Introduction

During this activity, we will construct and calibrate a simple temperature-measuring circuit, first on a breadboard and then by soldering it to a circuit board. We will use a silicon diode as the temperature sensor, measuring the temperature from changes in its forward voltage.

We will first build a prototype on a breadboard, then solder a duplicate circuit onto a PCB, so we have a more permanent version for our final calibration.

We will go through the assembly and calibration of the diode circuit step by step to measure an initial temperature range. The final part of the activity will be to change the circuit for a different temperature range. Your activity kits should have enough parts to build 4 circuits total. A breadboarded diode circuit, a soldered diode circuit, and spare components for each. The final schematic for the diode circuit is shown in Figure 1. A completely assembled circuit is shown in Figure 2.

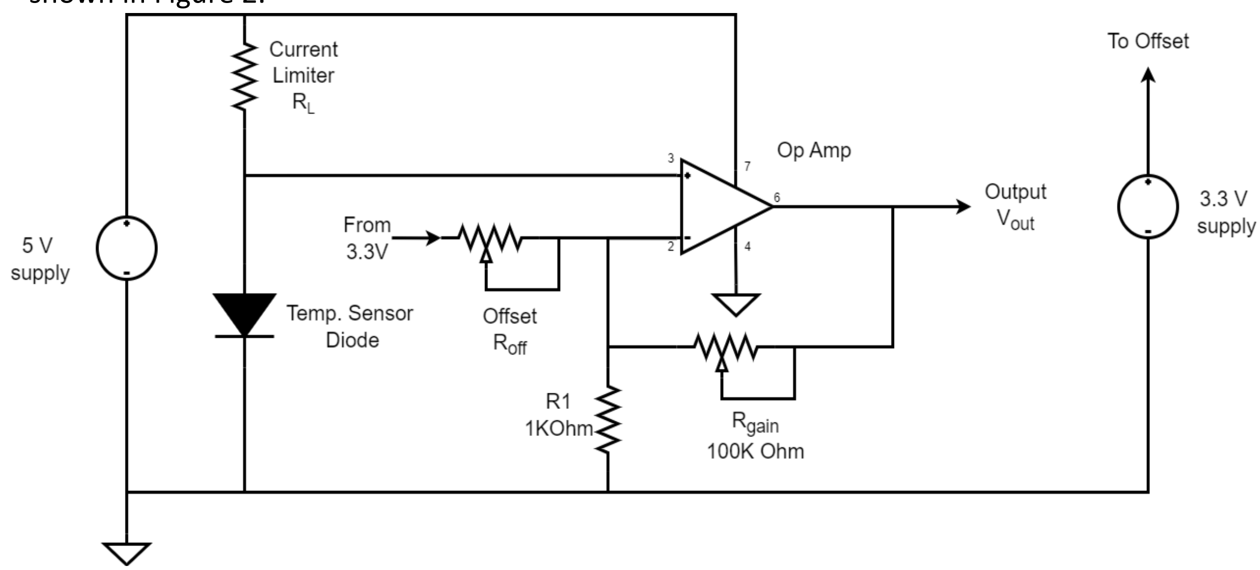

Figure 1: Completed diode temperature sensor. Over the course of this activity, we will prototype this circuit and solder it together.

As you go through the activity, be sure to take thorough notes in your **lab notebook**. Once the calibration is complete, you will need to write a short report to explain how you calibrated the temperature sensor. The soldered circuit will also be used when we start using Arduino to ready sensors.

It is recommended that you review the Temperature Calibration Report Guidelines (at the end of this activity) before starting the activity, so you know what information you will need to include in your report.

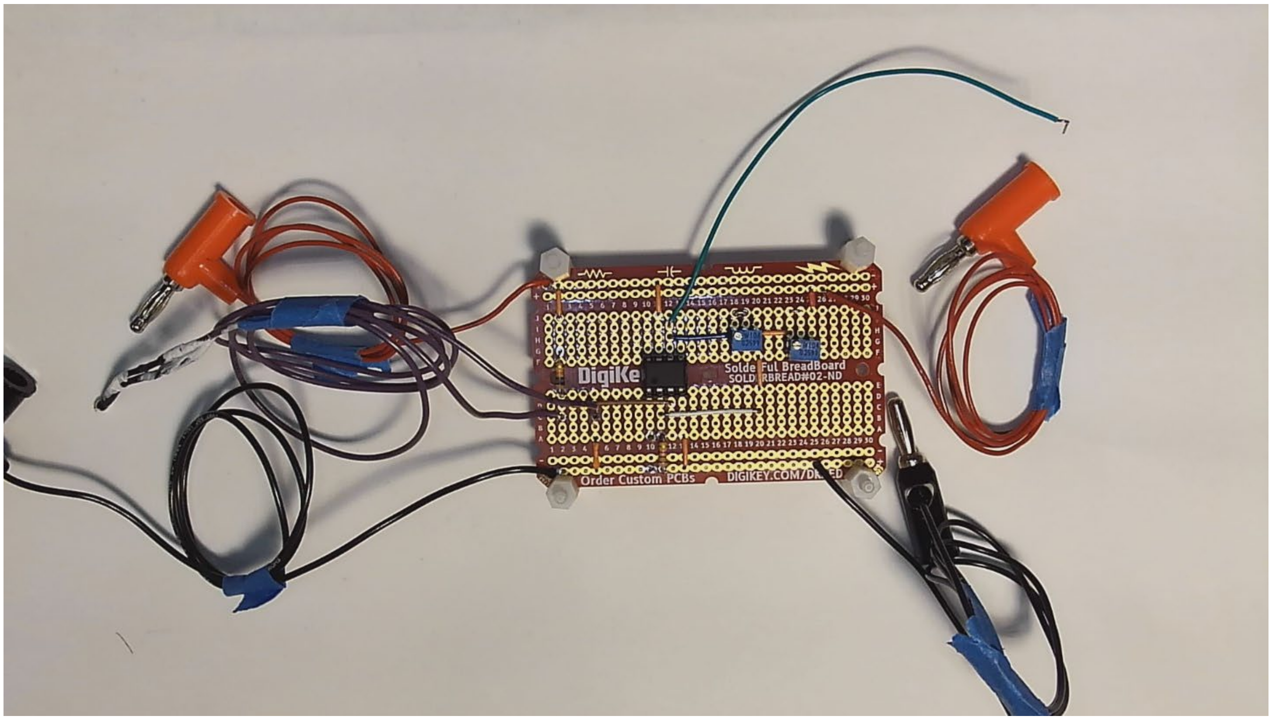

Figure 2: Fully assembled and soldered diode temperature sensor circuit. The two power connections are for 5V main power and 3.3V offset. Two 100kOhm potentiometers allow for adjustment of offset and gain with the green jumper connected to the output for easy measurement.

