Thermometer Report
4/26/2025

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Proposal Statement

Thermometers are used to monitor and record temperature across a wide range of objects. We planned to create a touchless thermometer which outputs the precise temperature (in Celsius), including warnings for too hot and too cold with customizable thresholds. In order to achieve the non-contact temperature readings, we planned to utilize a TS305-11C55 thermopile which senses infrared radiation. This is thermal energy that gets converted to electrical energy which is the output of the thermopile. However, because of sensor issues, we finally used the TMP 36 touch sensor to create a regular touch-based thermometer. This sensor uses solid-state technique and monitors voltage drops across its base and emitter to detect changes in voltage with changes in temperature, and produces and output. Our project involved processing the output signal with an amplifier circuit (milestone 1), connecting it to an ADC circuit to convert the analog voltage into binary (milestone 2). This was then fed into a 7-segmented display circuit to output the first digit of accuracy (10s place) (milestone 3). The amplified voltage will also be connected to a separate logic circuit with comparators which will check whether the output is past the thresholds or past the accuracy range of the thermopile (milestone 5). If outside of the thresholds, we will output a buzzer and a red or blue LED accordingly, and if the hot/cold thresholds are impossible (e.g. hot threshold less than cold threshold), we will output an error buzzer and LED (milestone 6). If time permitted, we were going to add additional processing in order to acquire the 1s digit and display it to a separate 7-segment display (milestone 4), but were not able to complete this milestone. The biggest challenge that we anticipated facing is maintaining accuracy in the ADC, particularly for the ones digit. Our original planned timeline was to complete the milestones in order, week after week.

Milestones

Week 6:

We began building the project this week. Our first deviation from the original plan was that we decided to split up the milestones and work on two at once, which would help us complete our goals quicker. So, we began with milestone 1, the amplifier circuit, and milestone 6, the digital logic controlling outputs.

For milestone 1, we originally planned to follow the amplifier schematic given in the datasheet for the thermopile, using the LM358 as the op-amp.

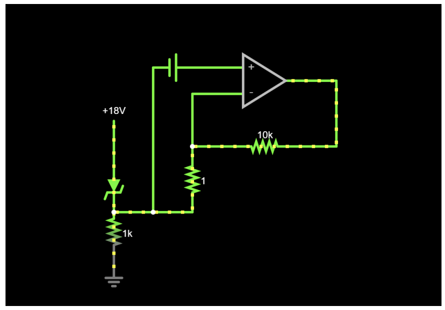

Figure 1: Original planned amplifier schematic (independent voltage source is the thermopile)

We found that we couldn't directly use a traditional amplifier circuit due to the fact that the thermopile outputs negative voltages at certain temperatures, so amplifying all values by a scalar would not work. So, we planned to use a shifted virtual ground, detailed in the schematic, to shift all input voltage values up into a positive voltage range, and then amplify the result. However, during testing we found issues with this design. Since we didn't have the thermopile yet, we used a power supply to simulate the thermopile input and measured the output of the LM358 with the oscilloscope. We then varied the input voltage to see if we would see an accompanying increase in the output. However, we found that the output would only jump to high or low depending on the input, and it wouldn't increase accordingly with an increase in input. So, we would have to use a different design for this, which we began researching.

For milestone 6, we did not receive the decoder yet so we simply decided to implement that part with AND/NOT gates instead, as it seemed simpler and easier.

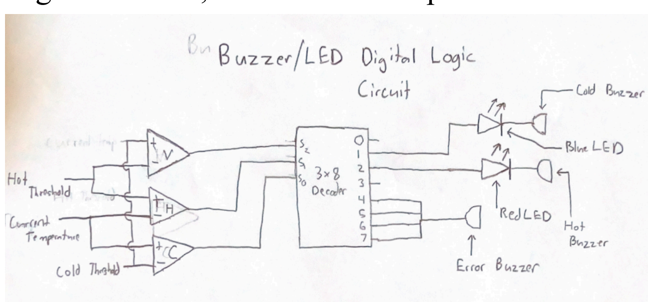

Figure 2: Original planned output logic circuit

We had to create a separate 5.1V rail using a zener diode and resistor since most of the digital logic components took a max supply voltage of 5.1V. We then measured the voltage at the 5.1V rail to ensure it was correct and the chips wouldn't get too much voltage.

Week 7:

This week, we tested and completed an alternate design for milestone 1, began constructing milestone 2 (ADC), and tested and completed milestone 6.

For milestone 1, with some help from the TA we designed a new amplification circuit.

