Heat-N-Cool Coaster

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Abstract

Many drinks need to be prepared to an optimal temperature to be fully enjoyed, but their temperatures need to be modified from their initial storage temperatures. Common household appliances that achieve this functionality, like microwaves and refrigerators, are often inaccessible and expensive. The previous group's solution to the problem involved an encapsulating box that could heat and cool a drink inside of it through indirect heat transfer. Our solution modifies this process by implementing a coaster that the drink will rest on, allowing for direct transfer of heat to allow for more efficient heating and cooling, with system control being dictated by a smartphone application on which users can define their desired drink temperature.

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1 Second Project Motivation

1.1 Updated Problem Statement

To be fully enjoyed by a consumer, many drinks, like hot coffee, need to be prepared to an optimal temperature. The problem is that the initial temperature of a drink is correlated to the temperature it is stored in, without prior preparation. The storage temperature range can vary from frozen to chilled to normal room temperature. The most common way of changing the temperature of a drink from its storage temperature would be through the use of a refrigerator or microwave, but these appliances are not always affordable and accessible to everyone, as mentioned in the "Electric Thermos Box" project from the Spring 2020 semester [1]. Furthermore, these appliances are not capable of taking user inputs to cool or heat drinks to a desired temperature range.

The problem we are trying to solve is essentially the same as the "Electric Thermos Box" project. In that project the solution was to have a thermos that could heat/cool a drink to a certain temperature set by the user [1]. This problem is important because if hot drinks like coffee are not served at an optimal temperature, the experience of drinking them will not be satisfying. According to a study published in *Nature* journal, there exist TRPM5 sensory channels within our taste buds [2]. TRPM5 receptors are responsible for the varying perceptions we experience when tasting foods and drinks at different temperatures. The reactions of TRPM5 send intense signals to the brain that result in an enhanced ability to distinguish taste when consuming food and drink at higher temperatures. These electric signals sent to the brain are not as intense when consuming lower-temperature foods, like ice cream. In order to make sure that hot beverages can thus be fully enjoyed by our TRPM5 receptors, it is important to define an optimal temperature range that our coaster can warm up a user's drinks to. A study done by MEDLINE defined how hot beverages like tea, hot chocolate, and coffee are frequently served in restaurants within a range of 160-185° F, even though severe scalding of the mouth can occur even with light exposure to these temperatures. By surveying 300 subjects to find the balance between limiting scalding hazards and maintaining the drinks to an optimal temperature at which they are still satisfactory, the study's researchers were able to approximate the optimal drinking temperature to be 136° F [3]. Given the conclusion of this study, we decided to set 136° F, or about 58° C, as the upper bound of our coaster's heating capabilities in order to ensure that our product will prepare the user's drink to a satisfactory temperature while simultaneously limiting the dangers of burns during consumption.

1.2 Updated Solution

To address the problem of inaccuracy and inefficiency in controlling drink temperatures, we propose a drink coaster that will emit a user-defined temperature, as mentioned in the previous section. Users can control the coaster through an external smartphone app connected through Bluetooth in order to heat and cool their drinks to a desired temperature within a specific range. We believe that our product would be useful for people who do not own the appliances mentioned above, or for those that want a simple and efficient way to modify the temperature of their drink. In addition, the portable nature of the coaster affords users the luxury of taking it on-the-go to heat and cool their drinks, something that is not afforded by major household appliances.

Although there are some electric powered coasters on the market, there are a few key differences that make our solution unique. One such coaster available to purchase is the Per Coffee Mug Warmer, which is a small coaster that can keep the cup of a hot drink warm [4]. This differs from our solution as there is no ability to cool the drink, and a temperature cannot be set externally to bring the drink to a certain temperature. Similarly, the Drink Induction Chiller is a thermoelectric coaster that can keep a cool drink refrigerated given several different cups [5]. However, this solution provides no means to heat a drink, and there is also no ability to request a specific temperature for the drink. Looking at various electric coasters on the market, our solution stands out to both heat and cool a drink on the same coaster. Along with this, having a smartphone application to allow the user to set what temperature they want their drink gives another clear difference between our solution and ones on the market. Additionally, the “Electric Thermos Box” included the design of a box that was fitted with multiple Peltier modules that would encapsulate the user’s drink and heat it up through indirect contact [1]. Our design removes the need for the surrounding box and offers a portable coaster that can heat up drinks through direct contact with the Peltier module within the design. Below is a further discussion of how our project differs from the “Electric Thermos Box” and how we plan to improve the design in terms of heating techniques and user interface.

A core area of analysis that greatly impacts the performance is the difference in heating techniques proposed by the prior team compared to our implementation. The prior group’s design mostly focused on the box shape to heat the drink via convection and conduction while our project seeks to simplify the process down to strict conduction through more direct contact [1]. We can observe via the heat transfer equation shown below in Equation 1 [6]:

$$Q = mc\triangle T \tag{1}$$

where Q is the rate of heat energy flow for the system, m is the mass of the heated substance, c is the specific heat of the system, and $\triangle$T is the change in temperature of said system that the change in temperature of the drink is proportional to its intake or production of heat energy. One key distinction between convection and conduction is the specific heat of the heat transfer mediums is higher within air (1.020 J/(g*K)) than a conducting surface that we plan to place the drink on [7]. Referring back to the efficiency discussion held in the Tolerance Analysis section, this higher specific heat would inherently act as more of insulating material compared a conductor such as aluminum with a specific heat capacity of 0.900 J/(g*K) [7]. This would incur more losses and fail to significantly change the temperature. The losses here are inversely proportional to the specific heat capacities shown via Equation 1 above due to Q modelling heat loss in the medium. This tells us that heat transfer through aluminum is significantly more efficient compared to that of air. This fact drastically lowers the effectiveness of the design choice to have Peltier modules on the sides of the “Electric Thermos Box” as it would have significantly less efficiency than the our design with the module on the bottom of the device. Therefore, by keeping the device more concise and sticking to purely conduction heating we are making a more user-friendly device and increasing the efficiency of the overall system.

The second main area of improvement to the prior design is the replacement of the hardware user interface buttons with a software user interface phone application. As discussed in the energy flow section above, being near the Peltier modules allows for energy transfer between the Peltier and the outside device. Looking at the design of the “Electric Thermos Box,” the placement of the buttons on the top of the box would not pose significant threat to the user’s safety as they would be away from the Peltier heat sources [1]. Due to the more compact nature of this design, heat interaction with potential buttons on our design can pose an issue. This is because there would be significantly less air space between the user interface and the heating modules. Modelling the available buttons using the Schurter 1301.9314 Push Button Switch we can see from the datasheet that silver is the main contact within these buttons [8]. The specific heat for silver is 0.240 J/(g*K) which shows that silver is an extremely efficient conductor of heat and thus the temperature increase will be very high even with a small amount of energy added to the system [7]. From the datasheet of the Peltier module, we know that the system can release 50 J of energy each second [9]. Assuming 10% of the heat energy from the Peltier is transferred into the buttons and that the silver content of the button is approximately half of the button’s weight of 0.12 g, the increase in temperature of the button per second would be approximately 22.6° C which would reach an unsafe temperature to touch after only a few seconds of use.

