Instrumentation Amplifiers

Introduction

A common problem in engineering is how to measure a small signal in a noisy environment. One way to do this is to use an *instrumentation amplifier* - also known as a differential amplifier. For example, suppose you want to measure the electrical signals to the heart as in Figure 1. If a single sensor was used, such as sensor A and ground, pretty much all you would see is a 60Hz signal on top of a very weak heartbeat. The reason for this is the human body acts as an antenna, picking up all of the 60Hz signals running throughout a building.

To get around this problem a second sensor, B, could be used. What sensor B does is it measures the environment - namely the noise that's on top of signal A. By subtracting the two and amplifying

$$Y = k(A - B)$$

most of the noise present on sensor A is canceled. All that gets through the differential amplifier are signals that are generated *between* sensors A and B - namely the person's heart.

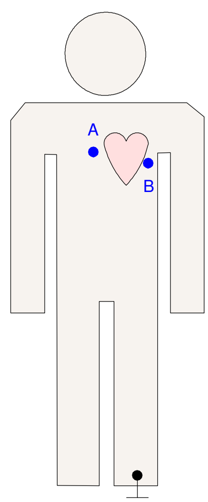

Figure 1: By amplifying the difference between sensors A and B, the common-mode noise at 60Hz can be rejected

In this lecture, three different types of instrumentation amplifiers will be presented:

- Single op-amp design,
- Two op-amp design, and
- Three op-amp design.

Finally, two applications will be presented:

- Converting resistance to -10V to +10V analog
- Converting temperature to -10V to +10V analog.

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Single Op-Amp Design

First, let's consider the single op-amp design for an instrumentation amplifier, presented in Figure 2. This is a circuit we've looked at before and has a gain of

$$Y = \left(\frac{R_1}{R_2}\right)(A - B)$$

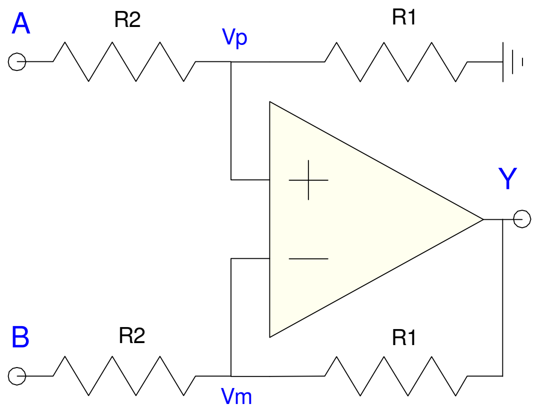

Figure 2: Single op-amp design for an instrumentation amplifier: Y = k(A - B)

This circuit has several advantages and disadvantages. On the up side,

- It requires only a single op-amp.

On the down side,

- Two resistors have to be adjusted if you want to change the gain.
- The input impedance is finite - defined by R1 and R2, and
- There is a common-mode gain if both R1's and R2's are slightly different.

To see the common-mode gain, assume the two R1's are slightly different as in Figure 3:

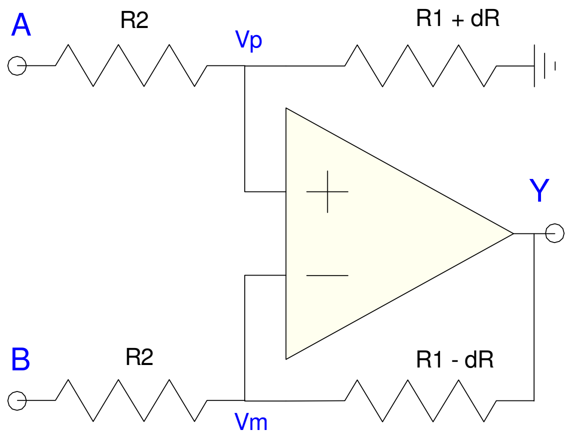

Figure 3: If the two R1's are slightly different, you get a common-mode gain

For this circuit, the output, Y, will be a function of A and B as

$$Y = \left(\frac{R_1+\delta R}{R_2}\right)A - \left(\frac{R_1-\delta R}{R_2}\right)B$$

Doing some algebra, this can be rewritten as

$$Y = \left(\frac{R_1}{R_2}\right)(A-B) + \left(\frac{\delta R}{R_2}\right)(A+B)$$

The fist term is the differential signal - the thing you want. The second term is the common-mode signal. This is the large noise signal and what you are trying to get rid of.

