Temperature Alarm Design

ENGR 2514

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Prepared for Dr. Zhen Zhu

Abstract

The purpose of the ENGR 2514 design project is to create a temperature alarm circuit which indicates whether the temperature read by a thermistor sensor is within a desired range (30-50 C) using only a thermistor, resistors, operational amplifiers, and two LEDs. The resistance of the thermistor is converted to an output voltage, compared to voltages which correspond to the upper and lower limits of the temperature range, and then summed to either 12 V or 0 V which drive the LED circuit. Although the response of the thermistor to changes in temperature is nonlinear, the circuit linearizes the response and ultimately transforms it into a simple indication of in or out of range.

Design

A thermistor is an electrical component which measures temperature. The resistance of the thermistor varies with temperature and is described by:

$$R_T = R_o e^{\beta\left(\frac{1}{T}-\frac{1}{To}\right)}$$

where:

T = temperature in *Kelvin (K)*
T_o = is a reference temperature (typically 298 K)
β = constant (material properties of the thermistor; **3903.7**)
R_o = resistance value of R_T when $T = T_o$ ($\boldsymbol{R_o}$ **= 10 kΩ** at T = 298 K)

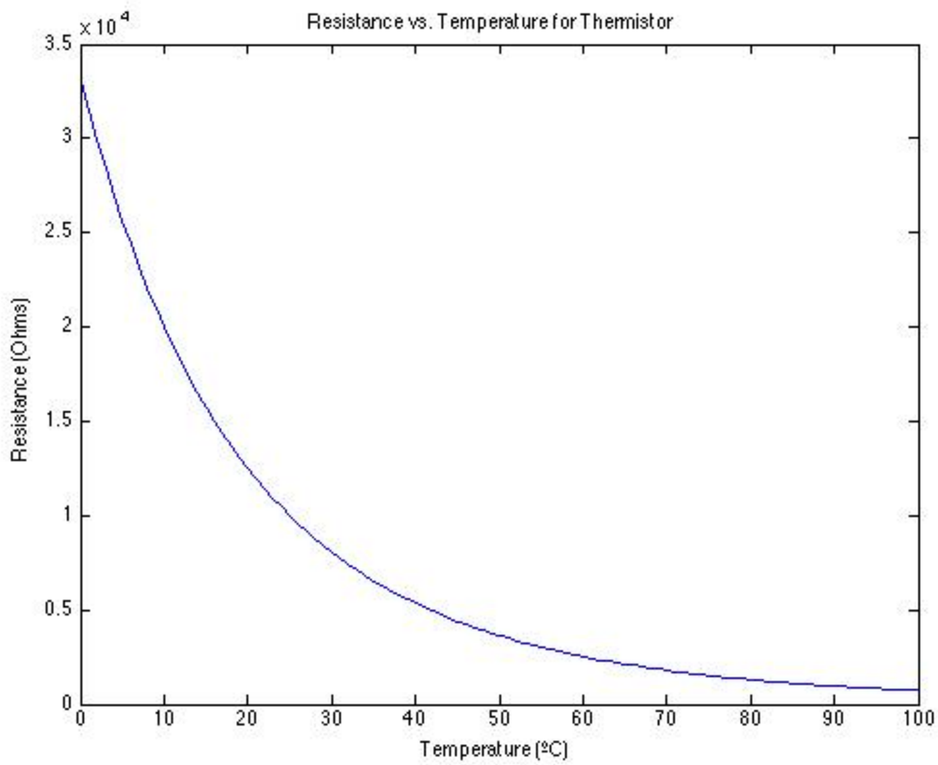

Figure 1

To design an alarm circuit, the changing resistance of the thermistor must somehow be converted into a quantity which can be used to determine if the temperature measured is in or out of range. A circuit called a Wheatstone bridge is implemented to do this. The Wheatstone bridge detects small changes in the resistance and converts these changes into a voltage. Put simply, changes in R_T produce changes in the voltage drops associated with each resistor for a given input voltage. Those changes in voltage appear at the input terminals of the op-amp and are consequently translated into an output voltage which can be operated upon by the rest of the temperature alarm circuit.

