

Name \_\_\_\_\_

OREGON STATE UNIVERSITY

DEPARTMENT OF CHEMISTRY

## Experiment 1A

## Integrated Laboratory Experiment

## CHEMICAL INSTRUMENTATION

## PART A. ELECTRONIC INSTRUMENTATION

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## EXPERIMENT 1

## Part A. Electronic Instrumentation

## I. INTRODUCTION.

In this experiment you will become familiar with the electronic and computer components and modules at your instrumental station. The circuits and concepts presented illustrate many of the basic design features and principles used in chemical instrumentation. First the digital multimeter and voltage source are studied. Next the use of computers for data acquisition is introduced. Finally the operation and common applications of operational amplifiers (OA's) and signal conditioning circuits are investigated.

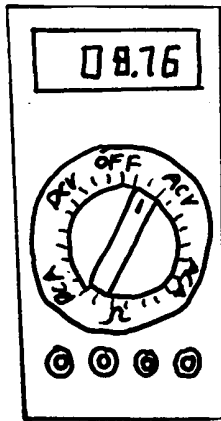
**Objectives:** Upon completion of this experiment, a student: 1. can operate electronic devices commonly used in chemistry laboratories including digital voltmeters, voltage sources, and computers; 2. can wire, troubleshoot, and calculate the expected output from simple circuits based on resistors, capacitors, and operational amplifiers; 3. can calculate systematic errors based on expected and experimental results.

Record data directly on the data sheets, do only calculations needed during lab, otherwise finish calculations and answers to questions on the provided Data Sheets after completing lab.

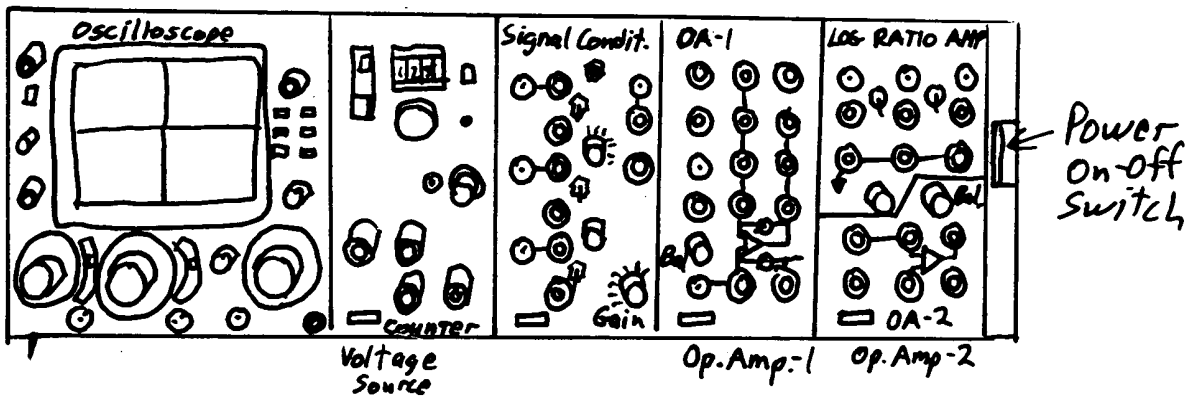
## II. GENERAL EQUIPMENT AND COMPONENTS.

The TEK TM506 console (see figure on the next page) provides the necessary power and voltages for most of the electronic modules used in the course. Note that many modules such as operational amplifiers and the voltage source plug into the console and are supplied with the proper power to operate. Turn the TEK console ON (pull switch on right side).

The cables and small components placed above the station are used to connect the various modules and construct circuits. The connections made are based on single banana plugs, double banana plugs, or BNC connectors as shown in Figure 1B. The resistors and capacitors are mounted in double banana plugs which are color coded for easy identification as listed in Table I.

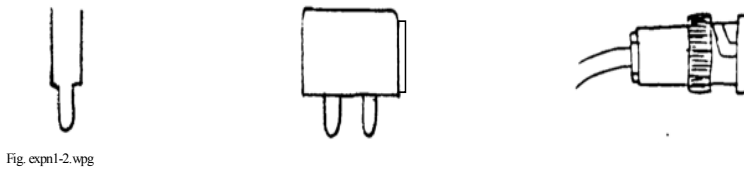


Digital  
Multimeter



ELECTRONIC MODULES  
in Tektronix TMS06  
Power Case

Figure 1A. Schematic of Electronic Modules at the Laboratory Stations



single banana plug

double banana plug

BNC connector

(note one side has ground tab)

Figure 1B. Types of connectors

Table I. Resistor and Capacitors

Resistors	Plug color	Capacitors	Plug color
100 $\Omega$	blue	0.001 $\mu\text{F}$	white
1 k $\Omega$	green	0.01 $\mu\text{F}$	black
10 k $\Omega$	yellow	0.1 $\mu\text{F}$	orange
100 k $\Omega$	red	1.0 $\mu\text{F}$	blue
1 M $\Omega$	gray	10 $\mu\text{F}$	violet

The color code in Table I is based on the color of the double banana plug which holds the component, not the color of the component. Note that blue is used for both a resistor and a capacitor. A resistor and capacitor can be differentiated by the color or shape of the component. Find a 100  $\Omega$  resistor and a 1  $\mu\text{F}$  capacitor and confirm with your team members that your choices are correct. The tolerances of the resistors and capacitors listed above are  $\pm 0.1\%$  and  $\pm 10\%$ , respectively. Hence, the actual resistance of the above resistors is within  $\pm 0.1\%$  of the specified value. For example, the 100  $\Omega$  resistor should yield 100.1 - 99.9  $\Omega$  and the 0.1  $\mu\text{F}$  capacitor will produce between 0.11 and 0.09  $\mu\text{F}$ .

