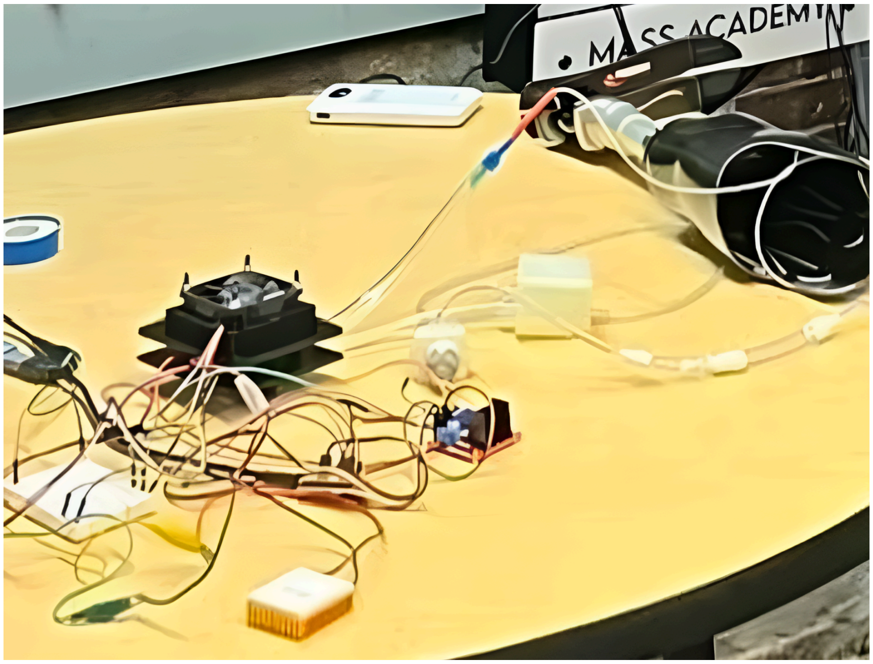
Frost Step

by Human+

Design Study and Project Report



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Section I. Introduction

Motivation (Written by Niranjan Nair, 5/21/25, reviewed by Raihan Ahmed 5/22/25)

Our group wanted to work on a project that could potentially help a large number of clients and that may have a big impact. Our previous experience included programming, robotics, mechanical engineering, CAD, and working with embedded systems like Arduinos. We felt prosthetic devices were an area of interest for many of us that matched our skillset fairly well. Because of this, we contacted Dr. Ian Gray from Next Step Prosthetics, where we discussed some potential problems that clients face. One problem that appeared across two rounds of discussion was a problem regarding heat in prosthetic devices, which Dr. Gray had mentioned many clients reporting (personal communication, March 3, 2025). We knew that a potential solution would complement our skills and help a large number of clients, hence we chose to work on this project.

Problem Statement (Written by Sriaditya Vaddadi, Andrew Brown and Raihan Ahmed, 5/21/25, reviewed by Niranjan Nair, 5/21/25)

Over 2 million people in the United States live with limb loss (Zhu et al., 2022). This paper will refer to individuals with limb differences as ILDs. Amputation can be very traumatic for a patient, as it often limits their ability to perform activities of daily life (ADLs). Most qualifying amputees will choose to use a prosthetic device to offset the issues caused by the loss of a limb, allowing them some sense of normalcy with the ability to integrate into society without the need for constant assistance. The component of the prosthetic limb that directly contacts the residual limb to form a connection between the body and the prosthetic is the socket. When properly fitted, a comfortable socket can be extremely influential in maximizing the prosthetic's utility in daily use, as otherwise the discomfort, or in some cases pain, will lead the amputee to abandon their prosthetic (Klute et al., 2001). Under the socket, ILDs must wear a silicone liner below the socket to improve comfort and safety (Zepeda, 2023). The silicone acts as a protective layer between the residual stump and the carbon fiber socket, providing equal pressure distribution and padding for the user's comfort. On top of this liner, they wear many layers of socks to ensure that the prosthetic device fits snugly.

Despite the benefits of using prosthetics and silicone layers, any amputees notice that after wearing their prosthesis for a few hours, especially if they were physically active in that period, their silicone liners can get very hot, and this often leads to discomfort in the form of irritation, infection, and an excessive buildup of perspiration, all of which may have a highly detrimental effect on quality of life (Ghoseiri & Safari, 2014). Many amputees with lowered quality of life will notice effects such as anxiety, depression, lower social output, and much more (Manz et al,. 2022), as well as a ceasing use of their prosthetics (Williams, 2020). In fact, over 53% of prosthetic users who discontinue use cite discomfort as a primary reason, suggesting that a cooling solution could mitigate non-use by overcoming these side-effects (Webster et al., 2023).

Target Audience (Written by Niranjan Nair, 5/21/25, reviewed by Raihan Ahmed, 5/22/25)

This product is intended for amputees and other ILDs who have issues with heat accumulation in their prosthetics. This includes much of the over 2 million people in the United States who live with limb loss (Zhu et al., 2022), because our product aimed to be usable for both individuals who rely on arm prosthetics and individuals who rely on leg prosthetics. However, our current device is tested with a leg prosthetic. We aimed to have a fairly broad target audience because we wanted to make a solution that could help a variety of individuals. Our direct target audience who will help with testing our device consists of patients from Next Step Prosthetics, who have generously allowed us to reach out and work with patients to see if our cooling solution may fit their needs. Since overheating seems to be a problem that many patients at Next Step report, we hoped our results from testing can be extrapolated to a wider audience of ILDs.

Engineering Goal (Written by Niranjan Nair, 5/21/25, reviewed by Raihan Ahmed, 5/22/25)

As a broad summary, our main engineering goal was to actively cool the residual limbs of ILDs with a compact and lightweight device that was durable enough for daily use. We wanted our device to be comfortable to wear, and we wanted it to empower clients who are moderately active ADLs more easily without reducing comfort in other ADLs. We also wanted a product that would not harm clients in failed test cases by avoiding the use of toxic chemicals and by having parts that were tightly held together.

Purpose of Document (Written by Niranjan Nair, 5/21/25, reviewed by Raihan Ahmed, 5/22/25)

First and foremost, this document aims to provide an overview of our design for the Assistive Technology project. It also aims to document our design process and research, and it aims to provide guidance on how to build, test, and use our device independently. Furthermore, it aims to address materials, costs, and future work that can improve on our current design, with apt comparisons to competing products.

Market Research (Written by Andrew Brown and Sriaditya Vaddadi, reviewed by Niranjan Nair 05/22/25)

Competitor 1

Our first competitor, patent US20160067062A1 by Jorgensen et al. in 2016, titled "Prosthesis cooling liner system", is a system in which people with prosthetic limbs wear a backpack containing a cooling liquid that is pumped into the liner system, cooling the prosthetic limb. As the person wearing the prosthetic limb must also wear a backpack, there is a level of extra discomfort. We believe that comfort is a necessity for our design, especially since our goal for this product is to increase the comfort for people with prosthetic limbs by reducing the sweat caused by excessive heat in prosthetics. Therefore, if we were to improve upon the product presented in this patent, we would attempt to focus on the comfort of the product. It is difficult to say exactly how effective the product is with regards to the quality of its cooling.