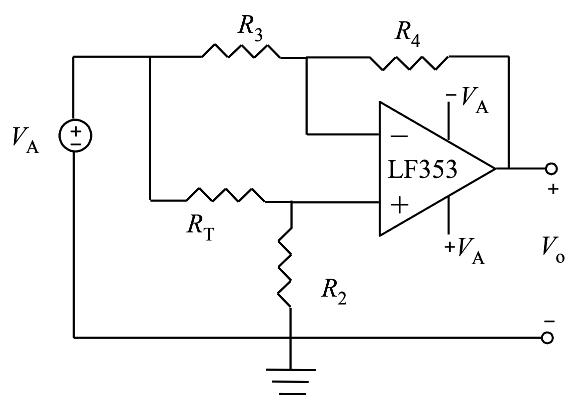

Figure 2

When designing the bridge circuit, the values of the non-varying resistors are a vital consideration. If possible, these resistor values should be chosen such that the thermistor produces something close to a linear output voltage. A non-linear output voltage response would be more difficult to analyze because of its volatility. Otherwise, small temperature changes might produce large fluctuations in the output voltage of the circuit.

Before the response can be linearized, the relationship between the resistor values and the output of the op-amp must be derived. Using the assumptions associated with ideal op-amps and Kirchhoff's current law, algebraic equations can be written.

$$\frac{V_i - \alpha}{R_3} = \frac{\alpha - V_o}{R_4}$$

$$\frac{V_i - \alpha}{R_T} = \frac{\alpha}{R_2}$$

$$\alpha = \frac{R_4 V_i + R_3 V_o}{R_3 + R_4} = \frac{R_2 V_i}{R_T + R_2}$$

$$V_o = V_i\left(\frac{R_2(R_3+R_4)}{R_3(R_T+R_2)} - \frac{R_4}{R_3}\right)$$

As the equations demonstrate, R_T and R_2 are essentially in series. Consequently, we can easily calculate the current through these two resistors and their voltage drops. The same applies to R_3 and R_4. To derive the expression for V_o, solve the first two current equations for alpha and set them equal to each other. Then, solve for V_o. One might also recognize that the output indicates that the thermistor circuit is essentially a difference amplifier.

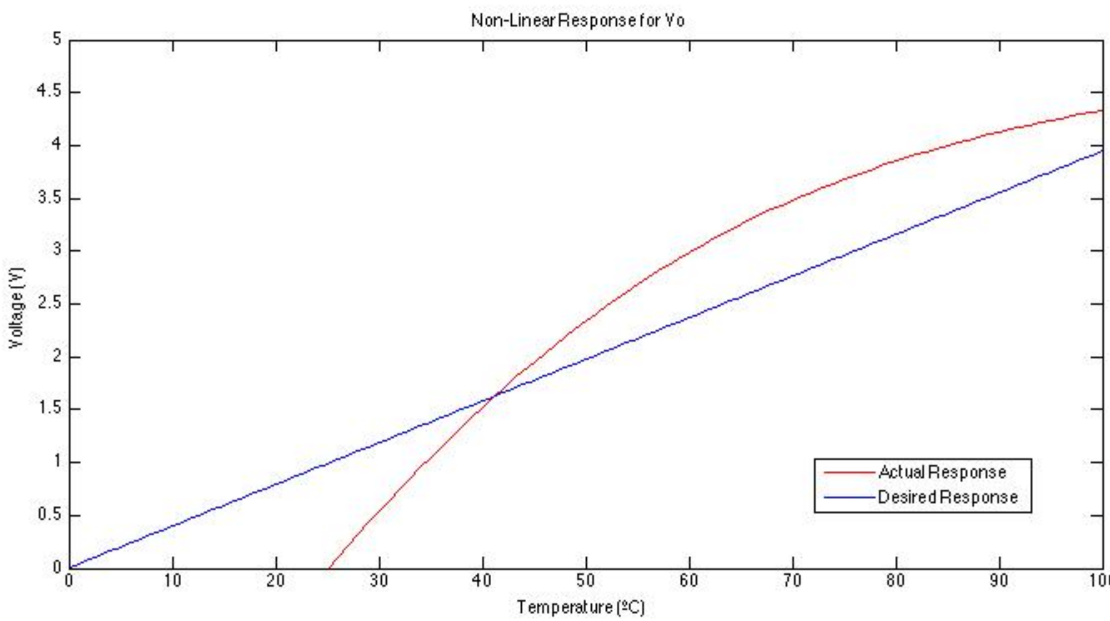

Figure 3

The figure shows a non-linearized output for the resistor values $R_2=R_3=R_4 = 10{,}000\Omega$ (random selection) versus the ideal linear response. By manipulating the resistor values, the thermistor curve can be "wrapped around" the ideal linear response.

