

18-100: Intro to Electrical and Computer Engineering

LAB04: Op-Amp Lab

Writeup Due: Thursday, February 24th, 2022 at 10 PM

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How to submit labs:

Download from this file from *Canvas* and edit it with whatever PDF editor you're most comfortable with. Some recommendations from other students and courses that use Gradescope include:

pdfescape.com A web-based PDF editor that works on most, if not all, devices.

Preview Pre-installed default MacOS PDF Editor.

iAnnotate A cross-platform editor for mobile devices (iOS/Android).

*If you have difficulties inserting your image into the PDF, simply append them as an extra page to the END of your lab packet and mark the given box. **Do NOT insert between pages.***

If you'd prefer not to edit a PDF, you can print the document, write your answers in neatly and scan it as a PDF. (*Note: We do not recommend this as unreadable lab reports will not be graded!*). Once you've completed the lab, upload and submit it to *Gradescope*.

Note that while you may work with other students on completing the lab, this writeup is to be completed alone. Do not exchange or copy measurements, plots, code, calculations, or answer in the lab writeup.

Your lab grade will consist of two components:

1. Answers to all lab questions in your lab handout. The questions consist of measurements taken during the lab activities, calculations on those measurements and questions on the lab material.
2. A demonstration of your working lab circuits and conceptual understanding of the material. These demos are scheduled on an individual basis with your group TA.

Question:	1	2	3	4	5	Total
Points:	13	8	6	10	23	60
Score:						

Lab Outline

This lab aims to teach students op amp configurations, their behaviors and applications.

1. Comparator Light Switch
2. Buffer (Unity-Gain Amplifier)
3. Inverting Amplifier
4. Non-Inverting Amplifier
5. Glucose Test Strip Front-End

Small Group Check-off Circuits

- ☐ Comparator light switch
- ☐ Glucose test strip front-end

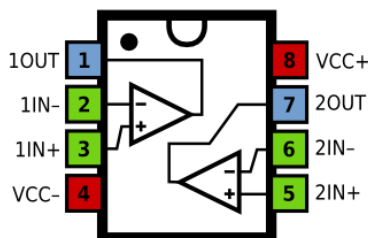
Equipment Required

- 1x Breadboard
- 2x 9V Battery with Battery Clip
- 1x Digital Multimeter
- 1x ADALM2000 {Power Suspply, Oscilloscope, Signal Generator}
- 1x Wire Strippers
- 1x Diagonal Cutters

Bill of Materials

- | | |
|--|---|
| 4x  1kΩ Resistor | 1x  4.7kΩ Resistor |
| 3x  10kΩ Resistor | 1x  100kΩ Resistor |
| 1x  47kΩ Resistor | 1x 20kΩ Potentiometer (B20K) |
| 2x Dual Op Amp IC Chip (TL072, Box 1) | 1x Light-dependent resistor (CdS cell, Box 2) |
| 8x Glucose Test Strips (pick up at small group) | Test solution (available in TechSpark) |

Pinouts



TL072 Op-Amp Pinout

Introduction and Setup

This lab focuses on a versatile subclass of amplifiers known as *operational amplifiers* ('op amps'). Since they are *active devices*, they require external power to run. In this lab, we will use a *dual-sided supply*, providing $+9\text{V}$ to $+V_{CC}$ and -9V to $-V_{CC}$. You can do this with two 9V batteries connected in series as shown in Figure 1.

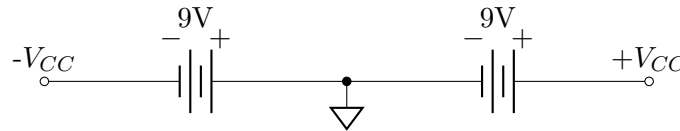


Figure 1: Making a dual-sided supply with two 9V batteries

i Note the polarity of the battery terminals (connected positive to negative)

Designate one half of your breadboard to use the $\pm 9\text{V}$ rails. **Please remove the connections connecting all of your supply rails together on this section of the board.** The blue rails will be the reference node (ground), one of the red rails will be $+9\text{V}$, and the other red rail will be -9V . Figure 2 is a breadboard diagram showing how to connect your batteries.

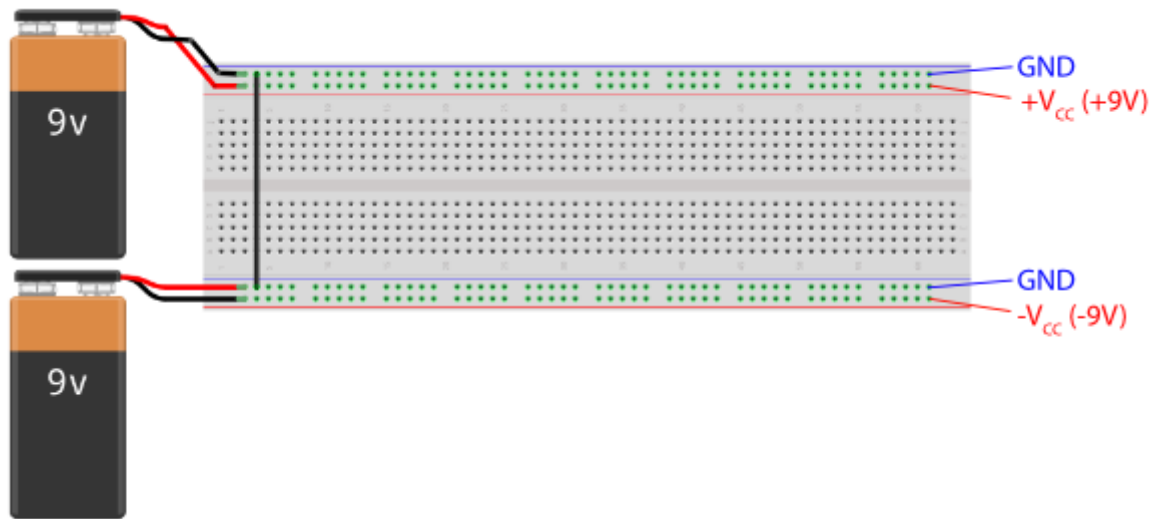


Figure 2: Making a dual-sided supply on a breadboard

A Before connecting devices to the supply rails, check voltages with multimeter!

