1.101 Structures Lab.
Fall 2005
Week 1 - The Tension Test

Our objective is to measure the *Elastic Modulus* of steel. This we do in two ways.

First, we will subject a specimen in the form of a steel rod to a tension using an *Instron* testing machine designed specifically for that purpose. An “extensonmeter” will be used to obtain a measure of strain and a “load cell” used to obtain a measure of stress.

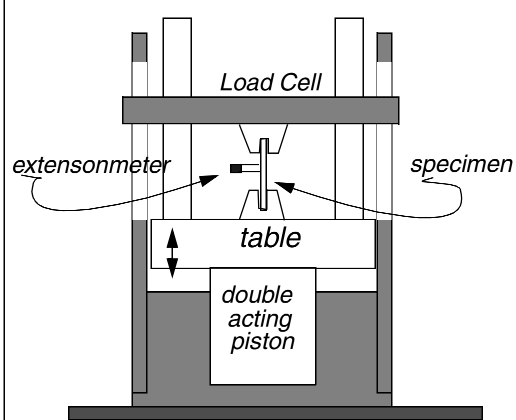
In the second part of the experiment. you will do a tension test of a steel member, loading the specimen using the dead weights available in the lab but measuring uniaxial deformation using strain gages.

You will use the pages that follow in reporting your results.

Wk 1.1 Instron Tension Test of steel.

The INSTRON machine is built specifically to subject structural elements to tension or compression. The figure at the right indicates how it works.

A double acting piston drives the table up, or down, when pressurized hydraulically. The test specimen is fixed relative to the top bar and the shaded cross bar by the grips; the shaded cross bar is fixed in space. Hence, the specimen is subject to a tensile load as the table moves downward.



INSTRON Machine

Test Sequence - Overview

Before the test, you will measure and record the diameter of the test specimen.

Steve Rudolph will set up the apparatus, fixing the specimen in the grips of the machine, attaching the extensonmeter, and setting the Instron for a “ramp” increase of load.

The output of the extensonmeter and the load cell will be automatically recorded on a pc. You are to make note of the load and displacement factors so that you can convert the voltage readings so recorded to force (then stress) and displacement (then strain). The original length between the points of attachment of the extensonmeter should also be noted.

The specimen will be loaded to failure. **Wear safety glasses.**

Parameters for determining tensile stress.

The load is sensed by a load cell integral with the top bar. It puts out a voltage proportional to the load. For our purposes, you need know the scaling factor for converting this voltage to a (tensile) force. This is obtained from a “full scale” setting, the “automatic calibration” of the load cell.

At full scale, the signal output is ______ *Volts*

and the *corresponding load is* _______ *KN* or ___________ *Kips*[1].

The load factor is then:

Load factor = ____________ KN/volt	or =	____________ Kips/volt

Knowing the cross-sectional area of the test specimen, we can, knowing the load, compute the tensile stress in the bar. We record that the diameter of the specimen as:

Diameter = ____________ +/- ? mm	or = ___________________+/- ? in.

So the cross sectional area is

Area = ____________ mm^2	or ______________________ in^2

The bar, made of ___________steel, has a

yield stress of ______ ksi.	and an ultimate stress of ________ ksi

Our goal is to graph how the tensile stress varies with the tensile strain. We need, then to go one step further and construct the factor for tensile stress in terms of voltage. Dividing the force by the area we obtain:

Stress factor = ____________ Pascals/volt	or =	____________ psi/volt

To compute the corresponding values of the strain, we need to measure the change in length of the specimen. The strain is the ratio of the change in length to the original length.

Parameters for determining tensile strain.

An extensonmeter will be used to measure the change in length between two points located on the surface of the cylindrical specimen. The two knife edges, which are held in place against the specimen by simple elastic bands, are initially spaced a preset distance apart. This “gage length” is

Gage Length = ____________ in	or ____________ mm

The gage factor is determined from “full scale” conditions. The extensonmeter we will use can accommodate a full scale displacement of ________ inches. The full scale output voltage is ________volts. Hence, the scale factor for displacement is

Displacement factor = __________ in/volt	or ____________ mm/volt

The strain factor is then, dividing by the gage length

Strain factor = __________ (in/in)/volt	or __________ (mm/mm)/volt

1. 1 Kip is 1000 pounds.