Materials List

1. From the activity kit
    1. 1N457 Signal Diode (x4) (For the temp sensors)
    2. TLV271 Op. Amp (x4)
    3. 8 Pin IC Socket (x2)
    4. 100 KOhm Potentiometer (x8) (For R_{off} and R_{gain})
    5. 1000 Ohm Resistor (x4) (For RL and R1)
    6. ~~56 KOhm Resistor (x4)~~
    7. Black Power "Banana" Connectors (x4)
    8. Red Power "Banana" Connectors (x4)
    9. Plastic Standoff (x16)
    10. Red Bread Board Pattern PCB (x2)
2. Tools and Lab Supplies
    1. Multimeter
    2. 2 Power Supplies (One for 5V and one for 3.3V)

3. Thermometer, thermocouple, or other temperature measurement device
4. Hot plate, beakers, ice (for a temperature bath for calibration)
5. Heat shrink, liquid electrical tape, or other means of waterproofing the sensors

Preparing Diodes and Thermistors for Sensor Use

We will be using a water bath to calibrate our sensors. Because of that, we want to solder long wires to the leads to the diodes so we can move the sensors around. Use stranded wire and not solid core to minimize the chance of wires breaking. Since stranded wires will not push into the breadboard, you can use short jumper wires in the breadboard and alligator clips to connect the diode leads

You should make at least 2 sensors.

For the diode, use two different-colored wires for the cathode and anode, as shown in the figures below. You do not need to use red and black, just different colors, so you can tell the positive(anode) and negative(cathode) ends when the diode is covered.

Make sure to write down which end is which color in your lab notebook.

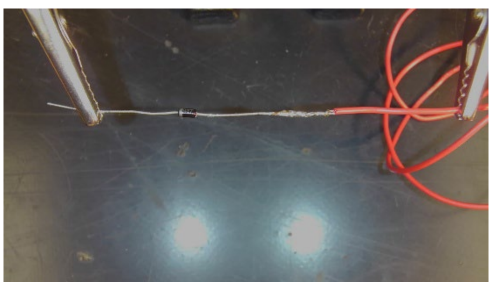

Figure 4: Soldering a red wire to the diode lead. Notice we have soldered this to (+) lead. We will not be able to see the stripe one the diode once we cover it with waterproofing

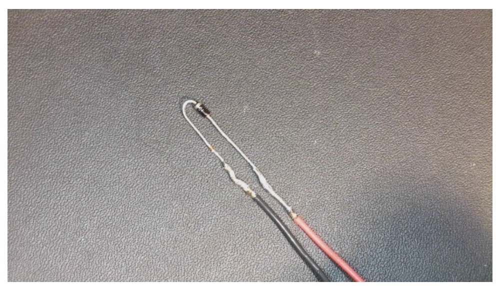

Figure 5: Diode with wires soldered to both leads

After the wires are soldered, you should waterproof the sensor by applying heat shrink. Make sure you cover any bare metal. For the best waterproofing, apply a layer of liquid electrical tape or another sealant.

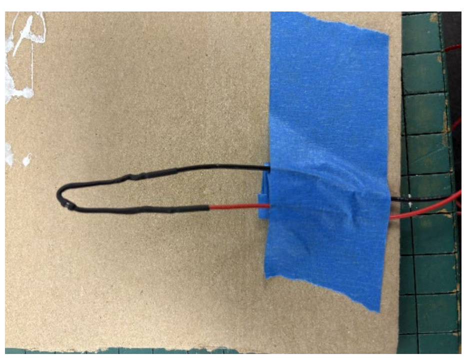

Figure 6: Diode with heat shrink applied

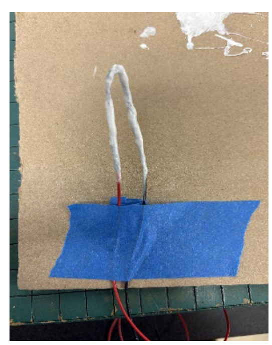

Figure 3: Diode with liquid electrical tape applied

Liquid electrical tape will take ~24 hours to properly cure. Ensure you wait before putting your sensors in the water.

Alternatively, you put your sensors in the Ziploc bag when you place them in the water.

Diode Sensor Theory of Operation

Diodes have a small voltage drop in the forward direction, V_f. This is the vertical line in the plot on the right. For an ideal diode, V_f does not change as the current changes. A real diode will have a small bit of resistance, so the forward voltage will have a slight slope.

V_f does change with temperature. As the temperature increases, electrons are thermally excited in the semiconductor, allowing them to flow more easily through the diode. This means they need less energy to get across the diode, causing V_f to decrease.

This means the diode voltage will decrease linearly as temperature increases. So V_f will be our temperature signal.

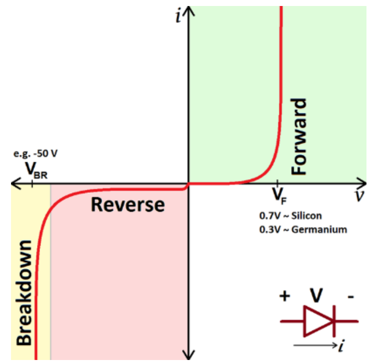

Figure 7: Diode forward voltage Vf depends on temperature.

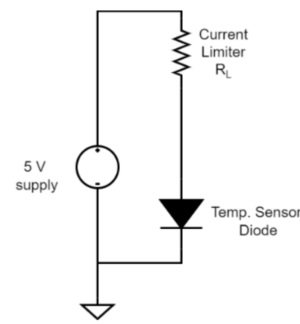

Figure 8: Diode Sensor Schematic

Building the Diode Sensor Circuit

We will start by building a standalone sensor circuit shown in Figure 8: Diode Sensor Schematic. We connect the diode in series with a resistor to limit the current flow through the diode.

Without the resistor, the current through the diode would be very large and quickly heat and damage the diode. The actual value of the resistor is not critical, so we will use a 1KOhm resistor **for R_L**. We also need to connect our diode to power.

NOTE: Remember the + and – markings on the breadboard are somewhat arbitrary. My

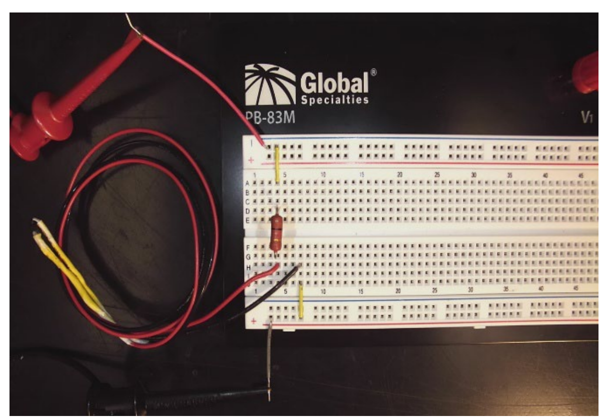

Figure 9: Diode sensor circuit on breadboard, notice we are using the top (-) row for +5V and the bottom (-) for ground.

recommendation is use the top rows for +Voltage and the bottom rows for ground or negative and ignore the markings.

We will use the topmost row for +5V (we will use the second row for +3.3V eventually) and the bottommost row for Ground. So put a jumper in the top row. Add a jumper on the bottom row. We will clip the power supply leads to these leads.

Now use a jumper to vertically connect the +5V to a column. Then add the 1 KOhm resistor, bridging the gap. Connect the positive lead of your diode in the same column as the resistor. Connect the negative diode lead to the breadboard, three columns to the right. Finally, use a vertical jumper to connect that column to ground.

Before connecting the power, set your power supply to 5V. Then connect the power leads to the +5V and Ground jumpers.