However, the graphs and quantitative data provided by the patent show that this product cools down prosthetic limbs much more efficiently than competitors.

Overall, an idea in which a cooling fluid is piped through the system in order to cool the prosthetic is intriguing. If we were to adapt this idea to our needs, we would likely focus on comfort (especially since wearing a backpack during exercise is clearly uncomfortable), and we would also have to gather more useful quantitative (and qualitative) data about the ambient cooling of the prosthetic cooling system.

Competitor 2

Our second competitor, patent US9155636B1 by Fikes in 2015, titled “Prosthesis socket liner”, details a prosthetic cooling system that uses air channels to help cool the prosthetic limbs. Specifically, the air channels are used to help transfer warm air out of the system, easing ambient cooling. This means that compared to the previous patent, this patent has much better ambient cooling and is likely more comfortable, as it is a compact design that can easily fit into the prosthetic (at least, from what is shown in the patent figures).

If our product were to be based on this patent, we would have to pay attention to temperature control. While it is easy to achieve ambient cooling using this solution, the lack of outside cooling methods means that the temperature cannot be changed outside of the ambient cooling. The usage of Peltier modules as an external cooling source could potentially adapt the patent to this shortcoming, as both ambient cooling through the air channels and temperature control through the Peltiers could be used in tandem for an overall more flexible cooling solution.

Competitor 3

Our third competitor, the WillowWood Alpha SmartTemp Gel Liner was specially highlighted by Dr. Gray during our meeting with him (personal communication, March 24, 2025). He mentioned multiple times how it is currently the leader in prosthetic cooling technology, and patients claim it works for quite a while. Further investigation reveals that this product works passively through the use of phase change materials (PCMs) (WillowWood, 2024). These materials are able to absorb heat radiating off the body, changing the phase of a material inside the liner. Because the liner absorbs the heat, it is not reflected back at the patient, keeping them at ambient temperatures. However, according to their website, this product will not last forever. Once the PCM has absorbed all the heat it can, the liner begins to act like a normal off-the-shelf liner. To fix this, the user is required to remove the liner and place it in an air conditioned room for multiple hours, leaving them without a cooled leg throughout that time.

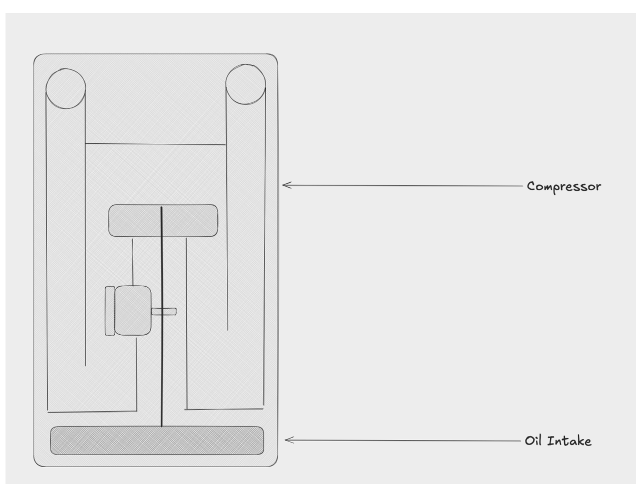
Preliminary Designs (Written by Niranjan Nair and Sriaditya Vaddadi, 05/22/25, reviewed by Raihan Ahmed 5/22/25)

Refrigerant-Based Cooling

The refrigerant-based cooling design involves the use of a condenser and refrigerant-based cooling. Refrigerant is used to cool the foot, being pumped through tubing around the residual limb. Refrigerants, however, are mostly toxic and expensive. Furthermore, this is the largest and heaviest of our three designs. However, there are non-toxic counterparts to refrigerant that we could use in tandem with the Peltier-Based Cooling method that will be explained in further detail later. Figure 1 shows a preliminary drawing of the refrigerant-based cooling method.

Figure 1

Refrigerant-based Cooling Design

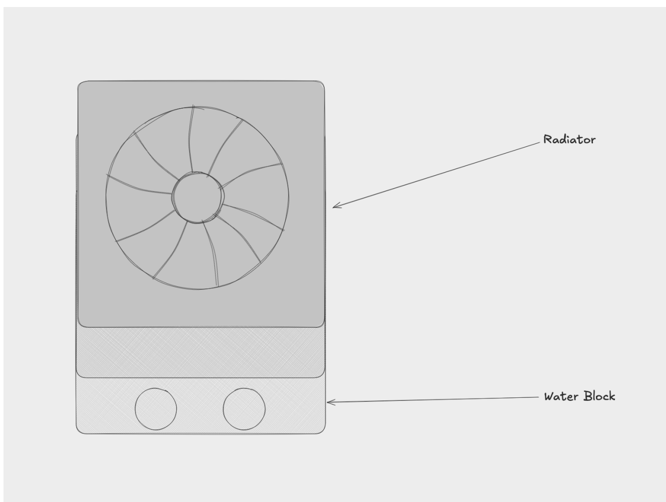


Radiator-Based Cooling

The radiator-based cooling design utilizes a radiator to passively cool a stream of water that flows through tubing around the prosthetic. The radiator connects to the water block, allowing it to efficiently dissipate heat. This design allows us to make a cooling attachment with a relatively small and quiet footprint, since it does not have many large parts and does not incorporate a fan. Figure 2 shows a preliminary drawing of the radiator-based cooling method.