### III. DIGITAL MULTIMETER (DMM)

#### A. Description

The **digital multimeter** or DMM is a convenient and portable readout device for measuring dc voltages. Because there is no scale to interpret, the operator does not have to make a conversion of a scale reading to a voltage while working “in the field”. Most digital multimeters are more accurate, have better linearity, and provide higher resolution than analog meters or recorders. In addition to dc voltages, the DMM can be used to measure ac voltage, ac and dc current, and resistance. Some contemporary multimeters provide a limited amount of memory to keep a record of signal versus time.

The functions and ranges of the 5 digit TPI Model 192 II DMM at your stations are selected with the large rotary switch on the front. Some of the functions, ranges and specifications, such as resolution and accuracy, are listed in Table II on the next page. The input impedance for this DMM is 10 M $\Omega$  on all ranges. A minus sign is displayed for negative dc voltages.

In Table II, the **resolution** indicates the minimum value that can be distinguished or read on a given range and corresponds to a value associated with the least significant digit. The **accuracy** is specified as a percentage plus a number of digits. For example, if 1.0000 V is measured on the  $\pm 5$  V range, the best one can expect for the accuracy is 0.05% of the reading, or in this case,  $\pm 0.0005$  V + 5 digits of the least significant digits for this range, in this case,  $\pm 0.0005$  V. These errors combine to yield a total accuracy of  $\pm 0.0010$  V. Note that if the measured voltage is close to the maximum of the scale setting, the relative (percentage) error term generally predominates, while if the measured voltage is close to zero, the absolute (least significant digit) error term generally predominates. In this example, both terms contribute equally.

Table II. Specifications for the DMM model TPI 192 II

**DC VOLTS**

<b>Range</b>	<b>Resolution</b>	<b>Accuracy<sup>a</sup></b>
±50 mV	1 μV	0.05% + 5
±500 mV	10 μV	
±5 V	100 μV	0.05% + 5
±50 V	1 mV	
±500 V	10 mV	0.1% + 5
±1000 V	100 mV	

**RESISTANCE**

<b>Range</b>	<b>Resolution</b>	<b>Accuracy</b>
50 Ω	1 mΩ	1% + 10
500 Ω	10 mΩ	0.05% + 10
5 kΩ	100 mΩ	
50 kΩ	1 Ω	
500 kΩ	10 Ω	
5 MΩ	100 Ω	1% + 10
50 MΩ	1 kΩ	

**DC CURRENT**

<b>Range</b>	<b>Resolution</b>	<b>Accuracy</b>
±500 μA	0.01 μA	0.15% + 10
±5000 μA	0.1 μA	
±50 mA	1 μA	
±500 mA	10 μA	
±5 A	100 μA	0.3% + 5
±10 A	1 mA	

<sup>a</sup> For example, on the 500 mV range with a 100 mV signal, the error is  $(0.05\% \times 100 \text{ mV}) + 5 \times$  the last digit (i.e., the resolution), which equals  $\pm (50 \text{ μV} + 5 \times 10 \text{ μV})$ , or  $\pm 100 \text{ μV}$ .

B. Experimental -- *Measure voltage, check common ground.*

Switch the DMM multimeter to the dc-millivolts mode by turning the rotary switch in the middle of the DMM to the “black mV with a solid and a broken straight line over it”. The meter starts out in the autorange mode as indicated by “AUTO” in the lower right hand side of the screen. Press the grey RANGE button to cycle between the 50 and 500 mV ranges, as indicated by the small numbers on the lower right-hand side of the screen. Hold the RANGE button in to return to the AUTO mode. Leave the DMM in the 500 mV range. Short the input terminals (V- $\Omega$  and COM) and check that the DMM reads  $\leq \pm 0.01$  mV. If not, check that the battery is good, finally check with the TA if there is another problem. Turn off the auto shut off function by pressing COMP while turning the meter on.

The various electronic plug-in modules which are powered by the TEK TM506 have a number of black terminals on the lower front marked *common* ( $\downarrow$ ). Although all these terminals are all connected to the same common ground through the TEK, the finite resistance of the module connections in the back plane may cause the individual commons to be at slightly different potentials when current is flowing through the system. Use the DMM on the 500-mV dc range to measure the voltage between a few pairs of common terminals and see how they compare with each other. For example, put the black lead of the DMM in a black terminal of OA-1, and move the red lead of the DMM sequentially to a black terminal of OA-2, the signal conditioning module, and the voltage source, measuring and **recording your observations on the Data Sheet** as you go. You will probably find some differences in the various “common” ground terminals. Therefore, it is important that the common terminal of the DMM or any readout device always be connected directly to the common terminal of the device or electronic module (e.g., OA, SCM) from which a voltage is measured.