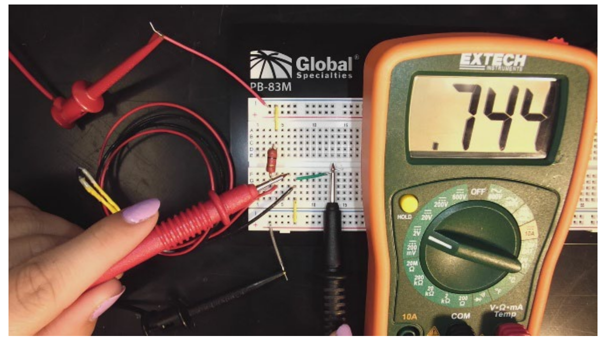

Figure 10: Diode Measuring diode voltage

Turn the power on. The current through the diode should be ~5mA or .005A. Your power supply current display may go that low. If it still shows 0, don't assume no current is flowing. Use your multimeter to measure the voltage across the diode. Your meter should be on the + and – leads of the diode, or their column.

The diode voltage should be ~0.7V. Make sure the (+) and the (–) leads of the diode are not in the same column; this will cause a short circuit and bypass the diode.

If you are reading 5V, 3 things could be happening. An open circuit, caused by a broken wire or bad connection, will read 5V. If the diode is backward, it will block current and act the same way. Finally, make sure you are not measuring the voltage across both the diode AND the resistor.

Table 1: Diode Voltage vs. Power Supply voltage

Power Setting	V_f
2V	
3V	
4V	
5V	

Once you have current, let's see how V_f changes with current. Reduce the power supply voltage to 2V and measure V_f. Record these values in your lab notebook. Repeat for 3V, 4V, 5V. You should see V_f increase slightly as the power-supply voltage rises.

This is due to the small internal resistance of the diode. To minimize this effect, we want to ensure that we perform all remaining measurements at the same power-supply voltage. Use your multimeter to measure the power supply voltage and record that number so you can set your supply to that value from now on.

Now, let's verify V_f changes with temperature. Briefly warm up the diode. You can do this with a heat gun, briefly dunking it in a warm water bath, or even holding it in your hands. You should see the voltage drop slightly and then rise as it cools off when you let go.

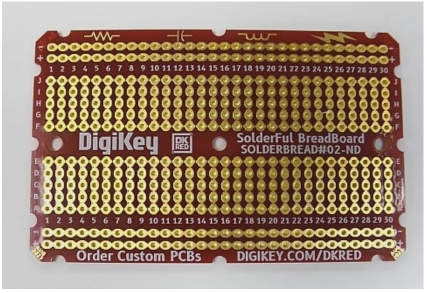

Figure 11: PCB breadboard. Notice this PCB has the same layout as the breadboard. The columns and rows are numbered differently.

Now we are ready to start building the soldered circuit.

DO NOT DISASSEMBLE THE BREADBOARDED CIRCUIT. WE WILL CONTINUE TO ADD THE BREADBOARD PROTOTYPE. YOUR KIT CONTAINS DUPLICATE COMPONENTS SO YOU CAN BUILD TWO CIRCUITS.

The PCBs supplied use the same pattern of connections as the breadboard.

Note: The power rows on the top and bottom are slightly closer to the vertical columns, so use jumpers that are 1 shorter (like orange instead of yellow). All other connections should be the same.

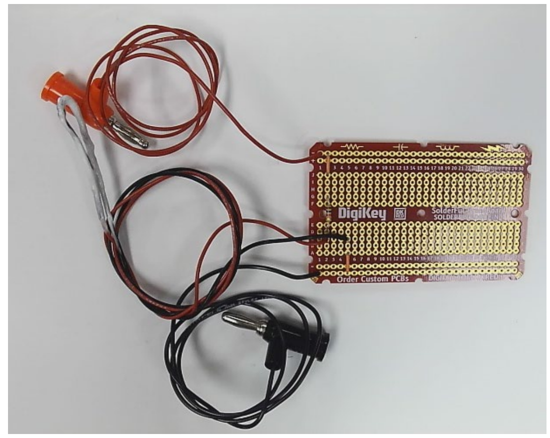

Figure 12: The diode sensor soldered to the PCB.

Now, duplicate the breadboard circuit on the PCB. After soldering components, don't forget to trim the leads to prevent shorts.

For the power leads, solder lengths of wire ~2-3 feet long into the top and bottom rows. Your kit includes power plugs that can be attached to the wires using a set screw in the top.

The kit includes plastic standoffs that can bolt onto the notches on the edge of the PCB to raise the board off your work surface, but it is recommended to wait until the circuit is complete to install them.

When complete, repeat all the checks you just performed on the breadboard with the soldered circuit. If needed, correct any bad solder joints.

Recording Diode Voltage Temperature Data

Using a hot plate, a water bath, and ice, take measurements every 10 degrees from 0 °C to 50 °C using the solder temperature sensor.

For each measurement point, record the actual temperature as measured by a thermometer or thermocouple and the diode voltage V_d.

Be sure to allow your diode temperature to stabilize and ensure neither your diode nor your thermometer is touching the walls of your water container since that will be slightly warmer than the water.

Table 2: Diode Voltage vs Temperature Measurements

Temperature Point	Measured Temperature (C)	V_d(V)
0-10 C		
10-20 C		
20-30 C		
30-40 C		
40-50 C		

Your measurements do not have to be exactly 10 degrees apart, but make sure you take at least 5 measurements, roughly evenly spaced from 0 °C to 50 °C .

Using graphing software such as Excel or Google Sheets, make a scatter plot with Temperature on the X axis and diode voltage on the Y. An example plot is shown in Figure 13.

Next, fit a line to the data. The equation of this line provides the conversion from temperature to diode voltage.

Note: Since this equation converts **from** a temperature **to** a voltage signal, we normally would not call it a calibration.

For a calibration equation, we want the reverse. A conversion **from** a sensor signal **to** the physical quantity being measured.

We will use this data to set our amplifier gain and offset in our final circuit. Using your fit equation, calculate what the diode voltage should be at exactly 0 °C and exactly 50 °C as V_0 and V_{50}.

For example, with the sample date V_0=0.789 V and V_{50}=0.709V

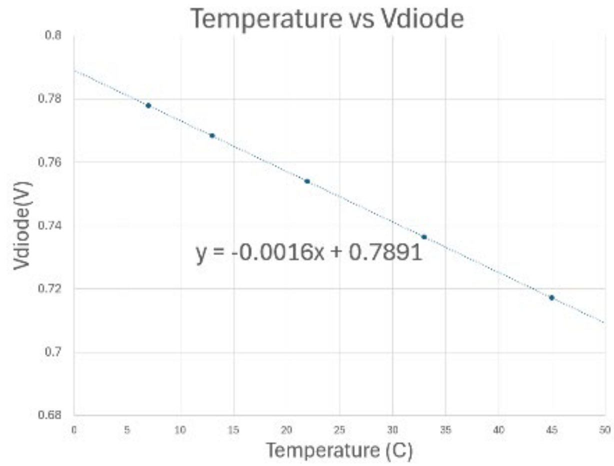

Figure 13: Example diode voltages measured from 0 – 50C.

