Instrumentation Amplifiers

ECE 211 Circuits I

Lecture #16

Please visit Bison Academy for corresponding lecture notes, homework sets, and solutions

Instrumentation Amplifiers

A very common type of op-amp amplifier is an instrumentation amplifier

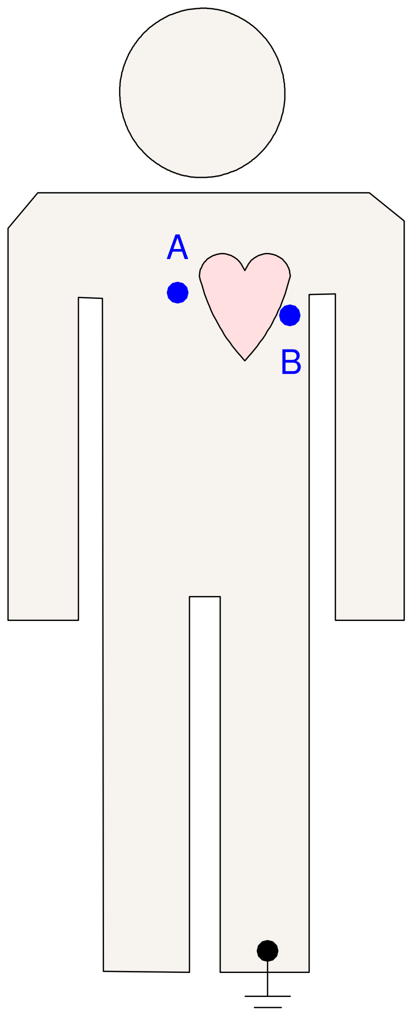
- Also known as a *differential amplifier*

The output is a gain time the difference between two voltages

$$Y = k(V_a - V_b)$$

This lets you...

- Remove 60Hz noise from a signal
  - *Both Va and Vb are corrupted by 60Hz noise*
- Measure EKG signals (heartbeats)
  - *Amplify only signal created between A and B*
- Measure a fetus's heartbeat
  - *Both Va and Vb are corrupted by the mother's heartbeat*
-



This Lecture

This lecture will cover three types of instrumentation amplifiers

- Single op-amp design
- Two op-amp design
- Three op-amp design

Using an instrumentation amplifier to measure temperature

- 0V @ 0C
- 5V @ 50C

Single Op-Amp Design

Covered previously

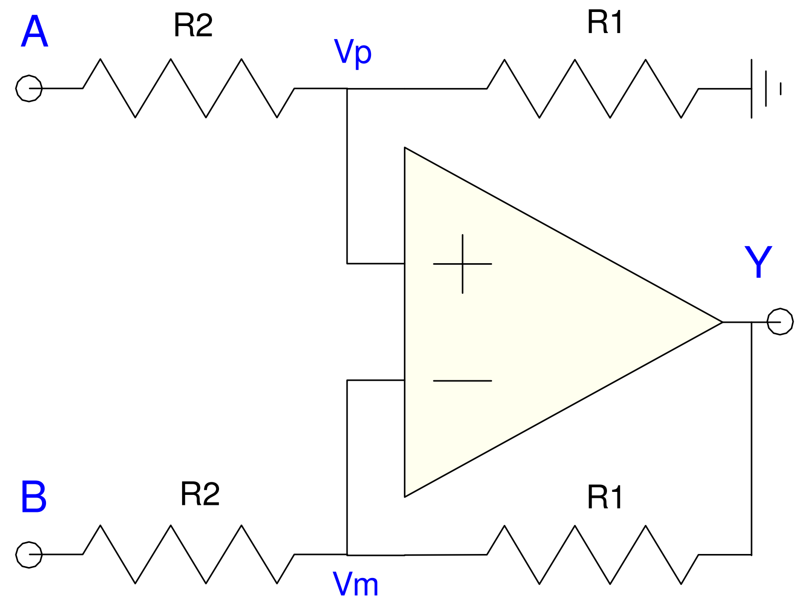
$$Y = \left(\frac{R_1}{R_2}\right)(A - B)$$

Advantages

- Simple design
- Only one op-amp

Disadvantages

- Need to change two resistors to adjust gain
- Common-mode gain if R's are different
- Loading on A and B



Common-Mode Gain

Assume R1's are slightly different

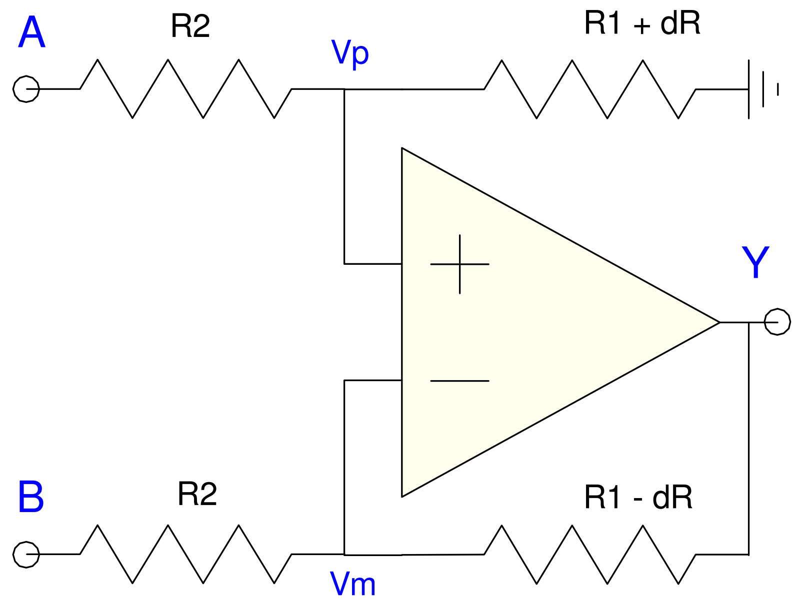
The overall gain is

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

Doing some algebra

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

The common-mode (A+B) gets through to the output



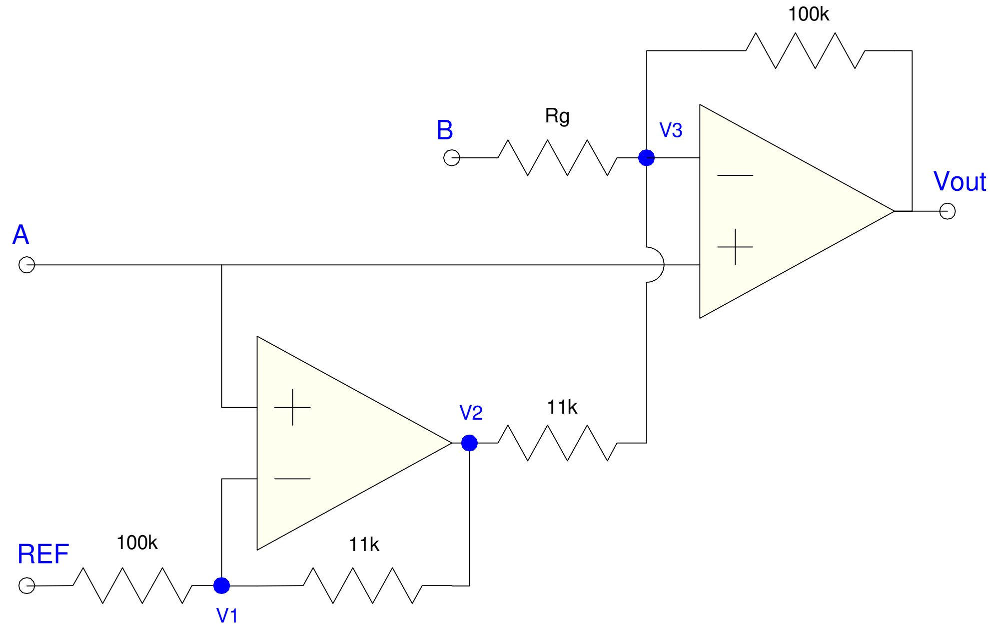
Two Op-Amp Design

- AMP04 op-amp ($19 ea)
- $0.12 if built using LM358 op-amps

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

Advantage

- Single resistor (Rg) adjusts gain
- 100dB Common Mode Rejection Ratio
- 4GΩ Input Impedance
  - *Buffers at inputs not shown*
- Output can be offset by REF
  - *Allows you to offset the output by 2.5V*



Calculations

Vp = Vm

$$V_1 = A$$

$$V_3 = A$$

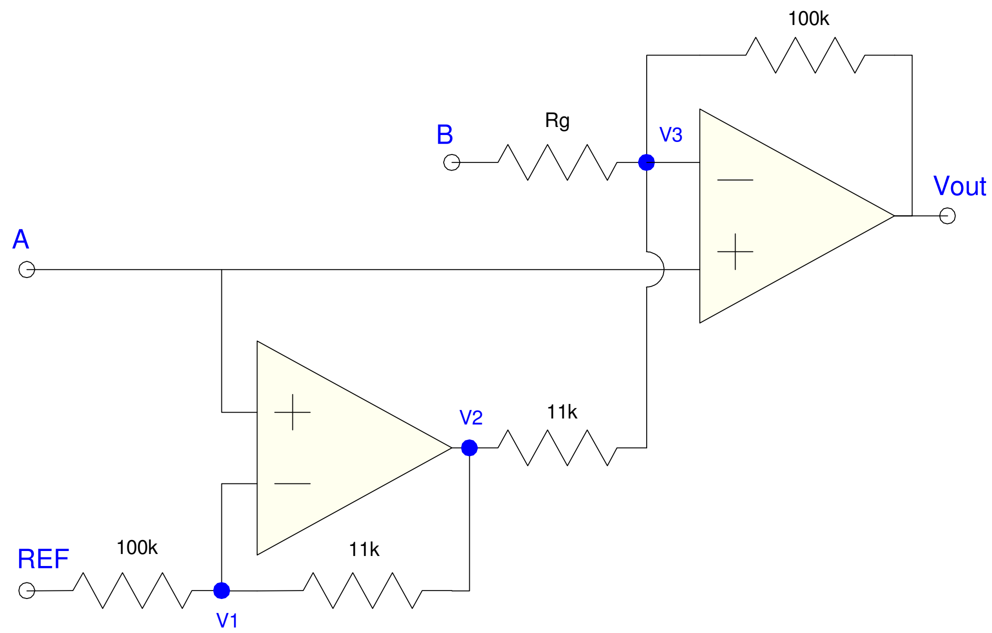
Voltage Node Equations

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

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

lots of algebra...