1.3 Updated High-Level Requirements

- A portable drink coaster that includes a temperature sensor, pressure sensor, and power supply that can heat and cool 1 cup (250 grams) of a liquid. LEDs must also be present on the coaster to indicate when the coaster is heating, cooling, or inactive.
- Given the drink is initially at room temperature (~23° C), the coaster must cool or heat it within ± 35° C and must do so in a timely manner, between 10-20 minutes depending on the temperature set by the user.
- A paired smartphone app connected to the coaster via Bluetooth will allow users to set the coaster to a desired temperature.

1.4 Updated Visual Aid

The design of the coaster depicted in Figure 1 will allow for users to place their standard-sized mugs upon the silver heating/cooling pad featured in the middle of the design. This pad will feature a Peltier module that can be used to then manipulate the temperature of the drink to the temperature that the user has defined on the smartphone application, which will be connected to the coaster via Bluetooth capability. The blue, red, and green LEDs on the front of the design will be used to indicate when the coaster is cooling, heating, or ready for use, respectively.

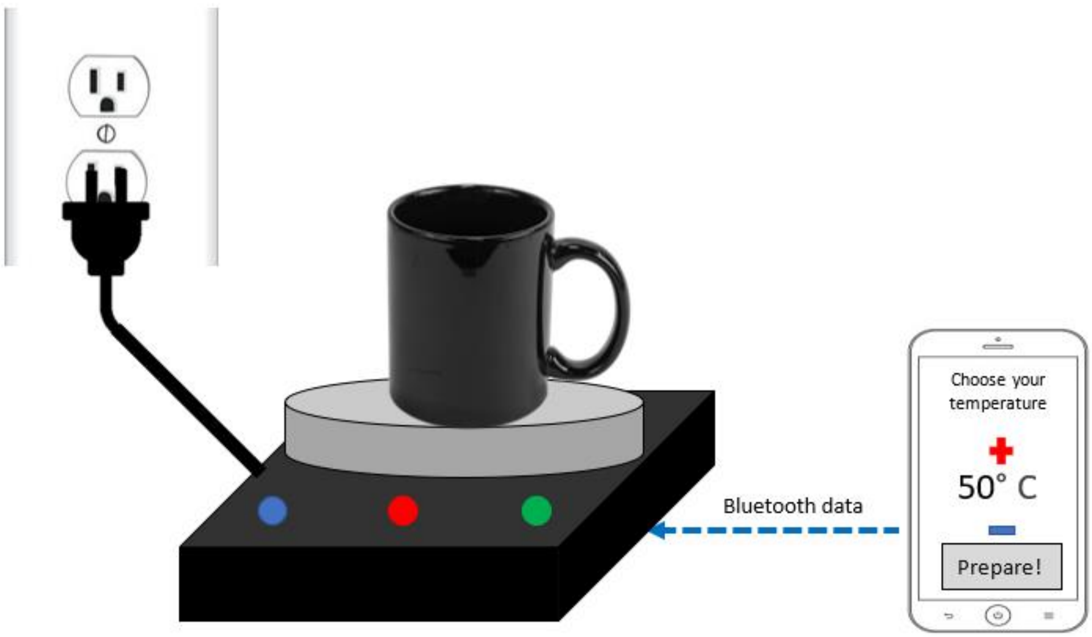

Figure 1. Visual Aid for Scale

1.5 Updated Block Diagram

The diagram featured in Figure 2 consists of six subsystems that each serve their own purpose that contribute to the overall function of the coaster. The power subsystem is what is responsible for providing power to the other various subsystems found within the coaster. Since the heating and cooling subsystem requires significantly more power than the other subsystems, we have decided that our coaster will need to draw power from a wall outlet, after which it will be passed through an AC/DC converter so that approximately 12 V DC is passed into the Peltier module through the H-bridge in the heating/cooling subsystem. All other subsystems, excluding the software user interface system, can be powered through a lithium ion battery that is regulated to output 3.3 V. The software user interface subsystem is simply an external phone application that is paired to the coaster via Bluetooth. This subsystem sends information to the Bluetooth transceiver within the control subsystem, which will notify the microcontroller that some heating or cooling process must occur. The microcontroller will then send a control signal to the Peltier module to initiate the desired process, and a 3.3 V PWM to the H-bridge to begin cooling or heating. Accordingly, this data is sent to the status LEDs in the hardware user interface subsystem to light up the corresponding LED. While this occurs, the sensing subsystem is polling for data relating to the presence and temperature of the liquid on the coaster and sends this data to the microcontroller. Once the microcontroller sees that the temperature of the liquid matches that of the inputted temperature, it will send another control signal to the heating/cooling subsystem to notify it to stop its current process, and will send data to the LED in the user hardware interface subsystem to notify the user that the drink is ready.