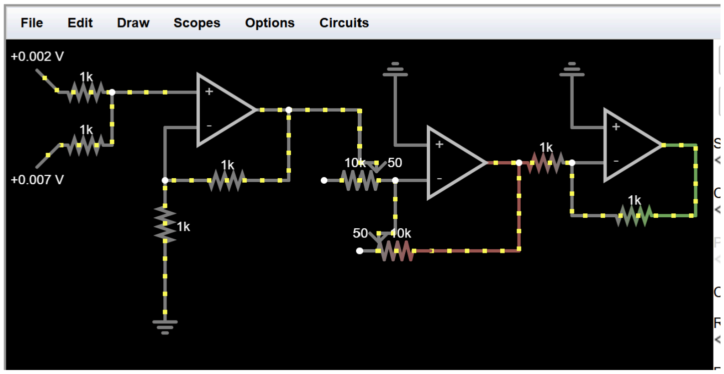

Figure 3: New Milestone 1 circuit

This circuit completes the signal processing in several steps. First we used a summer circuit to bring any possibly negative inputs to the positive range. Then we used an inverting amplifier, as we were told they were more stable. Then, we used another inverting unity gain amplifier to obtain our final processed output, since we needed to bring back the inverted voltage into positive output. The three opamps above are those circuits in order, all connected. To test this, we first verified the operation of the summer circuit by providing various combinations of two voltages from the power supply, and probing the output voltage of the first LM358 and seeing if it matches the sum. After this, we tested the other two LM358s in conjunction by providing a theoretical input voltage, and measuring the output voltage. We tuned the potentiometers for a gain which would bring our output voltages within a reasonable 0-6V range.

Theoretical thermopile temperature reading(Celsius)	Input voltage(after summing amp) (mV)	Output voltage(V)
0	0	0.4
5	1	1.2
25	2	2.0
40	3	2.4
50	4	2.8
65	5	3.6
75	6	4.0
85	7	4.5
90	8	5.2
100	9	6.0

Figure 4: Rough lookup table correlating theoretical thermopile temperature and output voltage

The reason we tested the first and second halves separately was simply that we didn't have enough power supply channels to test them all at once, as we would need two to simulate the input and added voltage, and two to provide +-9 volts to the amplifiers. After this, milestone 1 was complete.

For milestone 2, we began to construct the ADC circuit.

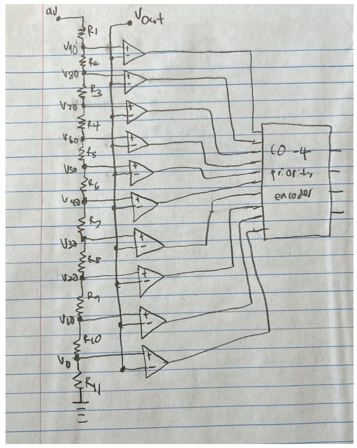

Figure 5: Milestone 2 circuit

We did not receive the 10-4 bit priority encoder yet so we simply built the comparators and voltage divider chain. Our plan was to have 10 different set voltages, which would match the voltage associated with 0, 10, 20, etc. degrees celsius. Then, we would compare our input voltage with each of these set voltages, and by seeing the comparator outputs, we could find out the range of our real input voltage (e.g. 40-50 degrees celsius). These comparator outputs would be fed into a 10-4 bit priority encoder, which would actually give us the binary of the 10s place digit. We did not yet test this circuit this week, however we made a small design change by using LM339 comparators instead of LM311s because they had 4 comparators on one chip vs 1, which would save a significant amount of space and make wiring slightly easier.

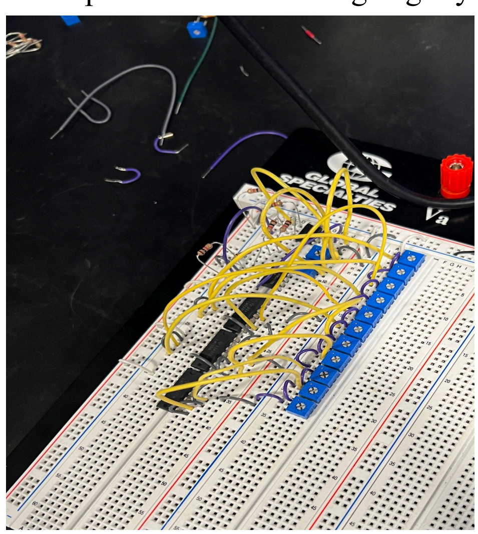

Figure 6: Amplifier circuit and ADC circuit built

For milestone 6, we tested the circuit built last week. We didn't have milestones 4 and 5 complete yet so we didn't have the real inputs to test the output logic with, so we simply used potentiometers to provide tunable variable input voltages to the circuit. We first tested the 'too hot' comparator by providing various combinations of inputs, and probing both the inputs and the comparator output. For example, we first tested with the input voltage less than the hot threshold voltage, and verified that the output of the comparator was low, and then checked with the input voltage being above the hot threshold voltage that the output of the comparator was low.