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



Calculations

$$V_{out} = aA + bB + rR$$

Let A=1, B=R=0

$$V_3 = V_1 = 1$$

$$V_2 = 1 + \left(\frac{11k}{100k}\right)$$

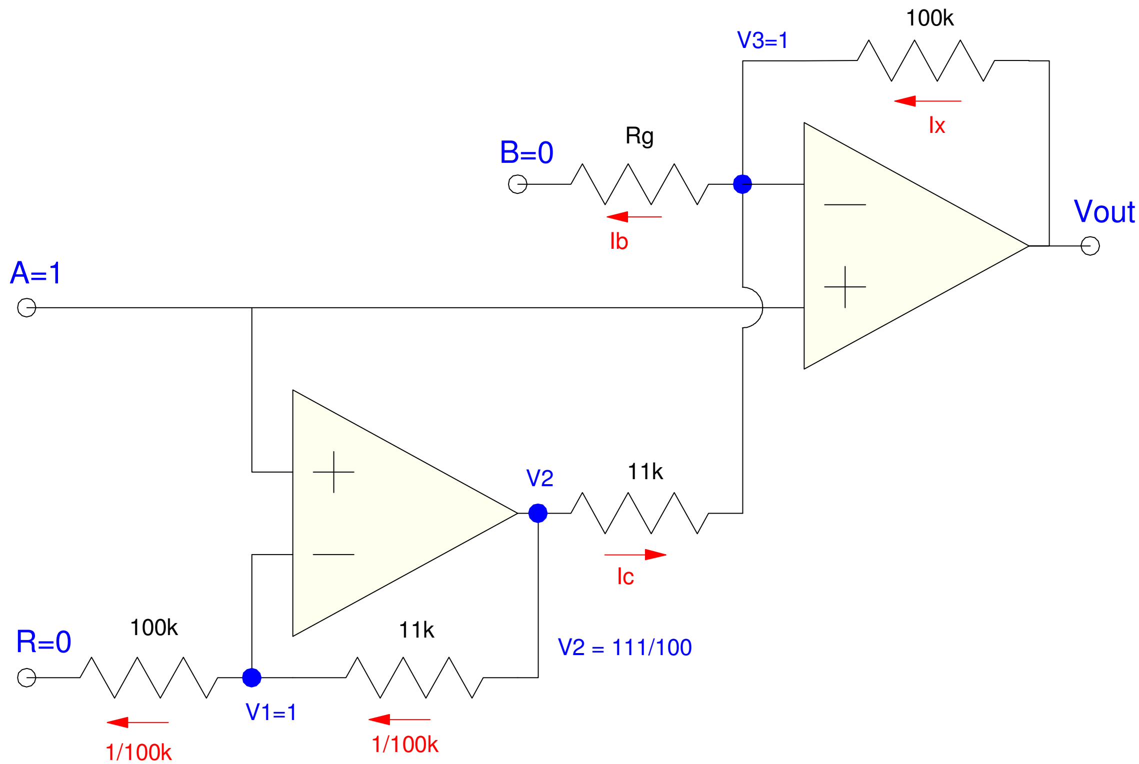
$$I_b = \left(\frac{1}{R_g}\right)$$

$$I_c = \left(\frac{1+\frac{11k}{100k}-1}{11k}\right) = \frac{1}{100k}$$

$$I_x = I_b - I_c$$

$$V_{out} = 1 + 100k \cdot I_x$$

$$V_{out} = \left(\frac{100k}{R_g}\right) = a$$



Calculations

$$V_{out} = aA + bB + rR$$

Let

- A = 0
- B = 1
- R = 0

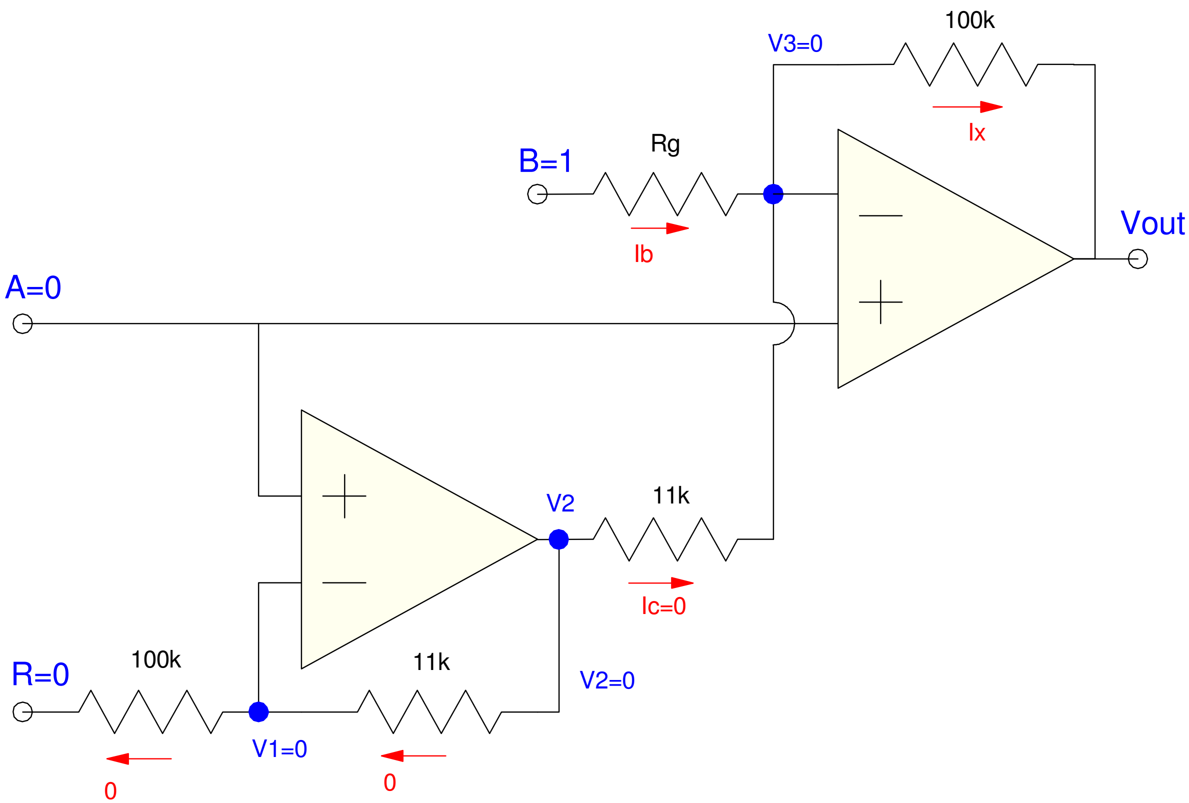
Then

$$I_b = \left(\frac{1}{R_g}\right)$$

$$I_x = I_b$$