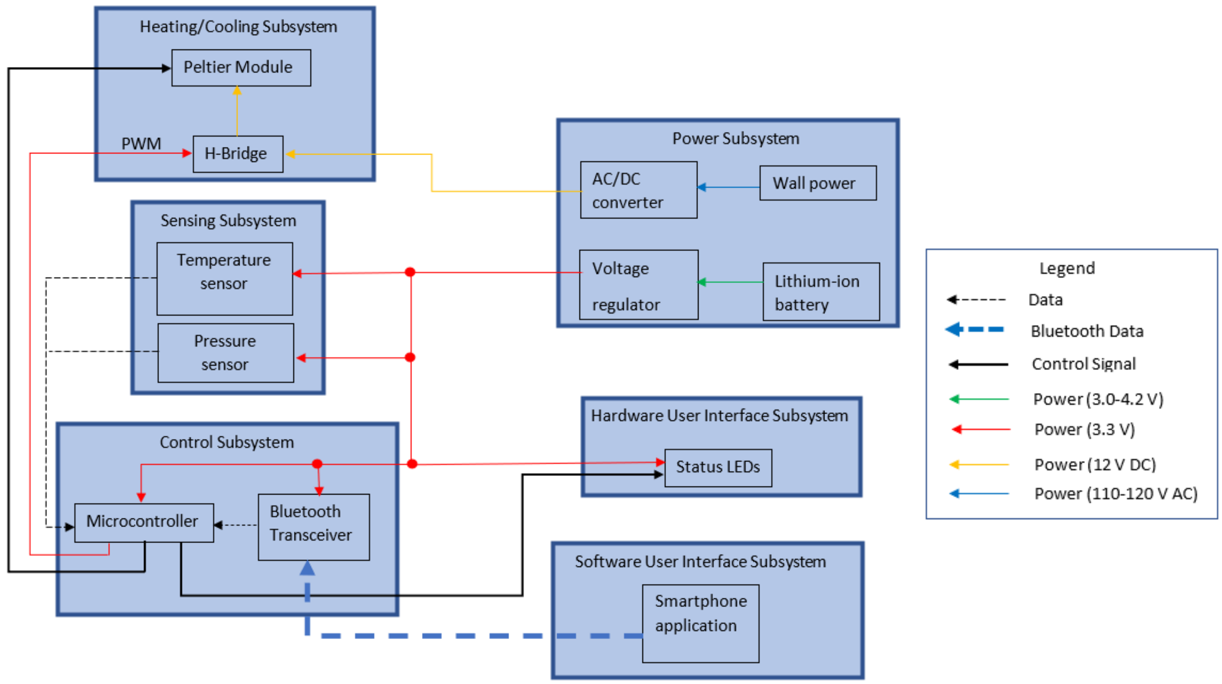

Figure 2. High-Level Block Diagram

2 Second Project Implementation

2.1 Power Subsystem

A source of power will be needed to supply the sensing, heating/cooling, control, and hardware user interface subsystems. All of the subsystems mentioned here except for the heating/cooling subsystem can be powered by a lithium-ion battery, which will have its voltage regulated by a voltage regulator to pass 3.3 V to power the rest of the subsystems in the design. As mentioned earlier, the heating/cooling subsystem requires significantly more power than a lithium-ion battery can provide, which is why it will need power from a wall outlet that is passed through a AC/DC converter to supply 12 V to power the Peltier module. The requirement and verification tables for the power subsystem are detailed in Tables 1-3 in Appendix A.

2.1.1 Lithium-ion battery

The lithium-ion battery will be used as the source of power for everything except the heating/cooling subsystem, providing the coaster's sensors, microcontroller, and LEDs with continuous power to allow for uninterrupted use. These subsystems must be powered by the lithium-ion battery for an extended period of time. Once the lithium-ion battery has run out of power, the coaster design must allow for easy removal and replacement of the battery. These requirements can be seen in Table 1 in Appendix A.

2.1.2 Voltage Regulator

Since the voltage range of the lithium-ion battery fluctuates between 3.0-4.2 V, there will be a voltage regulator connected to the lithium-ion battery that will be used to provide a constant 3.3 V supply of power to all subsystems, excluding the heating/cooling subsystem. This can be accomplished using a buck-boost converter, which will handle any fluctuations in voltage outputted by the lithium-ion battery. A circuit schematic for the buck-boost voltage converter is seen in Figure 3, and requirements for the voltage regulator are found in Table 2 in Appendix A.

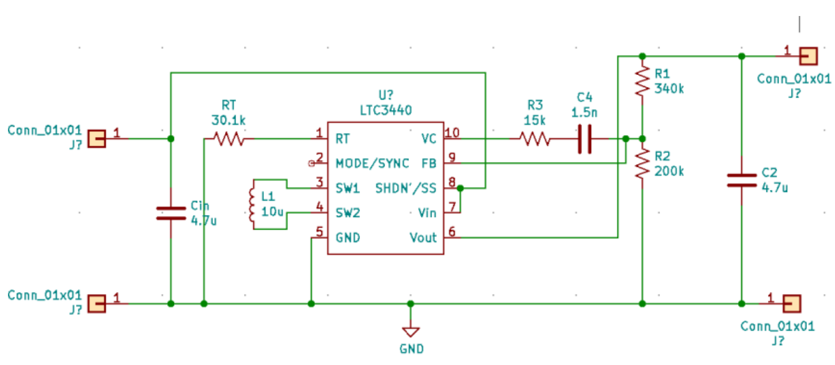

Figure 3. Circuit Schematic of Voltage Regulator

This voltage regulating circuit seen in Figure 3 is a buck-boost converter that can handle battery fluctuations from 3.0 to 4.2 V. The circuit takes in the input voltage from the battery on the left two pins and outputs 3.3 V on the right two pins when the input voltage is sent through the IC buck-boost. It is important that the correct inductor between SW1 and SW2 are selected. Input and output capacitors will help stabilize the voltage within the circuit design by maintaining a stable and efficient DC input.

2.1.3 Wall Outlet Power

To efficiently use the Peltier module, we will include wall outlet power to provide power with a higher voltage and current output. This will be utilized by using an AC/DC converter to then power the Peltier module. To ensure that the Peltier module is receiving the appropriate voltage it needs to operate efficiently, our design must draw power from a wall-outlet, which should be regulated between 110 - 120 V AC power, which we cannot verify with a voltmeter. This power can then be routed to an AC/DC converter to feed the correct DC power into the H-bridge within the heating/cooling subsystem.

2.1.4 AC/DC Converter

Due to the large power requirement of the Peltier Heating module there is the need for an additional power source with a higher voltage and current output. Implementing wall outlet power is the simplest and cheapest way to achieve such power ratings, however, this will require an AC/DC converter to bring outlet power down to a manageable 12 V required for the Peltier module [10]. The requirements for the AC/DC converter are as seen in Table 3 in Appendix A.

2.1.5 Power Analysis

Assuming a 17.5% efficiency as calculated within Section 2.3.1 remains constant at various temperatures, we can calculate the amount of power required to heat liquid up to the extreme temperatures suggested within the high-level requirements. For this the system needs to heat and cool to approximately 58 and -12° C. Assuming the liquid we want to heat is 250 grams and has a similar heat capacity compared to water (4.186 J/gram° C) it would require 36,627.5 J using Equation 1 [7]. Using the maximum allotted time by the high-level requirements of 20 minutes we can see that the power required to heat the drink is 30.52 W. Using the conversion from electrical power to heat power we can see that the electrical power needed would be 174.42 W.

2.2 Sensing Subsystem

The sensing subsystem of the coaster will include a temperature sensor and a pressure sensor to measure the amount of fluid and the initial temperature of the fluid. This data will be sent to the control subsystem to determine when the coaster should halt the heating/cooling process and send this information to the control subsystem. The requirement and verification tables for the sensing subsystem are detailed in Tables 4 and 5 in Appendix A.

2.2.1 Temperature Sensor

The temperature sensor will be used to measure the initial temperature of the drink before heating/cooling, and continuously monitor this temperature during the process. Per the requirements in Table 4 in Appendix A, the sensor then sends this information to the control subsystem, which will halt the process once the temperature reaches the temperature defined by the user on the application.

2.2.2 Pressure Sensor

The pressure sensor will be used to measure the amount of fluid in a drink, and the requirements for its use are found in Table 5 in Appendix A. The information collected by the Round Force-Sensitive pressure sensor will be used as one measurement to determine how much heating/cooling is needed to reach the desired temperature set by the user [11]. This information, along with the data outputted from the temperature sensor, will be sent to the microcontroller within the control subsystem to accurately heat up a given amount of fluid to the precise temperature defined by the user.

2.3 Heating/Cooling Subsystem

The heating/cooling subsystem will perform the heating/cooling of the drink given information from the sensing subsystem that is fed into the control subsystem, which will then send a control signal to this subsystem to begin heating or cooling. The requirement and verification tables for the heating/cooling subsystem are detailed in Tables 6 and 7 in Appendix A.