Most of the examples used in this course use this design.

Two Op-Amp Instrumentation Amplifier

An improved instrumentation amplifier design is presented in Figure 4. This circuit is what is implemented in the AMP04 instrumentation amplifier (costing $19 per amplifier). You can also build it using two independent op-amps ($0.14 using an LM358).

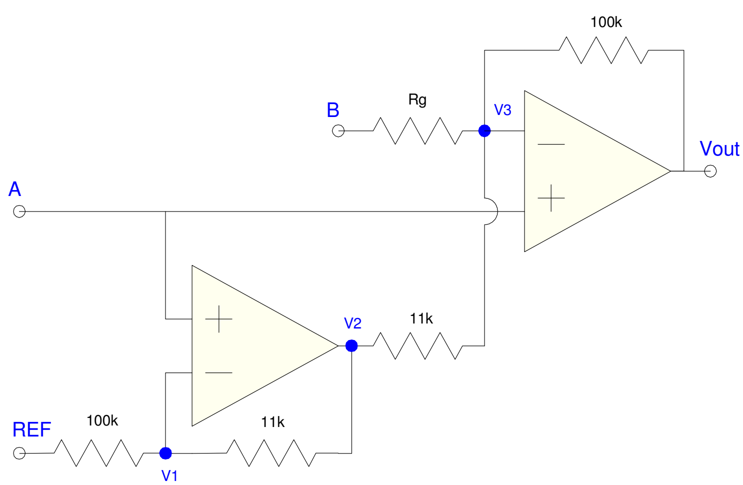

Figure 4: Two op-amp instrumentation amplifier (AMP04).

There are four voltage nodes. Hence, four equations are needed to solve for the four voltages. Start with the easy ones. Since Vm = Vp

$$V_1 = A$$

$$V_3 = A$$

For the last two equations, write the voltage node equation at node V1 and V3

$$\left(\frac{V_1-V_{ref}}{100k}\right) + \left(\frac{V_1-V_2}{11k}\right) = 0$$

$$\left(\frac{V_3-V_2}{11k}\right) + \left(\frac{V_3-B}{R_g}\right) + \left(\frac{V_3-V_{out}}{100k}\right) = 0$$

After a lot of algebra, this simplifies to

$$V_{out} = \left(\frac{100k\Omega}{R_g}\right)(A - B) + V_{ref}$$

This circuit has several advantages over the single op-amp design

- The gain is set by only one resistor, Rg
- The input impedance for A is large. Add a buffer op-amp and the input impedance for B can be large as well.
- The output can be offset by Vref. This is useful when using a single power supply: instead of clipping when a voltage goes negative, it can be offset allowing plus and minus swings.

Example: CdS Light Sensor

Assume a CdS light sensor is used to detect a signal riding on a laser beam. Assume the resistance varies about 2000 Ohms as

$$R = 2000 + 100 \cdot \sin(\omega t)\Omega$$

Design a circuit which outputs a

- 2Vpp sine wave, with a
- 4.5V DC offset.

Solution: The circuit in Figure 12 can do this

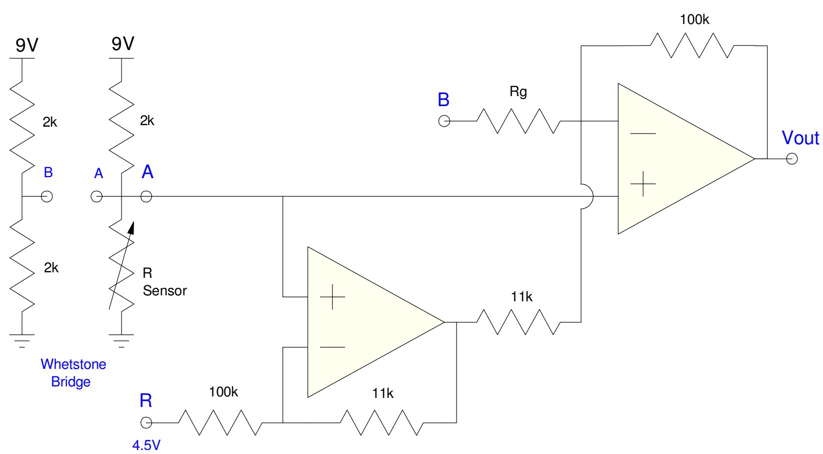

Figure 5: Two op-amp instrumentation amplifier outputs a 2Vpp sine wave riding on top of a 4.5V DC offset

First convert resistance to voltage using a voltage divider. Assuming a 2k resistor

$$V_a = \left(\frac{R}{R+2000}\right)9V$$

Next, remove the 2000 Ohm DC offset from A by mirroring the nominal circuit, generating voltage B.