Figure 2

Radiator-based Cooling Design

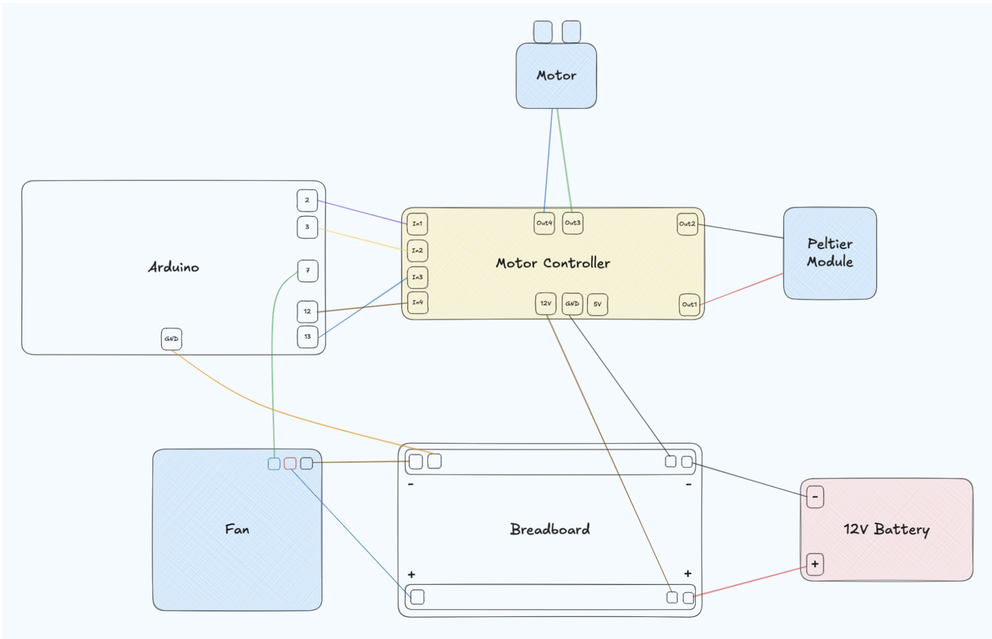


Peltier-Based Cooling

The Peltier-Based Cooling design uses a Peltier module to cool water that flows through tubing in the prosthetic. When the Peltier module is provided with electricity, the Peltier module gets cold on one side but hot on the other, so we are cooling the hot side using a fan. The Peltier module is connected to a metallic water block to efficiently cool the water, and a small pump is used to push the now cooled water through the tubing effectively cooling the residual limb. Figure 3 shows a preliminary drawing of the peltier-based cooling method.

Figure 3

Peltier-based Cooling Design



Section II. Builds and Testing

Build Steps (Written by Niranjan Nair and Raihan Ahmed, 5/22/25, Reviewed by Sriaditya Vaddadi, 5/22/25)

Summary of Parts

Our final design uses a breadboard, a 12V 2000mA power supply that connects to a wall outlet, an Arduino Nano, a motor controller, a motorized water pump, a 24V fan, a step-up converter, a Peltier module, a heat sink, a PLA-printed version of the CAD file with the casing (which can be found in our Google Drive), a resin-printed version of the CAD file for our reservoir (which can be found in our Google Drive), a metallic water block, and tubing with a 1mm OD (Outer Diameter).

Breadboard and Power Supply

The wall outlet power supply may be connected directly to the breadboard. For convenience, the voltage wire is connected to the positive row on the edge of the breadboard, while the ground wire is connected to the negative row on the opposite edge.

Peltier Block

The cool side of the Peltier module is attached to a water block that conducts heat towards it. The warm side of the Peltier is attached to a heat sink, and thermal paste is used to facilitate this adhesion. Extra care must be taken to ensure that the polarity of the battery is correct, or the Peltier will quickly overheat and possibly be damaged.

Fan and Casing

The printed design for the outer casing may now be assembled. Insert the Peltier block into the plastic container, making sure that the heat sink is above the bottom plate of plastic and that the water block is below this plate. Insert the fan into the top plate of the casing, and use M4 screws to secure the fan in place with the top and bottom plates. Make sure that wires are all still accessible.

Using the Motor

Connect the motor to output ports 1 and 2 of the motor controller. Make sure to reinforce the connections with screws to keep them tight and secure. Next, connect two large pieces of tubing to either end of the motor.

Wiring the Motor Controller

The motor controller can now be wired to the pins on the Arduino. Make sure to use the 12V ground rather than the 5V ground. The four consecutive outputs' corresponding inputs can be wired to pins A12, A13, A2, and A3 respectively. Then, wire the fan's adjustable output to pin A7.

Tubing and Reservoir

Connect the tubing off the motor controller to the reservoir, and use reservoir pins to connect the larger tubing to the smaller 1mm OD tubing that will be run inside the prosthetic. If a prosthetic is available, line the inside of the prosthetic with this thin tubing. Use a resin-printed pin (see Appendices) to connect the thinner tubing back to the thicker tubing of the motor.

Coding the Arduino

For the proof of concept, the Arduino code is rudimentary. It involves continuously supplying voltage to the motor controller as well as the control pin for the fan. The voltage specified in the code must be manually changed to give more power to these components, potentially in the case that the user wants to prime the water pump to remove air bubbles. A specific example of the code with the wiring described above can be seen in the Appendices section.

Running the Device

The user should begin by filling the reservoir with water and closing the lid. Then, the user should plug in the device to the wall outlet to provide it power. To ensure best performance, the pump and tubes should be primed before usage by running the device at a higher voltage until all air bubbles disappear.

Maintenance

Due to the 12V power supply, it is likely that after some time using it, the product's cooling will begin diminishing. If and when this occurs, the device should be removed and the battery must be charged prior to the next use. It is also recommended to charge the battery between uses if possible to make sure that the device has an adequate amount of power for cooling the limb temporarily. Priming the pump and tubes often will ensure maximum cooling efficiency, as well as refilling the reservoir in case of a leak. For maintenance purposes, it is also advised to keep the device safe from potential impacts in order to prevent damage to internal electronics. For this reason, various common activities are not recommended, including contact sports wherein electronics may get dislodged. If the electronics are damaged or fail to cool, remove power from the device and do not attempt to fix it yourself. In this scenario, call 774-486-0326 for customer support.

Safety

As water is being used in conjunction with electrical parts, there may be a significant risk to the wearer and/or electronics if the water and electronics come in direct contact. Therefore, it is necessary to seal the reservoir while the device is in use to reduce any water spillage. Furthermore, it is recommended to stay at relative rest throughout use of the device. Regular motions are fine, but any significant jolts of the leg may cause either the electronics to get loose or the reservoir seal to get loose, causing harm to users.

Experiments Overview (Written by Sriaditya Vaddadi, 05/22/25, reviewed by Raihan Ahmed 5/22/25)

Measuring Effectiveness

Our first design study/experiment helped us determine the overall cooling effectiveness of the first design. We did this by running water heated to roughly 91.4 degrees Fahrenheit through one of the first designs of our system over 11.5 minutes. The results of this design study can be seen in the "Design Study 1" subsection of Section III.

Comparing Fan Options

Our second design study/experiment helped us determine which fan to use for our current design - the Winsinn fan or the Pengdalantu fan. We did this by using both fans to directly cool the same temperature water for 5 minutes straight and determine which fan cooled the water more in the allotted time. The results of this design study can be seen in the "Design Study 2" subsection of Section III.

Section III. Analysis

Decision Matrix

Our current decision matrix consists of four competitors (three patents and one product actually in the market), two old designs and our current design (Table 1).