Connect the black probe (COM) to the blue GND rail and you should measure $+9\text{V}$ on one red rail and -9V on the other red rail. Make sure that you keep track of which is which. If you reverse the supply voltages going to the op amp chip, it can get very hot. **If the op-amp chip feels warm to the touch, disconnect the batteries immediately.**

1. Comparator Light Switch

Build the following circuit on your breadboard, which uses the light-dependent resistor (LDR) from Lab 1 to control an LED:

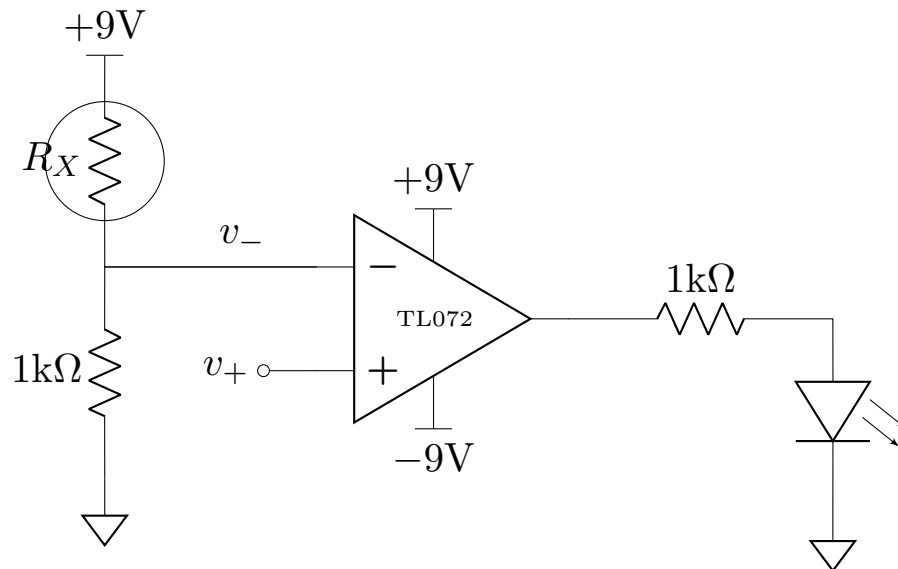


Figure 3: Comparator Circuit with LED indicator at output and light-dependent voltage divider at the inverting input.

This circuit uses the op amp in an open-loop configuration (i.e. no feedback). When the voltage at v_+ exceeds the voltage at v_- , the output will be driven to +9V and the LED will turn on. Otherwise, the LED will be off.

A voltage divider consisting of the LDR R_X and a 1 k Ω resistor provides a voltage to the v_- input. You will build a second voltage divider to provide $\approx 4.5\text{V}$ to the v_+ input. The comparator will compare v_- to v_+ and then drive its output to either high (LED on) or low (LED off).

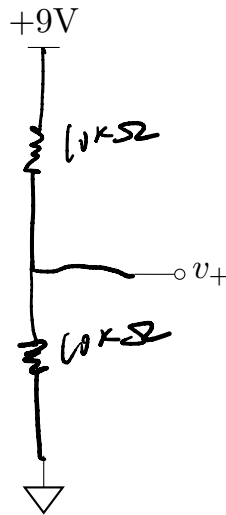
1 pts

- 1.1 Measure v_- using a digital multimeter, both when the LDR is well-lit and when the LDR is in the dark. What are the dark (V_{dark}) and light (V_{light}) voltages that you measured at v_- ?

$$V_{\text{dark}} = \boxed{0.49} \text{ V} \quad V_{\text{light}} = \boxed{1.91} \text{ V}$$

2 pts

- 1.2 Draw a voltage divider circuit that produces 4.5V at v_+ in the space below. Please use the +9V, ground, and v_+ connections provided. Use a resistance value of $10\text{k}\Omega$. Please be sure to label each of the resistors with their resistance.



10 pts

- 1.3 Complete your light-switch circuit on your breadboard by adding the voltage divider you drew in the previous part. The LED should have a different state when the LDR is well-lit versus when the LDR is in the dark. When you are finished, keep this circuit on your breadboard, as you will need it for small-group check-offs.

⚠ Do NOT take your circuit apart yet! You will need it for lab checkoff!

2. Buffer (Unity-Gain Amplifier)

Construct the following circuit in Figure 4. The goal of this circuit is to divide down the initial voltage, V_{in} , twice. Connect the ADALM power supply as V_{in} for this circuit and record the output voltage with a multimeter. $R_{1,2,3,4} = 1k\Omega$.

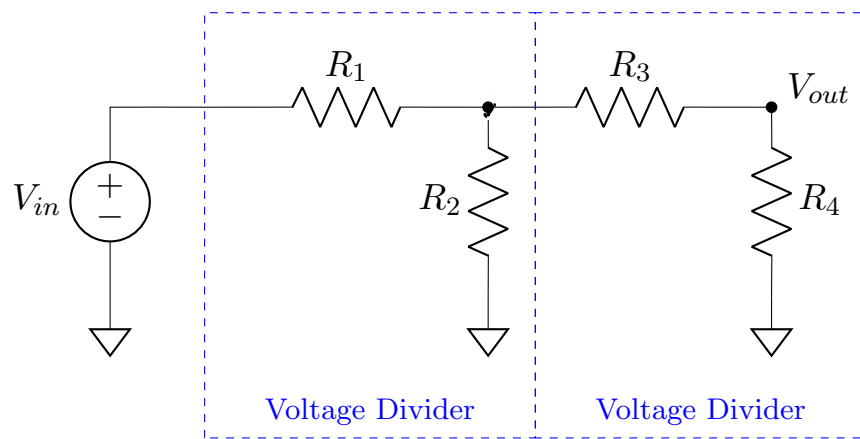
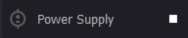
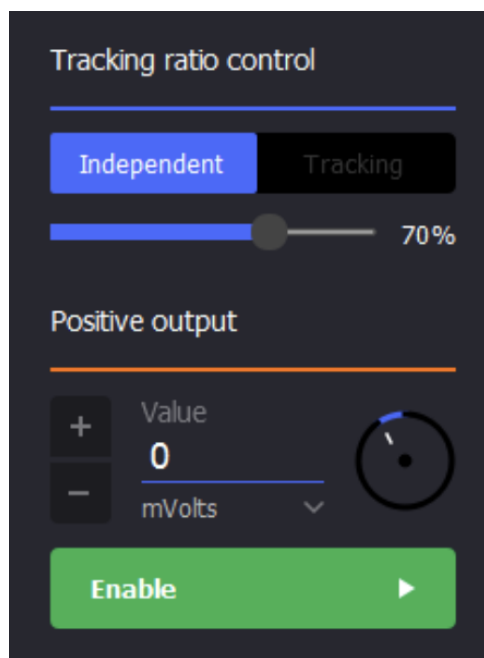


Figure 4: Cascading Voltage Dividers

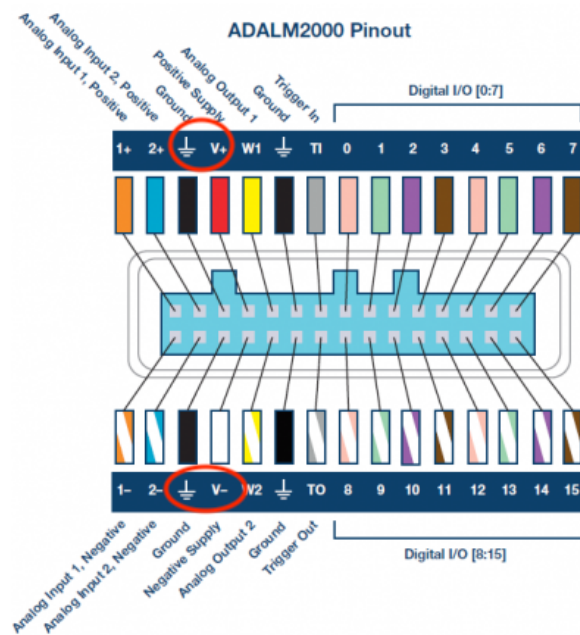
Using the ADALM Power Supply

Read through the ADALM2000 Power Supply wiki page: <https://wiki.analog.com/university/tools/m2k/scopy/power-supply>.

