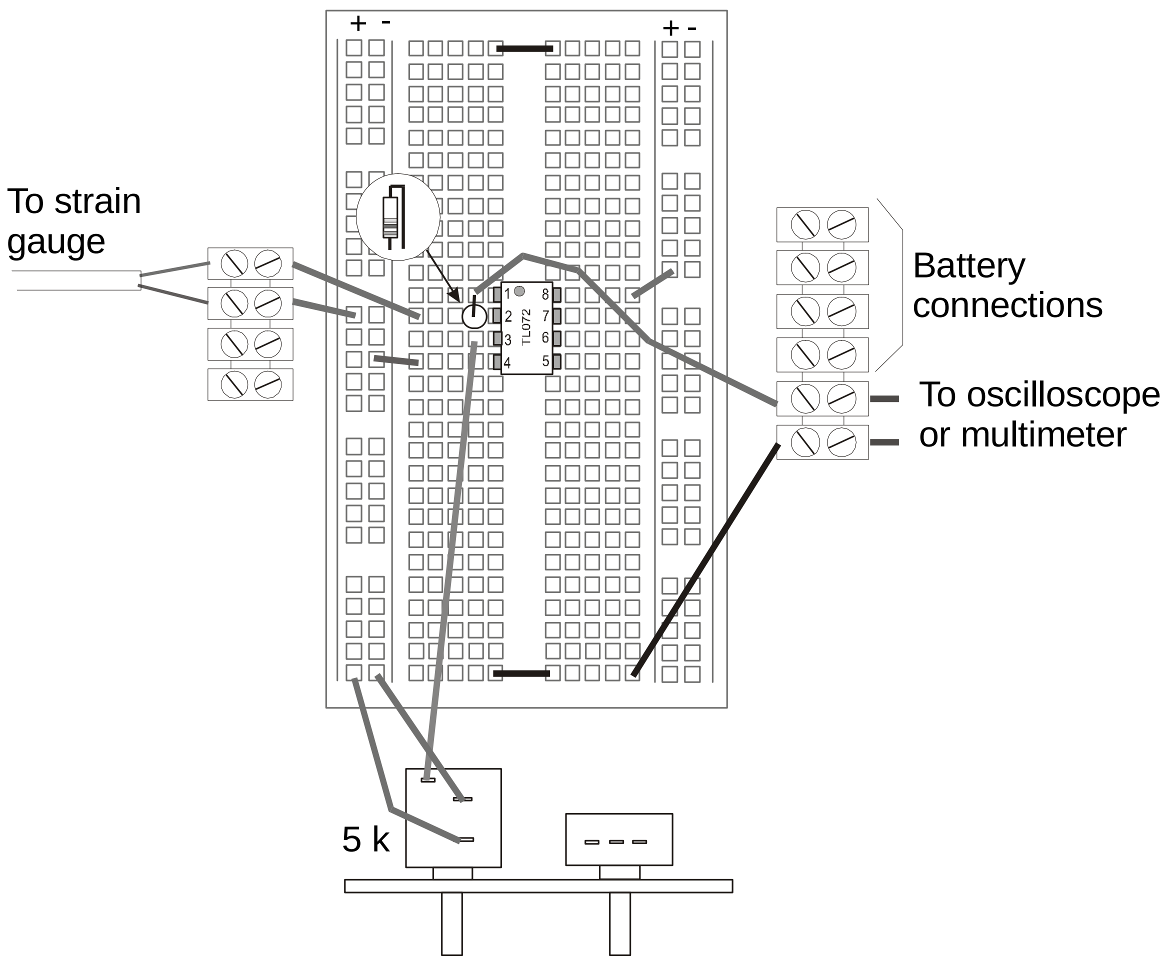
$$10 \times 10^{-3} \times (-100) = 10^{-2} \times (-10^{2}) = 1 \text{ volt}$$

Experiment 8. Connecting the strain gauge to the op amp

Now we have a means of amplifying the small signals from the strain gauge using an inverting op amp. Using a prototype board, insert the op amp and resistors as shown below. The numbers next to the op amp indicate pin numbers on the chip. Connect the dual battery power supply. One strain gauge connection is to the +9 volt battery, and the other to the inverting input (pin 2) of the op amp. Use the 5kΩ, 10-turn pot as a voltage divider as shown.