Table 1

Decision Matrix

#	Requirement Type	Description of Requirement	Level	Themoelectric v2	Thermoelectric v1	Radiator	Patent US20160067062A1	Patent US9155636B1	Patent US10624767B2	WillowWood Alpha SmartTemp Gel
1	Functional	Cools the prosthetic leg to an ambient temperature (below 70 degrees fahrenheit)	1	TRUE	TRUE	MAYBE	MAYBE (not enough info provided from graphs about specific temps)	UNKNOWN	UNKNOWN	TRUE
2	Physical	Does not cause signigicant discomfort to the user (qualitative)	1	UNKNOWN	UNKNOWN	UNKNOWN	UNKNOWN	UNKNOWN	UNKNOWN	TRUE
3	Physical	Product does not need to be carried in the clients hands	1	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
4	Physical	Product does not break/come loose from its compartment	1	UNKNOWN	UNKNOWN	UNKNOWN	UNKNOWN	UNKNOWN	UNKNOWN	TRUE
5	Physical	The product should not have any toxic comopnents or parts	1	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE
6	Functional	Users can control the temperature	2	MAYBE	FALSE	MAYBE	FALSE	FALSE	FALSE	FALSE
7	Functional	The product can be used in arm and leg prosthetics	2	TRUE	TRUE	TRUE	TRUE	MAYBE	FALSE (Only marketed towards leg prosthetics)	FALSE (Only marketed towards leg prosthetics)
8	Functional	The product can be used while the amputee is in motion	2	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
9	Functional	The product can automatically adapt temperature based on surroundings	2	MAYBE	FALSE	FALSE	TRUE	TRUE	TRUE	FALSE
10	Physical	The product adds less than 1lb to the prosthetic total weight	2	FALSE	FALSE	FALSE	UNKNOWN	UNKNOWN	UNKNOWN	TRUE
11	Budget	The product will not cost the user more than $300	3	TRUE	TRUE	TRUE	FALSE	UNKNOWN	UNKNOWN	FALSE
12	Functional	The product can be controlled with Bluetooth	3	TRUE (Not yet implemented for testing)	TRUE (Not yet implemented for testing)	TRUE (Not yet implemented for testing)	FALSE	FALSE	FALSE	FALSE
13	Physical	The product should not make more than 40dB of noise	3	TRUE	TRUE	TRUE	TRUE	MAYBE	MAYBE	TRUE
14	Functional	The product can be voice-controlled	3	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
15	Physical	The product is mounted on the prosthetic	3	MAYBE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE
				13	8	7	7	7	5	6

Prototyping Process (Written by Sriaditya Vaddadi, 05/22/25, reviewed by Raihan Ahmed 5/22/25)

Radiator-Based Cooling

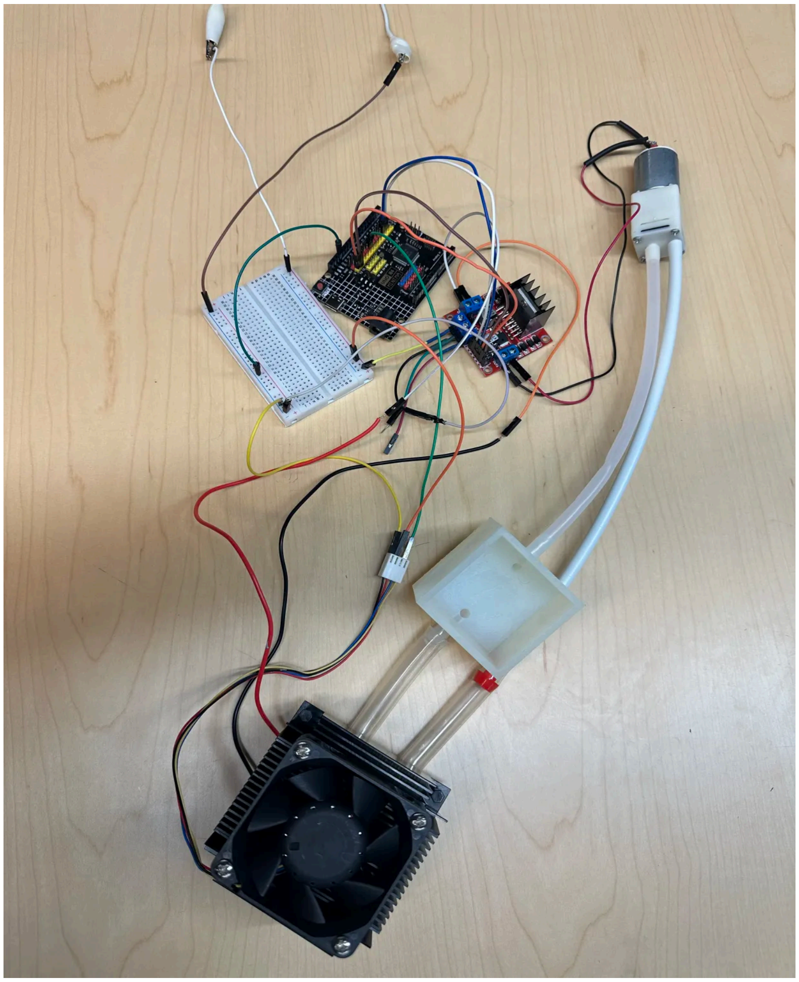
As explained earlier, the radiator-based cooling system works with a radiator and a water block, helping to passively cool water as it circulates through the system. One of our biggest concerns with this cooling method, and the main reason we did not pursue it further was its very bulky size and large weight, which would create an extra layer of uncomfortability for the user, something we are trying to avoid as much as possible. Therefore, we decided that the general idea of pumping water through the system, which would cool the prosthetic, should be kept, but that this idea should not be pursued due to the large weight.

Peltier-Based Cooling

Originally, our Peltier/Thermoelectric Cooling method could not be easily mounted to the actual prosthetic limb due to a multitude of factors, including general bulky size and shorter length of tubing meaning we could not wrap around the entire prosthetic. Therefore, we decided that we wished to continue working with the specific method of cooling, making small tweaks to these factors of the device.

Figure 4

Image of Peltier Design Prototype



Peltier Design Upgrades

With the knowledge that the previous Peltier-Based Cooling could not be directly placed on the prosthetic, we decided to design a "storage" for the device that could be mounted onto the prosthetic. We also bought more tubing to help wrap around the prosthetic. Since we wanted to place the tubing between the prosthetic and the liner, we had to acquire much thinner tubing, which also meant we had to make a connector between the large tube and the small tubing to avoid spillage.

Final Design Choices

Overall, as mentioned above, we decided to continue working with the Peltier-Based Cooling method due to its effective cooling while still being relatively lightweight. In order to improve the efficiency and overall comfortability of our cooling solution, we are currently working on fitting our design into a small storage that can be easily mounted on the prosthetic. We have also bought new thinner tubing in order to circulate water throughout the prosthetic without taking up too much space in the user's leg. Additionally, we have created new parts to hold the Peltier, connect the Peltier to the fan and waterblock, and connect the large tubing and small tubing together without leaving large gaps for air to enter.