The linearization parameters for V_o are:

$$(1)\quad V_o(0^o) = 0$$

$$(2)\quad V_o(50^o) = \frac{1}{2}V_o(100^o)$$

With these two conditions for V_o, another system of equations can be set up and solved.

$$\frac{R_2(R_3+R_4)}{R_3(33188+R_2)}-\frac{R_4}{R_3}=0$$

$$\frac{R_2(R_3+R_4)}{R_3(3628+R_2)}-\frac{R_4}{R_3}={}^1\!/_2\left[\frac{R_2(R_3+R_4)}{R_3(717.92+R_2)}-\frac{R_4}{R_3}\right]$$

Notice that there are three unknowns, but only two equations. This means that there is a free parameter in the system. Consequently, one of the resistors must be selected before the system can be solved. With guidance from more experienced engineers, R_4 was chosen to be 1kΩ. Now that there are two equations and only two unknowns, the system can be solved for R_2 and R_3.

R_2 and R_3 can be found in a variety of nifty ways, and one such way is to use MatLab. MatLab can even provide a nice symbolic expression for the resistors as well as a numerical value. The code below demonstrates how to do this.

```
%symbolically solve for R2 and R3

solve('(R2*(R3+R4))/(R3*(Rt0+R2))-R4/R3 = 0' , '(R2*(R3+R4))/(R3*(Rt50+R2))-
R4/R3 = .5*((R2*(R3+R4))/(R3*(Rt100+R2))-R4/R3)');

R2 = ans.R2
R3 = ans.R3

R2 =

(Rt0*Rt50 - 2.0*Rt0*Rt100 + Rt50*Rt100)/(Rt0 - 2.0*Rt50 + Rt100)

R3 =

(R4*Rt0^2 - 2.0*R4*Rt0*Rt50 + R4*Rt0*Rt100)/(Rt0*Rt50 - 2.0*Rt0*Rt100 +
Rt50*Rt100)
```

If R_4 is 1kΩ, the expressions evaluate to 2,827.7 Ω for R_2 and 11,736.7 Ω for R_3. Since the laboratory is equipped with 3kΩ and 12kΩ resistors, these values are acceptable.

Now that the resistor values which satisfy the linearization parameters have been found, the new thermistor output curve can be compared to the ideal linear response.