Data Collection and Analysis

Data will be recorded via the computer (equipped with analogue to digital conversion hardware). An ASCI text file will be produced in three column format.

Time	Displacement	Load
(sec.)	(volts)	(volts)

The first dozen or so readings will show negative values for the displacement and load as the specimen "takes up the load". Do not include these on your plot. The "good" data will be taken at a relatively high frequency so you should select a subset, or use an averaging, "smoothing" of the data before plotting by hand or using a spread sheet. Also, your plot should end well before breaking of the specimen - you want to show clearly the slope in the linear region of the stress-strain plot - so you will "truncate" the data set at the end as well as at the beginning. You do want to plot past the yield point figured at a 2% offset. Also indicate the ultimate stress - as a point on the stress axis. Attach your plot to this report.

Results

Once we have a plot, we determine the slope in the elastic range. We obtain in this way the following experimentally determined value for *E, the elastic, orYoung's modulus* :

E, the elastic, orYoung's modulus = ____________ +/- ? psi or ____________ +/-? Pascals

A graph of the stress-strain curve, ranging up to three or four times the strain at yield is shown below (Import the graph from a spread sheet or simply, include in this document as the next page).

The slope is indicated on the graph.

It differs from the "book value" by ~ ____________ %

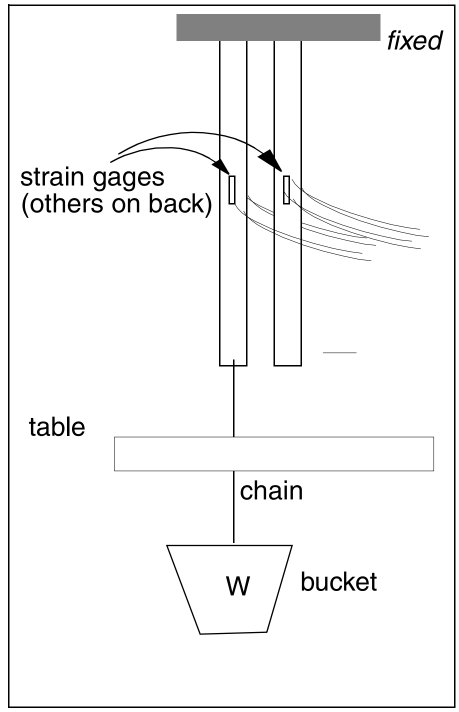
Reasons for this discrepancy include:

Wk 1.2 Dead weight tension test of steel.

We return to the lab and subject a thin, steel specimen of rectangular cross section to tension. We again measure pairs of values of applied loading and displacement but **we do not take the specimen to failure**. We will remain in the elastic range, then unload.

Setup of test specimen.

The schematic at the right shows the test setup. The two steel members will already have been secured at their tops to the rigid space frame atop the rigid table. Only one of the specimens will be subjected to tension; the other provides a way of nulling out the effects of temperature variation that might imbalance the bridge. The location of the four strain gages in the bridge circuit is shown in Appendix B. There you will also see the how the op-amp is configured.



The first step is to measure the cross-section dimensions of the specimen.