Open Scopy and click on the  button. Set the Tracking Ratio to Independent



(a) ADALM Power Supply Settings



(b) ADALM Pinout

2 pts

2.1 Using the ADALM's Power Supply, apply the following voltages V_{in} and measure the output voltage across V_{out} with your voltmeter.:

V_{in}	V_{out}	V_{in}	V_{out}
0V	0V	3V	0.41V
1V	0.08V	4V	0.64V
2V	0.25V	5V	0.8V

2 pts

2.2 Is the circuit dividing the voltage in half twice (i.e. is $V_{out} = \frac{V_{in}}{4}$)? Explain why or why not.

No, the V_{out} values aren't $\frac{V_{in}}{4}$. This is because there is no buffer used. The resistors R_3 and R_4 affect the voltage between R_1 and R_2 so the voltage isn't properly divided. More current goes through R_1 than R_2 .

Now we introduce a unity-gain buffer between the two voltage dividers in the previous circuit. Build the circuit in Figure 6 and perform the same measurements. Notice in Figure 6 that there is no external supply pictured for the op amp. When you see an op amp from now on, the +9V and -9V supply rails are implied. $R_{1,2,3,4} = 1\text{k}\Omega$.

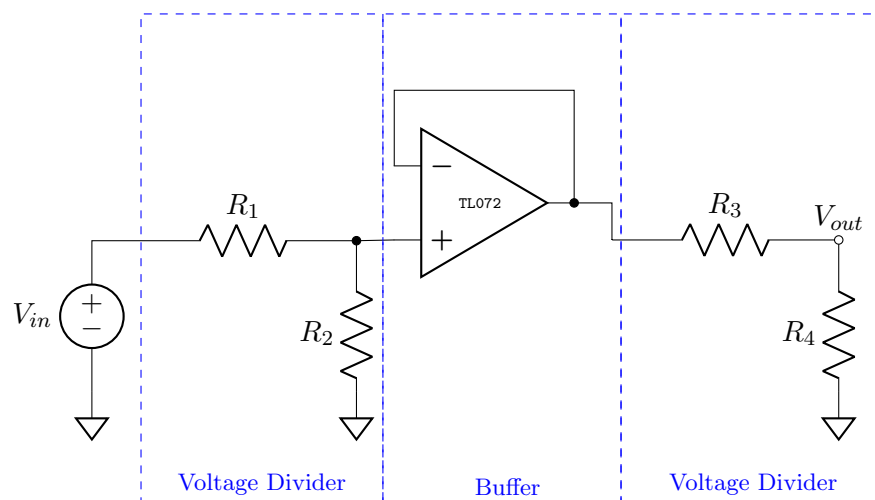


Figure 6: Consecutive voltage dividers separated by op amp buffer

2 pts

2.3 Measure the output voltage (V_{out}) with your multimeter for the following inputs:

V_{in}	V_{out}	V_{in}	V_{out}
0V	0V	3V	0.63V
1V	0.19V	4V	0.88V
2V	0.41V	5V	1.02V

2 pts

2.4 Explain why buffering the voltage dividers causes the correct level of voltage division. Refer to the input and output resistances of the op amp in your answer.

The buffer will isolate the R_1/R_2 from R_3/R_4 resistors. There is no current going into the op amp, so the voltage is divided between R_1 and R_2 . Moreover, the voltage is preserved across the buffer, which is then divided over again.

3. Inverting Amplifier

Now we're going to introduce some *amplification* to our op-amp circuits. The Inverting Amplifier (and its cousin the Non-Inverting Amplifier in the next section) use negative feedback and a voltage divider to amplify the signal at its input (V_{in}).

Assemble the following circuit in Figure 7 on your breadboard. Use a $4.7\text{k}\Omega$ resistor for R_f and a $1\text{k}\Omega$ resistor for R_i .

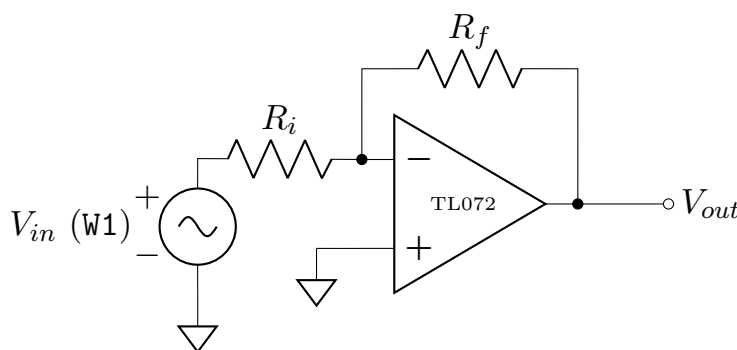


Figure 7: Inverting Amplifier with Fixed Gain

Using the Signal Generator

You may notice the sinusoidal voltage source, op-amps amplify more than just DC! In Scopy, open the **Signal Generator**. Read the following guide on how to configure and use the Signal Generator: <https://wiki.analog.com/university/tools/m2k/scopy/siggen>. Enter the settings menu for **CH1** and select “Waveform.” Configure the following settings:

Signal Generator	
Sine Wave	
Amplitude: $1V_{pp}$	Offset: $0V$
Frequency: 1kHz	Phase: 0 deg

In the circuit above, you'll connect the W1 pin on the ADALM in place of the positive terminal of V_{in} and the ADALM's GND pin to the negative terminal of V_{in} .