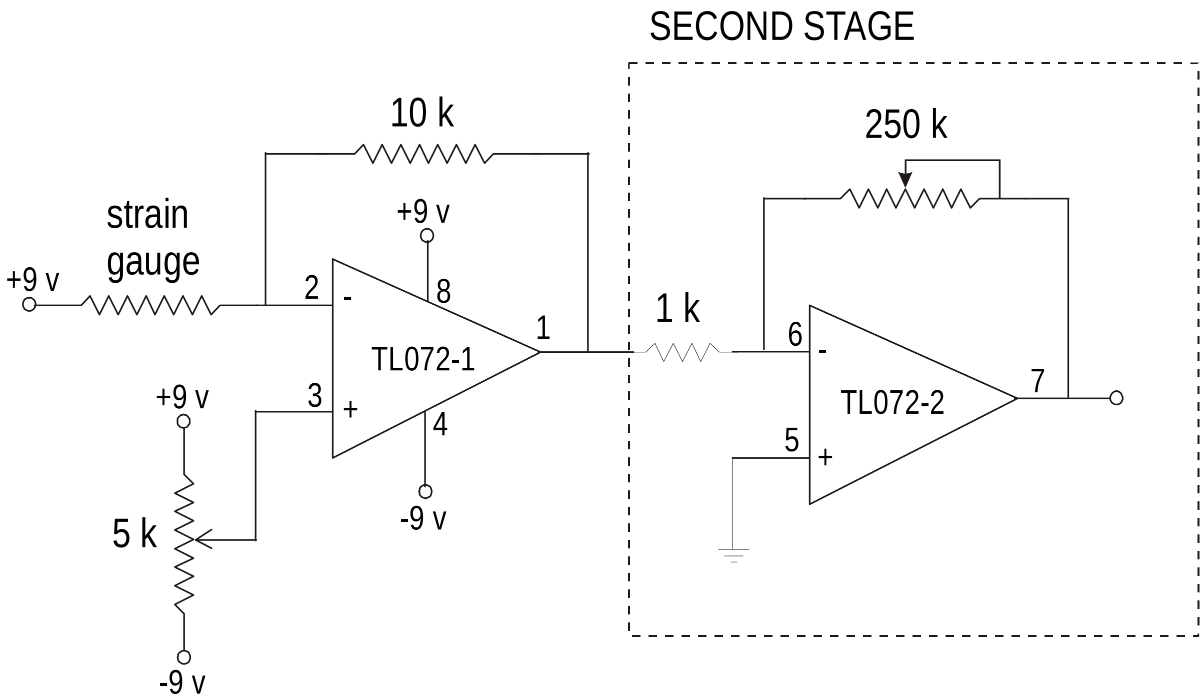
The reason for the voltage divider is that the input voltage from the strain gauge is high. Remember that the op amp wants to make the difference between the + and – input zero. So, we will use the pot to make a voltage at the + input (pin 3) very close to the no-force strain gauge voltage input at pin 2. The use of the 5k pot is sometimes called an “offset” or “zero adjust” circuit because the pot is adjusted so that the voltage at pin 3 just offsets the voltage at pin 2. Here’s how your prototype board could be wired:



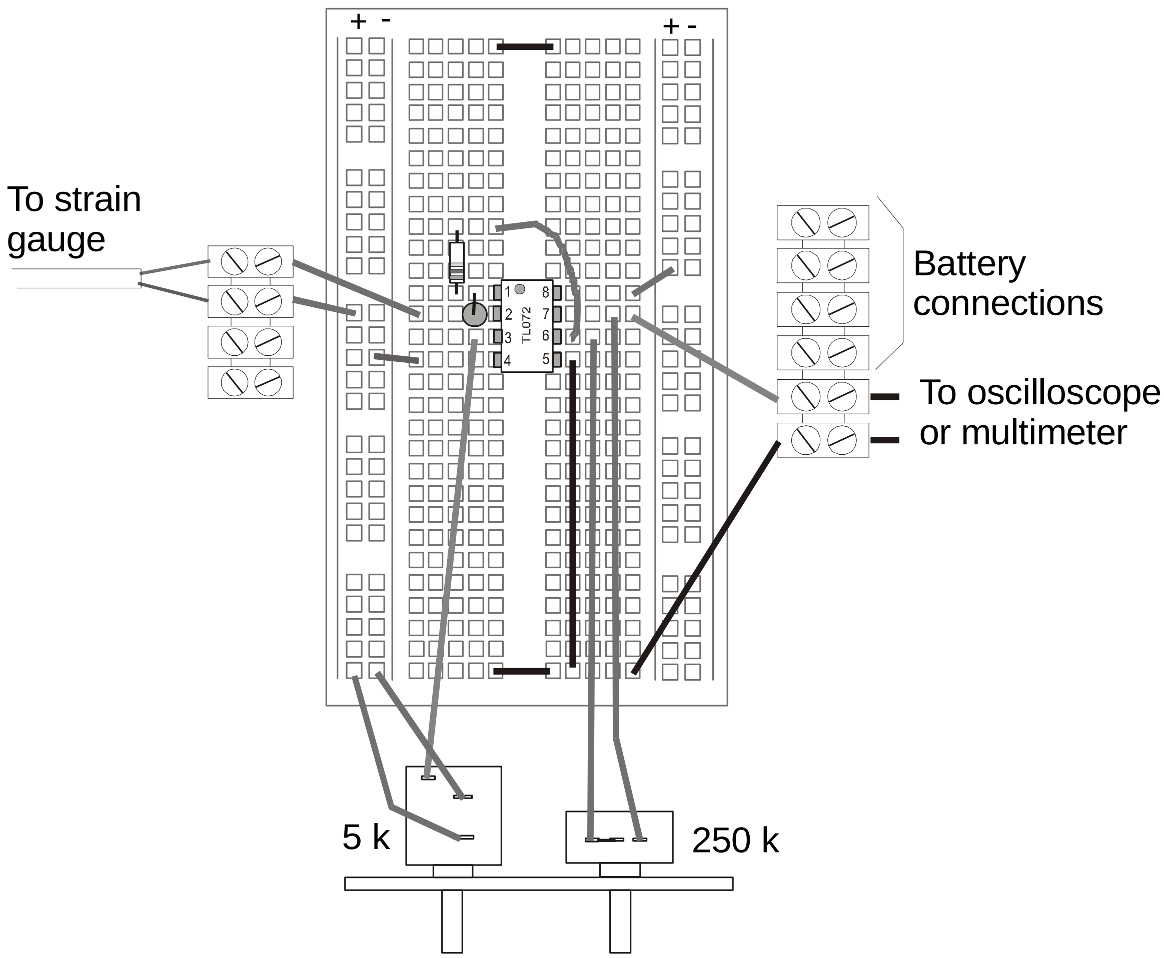
Connect the output of the op amp to an oscilloscope. Press up and down on the strain gauge and see what output voltages are produced. You probably will find that the voltage change is rather small. This is because the strain gauge resistance is high (~ 50 - 200 kΩ) and the feedback resistor is only 10 k. (What is the gain?) Even though the gain is small, this op amp “input” stage of our amplifier has served its purposes: (a) to turn the resistance change into a voltage change, and (b) to eliminate the high input voltage by using the offset adjustment pot. Thus, the first stage is a type of “preamplifier.” We can now amplify the signal from the strain gauge further by using the second op amp in the TL072.