b
w

b = _______ *(units?)*

w = ________*(units?)*

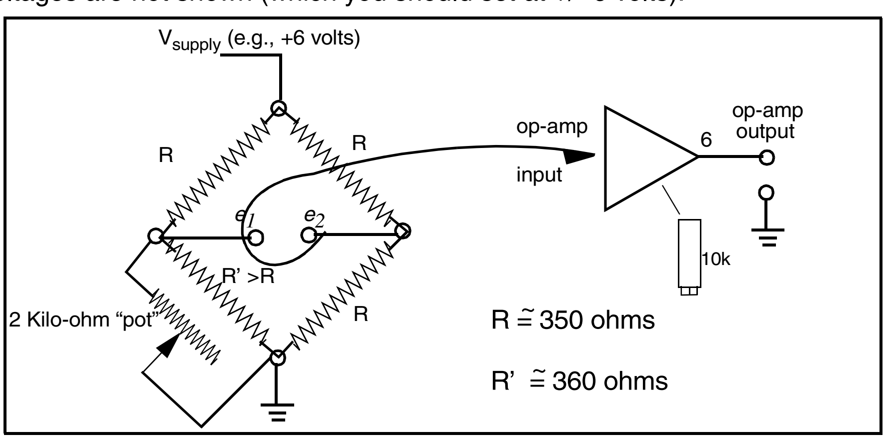
So the cross-sectional area is

A = _______ *(units?)*

Gain of the operational amplifier.

When you first confront the protoboard, the strain gages may not have been connected to the board. You should do so in accord with the circuit drawn in Appendix B.

The next step is to determine the gain of the op-amp. We do this by deliberately unbalancing the bridge, replacing one of the inactive gages with a resistor of suitable magnitude (Greater than the resistance of the strain gage, i.e., >350 ohms) in parallel with a 2 kilo-ohm potentiometer (“trim pot”). See Appendix B. for bridge, op-amp circuit diagram details. The figure below shows only what you will need to know in order to vary the *input* to the op-amp, then measure the *output*; e.g., the supply voltages are not shown (which you should set at +/- 6 volts).



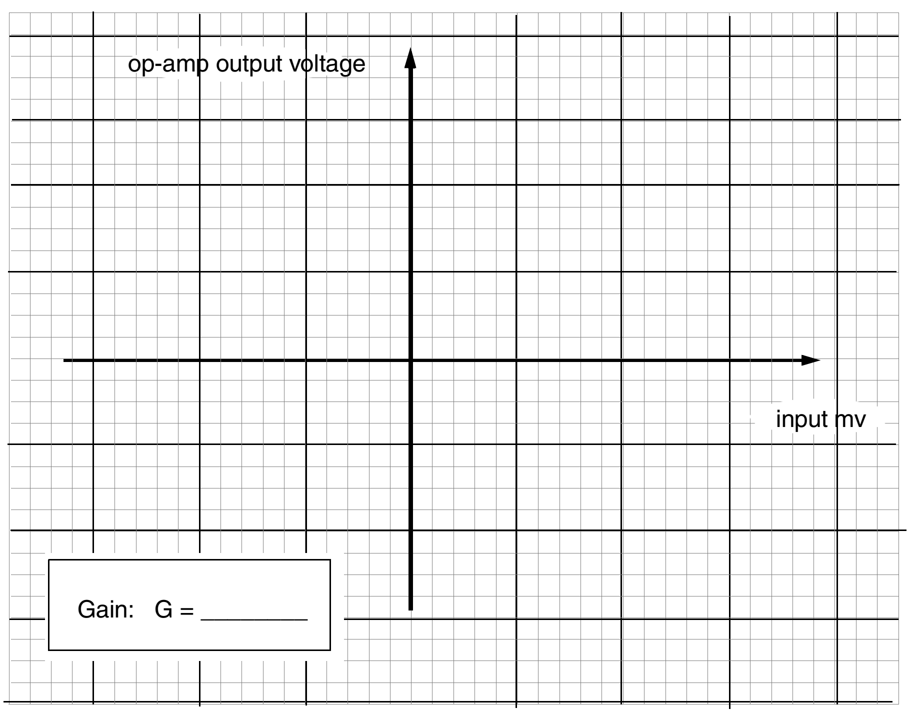
If available, use two voltmeters to measure both the input voltage to the op-amp e_1 - e_2, and the output voltage of the op-amp, pin 6 to ground. First, short out the input, connecting e_1 and e_2 using a short jumper wire. Then, adjust the 10 Kohm trim pot until the output of the op-amp is zero, i.e., within a few millivolts of zero. (Zero does not exist in the material world).