$$V_{out} = -100k \cdot I_x$$

$$V_{out} = -\left(\frac{100k}{R_g}\right) = b$$



Calculations

$$V_{out} = aA + bB + rR$$

Let

- $A = B = 0$
- $R = 1$

Then

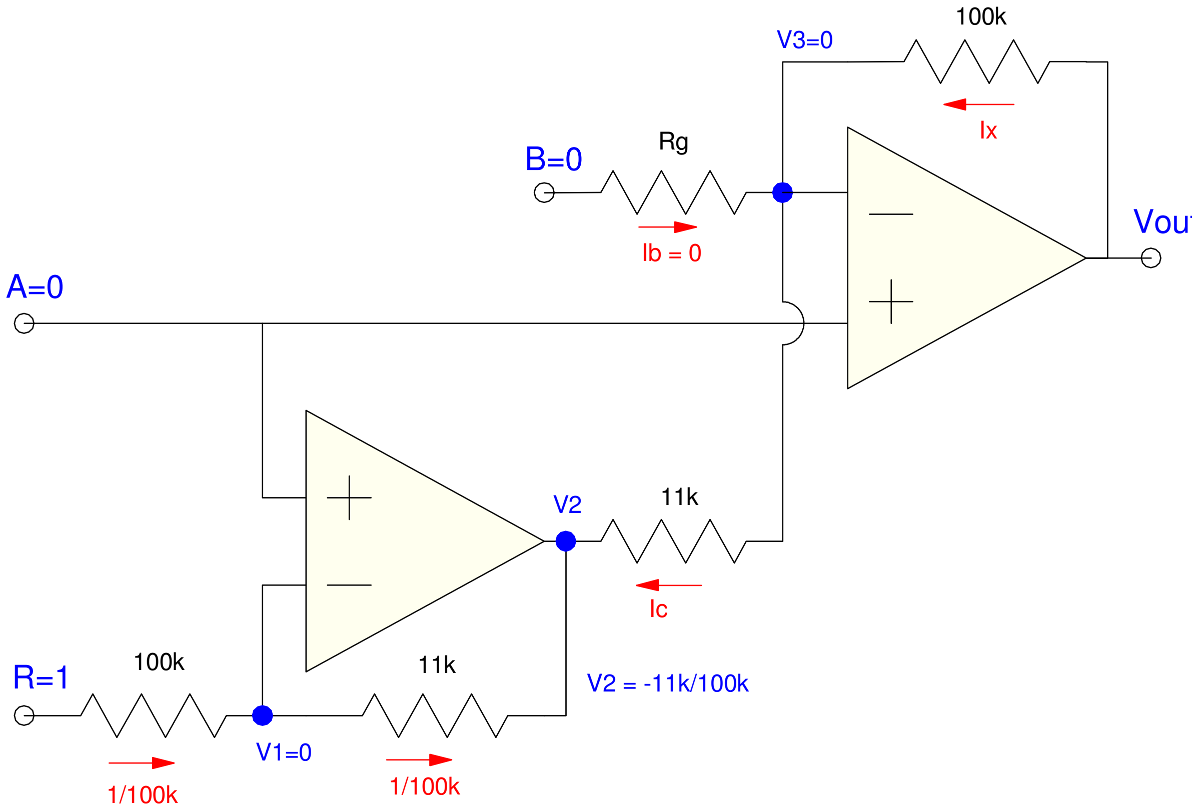
$$V_2 = -\left(\frac{11k}{100k}\right)$$

$$I_c = \left(\frac{0 - V_2}{11k}\right) = \left(\frac{1}{100k}\right)$$

$$I_x = I_c$$

$$V_{out} = 100k \cdot I_x$$

$$V_{out} = 1 = r$$



Example

A CdS light sensor is used to measure changing light levels.

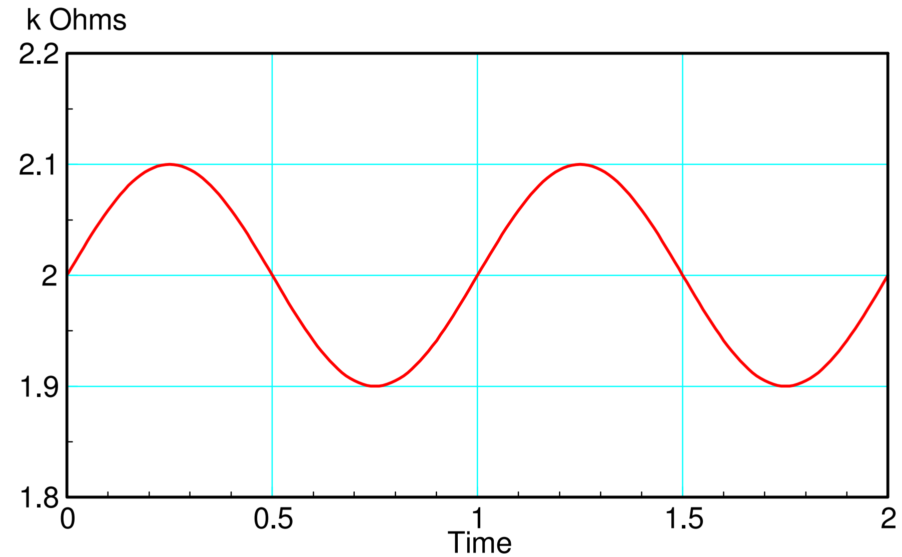
The resistance varies as

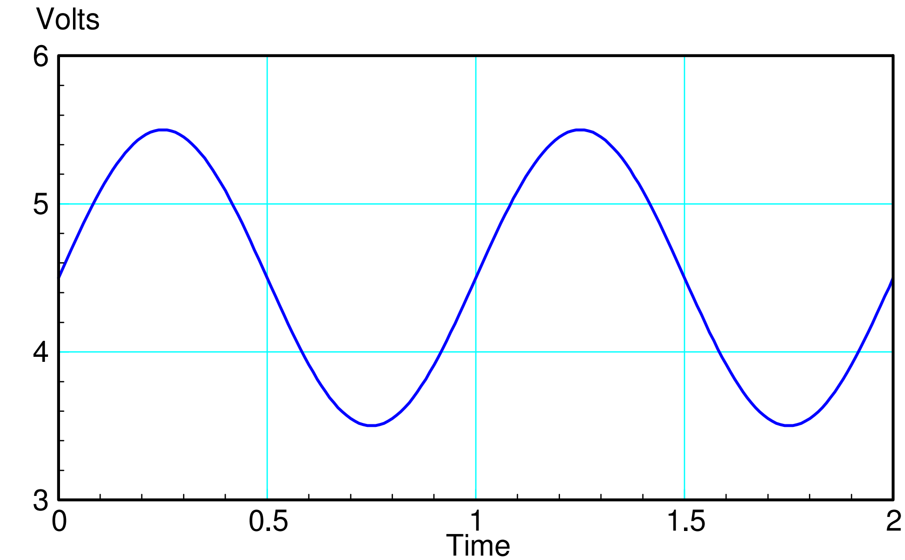
$$R = 2000 + 100 \cdot \sin(\omega t)\Omega$$