Adding A Non-Inverting Amplifier

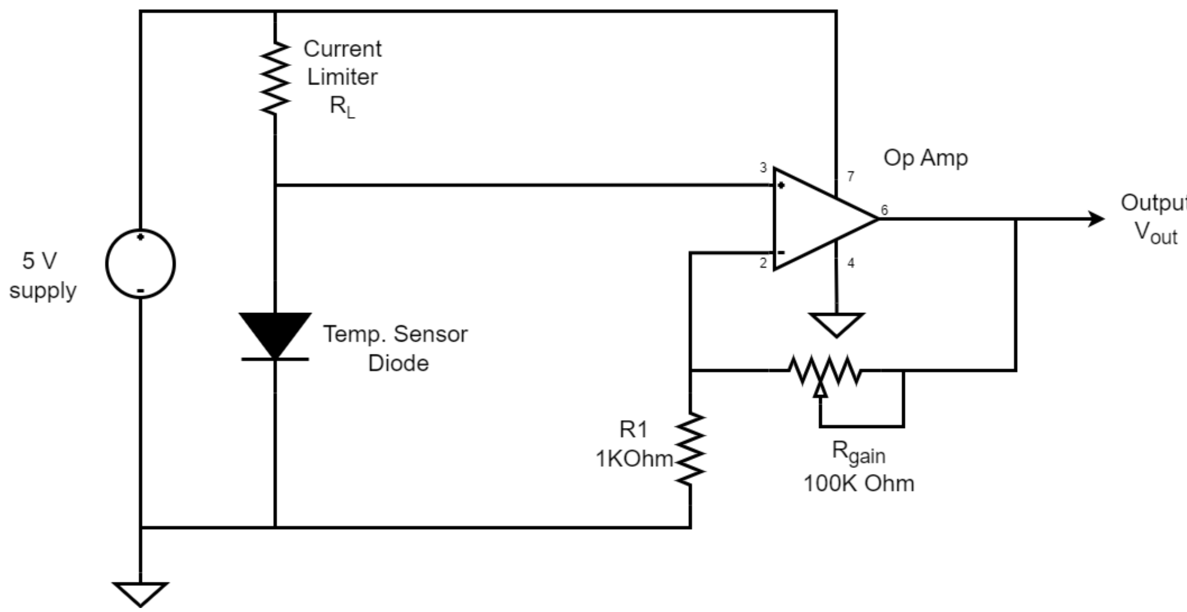

Figure 14: Temperature sensor circuit with a non-inverting amplifier. This circuit will amplify the input voltage from the diode V_d connected to pin 3 to a larger voltage V_{out} at the output on pin 6.

While V_d does change with temperature, it is a relatively small change (0.08V in our example) over 50 C. To make that change easier to measure, we want to make it larger using an amplifier.

To accomplish this, we will use an Op Amp. In this case, the TLV271 made by Texas Instruments. To determine the pin layout, we should look up its data sheet [1] and find the diagram of our specific part and package.

Be careful when looking up pin layouts because often a datasheet will include the information for a family of components (ex., Single, dual, and quad Op Amps) or a single part may come in multiple packages.

The correct pinout from [1] is shown in Figure 15. Looking at the chip, we can see a circular dimple indicating pin 1.

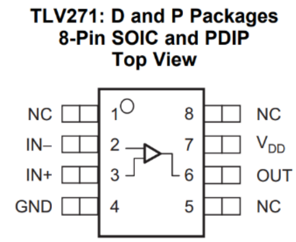

Figure 15: Pin out for Op Amp TLV271. V_{DD} is another common symbol for +V Power,

Install the chip in the breadboard to the right of the sensor diode with pin 1 to the left. This orientation will set up the +V supply pin on top and the -V supply (ground) on the bottom.

When inserting the chip into the breadboard, take care to line up the pins with the holes and not bend them when you push it in.

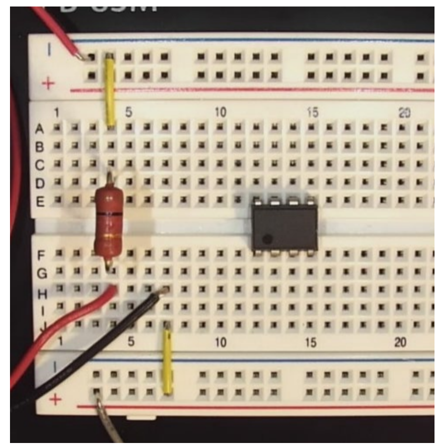

Figure 16: Proper orientation of the Op Amp in the breadboard.

We want to leave some space for any future connections, so install the chip so pin 1 is five columns to the right of the diode ground column (the diode is column 7 and pin 1 is column 12 in the image to the right).

Now add the power connections to pin 7 and pin 4. We want to try to leave as much room as possible for the amplifier resistors.

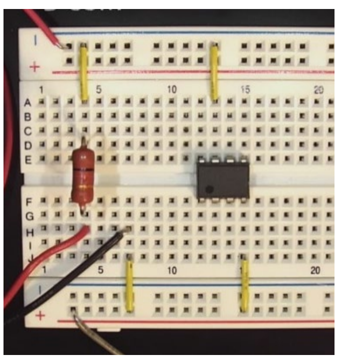

Figure 17: Connecting the Op Amp to Power and Ground.

Next, we need to connect the diode voltage to the non-inverting input V+ on pin 3. Looking at the schematic, we see that the positive side of the diode, R_L, and pin 3 of the op amp should all be connected to each other, so run a jumper from pin 3 to where the resistor and diode connect.

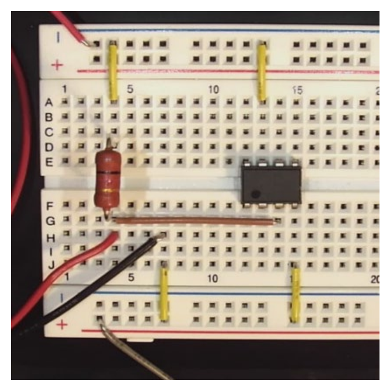

Figure 19: Connecting the diode V_{in} to the Op Amp. Note that the red wire, the resistor lead, and the brown jumper are connected to the same column.

Next is R_1. It connects pin 2 directly to ground. We just need to make sure we leave room to connect pin 2 to pin 6 via the gain resistor.

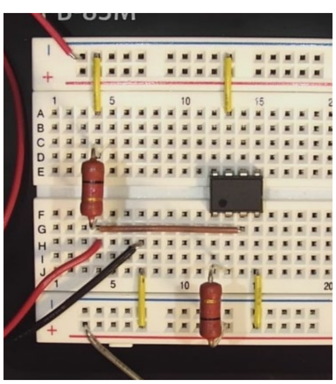

Figure 18: Connecting the diode V_{in} to the Op Amp.

Now it gets a bit trickier. Our gain potentiometer needs 3 columns since it must be placed horizontally. Also, the pins are staggered across two rows. Finally, we also need to connect two of its pins together.

It is best to move this part of the circuit away from the chip rather than trying to squeeze everything together. Figure 20 shows one way of accomplishing this.

Finally, we just need to install the potentiometer in the designated location, and our first amplifying circuit is complete.