## IV. VOLTAGE SOURCE

### A. Description

The **VOLTAGE SOURCE** is used to provide voltages to power the instruments that you will build. The PS-501-1 Power Supply in the TEK console provides voltages between the + (red) and - (black) terminals labeled 0-20 V. The voltage range is selected by pushing in gray button on left and can be either 0 to 10 V or 10 to 20 V. The voltage can be adjusted within the selected range by turning the 10-turn digital dial. The accuracy of the dial setting is  $\pm$  (0.5% of reading + 10 mV). **NOTE: Neither ground terminal of the voltage source is tied to the TEK ground potential - a condition known as a “floating”. This condition requires that you always provide a ground connection from the voltage source to the electronic module that you are using in a measurement.** In addition, there is a second power source available at the red terminal which provides a constant +5 V relative to its ground (the white terminal). The gray knob in the middle of the voltage supply controls the current output. Make sure that it is turned fully clockwise and the light is not lit.

The *voltage source adapter* is a small rectangular shaped black plastic adapter that can be plugged into the - and + terminals of the voltage source and is used to expand the available voltage ranges on the main voltage source. (From here on the “voltage source adapter” will be known as the “adapter”.) If the toggle switch on the adapter is in the **X1** setting with the 0-10 V range selected on the main source, there is no difference and 0 to 10 V are supplied; however, with the switch is in the **X .1** setting, 0 to 1 V is supplied. Use of this smaller range makes it easier to set the voltage source more precisely in the 0-1 V range. The polarity of the voltage is selected with the other switch labeled **INV**(erted) or **NORM**(al).

**Use the adapter for all of the following experiments.**

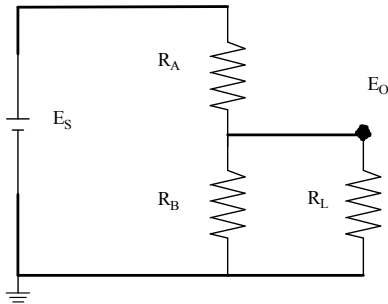
### B. Experimental -- *Determination of offset voltage and loading of voltage source*

1. *Measure offset voltage.* An offset voltage is the actual voltage delivered when the voltage source dial is set to 0.00 V. The offset voltage is not always symmetrical about zero volts when the polarity is switched between NORM and INV (+ and -).

Power up the voltage source, plug in the adapter on the front and select **X.1**. Connect the DMM to the adapter (+ on the adapter to V- $\Omega$  on the DMM and - to COM on the DMM) and set the DMM to the 5-V range.

To illustrate the offset, set the dial of the voltage source to 0.00 with the adapter in the

NORM setting. Note the voltage displayed by the DMM. Switch the voltage source polarity by flipping the INV/NORM switch on the adapter and again note the voltage displayed by the DMM. The offset for your voltage source should be no worse than  $\pm 10$  mV and it may be unsymmetrical.



2. *Voltage divider and effect of load.* The adapter is based on a simple *voltage divider* circuit, as illustrated in the figure. The output voltage of this circuit,  $E_O$ , (in the absence of any load,  $R_L$ ) can be calculated from the source voltage,  $E_S$ , and Ohm's Law:

$$E_O = \frac{E_S}{\frac{R_A}{R_B} + 1} \quad (1a)$$

If an electronic device represented by the load resistor  $R_L$  is attached to the circuit, the output voltage is found from Ohm's Law and the rules for series and parallel resistances to be:

$$E_O = \frac{E_S}{\frac{R_A}{R_B} + \frac{R_A}{R_L} + 1} \quad (1b)$$

Obviously if  $R_L \gg R_B$ ,  $E_O$  is unaffected by the load, but if  $R_L$  is of the same order of magnitude as  $R_B$ ,  $E_O$  can be significantly reduced. This voltage drop could have serious effects in an experiment if you thought that you were supplying a component with 5 V but instead due to loading the supply voltage was only 2 V! In this experiment you will determine the output voltage from the adapter without and with a known load resistor. From your data, you will be able to calculate effective values of  $R_A$  and  $R_B$  inside the adapter, and gain an idea of when you need to be concerned about loading of the voltage source.

**First determine the voltage without loading:** To do this, with the DMM still connected to the adapter (**use the X.1 position - switch to left**), adjust the voltage source dial to about 5 V so that the output of the adapter as measured with the DMM reads about +0.5 V (this is the voltage without loading,  $E_O$  in equation 1a). Record the exact voltage on the Data Sheet. Now temporarily switch the adapter to X1 (this switches the voltage divider in the adapter out of the circuit) and measure and record the direct source to the voltage divider,  $E_S$ . **Switch back to X.1.**

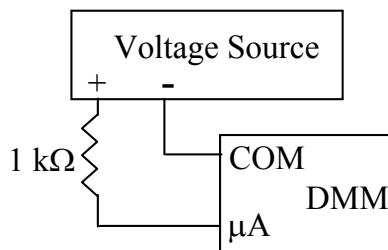
**Next, provide a load and re-measure the voltage.** To do this, place a 100 ohm resistor (blue) across the adapter terminals and re-measure the voltage across this resistor with the DMM. The load or input resistance ( $R_{in}$ ) that the voltage source sees now is essentially 100  $\Omega$ . The 100  $\Omega$  resistor is in parallel with effectively infinite resistance of the DMM (actually about  $10^7 \Omega$ ). Record the new voltage readings on the Data Sheet (the voltage should now be between 0.3 and 0.4 V).