Now, remove the jumper wire and set the op-amp input voltage (which you are measuring with one of the voltmeters) to some small value, either positive or negative, say on the order of 10 mv. Record this value, and the output value of the op-amp, in the table below. Repeat, increasing the input voltage by another 10 mv, or whatever, again measuring the corresponding op-amp output. Continue as you see fit, but do take values of the opposite sign as well. Make sure you enter an estimate of uncertainty in your readings in the row indicated at the top of the table (+/-??).

Op-amp Gain

input = e_1-e_2	output
mv	volts
[+/-??]=	[+/-??]=

A plot of the output - input, fit with a straight line, gives the gain as slope



When you are finished estimating the gain, disconnect the 2 kilo-ohm trim pot and replace the resistor R' with the (in-active) strain gage you had removed from the bridge at the outset.

The tension test

With all four gages now connected in the bridge circuit, adjust the 10 kohm pot to bring the output to zero, within a few millivolts. Note: if you measure the input you will find that it is not zero; there is a slight imbalance - slight in the sense of tolerable - in the bridge due to variability in gage resistance. They are not identically 350 ohms. This imbalance, a dc offset, is amplified by the op-amp but you should be able to null it out by the zero adjust on the op-amp, the 10k pot. If this does not seem possible, call for an instructor. Make sure you record the positive (and negative) supply voltage.

Attach the chain to the bottom of the specimen subject to loading, using an S hook. Attach the pail to the other end of the chain hanging below the test bed again using an S hook. Make sure the chain passes through the appropriate slot in the test bed to avoid contact with the bed.

The bottom of the pail should hang but a half inch off floor. Although the experiment should not take the specimen to failure, we want to make sure that, if failure did occur, the bucket would not drag the specimen and strain gauges through the slots in the table.

Record the output voltage of the op-amp with the empty bucket and chain in place. We will take this as our zero loading condition. (Alternatively, we could weigh the bucket and chain as our first load point, but since we are only interested in the slope of the stress/strain plot, and *since that relationship is linear for small strains*, it matters not if we work from an initial offset.)

Put on your safety glasses!!

Load with the dead weights provided, carefully placing one after another in the bucket. Do not exceed 40 pounds. Take data upon unloading as well.

TABLE 1. Tension Test Data   Date:

Load	op-amp output	e_1-e_2	$\Delta R/R_g$	Strain ε	Stress σ
[units]	[units]	[units]	[units]	[units]	[units]
+/- ???	+/-	+/-	+/-	+/-	+/-
Chain +pail		0	0	0	0
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6

Columns 1 and 2 are measured data.

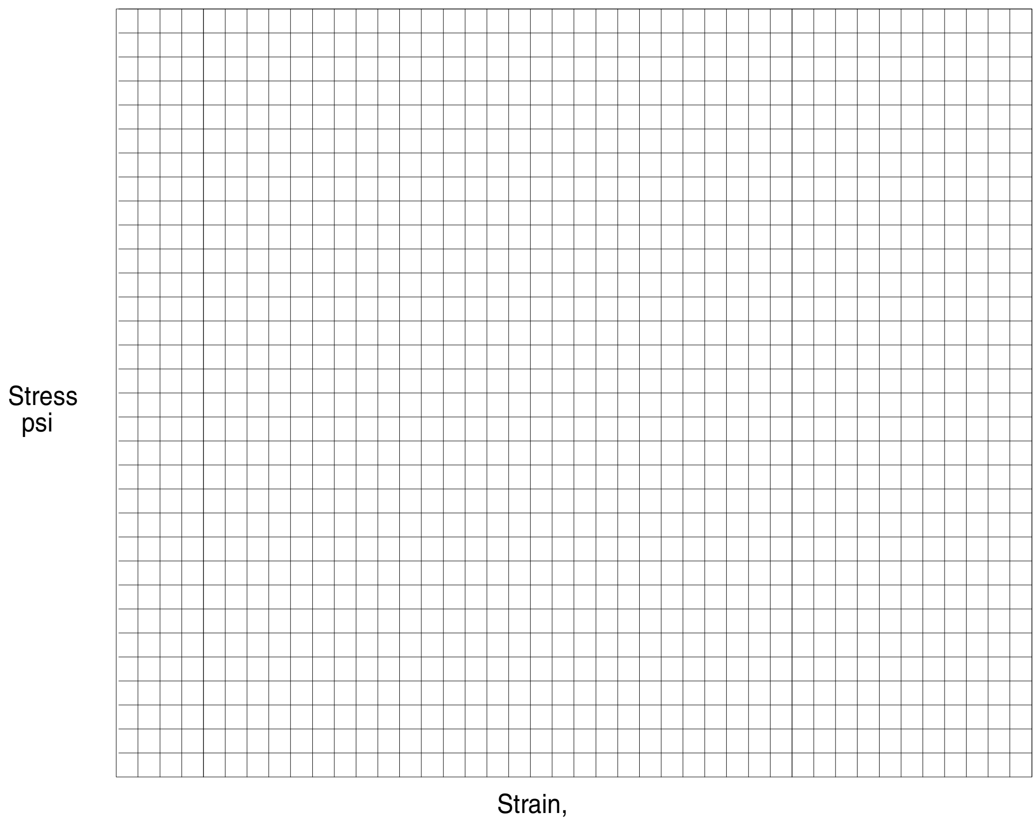
Column 3, the bridge “output” voltage e_1-e_2 - which is “input” to the op-amp - is obtained by dividing the op-amp output by the op-amp gain, *G.*