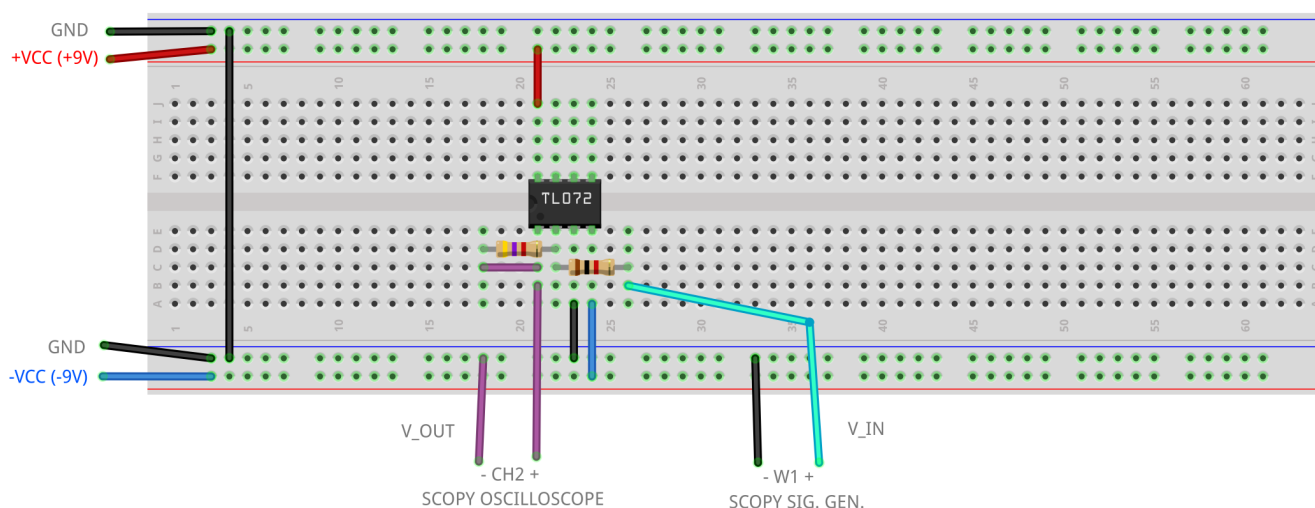


Figure 8: Inverting Op-Amp Breadboard Diagram

Using the Oscilloscope

Read the following guide on how to configure and use the Oscilloscope module in Scopy: <https://wiki.analog.com/university/tools/m2k/scopy/oscilloscope>. Configure the following settings for both channels (CH1 and CH2):

Oscilloscope		
Horizontal	Vertical	Settings
Time Base: 1ms Position: 0ms	Volts/Div: 500mV Position: 0ms	Probe Attenuation: 1X Software AC Coupling: Off

Connect a probe to CH1 and CH2 on the ADALM2000 Adapter Board. Make sure the switch on the probe is set to 1X and the coupling on the Adapter Board is set to “DC”. Then connect CH1 to the input of the inverting amp, and CH2 to the output.

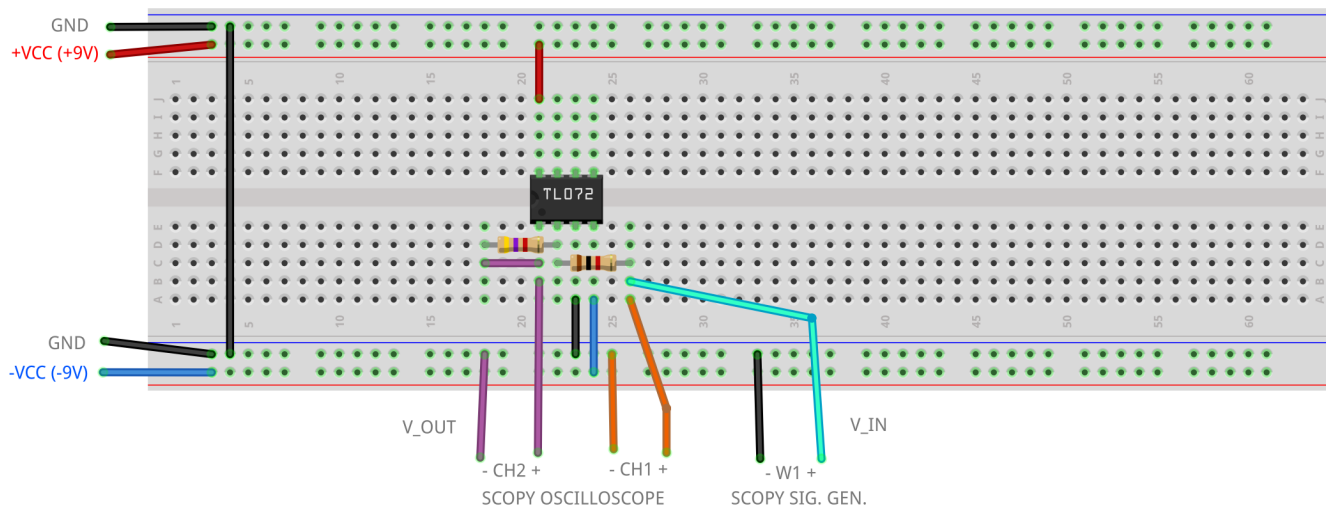
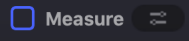


Figure 9: Inverting Op-Amp Osc. Inputs

Once your circuit is set up hit the  button to start measuring. The oscilloscope is plotting the voltage across the probe as a function of time. Going left to right (the x-axis), each box represents 20ms (the “Time Base” as set above). Top to bottom (the y-axis), each box represents 1V (the “Volts/Div”, with 0V being the center line).

Enable the **Measurement Tools** by clicking  located at the bottom right of the window. **Make sure the Frequency and Period measurements are enabled!**