Use the no-load value of  $E_O$  and Equation 1a to calculate the ratio  $R_A/R_B$ . With the known ratio  $R_A/R_B$  and the value of  $E_O$  with the load, calculate the value of  $R_A$  from Equation 1b. Finally calculate the value of  $R_B$  from the value of  $R_A$  and the known ratio  $R_A/R_B$ . **Remove the 100- $\Omega$  resistor.**

C. Experimental for other functions of the DMM - *Verify Ohm's law by independently measuring E, I and R.*

As previously mentioned, the DMM can also be used to measure resistance and current. To demonstrate these functions you will first set the voltage source under a load then, without changing the voltage, you will measure the current across the resistor in the circuit. Finally, you will remove the resistor from the circuit and measure the actual value for its resistance.

1. *Measure voltage.* Connect a 1-k $\Omega$  resistor between the - and + terminals of the adapter with the switch set to X1. Adjust the voltage source dial to about 1 V. Use the DMM to measure the actual voltage and record it on the Data Sheet. **Note that the voltage divider resistances discussed in part IV.B are not in the circuit here because the voltage source adapter is in the X1 mode.**



2. *Measure current.* **Turn off the DMM.** Now remove the 1-k $\Omega$  resistor from the adapter and put the DMM and resistor in series as shown in the figure (one end of the resistor plug will dangle in the air). Switch the cable lead on the DMM from the **V- $\Omega$**  to the  **$\mu$ A** plug, **turn on the DMM** and measure the current on the **50 mA dc**

**current range**, and record the data. (If you have trouble getting a good value, check with a TA.

The fuse in the DMM may have blown and need to be replaced.) Once you are done measuring the current, switch the cable lead back to the **V- $\Omega$**  plug to avoid blowing the fuse.

3. *Measure resistance.* Finally disassemble the circuit and measure the actual resistance value for the resistor by plugging it across the **V- $\Omega$**  and **COM** terminals on the DMM. Record the data on the Data Sheet .

## V. COMPUTER DATA ACQUISITION

### A. Introduction

The PC at your station will be used in many experiments to acquire data, control components, and perform operations. The **analog-to-digital converter (ADC)** on a special interfacing card in the PC converts a voltage into a binary representation which can be understood by the computer. Your station is equipped with a National Instruments 6221 board which can be configured in the bipolar mode to accept input voltages between -5 and +5 V, for example (other ranges are also software selectable). This ADC is a 16-bit version which means it has  $2^{16}$  or 65,546 resolution units. Thus the voltage resolution in the +/-5 V range is  $10 \text{ V}/65546$  or 0.15 mV; in the highest resolution mode of +/- 200 mV, it is capable of 6 microvolt resolution (this is more than is needed in this course). The connections to the internal board have been brought out to a connector interface box for convenience through a special cable. In this experiment, you will use two data acquisition programs. One is a digital voltmeter program called DVM that acquires analog voltage data, digitizes the voltage and performs some simple calculations on the data. The second program is called Electronic Chart Recorder (ECR) and can be used to record the output signal from a device over time and the program outputs this data to a file that can be opened and analyzed using Excel.

Turn on the PC system (power strip or power button on the computer and monitor). After the Windows operating system loads, input the general user name and password (GBAD313, chemistry, SCIENCE). Shortcuts to many of the programs that you will use in this course are in CH 461 folder on the desktop under this user name and password. Don't log in with onid!

### B. Using the DVM program.

Start the Digital Voltmeter program by double clicking the DVM icon in the CH 461 folder. The program you just loaded effectively makes the PC a recording digital voltmeter with timing and averaging capabilities.

Connect the voltage source without the adapter in parallel with the DMM on the 5-V voltage range using a BNC to double banana plug adapter. Next connect the voltage output to Channel zero (CH0) of the ADC interface box using a shielded BNC cable and set the switch to SE. **Dial in any voltage between 1 and 2 V on the source.** The DVM program is pretty much self-explanatory. Explore the various options and buttons in the program to see what they do. Experimental:

(1) First set the program to the manual mode (under the Time Base Selection button), take ten readings, and then choose “stop meter” button. The program will calculate the average and standard deviation of the readings and display this in a box on the lower right. Is the program reporting the same voltage as the reading on the DMM? If not something is wrong so check the connections. Save the data to a file. The file is a CSV type that can be easily opened in Excel. Keep track of where you are writing the file. If you don't save the data it will be lost when the program closes.

(2) Second take ten points in the timing mode with a 1-s spacing. Save the data to a file. Exit the DVM program. Copy the statistics information to your note book or copy and paste into a spreadsheet. Later open the files in Excel and use the STDEV and AVERAGE functions in Excel to confirm that the mean and standard deviation values reported by the DVM program are correct. Attach a hardcopy of your data to the final Data Sheet.

### C. Using the Electronic Chart Recorder Program (ECR)

ECR is a LabView program designed to operate like a chart recorder. This program takes voltage measurements from the analog input on a NI interface board and plots the voltage vs. time on the monitor and saves the data to a spreadsheet file. Start the ECR by double clicking the ECR shortcut in the CH 461 folder. Explore the various options and buttons in the program to see what they do.

Experimental:

(1) Insert the adapter between the DMM and the voltage source. Set the voltage source at 4 V and the adapter to **X.1**. Start the ECR program and switch the adapter between INV and NORM at 15 second intervals for several cycles. Check that the ECR program reports the same values as the DMM. If not check the connections and rerun. Save the file.

(2) Each team member should run this experiment but use one of the other available full scale voltage settings: +/- 1 V fullscale; +/- 5 V; or +/- 10 V.

(3) When finished, exit ECR. Later each team member will plot their own data by opening the file in Excel and producing a chart of signal versus time, label the axes and title the chart. Attach a hardcopy of the chart plotted in Excel with your final Data Sheet.