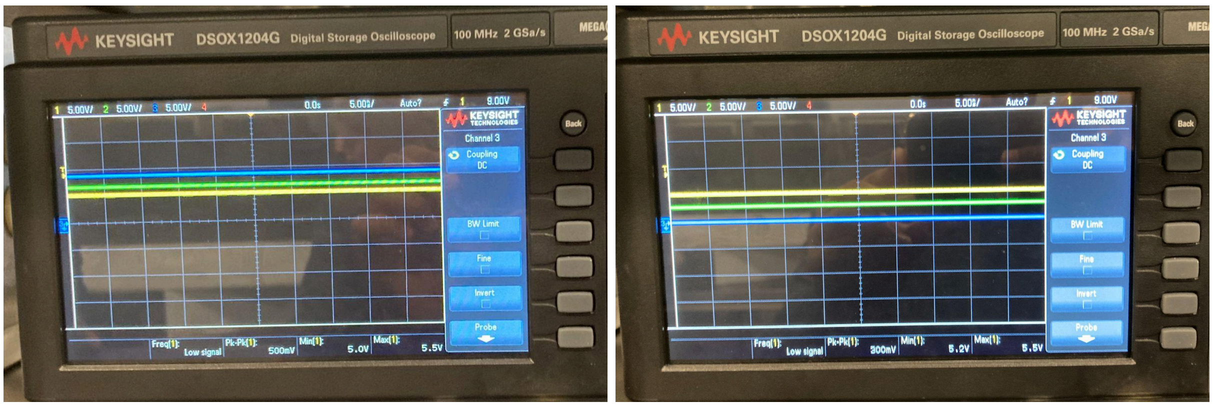

Figure 7: Verification of 'too hot' comparator. Yellow is hot threshold, blue is comparator output, green is input voltage

We repeated this type of verification for all 3 comparators, verifying their functionality. Then, we verified the logic circuit which would take these comparator outputs and correspondingly light LEDs. We probed the output for each LED, as well as the hot and cold thresholds and the input voltage. For example, the 'too hot' LED should be lit if the input voltage is greater than the hot threshold, and the hot threshold is greater than the cold threshold (otherwise this would be an error and the error LED would light).

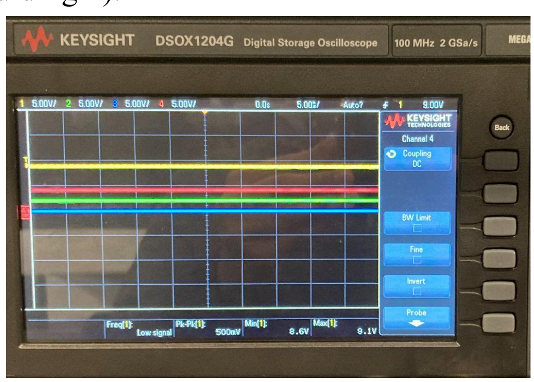

Figure 8: Verification of 'too hot' LED output. Yellow is input, green is hot threshold, blue is cold threshold, red is LED output.

We also tested all other possible states of the input and hot/cold thresholds, verifying that the LED output was low for all of those states. We repeated this type of verification for the other two LED outputs, namely the 'too cold' and 'error' LEDs. With this verification done, we verified the completion of milestone 6.

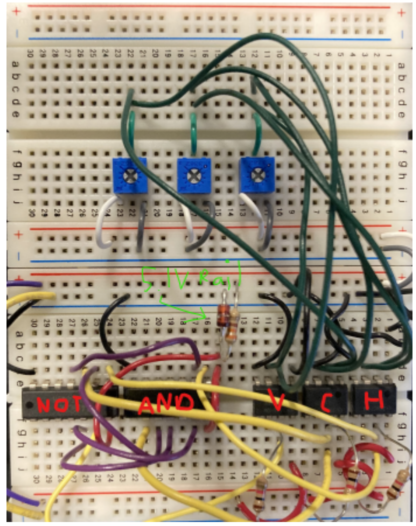

Figure 9: Completed milestone 6 circuit

Week 8:

This week we transferred the milestone 6 circuit to the large breadboard, built the milestone 3 circuit (7-segment display output), and received the thermopile sensor, which we began testing.