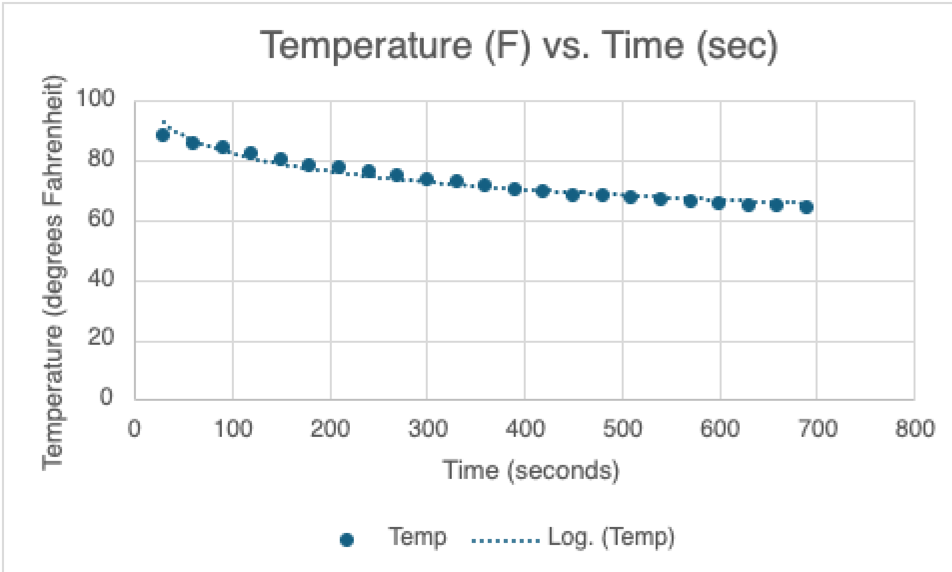
Design Studies

Design Study 1: Measuring Effectiveness (Written by Sriaditya Vaddadi, 05/22/25, reviewed by Raihan Ahmed 5/22/25)

This design study is a continuation of the "Measuring Effectiveness" subsubsection in Section II. The result of this study, as shown in Figure 4, was that our first design was able to cool the water from an initial temperature of 91.4 degrees Fahrenheit/33 degrees Celsius to 64.4 degrees Fahrenheit/18 degrees Celsius in 11.5 minutes. The relatively quick cooling of the water while the water is being circulated through the system highlights the effectiveness of our design.

Figure 5

First Design Study

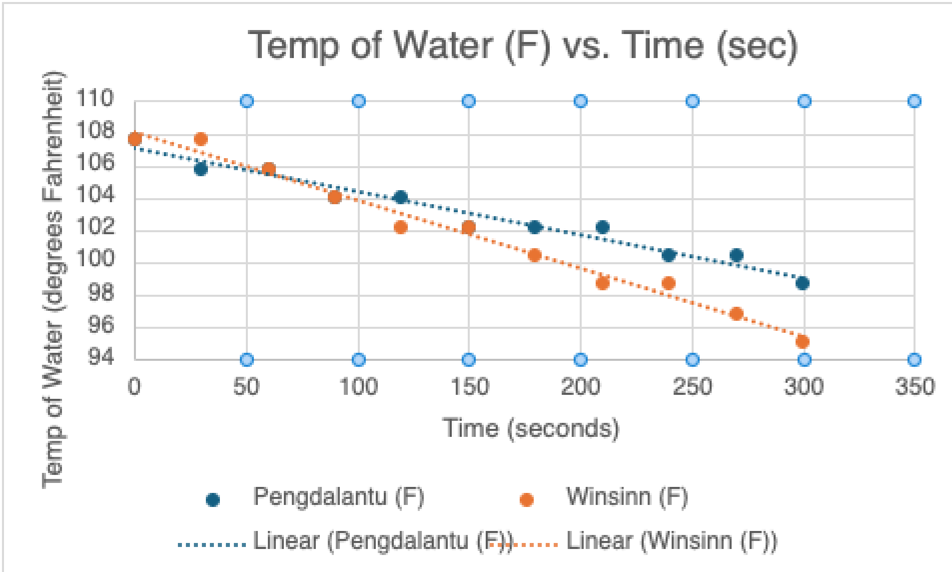


Design Study 2: Comparing Fan Options (Written by Sriaditya Vaddadi, 05/22/25, reviewed by Raihan Ahmed 5/22/25)

This design study is a continuation of the “Comparing Fan Options” subsubsection in Section II. The result of this study, as shown in Figure 5, was that the Winsinn fan was able to cool the water from almost 4 degrees Fahrenheit more than the Pengdalantu fan in the allotted time of 5 minutes. Therefore, we made the decision to use the Winsinn fan for our current design.

Figure 6

Second Design Study



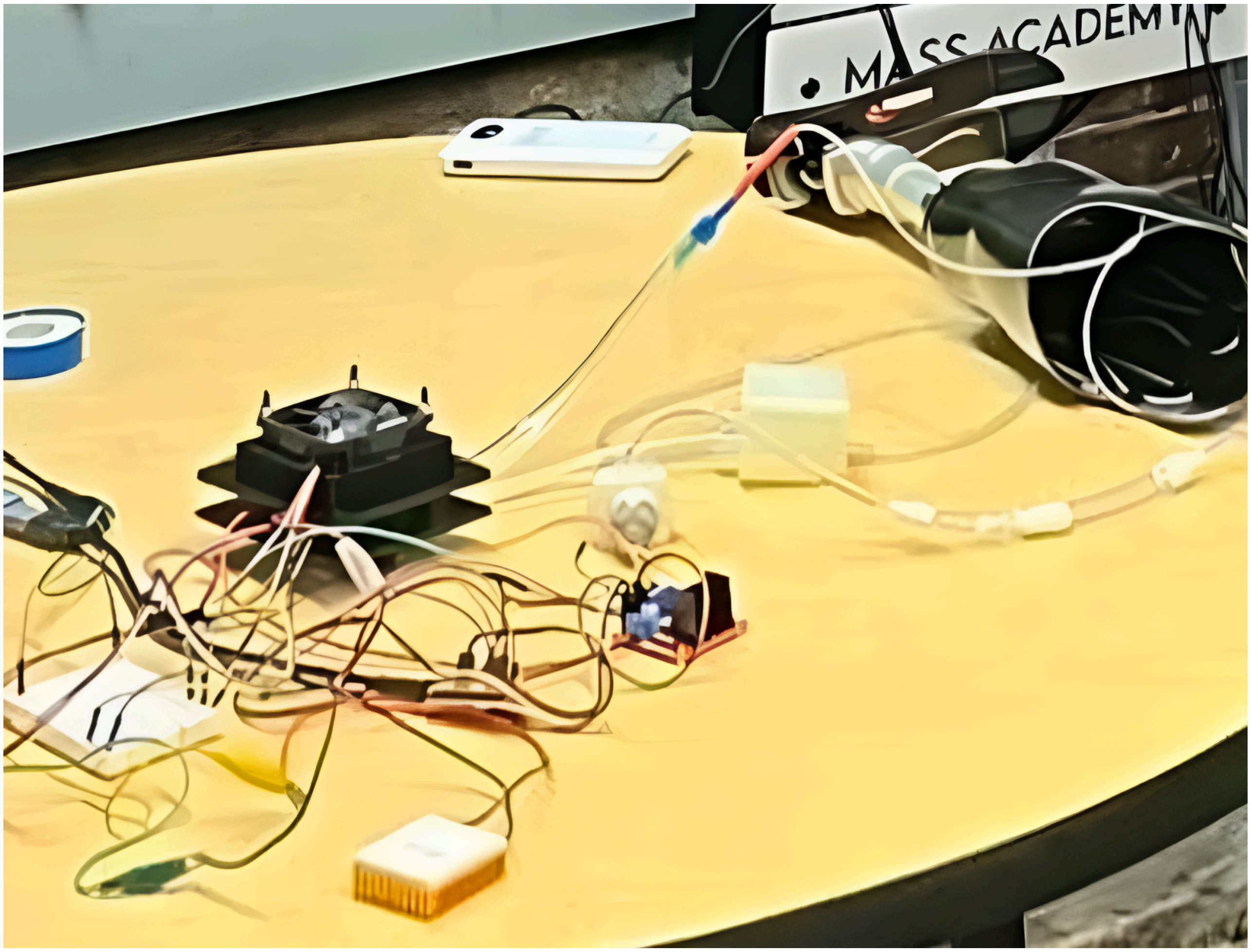
Final Design Summary (Written by Niranjan Nair and Raihan Ahmed, 5/22/25)