Third, use an instrumentation amplifier to amplify (A-B).

- Send the signal from A to the plus input, and
- Send the signal from B to the minus input.

Fourth, determine the gain needed. The maximum voltage seen at A is

$$\max(A) = \left(\frac{2100\Omega}{2100\Omega+2000\Omega}\right)9V = 4.6098V$$

The minimum voltage at A is

$$\min(A) = \left(\frac{1900\Omega}{1900\Omega+2000\Omega}\right)9V = 4.3846V$$

The spread at A is

$$A_{pp} = \max(A) - \min(A) = 225.1mV_{pp}$$

The output should be 2Vpp. Hence, the gain required is

$$gain = \left(\frac{\text{output}}{\text{input}}\right) = \left(\frac{2V_{pp}}{225.1mV_{pp}}\right) = 8.8833$$

Rg sets the gain as

$$gain = \left(\frac{100k}{R_g}\right) = 8.8833$$

giving

$$R_g = 11.257k\Omega$$

Finally, to offset Y by 4.5V, apply 4.5V to Ref. This gives the circuit of Figure 5.

Three Op-Amp Instrumentation Amplifier

Finally, there is the three op-amp instrumentation amplifier as presented in Figure 6

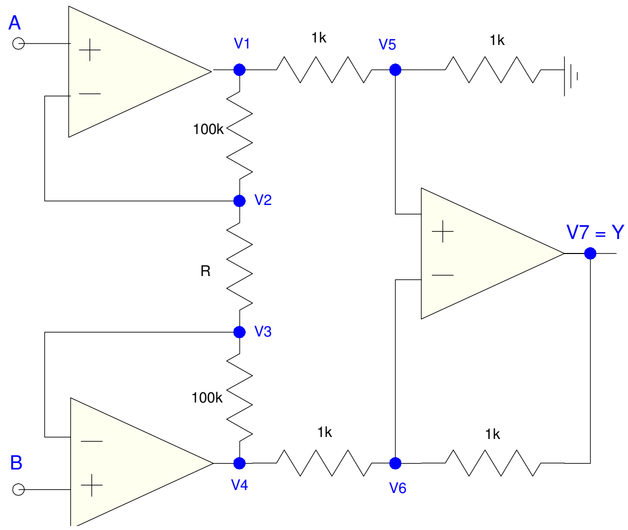

Figure 6: Three op-amp instrumentation amplifier

Calculations: There are seven voltage nodes. Hence you need seven equations for seven unknowns. Starting with the easy ones:

Vp = Vm

$$V_2 = A$$

$$V_3 = B$$

$$V_5 = V_6$$

For the last four equations, write the voltage node equations at V2, V3, V5, and V6

$$\left(\frac{V_2 - V_1}{100k}\right) + \left(\frac{V_2 - V_3}{R}\right) = 0$$

$$\left(\frac{V_3 - V_2}{R}\right) + \left(\frac{V_3 - V_4}{100k}\right) = 0$$

$$\left(\frac{V_5 - V_1}{1k}\right) + \left(\frac{V_5}{1k}\right) = 0$$

$$\left(\frac{V_6 - V_4}{1k}\right) + \left(\frac{V_6 - V_7}{1k}\right) = 0$$

After a lot of algebra, this results in

$$Y = \left(1 + \frac{200k}{R}\right)(A - B)$$

This circuit also has some advantages:

- A single resistor sets the gain,
- The input impedances for both A and B are large
- If placed on a single IC, the resistors can be matched, keeping the common-mode gain small.

Instrumentation Amplifier Applications

Using instrumentation amplifiers, several circuits can be designed fairly easily.