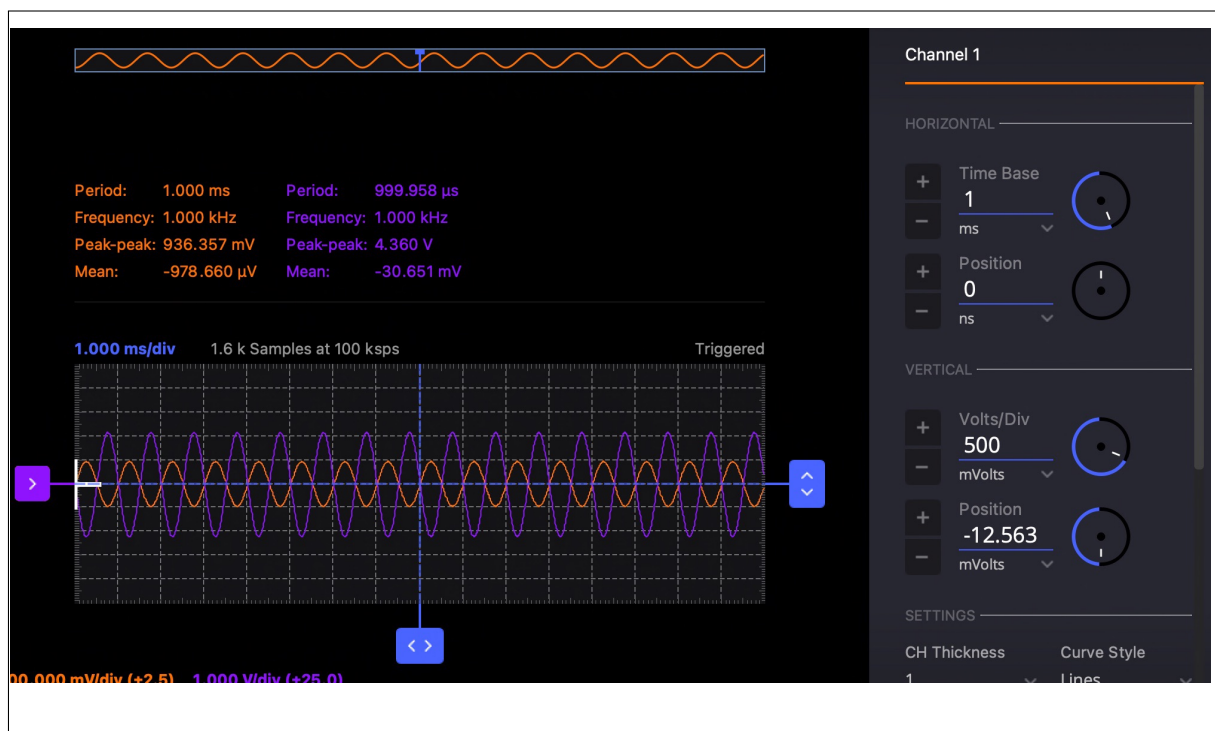
1 pts

3.1 What is the frequency measured? What is the period?

Frequency = Hz Period = s

3 pts

- 3.2 Paste a screenshot of your oscilloscope plot for the amplifier circuit. Make sure both CH1 and CH2 are enabled and have the same voltage scale (volts/div). It is up to you to size the window and choose the correct settings. Any window in which both your input and output waveforms are clearly visible, as well as the voltage scale and measurements, will receive full credit.)



1 pts

- 3.3 Using the oscilloscope, measure the peak-to-peak voltage at both the input and the output. What is the gain of this circuit?

$$\text{Gain} = \frac{V_{out} = 4.4 \text{ V}}{V_{in} = 0.93 \text{ V}} = 4.732$$

1 pts

- 3.4 Calculate the gain for the circuit in Figure 7 given an ideal op-amp. Show that, for the resistance values used, the ideal gain is approximate to the measured gain.

$$G_{\text{ain}} = \left| \frac{V_{out}}{V_{in}} \right| = \left| \frac{-4700}{1000} \right| = 4.7$$

$4.7 \approx 4.732$

4. Non-Inverting Amplifier

Assemble the following circuit in Figure 10 on your breadboard. Use a 1kHz $1V_{pp}$ sine wave for V_{in} . Supply $\pm 9V$ to power the rails of the op amp. Use a $20k\Omega$ potentiometer for R_f and a $1k\Omega$ resistor for R_i .

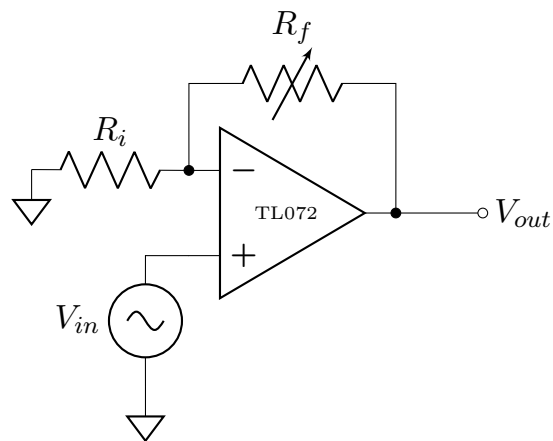
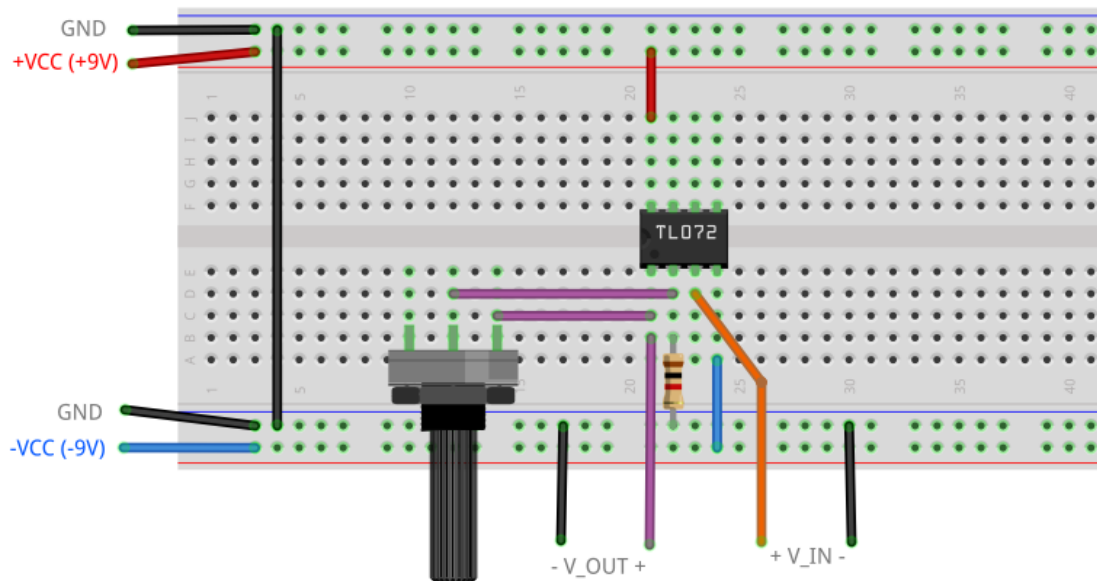