Description

Our final design consists of an Arduino Nano that is connected to a motor controller, which then connects to a Peltier module and a motorized water pump. The Arduino is also connected to a 24V fan through a step-up converter. We use a 12V 2000mA power supply that connects to a wall outlet, and we use a breadboard to connect our power supply to our device. Connected to the water pump is a long stretch of tubing, with a thin 1mm OD tubing lining the inside of the prosthetic. A heat sink is connected to the Peltier module, and the fan is attached on top of the heat sink, adding with it a plastic shell around this part of the device. A resin-printed reservoir is attached between the tubing, serving as an easy way to load water into the system or to deposit water out of the system.

Figure 7

Image of Final Design



Requirements

Our final Level 1 design requirements are shown in Table 2, which also lists whether or not these requirements were met.

Table 2

Level 1 Design Requirements

Type	Requirement	Met? (Y/N)
Functional	Cools the prosthetic leg to an ambient temperature (below 70 degrees fahrenheit)	Y
Physical	Does not cause significant discomfort to the user (qualitative)	?
Physical	Product does not need to be carried in the clients hands	Y
Physical	Product does not break/come loose from its compartment	Y
Physical	The product should not have any toxic components or parts	Y

Final Materials

There were various materials used in our final design. We used a 24V Winsinn fan, a step-up converter, a motor controller, an Arduino Nano, a breadboard, a 12V 2000mA power supply, 1mm OD tubing (approximately 10 ft), and a motorized water pump, a peltier module, a water block, a heat sink, and some parts specially created for this project using CAD (i.e. to stop leaking or to store the water, etc.).

Future Work and Ideal Design

In the future, we will mount our device onto a backpack or fanny pack so that it becomes wearable. We will attempt to increase the compactness of the wiring by putting the circuitry on a PCB (printed circuit board). We are hoping to include a probe temperature sensor to detect when the residual limb overheats so that the Arduino can automatically control the cooling as needed. To augment this, we plan to add Bluetooth connectivity to the device so that the user can use an app to choose whether the device should be activated or powered off.

Costs

Costs were fairly difficult to track since many parts for this project were kindly provided to us free of charge. However, our initial materials cost about $70 (including 3 small 12V fans, 3 heat sinks, 3 Peltiers, a water block, some tubing, and a large radiator fan), though not all of these materials were used in our final design. The total cost of our final design was roughly $70 as well, with many parts being reused while some new parts were added. The parts that were reused account for about $25 worth of costs, while the remaining costs come from the parts that were provided to us for our project.

Section IV. Appendix

Bill of Materials

- Motor Controller
- Arduino Nano
- Breadboard
- Step-Up Converter
- 1mm OD Tubing
- 12V Motorized Water Pump
- 24V Winsinn Fan
- Heat Sink
- Peltier Module

Tools Used

- Arduino IDE
- Soldering Iron
- Heat Gun
- Thermal Paste

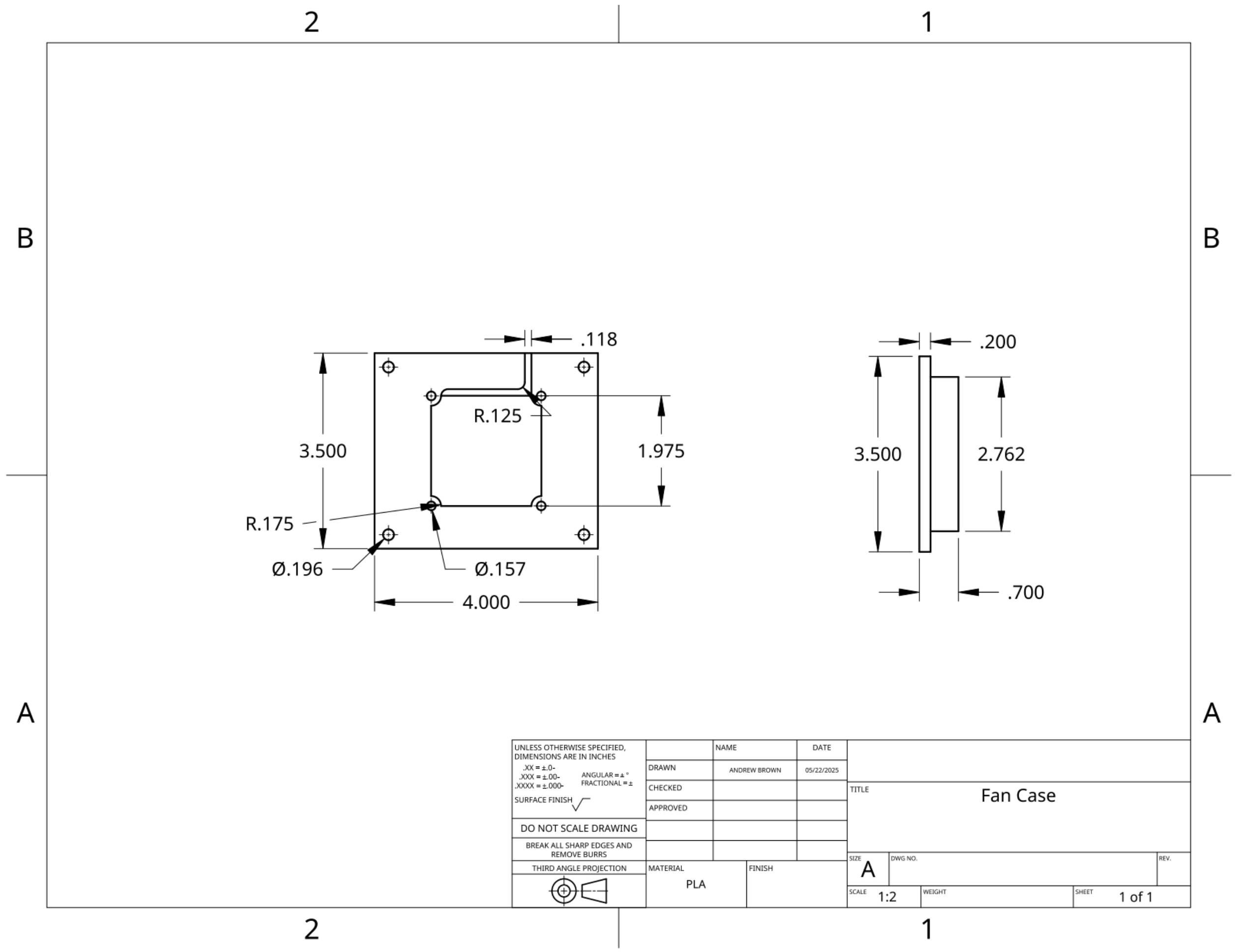
Arduino Code

```
// example code used is from
https://projecthub.arduino.cc/lakshyajhalani56/l298n-motor-driver-arduino-motors-mot
or-driver-l298n-7e1b3b
// code will be changed as per our needs

int motor1pin1 = 2;
int motor1pin2 = 3;
int motor1pin4 = 12;
int motor1pin3 = 13;
int fanmotor = 7;
```