Design a circuit which outputs a

- 2Vpp signal
- Offset by 4.5V

so that you can use a single 9V supply





Solution

Convert R to V using a voltage divider

Assume a 2k resistor

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

Va has a spread of 0.2251Vpp

Vout has a spread of 2Vpp

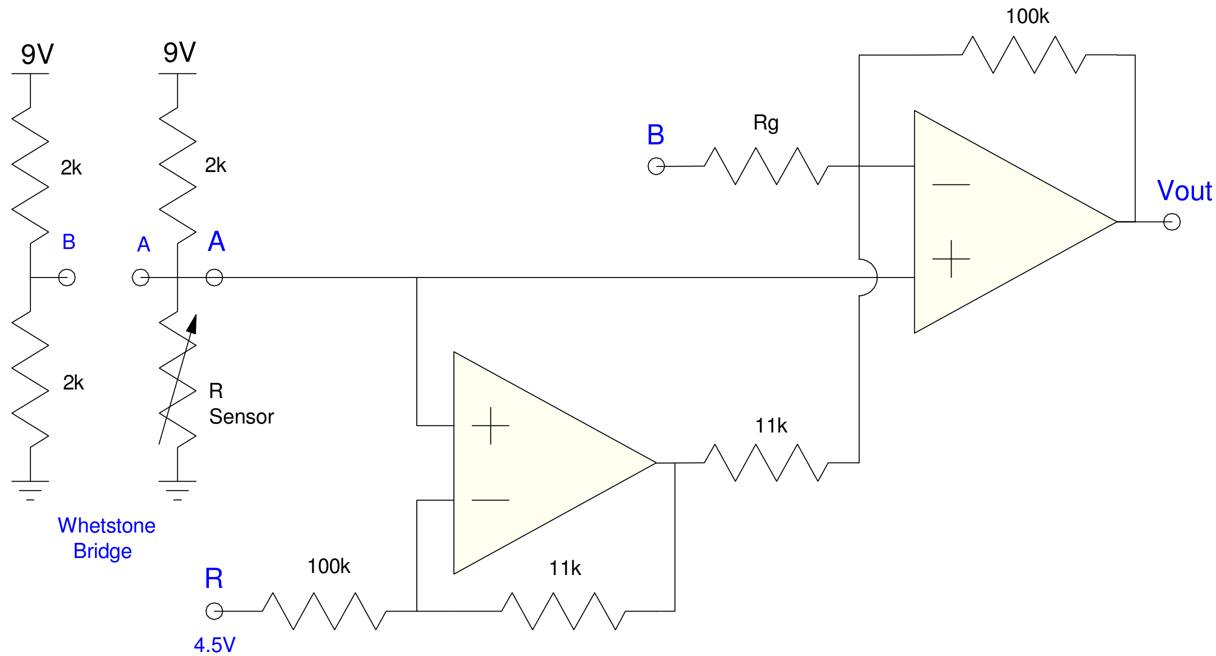
The gain needed is

$$gain = \left(\frac{2V_{pp}}{0.2251V_{pp}}\right) = 8.8833$$

Rg is then

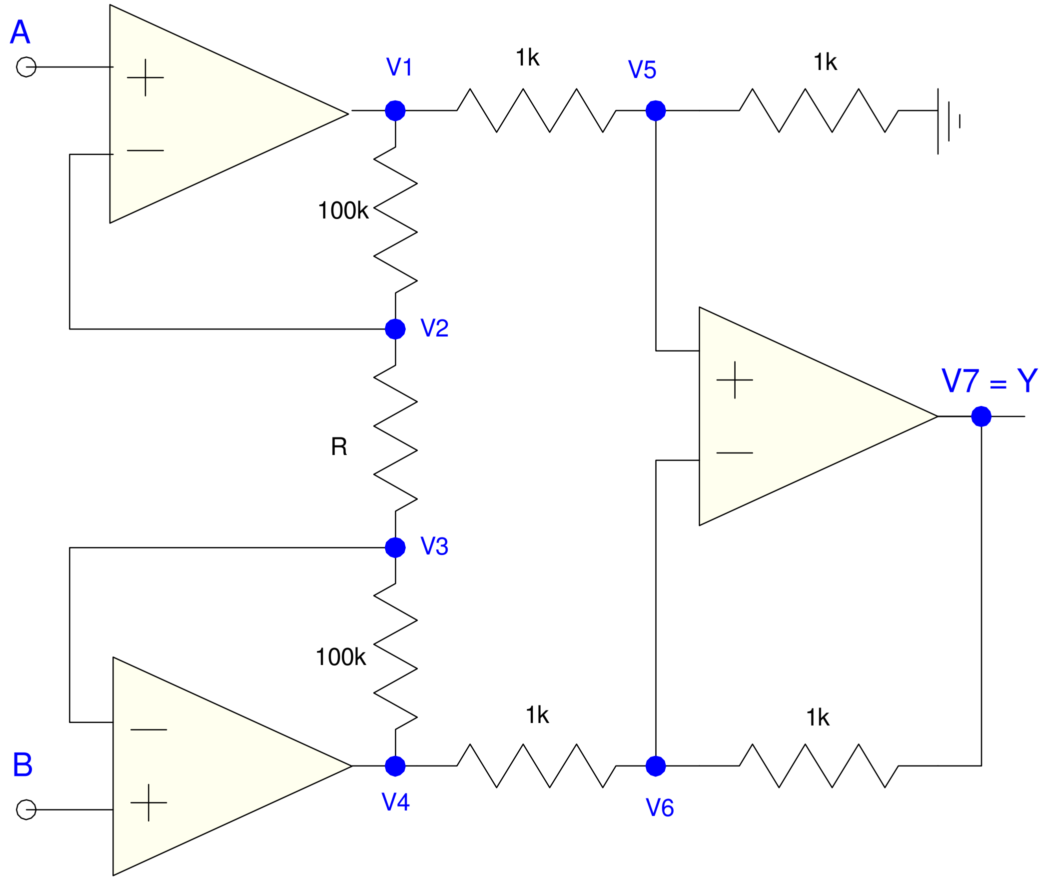
$$gain = \left(\frac{100k}{R_g}\right) \Rightarrow R_g = 11.257k$$

For a 4.5V offset, Ref = 4.5V



Three Op-Amp Design

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



Advantages

- Single resistor adjusts gain
- High input impedance

Calculations

Vp = Vm

$$V_2 = A$$

$$V_3 = B$$

$$V_5 = V_6$$

Node equations

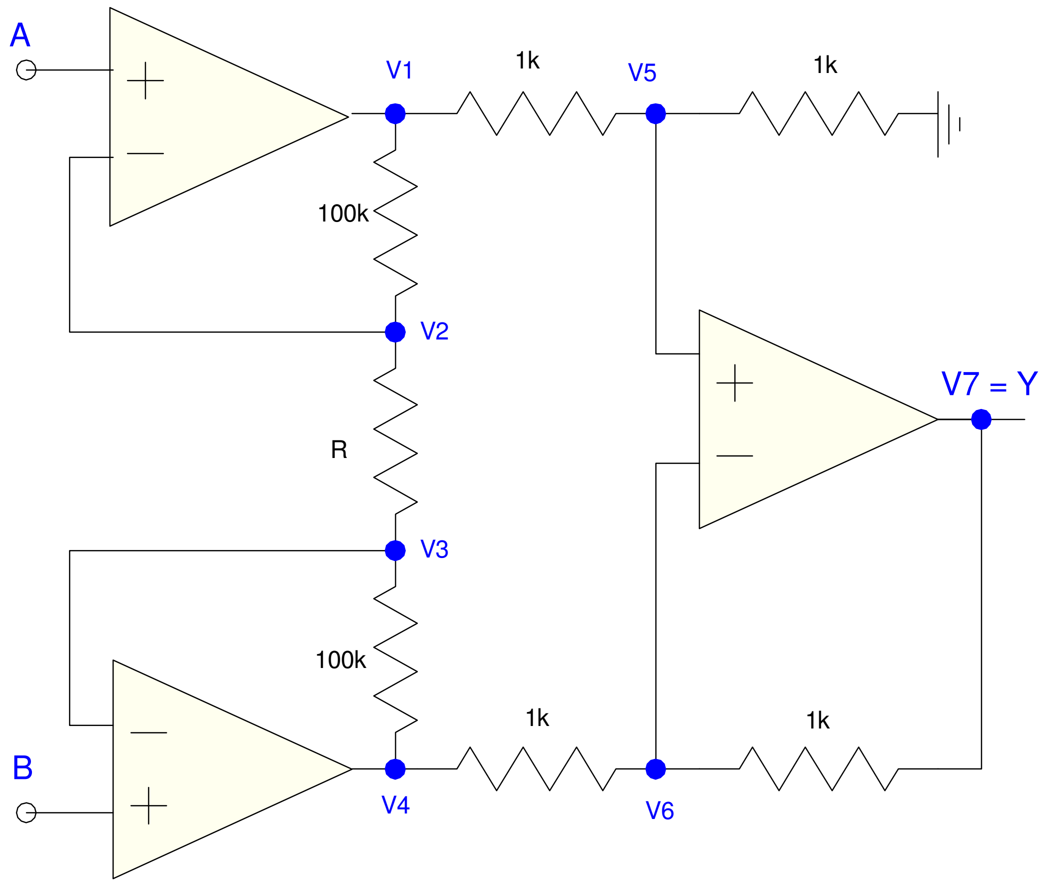
$$\left(\frac{V_2 - V_1}{100k}\right) + \left(\frac{V_2 - V_3}{R}\right) = 0$$

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

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

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

Solve....