Second stage amplifier

Connect the second op amp in the TL072 as shown below. The second stage amplifier is also in the inverting configuration, thus, we will multiply the signal from the first op amp by $-G_2$, the second stage gain. The second stage feedback resistor is a 250 k pot that will allow the resistance to vary from 0 to 250 k, thus the gain of the second stage will be variable from 0 to 250 (i.e., 250 k/ 1k).



Experiment 9. Wire the second stage as shown in the schematic diagram above and the drawing shown below. Now, connect the second stage output to an oscilloscope. Without any pressure on the strain gauge, adjust the offset pot so that the output is as close to 0 volts as possible. Then press gently on the strain gauge. You should see a large change in output as a result. If not, increase the Gain pot and try again.

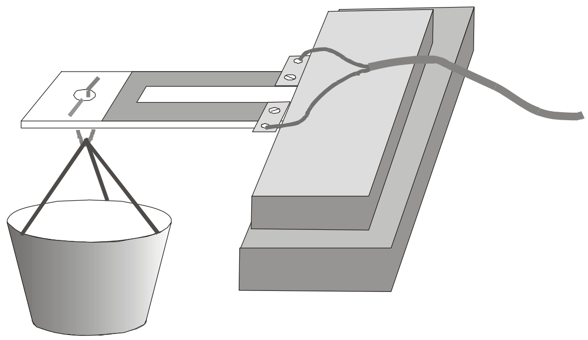


Experiment 10. Adjusting gain and offset.

Most DC amplifiers such as the one you have just constructed require adjustment of the gain and zero offset for proper operation. The idea is that zero input (i.e., no force on the strain gauge) should produce 0 volts output and that when the full expected force is applied, the output should be a specified voltage. The strain gauge and amplifier will be used for two further experiments: (1) calibration and (2) operation of an Analog-to-Digital converter. For both experiments, we want to measure the forces that are applied when a small cup attached to the strain gauge (see below) is filled with metal nuts. Further, we want the output of the amplifier to be 6.0 v when the cup is full. Here's the procedure:

- Clamp the wood strain gauge holder to the table top with the strain gauge hanging out.
- Without the cup attached, adjust zero offset so the output voltage is 0 v.
- Fill the container with ¼-20 nuts and attach it to the strain gauge as shown.
  Adjust the Gain so the output is 6.0 v
- Remove the container and check if the voltage returns to 0 v.
  If not, readjust the zero offset for 0 v.

- Repeat the previous steps until the output is 0 v for no weight and 6 v for the filled cup.



You will probably find that the output voltage does not return to zero when the weight is removed from the strain gauge. In part this is due to interaction of the gain and offset controls. Another important factor is the plastic from which the strain gauge is constructed: it is not a perfect spring, but rather has significant “memory” or hysteresis. It may be helpful to grasp the end of the strain gauge and wiggle it up and down roughly equal distances and note on the oscilloscope the middle of the swing. Adjust the zero so that the middle of the swing is at about 0 v. Doing this several times helps the plastic “relax.”