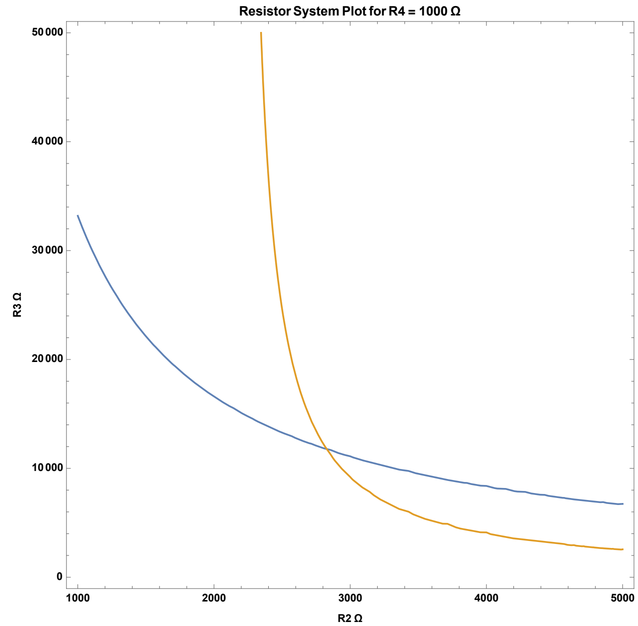

Figure 4

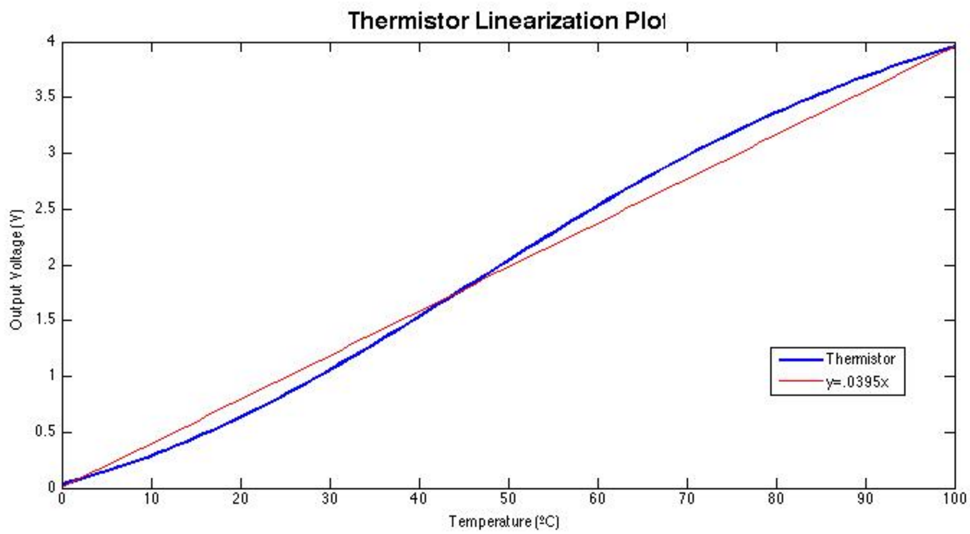

Figure 5

Things already look much better, but how effective were the parameters at linearizing the output? Using MatLab, the deviations from the ideal linear response can be calculated. The following code helps do that:

```
%plots output voltage of thermistor circuit for random resistor values zhu
%gave us
%we also make some statistically iffy residual plots and find the max
```

```
%deviation

data = TempAlarm(3000,12000,1000,5);

temp = 0:1:100;

plot(data,temp)
title('Residual Analysis Plot')
xlabel('Output Voltage (V)')
ylabel('Temperature (ºC)')

hold on

y = .0395*temp;
plot(y,temp)

hold off
figure(2)
resid = (y - data).^2;
plot(temp, resid,'r*')
xlabel('Output Voltage (V)')
ylabel('(Linear Temp - Actual Temp)^2 (C^2)')
title('Temperature Deviation from Linear Response Using Calculated Resistor Values')
[B,I]=max(resid)
%here, I'm just finding the largest value in the vector and taking the
%square root to cancel the whole squaring thing which helped us get rid of
%the negative stuff so we could compare magnitudes
CorrB = sqrt(B)

%this plot is for the resistor values given in part 4.f in the submission
%requirements document
%Rto=33188
%R3 = 3318.8
dataf = TempAlarm(100000,10000,3318.8,5);
figure(3)
resid2 = (y - dataf).^2;
plot(temp,resid2,'gd')
title('Temperature Deviation from Linear Response for Zhus Resistor Values')
xlabel('Output Voltage (V)')
ylabel('(Linear Temp - Actual Temp)^2 (C^2)')
[G,Q]=max(resid2)
CorrG = sqrt(G)
```

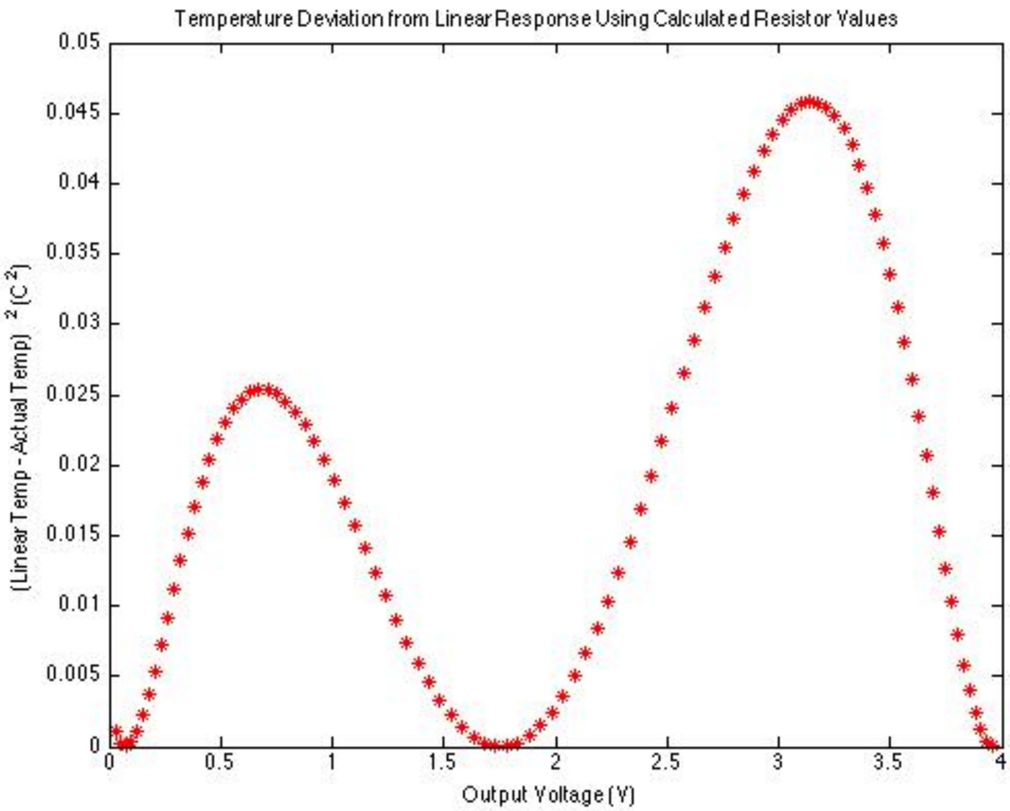

Figure 6

Figure 6 shows that the squared temperature difference for a given output voltage between the ideal linear response and the linearized thermistor response is less than 0.05. That sounds pretty great, but how does this compare to the output from a thermistor circuit for which the resistor values were chosen without adhering to any particular parameters?

