Practical 2P12

Semiconductor Devices

Safety

All procedures and experiments in this practical do not involve any hazardous or unsafe activities.

All students must comply with the Laboratory rules, be familiar with the 'Department Safety in Laboratories' document, and endeavour to follow good laboratory practices.

Read the script carefully, listen to the SD and JD briefing, and follow instructions carefully. If you do not understand instructions then consult JD.

What you should learn from this practical

Science

This practical provides hand-on experience measuring physical quantities in semiconductor devices. The background concepts for the operation of such devices were studied in the lectures. Here you will be able to relate the theory to the real life operation of bipolar transistors and integrated circuits.

Practical Skills

You will gain experience in constructing very simple electronic circuits using breadboard, voltage power supplies, you will be able to use LabView to generate and read voltage signals, and characterise circuits using digital multimeters (DMM's).

Overview of the practical

This practical has two elements:

(1) to investigate the electrical characteristics of a bipolar transistor,

(2) to study some of the basic electrical characteristics of a standard type 741 integrated circuit operational amplifier, using a LabVIEW assisted DAQ (Data acquisition) card and oscilloscope, to generate and measure the medium frequency signals.

Experimental

(1) Investigation of the electrical characteristics of a bipolar transistor

You are provided with a BU406 power transistor, a prototype board, a power supply, a 1 kΩ resistor, three digital multi-meters (DMM's) and some lengths of wire. The BU406 is an npn transistor and its circuit symbol is shown in fig.

1. It can be considered to be composed of a "sandwich" of three adjacent layers of differently doped semiconductor, in this case silicon. For an npn transistor, the first layer, called the emitter, is heavily doped n-type, next to this is a very thin layer of p-type material known as the base, and the final layer, again n doped, is the collector. In this way the device can be thought of as two back-to-back pn junctions. Under normal operating conditions the emitter base junction is forward biased which in this case entails making the emitter more negative than the base, whilst the base collector junction is reverse biased which is achieved by making the base more negative than the collector.
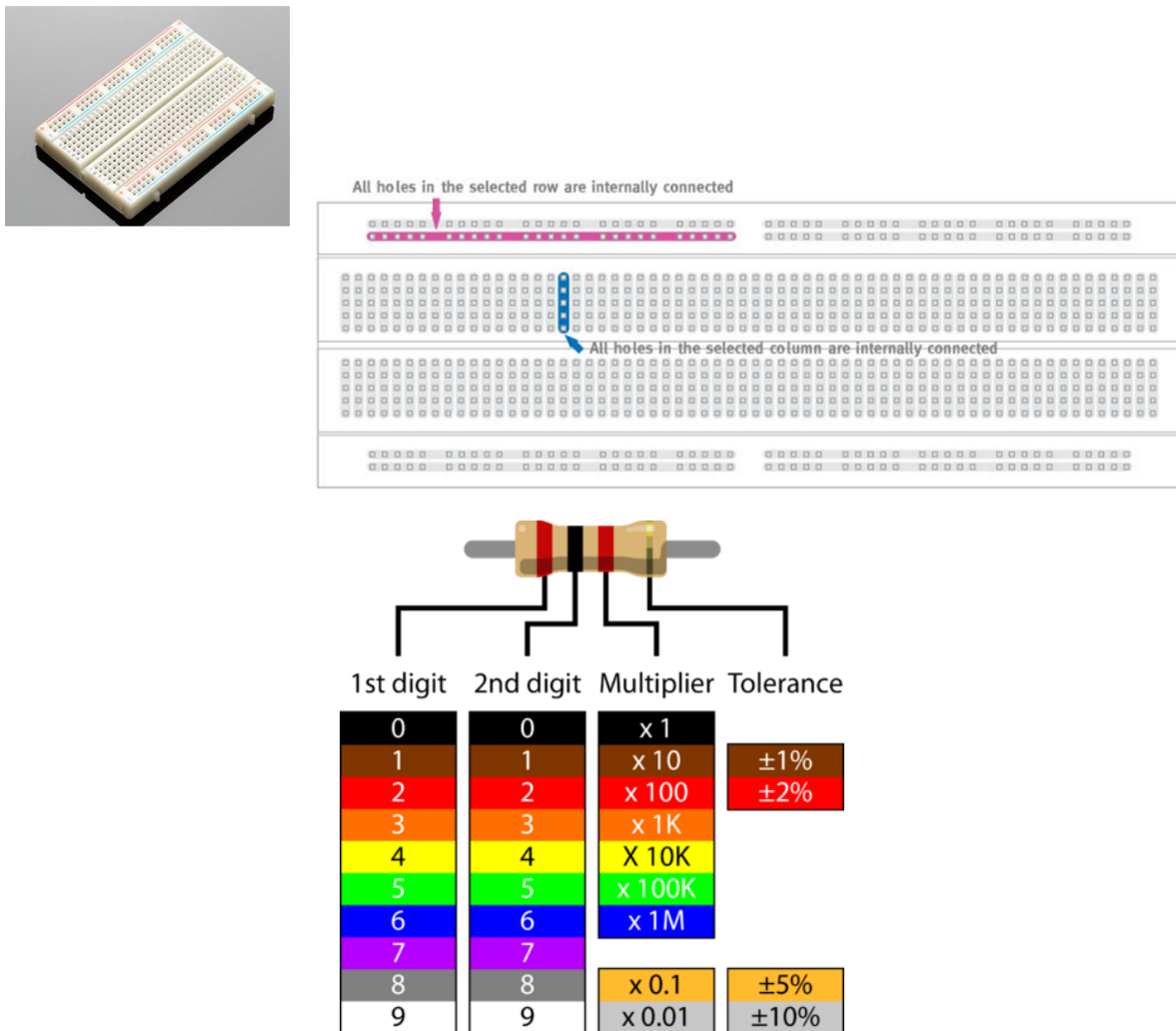
Figure 1:

PIN 1. BASE
2. COLLECTOR
3. EMITTER
TO-220C package
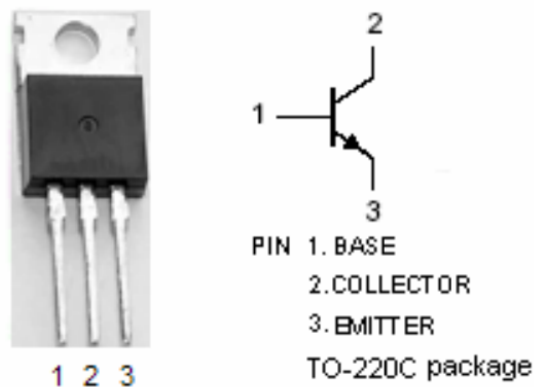
The prototype board is used to construct simple electronic circuits quickly without the need for making soldered joints. Electrical connections are made by pushing wires into the holes in the surface of the board. The holes in the board are arranged in rows with all the holes in any given row electrically connected to each other whilst being electrically isolated from all other holes on the board. There are 94 rows each with 5 interconnected contacts on the board you are provided with. Electrical contact between wires is achieved simply by pushing them into holes which lie anywhere in the same row on the board. The next set of electrical contacts can then be made by using holes

in another row of the board and so on until the circuit is completed. An scheme of a typical prototyping (bread) board is given in Fig 2, together with a colour code chart to select resistor correctly.

Figure 2:

All holes in the selected row are internally connected

All holes in the selected column are internally connected

1st digit	2nd digit	Multiplier	Tolerance
0	0	x 1	
1	1	x 10	±1%
2	2	x 100	±2%
3	3	x 1K	
4	4	X 10K	
5	5	x 100K	
6	6	x 1M	
7	7		
8	8	x 0.1	±5%
9	9	x 0.01	±10%

For example: 2000 Ω.

A DMM is a tape measure for making electrical measurements. It may have any number of special features, but mainly a DMM measures volts, ohms, and amperes. Resolution refers to how fine a measurement a meter can make. By knowing the resolution of a meter, you can determine if it is possible to see a small change in the measured signal. For example, if the DMM has

a resolution of 1 mV on the 4 V range, it is possible to see a change of 1 mV (1/1000 of a volt) while reading 1 V. You wouldn't buy a ruler marked in one-centimeter segments if you had to measure down to one millimeter. Accuracy is the largest allowable error that will occur under specific operating conditions. In other words, it is an indication of how close the DMM's displayed measurement is to the actual value of the signal being measured. Accuracy for a DMM is usually expressed as a percent of reading. An accuracy of one percent of reading means that for a displayed reading of 100 volts, the actual value of the voltage could be anywhere between 99 volts and 101 volts. What is the accuracy of the instrument you are using?