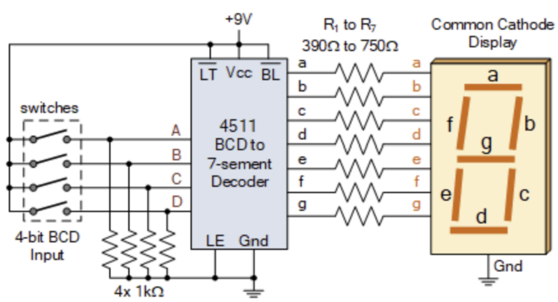

Figure 10: Milestone 6 circuit, switches will be replaced by output from milestone 2

For milestones 6, the transfer happened successfully. For milestone 3, we built the circuit but we did not yet test it because the thermopile arrived and we wanted to test that instead.

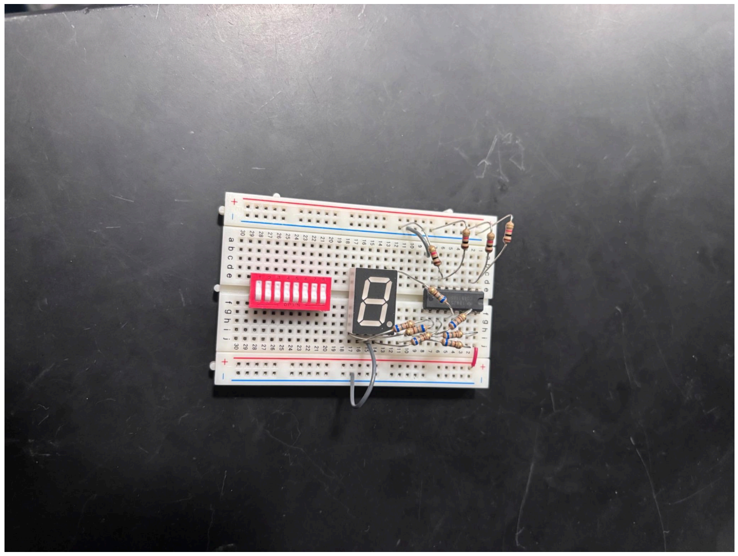

Figure 10: Completed 7-segmented display circuit with driver and testing switches

We built the milestone 3 circuit with switches because we did not have the output of milestone 2 yet, so we could debug by simply turning the switches. However, the switches will later be replaced by the binary output of milestone 2.

For the thermopile testing, we tested it by probing pins 1 and 3 with the oscilloscope, and put objects of varying heat levels over it.

ELECTRICAL CONNECTIONS

Pin	Symbol
1	TP +
2	NTC
3	TP -
4	GND

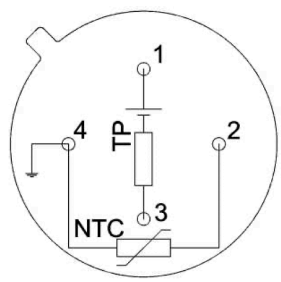

Figure 11: Pin configuration for thermopile

However, we were not able to detect whether the thermopile was actually responding to temperature changes. Theoretically, since the temperature of the human body is about 37 Celsius, the thermopile voltage should see a change from room temperature to when it's reading our hands. However, it was very inconsistent, displayed a lot of noise in its output voltage, and often seemed like it didn't respond to our hands.So, we decided to use the heat gun in order to try to induce a change in the thermopile output. Although the heat gun did change the output, it changed it by about 10 mV, while the datasheet states that the operating range of the thermopile is about 8 mV, so we believe that the thermopile isn't meant to operate in those conditions. Additionally, we realized that since the sensor is IR, it likely shouldn't respond to the heat gun's temperature changes. Lastly, we realized we were testing without plugging in the built-in thermistor in the thermopile, which it uses to detect the absolute temperature, which could have been causing the issues.

Week 9:

This week we tested the milestone 2 comparator circuit, the milestone 3 7-segment display, and the thermopile.

For milestone 2, since we didn't receive the 10-4 priority encoder yet, we would just check the outputs of the comparators. Our idea was to probe two comparison voltages (the voltage corresponding to temperature, for example the voltages could be corresponding to 10 and 20 degrees celsius), and use a power supply for an input voltage that's between the two comparison voltages, and see if the comparators work as intended. However, we found that it didn't work, so we analyzed the LM339 chip more closely. Originally, we planned to use LM311 comparators, but they are less space efficient and we needed 10 of them, so we switched to the much more compact LM339. However, when we tested the LM339 chip in isolation, it didn't behave the same way as the LM311, it didn't go high if the + input was higher than the - input or if it was lower. So, we had to do further research in the coming weeks on how to get the LM339 to work.