2.3.1 Peltier Module

The Peltier module will serve as the primary function to be controlled within the project and should be located on top of the coaster to allow easy contact with the cup on top of it. It is a thermoelectric module that acts as a small heat pump, transferring heat between each side of the device [12]. This gives the ability for an object to be heated/cooled on one side of the device while the other side has the opposite effect. The outer half of the module is where the drink will be placed, allowing for the necessary heating/cooling to be done while the other side is not in contact with the user. These requirements are laid out in Table 6 in Appendix A.

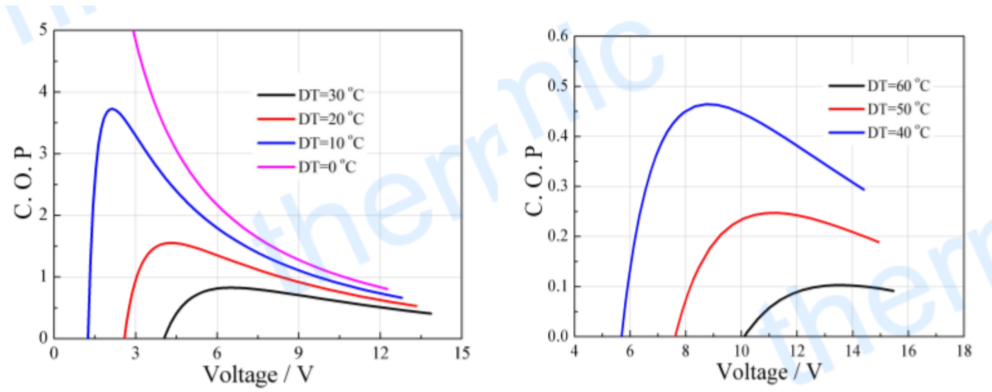

Figure 4. Performance Curves for Peltier Module

Seen in Figure 4 are the performance curves for the Peltier module at various temperatures when placed in an environment of dry air, 27° C, which corresponds to the initial temperature range of the drink on the coaster. On the x-axis is the input voltage and on the y-axis is the coefficient of performance (C.O.P), which is the cooling power over the input voltage [13]. We can see here that performance varies inversely with voltage, and with an input voltage of 12 V from the H-bridge into the Peltier module, this performance is relatively the same for lower temperatures, while the C.O.P. for higher temperatures differs by about 0.1 per 10° C.

Given the cost of Peltier modules, which will be the main feature of the heating and cooling subsystem, we are limited in how many we can implement within our design. Therefore, it is important to take note of the heat efficiency of our coaster given that our design will only be using one Peltier module. For the purpose of estimating efficiency we can use the knowledge that water has a specific heat of 4.2 kJ/(kg * °C), meaning that it takes 4.2 kJ of energy to heat 1 kg of water by 1° C. To meet our requirement of heating 250 g of water, we can divide this specific heat by 4 to get a necessary 1.05 kJ of energy needed to heat the water by 1° C. We can then calculate the power needed to do so using Equation 2 [14]:

$$Power = Work / Time \tag{2}$$

Let us say that we want to heat a cup of water by 5° C within 10 minutes which is the lower end of our time range. 1.05 kJ * 5 = 5.25 kJ and 5.25 kJ / 600 s = 8.75 W which means 8.75 W would be the power necessary for the coaster to make the heating happen successfully. However, when taking into account the given efficiency equation, we can see from Equation 3 that this power efficiency changes based on how many Peltier modules we implement [15].

$$Efficiency = (Work / Heat\ Input) * 100 \tag{3}$$

Factoring this equation in, we know from the Peltier module datasheet that it gives 50 W of power [9]. With the use only one module, we would have an efficiency of (8.75 W / 50 W) * 100 = 17.5%. When increased to 3 modules, the efficiency would be (8.75 W / 150 W) * 100 =

5.83%. We can see that by increasing the number of Peltier modules we use, the heat efficiency will lower, justifying our choice to use only one Peltier module in our design.

Examining this further, if we know that 8.75 W of power is needed for the coaster to heat a cup of water by 5° C within 10 minutes, we can calculate what the surface temperature of the Peltier module would need to be. We can use an equation for conductive heat transfer which is expressed by Fourier's Law as follows in Equation 4 [16].

$$Q = (k/s) * A * dT \tag{4}$$

We will use the assumption that a standard ceramic mug will be used to hold the cup of water, meaning that the k value for thermal conductivity is 3.8 W/mK [17]. Given that the thickness of the bottom of a standard ceramic mug is 8.5 mm, we will divide this from the k value to get 447.06 [18]. Continuing with the assumption that the surface area of the bottom of the mug is 0.00515 m^2, we can multiply the area with 447.06 and then divide 8.75 by the resulting value to get dT = 3.8 [18]. This would mean that given that the initial temperature of the drink on the coaster is 27° C, the surface of the Peltier module would need to be 30.8° C. We can then make the assumption that if the temperature sensor is constantly polling the internal temperature of the heating pad that the Peltier module is placed on, the microcontroller would need to take this information and send a control signal to stop the heating or cooling process whenever the Peltier module's temperature is exactly 3.8° C away from the temperature defined by the user on the smartphone application.

Since our solution does not include any encapsulation of the coaster and drink, we felt it was necessary to analyze how this might affect the heating/cooling of the drink. For example, in a situation where the user would be using the coaster outside, there would be some heat transfer between the outside air and the drink. The equation for convection heat transfer is expressed in Equation 5 [19].

$$Q = h * A * dT \tag{5}$$

Following our previous example, let us say the drink is at 27° C and it is resting on the coaster outside. We are still trying to heat this drink by 5° C within 10 minutes. If it is a cooler day and the outside air temperature is 15° C then dT would equal 12° C. For the purpose of estimating this heat transfer we will say that the convective heat transfer coefficient for air is about 50 W/m^2K [20]. The surface area of the standard ceramic mug will then be used as the value of the area of heat transfer, meaning that A will equal 0.0286 m^2 [18]. These values multiplied together will result in Q = 17.14 W. Referring back to Equation 3 for heat efficiency, we can add this to the heat input and have an efficiency of (8.75 / (50 + 17.14)) * 100 = 13.03%. In this case there would be a 4.47% decrease in efficiency given that initially the efficiency was 17.5% without factoring in a scenario for outside air. While this drop in efficiency is not ideal, we believe our solution is still better suited to not have any encapsulation due to the portability and ease of use that a coaster provides. Having the one Peltier module heat/cool a drink through direct contact provides us with the best possible efficiency while maintaining the requirements for our coaster design.

2.3.2 H-Bridge Heating/Cooling Control

The H-Bridge motor driver will function as an available current and voltage inverter for the system which will allow for the dual ability of both heating and cooling [12]. By adjusting the switching frequency and duty cycle of the PWM input to the H-Bridge sent from the microcontroller's voltage output, the amount of heating/cooling that the Peltier module can output can be controlled [21]. As seen in Table 7 in Appendix A, the H-bridge must send a constant 12 V over 1 A power supply to the Peltier module in order for it to begin and continue heating or cooling.