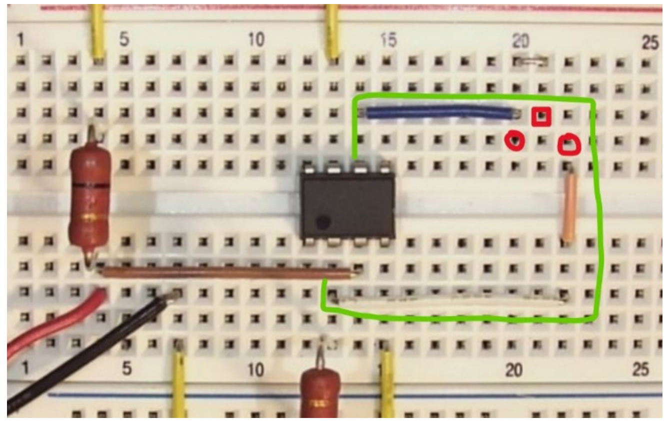

Figure 20: Connecting pin 2 (V-) to pin 6 (Vout). The green line roughly shows the path formed by the jumper connections. The red circles indicate where the potentiometer will be installed. Note the white jumper connecting columns 13 to 22 and the bare jumper at the top connecting columns 21 and 22.

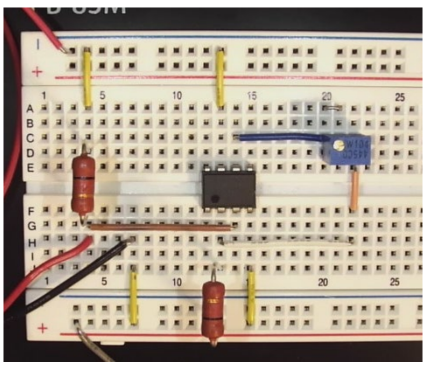

Figure 21: Installing the gain potentiometer completing the feedback path.

Testing the amplifier

Recall that the equation for a non-inverting amplifier (using our resistor symbols) is:

$$V_{out} = \left(1 + \frac{R_{gain}}{R1}\right) V_{in}\ ,\ Gain = \left(1 + \frac{R_{gain}}{R1}\right)$$

With R_1=1000 and R_g 0 – 100K

Since V_{in} ~0.7V let us first set our gain to ~5. Which should set V_{out} to ~3.5V. So we need to set R_g to 4000

Note: Make sure the circuit is unpowered when measuring resistance. Some power supplies have very low resistance between + and – V when off, so it is best to disconnect at least one of the power leads when setting resistors in order to prevent erroneous readings.

To set R_g, place your multimeter leads on pin 6 and pin 2. Then use a screwdriver to turn the screw on the potentiometer until the desired value is reached.

Do not worry about getting the resistance exactly to 4000; just get it close and record the setting.

Reconnect power and measure V_{in} on pin 3 and V_{out} on pin 6. Calculate the actual gain by dividing V_{out} by V_{in}. Record these values in your lab notebook.

Repeat this for gains of 4, 3, and 2, as shown in Table 3.

Table 3: Gain Measurements

Target Gain	Target R_g (Ohm)	Actual R_g (Ohm)	V_{out} (V)	V_{in} (V)	Actual Gain
5	4000				
4	3000				
3	2000				
2	1000				

Now reset the gain to ~5. While measuring V_{out}, slowly reduce the voltage of the power supply to 2V. What happens when the supply voltage drops below the original output voltage? Now slowly raise the supply voltage to 7V. What happens to V_{out}? When done, reset the power supply to the value of 5V you have written in your lab notebook.

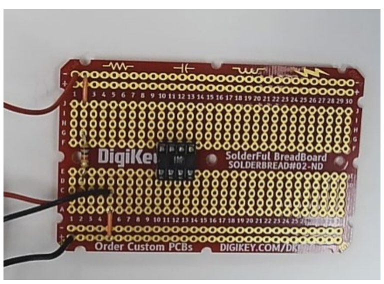

Figure 22: Soldering Op Amp socket in the PCB

Now we will add the amplifier to our PCB circuit. To allow easy chip replacement and protect the IC from heat, we will use an IC socket. Solder the socket into the board in the same spot as the breadboard (5 to the right of the diode ground again).

Now, add the 1000 Ohm resistor R1 and the jumpers to the breadboard one at a time. Take your time and ensure the components are in the correct place before soldering them in place. If you try to do several components at once, they are more likely to fall out or be misplaced when you flip the board to the backside for soldering.

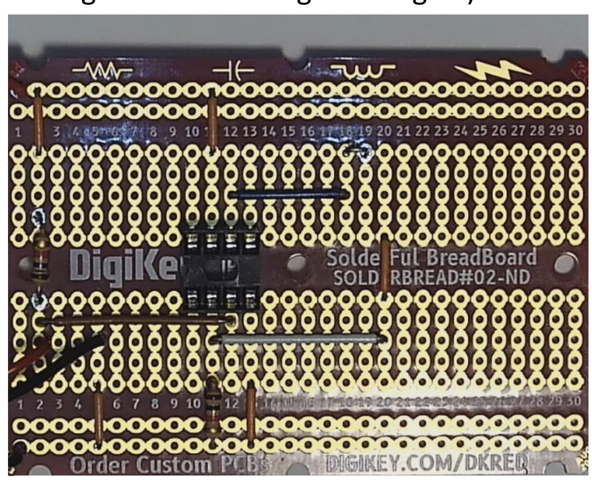

Figure 23: Adding the jumpers to the PCB.

We will wait to install the potentiometer and IC until we have all jumpers installed for the final circuit.

Adding An Offset to the Amplifier

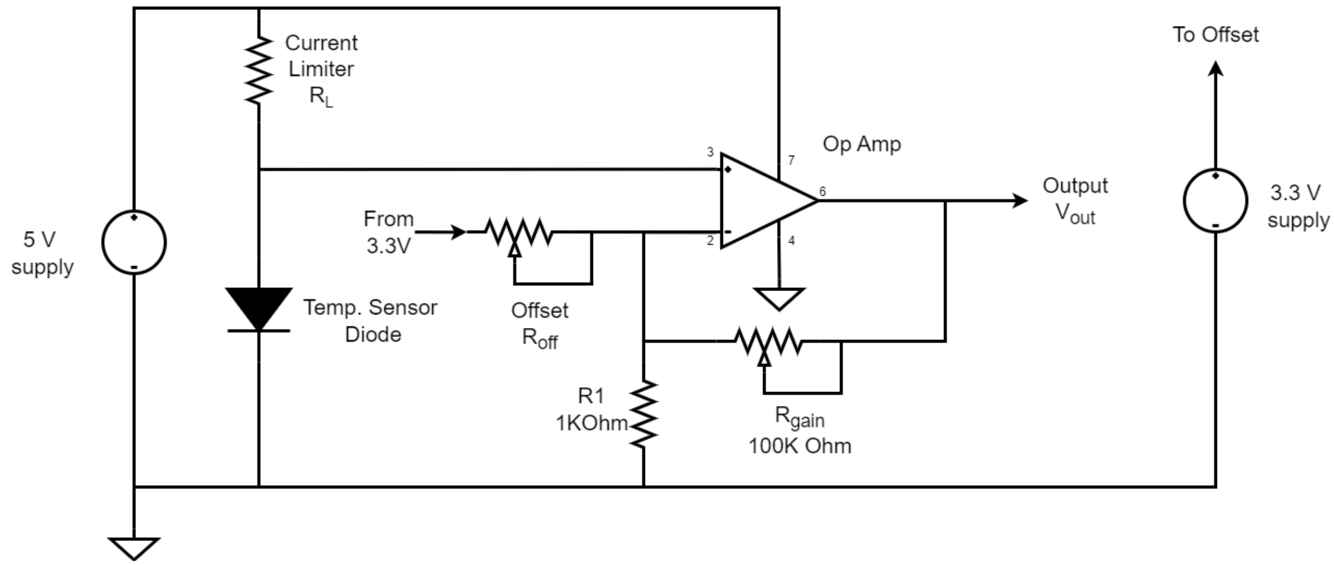

Figure 24: Adding the offset to the amplifying circuit. Notice the arrows showing that the potentiometer R_{off} is connected to the 3.3V supply. This is often done on schematics to prevent having an excessive number of confused crossovers in the schematic.