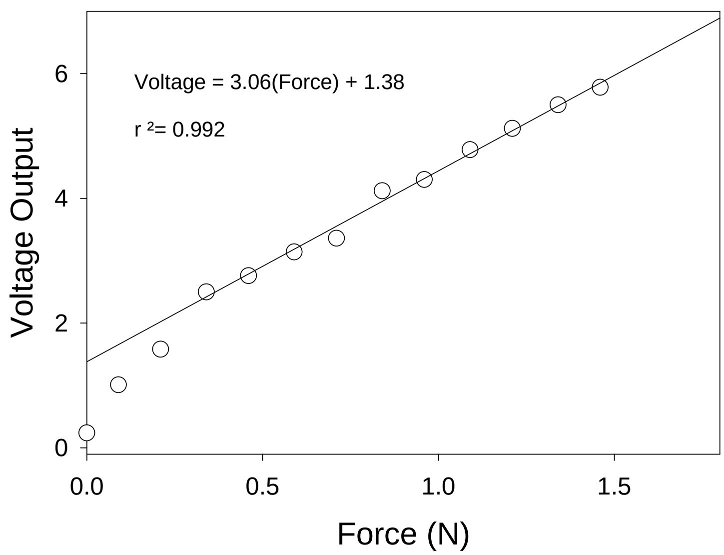
Experiment 11. Calibrating the strain gauge measurement system

The next step is to determine the relationship between a force on the strain gauge and the resulting voltage output from the amplifier. To do this, connect the output of the amplifier to the digital multimeter set on the voltage scale. Measure and record the output voltage with just the cup attached. Now add known weights (two nuts at a time) to the cup, each time recording the output voltage. Enter the data into a spreadsheet program such as Excel. For each weight increment, calculate the Force, F, in Newtons using the relationship

$$F = m \times a$$

Where *m* is the mass in kilograms, and *a* is the acceleration due to gravity (9.8 m/sec^2). Plot *F* vs. *V*, the voltage, using Sigma Plot or some other scientific plotting program. Using a linear regression model, find the best fitting relationship between *V* and *F*. Here is an example of such a calibration:

Grams	Force	Voltage
0.00	0.00	0.24
8.60	0.09	1.01
21.28	0.21	1.58
33.96	0.34	2.50
46.64	0.46	2.76
59.32	0.59	3.14
72.00	0.71	3.36
84.68	0.84	4.12
97.36	0.96	4.30
110.04	1.09	4.78
122.72	1.21	5.12
135.40	1.34	5.50
148.08	1.46	5.78



Overall, the voltage vs. force relationship appears nonlinear at low forces. Specifically, the three points nearest to 0 N do not fall on the same line as the higher force points. This means that the strain gauge is nonlinear. Using the strain gauge you have constructed, try to find an explanation for this nonlinearity. For the purposes of calibration, the three open circle data points were not included. A linear regression line was fit to the remaining points with the equation shown.

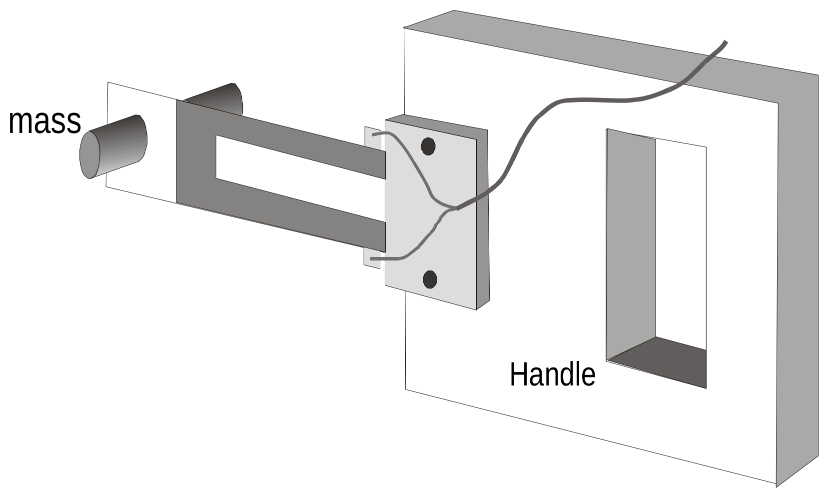
Try calibrating the strain gauge for upward as well as downward forces. You may find that the calibration function is not symmetrical. Why is this true? How could you correct it?

Experiment 12. Using the strain gauge for force measurements.

The range of forces that can be measured with the strain gauge is quite limited. Consequently it is probably not practical for measurement of human biomechanical parameters. How could you adapt the strain gauge for such measurements? Try blowing gently on the strain gauge and measuring the output. Try touching the strain gauge with you eyes closed and maintaining a constant force.

Experiment 13. Make an accelerometer using the strain gauge.

Add a mass to the end of the strain gauge using a ¼ inch bolt and some nuts as shown below. Connect the output of the strain gauge amplifier to an oscilloscope or computer with A/D converter. Grasp the "handle" and swing the device back and forth.



You should see an output similar to that shown in the top graph below. The top graph shows voltage as function of time in seconds. The A/D converter was set to sample at 100 Hz.