	R_2	R_3	R_4
Calculated Resistors (Ω)	3,000	12,000	1,000
Comparison Resistors (Ω)	100,000	3,318.8	10,000

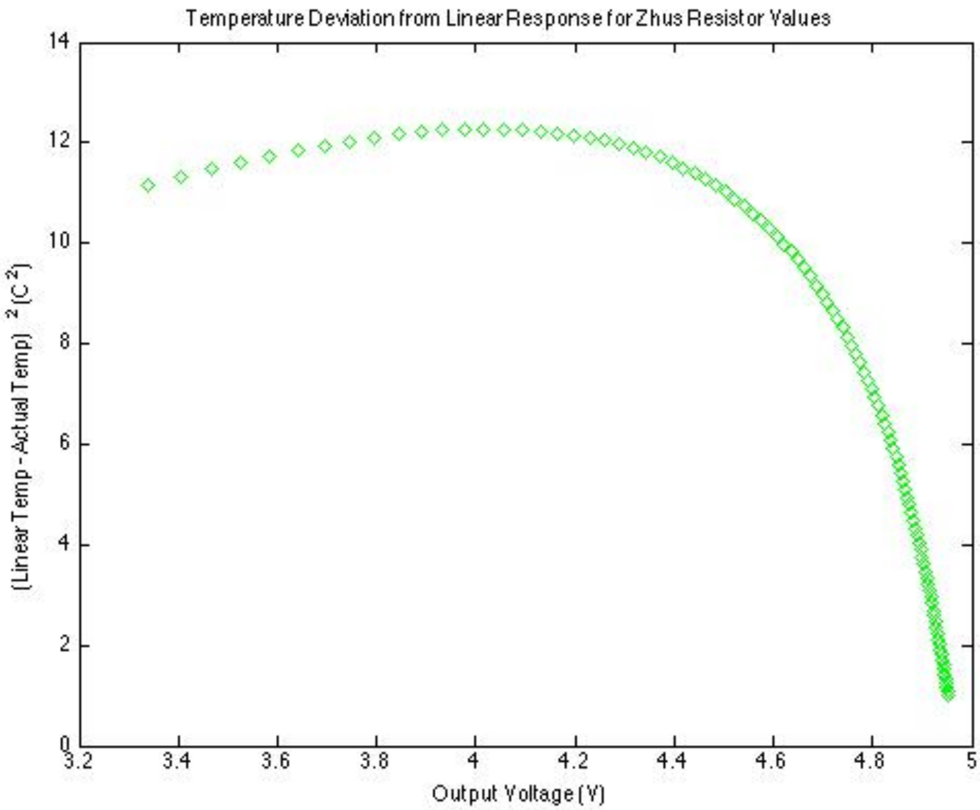

Figure 7

	Max Deviation (C)	Voltage (V)
Calculated Resistors	0.2141	3.1371
Comparison Resistors	3.5031	4.0166

The data clearly demonstrates that the linearized curve is much closer to the linear ideal response. Now that the response has been linearized, a comparing circuit must be built to determine whether the temperature is in or out of range.

The comparator circuit is implemented with two op-amps with no feedback resistors. The two voltages at the input terminals are compared, and depending on whether one is bigger or smaller than the other, the op-amp kicks out a large positive or negative output due to the open-loop gain. The tables provided summarize the input and output combinations.

$$v_{output} = \begin{cases} VA+, & v_+ > v_- \\ VA-, & v_+ < v_- \end{cases}$$

The voltages which constitute the upper and lower limits of our temperature range (30-50 degrees Celsius) are fed into the appropriate terminals through simple voltage divider circuits. The MatLab function which calculates the output voltage of the thermistor is used to calculate the voltages which make up the upper and lower limits of the range.

	Upper Limit (50 C)	**Lower Limit (30 C)**
Output Voltage (V)	2.0351	1.0531

	v_1	v_2
$V_o > V_{UPPER}$	12 V	-12 V
$V_{UPPER} > V_o > V_{LOWER}$	-12 V	-12 V
$V_o < V_{LOWER}$	-12 V	12 V

The tables show that when the temperature is within range, the output from both op-amps is the same. Otherwise, the outputs are of opposite sign.