We next want to add an offset to our amplifying circuit. This will allow us to shift our amplification line up and down. To do so, we need to add a second power supply and another potentiometer R_{off}. The equation for the new amplifying circuit can be determined using KCL, KVL, and the Op Amp Golden rules. Doing so gives us:

$$V_{out} = V_{in}\left(1 + R_{gain}\left(\frac{1}{R_1} + \frac{1}{R_{off}}\right)\right) - V_{off}\frac{R_{gain}}{R_{off}}$$

Where V_{off}=3.3V, R_1=1000 Ohms, and R_{gain} and R_{off} are 0-100KOhm.

We could also supply the offset from the 5V supply, but that would mean our amplifier output would vary with supply voltage, which is usually undesirable (consider if using batteries, the voltage would drop as the batteries drain).

We will use the 2nd Power Rail at the top for our +3.3V supply. The negative lead will connect to the bottom row (our ground). Then each supply will be relative to the same 0V point.

When connecting multiple devices, it is important to ensure they have the same 0V reference point. This is usually accomplished by connecting their V- or Ground connections together.

First, let's remove R_{gain} to keep it out of the way while we build the circuit. Looking at the schematic, we need to connect 3.3V to pin 2 through the second potentiometer R_{off}.

If we have plenty of space to the right of R_{gain}, that will allow easy connection to the 3.3V supply on the second power rail at the top of the circuit.

We will connect the 3.3V supply to the 2nd row on top and bottom power row.

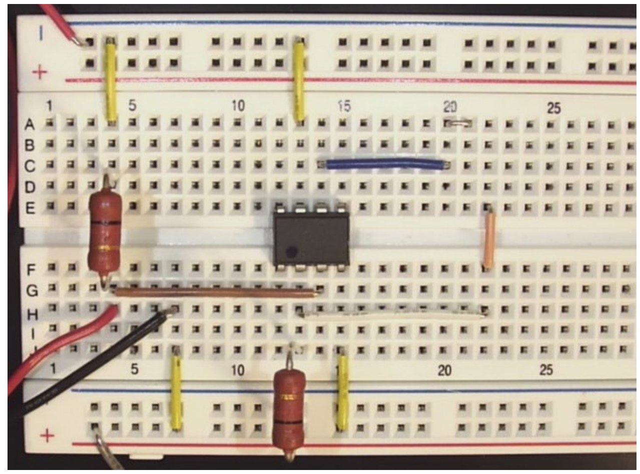

Figure 25: Amplifier with potentiometer removed. If we connect our offset resistor to the orange jumper on column 23, it will be connect to pin 2 through the orange and white jumpers.

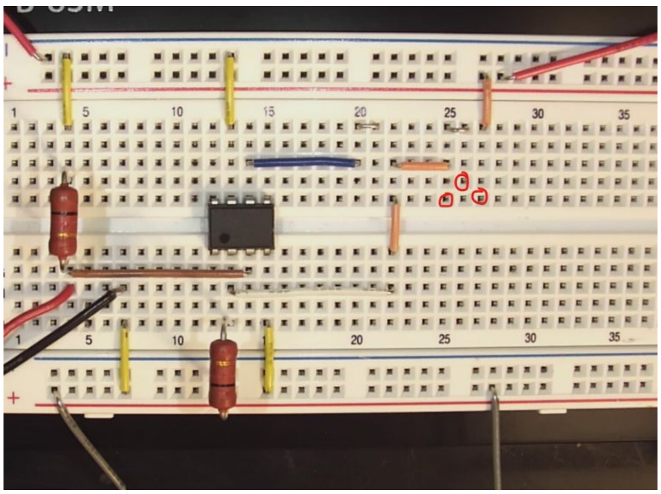

Figure 26: Adding the jumpers for the offset potentiometer. Make sure you notice the bare wire jumper connected column 25 to 26; this connects two of the potentiometer leads together. The red circles show where R_{off} will be installed.

The +5V and +3.3V connections from the power supplies need to be on different rows. But the (-) ground connection should be on the same row, so they are using the same 0 volt ground.

Then use a horizontal jumper to connect from the rightmost column where R_{gain} would sit. This should be where you have a jumper across the gap connecting to pin 2. Install a 1-space bypass jumper. And finally, add a vertical jumper from the 3.3V rail to the right of the bypass jumper. When done, it should look like Figure 26.

Now we just need to install R_{gain} and R_{off}, and our breadboard circuit will be complete as show in Figure 27.

Finally, before we proceed further, let's record our settings for the

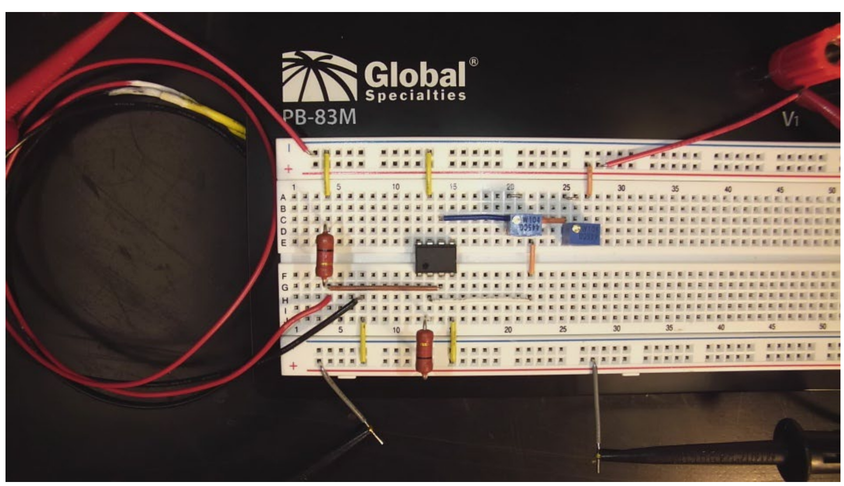

Figure 27: Complete breadboard diode temperature sensor circuit.

3.3V supply. With the power supply disconnected, set it close to 3.3V. Measure the exact voltage with your multimeter and write it down in your lab notebook. Whenever we are working, we want to set our 3.3V supply to that same value.

Determining Desired Transfer Equation

Now we want to determine how to set R_{gain} and R_{off}. To do that, we need to decide what we want our transfer function to be. For this exercise, we want the circuit to measure 0 °C to 50 °C and have an output range of 0-5V.

We already calculated what the V_{in} should be at 0 °C and 50 °C, V_0 and V_{50}. Notice V_0 is larger than V_{50}. If we plot a line through (V_{50}, 0V) and (V_0, 5V), the equation of the line will be our desired transfer equation. The slope of the line is our Gain, and the y-intercept is the offset.

The line for our sample data is shown in Figure 28.