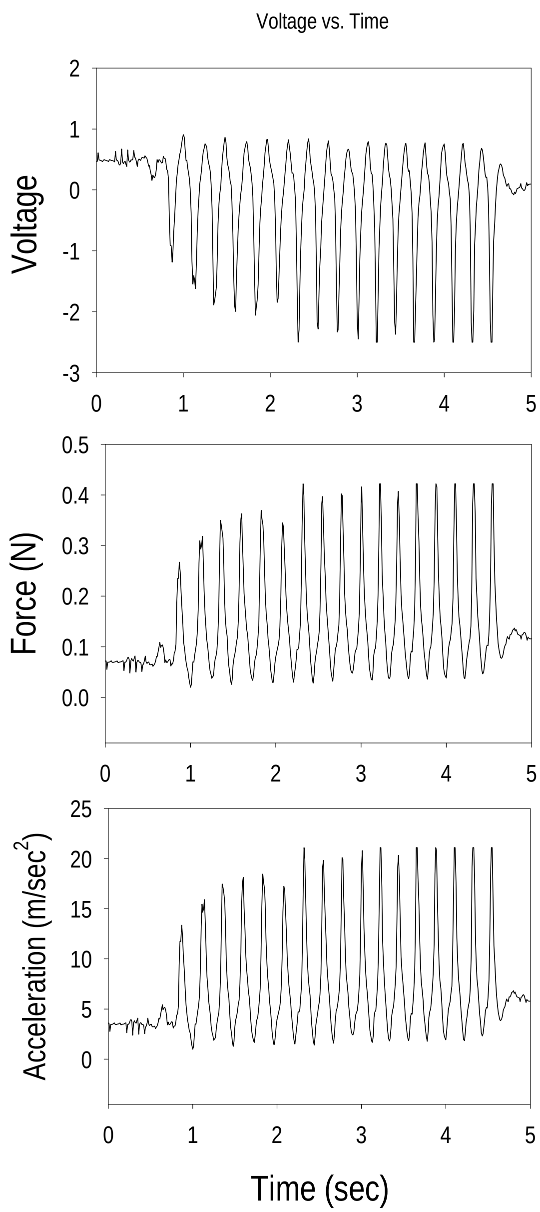
Using a spreadsheet program, the voltage vs. time data were converted to force (N) vs. time using the calibration equation shown above (N = 0.127 – 0.118 V). Notice that the peak force was about 0.4 N.

The spread sheet program was then used to calculate acceleration. To do this, you need to know the mass at the end of the strain gauge; I used 20 g.

$$F = ma$$

$$a = F/.02$$

The peak acceleration was about 20 m/sec^2. You can calculate the velocity by numerically integrating the acceleration plot in the spreadsheet.



II. Digital Electronics: Analog to Digital Conversion

Thus far, we have dealt with voltages that represent force or resistance. The amplifier you constructed takes a change in resistance from a strain gauge and turns it into a voltage that varies with the force applied to the strain gauge. Thus, output voltage is an *analog* of force. The op amp circuit that you constructed is thus referred to as an analog circuit. In contrast, computers use digital circuits in which the voltages are either a “1” or a “0.” In most computers, 0 is represented by 0 v (ground) and 1 is represented by +5 v. Thus, computer use binary numbers represented by two voltage levels for inputs, outputs, and calculations. To couple our strain gauge (or any other analog electronic device) to a computer, we need to translate the analog signal into binary. This is accomplished using devices called Analog-to-Digital Converters, or “A/D” converters. To understand how A/D converters function, it is necessary to know something about binary numbers.

Counting in binary

There are only two “digits” in the binary number system, 1 and 0. To count in binary, we can start with 0 and keep adding 1’s.

000
+1
001
+1 Here we have a problem. 1 +1 is 2, but there is no 2 in binary, so we carry the 1
010
+1
011
+1
100 Again, we had to carry the 1 two times.
+1
101
+1
110
+1
111

We have now counted to 7 in binary as shown in the table below.

Binary	Decimal
000	0
001	1
010	2
011	3
100	4
101	5
110	6
111	7

We will use 8 binary digits with our A/D converter. How many decimal numbers can we count? The general answer is $N = 2^n$ where n is the number of binary digits. Thus, for our 8 digits, we can count to $2^8 = 256$.

In the electronics and computer world, the digits of a binary number are referred to as “bits.” An 8-digit binary number represented as +5 v and 0 v signals would thus be called an 8-bit number. An 8-bit digital number is also called a “byte.” The first four digits (the 4 on the right) are called a “nibble.” An 8-bit binary digit has two 4-bit nibbles. This is important because each 4-bit nibble can be turned into a new base 16 number called Hexadecimal.