For milestone 3, we tested it by using a switch for the inputs, and giving it binary combinations to see if the 7-segment display would light up accordingly. For example, we would flip the third switch, giving the circuit 0100 and seeing if it gave 4 on the display. However, it didn't work as expected and further testing would need to be done.

For the thermopile, we added the voltage divider for the thermistor that was recommended to us.

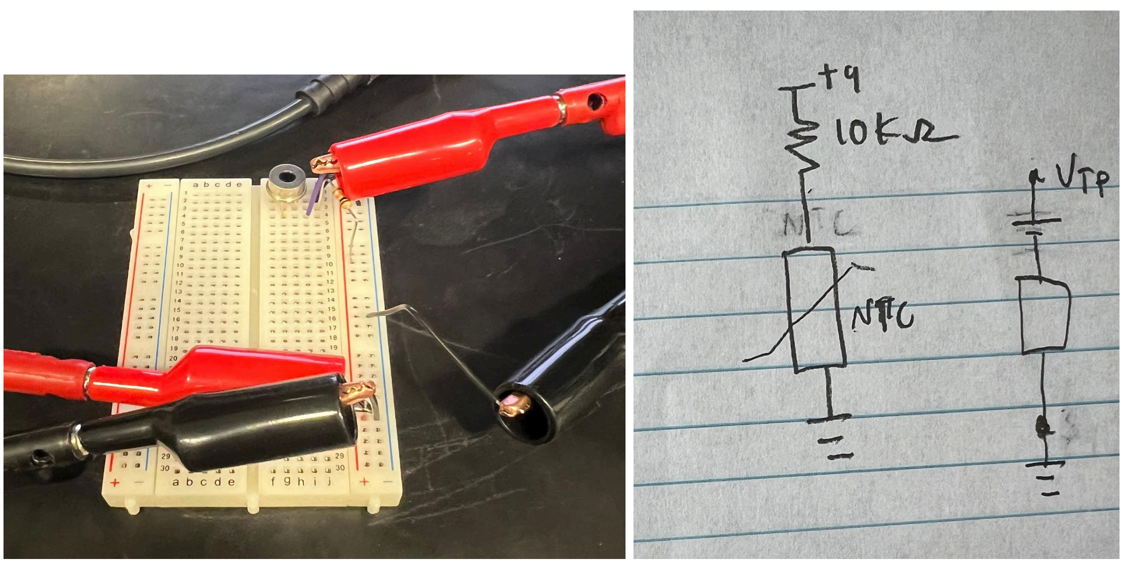

Figure 12: Oscilloscope setup and circuit schematic (note: the NTC thermistor and the thermopile on the right are integrated into the sensor)

We then proceeded to try putting our hand over it and look for an associated change in the output voltage. Sometimes, it seemed like it would work, but other times it wouldn't. So, we instead tested it by heating a water bottle with the heat gun, and putting the water bottle over the sensor.

This also seemed to work sometimes, but was again inconsistent. Overall, we weren't sure whether the thermopile would work or not, and we would have to do further testing.

Week 10:

We continued to try getting satisfactory output from our thermopile by consulting our mentor, and got the idea to use a differential amplifier. We noted this but didn't construct that circuit as we decided to focus on wrapping up other milestones. We completed milestone 2, our analog-to-digital converter, after successfully replacing many LM311 comparators with just three LM339 comparators by adding a pull-up resistor at each output. We also tested and completed milestone 3, the segmented display.

Milestone 5 was also well underway, but there was a problem. One of the digits was not lighting up correctly, despite referring to the same voltages from the lookup table. We consulted the Head TA, Jason, and got his approval to use an Arduino Uno for this milestone as there was limited breadboard space, and the mapping to the lookup table of the thermopile would be more effective in code rather than manually tuning another ADC.