Current measurements taken with the DMM alone require placing the meter in series with the circuit being measured. This means opening the circuit and using the DMM test leads to complete the circuit. This way all the circuit current flows through the DMM's circuitry. How to make current measurements: 1. Turn off power to the circuit. 2. Cut or unsolder the circuit, creating a place where the meter probes can be inserted. 3. Select A~ (ac) or A (dc) as desired. 4. Plug the black test probe into the COM input jack. Plug the red test probe into the amp or milliamp input jack, depending on the expected value of the reading. 5. Connect the probe tips to the circuit across the break so that all current will flow through the DMM (a series connection). 6. Turn the circuit power back on. 7. View the reading, being sure to note the unit of measurement. A common mistake is to exceed the current that the meter can measure and it is likely to break its fuse. Please follow the instructions given to limit the current in the power supplies and if in doubt ask the JD.

Experimental Procedure

a) Measure the I-V characteristics of the emitter base junction of the transistor by constructing the circuit as shown in Figure 3. Use positive and negative values of Vsource, but DO NOT apply more than 10V reverse bias to the base-emitter junction otherwise the transistor will be destroyed.

Figure 3:
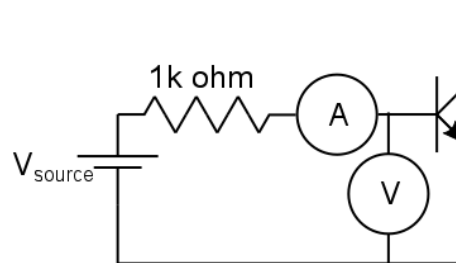
Note: the input resistance of the DMM when configured to measure voltage is 10MΩ. How does this influence your measurement of current?

Use your data to compare the characteristics of the junction with those predicted by the ideal diode equation:

$$I = I_0 \left[\exp\left(\frac{V}{kT}\right) - 1 \right]$$

Try to give reasons for any differences or non-idealities that you find. How would you model them and where do they come from?

b) Verify that the I-V characteristics of the collector base junction are similar to those you have just measured for the emitter base junction. (No more than 30 data points are required).

Figure 4:
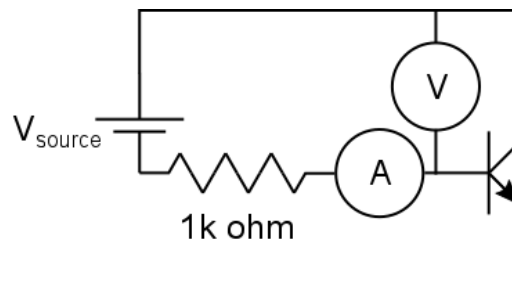
c) Investigate the behaviour of the transistor by constructing the circuit shown in Fig 5. In this case use the BU406 transistor with the large heat sink attached, and vary V_{source} between 0 to 2 V. Verify the relationship $I_e = I_b + I_c$ for the currents flowing respectively in the emitter, base and collector. Note that a relatively small current in the base of the transistor can be used to control a much larger current through the collector. For a power transistor such as the BU406 this allows relatively large power dissipation loads to be driven. What is the amplification factor for this BJT? How does it relate to the properties of the PN junctions inside it? Is this expected from the specification sheet? Plots of I_e vs I_b, and I_e-I_c vs I_b, can help visualise this.