## VI. OPERATIONAL AMPLIFIERS

**Operational amplifiers (OA's or OpAmps)** are electronic devices that are used extensively in chemical instrumentation. An OA is a high-gain difference amplifier and is used, for example, to amplify, buffer and filter detector signals, as well as to do arithmetic on signals (e.g., compare, take logs, integrate). The experiments in this section illustrate the characteristics and operation of OA's.

As illustrated in Figure 2 for example, OA's are most commonly used with the **output (O)** connected to the **summing point (S)** through some feedback component or element (e.g, resistor, capacitor, or diode). The device works to hold the summing point at essentially ground potential. No current flows into or out of the inputs of the amplifier (except for a small negligible leakage current). The inputs on the OA are used only to sense the voltage at the points selected by the user for some circuit. The **output voltage ( $E_o$ )** generated by the amplifier in the feedback configuration is such that the current through the feedback component or element is equal to the algebraic sum of all the input currents into or away from the summing point.

Your station has a module marked OA-1. It is based on the Analog Devices brand AD545 model operational amplifier. Solid lines on the front indicate plugs that are internally connected together. **Turn off the power to the TEK** and carefully pull out the OA-1 module. Investigate how the following plugs or switches are connected to the internal components (ask if you have

questions):

- green plugs - connected to OA summing point(s) or inverting input (-)
- blue plugs - connected to OA output
- black plugs - connected to common ground
- orange plugs - connected to OA non-inverting input (+)
- yellow plugs - not connected to the OA, often a resistor ( $R_{in}$ ) will be plugged in across the **lower** yellow-green plug socket pair (the upper pair are isolated)
- upper switch - toggle switch in **right** position shorts the yellow plug to common (useful for balancing the OA)
- middle switch - toggle switch in right position shorts the OA summing point to the output
- lower switch - toggle switch in right position shorts the + OA input to common

Carefully insert the OA-1 module back in the TEK power case. Make sure that the module snaps back into place and fits snugly as before and turn the TEK power back on.

#### A. Voltage Balance

Before an OA can be used it must be properly **voltage balanced**. This means that the output should be zero volts when there is zero input current to the summing point. Balancing is accomplished by making the input current zero by connecting the summing point to ground through a resistor and adjusting an internally connected **potentiometer** to produce zero volts at the output of the OA under a high gain configuration. A potentiometer is a variable resistor with adjustable centertap and is controlled with the **BAL** knob located on the OA-1 module.

Each team member at your station should get practice with this operation. Balance OA1 with the following procedure. Wire up a gain of 100 amplifier as shown in Figure 2. This is a high gain and will reveal if zero in is really zero out.

**The expression "wire up" means to connect to the terminals on the OA module, all necessary resistors and capacitors as well as wires between the voltage source and DMM and/or ADC to accomplish the required configuration.**

Note that the three switches on the OA are hardwired internally and only require that you understand what direction they should be in to make the labeled connection.

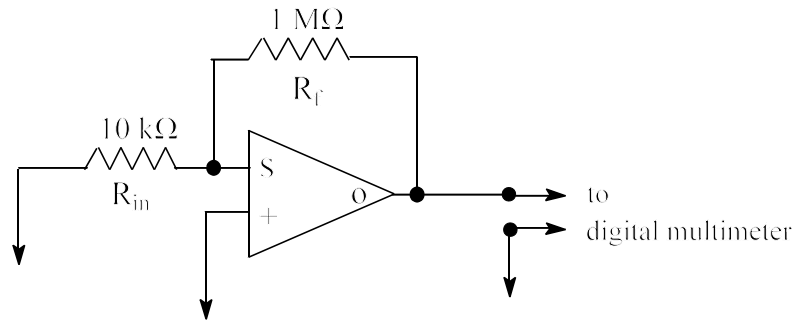


Figure 2. Schematic for balancing the OA

The 10 kΩ resistor plugs in between the **lower yellow and green plugs**. Use the lower switch to ground the + input of the OA (switch to the right) and the upper switch to connect the input resistor to ground (switch to the left). Be sure the middle switch between the OA output and summing point is switched to the left (this is the open position).

**With the DMM on the 5-V or 500-mV scale, turn the BAL knob on the OA until the output voltage is zero volts ( $\pm 1$  mV). Congratulations!** The OA is now balanced. Make sure all your team members get a chance to do this operation. We will use the balanced OA to perform different operations by demonstrating the most common configurations. In all cases, you should measure and record the exact input voltage and then measure and record the corresponding output voltage. Later you will check if the output voltage is correct.

## B. Voltage Follower

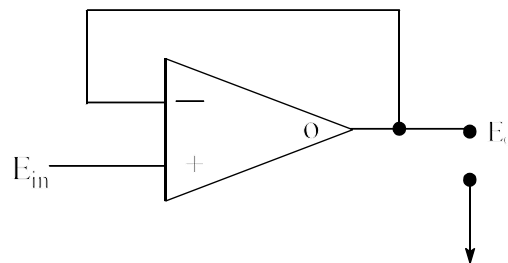


Figure 3. Schematic for a voltage follower

The relationship between the input and output voltage for a **voltage follower** is quite simple:

$$E_o = E_{in} \quad (2)$$

Although this circuit does not appear to do much, it is often used to buffer a voltage source from



other parts of a circuit (e.g., to prevent loading because of the high input impedance of the OA ). A common application for this circuit is a pH meter. For a voltage follower, the input voltage is connected to the + **input**, and the output and - **input** are shorted.