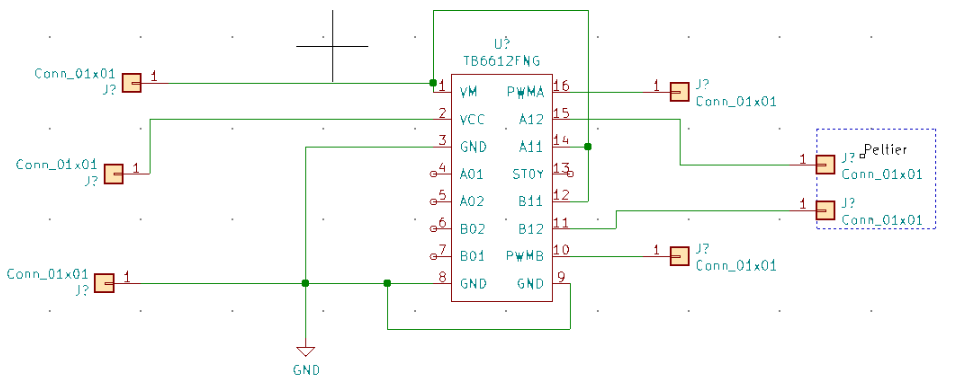

Figure 5. Circuit Schematic of H-Bridge

The schematic shown in Figure 5 shows the interconnection between the H-Bridge motor driver circuit to the Peltier module as well as the various inputs into the device to allow it to output a square wave from -12 V and -1 A to 12 V and 1 A to the Peltier. To do this the H-Bridge needs two 3.3 V PWM signals from the microcontroller which can control the frequency and duty cycle of this waveform. These PWM waveforms must be 180° out of phase with one another with some preset delay between the two cycles to avoid the H-Bridge temporarily shorting to ground. These inputs are shown on the right two connectors within Figure 5. The H-Bridge must also be fed power signals for turn on and its maximum voltage output magnitude. These signals are represented on the left side of the schematic and in order of top to bottom are: 12 V 1 A, 3.3 V Logic Signal, and GND.

2.4 Control Subsystem

The control subsystem will include a microcontroller that will be used to receive data from the sensors and use this to send appropriate control signals to the heating/cooling subsystem and status LEDs on the coaster. There will also be a Bluetooth transceiver connected to the microcontroller that will get information from the smartphone application regarding the user's desired temperature. The requirement and verification tables for the control subsystem are detailed in Tables 8 and 9 in Appendix A.

2.4.1 Microcontroller

There will be a programmable NRF52840-DK Microcontroller that will store data from the sensors and smartphone application. This information will be processed and used to control the heating/cooling of the coaster. It will also be used to activate the proper status LEDs to indicate the state of the coaster. These requirements are detailed in Table 8 in Appendix A.

2.4.2 Bluetooth Transceiver

Requirements for the Bluetooth transceiver are presented in Table 9 in Appendix A. The transceiver will be connected to the microcontroller and establish a connection between the coaster and the smartphone. Information about the user's desired drink temperature will be sent from the application to the microcontroller using this Bluetooth connection.

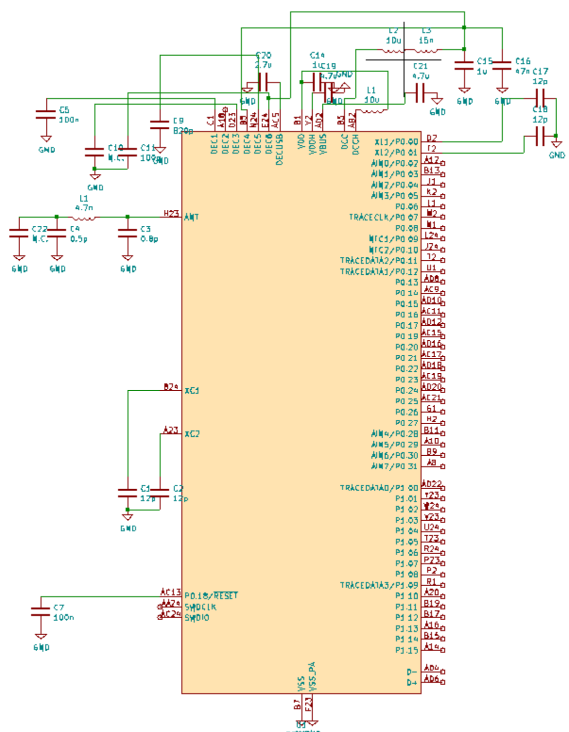

Figure 6. Circuit Schematic of BLE

The schematic in Figure 6 will be the central processing unit, Bluetooth transmitting device, and microprocessor for the design. As shown on the right of the schematic, the microprocessor has compatibility with SPI, I2C, and FIFO inputs via the general I/O pins. These data inputs align with the data types that will be fed out of the outputs from the sensors within the sensing subsystem, so the microprocessor will be able to process and store data from these inputs.

2.5 Software User Interface Subsystem

The software user interface subsystem will include a smartphone application that will send data about the desired temperature of the drink through Bluetooth to the coaster's transceiver within the control unit. This information will then be used by the control unit in conjunction with the sensing subsystem to ensure that the heating/cooling subsystem prepares the user's drink to the temperature specified on the application. The requirement and verification tables for the power subsystem are detailed in Tables 10 and 11 in Appendix A.

2.5.1 Smartphone Application

The smartphone application will have a simplistic user interface that allows the user to define what temperature they want the drink to be. After a temperature value is set the application will communicate this data to the coaster through Bluetooth. According to Table 10 in Appendix A, another one of the requirements is that the application has a user interface that is simplistic and easy for anyone to set or modify the temperature they want to prepare their drink to.

```
#include <iostream>

using namespace std;

int buttonPress = 1;
int buttonInput = 1;
int buttonState = 0;
int peltier = 6;

void setup() {
    pinMode(buttonPress, INPUT);
}

void loop() {

    buttonInput = digitalRead(buttonPress);
    if (buttonInput == 0){
        if (buttonState == 0) buttonState = 1;
        else buttonState = 0;
    }

    if (buttonState == 1) analogWrite(peltier, 255); // 255 = 5V
    else analogWrite(peltier, 0);
}
```

Figure 7. Code to Enable Peltier Module

Figure 7 shows two simple C++ functions that can be used by the smartphone application to toggle the Peltier module between an active and inactive state depending on button presses within the app. The code will first set up any button presses received to be an input that will toggle whether the button is active. If the button is in an active state, 5V will be sent to the Peltier module through the H-bridge. If the button is in an inactive state, no voltage is sent to the Peltier module. The user can toggle between these two states by clicking the 'Prepare!' button on the smartphone application as seen in Figure 1, dictating whether the Peltier module will receive an input voltage.

2.6 Hardware User Interface Subsystem

The hardware user interface subsystem will have status LEDs that correspond to the different states the coaster might have. This subsystem receives information from the microcontroller regarding which LED to light up during various stages of the heating or cooling process, always ending with the green LED lit to signify that the user's drink is ready.

2.6.1 Status LEDs

The status LEDs represent the different states of the coaster which are 'heating', 'cooling', and 'ready', corresponding to a red, blue, and green LED, respectively. They are controlled by a data output from the microcontroller which signals what state the coaster is in, which then activates the respective LED. The requirements for the intended implementation of the LEDs on the coaster are presented in Table 11 in Appendix A.