Figure 10: Non-Inverting Amplifier with Variable Gain

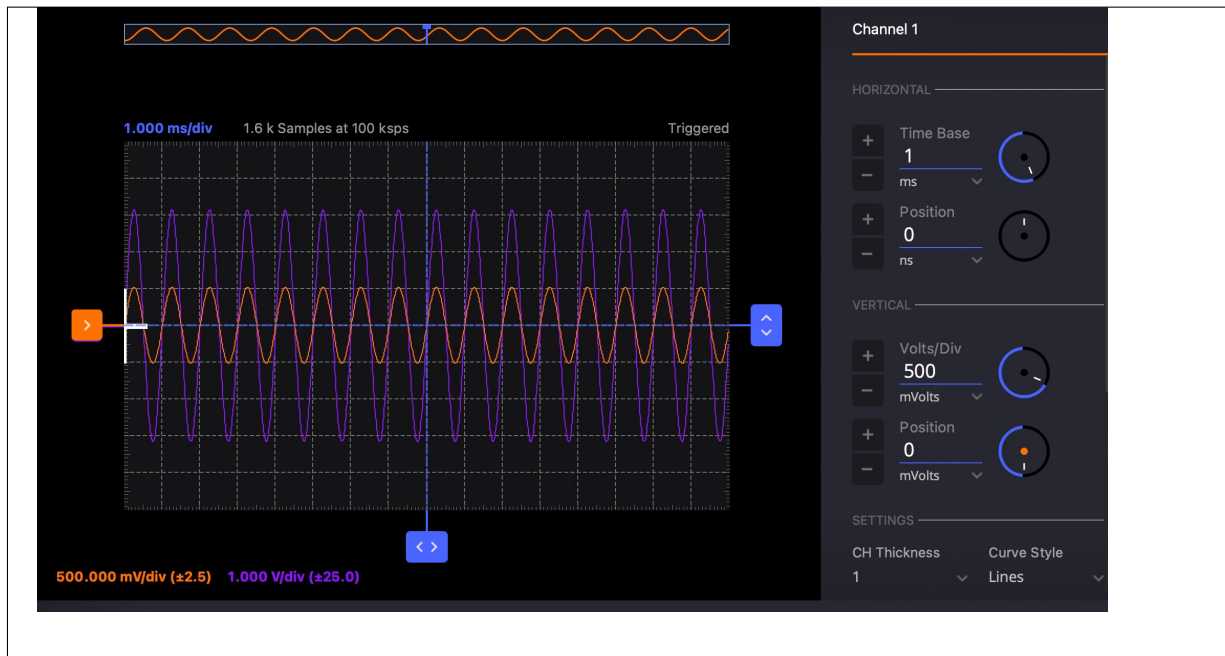
A breadboard diagram has been provided below:



Connect CH1 of your oscilloscope to V_{in} and CH2 to V_{out} . Enable measurements for both channels.

3 pts

- 4.1 Set R_f to $5\text{k}\Omega$. Paste a screenshot of your oscilloscope plot for the amplifier circuit. Make sure both CH1 and CH2 are enabled and have the same voltage scale (volts/div). It is up to you to size the window and choose the correct settings. Any window in which both your input and output waveforms are clearly visible, as well as the voltage scale and measurements, will receive full credit.)



1 pts

- 4.2 Measure the peak-to-peak voltage at both the input and the output for your oscilloscope plot from the last part. What is the gain of this circuit?

$$\text{Gain} = \frac{V_{out} = 6.231 \text{ V}}{V_{in} = 1 \text{ V}} = 6.231$$

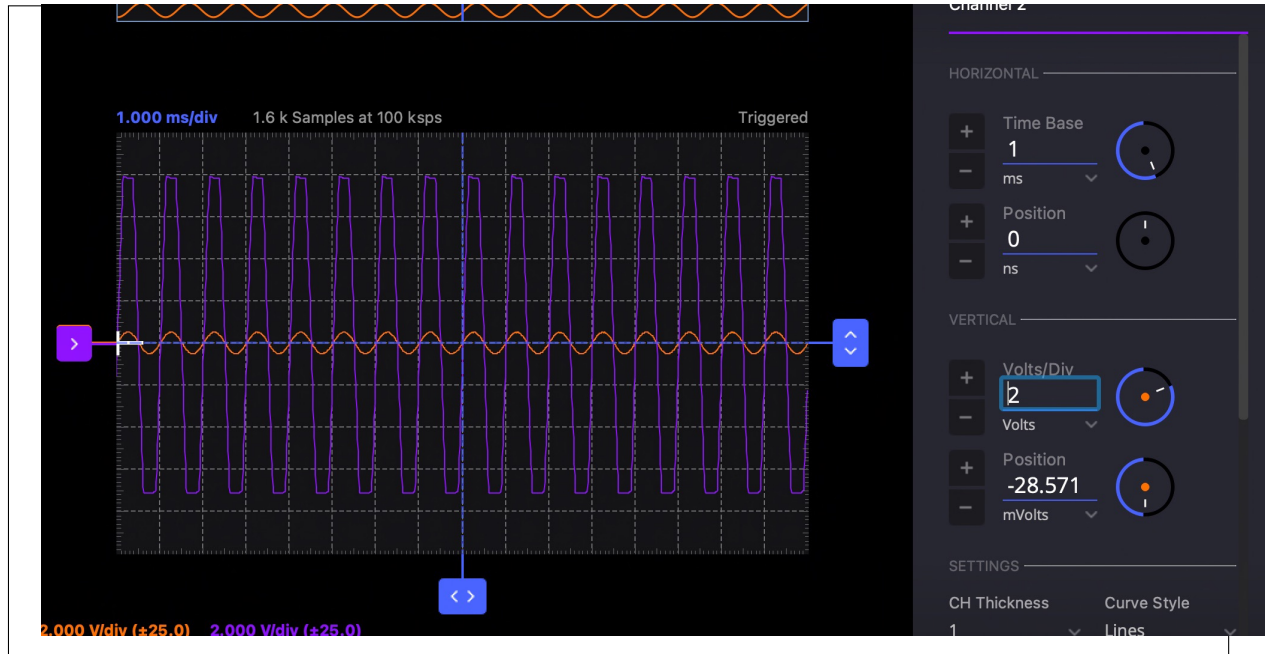
1 pts

- 4.3 Adjust R_f by turning the potentiometer and observe V_{out} . How does increasing R_f affect V_{out} ?

It increases V_{out}

3 pts

- 4.4 Increase the resistance of R_f to $20\text{k}\Omega$, its maximum value. Paste a screenshot of your oscilloscope plot for the amplifier circuit. Make sure both CH1 and CH2 are enabled and have the same voltage scale (volts/div).



2 pts

- 4.5 What happens to the output as the input increases? Describe the waveform you see. Why does it look that way?

Output increases as input increases,
 If it gets close to 9V , it levels off.
 This because the op amp amplifies the signal. It is in-phase since
 it is non-inverting. At 9V , it should level off since the op amp becomes
 saturated.

5. Glucose Sensor Front End

Diabetic people require external insulin injections to manage a sharp increase in blood glucose. Since we cannot directly ask the pancreas about blood glucose levels, bioengineers have devised a way to measure glucose outside the body. In this section, you will build a circuit that interfaces with a test strip to measure the glucose content of a sample liquid.