Wire up the voltage follower shown in figure 3 and test the circuit with an input voltage of 1 V. You can use the shorting switch for the "wire" between the output and inverting input. Make sure that the - (black) input of the **adaptor is connected to a ground terminal** on the OA module through a wire.

To test the circuit, connect the DMM (set to the 5-V dc range) to the voltage source with adaptor and adjust the voltage source so that the output of the voltage source (not the OA output) is close to 1.000 V. Record the actual value on the Data Sheet (this is  $E_{in}$ ). Now move the DMM signal lead (red) to the output of the OA and record the output voltage. Check at this time that the measured output voltage is within 1% of the theoretical value. **Use this procedure of moving the lead to set and read the input voltage and then read the output voltage for the remainder of the OA experiments.** Record the input and output voltages in the Data Sheet for each part.

### C. Voltage Amplifier Circuit

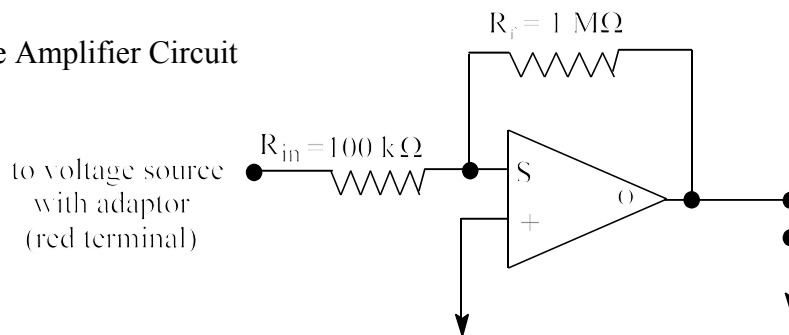


Figure 4. Voltage amplifier circuit (gain of  $10^6/10^5 = 10$ )

In this experiment, use of the OA for voltage amplification will be demonstrated for which the following equation applies

$$E_o = -R_f \sum_{i=1}^n (E_{in})_i / (R_{in})_i \quad (3)$$

where  $E_o$  is the output voltage,  $R_f$  is the feedback resistance and  $(E_{in})_i$  and  $(R_{in})_i$  are the input voltage and input resistance for the  $i$ th input. For one input this equation reduces to

$$E_o = -E_{in}(R_f/R_{in}) \quad (4)$$

Note that the output is inverted in sign and that  $(R_f/R_{in})$  is the **amplification factor or gain** of the circuit.

Wire up OA1 as shown in Figure 4 with a 10 gain. Note that this is the same circuit as Fig. 2 except that  $R_{in}$  is connected to the voltage source instead of to ground and a 100 k $\Omega$  input resistor replaces the 10 k $\Omega$  resistor.

**After you have wired the circuit, check the following:**

1. The - (black) input of the **adaptor must be connected to a ground terminal** on the OA module through a wire.
2. The **input resistor is not connected to ground** (upper switch to the right).

Connect the DMM (set to the 50-V dc range) to the voltage source with adapter and adjust the voltage source so that the output of the voltage source is close to -1.000 V. Record the actual value on the data sheet (this is  $E_{in}$ ). Now move the DMM signal lead (red) to the output of the OA and record the sign and value for the output voltage.

#### D. Response time

The **response time** of a circuit is a measure of the time it takes the output of the circuit to respond effectively to a change in the input of the circuit. The response time for the OA circuit is determined by the choice of the resistor-capacitor combination placed in parallel in the feedback loop. The **RC time constant ( $\tau$ )** in seconds is simply the product of R and C where C is the feedback capacitance in farads and R is the feedback resistance in ohms. The response time of an RC circuit is described as

$$E_t = \Delta E (1 - e^{-t/\tau}) + E_0 \quad (5)$$

where  $\Delta E = E_f - E_0$ .  $E_t$  is the voltage at time t,  $E_f$  is the final voltage (at infinite time) and  $E_0$  is the initial voltage at t = 0. In one  $\tau$ , a circuit responds to 1/e or 37% of the expected final voltage. **The response time is a characteristic parameter for a circuit and is often defined as 5 X RC.** Thus, if  $R_f = 1 \text{ M}\Omega$  ( $10^6$  ohms) and  $C_f = 1 \text{ }\mu\text{F}$  ( $10^{-6}$  farads) the RC time constant is 1 s and the response

time is about 5 s. Analog recorders have a finite response time which depends on the amount of damping and is on the order of 1 s. One advantage of increasing the RC time constant or the response time is to decrease the noise on the displayed signal. This issue is discussed in more detail later.

The effect of response time is demonstrated in the following experiment.