Calculations

- Take 2
- Let B = 0

$$V_1 = \left(1 + \frac{100k}{R}\right)A$$

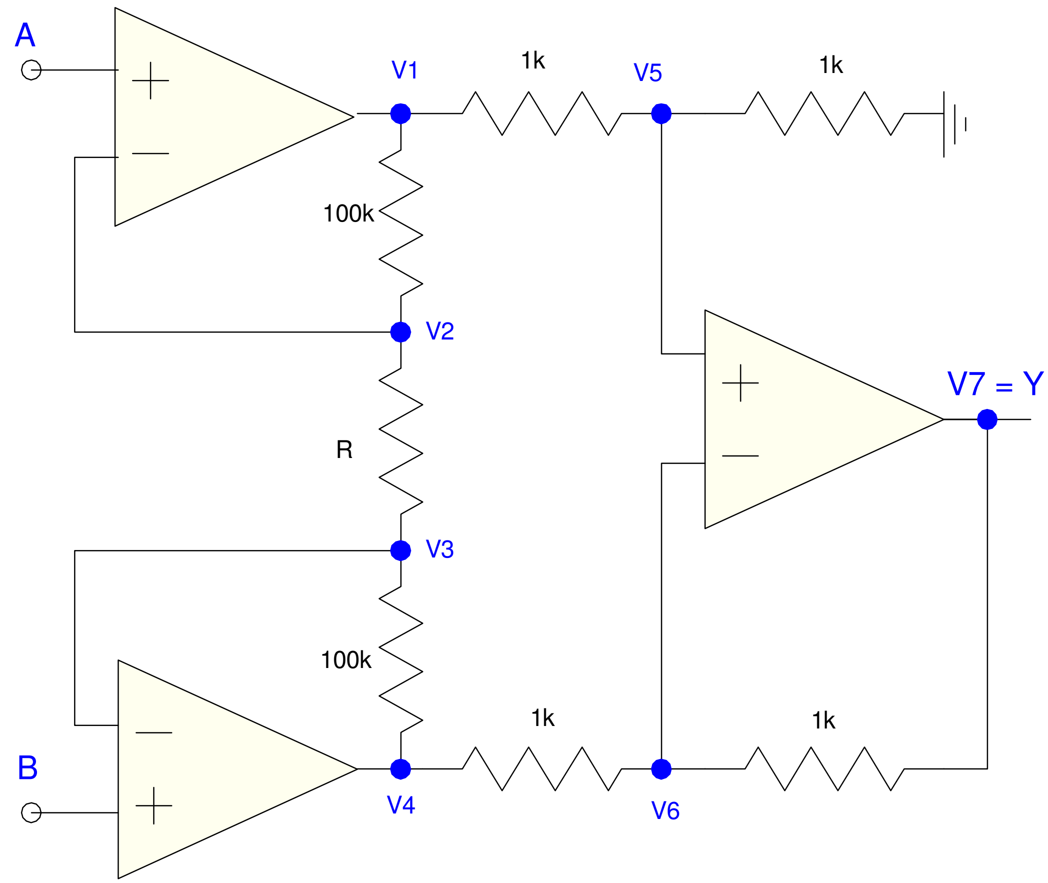
$$V_4 = -\left(\frac{100k}{R}\right)A$$

Observe that the right op-amp is a differential amplifier

$$V_7 = (V_1 - V_4)$$

Then

$$V_7 = \left(1 + \frac{200k}{R}\right)A$$



Calculations

- Take 2
- Let A = 0

$$V_4 = \left(1 + \frac{100k}{R}\right) B$$

$$V_1 = -\left(\frac{100k}{R}\right) B$$

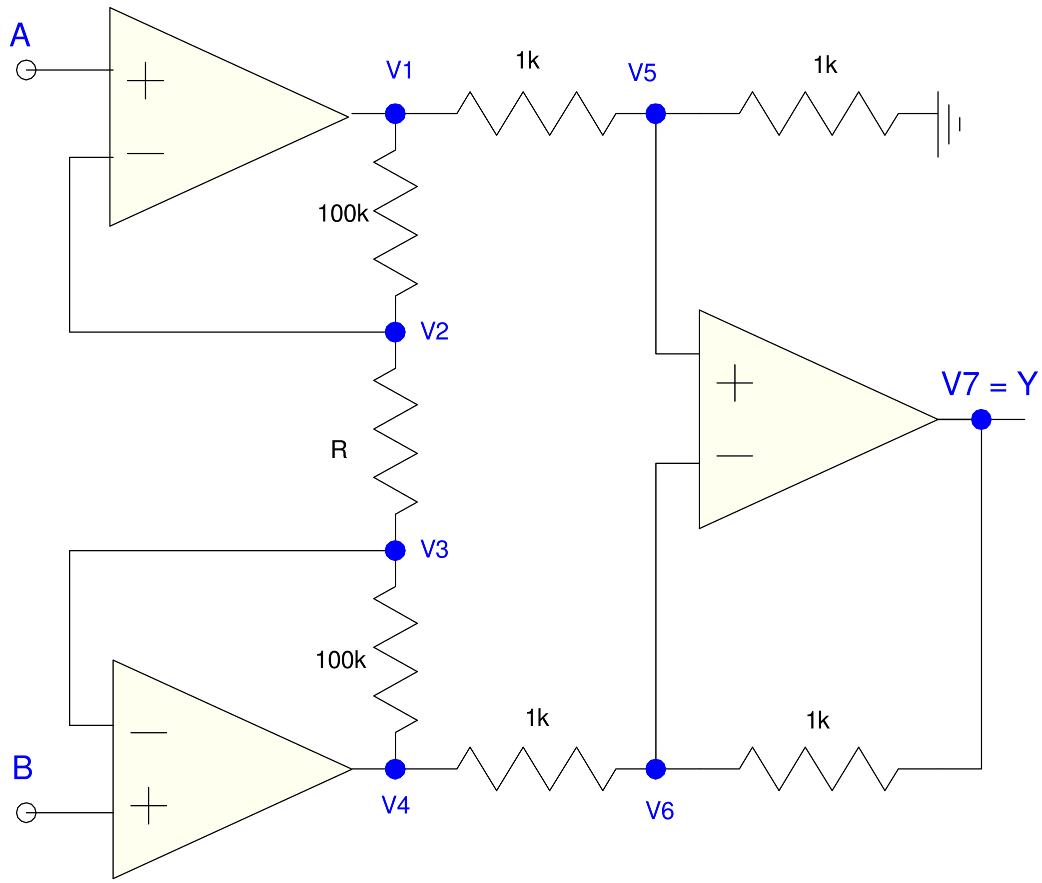
V7 is an instrumentation amplifier

$$V_7 = (V_1 - V_4)$$

$$V_7 = -\left(1 + \frac{200k}{R}\right) B$$

Together

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



Applications

Case 1: Voltage Amplification

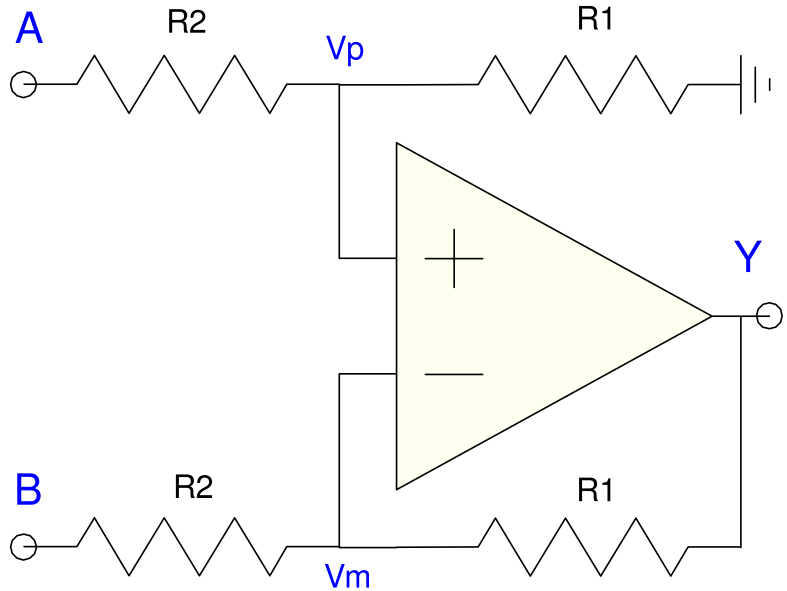
Design a circuit to convert 0..5V to -10V..+10V

Input

- X = 0..5V analog voltage

Output

- Y = -10V .. +10V analog voltage



Solution

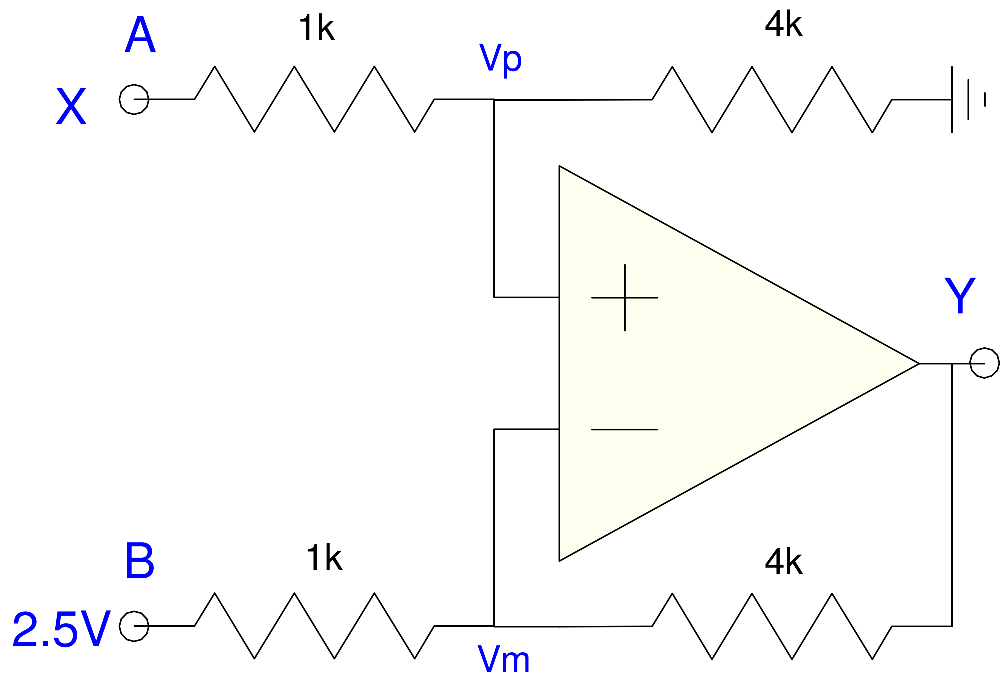
Express y = f(x)

$$y = 4x - 10$$

Rewrite as

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

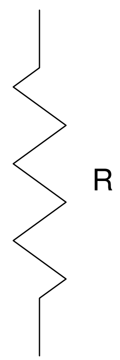
$$y = 4(x - 2.5)$$

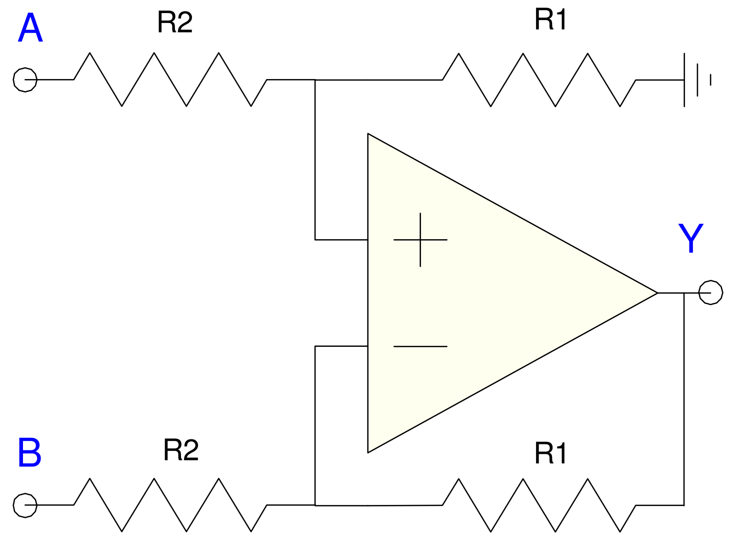


Case 2: V = f(R) (OhmMeter)

Output

- -10V when R = 2000 Ohms
- +10V when R = 2200 Ohms





Solution:

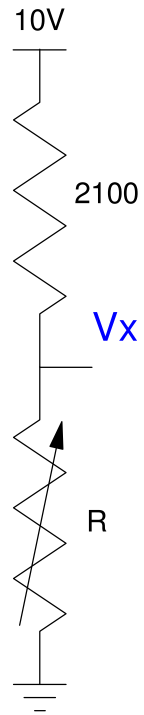
- Convert R to a voltage
- Assume a 2100 Ohm resistor

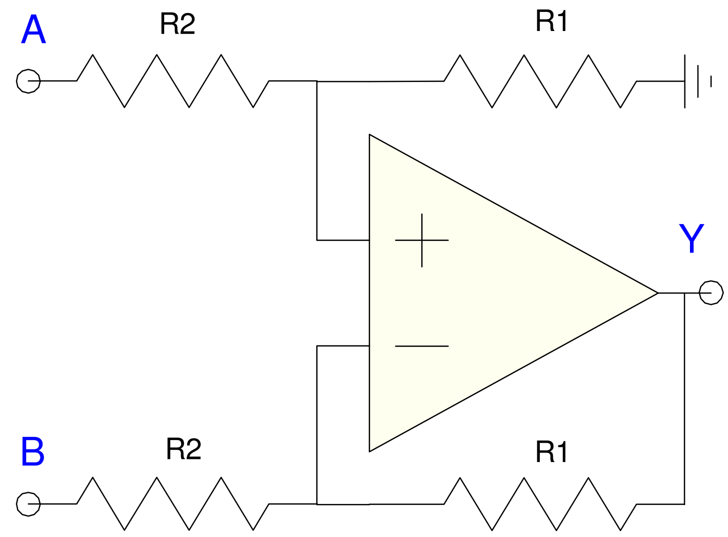
R = 2000 Ohms (Y = -10V)

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

R = 2200 Ohms (Y = +10V)

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



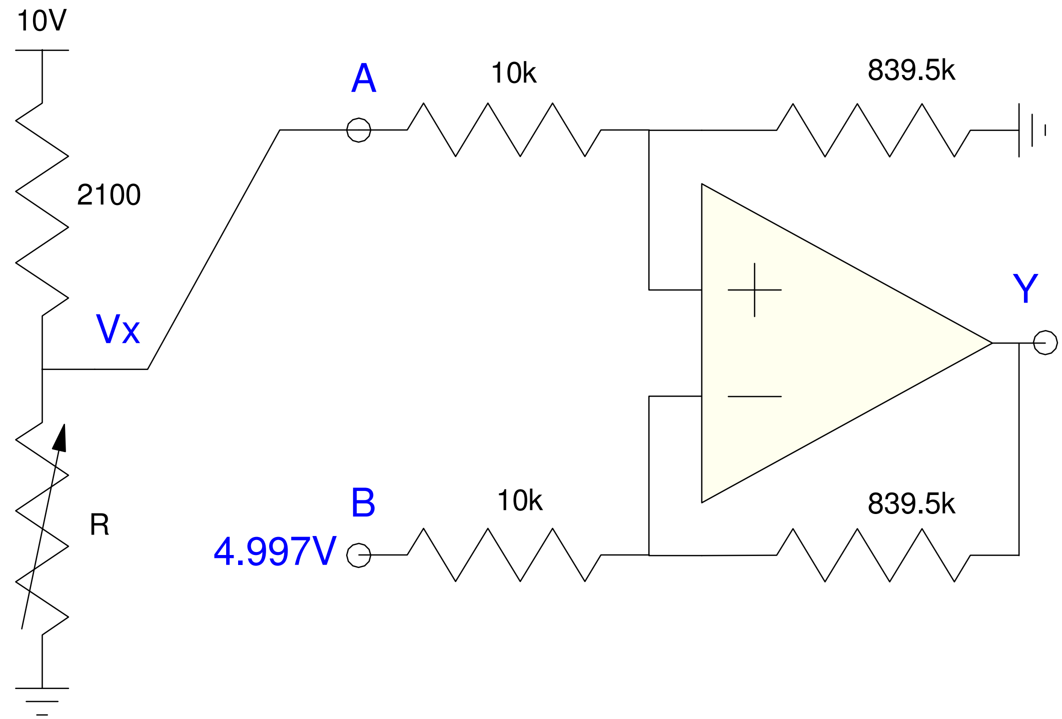


The gain you need is

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

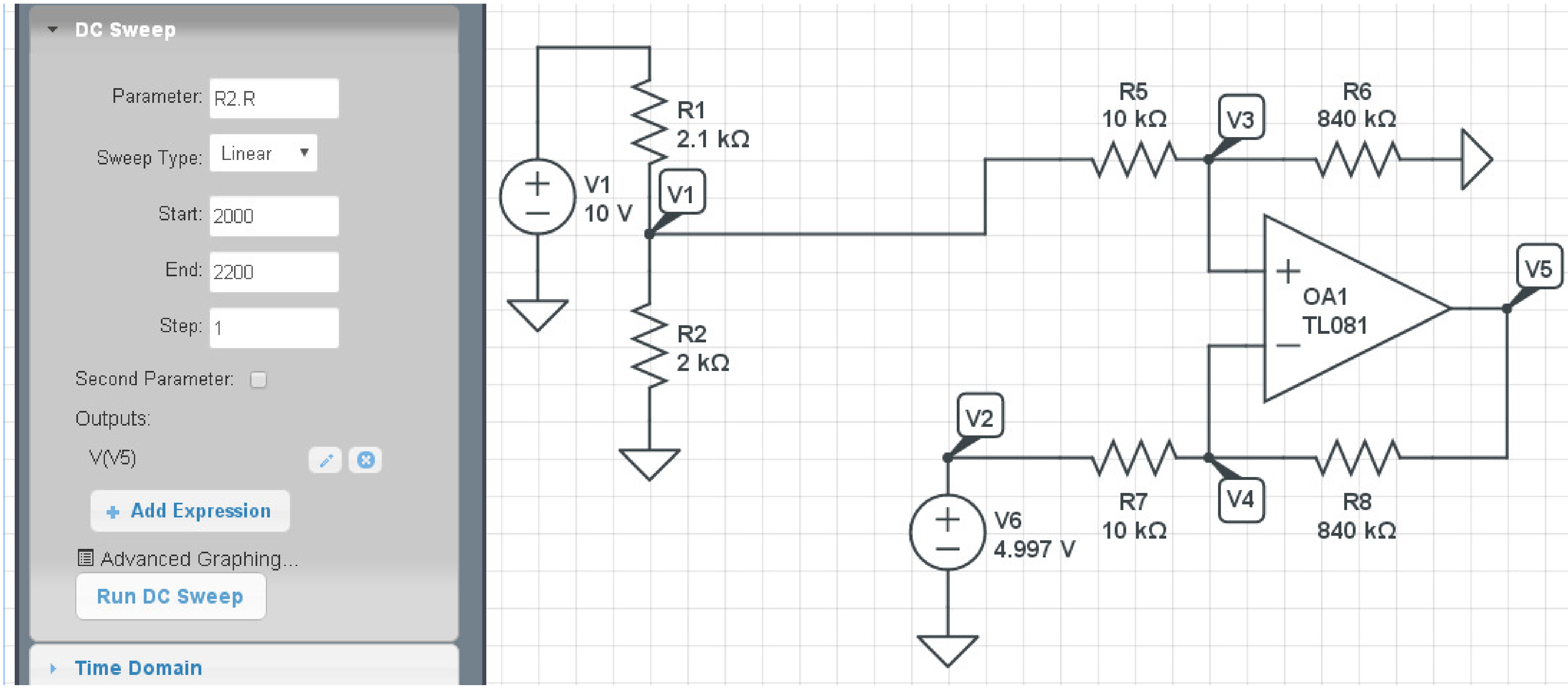
The output should be 0V (midband) when the input is midband