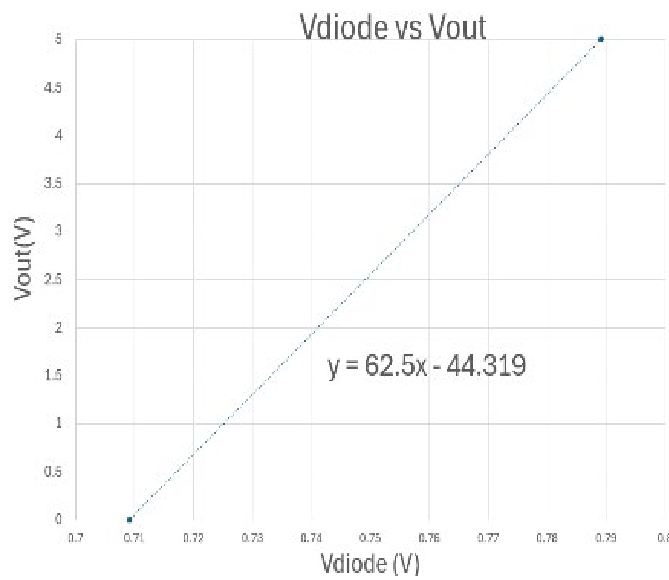

Figure 28: Plot of V_{in} vs desired V_{out}(0 to 5V)

Now we can calculate the settings for R_{gain} and R_{off}. If we set the amplifier equation

$$V_{out} = V_{in}\left(1 + R_{gain}\left(\frac{1}{R_1} + \frac{1}{R_{off}}\right)\right) - V_{off}\frac{R_{gain}}{R_{off}}$$

Equal to the Transfer function

$$V_{out} = Gain * V_{in} + Offset$$

We will get two equations:

$Gain = \left(1 + R_{gain}\left(\frac{1}{R_1} + \frac{1}{R_{off}}\right)\right)$ and

$Offset = -V_{off}\frac{R_{gain}}{R_{off}}$

Plugging in the values (be sure to use your values for Gain, Offset, and V_{off} not the sample values shown here) yields

$$62.5 = 1 + R_{gain}\left(\frac{1}{1000} + \frac{1}{R_{off}}\right), \qquad -44.319 = -\frac{3.3R_{gain}}{R_{off}}$$

Now we have 2 equations and 2 unknowns. We will need to solve for R_{gain} and R_{off} numerically using software such as Wolfram Alpha or MATLAB. Or we can make plots, replace R_{gain} with X,

R_{off} with y, and plot the 2 equations on a graphing program like https://www.desmos.com/calculator. The point where the lines intersect is the desired values for R_{gain} and R_{off}. For our sample data, R_{gain}=48KOhm and R_{off}=3.6KOhm. Record your values calculated values in your lab notebook as target R_{gain} and R_{off}.

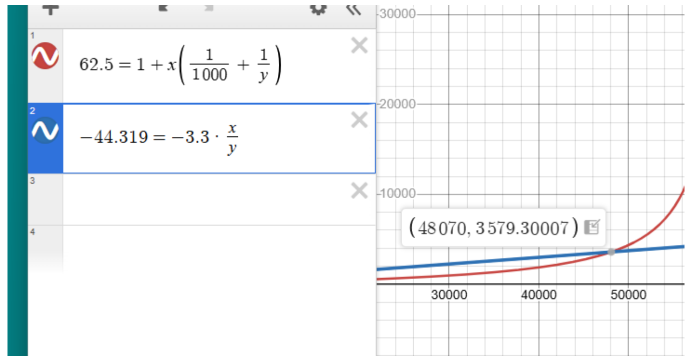

Figure 29: Example of using a graph to solve for gain and offset resistors values.

Note: if you get a number less than 0 or greater than 100,000, you cannot achieve the needed gain and offset with existing components. Possible solutions would be changing the values of R_1 or the 3.3V supply, getting a different sensor, or getting bigger potentiometers.

Setting Amplifier Gain and Offset

Now you want to set the potentiometers. Be sure the power supplies are disconnected from the circuit. To set $R_{gain,}$ place your multimeter on pins 2 and pin 6 of the Op Amp while turning the screw on R_{gain}. For $R_{off,}$ put your meter on pin 2 and the 3.3V power connector.

You likely will not be able to set the potentiometer exactly to your calculated values. Set them as close as you can and record the set values in your lab notebook as actual R_{gain} and R_{off}.

Once the resistors are set, reconnect both 5V and 3.3V supplies and turn them on. You may want to check that both are set to the correct values, matching what you have recorded.

You should now measure V_{in} and V_{out}. V_{in} should be ~0.7, and Vout should be between 2 and 3 V. If not, check your circuit for proper connections and double-check your potentiometer settings. You should also be able to heat your diode and see both V_{in} and V_{out}. Once you are satisfied your circuit is working, measure V_{in} and V_{out} at two different temperatures (one may be room temperature). Plot the line between those two points with V_{in} on the X axis. Compare that line to your target transfer function. If it is significantly different, the potentiometers may not be correctly set.

Table 4: Amplifier Verification Measurement

V_{in}	V_{out}

Completing the PCB Circuit

Once you have properly set up and are working with a breadboard circuit, you are ready to finish the breadboard circuit.

Add the three jumpers for R_{off} to the right side of the circuit.

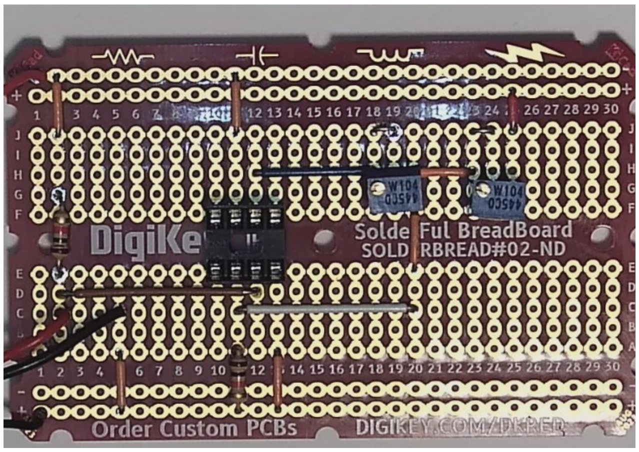

Figure 31: Soldering in R_{gain} and R_{off}

You can set the potentiometers before installing the Op Amp. You should use the same settings as you used on the breadboard.

To set R_{gain}, install your meter on pins 2 and 6. For R_{off} use pin 2 and the 3.3V supply rail.

Install a long lead to the output on Pin 6. This does not affect the circuit but will make taking our final measurements easier.

Finally, install the Op Amp in the socket, making sure the orientation is correct.

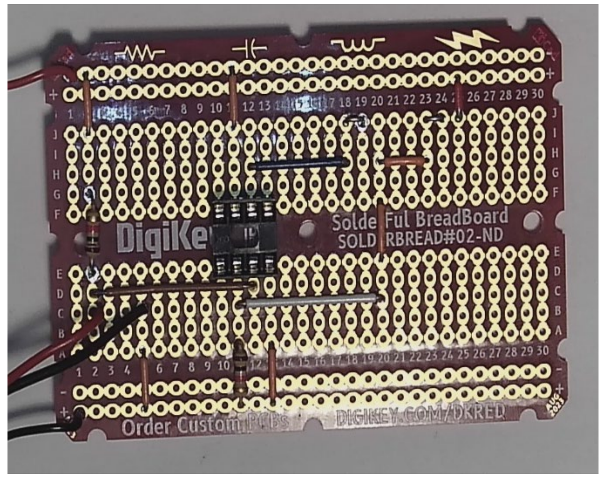

Figure 30: Jumpers for offset connection.