2.7 Bill of Materials and Total Project Costs

Assuming a ten hour work week, where each member of the group works at a $40 hourly rate, and accounting for a multiplier of 2.5 for overhead costs, our total cost of labor is can be calculated using Equation 6 [22]:

$$\textit{3 members} * \$40/\textit{hour} * 10\ \textit{hours/week} * 10\ \textit{weeks} * 2.5 = \$30{,}000 \quad (6)$$

We conclude that the total labor cost of our design process over the next 10 weeks will amount to $30,000. Listed in Table 12 in Appendix B are the parts to be implemented within the design, including information about the part manufacturer, part number and name, as well as the quantity of the needed parts. After all part costs have been added up, the total comes out to $139.40. Concluding our analysis, we find that the total costs of our project will be the sum of labor costs calculated with Equation 4 in and the total of the parts cost calculated in Table 12. The grand total of the project cost comes out to be $30,139.40.

3 Project Conclusions

3.1 Implementation Summary

There were many significant design choices that were made regarding the implementation of the project described in Chapter Two of this report. First, we all had to conduct research into which parts we wanted to include in our design. This led us to choose a specific microcontroller with Bluetooth transceiver capabilities included, discovered by Michael, which would be at the heart of our control subsystem. In addition, we needed a specific Peltier module to achieve our intended functionality of dual heating and cooling. This required research on the optimal temperature ranges that the Peltier module could function within, as well as calculations on the efficiency and heat flux provided by varying numbers of modules within our design, which were carried out by Vignesh. Further research, done by Nitin, was also required on how to power the heating and cooling subsystem, since it could not be powered by the single lithium-ion battery that was being used to power the other subsystems within the design. This led to the conclusion that wall power was necessary to supply this specific subsystem with the power it needed, which then led to us deciding to implement an AC/DC converter and an H-bridge in our design. With these additional parts, we could ensure that our problem statement of heating and cooling a drink past its initial storage temperature could be executed by our design. Finally, Michael succeeded in making schematics for the significant parts of our design, which helped us to visualize the inputs and outputs of these parts that would contribute to the overall functionality of the design as laid out in the block diagram. In turn, Nitin and Vignesh began developing an initial interface to be used by the smartphone application to receive user input data to be sent through the microcontroller to ensure functionality of the Peltier module. Though these implementations were mainly theoretical, we are confident in the design choices we were able to make without having access to the lab to physically test and debug our system.

3.2 Unknowns, Uncertainties, Testing Needed

In order to fully understand the scope of our project and how the parts we decided to include in our design all worked together, a lot of testing would have been necessary within the lab. Unfortunately, due to the circumstances of the ongoing coronavirus epidemic, this lab time was not afforded to us, but we have an understanding of what we could have tested had we been given the chance to work in the lab. First, we would need to test the limits of the connection between the Bluetooth transceiver within the coaster to the smartphone application as well as the microcontroller. The transceiver is what receives the information from the application to the microcontroller regarding temperature, and we would have needed further testing to see at what rate data is sent from application to transceiver to microcontroller. This would then impact the rate that the microcontroller can send PWM control signals to the H-bridge to specify the polarity for the Peltier module, as well as how often the microcontroller sends signals to the LEDs within the hardware user interface subsystem to change which one is lit up according to the current state of the system. Furthermore, we would test the temperature range of the Peltier module by using an external thermometer and a sample drink to ensure heating/cooling can be done within the required range. Timing this process would also allow us to test if our time range is appropriate and give us more information about exactly how long it takes for the module to heat/cool to certain temperatures. Lastly, we would test the coaster in outside environments to note any major changes in the heating/cooling functionality as well as how long it takes the Peltier module to bring the drink to the target temperature. This test could also be used in addressing any potential issues with the drink not being encapsulated by the design. We also would have required further testing on the data polling rate of the sensors within the sensing subsystem. With access to the lab materials, we could have determined how often data from the sensors is being sent to the microcontroller in order to provide timely updates on changes to the weight on the coaster determined by the pressure sensor, or the temperature of the drink determined by the temperature sensor. Overall, due to unforeseen circumstances we were really hindered in our ability to physically design many aspects of the project that would have depended on extensive access to the lab this semester.

3.3 Ethics and Safety

There is a potential ethical issue that the durability of the coaster would be compromised in situations that involve direct contact with objects or liquids that may damage or destroy the integrity of the circuit. Our product should "hold paramount the safety, health, and welfare of the public, ... strive to comply with ethical design and sustainable development practices, … [and] disclose promptly factors that might endanger the public or the environment," according to Code #1 of the IEEE Code of Ethics [23]. To circumvent this ethical concern, we will need to have a degree of water resistance for the outer structure of the coaster, in accordance with IP66 guidelines [24]. By doing so, we avoid potential issues where the user is shocked when spilling a liquid onto the device, or even further shorting the entire circuit design. Wires becoming exposed within our design are also a safety issue, especially given our design's use of high current to power the heating module. To combat this issue, our coaster's exterior should be composed of a durable and shock-absorbent material like plastic to nullify minor physical collisions that may damage the internal circuit or expose wires within the design.

Another possible damage and safety concern that could arise from the project include the heat generated from the Peltier module. According to the IEEE Code of Ethics #9, "to avoid injuring others, their property, reputation, or employment by false or malicious action" [23], this module must be insulated from the outside world and have clear indication of the high temperature when it is active within the devices. To deal with the safety concern of burning an individual there will be LED indicators for heating modes that are clear and easy to see. Another potential concern here is damage to the surface that the user has placed the device on. For this issue there will be a layer of insulating material between the heating device and the surface it is resting on.

Our coaster will be collecting information from the user's phone regarding the desired temperature. This can lead to an ethical concern over how the user's data is used and where this information is sent to. According to the IEEE Code of Ethics #5, "to improve the understanding by individuals and society of the capabilities and societal implications of conventional and emerging technologies, including intelligent systems" [23], the user's data that is currently on their phone will not be accessed by our application. Data that is sent from the user's smartphone to the microcontroller is being stored for the sole purpose of controlling the coaster and no other data will be accessed or sent.

The use of lithium-ion batteries within our design is also another safety issue given the risk of overcharging them. Though lithium-ion batteries are integral to our design given their small size and high-power output, their inherent danger is that they are extremely flammable [25]. The course staff recommends fire extinguisher and safety training when handling lithium-ion batteries that may catch on fire if excessively overcharged, discharged, or exposed to extreme temperatures. In addition, our design will incorporate a threshold circuit to ensure that the voltage from the lithium-ion battery does not exceed the range of 3.0 - 4.2 V, as well as a voltage regulator circuit. To ensure that we follow the guidelines set in place by course staff for safe practice with lithium-ion batteries, any of our tests that involve charging and discharging the battery will need to be done when the battery is contained inside of a lithium safety bag. Additionally, two TAs will also need to approve the design of our charging/discharging circuit to make sure that they are not hazardous to others [25].