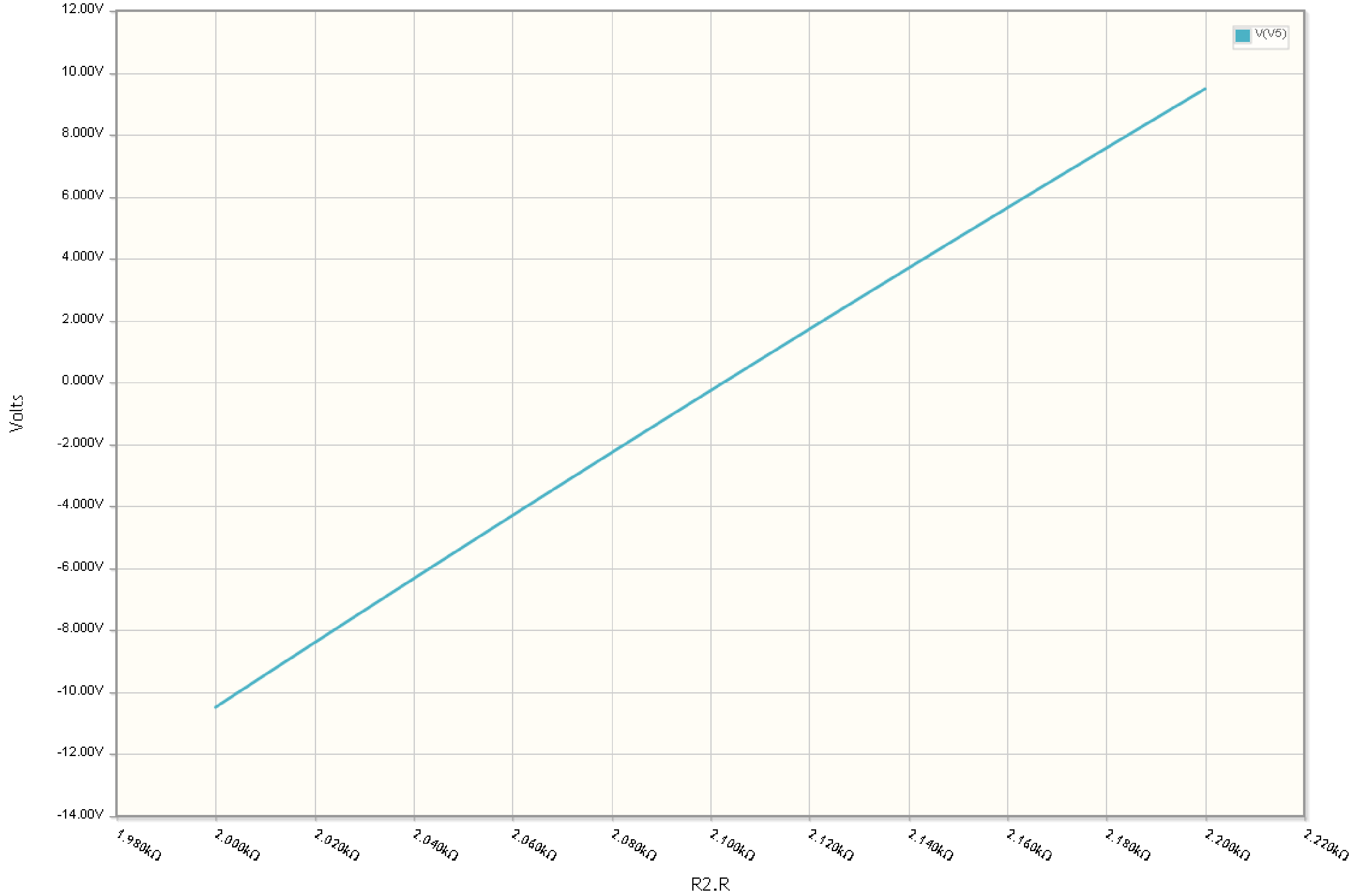
$$V_b = \left(\frac{4.878V+5.116V}{2}\right) = 4.997V$$



Verification: Use CircuitLab

- Sweep R2 from 2000 to 2200 Ohms
- V5 should vary from -10V to +10V





V(V5)
Volts
12.00V
10.00V
8.000V
6.000V
4.000V
2.000V
0.000V
-2.000V
-4.000V
-6.000V
-8.000V
-10.00V
-12.00V
-14.00V
1.980kΩ
2.000kΩ
2.020kΩ
2.040kΩ
2.060kΩ
2.080kΩ
2.100kΩ
2.120kΩ
2.140kΩ
2.160kΩ
2.180kΩ
2.200kΩ
2.220kΩ
R2.R

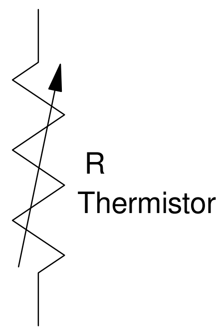
Case 3: Thermistor

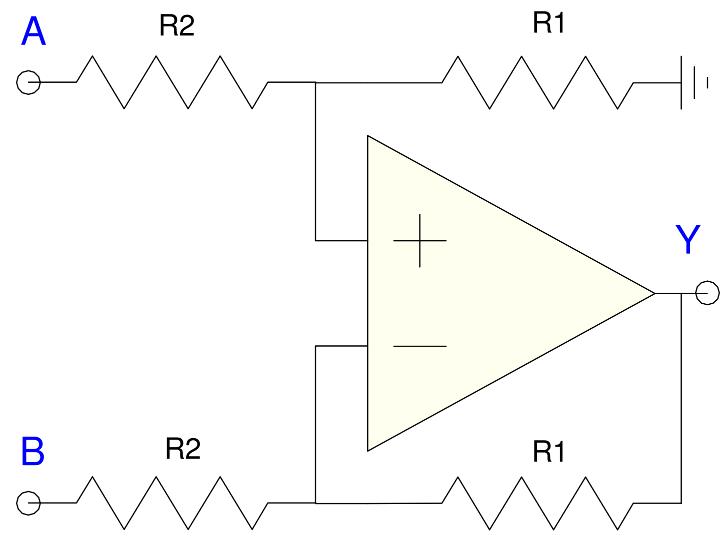
Assume a thermistor: (T = degrees C)

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

Design a circuit which outputs

- 0V at 0C
  - *R = 3320.125 Ohms*
- +10V at +40C
  - *R = 533.664 Ohms*





Solution:

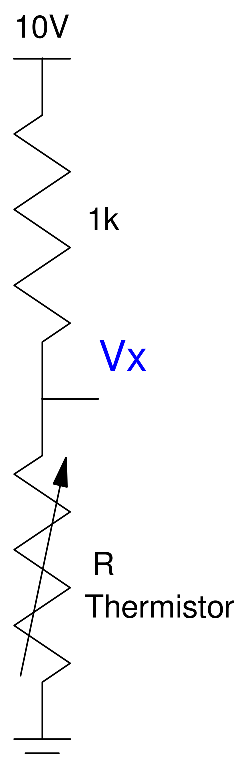
Use a voltage divider to convert R to V

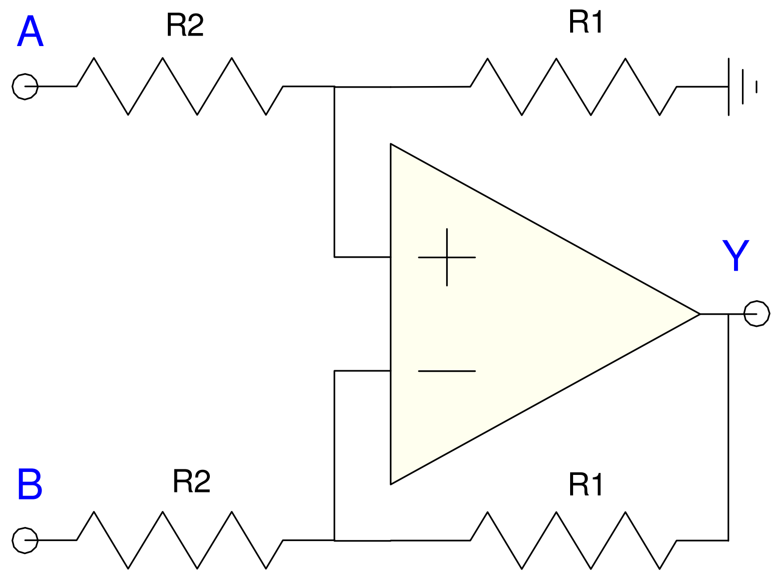
At 0C (Vy = 0.00V)

- R = 3320.125 Ohms
- Vx = 7.6853 V

At +40C (Vy = 10.00V)

- R = 533.664 Ohms
- Vx = 3.4797V





Solution

As Vb goes down, Y goes up

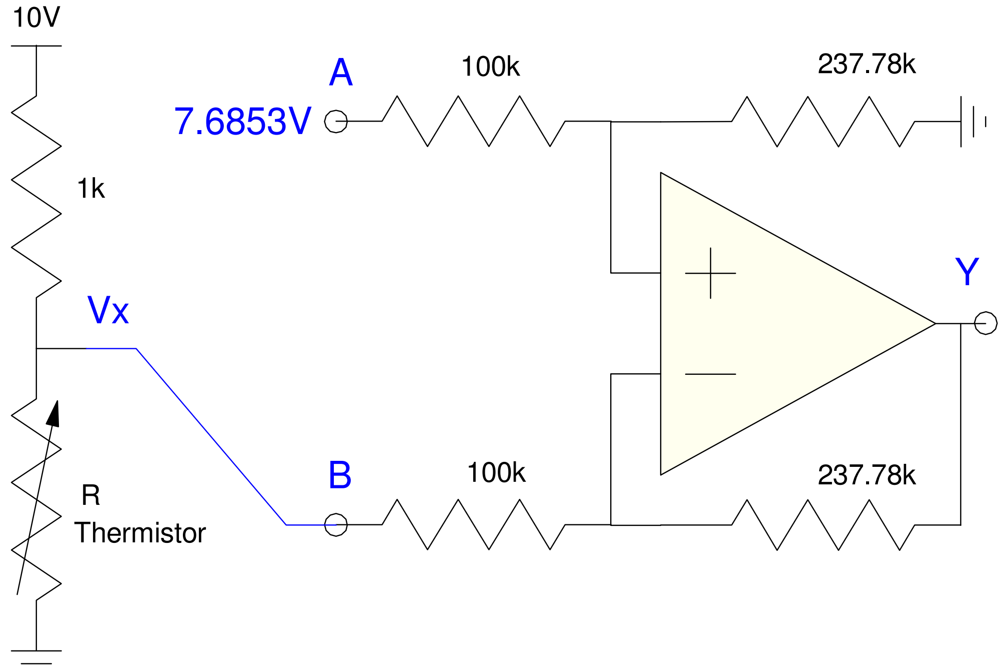
- Connect Vb to the minis input (B)