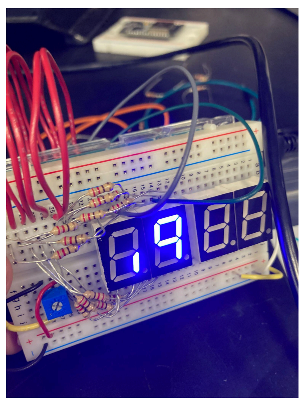

Figure 13: Display progress in milestone 5 - digit should be 19

Week 11:

This lab, we focused on documenting oscilloscope graphs and videos of our milestone circuits. In milestone 5, we created both hot and cold thresholds. We swapped 330 ohm resistors for 220 ohm resistors, and connected all four digits together with wires to allow more current to go through them. After fixing some additional loose connections, the circuit worked properly for all four digits. We added a second potentiometer analog input to work on the second set of 7 segment displays. This is the Arduino file used[9].

We also fixed an error in the milestone 2 circuit where we had reversed some of the connections in the comparators, which we figured out from the oscilloscope output being different from our expectations.

We also got the priority encoder chip, so our plan for next week is to integrate it with the rest of the components of the project.

Week 12:

At this point of the semester, getting our thermopile sensor to was becoming more and more crucial to the overall progress of the project. We tried a different circuit to test it as seen in the figures below (https://www.instructables.com/Thermopile-Sensor/ and https://www.amphenol-sensors.com/hubfs/AAS-930-306A-Thermometrics-IR-Detectors-060624-web-1.pdf). This circuit aimed to amplify the output and simultaneously reduce noise, because those were two highlights of the outputs we got in any of our tests with the thermopile.

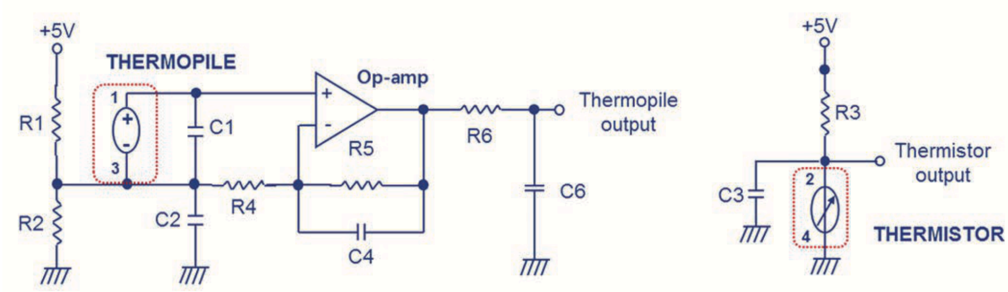

Figure 14: Reference circuit (a)

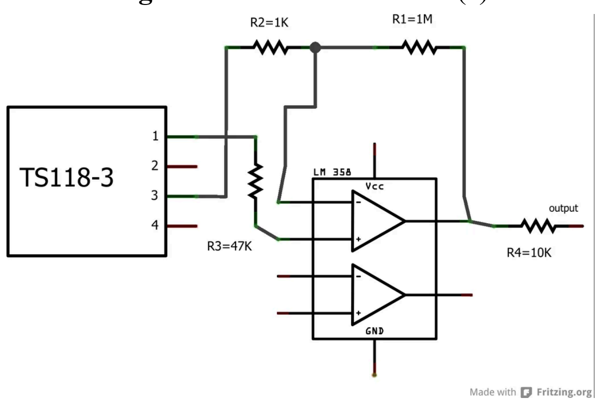

Figure 15: Reference circuit (b)

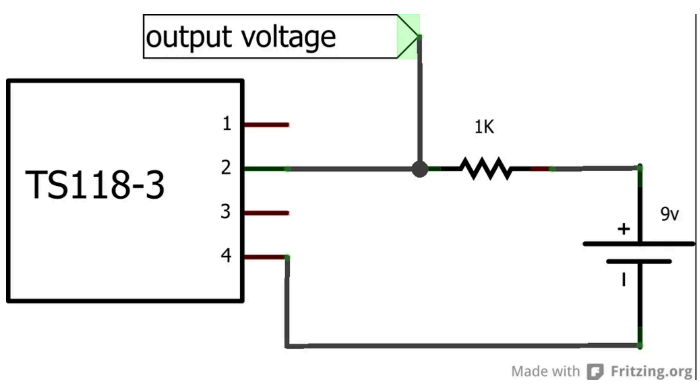

Figure 16: Reference circuit ©

This did not produce satisfactory results, so we decided to look for a touch-based sensor as back-up. We finalised on the TMP 36 sensor[10].

Additionally, we connected milestone 2 (ADC) to milestone 3 (binary to display) with the 10-4 bit priority encoder and hex inverter, and tested for all temperature intervals. By providing the voltages from our lookup table, we got the expected 10th place of accuracy for the temperature. We added a hex inverter because the output of the priority encoder chip was the inverse of what was expected.