Columns 4, the fractional change in gage resistance due to strain, is obtained from the analysis of the bridge circuit, assuming the fractional change is small, i.e., $e_1 - e_2 = (V_{supply}/2)(\Delta R/Rg)$

The strain, column 5, is related to the fractional change in resistance by $\varepsilon = (1/F_{gage})(\Delta R/Rg)$ where F_{gage} is the “gage factor” stated by the manufacturer[1] to be F_{gage} = 2.07 +/- 0.5%

Results

The plot below shows the stress strain curve obtained. We also redraw the linear portion of the curve obtained from the instron test on the same plot.



Stress versus strain - Uniaxial Tension Test
Steel Bar & Rod

The slope of the stress/strain curve in the linear elastic range gives a value for the elastic modulus for the rod of

E, the elastic, or Young’s modulus = ____________ +/- ?? psi

Again, we see this is (above, below?) the book value by a (significant, small?) amount. This difference (can, can not?) be accounted for by uncertainty in our making of measurements.

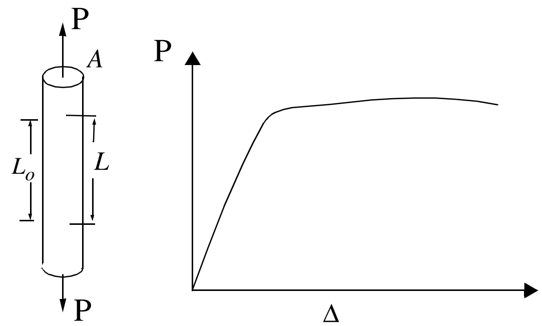
Discuss (on an added page).

1. BLH Electronics, Inc.

Appendix A. - Uniaxial Tensile Test.

The tension test.

The tension test is a standard test[1] for characterizing the behavior of a material under uniaxial load and for determining the elastic modulus, *E*. The test consists of pulling on a circular shaft, nominally a centimeter in diameter, and measuring the *applied force* and the *relative displacement* of two points on the surface of the shaft in-line with its axis. As the load *P* increases from zero on up until the specimen breaks, the relative distance between the two points increases from L_0 to some final length just before separation. The graph at the right indicates the trace of data points one might obtain for load P versus Δ where