Figure 5:
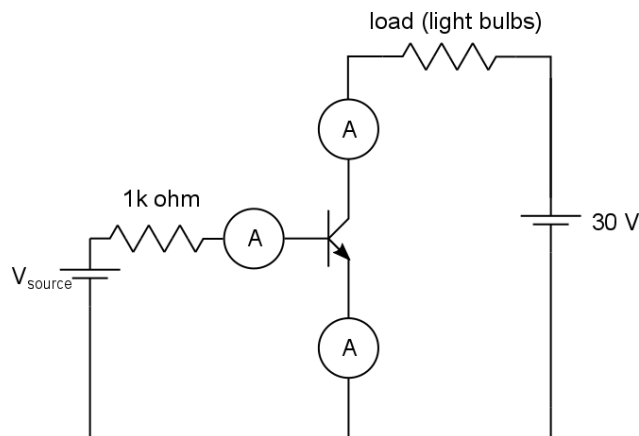
CAUTION: The transistor, resistor and load will get HOT during these measurements! Do not leave on for periods of more than approximately one minute.
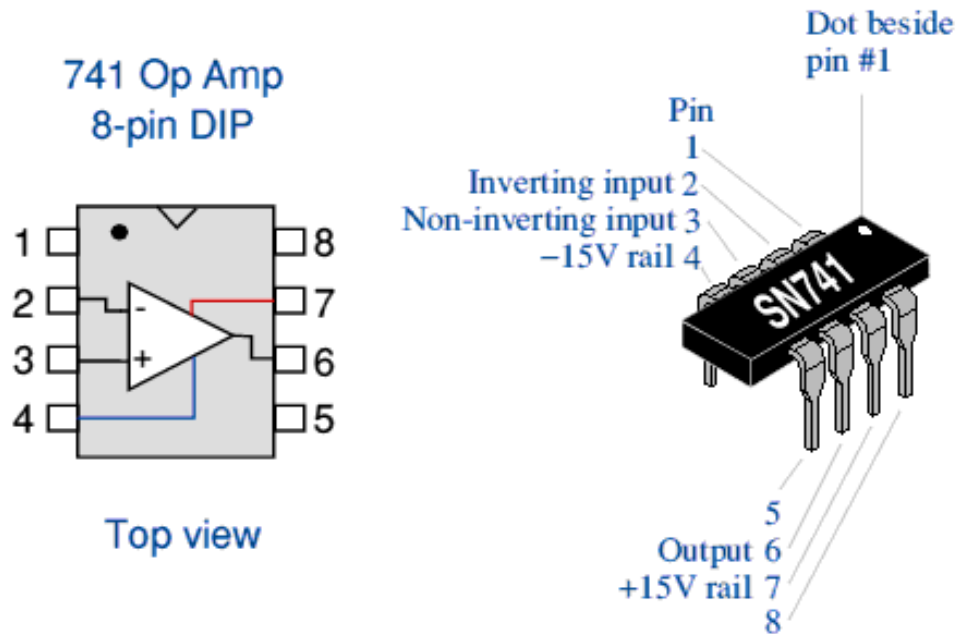
(2) Investigation of the electrical characteristics of an op amp

The industry standard 741 chip, is an integrated circuit operational amplifier available from many manufacturers. The actual silicon chip is encapsulated in a plastic encasing, and it contains 20 transistors, 11 resistors and a few capacitors. Look up the spec sheet of these circuit and see that it indeed has these components interconnected in a special manner to create a very useful device. What properties does the op amp have? What are op amps used for? What electrical characteristics of transistors are advantageous to construct the op amp circuit?

The standard circuit symbol for an op amp is the triangle, with the various connections shown in Fig.6. In the usual top view of the plastic encapsulated version there are 8 pins numbered in an anticlockwise sequence starting from the top left corner, which can be identified by the notch in the 'top' of the package and the indent spot against pin 1. In the 741 frequency compensation is internal and pins 1 and 5 for offset null are rarely required, making this circuit very easy to use at medium frequencies, such as audio applications. The power connections are usually plus and minus 15 volts from a stabilised power supply, and the input and output signals can then be up to ± 12 volts, at low (mA) current.

Figure 6:

741 Op Amp
8-pin DIP

Top view

Dot beside
pin #1

Pin 1
Inverting input 2
Non-inverting input 3
−15V rail 4
SN741
5
Output 6
+15V rail 7
8

Two basic applications - there are hundreds of others - use negative feedback for stable and predictable performance; see figures 9 and 12. A proportion of the output signal (determined by the choice of resistor R_f) is feedback the negative input to produce, as far as possible, a zero voltage difference between the two input terminals of the amplifier. The gain of the amplifier depends on the mode of connection (whether inverting etc.) and the value of the input (R_{in}) and feedback (R_f) resistors. Look up the theory of the op amp and familiarise yourself with what different circuits can do.

You are given with:

(i)   A few 741 operational amplifiers, wires and assorted resistors.

(ii) A stabilised power supply (CAUTION: BOX CONTAINS MAINS VOLTAGES) for the internal circuitry with external connections.