1. Wire up a gain of 10 amplifier with OA1 as shown in Fig. 5, where  $R_{in} = 100 \text{ k}\Omega$  (red plug),  $R_f = 1 \text{ M}\Omega$  (gray plug), and add the  $C_f = 10 \text{ }\mu\text{F}$  (violet plug) in parallel so the circuit will have a 10 s RC time constant. **Make sure that the positive side of the capacitor is connected to the OA output.** Figuring out the positive side can be tricky so do not be shy about asking for help. There

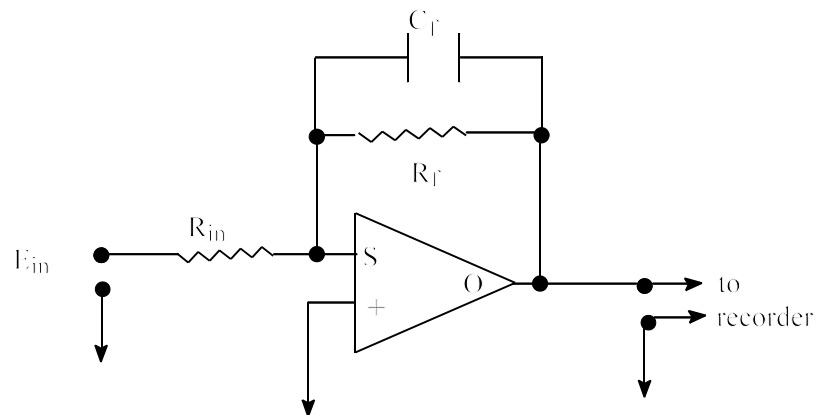


Figure 5. Circuit for measuring response time

often is a + sign or a dot visible on the positive side of the capacitor. If the capacitor is shaped like a bullet, the + side is the rounded end.

2. Adjust the voltage source with the aid of the DMM so that  $E_{in} = -0.20 \text{ V}$  and use the middle switch on the OA to short the output to the summing point (switch to the right).
3. Turn on the computer and load the ECR program. Connect the OA to the ADC 0 channel on the connector box.

4. Start the ECR program. Now, open the middle switch between the output and summing point. The RC time constant is 10 s so that it should take about 50 s (the response time) for the output to reach 2.0 V (within 10 - 20 mV). Make a note of  $E_0$  and  $E_f$ . If the signal does not reach 2.0 V, estimate the final value ( $E_f$ ) by plotting the data in Excel and use this estimate in subsequent calculations. Calculate the experimental value for RC from the measured time it takes the output signal to reach 50% of the final expected value ( $E_t/E_f = 0.5$ ) - estimate from the measured data - don't fit the data. Note that with  $E_0 = 0$  and  $\Delta E = E_f$  equation 5 simplifies to:  $(E_t/E_f)_{50\%} = e^{-t/\tau}$ .
5. Replace the 10  $\mu\text{F}$  capacitor with a 1  $\mu\text{F}$  capacitor (blue plug). Repeat the experiment. Estimate the response time from how long it takes the measured signal to reach near the final expected value (detailed calculations as in part 4 are not required) and record the response time in the Data Sheet.

#### E. Integrator

An **integrator** is built by putting a capacitor in the feedback loop of an OA rather than a resistor. In this configuration the OA provides an output voltage  $E_o$  that is proportional to the time-integral of the input current or, if an input resistor  $R_{in}$  is used, the input voltage  $E_{in}$ . If  $E_{in}$  is constant the OA output is given by

$$\frac{\Delta E_o}{\Delta t} = \frac{-E_{in}}{R_{in} C_f} \quad (6)$$

Therefore the OA in this configuration can be used as a linear voltage ramp generator with a known slope as demonstrated in the following experiment.

Wire up an integrator as shown in Figure 6 with OA1. Use  $R_{in} = 1 \text{ M}\Omega$  (gray plug) and  $C_f = 1 \mu\text{F}$  (blue plug). Initially set the middle switch of OA1 between the output and summing point, S3 in the figure in the short position (to the right). Connect  $R_{in}$  to the voltage source and adjust  $E_{in}$  to about -50 mV. Record the exact value. Connect the OA output to ADC 0 as before. Start the ECR program.

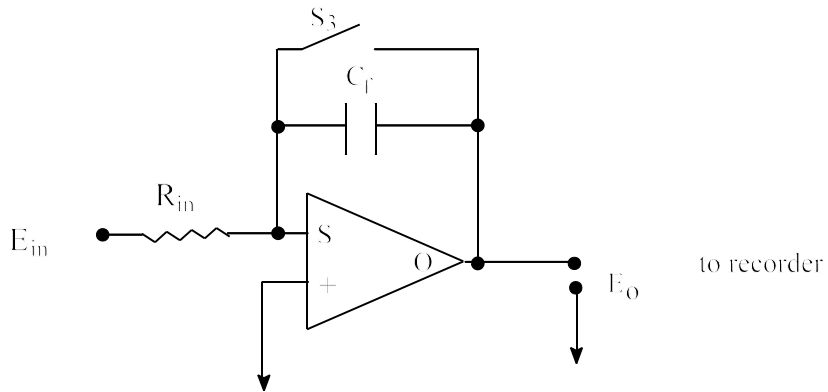


Figure 6. Integrator configuration

Now open  $S_3$ , the middle switch, by moving it to the left. When the output signal reaches 1V, reverse the polarity of the voltage source with the switch on the adapter and scan back to zero volts. Save the file with a descriptive name as usual. The integrator can be reset to zero by shorting out the capacitor (closing the switch). The ECR program provides a convenient record of voltage versus time.

Open the file in Excel and plot the data. Later you will determine the two voltage ramp slopes (one positive and one negative going) from the data. Report the average absolute value of the ramp on the Data Sheet. Finally calculate the theoretical ramp using Equation 6. Remember that the sign of the slope depends on the sign of the input voltage which you changed to alter the direction.

## VII. LAB REPORT

Your report for Experiment 1A is just the Data Sheets filled out with all the data, calculations and answers to questions in complete sentences; include the **labeled** Excel charts from parts VC, VID and VIE and a hardcopy of the DVM data from part VB. Clean copies of the Data Sheets are on the CH 461 web site.