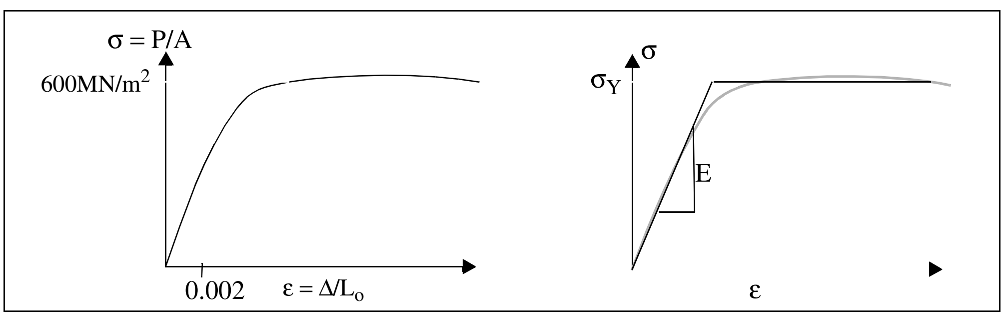


$$\Delta = L - L_o$$

If we double the cross-sectional area, A, we expect to have to double the load to obtain the same change in length of the two points on the surface. That indeed is the case. Thus, we can extend our results obtained from a single test on a specimen of cross sectional area *A* and length L_0 to another specimen of the same length but different area if we plot the ratio of load to area, the *tensile stress*, in place of P. Similarly, if, instead of plotting the change in length, Δ, of the two points, we plot the stress against the *ratio of the change in length to the original length* between the two points our results will be applicable to specimens of varying length. The ratio of change in length to original length is called the *extensional strain*. We designate the *tensile stress* by σ and the *extensional strain* by ε. The tensile stress is defined as

$$\sigma \equiv P/A \qquad \text{and the extensional strain by} \quad \varepsilon \equiv \Delta/L_o .$$

The figure below left shows the results of a test of *1020, Cold Rolled Steel*. Stress, σ is plotted versus strain ε. The figure below right shows an abstract representation of the stress-strain behavior as *elastic, perfectly plastic* material.



Observe:

- The plot shows a region where stress is proportional to the strain. The linear relationship which holds within this region, may be written $\sigma = E\varepsilon$ where *E* is the *elastic modulus*, often called *Young's modulus*.

1. Standard tests for material properties, for failure stress levels, and the like are well documented in the American Society for Testing Materials, ASTM, publications. Go there for the description of how to conduct a tensile test.

• The behavior of the bar in this region is called *elastic*. **Elastic means that when the load is removed, the bar returns to its original, undeformed configuration.** That is L returns to L_0. There is no *permanent set*.

• The relative displacements of points — the strains in the elastic region — are very small, generally insensible without instruments to amplify their magnitude. To "see" a relative displacement of two points originally 100 *mm* apart when the stress is on the order of 400 *Mega Newtons*/m^2 your eyes would have to be capable of resolving a relative displacement of the two points of 0.2 *mm*! Strains in most structural materials are on the order of *tenths of a percent at most*.

• At some stress level, the bar **does not** return to its undeformed shape after removing the load. This stress level is called the *yield strength*. The yield strength defines the limit of elastic behavior; beyond the yield point the material behaves *plastically*. In the graphs above, we show the *yield strength* defined at a *2% offset*, that is, as the intersection of the experimentally obtained stress-strain curve with a straight line of slope, E, intersecting the strain axis at a strain of 0.002. Its value is approximately 600 *MN*/m^2.

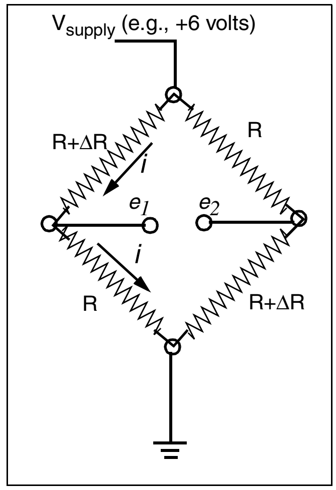
• Loading of the bar beyond the yield strength engenders very large relative displacements for relatively small further increments in the stress, σ.

Appendix B. - The electronics.

The bridge circuit.

The "Wheatstone bridge" produces an output voltage proportional to the change in resistance of the active strain gages. This voltage signal, in turn, is input into an operational amplifier, which boosts the (dc) signal by a factor, the Gain factor. First we analyze the bridge circuit, then turn to the op-amp.