To ensure that our team has the necessary knowledge to work efficiently and safely within the design lab, it is also imperative that we successfully completed the Lab Safety Training provided to us by the course staff. By having done so, we are acting in accordance with policies regarding Campus Environmental Health and Safety as defined by the University of Illinois at Urbana-Champaign, in order to conduct "university operations in compliance with all applicable laws and regulations … [to provide] a safe and healthful workplace" [26].

3.4 Project Improvements

Given more time to complete this project, we believe that there are three significant improvements that could be made towards our design. These improvements could be implemented on both the software and hardware components of the project in order to make a more streamlined, intelligent, and user-friendly system. The first is to expand the software capabilities to track real-time changes in the temperature of the drink. By implementing this, the user could use the smartphone app for more than just setting a standard temperature, as they could see in real-time how their drink is being heated or cooled by the coaster to decide if they want to stop the process early. Next, we can introduce voice control into the design by adding a microphone and additional software capabilities to take voice inputs from the user to heat or cool the drink, which would actually eliminate the need for a smartphone application to define their desired temperature. Finally, we would explore hardware improvements to lessen the time range needed for our coaster to heat and cool within a range of temperatures. This would require much deeper evaluation on Peltier module efficiencies and power flux, but we would ideally like our project to execute its intended functionality faster than common household appliances.

4 Progress Made on First Project

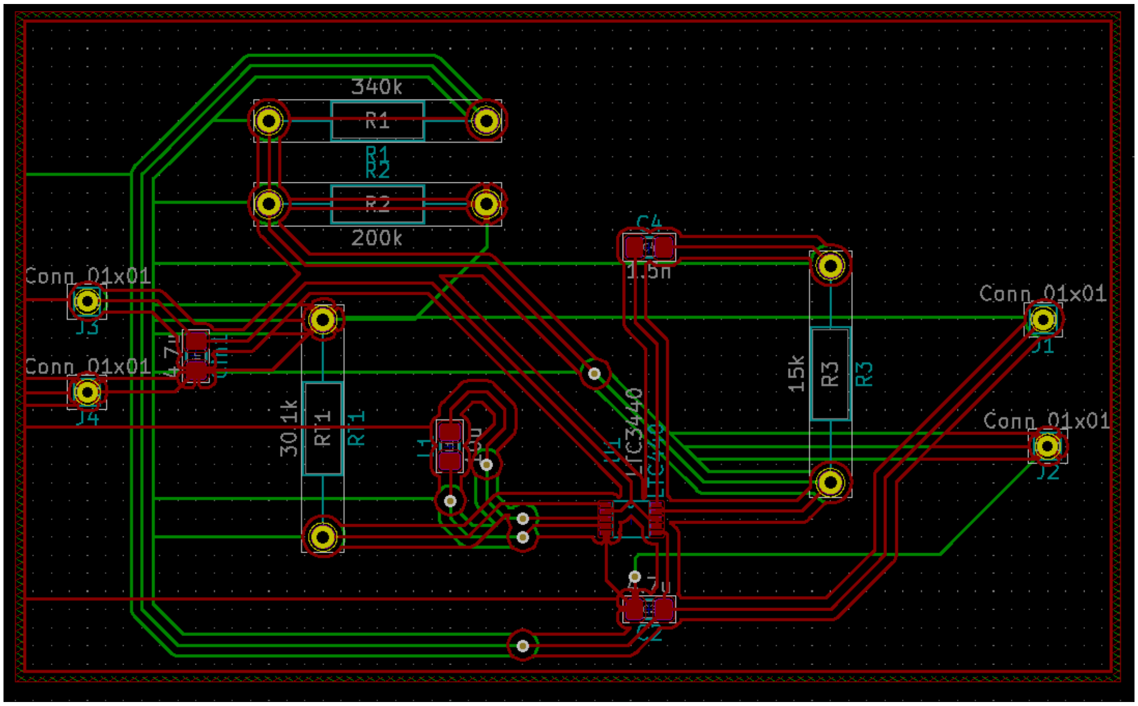

Figure 8. First Project PCB Schematic

Prior to the announcement changing the overall structure of the class our group had been working on developing several PCB layouts of several components that would be encapsulated within the wristband. Figure 8 depicts the completed layout of the 3.3 V voltage regulator within the Power Subsystem. As shown in the image the PCB consisted mostly of resistive and inductive elements to dynamically control the current output of the regulator. The value of the inductor was easily interchangeable due its standardized size which made the system significantly more adjustable if the proposed other aspects of the project drew more power than expected. Another key design decision made within this PCB was the size of the board which was approximately 3.5 by 2 centimeters which would be easily encapsulated by the wristband.

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Appendix A Requirement and Verification Tables

Table 1. Lithium-ion Battery Requirements and Verifications

Requirement	Verification
Must supply between 3.0-4.2 V to the circuit.	1. Measure output at various points in the battery's life using a voltmeter to ensure that the reading is within the required threshold.
Must supply continuous power to design components for 6-8 hours on full charge.	1. Drain battery charge. 2. Provide constant 4.2V to fully charge the battery. 3. During a 6 to 8-hour time frame, probe voltmeter to ensure there is above 3.0V being outputted.
Must be easily replaceable by the user.	1. Drain battery charge. 2. Ensure that the battery can be removed from the PCB and replaced with another one easily. 3. Measure battery output to ensure that the required voltage is being supplied by the new battery.

Table 2. Voltage Regulator Requirements and Verifications

Requirement	Verification
Must supply the voltage from the battery into the rest of the subsystems near the target 3.3V (±5%).	1. Measure output voltage from the regulator using a voltmeter to ensure that the reading is within the required threshold.
Must supply ample current for the design components and operates between 0-300 mA.	1. Use a multimeter on the voltage regulator's output to ensure that it will operate between 0-300 mA.

Table 3. AC/DC Converter Requirements and Verifications

Requirement	Verification
Must supply constant 12 V at over 1 A to the Peltier module.	1. Measure output voltage from the AC/DC converter using a voltmeter to ensure that 12 V supply is available. 2. Measure output current from the AC/DC converter using a multimeter to ensure 1 A current is outputted.

Table 4. Temperature Sensor Requirements and Verifications

Requirement	Verification
Must detect the temperature of a drink inside of a cup within ± 1° C.	1. Connect SDA/PWM digital I/O output from the temperature sensor to the GPIO input of the microcontroller. 2. Place a cup with 250 grams of room-temperature liquid on the coaster and record output data from the microcontroller. 3. Compare the temperature sensor value to the room temperature and ensure the reading is within ± 1° C.
Must be able to read temperatures between -12° C and 58° C.	1. Connect SDA/PWM digital I/O output from the temperature sensor to the GPIO input of the microcontroller. 2. Externally heat 250 grams of a liquid to 58° C and use a thermometer to determine when this temperature is reached. 3. Place the heated cup on the coaster and read temperature sensor value to ensure temperature reading is within ± 1° C of 58° C.