(iii) A standard breadboard to construct the circuit, which will consist: Op-Amp configurations, voltage divider, connection to the power supply, and DAQ (Data acquisition card).
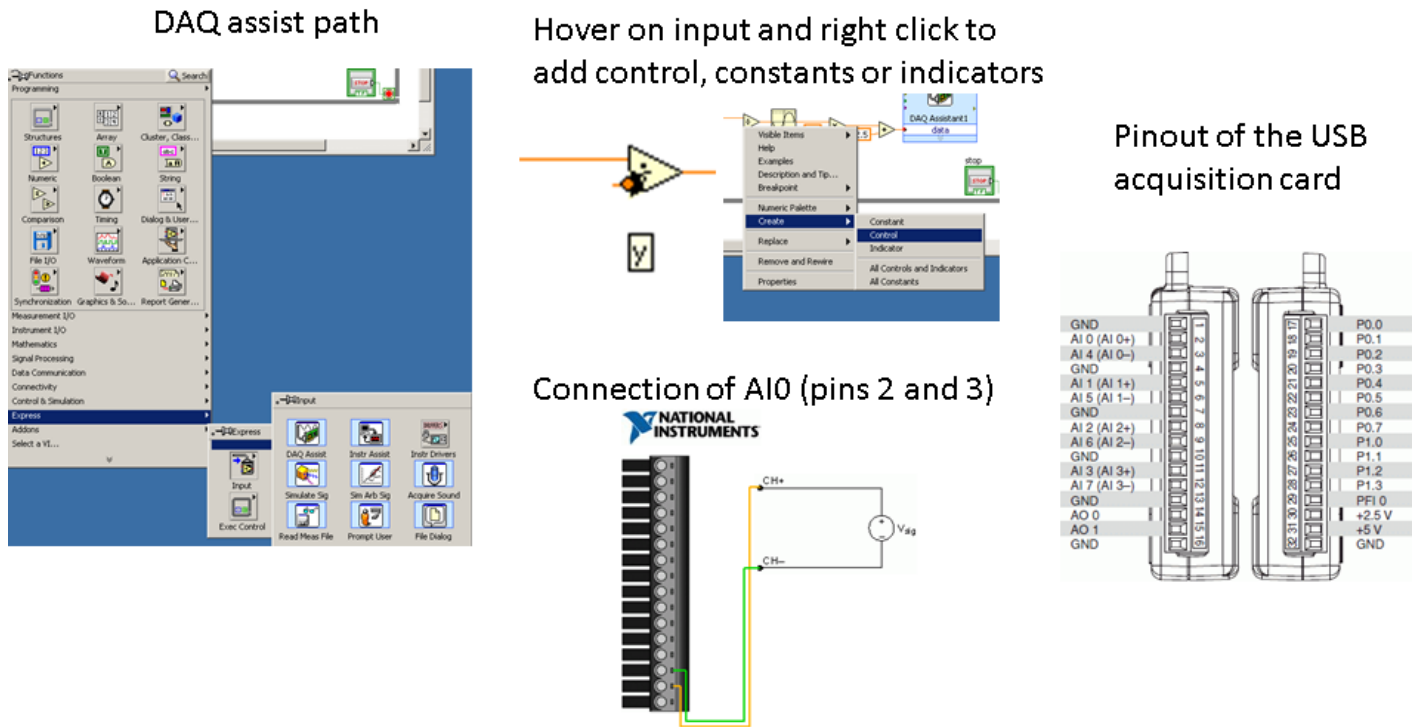
Experimentation

1. Your first task is to use LabView software (you should already be familiar with the basics of using LabView) and a DAQ (Data acquisition) card to generate and acquire voltage waveforms. Open Labview and build the circuit illustrated in Figure 7 to generate a sinusoidal 0-5 volts signal in AO0 and read it back in AI0.