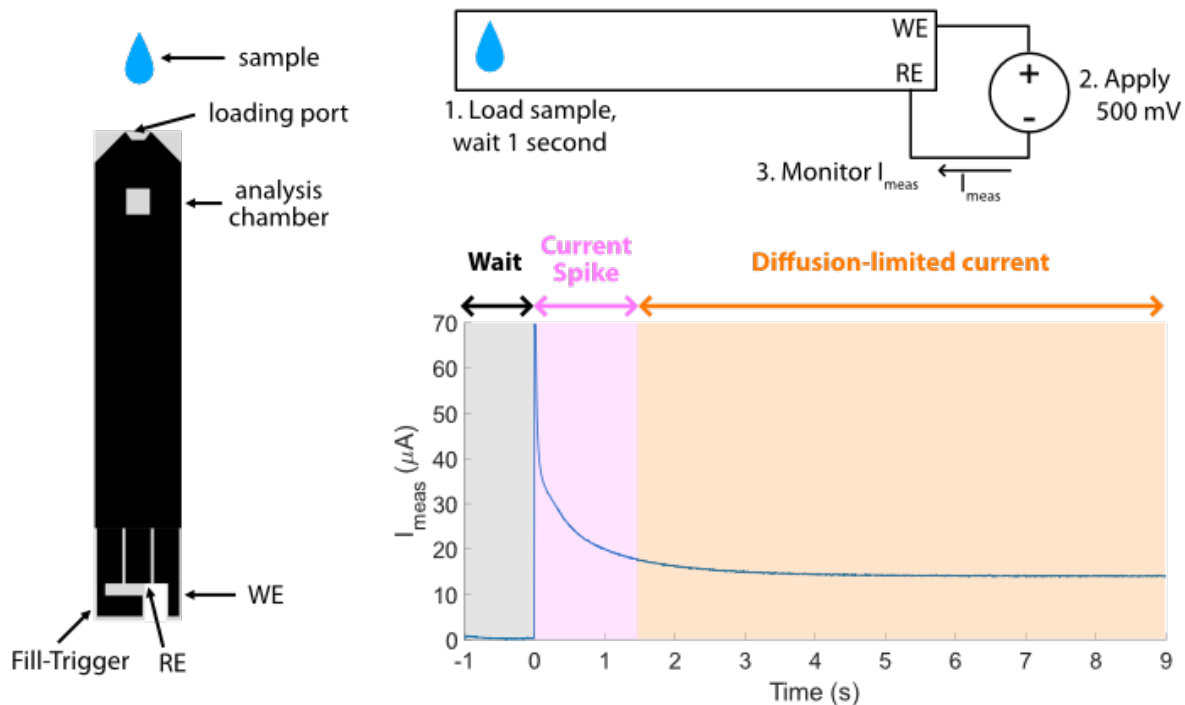


Figure 11: Test strip electrodes and sample current curve for 7.5 mM glucose (135 mg/dL).

The glucose test strips that we have provided to you have three electrodes (Figure 11). We will be using two: the Working Electrode (WE) and Reference Electrode (RE) (the third electrode, the Fill-Trigger is not used). Your circuit will apply a **+500 mV potential step** between the WE and RE and then measure the glucose-dependent current that develops.

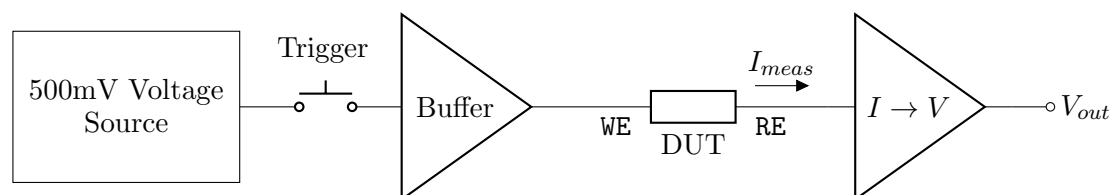


Figure 12: Glucose Test Strip Front End Block Diagram

The circuit utilizes voltage divider and a buffer to generate 500mV. The voltage is applied across the device under test (DUT; in this case, the glucose strip) using a push button. The current out of the strip is converted to a voltage using a *Transimpedance Amplifier* ($I \rightarrow V$; an amplifier that converts a current to a voltage and amplifies it). The voltage is then measured using your oscilloscope in Scopy.

+500mV Buffered Source

The first part of the circuit requires a stable 500mV source that controls a trigger voltage point $V_{trigger}$. Build the following circuit on your breadboard:

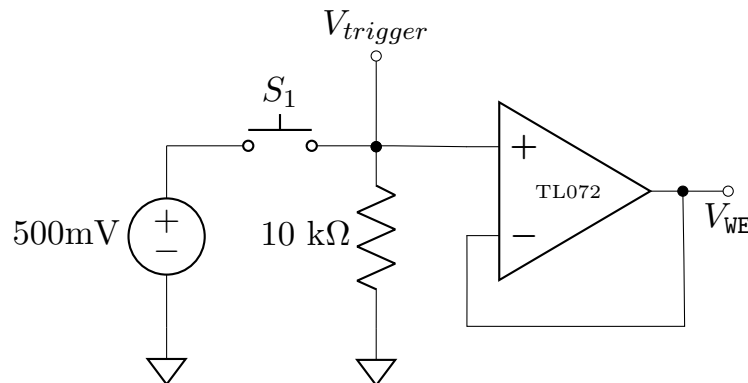


Figure 13: Buffered source circuit

Use the power supply of the ADALM2000 as the 500 mV source in this circuit. Please verify with your voltmeter that the voltage at V_{WE} is 500 mV when $V_{trigger}$ is pressed and 0V when unpressed (pulled down by the 10kΩ resistor).

Testing the Circuit with a Resistor

Now, complete the circuit in Figure 14 which consists of your buffer and a current-to-voltage converter. This circuit uses the buffer to apply 500 mV across the DUT (Device Under Test), and then uses the current-to-voltage converter to amplify the resultant current I_{meas} . You will first use a 47kΩ resistor as the DUT to test your circuit. Once you confirm your circuit is working, you will replace the 47kΩ with your glucose test strip. We want to capture a single voltage curve, so you will get to know the all-important *trigger* function of the oscilloscope.