The two strain gages fixed to the specimen subject to loading are positioned diagonally opposite as shown. These two will experience an increase in resistance ΔR when the load is applied. The "in-active" gages attached to the specimen which simply stands by, unloaded, are positioned in the remaining two, diagonally opposed, legs of the bridge. We apply the circuit laws to determine the output voltage e_1 - e_2 as a function of ΔR/R.



Consider the current flow through the two resistors on the left side of the bridge. From the usual circuit laws, we have.

$$V_{supply} - e_1 = i \cdot (R + \Delta R)$$
$$e_1 - 0 = i \cdot (R)$$

which yields $$e_1 = \frac{V_{supply}}{(2 + \Delta R/R)}$$

Note that the voltage e_1 is less than the supply voltage. We say that the circuit "divides" the (supply) voltage; the two resistors in series function as a "voltage divider". (If ΔR is zero, the supply voltage is divided in two). The same kind of analysis gives, for the current flow through the two resistors on the right,

$$e_2 = \frac{V_{supply} \cdot (1 + \Delta R/R)}{(2 + \Delta R/R)}$$

The output of the bridge, the voltage difference e_1 - e_2 is then $e_2 - e_1 = \dfrac{V_{supply}(\Delta R/R)}{(2 + \Delta R/R)}$.

But the ratio ΔR/R is going to be much less than 1.0, so we neglect this ratio with respect to 2.0 in the denominator and write, $e_2 - e_1 = \dfrac{V_{supply}}{2}(\Delta R/R)$

Now the change in resistance is proportional to the strain, that is $\Delta R/R = F_{gage}\varepsilon$[1] where the gage factor is approximately 2.0 So knowing the output voltage (difference) e_1 - e_2 we can use these last two equations to determine the strain, ε. (The voltage (difference) e_1 - e_2 is obtained from the output of the op-amp, reduced by the Gain factor, i.e., e_1 - e_2 = (Op-amp output)/(Op-amp Gain)

1. For determination of F_{gage}, see Ulm, 1.050 lecture notes, and/or the notes of Roylance, of the Department of Materials Science, "Experimental Strain Analysis" posted on our MIT server.

The op-amp.

We treat the op-amp as a “black box”, restricting our attention to how to configure resistance values in the input and feedback lines to obtain the desired relationship of output to input, in our case, a gain of approximately 50.

The figure, taken from *The Art of Electronics*[1] superimposes the conventional symbol for an operational amplifier, the triangle, on the physical form of the chip - an 8pin, “dual in-line package” (DIP).

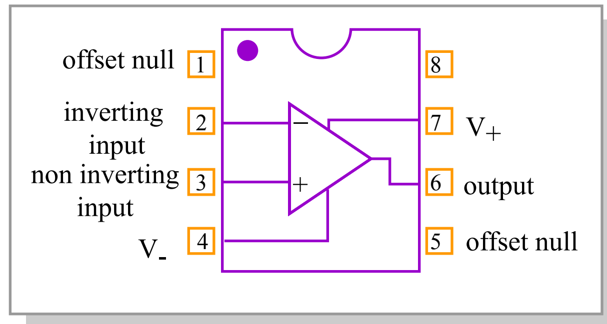
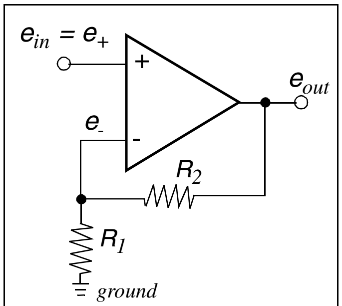


Figure by MIT OCW.

Pins 1 and 5 are where we connect the 10 kohm potentiometer end terminals. The “wiper” of this trim pot is connected to pin 4. This will enable nulling the output when the input is nil.

Pins 2 and 3 are where our differential voltage output from the bridge is input. The minus, -, and plus, +, signs do *not* mean that we must connect the greater of e_1 and e_2 to pin 3 and the lessor to pin 2. The “inverting” and “non inverting” labels enable one to determine the relative sign (phase) of the output to input when the op-amp sees a single, rather than differential, input. This relative phase is not of concern in our case since we are interested only in the magnitude of the output relative to the input.