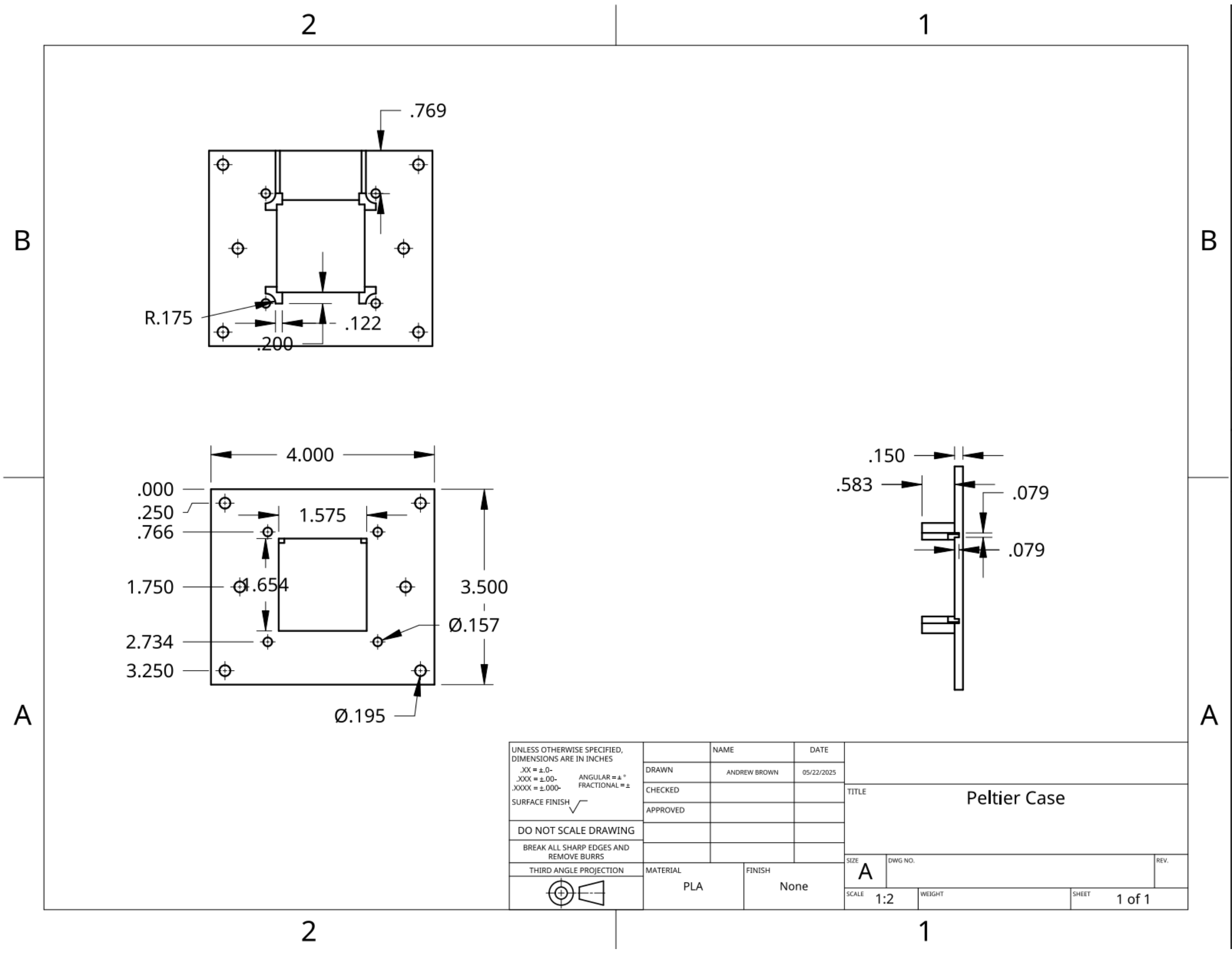
```
void setup() {
 Serial.begin(9600);

 pinMode(motor1pin1, OUTPUT);
 pinMode(motor1pin2, OUTPUT);
 pinMode(motor1pin4, OUTPUT);
 pinMode(motor1pin3, OUTPUT);
 pinMode(fanmotor, OUTPUT);
 }

void loop() {
 //Controlling speed (0   = off and 255 = max speed):

 digitalWrite(motor1pin1, HIGH); // 2 high
 digitalWrite(motor1pin2, LOW); // 3 high
 digitalWrite(motor1pin4, LOW); // 12 low
 digitalWrite(motor1pin3, HIGH); // 13 high
 digitalWrite(fanmotor, HIGH); // 7 high

}
```