Solder the two potentiometers in place.

Finally, solder two long power leads to the second power and bottom power rails for the 3.3V supply.

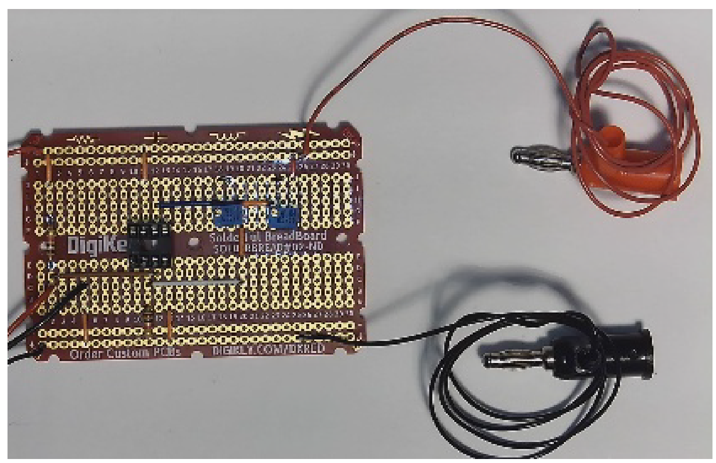

Figure 32: Connections for 3.3V Power Supply. Notice the +3.3V is on a different row from the +5V supply.

You should not have a complete circuit as shown in Figure 33. You connect power and verify the circuit is operating correctly by repeating the measurements of V_{in} and V_{out} like you just did on the breadboard circuit.

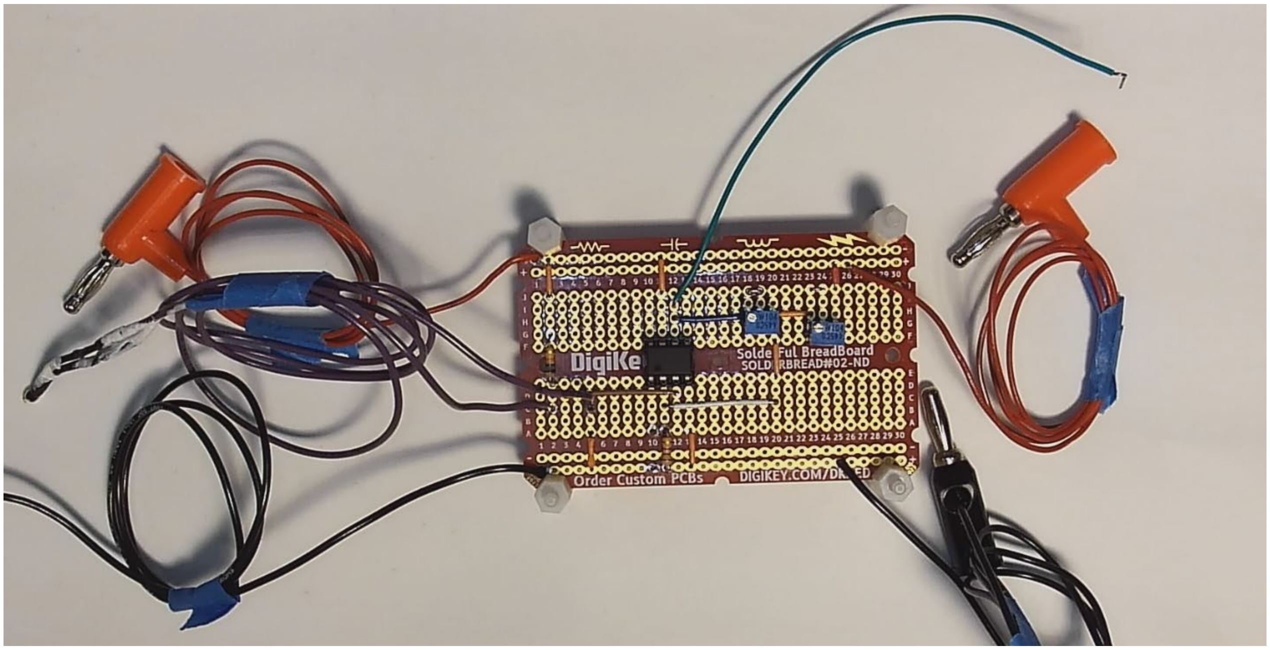

Figure 33: Complete Diode Temperature sensor circuit.

Final Calibration of the Diode Circuit

We are now ready to take final calibration measurements of our diode temperature circuit.

At a minimum of 5 temperatures between 0 and 50 °C, measure Temperature, V_{in} and V_{out}. Be sure to record photos of your water bath calibration setup for your report.

Table 5: Diode Sensor Final Calibration Points

Temperature Point	Measured Temperature (C)	V_{in}(V)	V_{out}(V)
0-10 C			
10-20 C			
20-30 C			
30-40 C			
40-50 C			

Make a plot of V_{in} (x) vs V_{out}(y) and fit a line to your data. This is the actual amplifier performance.

Next plot V_{out} (x) vs Temperature(y). Again, fit a line to this data. This is your calibration equation, it allows you to convert a voltage reading from the sensor to a Temperature in Celsius.

Changing the Temperature Range

Now, you should be able to determine what you need to set the resistors for a different temperature range. In a balloon flight, your payload will go through the coldest part of the atmosphere, called the tropopause. Temperatures there can easily go below -50 °C.

Repeat all necessary measurements to set the amplifier's gain and offset. But this time set the amplifier so that it outputs **0V at 50 °C and 5V at -50 °C.**

Then repeat the final calibration measurements to show the actual performance of the modified amplifier. You do not need to take measurements below 0°C, but you should extrapolate to show what the output would be at -50 °C.

Temperature Calibration Report Guidelines

After you have built and calibrated the diode circuit, you will write a report. The report should contain the following sections and elements.

You only need to discuss data from your soldered PCB version, not the breadboard prototype.

Introduction

Briefly (1 to 2 paragraphs each) explain how the temperature sensor works, including circuit diagrams of the circuit and photos of your breadboard and PCB circuits.

Amplifier Setting

Explain how you set the amplification. This should include(for both sensors):

- Plot of V_{in} vs Temperature showing your diodes' behavior with temperature.
- The plots used to determine your transfer function (and the values for gain and offset) for both the 0-50 °C and -50 to +50 °C amplifiers.
- Target and Actual resistor settings for potentiometers R_{gain} and R_{off} for both the 0-50 °C and -50 to +50 °C amplifiers.

Calibration Procedure

Briefly (again, 1 to 2 paragraphs) explain how you took your final calibration data for each circuit. Be sure to include how you controlled the water temperature, how you measured it, photos of your calibration setup, and any additional equipment used.

Calibration Results

Show your calibration results for both the initial 50 °C and -50 to +50 °C amplifiers.

Include your final V_{in} vs V_{out} and V_{out} vs Temperature. Be sure to include both calibration equations. Compare the actual amplifier performance with the target values you calculated for gain and offset.

References

[1] T. Instruments, "TLV271 Datasheet," [Online]. Available: https://www.ti.com/product/TLV271.