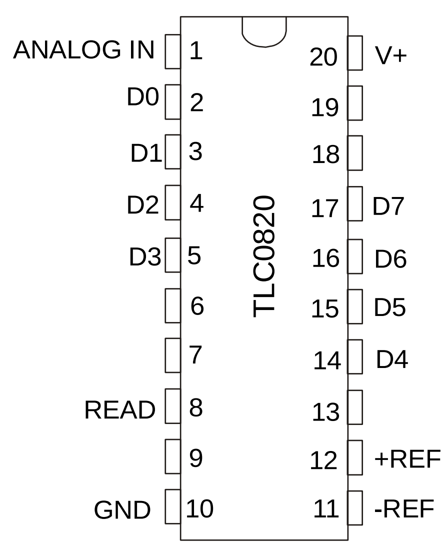
Problem. Here is a computer representation of a binary number

+5 v	0 v	0 v	+5 v	+5 v	0 v	0 v	+5 v

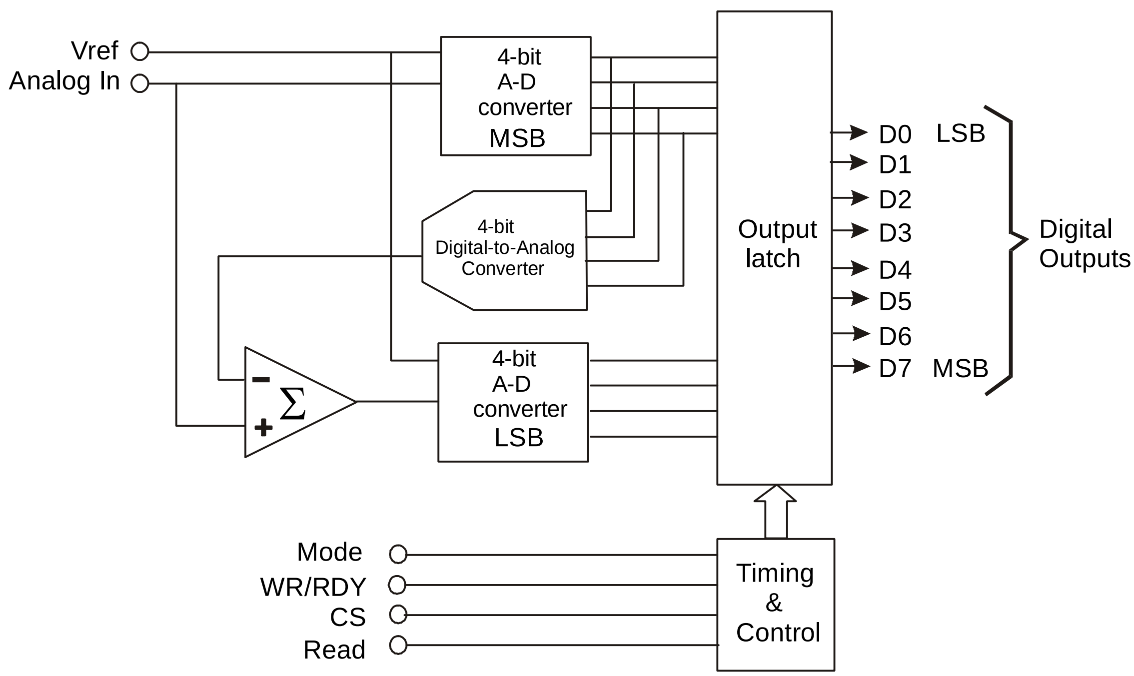
What is the number in decimal? You may find it useful to use the Calculator function of a Windows computer. Click on Calculator, then under “View” click on “Scientific.” You can use the Dec, Bin, Oct, and Hex buttons to enter numbers and convert them to other bases.

A/D Converter

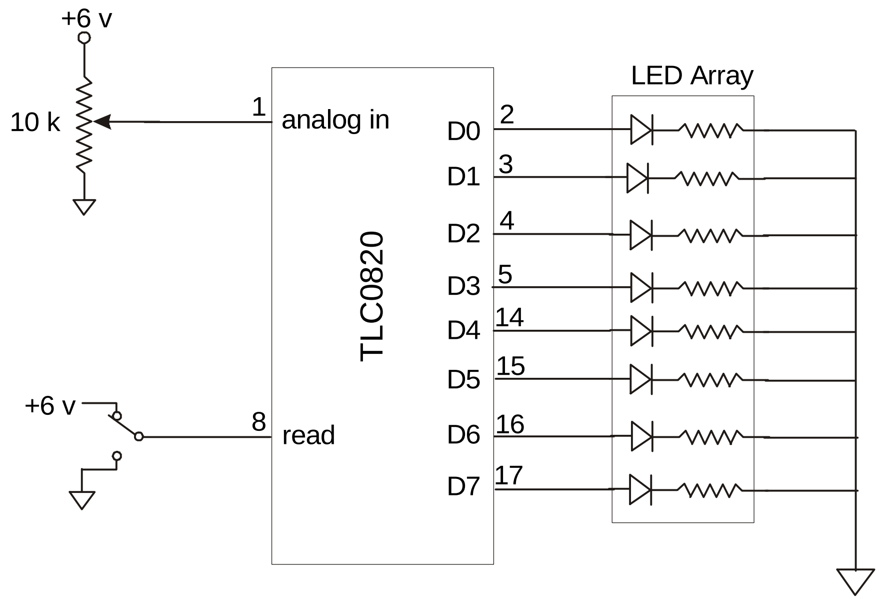
We will use a TLC0802 Analog-to-Digital converter chip made by Texas Instruments. This chip is designed for easy interfacing to microprocessors, but we will not use many of the sophisticated functions for this interfacing. The chip is illustrated below. It has 20 pins, 8 of which are digital outputs (D0 through D7). The digital outputs can be either 0 (0 v) or 1 (+5 v). The “READ” input will receive a signal (1 or 0) that causes the ANALOG IN voltage to be digitized. A-to-D converters require a reference voltage which is compared to the analog input voltage.