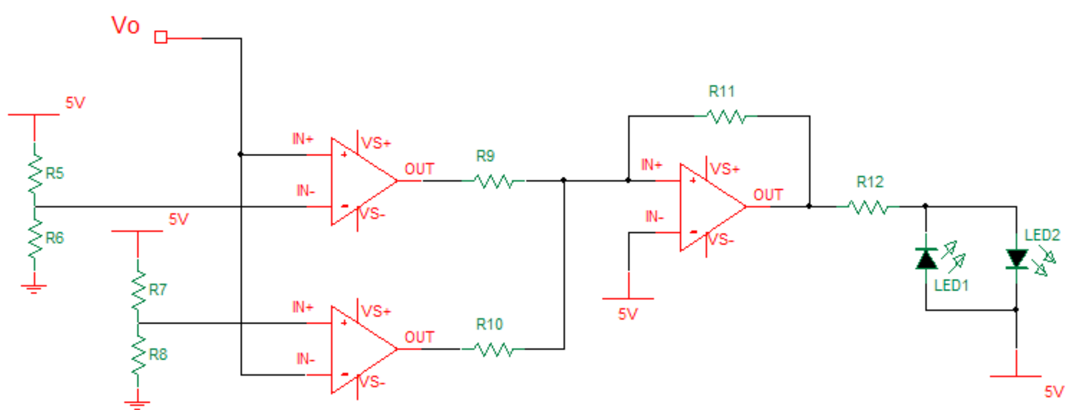

Figure 8

Next, the output of the comparator circuit is fed into a summing amplifier which outputs 12 V if both inputs are low and outputs 0 V if one input is high and the other is low. Two LEDs are then connected (in opposite directions) to the output of the summing amplifier with a 5 V source connected beneath the LEDs. When the output from the thermistor circuit is out of range, the comparator puts out a high and low which sums to 0 V. Consequently, current flows up from the 5 V source to the summer output, and the red light comes on. When the output from the thermistor is in range, the comparator spits out two lows which sum to 12 V. The current then flows in the opposite direction, and the green light comes on. The resistor between the LEDs and the summing amplifier output limits the current through the LEDs to their working range which is approximately 10 mA.