Dimensional Drawings of Parts Created Using CAD

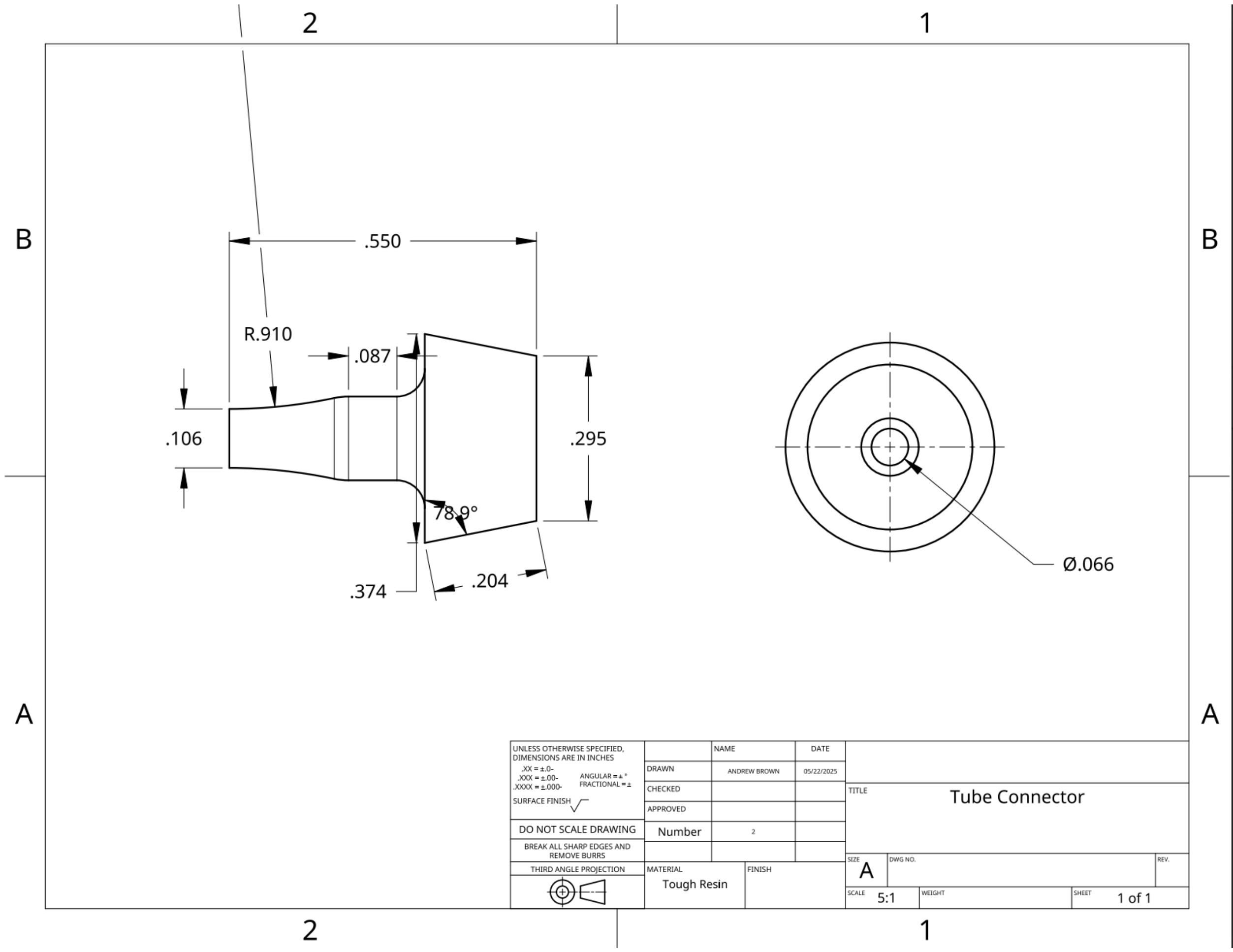
Fan Case



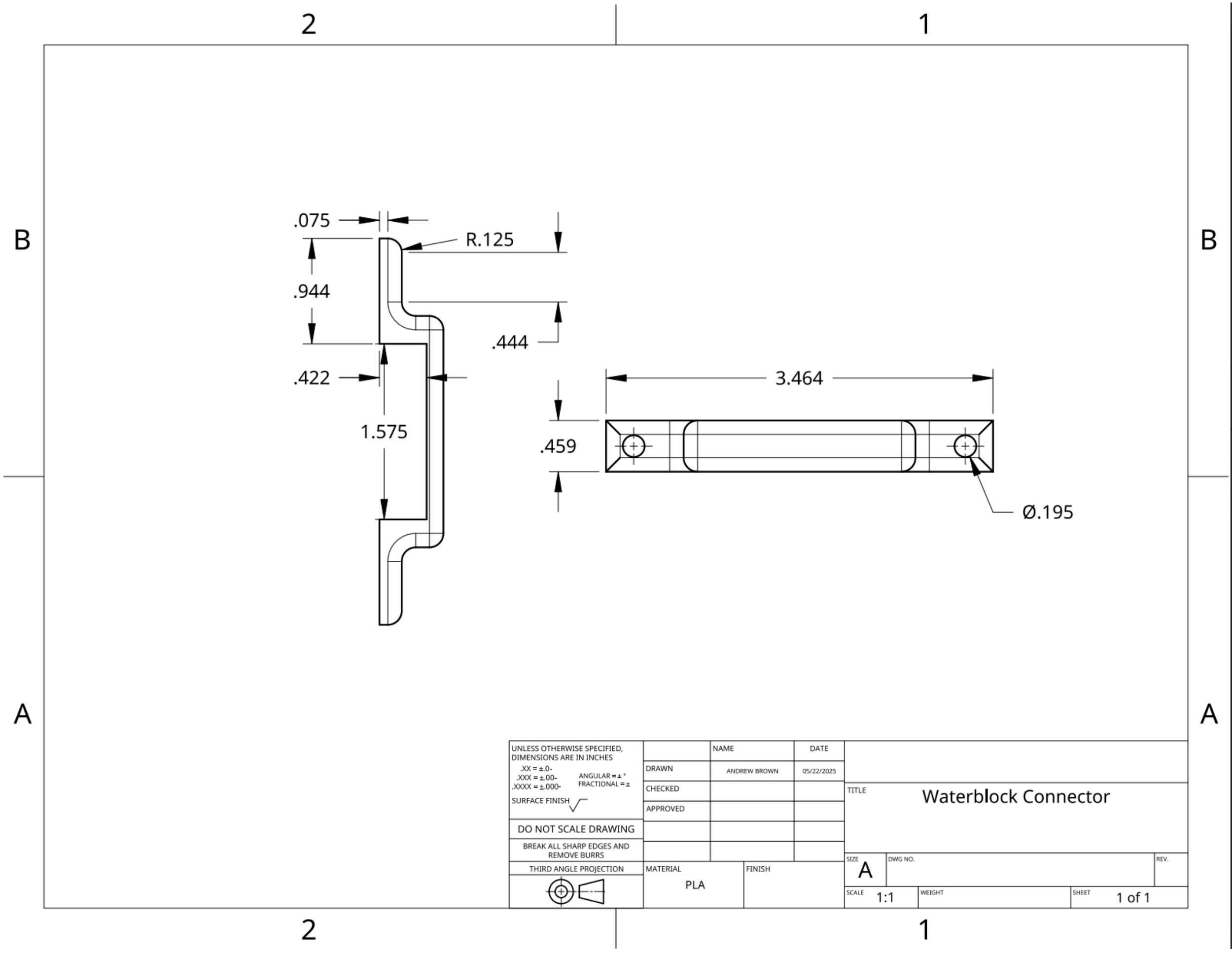
Peltier Case



Tube Connection



Water Block Connector



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