Table 4. Temperature Sensor Requirements and Verifications (continued)

Must be able to read temperatures between -12° C and 58° C.	4. Externally cool 250 grams of a liquid cooled to be -12° C and use a thermometer to verify the temperature is correct. 5. Place the cup on the coaster and read temperature sensor value to ensure temperature reading is within ± 1° C of -12° C.
Must be able to gather and send the drink's temperature information to the microcontroller.	1. Connect SDA/PWM digital I/O output from the temperature sensor to the GPIO input of the microcontroller. 2. Place a filled cup on the coaster and ensure output data from the microcontroller is readable.

Table 5. Pressure Sensor Requirements and Verifications

Requirement	**Verification**
Must determine the amount of fluid in a cup within ± 5 grams.	1. Connect output from the pressure sensor to the GPIO input of the microcontroller. 2. Fill a cup with 250 grams of water. 3. Place the cup on the coaster and record output voltage from the microcontroller via voltage divider. 4. Compare the pressure sensor converted value to the predetermined amount of water and ensure the reading is within ± 5 grams.

Table 5. Pressure Sensor Requirements and Verifications (continued)

Must be able to gather and send information to the microcontroller about the amount of fluid in a cup.	1. Connect output from the pressure sensor to the GPIO input of the microcontroller using a voltage divider. 2. Place a filled cup on the coaster and ensure output data from the microcontroller is readable.

Table 6. Peltier Module Requirements and Verifications

Requirement	Verification
Must be easily controllable via the microcontroller's input to the device.	1. Connect microcontroller GPIO voltage output to Peltier module. 2. Place 250 grams of a room temperature liquid on the coaster. 3. Use smartphone application to set desired temperature to be 5° C above current temperature. 4. Ensure drink temperature is 5° C above the initial temperature using a thermometer.
Can heat/cool the drink placed on top to a user specified temperature between -12° C and 58° C, as specified in the high-level requirements.	1. Place 250 grams of a liquid at room temperature in a cup on the coaster. 2. Set the desired temperature to be 58° C using the smartphone app. 3. Ensure the drink temperature is 58° C using a thermometer. 4. Allow the drink to cool back to room temperature, then repeat steps 2 and 3 with the desired temperature instead set to -12° C.

Table 6. Peltier Module Requirements and Verifications (continued)

Must heat/cool a drink within a range of 10-20 minutes.	1. Prepare 250 grams of a drink at room temperature and place the cup upon the coaster, squarely in the middle of the heating pad. 2. Use smartphone application to set desired temperature to be 35° C above current temperature. 3. Ensure using a thermometer that the drink is 35° C above the initial temperature within 20 minutes. 4. Repeat steps 2 and 3 with the desired temperature instead set to 35° C below current temperature.
Must be able to heat/cool on the same side of the Peltier module where a drink is placed.	1. Place 250 grams of a drink in a cup on the coaster at room temperature. 2. Use the smartphone application to set the desired temperature to be 5° C above the current temperature. 3. Use a thermometer to check that the temperature has sufficiently changed. 4. Repeat steps 2 and 3, setting the desired temperature to be 5° C below the current temperature.

Table 7. H-Bridge Requirements and Verifications

Requirement	**Verification**
Must be able to create a PWM output of 12 V and 1 A.	1. Connect chip outputs to the oscilloscope and input 12 V 1 A signal with a 3.3 V PWM signal. 2. Observe 12 V 1 A output waveform on the oscilloscope to verify.

Table 8. Microcontroller Requirements and Verifications

Requirement	Verification
Must be able to store data from the sensors and Bluetooth transceiver.	1. Connect sensor outputs to different GPIO inputs on the microcontroller. 2. Read information from GPIO ports to ensure there is data being stored. 3. Test the input signal by creating pressure on the pressure sensor. 4. Read information from the GPIO port the pressure sensor is connected to and verify that it has received the input.
Must be programmable to control heating/cooling subsystem and status LEDs.	1. Connect status LEDs to the microcontroller. 2. Create a test program to light up LEDs according to the temperature defined on the smartphone application. 3. Use the USB port to program the microcontroller. 4. Run the program and record how LEDs are lit and how various temperatures are handled to verify functionality.

Table 9. Bluetooth Transceiver Requirements and Verifications

Requirement	Verification
Must be able to transmit data within a range of 5 meters.	1. Connect a status LED input to a GPIO port on the microcontroller. 2. Program the microcontroller using USB to send temperature data through Bluetooth transceiver. 3. Have smartphone application backend print data it sends through Bluetooth.

Table 9. Bluetooth Transceiver Requirements and Verifications (continued)

Must be able to transmit data within a range of 5 meters.	4. Keep the smartphone 5 meters away from the coaster and verify that data is received on the microcontroller input.
Must reliably send the user's input data from the phone to the microcontroller without corruption.	1. Ensure that temperature sensor output is connected to a respective GPIO port on the microcontroller. 2. Verify that data from the Bluetooth transceiver is sent to the microcontroller. 3. Have smartphone application backend print data it sends through Bluetooth. 4. Record data and verify that it is readable and consistent with temperature sensor status.

Table 10. Smartphone Application Requirements and Verifications

Requirement	**Verification**
Must be Bluetooth compatible to send data to the coaster.	1. Ensure that the smartphone has Bluetooth capability turned on. 2. Send test data through the application to the Bluetooth transceiver on the coaster. 3. Read output data from the Bluetooth transceiver through the microcontroller and check that it is valid.
Must have a basic interface that allows users to easily specify what temperature they would like to prepare their drink at.	1. Compare user interface of application with standard iOS and Android utility applications. 2. Analyze any differences and verify that the user interface follows an expected design, making it easy to use.

Table 11. Status LEDs Requirements and Verifications

Requirement	Verification
Must be easily visible to the user while the coaster faces upward.	1. Verify that LEDs can be seen on the coaster when standing up to 5 meters away.
Must accurately light up respective LEDs according to control signals from the microcontroller.	1. On the smartphone application, choose a temperature that is higher than room temperature, and send this data to the coaster. 2. Ensure that the microcontroller's output port sends a control signal to the Peltier module to begin heating until it reaches the desired temperature, as well as data to the proper LED. 3. Allow for the coaster to return to room temperature. 4. Repeat steps 1 and 2, this time for a temperature cooler than room temperature.

Appendix B Cost of Components

Table 12. Breakdown of Components Costs

Part	Quantity	Cost
NRF52840-DK Microcontroller and Bluetooth Transceiver	1	$49
Melexis MLX90614ESF-BAA Infrared thermometer	1	$29.95
Hebei TEC1-12706 Peltier Module	1	$6.49
Adafruit Industries 3898 Lithium Ion battery	1	$6.95
Omron Electronic Components 2SMPP-02 Pressure sensor Round Force-Sensitive Resistor (FSR) - Interlink 402	1	$7.00
LTC3440EMS#TRPBF Buck-Boost Voltage Regulator	1	$6.99
Sparkfun Electronics COM-11120 RGB LEDs	3	$3.15
SL Power Electronics GECA20-12G AC/DC Converter	1	$24.92
Sparkfun Electronics H-Bridge ROB-14451	1	$4.95
Total	**11**	**$139.40**