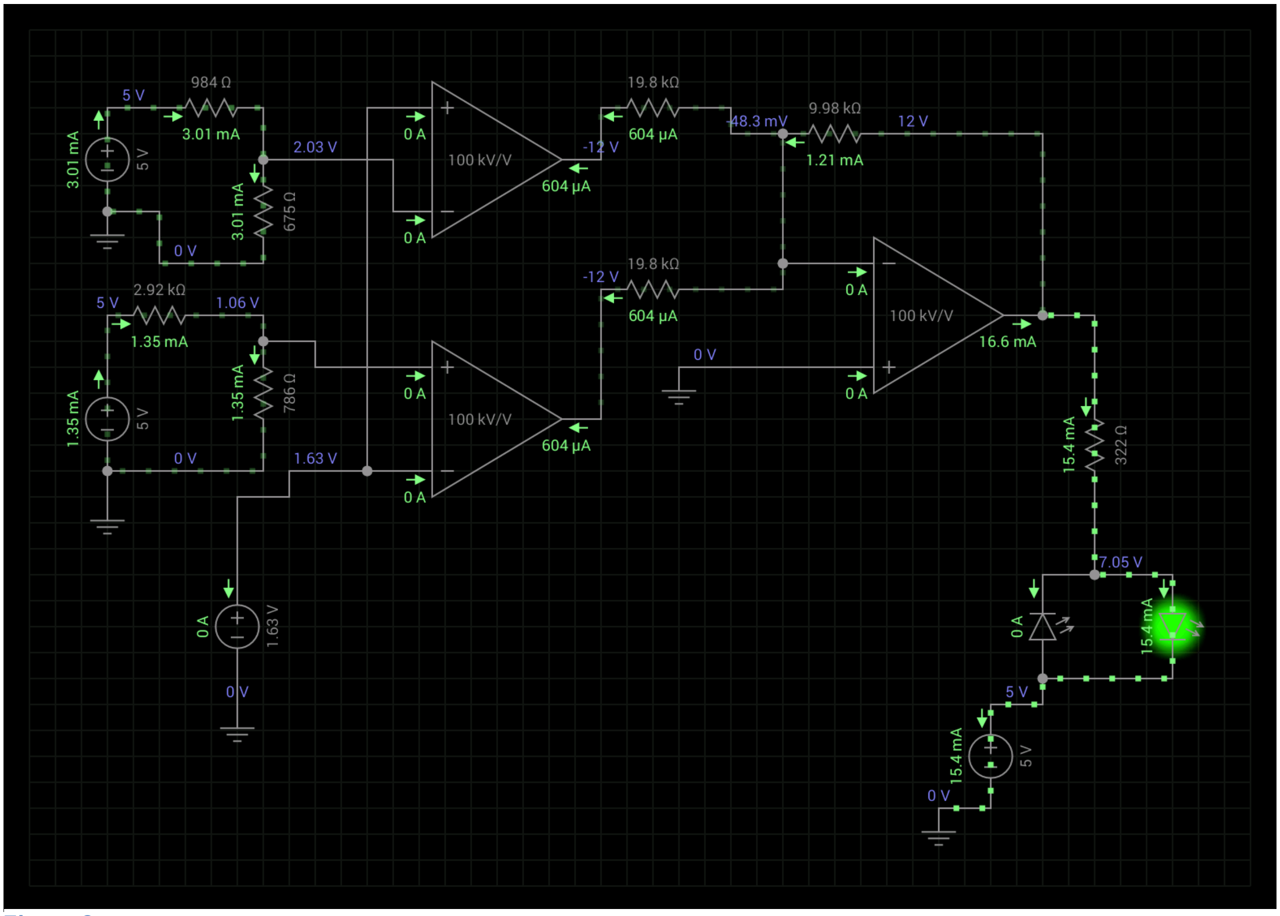

Figure 9

The schematic above details the circuit response to a thermistor output voltage of 1.63 V. The 1.63 V is compared to the voltages supplied by the voltage divider circuits on the far left, and then the comparators spit out -12 V. That -12 V is then summed to +12 volts and the current flows down and through the green LED indicating the temperature is within range. This schematic also indicates the actual, measured resistances of the resistors used in the real circuit.