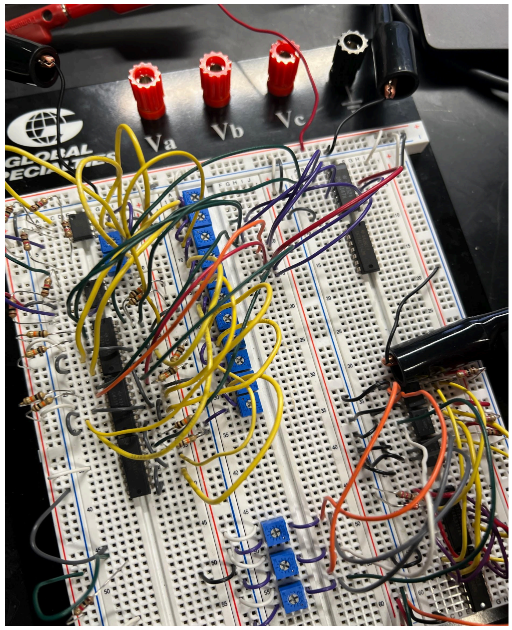

Figure 17: Completed milestone 2, priority encoder and hex inverter at top right

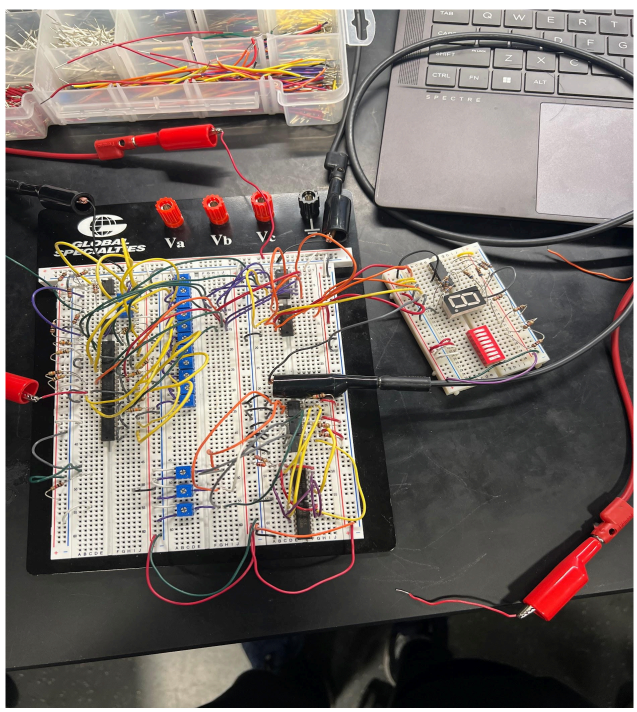

Figure 18: Overall circuit so far, we have milestones 1-3 integrated, and milestones 5-6 integrated.

We discussed plans to pivot to a touch sensor, since the sensor is a crucial component of the project and more work would be required next week to finalize the project with the sensor output. Also, our plans for milestone 4 (voltage subtractor for one's place of temperature accuracy) were based on whether we had enough time in the upcoming weeks. The next week's priority is to also debug milestone 6, where the AND gates (in the error and threshold LEDs) are not working as expected.

Week 13:

We got the TMP 36 - touch-based sensor, tested it, and finalized that as our sensor for the project. According to the datasheet[11], we powered the sensor with 3 V and built a separate amplifier circuit because we did not need our adder. This sensor gave a linear output, and all temperature ranges were in the positive voltage range.

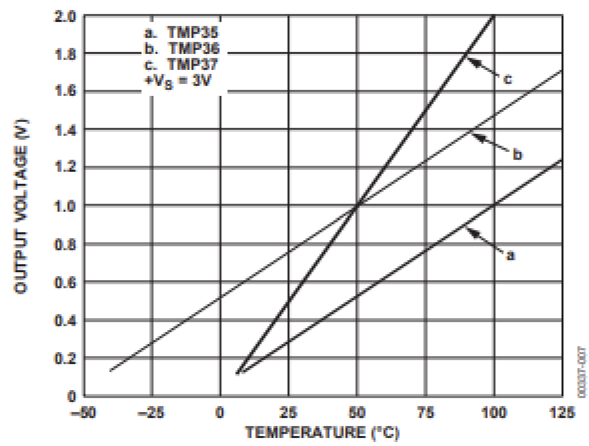

Figure 19: Linear output for voltage vs. temperature (from linked datasheet)

We decided on a gain of 4.6 as this was sufficiently high voltage to work with the rest of the circuit. All the potentiometers from milestone 2 (ADC) needed to be tuned to the same value because the output voltage is linear to the change in temperature.