A more detailed functional diagram of the chip is shown below. There are two 4-bit A/D converters, one for the Most Significant Bits (MSB) and another for the Least Significant Bits (LSB). The MSB's are the ones that represent the highest binary numbers. In operation, the MSB A/D converter receives the analog input voltage and converts it to a 4-bit binary number. This number is reconverted to a voltage by a Digital-to-Analog converter (DAC). The DAC output voltage is then subtracted from the analog in voltage and a separate 4-bit A/D converter digitizes the output for the LSB's. When the "Read" input is high (i.e., +5 v), all eight bits are transferred to an "Output Latch" and are available on pins 2 – 5 and 14 – 17. The "Mode", WR/RDY, and CS controls are used in conjunction with interfacing the chip to a microprocessor and will not be used here.

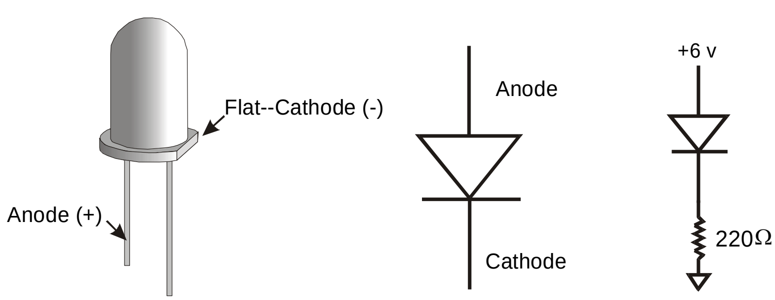


The wiring of the TLC0820 on the prototype board is illustrated below. All of the control inputs have been pre-wired on your prototype board with the exception of the "Read" input. You need only connect the analog voltage input (Pin 1), the READ input (Pin 8), and connect the TLC0820 digital outputs to the LED array using the 4 inch yellow wires provided. The reference voltage, V_{ref}, has been connected to ground. This means we will measure our analog input voltages with respect to ground (0 v). Although 5 v is the standard voltage level for digital logic, we will use 6 v from a battery since there are no 5 v batteries available.



The A/D prototype board has a switch that will be used to initiate an analog to digital conversion. The switch is a "single pole, double throw" or "SPDT." Conceptually, you can think of the switch as a metal lever that swings from one contact to the other. The contacts are called "throws" and the lever is always connected to the "pole." In the diagram above, the common pole of the switch is connected either to +6 v or to ground, depending on whether the switch lever is up or down. Wire the switch to the A/D converter as shown.

A LED array has been provided so that we can see whether a bit is high (LED lit) or low (LED unlit). LED's (Light Emitting Diodes) are a type of diode. Diodes are devices that conduct current in only one direction unlike a wire or resistor. LED's have an Anode (+) side and a Cathode (-) side. Current flows from the anode to the cathode, but not the reverse. The Cathode of a LED can often be identified as the lead nearest a flat area on the plastic. The symbol for the LED (or any diode) is shown below.



LED's will "try" to conduct very large currents when a voltage is applied to them. These large currents quickly burn out the LED. Consequently, it is necessary to put a "current limiting" resistor in series with the diode as shown above. LED's have specified voltage drops and currents. The voltage drop across a LED in a circuit is called V_{LED} and is typically about 2 volts. LED currents have a large range, but 20 mA (20 X 10^{-3} A) is typical. The maximum LED current is I_{LED}. Using typical values for V_{LED} and I_{LED}, we can calculate the value of the current limiting resistor when using a 6.0 v battery power supply:

$$R_S = \frac{V_{IN} - V_{LED}}{I_{LED}}$$

$$R_S = \frac{6.0\text{v} - 2.0\text{v}}{0.020\text{A}}$$

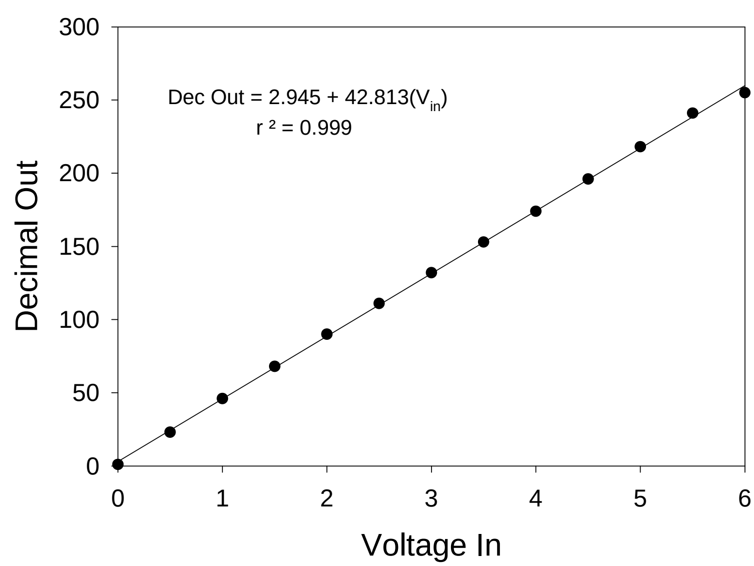
$$R_S = \frac{4.0\text{v}}{0.020\text{A}} = 200\Omega$$

Experiment 14. Using the red LED and the 221Ω resistor in your supplies, wire up the LED as shown. The resistor is rated at ¼ Watt. Is this sufficient to dissipate the power due to the calculated current flow?

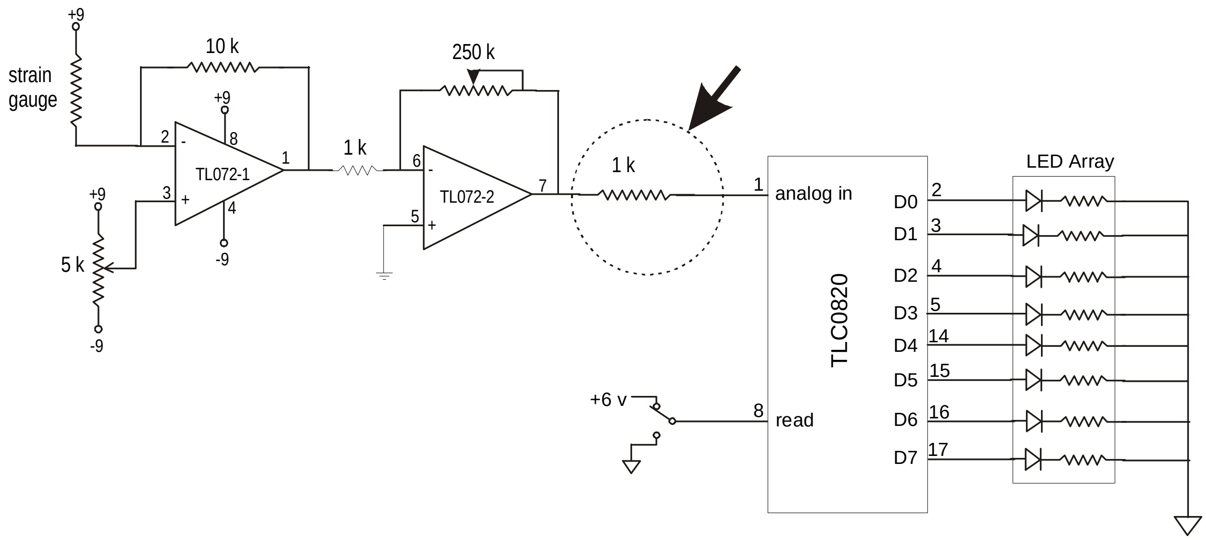
Fortunately, the "bar-graph" LED array we use has the current limiting resistors incorporated in the package, so we don't have to wire up eight separate LED's.

Experiment 15. The prototype board has a 10 k pot. Connect the pot as shown above in order to input various voltages between 0 and 6 v to the A/D input (Pin 1). Connect your multimeter to the analog input or the pot slider and set the pot for a particular voltage. Now flip the switch up. The LED's should light in a particular binary pattern. Change the voltage and do another A/D conversion by flipping the switch. You should see a different binary number. Finally, set the pot for 0 v and perform an A/D conversion and record the binary number. Repeat this after incrementing the voltage by 0.5 v and continue up to 6.0 v. Each time write down the binary output. (Make sure that the LED display is OFF as much as possible since the LED's drain the battery.) Finally, convert the binary numbers to decimal and make a plot of binary number out versus voltage in. Here is an example:

Voltage	Binary	Decimal
0.0	00000001	1
0.5	00010111	23
1.0	00101110	46
1.5	01000100	68
2.0	01011010	90
2.5	01101111	111
3.0	10000100	132
3.5	10011001	153
4.0	10101110	174
4.5	11000100	196
5.0	11011010	218
5.5	11110001	241
6.0	11111111	255



Experiment 16. Now connect the strain gauge and amplifier to the A/D converter. A 1 k resistor must be placed between the op amp output and the A/D input. It is easiest to do this on the op amp board as shown.



Adjust the strain gauge amplifier zero and gain so that there are 0 v out without weights attached to the strain gauge and 6.0 v out with the cup full of weight attached. Now, make A/D readings as you previously did when calibrating the strain gauge. Record the number of nuts added and the binary output. Plot the results.