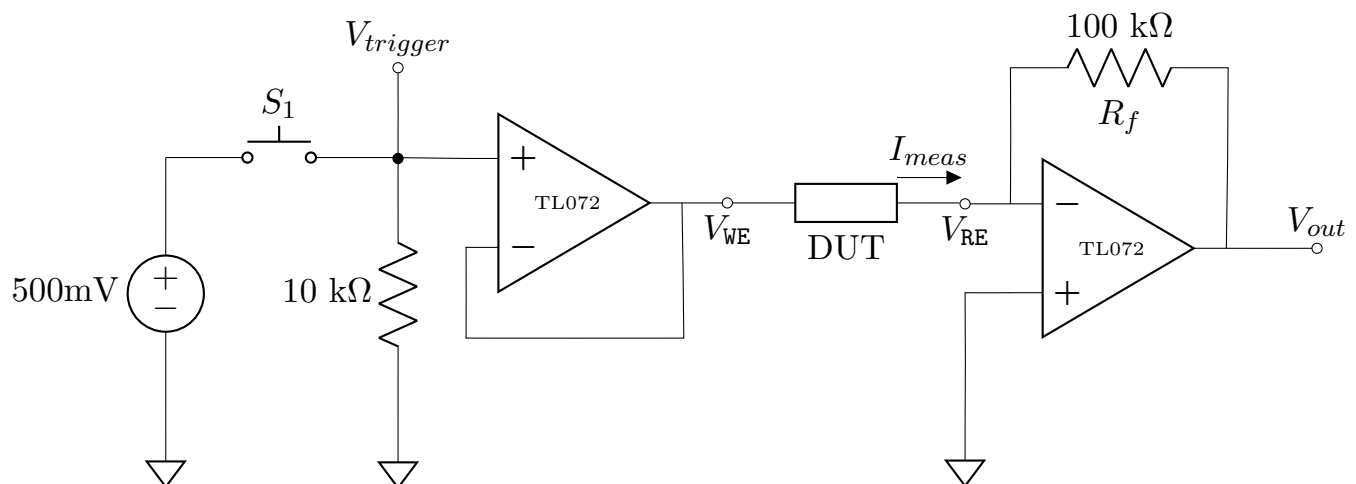
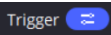


Figure 14: Glucose test strip front-end circuit. 500 mV should be provided by the ADALM2000 power supply. $V_{trigger}$ should be measured by CH1 on the ADALM2000 oscilloscope. V_{out} should be measured by CH2 on the ADALM2000 oscilloscope.

Once you build the circuit and put 47kΩ resistor in the place of DUT, set up your oscilloscope capture settings. Use CH1 to measure $V_{trigger}$ and CH2 to measure V_{out} . In the **Trigger**  submenu of the Scopy oscilloscope, select the following options:

Trigger mode	normal
Internal (Analog)	on
Source	Channel 1
Condition	Rising Edge
Level	250 mV
Hysteresis	50 mV

In the CH1 and CH2 submenus, select the following options as a starting point (you may adjust these settings as you see fit to best capture your waveforms):

CH1 Settings		CH2 Settings	
Time Base	200 ms	Time Base	200 ms
Horizontal Position	1.4 s	Horizontal Position	1.4 s
Volts/Div	1 V	Volts/Div	1 V
Vertical Position	0 V	Vertical Position	4 V

This will result in the oscilloscope triggering one full trace capture of CH1 and CH2 when CH1 detects a voltage *increase* of 250 mV or more (i.e. a rising edge). Press the **Single**  button to prime the oscilloscope to wait for the trigger signal.

1 pts

5.1 Now trigger a full capture of both CH1 and CH2 by pressing the pushbutton switch. Press, hold, and un-press the switch several times during the capture. Paste a screenshot of the full voltage trace capture here.

Paste Screenshot Here

☐ I have appended the screenshot to the back of my lab writeup



1 pts

5.2 According to your measured voltage trace at CH2, what was the current I_{meas} through your resistor? Please note units, and recall that $R_f = 100\text{k}\Omega$ in your $I \rightarrow V$ amplifier.

$$I_{meas} = \boxed{34.6} \mu\text{A}$$

$$\frac{3.46\text{V}}{100\text{k}\Omega} =$$

Measuring Glucose-Dependent Current

Now that you've made it this far, you're ready to use your circuit to measure the current from a glucose test strip. In order to do this, remove the connections from the breadboard binding posts to the breadboard supply rails. Then, connect a banana-to-minigrabber cable to each of the binding posts. These will allow you to more easily connect your glucose test strip to your breadboard circuit as shown in Figure 15. V_{RE} and V_{WE} should be connected to the appropriate rows on the breadboard.

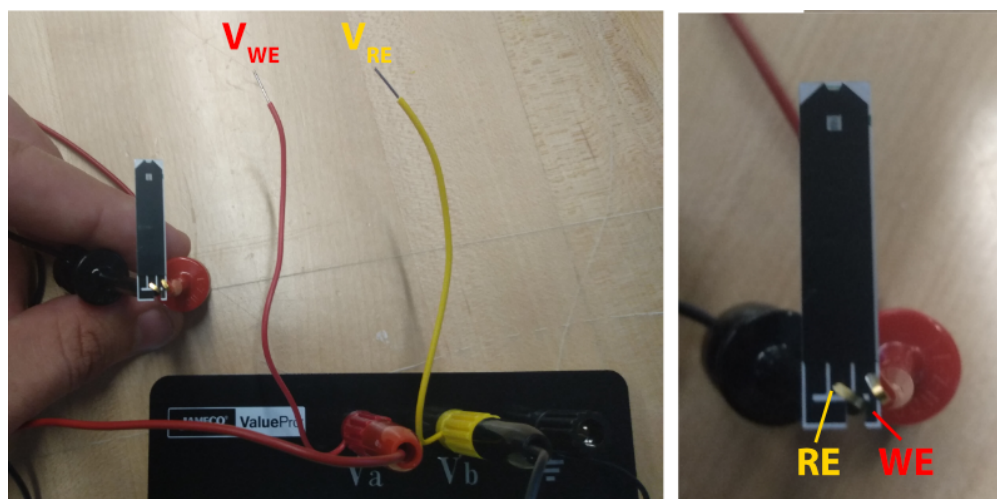


Figure 15: How to interface the glucose test strips to your breadboard's binding posts.

Use your mini-grabber leads to connect a glucose test strip to your circuit. Put a small amount of your test sample in a low-sided container (e.g. a soda bottle cap). **Test strips wear out over time, and should not be used more than once, though you can reuse a strip several times while you are debugging. If you are having problems getting a good measurement, come in to office hours so a TA can help you!**

The sequence to take a measurement is:

1. Prepare your oscilloscope for a capture by pressing the **Single** capture button.
2. Dunk the loading end of the test strip into the sample and remove it. (This loading step should only take a fraction of a second - the liquid will quickly wick into the analysis chamber.)
3. Wait 1 second.
4. Press S_1 to trigger the capture and hold it down.
5. Continue to hold S_1 until the capture has ended.
6. If you missed part of the trace, adjust the vertical axis (Volts/div) and try again.

5 pts

5.3 Paste a screenshot of the full voltage trace capture below.



1 pts

5.4 What was the current level that you measured 3 seconds into the capture? Please note units, and recall that $R_f = 100\text{k}\Omega$ in your $I \rightarrow V$ amplifier.

$$\frac{0.35 \text{ V}}{100\text{k}\Omega} = 0.000035 \text{ A}$$

I_{meas} at 3 s = 3.5 μA

15 pts

5.5 Be prepared to demonstrate your glucose test circuit to your small group TAs, using the sample test solution in TechSpark.

⚠ Do NOT take your circuit apart yet! You will need it for lab checkoff!