Figure 7:
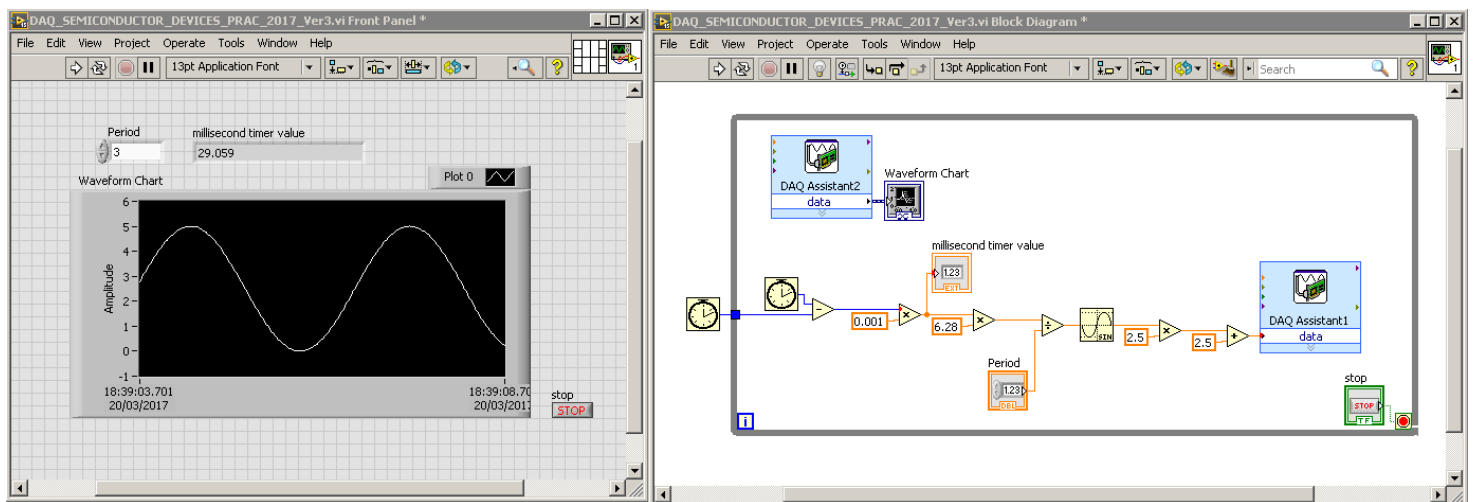
Help: The DAQ Assistant path is illustrated in Figure 8 below. Once you place the DAQ Assistant box 1, select Generate, Analog Signal, Analog Output, Port 0 (AO0). This will generate a Signal on pin 14 with respect to GND (eg pin 16). To construct the rest of the circuit use the right click, and search functions like the Sine, product, sum, etc. Once the DAQ Assist 1 is done, place another DAQ assist, number 2, and instead of generating, select acquire signal, voltage, analog input 0, AI0. The connection diagram of AI0 is shown below. After this connect the pin 14 (AO0) to pin 2 (AI0+), and pin 3 (AI0-) to pin 1 (GND).

Figure 8:

DAQ assist path

Hover on input and right click to add control, constants or indicators

Pinout of the USB acquisition card

Connection of AI0 (pins 2 and 3)

2. The first typical configuration of an operational amplifier that will be investigated is the voltage follower. Using the breadboard, some small wires, and the voltage power supply construct the circuit in Figure 9. To help you familiarise yourself with the way this circuit can be built in a breadboard please refer to Figure 10.
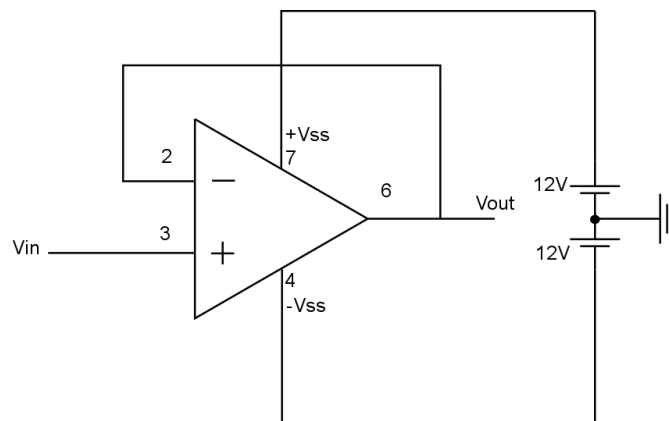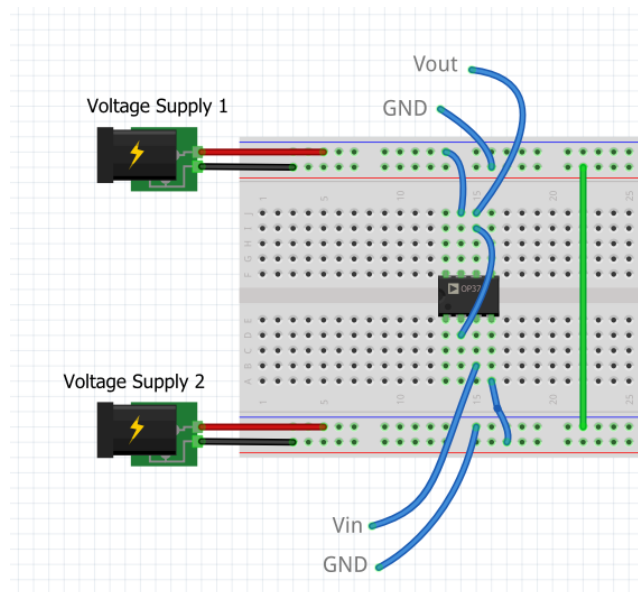
Figure 9: Voltage follower