Voltage Amplification

Design a circuit which converts 0V..5V to -10V..+10V

Input:

- X is a 0V to 5V analog voltage

Output

- Y is an analog voltage that swings from -10V when X=0 to +10V when X=5

Solution: The relationship between X and Y is

$$Y = 4X - 10$$

Rewrite this as

$$Y = 4(X - 2.5)$$

and you can use the single op-amp instrumentation amplifier, where the output is

$$Y = \left(\frac{R_1}{R_2}\right)(A - B)$$

Matching terms

$$\frac{R_1}{R_2} = 4$$

$$A = X$$

$$B = 2.5V$$

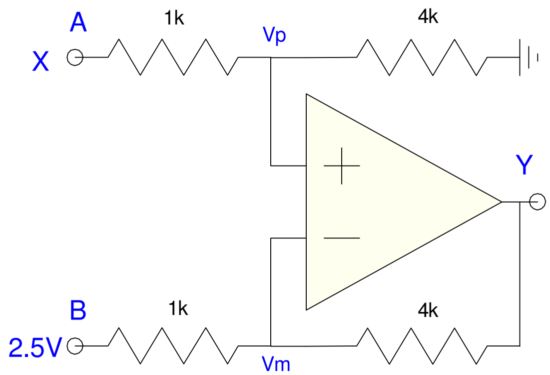

Figure 7: Circuit to convert 0.5V to -10..+10V

Ohmmeter

Assume you want to measure a resistor which varies from 2000 Ohms to 2200 Ohms. Design a circuit which outputs

- -10V when R = 2000 Ohms,
- +10V when R = 2200 Ohms, and
- The output is proportional to R in between 2000 and 2200 Ohms

Solution: First, convert resistance to a voltage. Use a voltage divide with a 2100 Ohm resistor as shown in Figure 8. At R = 2000 and 2200 Ohms, Vx is

$$V_x = \left(\frac{2000}{2000+2100}\right)10V = 4.878V$$

$$V_x = \left(\frac{2200}{2200+2100}\right)10V = 5.116V$$

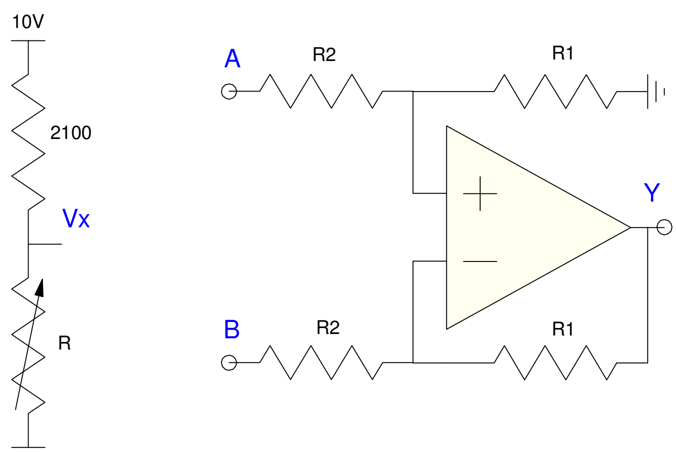

Figure 8: Y varies from -10V when R=2000 to +20V when R=2200 Ohms

Note that Vx goes up as Y goes up. Connect Vx to the plus input.

The gain required is

$$gain = \left(\frac{\text{change in output}}{\text{change in input}}\right) = \left(\frac{10V-(-10V)}{5.116V-4.878V}\right) = 83.95$$

The output should be 0V (midband) when the input is midband, Hence, set the offset to

$$V_b = \left(\frac{4.878V+5.116V}{2}\right) = 4.997V$$

The final design is given in Figure 9

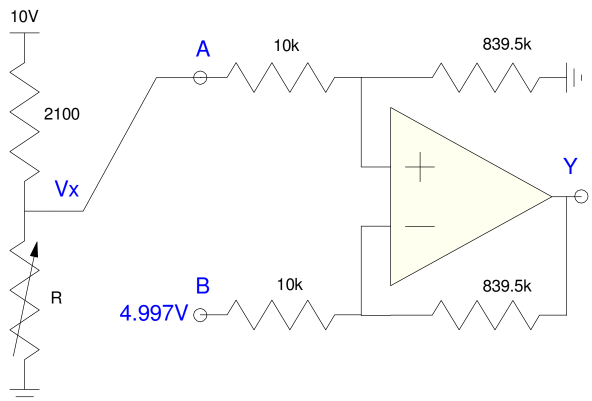

Figure 9: Circuit to convert 2000 - 2200 Ohms to -10V to +10V

In CircuitLab, you can verify this design by sweeping R from 2000 to 2200 Ohms. First, input the circuit into CircuitLab