The output is 0V when Vb = 7.6853V

- Make A = 7.6853V

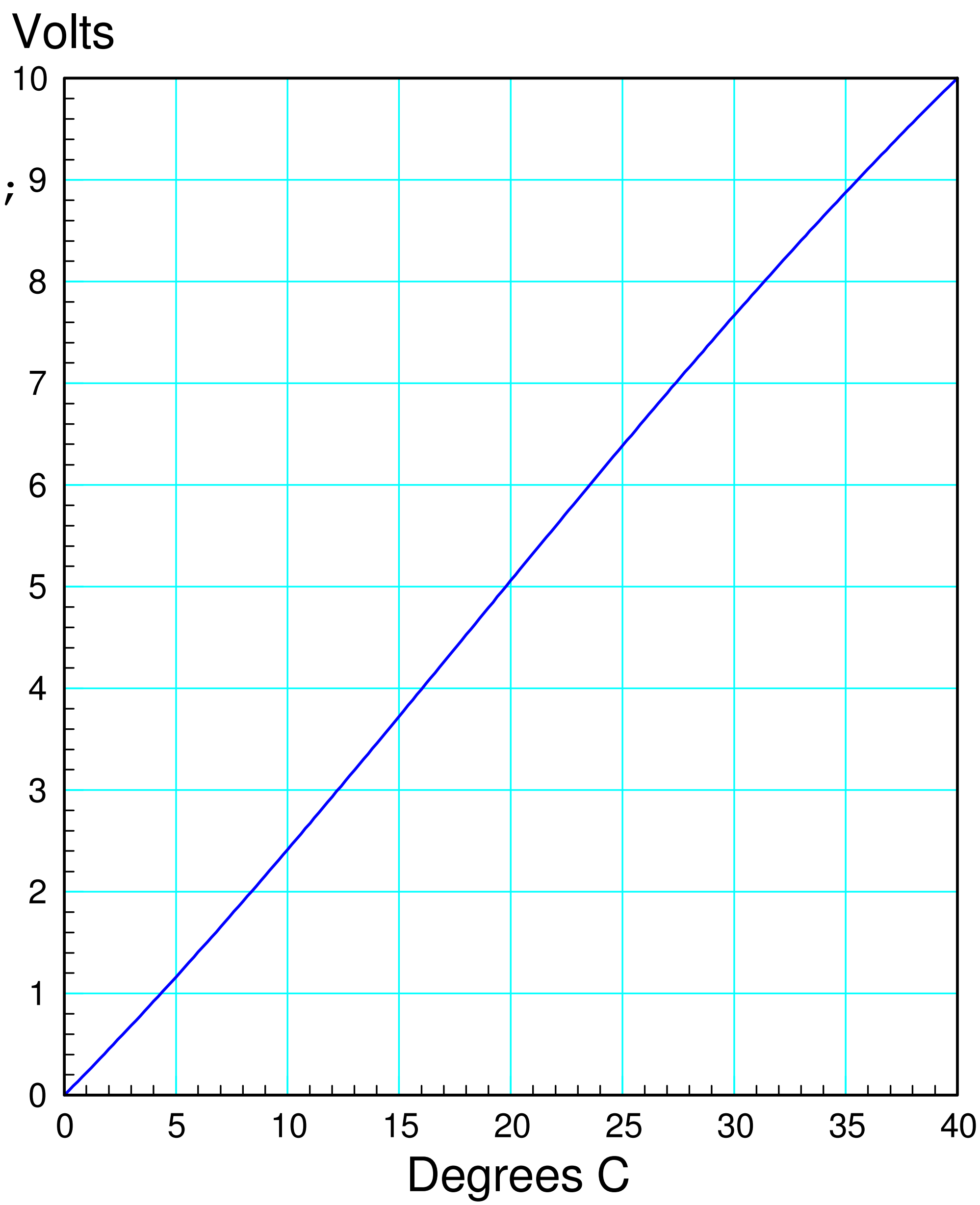
The gain needed is

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



Checking in Matlab.

```
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);
```



Note:

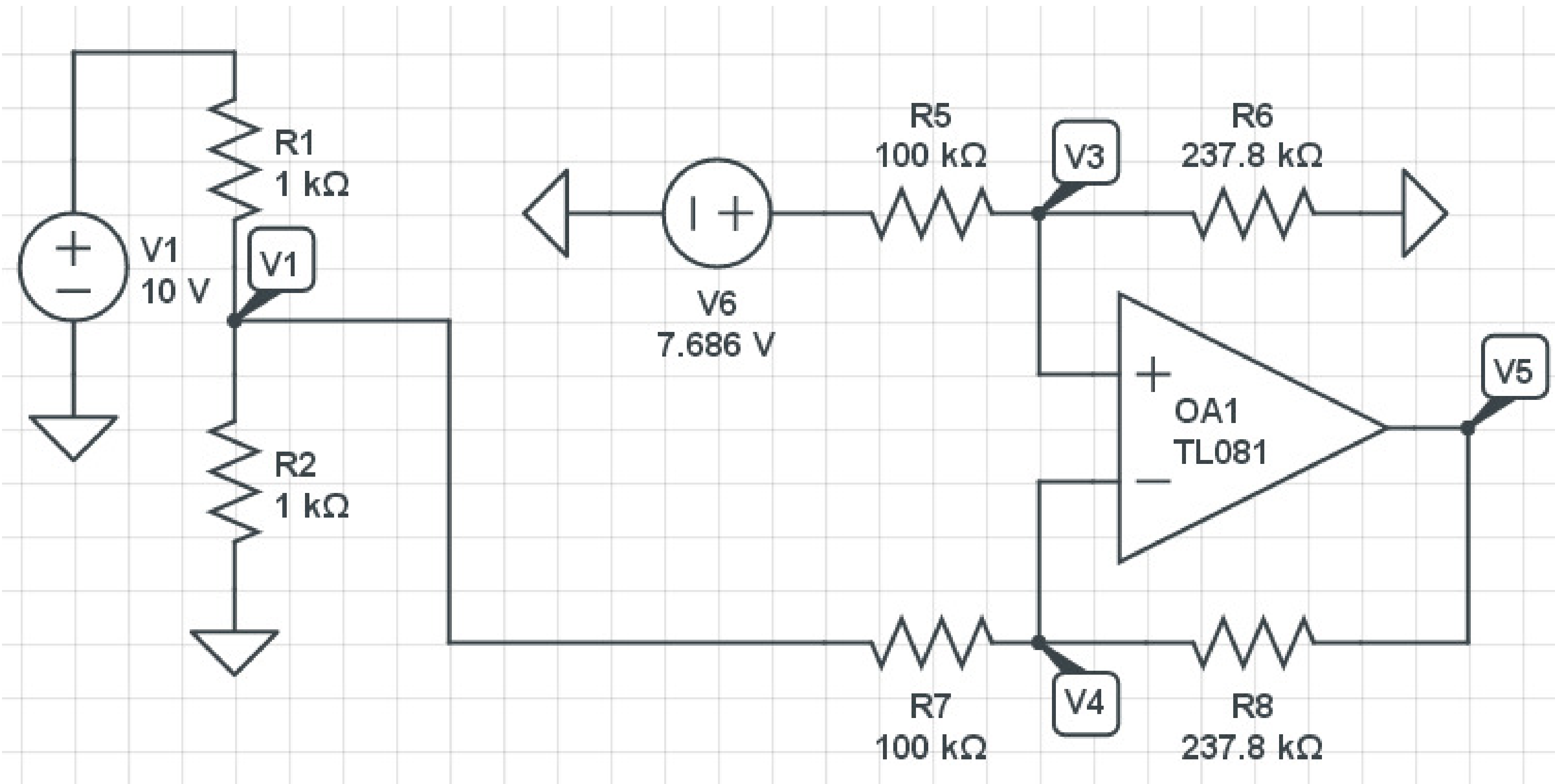
- 0V @ 0C
- 10V @ 40C

Not quite linear

- The thermistor is nonlinear
- Voltage division is nonlinear
- Result is nonlinear

Checking in CircuitLab. Check

- 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)



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

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

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)

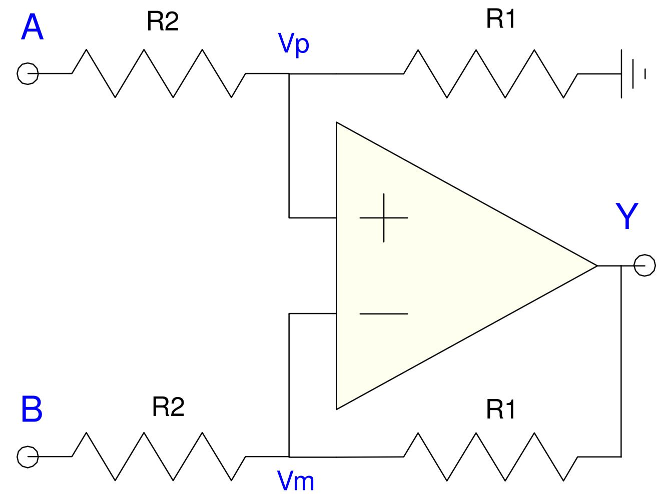
Summary

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