Figure 10: Breadboard example

3. You will now add to your LabView program an additional voltage input in the data acquisition (DAQ) box. Double click the DAQ Assist 2 and add a voltage input on channel AI2 (Pins 8 and 9). This is illustrated in Figure 11. Once you have done this, use a cable to connect the Sinusoidal signal generated before to the input of you operational amplifier. Then also connect Vout and GND from your voltage follower in (2), Figure 10, to the Analog Input 2 of the acquisition card you have just created. Show that you can visualise and plot two signals (Vin and Vout in the op amp). Compare these two signals. Check what the voltage follower does in theory and see if this is accomplished in practice. Note: remember to connect a GND wire between your breadboard and the acquisition card.
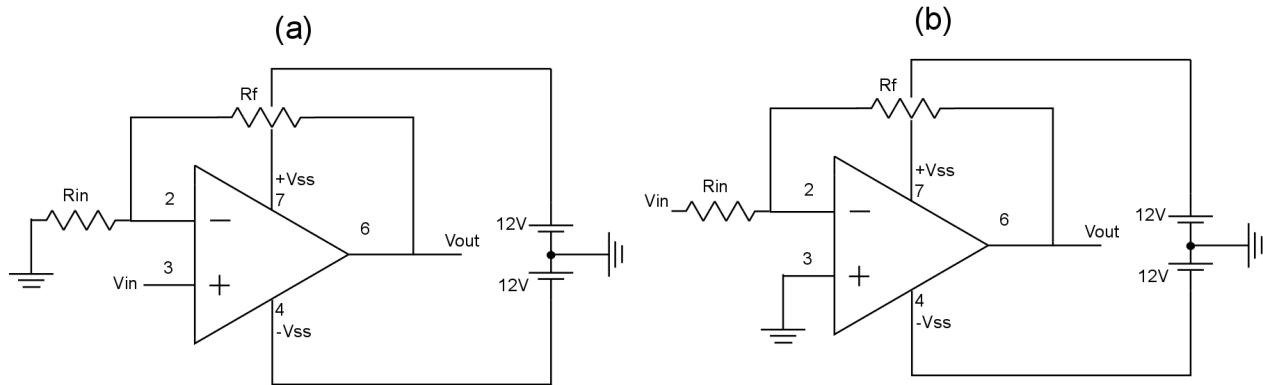
Figure 11:
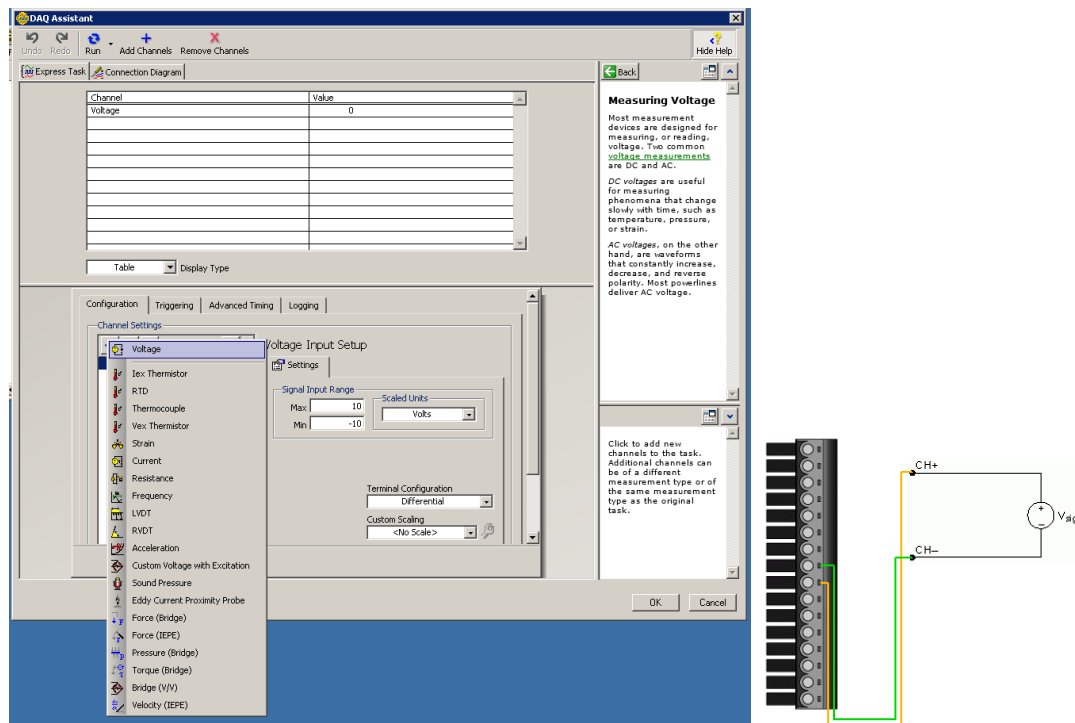
4. The second common application of an op amp is the voltage amplifier. You will now be exploring a range of voltage amplification configurations. First modify your circuit in Figure 9 by adding two 10 K Ohm resistors as Rin and Rf shown in Figure 12.a. Are your resistors exactly 10 K Ohm? What are the new values of Vin and Vout of this configuration as displayed in your Labview software? What amplification factor are you getting? Can you construct a function f such that $V_{out} = f(Rin, Rf, V_{in})$? What would it be theoretically? Change Rf to 5 K Ohm and repeat. Change Rf to 2 K Ohm and repeat. Note: It helps to construct a plot of V_{out} vs V_{in} to determine the function.