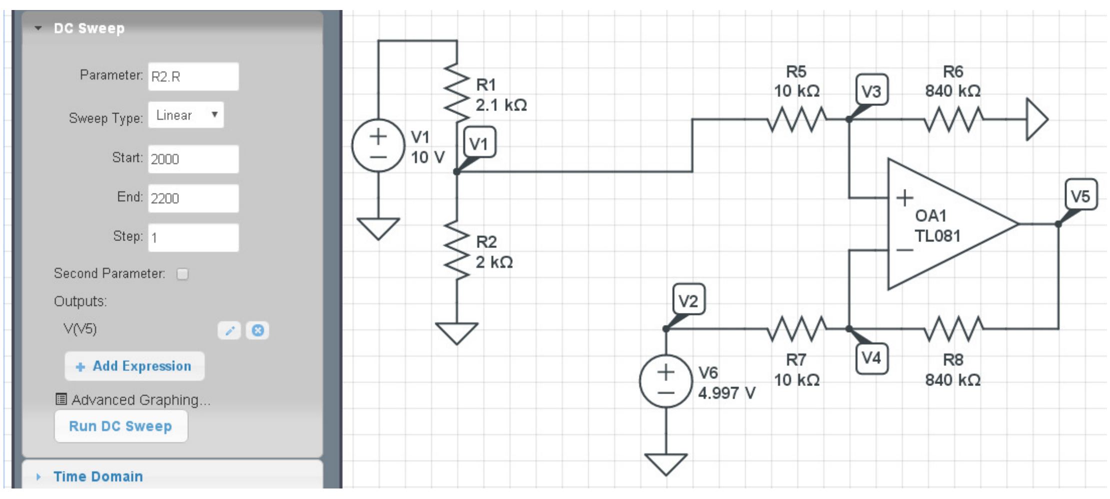

Figure 10: Verifying the circuit using CircuitLab

This results in the output (V5) sweeping from -10V to +10V as shown in Figure 11.

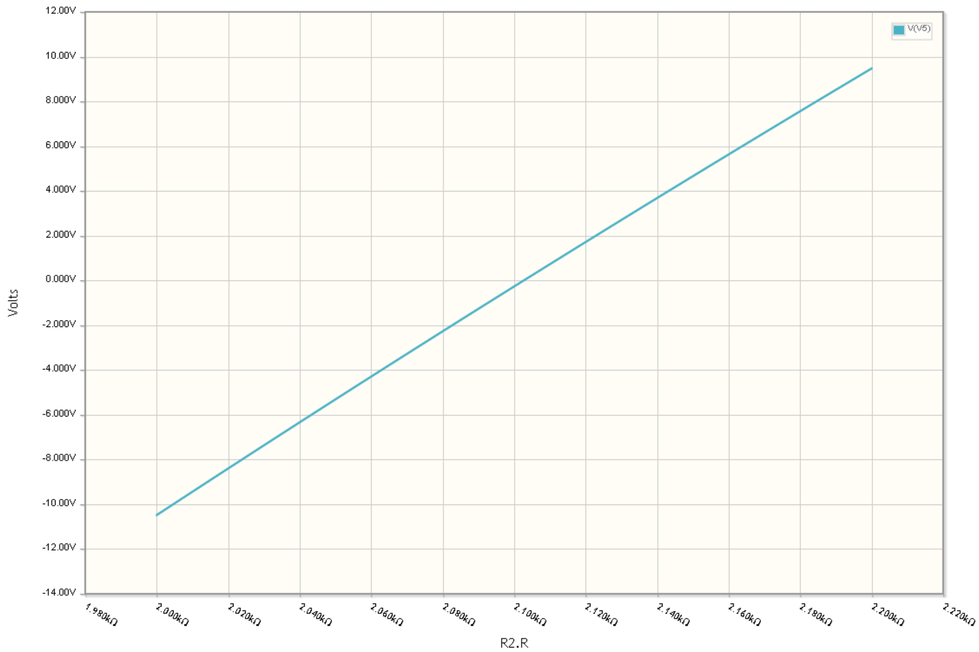

Figure 11: The output swings from -10V to +10V as R varies from 2000 to 2200 Ohms.