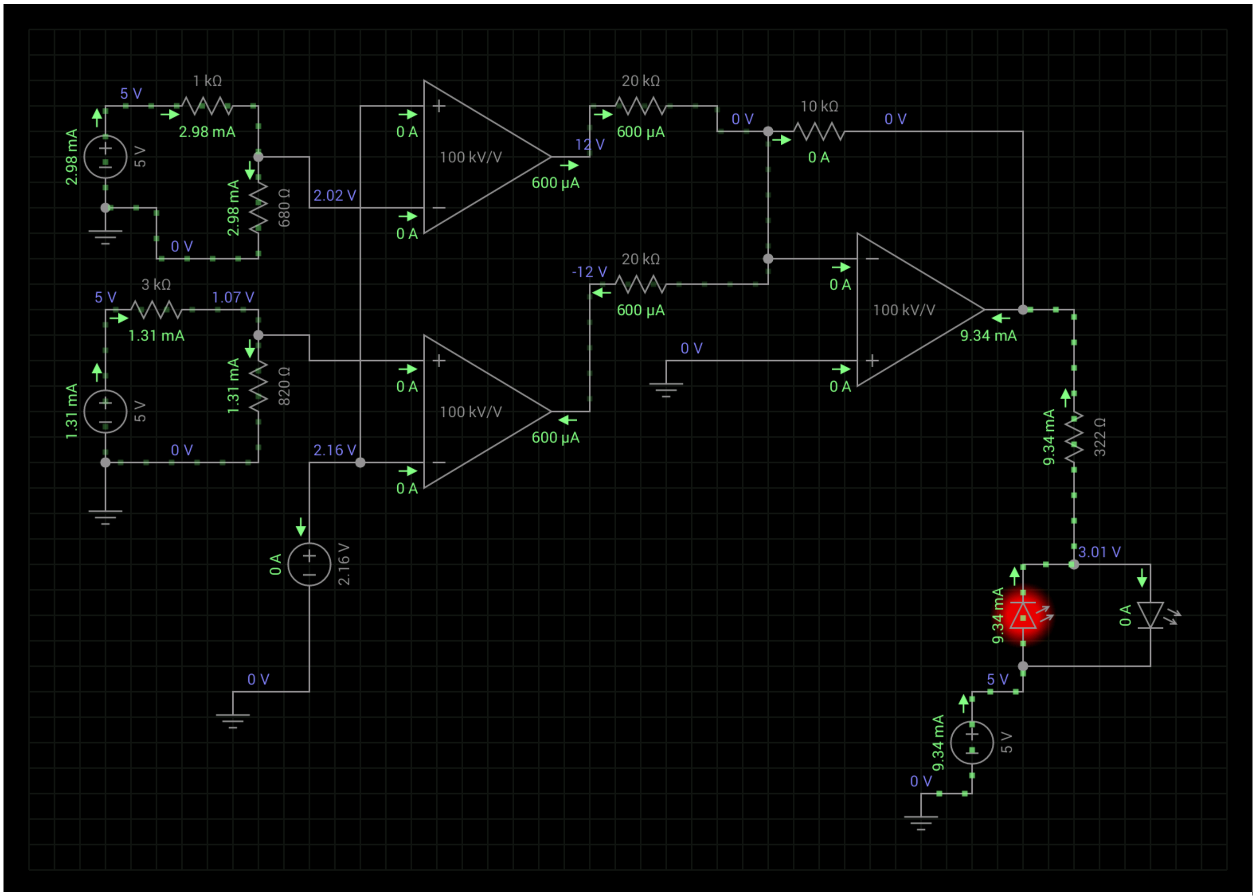

Figure 10

In the case shown in the schematic above, the thermistor output voltage of 2.16 V is out of range. The comparators output a +12 V and -12V which are summed to 0 V. The current then flows up through the red LED indicating that the voltage is out of range.

Real Circuit

The real circuit, operating within range is pictured below. In order to test the circuit, the thermistor was wrapped around a thermometer and placed in boiling water while it was allowed to cool. The upper transition was at approximately 50.4 C. Once the water cooled to below the upper limit, ice was added to the water to get the temperature to drop below 30 C. The lower transition occurred at approximately 31 C.

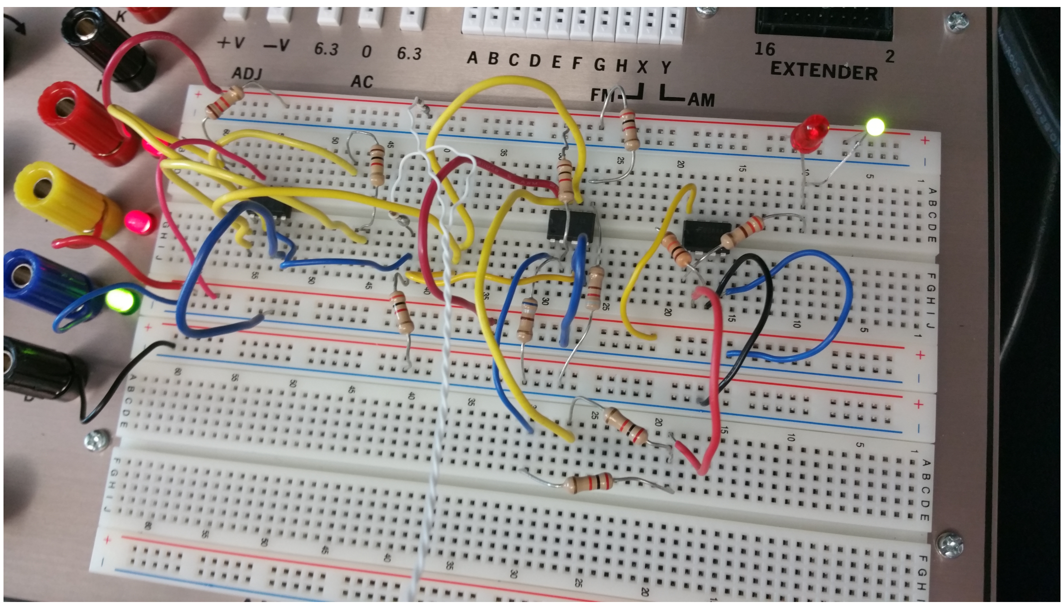

Figure 11

Reflection

First of all, my circuit building skills and my familiarity with the breadboard was dramatically improved. I finally figured out how to follow the circuit from one node to the next. Analyzing circuits on paper is one thing, but translating that to the real world can be perplexing. Building the temperature alarm helped me become much more comfortable in a circuits laboratory.

Additionally, I was able to apply the basics of circuit analysis like KCL towards some tangible end. This application illuminated the fundamentals. For example, prior to completing the project, I didn't really have a firm grasp on how operational amplifiers could be so useful. However, in the temperature alarm circuit, we have applied them in three distinct ways: voltage amplification, comparison, and summing. I also saw how analog quantities could be manipulated to produce either a yes (green light) or a no (red light). Through these simple processes, I made a circuit that does something.

My MatLab skills have also improved. All of the MatLab programming in ENGR 2050 were very basic, and the problems were not exactly challenging. ENGR 2050 was a nice introduction, but the design project challenged me to learn how to use MatLab to solve my own problems. I am now much better at plotting in MatLab and manipulating vector quantities. I am also more familiar with writing longer code and using comments to help future me figure out what past me was up to. Future me appreciates this very much.

I would like to comment more on the accuracy of the real circuit, but I feel like I didn't get enough data to have a thorough discussion of the results. I was genuinely impressed to discover that the light switched over right at the desired temperatures.