5. Now input the voltage in pin 2 of your Op Amp, as illustrated in Fig 12.b. What do you obtain for Vin and Vout, what amplification factor, and function f do you get? Use Rf of 10 K, 5 K, and 2 K Ohms.

Figure 12:

(a)   (b)

6. Now replace Rf in Figure 12.b by a diode 1N4001 with the P side on the op amp pin 2, and the N side on the op amp pin 6. Look up the specification sheet of the diode if you need to know what the P and N sides are. What Vin vs Vout are you reading in Labview? What amplification factor are you obtaining? Can you create a new f? What would it be theoretically?

7. Change the diode to a 1N4148 diode and repeat 6.

Rough timetable

Day 1:   Electrical characterisation of the bipolar transistor and write up

Day 2 & 3: Characterisation of the op amp.

Day 3 :   Producing scientific plots and writing up.

The report

Aims: State clearly what you aim to achieve doing this practical.

Methods: Explain in bare detail what you did, the signals you measured. Include a good account of the analysis of errors and uncertainties in the instruments you used.

Results: Display and describe what you observed with an appropriate level of presentation, accuracy, and detail, and having in mind the accuracy of your measurements.

Discussion: Explain your results putting them in the context of semiconductors theory in the lectures. Make sure you have answered all questions posed in this script.

Summary: Summarise the findings and conclusions drawn from data observation and analysis.

Marking scheme: 10 marks in total divided in Aims 1, Methods and Errors 2, Results 2.5, Discussion and Analysis 3, and Summary 1.5.

All reports must be a maximum of 8 A4 pages, composed in (minimum) Arial 12, single spaced, normal margins.

You are encouraged to plot your data and analyse it in Excel or any software of your preference, embed the figures into the allowed 8 pages. Extra pages will be penalised with 0.5/10 marks per page.

References

Pierret, R. (1996). Semiconductor Device Fundamentals.

Streetman, B., & Banerjee, S. (2016). Solid State Electronic Devices

B. Van Zeghbroeck, 2011, http://ecee.colorado.edu/~bart/book/book/contents.htm.

Guidance on setting up the acquisition card, using the prototyping board, and report can be found on: http://semiconductor.materials.ox.ac.uk/sbonilla