Pin 4 is where we connect the negative supply voltage and pin 7 where we connect the positive supply voltage. Limits on the supply voltages are +/- 18 volts. (Use a value between +/-5 and +/-10 volts).



Non-inverting op-amp

As an example of a single input application, consider the “noninverting amplifier” shown at the left. First some rules of behavior of our black box. Quoting The Art of Electronics:

“Here are the simple rules for working out op-amp behavior with external feedback. [With the output, pin 6, connected to the negative input, pin 2, usually with a resistor in the line]....

First the op-amp voltage gain [op-amp alone] is so high that a fraction of a millivolt between the input terminals will swing the output over its full range [limited by the supply voltage], so we ignore that the small voltage and state golden rule I:

1. The output attempts to do whatever is necessary to make the voltage difference between the inputs zero.

Second, op-amps draw very little input current [on the order of nano and pico amps]; we round this off, stating golden rule II:

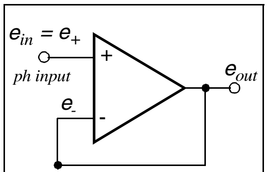
2. The inputs draw no current.”

For the noninverting amplifier, rule 2 means that there is no current flow from the node at the junction of R_1 and R_2 into the negative input terminal. This, in turns, allows us to treat the feedback and resistor to ground circuit as a voltage divider between e_o and ground. Thus: $e_- = \frac{R_1}{(R_1 + R_2)} \cdot e_o$

1. Horowitz, P., & Hill, W., *The Art of Electronics,* 2nd ed., Cambridge Univ. Press, 1989. Figure 4.3, p. 177.

But from rule I, $e_+ - e_- \sim 0$ so we have $e_o = \left(1 + \frac{R_2}{R_1}\right) \cdot e_{in}$. The gain is then $G = \left(1 + \frac{R_2}{R_1}\right)$.

Note that the input voltage is "not inverted", i.e., the output has the same sign (which might be negative) as the input.



"Follower" op-amp

Note too that if we let R_1 get very large (e.g., open the leg to ground) and let R_2 get vanishingly small (short circuit pin 2 to the output pin 6), then we have the circuit you used in the first part of the course as a "buffer" or "follower" - an instrumentation amplifier which did not "load down" your ph sensor (recall rule 2) and supplied as much current as needed at its output *with a gain of G = 1.*

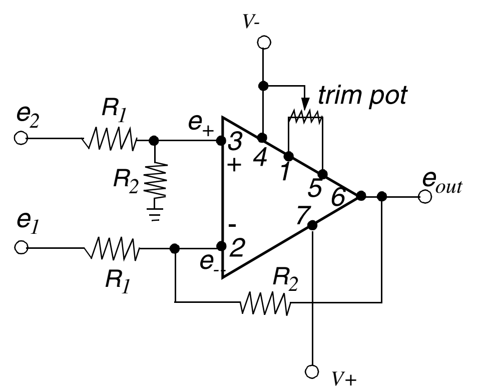
The circuit diagram at the right shows how we will use an op-amp to obtain a gain of G = 50 (approximately).

Ignore all but the input lines to pins 2 and 3 and the feedback line connecting pin 6 back to pin 2.

Consider the input to pin 3. Since there is no current flowing into pin 3, we again have a voltage divider between the input voltage, e_2 and ground.

We have, then $e_+ = \frac{R_2}{(R_1 + R_2)} \cdot e_2$.

Consider the input to pin 2. Since there is no current into pin 2, we again have a voltage divider between e_1 and the output voltage, e_{out} so



Differential amplifier

$e_{--} - e_{out} = \frac{R_2}{(R_1 + R_2)} \cdot (e_1 - e_{out})$ and since $e_+ = e_{--}$, we obtain, after some manipulation left as an exercise for the reader:

$$e_{out} = \frac{R_2}{R_1} \cdot (e_2 - e_1)$$

So the gain is set by the choice of resistors. We will take R_2 = *4.7 Mohm* and R_1= *100 Kohm* so the *nominal* gain is

G = 47. (dimensionless)