Note the following:

- the term **% error** means the difference between the **true value** (or calculated value) and the **experimental value** (or measured value) divided by the true value times 100 or  
$$\%error = 100 \times |true\ value - experimental\ value| / true\ value$$
- the **expected value** for a resistance or capacitance is the **nominal value** given on the component body (e.g., 100  $\Omega$  for a 100- $\Omega$  resistor).
- the **expected value** for a current or the output voltage of an OA circuit is the value calculated from the transfer function, the measured input voltages, and the nominal values of the resistors or capacitors in the circuit.

## DATA SHEET FOR EXP. 1A

Your Name: \_\_\_\_\_ Date: \_\_\_\_\_ Station #: \_\_\_\_\_

Names of other Team members:

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IIIB: Measurement of common ground voltages (not all blanks have to be filled):

Location of positive probe	Location of negative probe	Observed Voltage	Your choice for location positive probe	Your choice for location negative probe	Observed Voltage
Power Supply	SCM				
Power Supply	Log Amp				
Power Supply	OA-1				

IVB: 1. Offset voltage using the following switch settings:

NORM \_\_\_\_\_ V      INV \_\_\_\_\_ V

IVB: 2. Voltage source loading (show calculations)

Output voltage ( $E_O$ ) without 100  $\Omega$  load = \_\_\_\_\_ VSource Voltage ( $E_S$ ) = \_\_\_\_\_ VOutput voltage ( $E_O$ ) with 100  $\Omega$  load = \_\_\_\_\_ V $R_A/R_B$  = \_\_\_\_\_ $R_A$  = \_\_\_\_\_  $\Omega$  $R_B$  = \_\_\_\_\_  $\Omega$ Show calculation of  $R_A/R_B$ Show calculation of  $R_A$ Show calculation of  $R_B$

IVC: DMM Multimeter use (include units)

E (measured) = \_\_\_\_\_

i (measured) = \_\_\_\_\_

DMM current range used: \_\_\_\_\_

R (measured) = \_\_\_\_\_

% error in R (expected value is the nominal value) \_\_\_\_\_

Show calculation of the % error in R

i (calculated from E and R measured) = \_\_\_\_\_

Show calculation of the current i:

% difference between i calculated from E and R measured and i measured \_\_\_\_\_

Show calculation of the % difference in i:

VB: Attach a copy of the output from the DVM program and the Excel file proving that the STDDev and the Averages reported by the program are correct.

VC: Attach Excel chart, labeled with date, your name, a title, label voltage axis (+0.5 to -0.5 V) and the time axis with labels and units. Use proper significant figures.

VIA: Voltage Balance

Teammate's name:

Did Teammate performed voltage balance operation?

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_



VIB: Voltage follower

measured  $E_{in}$  = \_\_\_\_\_ measured  $E_o$  = \_\_\_\_\_ expected  $E_o$  = \_\_\_\_\_  
 % error = \_\_\_\_\_

VIC: Voltage amplifier (include units)

measured  $E_{in}$  = \_\_\_\_\_ measured  $E_o$  = \_\_\_\_\_ expected  $E_o$  = \_\_\_\_\_

% error = \_\_\_\_\_

Show formula and calculation of expected  $E_o$ :

VID: 1. Response time (for nominal 10-s time constant)

Mark on your Excel chart  $E_o$ ,  $E_f$  and the halfway point  $(E_o + E_f) / 2$ , label axes, and attach a copy of the chart.

How many seconds does it take to reach 50% of the final voltage ? \_\_\_\_\_s

What is the expected RC (calculated from R & C)? \_\_\_\_\_s

What is the experimental value of RC (calculated from time to reach 50%)? \_\_\_\_\_s

% error in RC = \_\_\_\_\_

What is the response time (not time constant) based on experimental value for RC?

\_\_\_\_\_s

2. Response time (for nominal 1-s time constant)

Mark on your Excel chart  $E_o$ ,  $E_f$  and the halfway point  $(E_o + E_f) / 2$ , label axes, and attach a copy of the chart.

The response time estimated from the chart is \_\_\_\_\_s.

From your experimental results, by what factor does the response time decrease when RC is decreased by a factor of 10? (just give one significant figure) \_\_\_\_\_

VIE: Integrator

Measured  $E_{in}$  = \_\_\_\_\_ mV

Open the file in Excel and produce a labeled chart; attach a hardcopy of the chart

Determine slope up and slope down using trendlines = 1. \_\_\_\_\_ 2. \_\_\_\_\_ mV/s

Average of absolute value of slopes for 2 runs = \_\_\_\_\_ mV/s

Theoretical slope of OA output  
(calculated from equation 6) ..... = \_\_\_\_\_ mV/s

Show calculation

Experimental % error in slope ..... = \_\_\_\_\_  
(based on values above)

Estimated % error in slope ..... = \_\_\_\_\_

Below show the calculation of the estimated % error in the slope (uncertainty). It is based on propagation of error or uncertainty mathematics and estimates of the uncertainty due to the R and C component tolerances (Table I) and the uncertainty due to the DMM used to measure  $E_{in}$  (Table II). (See lecture notes or Harris for propagation of *systematic* error.)

Is your experimental error within your estimated error? \_\_\_\_\_

Based on this calculation, what is the main source of the experimental error?

\_\_\_\_\_