Thermometer

Finally, design a circuit with outputs

- 0V at 0V and
- +10V at +40C

Assume you're using a thermistor where the resistance varies with temperature

$$R \approx 1000\ \exp\left(\frac{3905}{T+273} - \frac{3905}{298}\right)\ \Omega$$

where T is the temperature in degrees C. At the endpoints

- R = 3320.125 Ohms @ 0C
- R = 533.664 Ohms @ 40C

Like before, use a voltage divider to convert resistance to voltage. Assuming a 1k resistor, the voltages become

- Vx = 7.6853V @ 0C
- Vx = 3.4797V @ 40C

Note that as temperature goes up

- Y goes up (0V to +10V), and
- Vx goes down (7.68V to 3.47V).

Connect to the minus input to get this negative correlation.

The output should be 0V when Vx is 7.6853V. Make the offset 7.6853V.

The gain required is

$$gain = \left(\frac{10V - 0V}{3.4797V - 7.6853V}\right) = -2.3778$$

The negative sign is already taken into account by connecting to the minus input. To get a gain of 2.3778, make the resistor ratio 2.3778.

The final design is shown in Figure 12

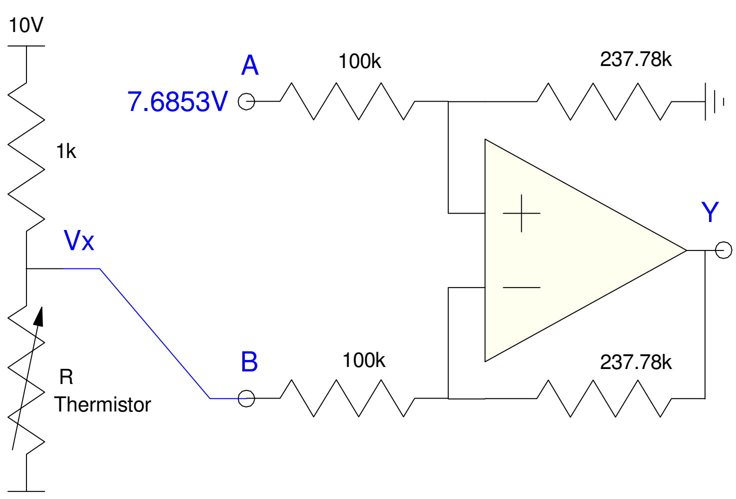

Figure 12: Y goes from 0V @ 0C to +10V @ +40C

In Matlab, you can check this design:

```
T = [0:0.2:40]';
R = 1000*exp(3905./(T+273)-  3905/298);
Va = R ./ (1000 + R) * 10;
Y = 2.3778 * (7.6853 - Va);
plot(T,Y);
```