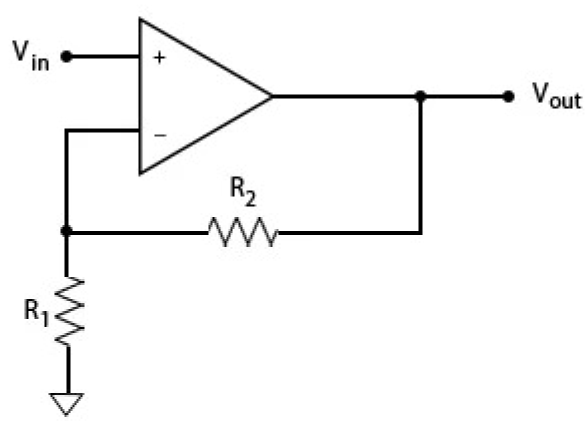

Figure 20: Non-inverting amplifier circuit used for the TMP 36

Temperatures vs voltages for the TMP36:

Temperature (celsius)	Output voltage (volts)	Output voltage after amplification (volts, we amplified with gain 4.6)
0	0.5	2.335
10	0.598	2.793
20	0.696	3.250
30	0.794	3.707
40	0.892	4.165
50	0.99	4.554
60	1.088	5.0048
70	1.186	5.4556
80	1.284	5.9064
90	1.382	6.3572
100	1.48	6.808

Then, we connected the new amplifier circuit (TMP output) to the comparator's input. We tuned all the comparator circuit voltages, (potentiometers were all the same resistance - tuned to maximum) and tuned the amplifier gain to match the above table. Finally, we tested it using objects of known temperature. When one of us touched the sensor (human body = 37 C) the display changed from 20 to 30. On heating a water bottle using a heat gun, we saw the display change from 20 to 60. The display numbers gradually reduced back to 20 when the objects were removed.

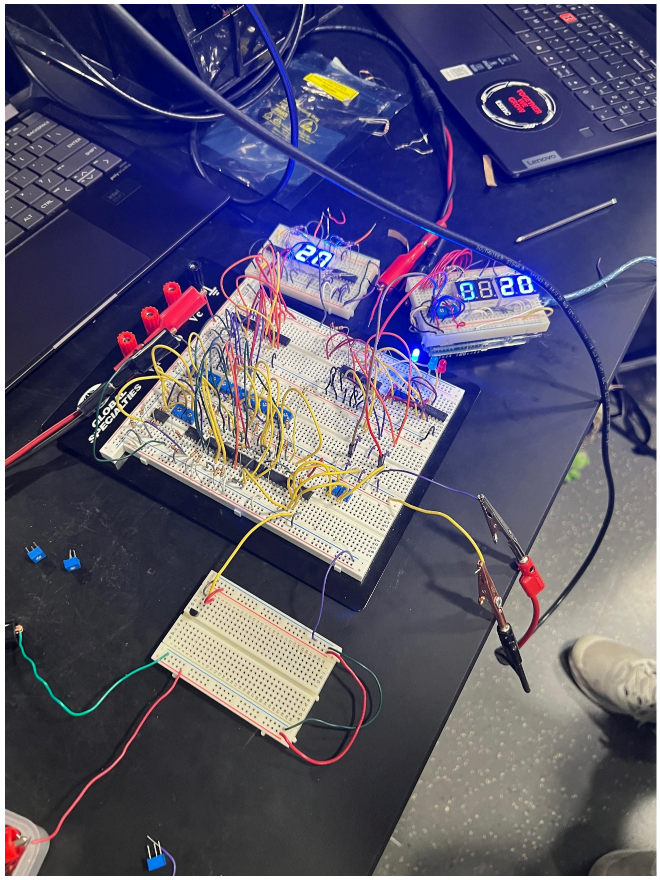

Figure 21: Final circuit

Conclusions and Future:

As the project slowly comes to an end, we reflect on our experience with this project. For the future lab sessions, we will make a voltage adder of 2.335 volts for milestones 5 and 6 to work, as when we were integrating all milestones on the big breadboard, there was a cap at 1.1 volts. Aside from that, we felt that we spent a lot of time testing the touchless temperature sensor in the hopes that it would work, but it ended up being discarded from the plan. We learned that we didn't need to spend too much time on something that was unlikely to work. With that additional time, we could have focused on improving the circuit using the touch-based sensor, or perhaps in building the circuit to give us the one's place of accuracy in the temperature reading.

References:

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