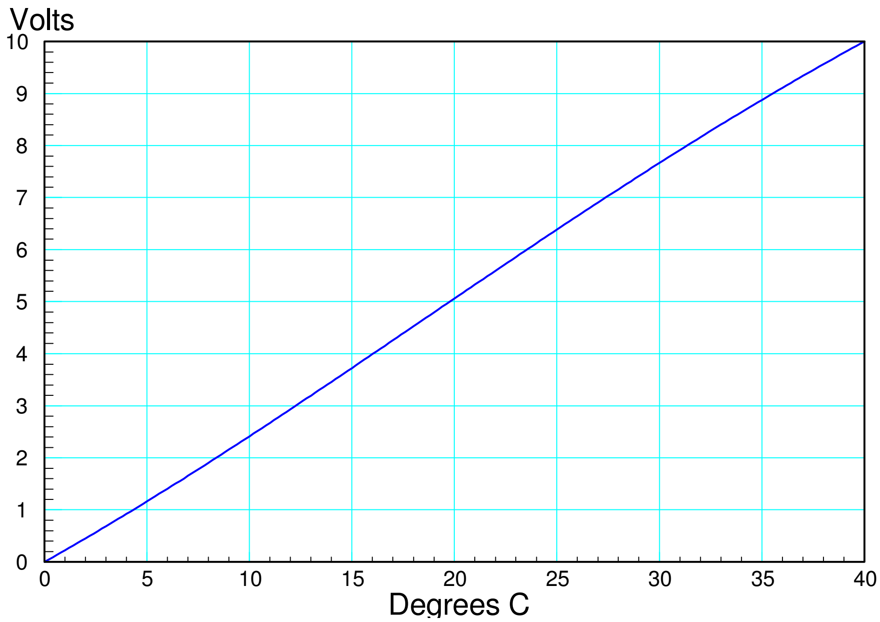

Figure 13: Resulting temperature vs. voltage relationship

Note that

- The voltage varies with temperature and
- The relationship isn't *quite* linear

The nonlinear relationship results from

- Voltage division being nonlinear and
- The thermistor equation is nonlinear.

The former is a convex function whereas the latter is a concave function. The two *almost* cancel, but not quite.

Using CircuitLab, you can also check this design. CircuitLab doesn't have thermistors. Instead, just use a resistor, R2, to simulate the thermistor

- The left endpoint (0C or R2 = 3320.125 Ohms)
- The midpoint (20C or R2 = 1250.593 Ohms)
- The right endpoint (40C or R2 = 533.664 Ohms)

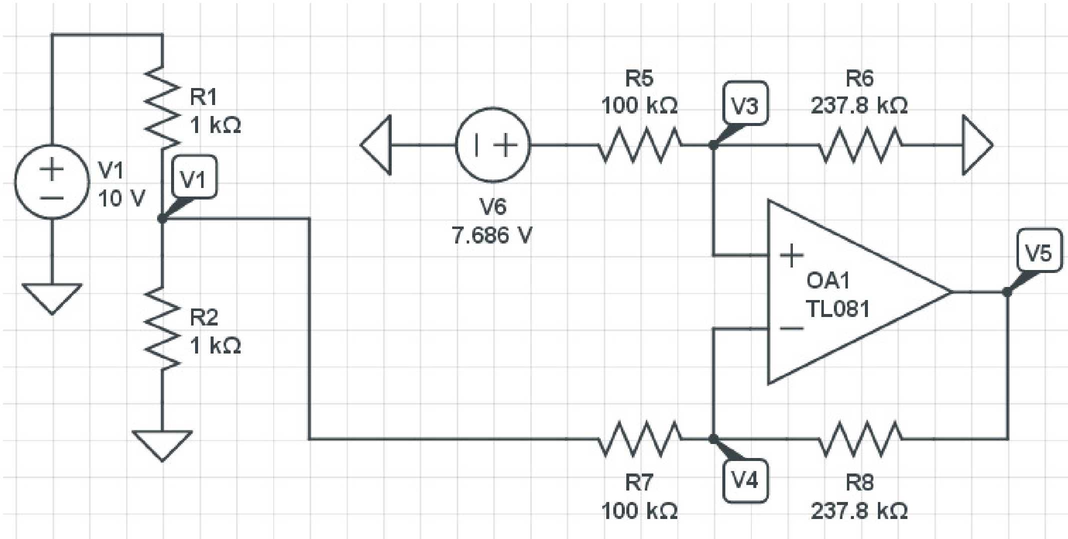

Figure 13: Simulate the changes with temperature by varying R2

Running a DC simulation, the voltages at different temperatures can be found with CirucuitLab

V(V1)	7.668 V
V(V3)	5.410 V
V(V4)	5.410 V
V(V5)	42.32 mV

Figure 14: Output (V5) at 0C = 0.04232V (0V ideally)

V(V1)	5.556 V
V(V3)	5.410 V
V(V4)	5.410 V
V(V5)	5.064 V

Figure 15: Output (V5) at +20C = 5.064V (5.000V ideally)

V(V1)	3.486 V
V(V3)	5.410 V
V(V4)	5.410 V
V(V5)	9.985 V

Output (V5) at +40C = 9.985V (10.000V ideally)

Summary

Instrumentation amplifiers are differential amplifiers

$$Y = k(A - B)$$

Several variations exist

- More op-amps generally give better designs
- Single op-amp version is usually used in Circuits

With an instrumentation amplifier, you can

- Implement y = ax + b
- Output -10V to +10V as a resistor varies
- Output -10V to +10V as temperature varies